Low-pressure emplacement of epidote-bearing metaluminous granitoids in the Sierra de Chepes (Famatinian Orogen, Argentina) and relationships with the magma source

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ABSTRACT

A petrological and geochemical study of Lower Ordovician epidote-bearing granitoids of the Sierra de Chepes (Famatinian Orogen, Sierras Pampeanas, Argentina) indicates low-pressure emplacement of these extensive metaluminous suites. Textural relationships combined with major oxide and REE data support a magmatic origin for the ubiquitous epidote in hornblende-biotite granodiorite and tonalite plutons. Geothermobarometry using mineral assemblages in igneous rocks indicates a temperature interval from 780 to 850°C, and low emplacement pressures in the range of 2.2 to 4.1 kbar, consistent with those estimated from the metasedimentary envelope of the plutons. The widespread occurrence of primary epidote is a distinctive characteristic of the Lower Ordovician granitoids as opposed to the Andean Carboniferous granitoids emplaced at middle pressures (*e.g.*, Santo Domingo Complex, 7 kbar), where magmatic epidote-granitoids are scarce and secondary epidote is commonly present. On the other hand, the pistacite value ($Ps=[Fe^{3+}/(Fe^{3+}+Al)] \times 100$, in %) in magmatic epidote of the Ordovician granitoids (average Ps=28) sharply contrasts with that of magmatic epidote in the Carboniferous Andean granitoids (average Ps=24). This strongly suggests that the occurrence of magmatic epidote-bearing granitoids might be related to different sources, the Famatinian Orogen granitoids being mainly derived by melting of old continental lithosphere with probable partial contribution from subcontinental lithospheric mantle, and the Carboniferous Andean granitoids mainly resulting from mixing of crustal- and mantle- derived magmas. If the relationship of epidote-bearing granitoids to the characteristics of the source is confirmed in future studies, this will constrain the geotectonic environment in which the epidote-bearing magmas occur.

Key words: Magmatic Epidote, Metaluminous granitoids, Lower Ordovician, Low emplacement pressure, Geothermobarometry, Famatinian Orogen.

RESUMEN

Granitoides metaluminosos con epidota emplazados a baja presión en la Sierra de Chepes (Orógeno Famatiniano, Sierras Pampeanas, Argentina) y su relación con la fuente magmática. Un estudio petrológico y geoquímico de los granitoides metaluminosos con epidota, de la Sierra de Chepes (Orogenia Famatiniana, Sierras Pampeanas, Argentina), de edad ordovícica inferior, indica baja presión de emplazamiento de esta extensa serie metaluminosa. La combinación de relaciones texturales, elementos mayoritarios y de Tierras Raras, apoyan un origen magmático para los epidotos que se presentan en plutones granodioríticos y tonalíticos, con hornblenda y biotita. Cálculos geotermobarométricos utilizando asociaciones minerales en rocas ígneas, indican intervalos de temperaturas de 780 a 850°C, y bajas presiones de emplazamiento en el rango de 2, 2 a 4,1 kbar, que son consistentes con aquellas estimadas a partir de los metasedimentos donde se emplazaron los plutones. La abundancia de epidota magmática es una característica distintiva de los granitoides del Ordovícico Inferior, en oposición a los granitoides

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andinos del Carbonífero (*e.g.*, el Complejo Santo Domingo, 7 kbar), donde la epidota magmática es escasa y la presencia de epidota secundaria es común. Por otro lado, el valor de pistacita (Ps=[Fe^{3+}/(Fe^{3+}+Al)] x 100, en %) en la epidota magmática de los granitoides ordovícicos (promedio Ps=28) contrasta marcadamente con los valores de pistacita observados en los epidotas magmáticas de los granitoides andinos carboníferos (promedio Ps=24). Esto sugiere, que la presencia de epidota magmática en granitoides puede ser relacionado con diferencias en la fuente, ya que los granitoides del Orógeno Famatiniano fueron esencialmente derivados por fusión de una litósfera continental antigua con probable contribución parcial del manto litosférico subcontinental, y los granitoides andinos carboníferos son, esencialmente, el resultado de una mezcla de magmas derivados de la corteza y el manto. Si la relación entre la presencia de epidota magmática en granitoides y la fuente es confirmada en estudios posteriores, se podrá entender de mejor manera el ambiente geotectónico en el cual los magmas alojan epidota.

Palabras claves: Epidota magmática, Granitoides metaluminosos, Ordovícico Inferior, Baja presión de emplazamiento, Geotermobarometría, Orógeno Famatiniano.

INTRODUCTION

After experiments by Naney (1983), which demonstrated that the epidote (Ep, mineral abbreviation from Kretz, 1983) in granodiorites and monzogranites could be stable above the solidus (~ 675-710°C) at pressures of 2 to 8 kbar, this mineral became a matter of petrologic interest. Originally, Zen and Hammarstrom (1984), based on Naney's experimental work and their own pressure estimates from contact aureoles, estimated that epidote-bearing granitic plutons crystallised at high pressures (about 8 kbar), indicating deep emplacement for the granitic magmas. Tulloch (1986) questioned the idea that magmatic Ep stability in granitic plutons required high pressure. Moench (1986) described primary Ep from granitic plutons emplaced at pressures of 2-4 kbar. Johnson and Rutherford (1989) pointed out that intermediate pressures, between 2 and 8 kbar, had not been investigated, and thus the minimum pressure required for igneous Ep stability was unknown. Later, Vhynal *et al.* (1991), observed that Ep exhibiting textural and compositional characteristics suggestive of magmatic origin occurred in plutons emplaced at intermediate-low pressures (3-5±0.5 kbar).

Schmidt and Thompson (1996) demonstrated from experiments, performed with fo_2 buffered by hematite-magnetite(HM), that Ep could be stable in calc-alkaline magmas (tonalitic compositions) at pressures of less than 3 kbar. Based on experimental measures of Ep dissolution, Brandon *et al.* (1996) proposed that the transport of magma from the deep crust was fast enough to prevent complete Ep resorption. These authors also concluded that the presence of magmatic Ep in granitoids is not sufficient in itself to establish high-pressure conditions of granite solidification. All this illustrates the existing controversy over the origin and petrological meaning of magmatic Ep.

This paper is focused on the study of magmatic epidote-bearing metaluminous granitoids, located in the Sierra de Chepes, which is part of an extensive magmatic province in the central Argentina, east of the main Andean cordillera (Fig. 1a). These granitoids were formed in the Lower Ordovician during the Famatinian orogeny, which took place along the proto-Andean margin of Gondwana. The combination of textural and chemical (major oxides and Rare Earth Elements, REE) evidence, leads to the conclusion that the Ep has a magmatic origin, even though the granitoids where Ep is lodged were intruded at low pressure conditions, indicated by pressures in the range 2.7-3.6 ± 0.5 kbar calculated using the Al-in-Hbl geobarometer of Johnson and Rutherford (1989), or 3.0 ± 0.6 kbar obtained using the calibration of Anderson and Smith (1995) for mineral assemblages in equilibrium at less than 800°C. These results are consistent with the pressure values obtained from the metamorphic rocks associated with the magmatism (2.5±0.5 kbar, Dahlquist and Baldo, 1996; Pankhurst *et al.*, 1998).

It is important to emphasise that the magmatic rocks formed during the Famatinian Orogen show different isotopic signatures from those of the Carboniferous Andean batholiths (Pankhurst *et al.*, 1998; Parada *et al.*, 1999). The Ordovician granitoids were derived from melting of an old continental lithosphere (~ 1700 Ma) perhaps with partial contribution of subcontinental mantle (Pankhurst *et al.*,

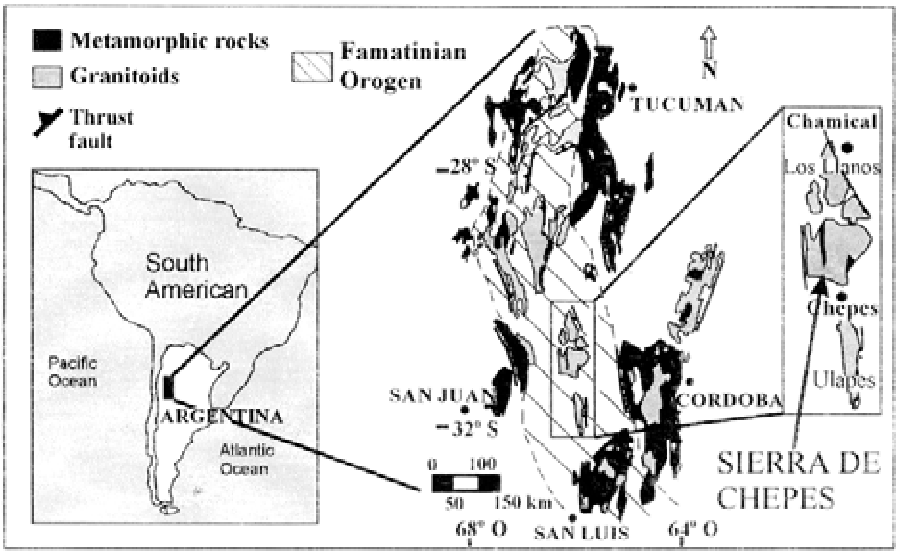


FIG. 1a. Simplified sketch map of the Sierras Pampeanas, Argentina. The main belt of the Famatinian magmatic arc (Early to Mid-Ordovician) is indicated by the stripe field.

1998, 2000; Rapela, 2000), while the Carboniferous Andean metaluminous granitoids resulted from different degrees of mixing of crustal- and mantle- derived magmas (Parada *et al.*, 1999).

The widespread occurrence of primary Ep in granitoids emplaced at low-middle pressure (2,5-7.5 kbar) conditions is a remarkable characteristic of the Ordovician orogen (Saavedra *et al.*, 1987; Sial *et al.*, 1999; Dahlquist, 2000) that is not observed in the Carboniferous Andean granitoids. The latter have relatively scarce magmatic Ep with different pistacite values (Sial *et al.*, 1999) and middle emplacement pressures (7 kbar, Parada *et al.*, 1999). The granitoids of these two suites have similar major and trace element abundances, but different isotopic signatures. Thus, the characteristics of the Ordovician granitoids can help to better define the geotectonic environment in which these high-level magmas with magmatic Ep crystallised.

GEOLOGICAL SETTING

The Sierra de Chepes (Fig. 1a, b) is set within the Famatinian orogenic belt, developed during the Lower Palaezoic in the proto-Andean margin of Gondwana (Pankhurst *et al.*, 1998; Rapela *et al.*, 1999). It is mainly composed of Lower Ordovician, metaluminous dominant, calc-alkaline granitoid suites. Petrological, geochemical and isotopic studies indicate that the observed compositional range of 60 to 75% SiO_2 of the granitic rocks was produced by fractionation of primary magmas generated in turn from partial melting of an old lower crust (Pankhurst *et al.*, 1998; Dahlquist, 2000). There is an isotopic homogeneity in initial $^{87}Sr/^{86}Sr$ and $^{143}Sm/^{144}Nd$ ratios, which has been interpreted as the result of a closed crystallisation system without an important contamination of the magma during its evolution (Pankhurst *et al.*, 1998; Dahlquist, 2000), being fractional crystallisation the main differentiation process (Dahlquist and Rapela, 1997; Pankhurst *et al.*, 1998; Dahlquist, 2000).

The Sierra de Chepes is dominated by a lithology of granodiorites and tonalites, with less abundant monzogranites and leucogranites (Pankhurst *et al.*, 1998; Dahlquist, 2000). Two main magmatic units

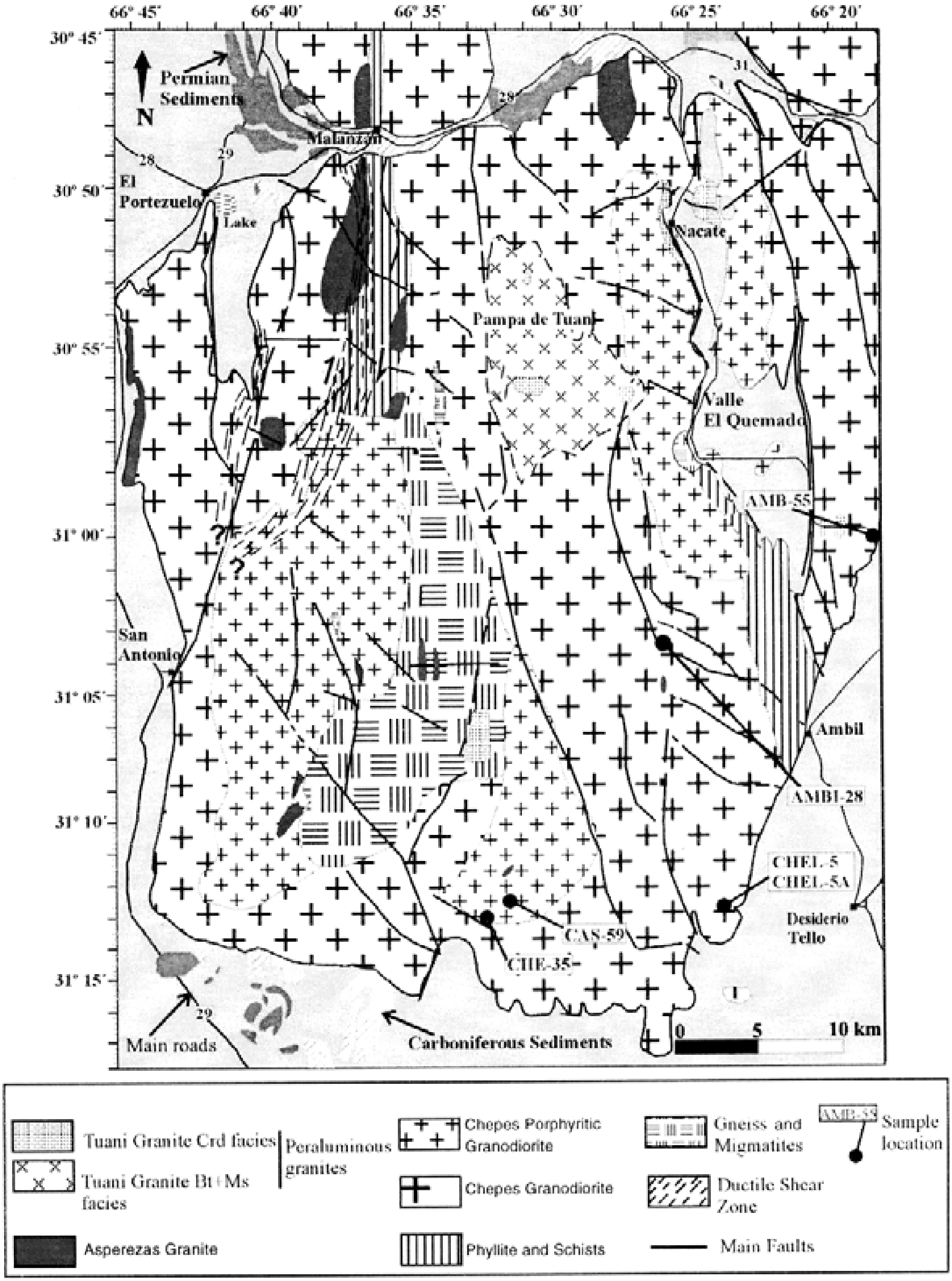


FIG. 1b. Simplified geological map of the Sierra de Chepes, from Pankhurst *et al.* (1998) and Dahlquist (2000), with location of the studied samples.

are recognised in the Sierra de Chepes: the Chepes granodiorite (ChG) and the Chepes Porphyritic granodiorite (ChPG).

The ChG unit is the most abundant, it is equigranular, and medium grained (1.5 cm), with the typical presence of microgranular mafic enclaves. The magmatic paragenesis is: microcline (Mc), plagioclase (Pl), biotite (Bt) and hornblende (Hbl), and the accessory minerals are: epidote (Ep)± allanite (Aln), titanite (Ttn), apatite (Ap) and zircon (Zrn). The ChPG unit is coarse-grained (2-2.5 cm) characterised by the presence of alkali feldspar megacrysts (4 cm) and scarce or absent mafic microgranular enclaves. The mineral paragenesis is similar to that of the ChG except for an increase of some felsic mineral phases such as Mc and Qtz, and Aln minerals. Major element geochemistry indicates that both units are metaluminous (Aluminium Saturation Index=0.92- 1.1), displaying K_2O content between 1.5 and 3.5%, and a Peacock index of 63.5, indicating a calcic association. The ChG unit shows a silica range between 60 and 67% (average = 65%) while the ChPG unit shows a silica range between 66 and 70% (average= 68%). Detailed petrological and geochemical information about Sierra de Chepes is reported in Pankhurst *et al.* (1998) and Dahlquist (2000).

TEXTURES AND ROCK FORMING MINERALS

The average model of the magmatic assemblage for the unit ChG is 7% Mc (Or_{90}–Or_{97}) 35% Pl ($An_{52(core)}$ – An_{39}), 33% Qtz, 16 % Bt [$Fe^{2+}/(Fe^{2+}+Mg)$ = 0.48 in average] and 3% magnesian Hbl; Ap, Ttn, Ep, Aln, Mag (Ti-maximum = 0.05) and Zrn (6%).

The magmatic association for the ChPG consists of 14% Mc (Or_{87-95}), 34% Qtz, 34% Pl ($An_{54(core)}$-An_{39}), 12% Bt [Fe^{2+}/ (Fe^{2+}+Mg) = 0.50 in average)] and 1% magnesian Hbl; Ap, Ttn, Ep, Aln, Mag (Ti-maximum = 0.04) and Zrn (5%), although with a higher quantity of Aln than the ChG unit. Both units show myrmekites and albitic exsolutions associated to Pl and Mc. The assemblage and abundance of the accessory minerals (*e.g.*, Aln, Ep, Ttn, Ap, Zrn and Mag) in ChG and ChPG units are a distinctive characteristic of the metaluminous magmatism in the Sierra de Chepes (Dahlquist, 2000).

The alkali feldspar is Mc with cross-hatched twinning, perthitic crystals of this mineral with similar textural characteristics being common. The Mc appears as poiquilitic phenocrysts (Mc_a) and fine-grained Mc (Mc_b). The Mc_a exhibits approximately square sections in thin section, is anhedral with mineral inclusions of Pl, Bt, Qtz and Hbl. Similar characteristics are shown by the Mc in the ChPG unit, despite the Mc_a being here bigger (9 mm x 10 mm) with scarce inclusions. The Mc_b is fine-grained (0.7 mm x 0.4 mm), generally anhedral and without inclusions. The Pl is abundant and crystals of three sizes are identified: **a-** coarse grained Pl (2.5 mm x 1.2 mm, Pl_a); **b-** medium grained Pl (1.2 mm x 0.5 mm, Pl_b) and **c-** fine grained Pl (0.25 mm x 0.5 mm, Pl_c). The Pl_a has rectangular sections, with rim overgrowths, polysynthetic twinning, normal and/or 'patchy' zonation. These larger plagioclase grains may have small Hbl inclusions (0.5 mm), located in the core of the mineral. The Pl_b and Pl_c are subhedral, presenting rectangular sections in thin section, with polysynthetic twinning and/or normal zonation. The Pl_a is not abundant and is homogeneously distributed in the rock. The Pl_b and Pl_c, dominant varieties, are homogeneously spread in the crystalline frame and constitute several inclusions in the Mc_a.

The Qtz shows two varieties, a coarse grained one (3-2 mm diameter Qtz_a) and a fine-grained (0.4-0.8 mm diameter Qtz_b). Qtz_a arises as an individual mineral phase, whilst Qtz_b appears essentially as an inclusion in the Mc_a. The mafic minerals (Bt and Hbl), have two grain sizes; **a-** coarse grained (2-3 mm x 0.8-1mm, Bt_a and Hbl_a) and **b-** medium/fine grained (1-0.5 mm x 0.7-0.4mm, Bt_b and Hbl_b). The Bt and Hbl (a) variety are dispersed uniformly in the crystalline frame, while Bt and Hbl variety (b) is included in the Mc_a. Both varieties of Hbl and Bt are characteristically subhedral. Chlorite replancing Bt and/or Hbl as a secondary mineral has been observed.

ANALYTICAL METHODOLOGY

The principal mineral phases were analysed with a JEOL-JXA-8900M electron microprobe in the Luis Brú Electron Microscopy Centre, Universidad Complutense, Madrid, Spain. Accelerating voltage was 20 kV and beam current 15 nA, while beam diameter was 5 μ. The counting time was approximately 10 s. Two accessory minerals, Aln and Ep, also have been analysed with the same electron microprobe. In this case accelerating voltage was 20 kV and beam current was between 15 and 50 nA while beam diameter was between 2 and 5 micron. The counting ranged from 10 to 100 s, depending on the element to measure. The standards selected are those of the Smithsonian Institute, Washington, that have been described by Jarosewich and Boatner (1991). Interelemental interferences were suppressed by peak-overlap corrections (Roeder, 1985). More details referring the measurement conditions can be checked in González del Tánago (1997).

EPIDOTE: EVIDENCES OF MAGMATIC ORIGIN

Detailed textural and compositional information are reported in Dahlquist (1998, 2000). A brief description of the textural relationships of Ep and Aln follows. The latter is a mineral which always occurs in association with Ep.

ALLANITE

It can be found in both ChG and ChPG units, although it is more common in the latter. Its modal occurrence is very variable (0-0.5%). If two thin sections of the same rock are considered, it can be present in one and absent in the other. Consequently, it is very difficult to quantify the Aln modal presence in any plutonic unit of the Sierra de Chepes. Although it is feasible to estimate the approximate modal content of an accessory mineral in a single thin section, it is not usually possible to infer its accurate whole-rock abundance due to the very inhomogeneous distribution.

The Aln is euhedral to subhedral; they generally show zonation and are rimmed by Ep and more externally by Bt (Fig. 2a). It also may be associated with large size of Ttn minerals (Fig. 2b). A general characteristic of the Aln is a clear oscillatory zonation as can be seen in Figs. 2a, b, and c.

The Aln analysed in this paper (Fig. 2a), shows almost rectangular sections in thin section (1 mm x 0.5 mm), with subhedral irregular contacts with Pl and Ep. The Ep surrounds the Aln, having possibly been grown from the Aln. Optically, the Aln displays an oscillatory zonation, with a small crystal of euhedral Bt that, in turn, has a very small innermost core of Aln (Fig. 2a).

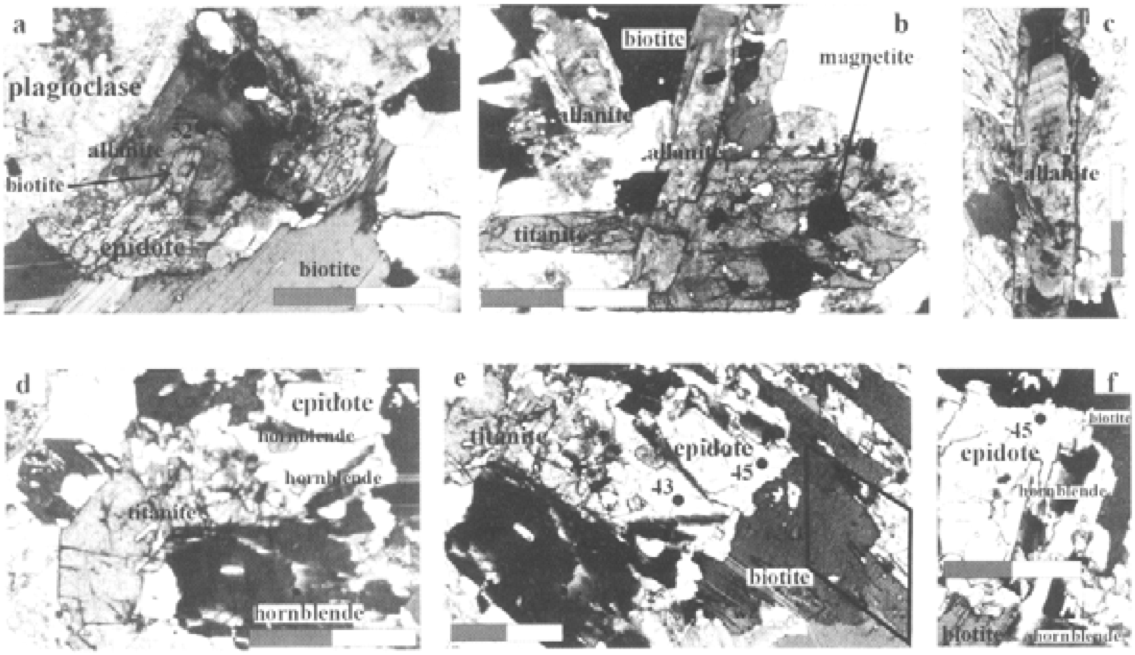
Figure 2a shows the place where the mineral was analysed and the associated textural context, while the data obtained are on table 1. Figure 3a indicates that the Aln is enriched in REE, in particular the light REE (La, Pr and Nd). The REE pattern is similar to that determined by Gromet and Silver (1983) and Sawka (1988), though the Aln analysed is comparatively more enriched in medium and heavy REE (with a quite remarkable peak at Gd). The contents of Y and Zr are low while that of Th is high, the latter being the most abundant element together with light REE (Fig. 3a).

EPIDOTE

This mineral occurs in both granodioritic units, showing variable modal proportions between 0.1 and 3.3% (Dahlquist, 2000). The textural evidence allows discrimination of two main Ep groups: Group I; magmatic epidote (GI-Ep) and Group II; secondary epidote (GII-Ep).

GI-Ep exhibits the following textural characteristics (Figs. 2a, d, e, f, g):
(i) euhedral rims in the contact with Bt and/or Hbl;
(ii) euhedral Aln with marked zonation, surrounded by Ep;
(iii) inclusions of Hbl-Bt in the Ep;
(iv) Ap included in Ep.

Figures 2a, d, e, f illustrate the textural context of the analysed Ep. Figure 2e shows the analysed



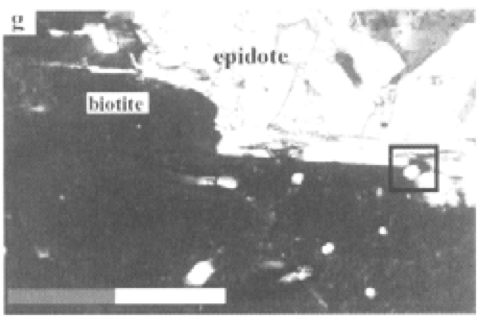


FIG. 2. Plane-polarized light photomicrographs of the analysed minerals. Scale bar represents 1 mm in photomicrographs a, b, c and d. In photomicrographs e, f and g scale bar represents 0.5 mm. FIG. 2 shows the electron microprobe spot locations where the mineral was analysed and the associated textural context (see mineral analysed in Table 1); **a-** euhedral allanite it with oscillatory zoning surronded by epidote and rimmed by biotite.; **b-** two euhedral allanite crystals with remarkable growth associated with titanite, biotite and hornblende. Both allanite display oscillatory zoning; **c-** oscillatory zoning in allanite; **d-** textural context ofthe analysed epidote and titanite. Small inclusions of hornblende in epidote, and euhedral-subhedral contact between biotite and epidote can be seen in detail in e, f and g. this figure is detailed from black frame in e. Small inclusions of apatite (hexagonal) in biotite and in the epidote-biotite contact (see black frames). Inclusions of apatite in epidote cannot be observed for very small size.

area results detailed in table 1. Two representative analyses have been chosen in order to illustrate the general Ep composition. Figures 2d, e, f, show a somewhat rectangular section of Ep with euhedral to subhedral rims in contact with Bt, Hbl and Ttn. It shows a relatively large size (1 mmx1.3 mm) with inclusions of Hbl and occasionally, Ap (Fig. 2g).

The Ep has high contents of some light REE, such as La and Ce and relatively high contents of heavy REE such as Er and Yb (Fig. 3b and Table 1). In the Sierra de Chepes, the Ep shows lower Y and Zr contents (Fig. 3b). The REE contents are similar to those reported by Dawes and Evans (1991) and Keane and Morrison (1997) for primary Ep, though with higher heavy REE values (Fig. 3b).

The content of pistacite (in %) [Ps=Fe^{3+}/(Fe^{3+}/Al)) x 100] for the analysed Ep varies from 26 to 31, with an average value of 28 (Fig. 4). The Ps content of magmatic Ep is very similar to those obtained in experimental works (as Ep crystallisation from intermediate composition melt, such as granodiorite, *e.g.*, Liou, 1973; Naney, 1983), and Ep that has been considered magmatic in petrological studies by different authors (Zen and Hammarstrom, 1984; Tulloch, 1986; Brandon *et al.*, 1996; Vhynal *et al.*, 1991; Keane and Morrison, 1997).

EMPLACEMENT CONDITIONS OF THE IGNEOUS ROCKS

Anderson and Smith (1995) concluded that temperature and in particular fo_2 are parameters that should be carefully evaluated before the application of a given geobarometer. The following considerations were carried out in the analysed rocks prior to the application of the Al-in-Hbl geobarometer. In the first place, selected hornblende-plagioclase assemblages used in the pressure and temperature calculations are described.

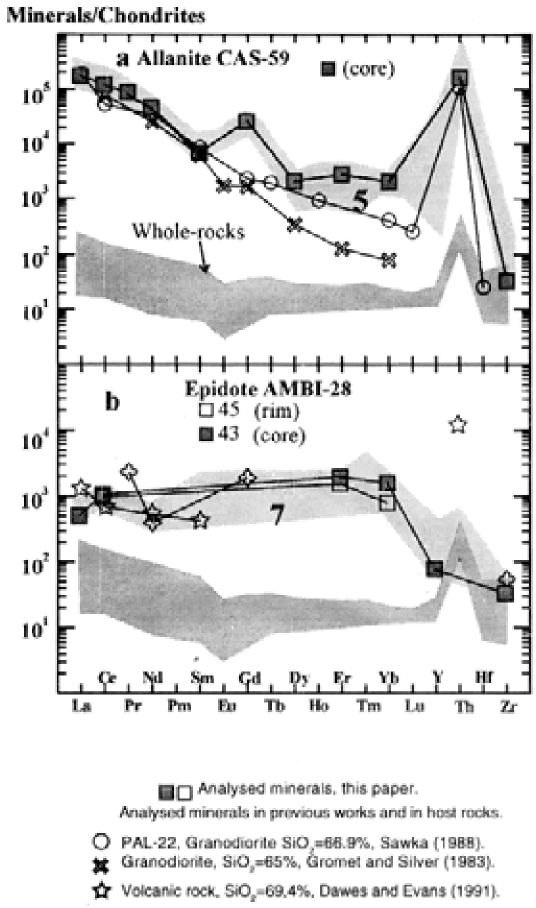


FIG. 3. Chondrite normalised trace element patterns of minerals analysed in this and in previous works. Normalised values for REE after Nakamura (1974) and Y, Th, Hf and Zr after Thompson (1982). The lower shaded fields are representative of the whole-rock (granodiorites, monzogranites and aplites) trace element chondrite normalised patterns for the granitoid rocks of the Sierra de Chepes. The upper shaded fields are representative of the mineral trace element chondrite normalised patterns for allanite and epidote. The number over shaded fields is indicative of the analysis number.

CRITICAL MINERAL ASSEMBLAGE

The typical magmatic assemblage for the igneous units composed of Mc+Pl+Qtz+ Bt+Hbl+Ttn+Mag+ Ep + Ap + Zrn allows the application of the different Al-in Hbl geobarometers reported in the literature. Details of the textural relationships have been described by Dahlquist (1998, 2000), concluding that the sequence of the crystallisation history is: **1-** Pl_a, Hbl_a, Bt_a and late Qtz_a; **2-** Pl_b, Mc_a, Hbl_b, Bt_b; late Pl_c, Qtz_b and **3-** Mc_b. Based on this textural study, the composition of selected Pl - Hbl pairs and Hbl grains were chosen for temperature and pressure estimations.

The Hbl-Pl pairs analysed in the ChPG unit (sample CHE-35) and in the mafic microgranular enclave (sample CHEL-5A) have a similar fabric arrangement. The core of the larger Pl grains (Pl_a) and small inclusions of Hbl located near the core of the same Pl grain were selected (data and calculations are shown in tables 2 and 3). These small Hbl inclusions do not exhibit zonation, suggesting a simple origin by growth in a magmatic environment. A Pl_b and Hbl_b pair that share a grain boundary was selected (similar fabric arrangement used by Blundy and Holland, 1990, p. 219), since the textural studies suggest simultaneous crystallisation of both minerals (sample AMB-35, ChG unit, Dahlquist 1998, 2000). The Hbl analyses (that share grain boundary with Pl or Qtz) exhibit a small compositional difference between core and rim, the former enriched in Al^{IV} and impoverished in Al^{VI}. This compositional variation can be ascribed to a decreasing temperature during the magma cooling (the Al entrance in the tetrahedral site decreases with decreasing temperature). Crystallisation pressure and temperature were calculated from selected Hbl rim compositions (Tables 2 and 3).

TEMPERATURE

Schmidt (1992) concluded that the Al-in-hornblende geobarometer of Johnson and Rutherford

TABLE 1. REPRESENTATIVE MINERAL ANALYSES DETERMINED WITH ELECTRON MICROPROBE.

Igneous Unit Sample Mineral	ChPG CAS-59 Allanite-52 Core	ChG AMBI-28 Epidote-43 core	ChG AMBI-28 Epidote-45 rim
wt%			
SiO_2	30.39	35.13	35.26
TiO_2	1.33	0.08	0.3
Al_2O_3	14.9	23.77	22.7
FeO[1]	7.8	-	-
Fe_2O_3	5.3	13.08	14
MnO	0.42	0.44	0.15
MgO	2.35	0.03	0.02
CaO	11.07	23.42	24.09
P_2O_5	0.05	0.04	0.02
REEt[2]	24.42	0.32	0.28
Total	*98.03*	*96.31*	*96.82*
Ps		*26*	*28*
ppm			
La	54320	170	bdl
Ce	98683	939	854
Pr	9371	bdl	bdl
Nd	28583	bdl	bdl
Sm	1379	bdl	bdl
Gd	6930	bdl	bdl
Tb	bdl	bdl	bdl
Dy	697	bdl	bdl
Ho	bdl	bdl	bdl
Er	613	438	350
Tm	bdl	bdl	bdl
Yb	439	351	176
Lu	bdl	bdl	bdl
Th	6503	bdl	bdl
Y	bdl	157	bdl
Zr	bdl	229	bdl
Hf	bdl	bdl	bdl

Notes: Na_2O, K_2O, Eu and Nb not determined. [1] Total iron measured as FeO. All iron assumed to be ferric for epidote, except for allanite where the following formulae were used: Fe^{2+} = Zrn+Ti+ 2.Th+ ΫREE+Y-Mg-Mn, and ΫFe-Fe^{2+} = Fe^{3+}. All Mn assumed to be divalent for allanite and trivalent for epidote. Normalisation based on 8 cations. H_2O calculated by stoichiometry. [2] plus Th, Y, Zr and Hf. bdl = below detection limits. ChG = Chepes granodiorite; ChPG = Chepes Porphyritic granodiorite. The number against the mineral is indicative of the electron microprobe spot analyses illustrated in figure 2.

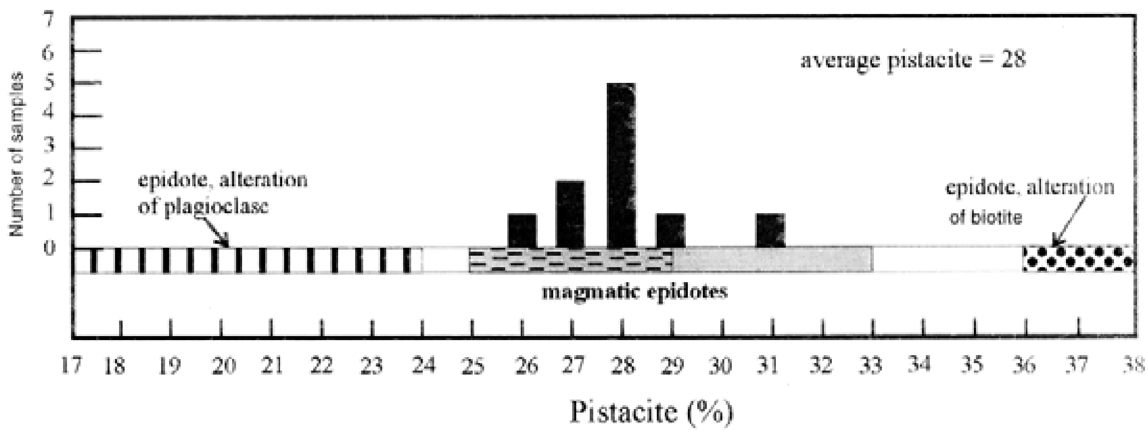


FIG. 4. Mole percent (mol%) pistacite in magmatic epidotes from igneous rocks of the Sierra de Chepes (Chepes Granodiorite and Chepes Porphyritic Granodiorite units). The observed values of pistacite indicate magmatic origin for epidotes. The compositional ranges of subsolidus epidotes from alteration of plagioclase and biotites are from Tulloch (1986). The compositional ranges for magmatic epidotes, stripe dotted field, are from Tulloch (1986). The compositional ranges for magmatic epidotes, shadowed field, from Tulloch (1986) and Zen (1988), who related the composition of magmatic epidote to fo_2. Epidote breakdown curves (Liou 1973) indicate that within probable fo_2 limits for magmas (*i.e.*, between the HM and NiNiO buffers) epidote should range only from pistacite 25-33. Data from Dahlquist (2000), and Dahlquist (unpublished data). Representative sample in table 1.

(1989) is valid only for Hbl that crystallised at high temperatures (~ 760°C). Using the geothermometer of Holland and Blundy (1994) for Hbl-Pl pairs, temperatures ranging between 780 and 850°C (Table 2) were obtained for granitoids (including mafic microgranular enclaves lodged in the granitoids) of the Sierra de Chepes, and between 700 and 750°C for the adjacent co-magmatic rocks of the Sierra de Ulapes (Murra and Baldo, 2000). These results are supported by the observation that the analysed Hbl are richer in alkalis in site-A, as a consequence of high Ca content filling site-B (Table 3). Schmidt (1992) found that Hbl that crystallise in high temperature experimental calibrations (Johnson and Rutherford, 1989) are richer in alkalis in site-A when compared to Hbl calibrated at low temperature. Schmidt (1992) also concluded that his calibration was consistent with that of Johnson and Rutherford (1989) at higher temperatures, stabilising the required buffer assemblage by using a CO_2-H_2O-fluid mix. From these, it is inferred that the pressure calculated from hornblende composition is indirectly a function of the fluid composition in the magma (Schmidt, 1992).

TABLE 2. REPRESENTATIVE HORNBLENDE[1] GEOCHEMISTRY AND GEOBAROMETRY FROM IGNEOUS ROCKS OF SIERRA DE CHEPES.

Sample	Al^T	Si	X_{Ab}	P (kbar)[2]	P (kbar)[3]	T (°C)
AMB-55 (ChG)	1.45	6.67	0.48	2.7		850
CHE-35 (ChPG)	1.67	6.55	0.49	3.6		840
CHEL-5A (MME)	1.62	6.62	0.55	3.4	3.0	780

Notes: Al^T and Si from table 3. X_{ab} = mole fraction of albite in plagioclase. MME = mafic microgranular enclave.
[1] Hornblende-plagioclase assemblages indicating simultaneous crystallisation were chosen from detailed textural studies (explanation in the text), using their respective chemical compositions in the calculations.
[2] Pressure based on the Johnson and Rutherford (1989) calibration.
[3] Pressure based on the Anderson and Smith (1995) expression. Temperature calculated from the equations of Holland and Blundy (1994).

The temperature values obtained in the analysed rocks (Table 2) seem to agree with the considerations of Anderson and Smith (1995, Fig. 5), who, based on pressure and temperature values (pressure from Al-in-Hbl geobarometer Anderson and Smith, 1995 and temperature from geothermometer Blundy and Holland, 1990), observed that plutons are able to crystallise within a wide range of temperatures, far from the solidus of a water-saturated granite (650°C).

On the other hand, high temperatures in granitic rocks emplaced at intermediate and low pressures have been obtained for granodiorites with mineral assemblages similar to those observed in the rocks from Sierra de Chepes. Vhynal *et al.* (1991) analysed Piedmont plutons with magmatic Ep and determined pressure and temperature values ranging between 3-5 kbar and 730-788°C. Cotkin and Medaris (1993, Table 5, p. 557) obtained a crystallisation interval from -900 to ~700°C for the granodiorites of the Russian Peak Complex, and an average temperature value of 870°C (average without one value of 690°C, near the solidus).

fO_2

The [$Fe^{total}/(Fe^{total}+Mg)$=0.44-0.48] and [$Fe^{3+}/(Fe^{3+}+Mg)$ = 0.20-0.33]ratios for Hbl in granodiorites of the ChG and ChPG units (Figs. 5a and 5b) are in the same range as those for Hbl used in most experimental calibrations (Anderson and Smith, 1995). These ratios suggest crystallisation at high fo_2 (Figs. 5a and 5b), which is consistent with the occurrence of magmatic Ep at low pressure, according to the experimental work of Schmidt and Thompson (1996), that demonstrated that Ep could be stable in calc-alkaline magmas (tonalitic compositions) in pressures of less than 3 kbar.

PRESSURE

Because the Hbl had crystallised at high temperature (temperature obtained from geothemometer of Holland and Blundy 1994), the calibration of Johnson and Rutherford (1989) was used for pressure calculations. Also the Anderson and Smith (1995) geobarometer was used in order to have more control on the pressure estimations, as their calibration combines the experimental data from Johnson and Rutherford (1989) and Schmidt (1992), into one expression. Inconsistent, very low pressure values, were obtained from Hbl that crystallised at temperatures considerably higher than 800°C. In this sense, Anderson and Smith (1995) had indicated that the new expression probably should not be applied to plutons that crystallised at temperatures largely in excess of 800°C.

TABLE 3. REPRESENTATIVE ELECTRON MICROPROBE ANALISES OF HORNBLENDE USED IN THE GEOBAROMETRY AND GEOTHERMOMETRY.

Igneous Units		Mafic Microgranular Enclave (MME)	ChG	ChPG
Sample		CHEL-5A	AMB-55	CHE-35
Mineral		Hornblende[1]	Hornblende[2] (rim)	Hornblende[1]
wt%				
SiO_2		44.07	45.12	44.03
Al_2O_3		9.15	8.30	9.51
FeO*		17.81	16.81	16.14
MnO		0.79	0.66	0.71
MgO		10.21	11.84	11.47
CaO		11.88	12.66	12.72
Na_2O		1.10	0.99	1.03
K_2O		0.98	0.75	0.82
TiO_2		1.19	0.98	1.20
NiO		0	0	0
Cr_2O_3		0	0.02	0
Total		*97.32*	*98.13*	*97.63*
FORMULA PER 13 CATIONS				
Tetrahedral site				
Si		6.62	6.67	6.55
Al^{IV}		1.38	1.33	1.45
	Sum	8	8	8
M1, M2, M3 sites				
Al^{VI}		0.24	0.12	0.22
Cr		0	0.00	0
Fe^{3+}		0.54	0.55	0.44
Ti		0.14	0.11	0.13
Mg		2.29	2.61	2.54
Fe^{2+}		1.70	1.52	1.56
Mn		0.10	0.08	0.09
	Sum	5	5	5
M4 site				
Ca		1.91	2	2
Na		0.09	0	0
	Sum	2	2	2
A site				
Ca		0	0.01	0.03
Na		0.23	0.28	0.30
K		0.19	0.14	0.15
	Sum	0.42	0.43	0.48
$Fe^{total}/(Fe^{total}+Mg)$		*0.49*	*0.44*	*0.44*
$Fe^{3+}/(Fe^{3+}+Fe^{2+})$		*0.24*	*0.27*	*0.22*

*Total Fe measured as FeO. The mineral analyses were recalculated into mineral formula and cationic proportions using the computer programs MINPET for Windows (Richard, 1995). Note that the A-site is richer in alkalies as a consequence of high content of Ca filling M4-site.

[1]Small hornblende inclusions in larger plagioclases grains; [2]hornblende-plagioclase pair which share grain boundary (for more details see text).

For Hbl that crystallised at 780°C, the pressure value is consistent with the pressures obtained from Johnson and Rutherford' s geobarometer. The results show that the emplacement pressures for the granitoids are low, with maximum values of 3.6 ±0.5 kbar (Table 2). This conclusion is consistent with the pressure range 2.5±0.5 kbar obtained in the metamorphic rocks coevally developed with the granite emplacement, with paragenesis that include And, Crd, Kfs and are devoid of garnet at the highest temperature zone (Dahlquist and Baldo, 1996; Pankhurst *et al.*, 1998).

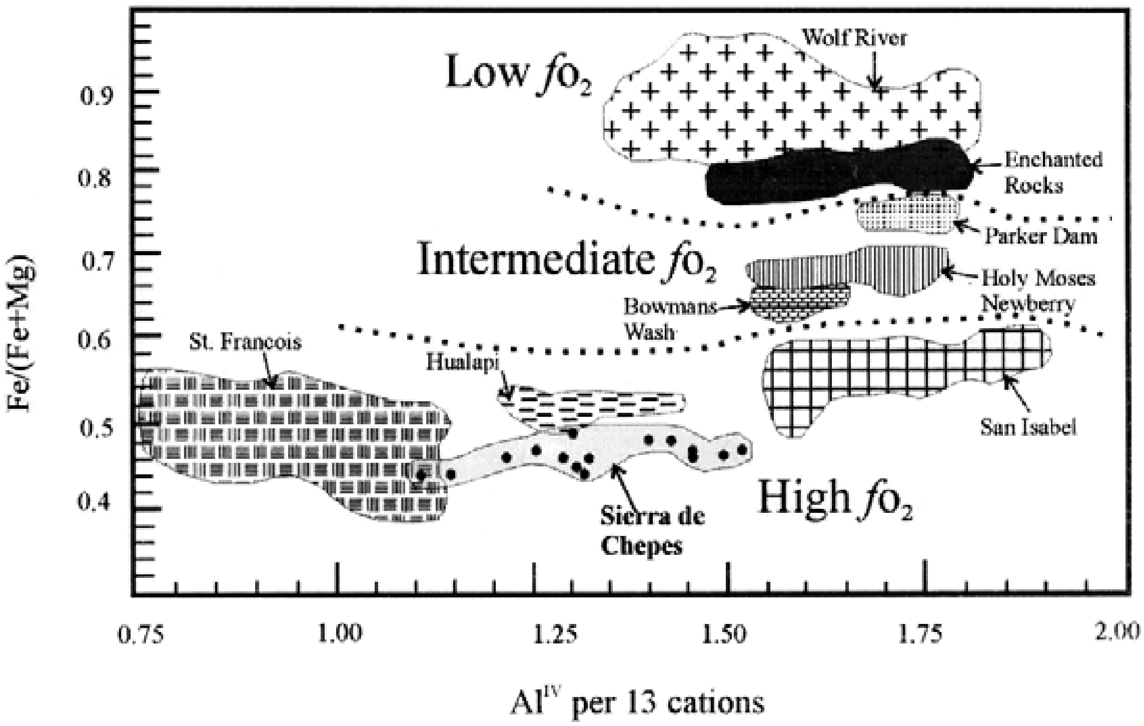


FIG. 5a. Hornblendes from igneous rocks of the Sierra de Chepes (Chepes Granodiorite and Chepes Porphyritic Granodiorite units) have Fe/(Fe + Mg) ratios and values of Al^{IV} typical of rocks crystallised in high-fo_2 conditions. Figure modified fromAnderson and Smith (1995).

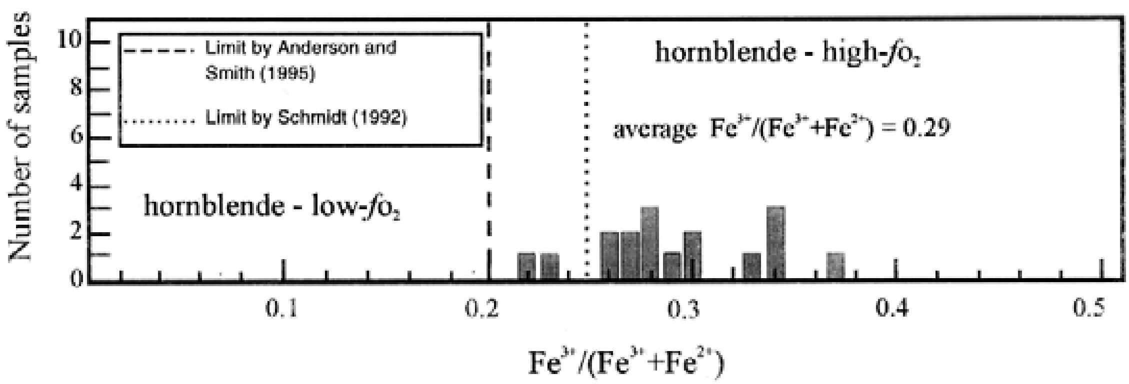


FIG. 5b. The calculated $Fe^{3+}/(Fe^{3+}+Fe^{2+})$ ratios for the hornblendes in the Chepes Porphyritic Granodiorite units indicate that it crystallized under high-fo_2 conditions. This figure confirms the results observed in figure 5a. Data from Dahlquist (2000) and Dahlquist (Unpublished). Representative samples in table 3. Figure modified from Anderson and Smith (1995).

DISCUSSION AND CONCLUSIONS

From the combined textural and both major and REE data presented in this paper, there is a concurrent evidence to support a magmatic origin for the widespread Ep that occurs in the ChG and ChPG units. Textural evidences are: (i) euhedral rims in the contact with Bt and/or Hbl; (ii) euhedral Aln with marked zonation, surrounded by Ep; (iii) inclusions of Hbl-Bt in the Ep, which suggest partial resorption of Hbl by the magma and subsequent precipitation of Ep around Hbl (Naney s experiment, 1983; Zen and Hammarstrom, 1984); (iv) Ap included in Ep, (cf. Dawes and Evans, 1991 that reported Ap intergrowth with magmatic Ep in volcanic rocks).

The chemical analyses indicate Ps contents similar to those obtained in diverse experimental works (Liou, 1973; Naney, 1983) and observed in different petrological studies of magmatic Ep (Zen and Hammarstrom, 1984; Tulloch, 1986; Brandon *et al.*, 1996; Vhynal *et al.*, 1991; Keane and Morrison, 1997). Moreover, the REE patterns obtained for the Ep here are similar to those of Ep that has been considered magmatic by other authors (Dawes and Evans, 1991; Keane and Morrison, 1997).

The values from the geobarometers of Johnson and Rutherford (1989) and Anderson and Smith (1995) indicate low emplacement pressures (2.7-3.6± 0.5 kbar and 3.0 ± 0.6 kbar respectively), with high temperatures (780-850°C, Blundy and Holland geothermometer, 1994), and these data are consistent with the high temperature and low pressure metamorphism (Dahlquist and Baldo, 1996; Pankhurst *et al.*, 1998) which occurred during Famatinian magmatism in the Sierra de Chepes (Pankhurst *et al.*, 1998).

During the Lower Ordovician Famatinian Orogeny, extensive metaluminous plutonism occurred along the proto-Andean margin of Gondwana (Pankhurst *et al.*, 1998), characterised by abundant Ep-bearing granitoids (Saavedra *et al.*, 1987; Sial *et al.*, 1999). The study of the metaluminous granitoids from Sierra de Chepes indicates that they are magmatic Ep-bearing granitoids emplaced at low pressures.

The remarkable widespread occurrence of Ep-bearing facies in the Famatinian metaluminous series contrasts with the relatively scarce occurrence of magmatic Ep-granitoids and the common presence of secondary Ep in Carboniferous Andean batholiths (*e.g.*, Santo Domingo Complex, Sial *et al.*, 1999; Parada *et al.*, 1999). On the other hand, middle emplacement pressures have been deduced for these Carboniferous Andean metaluminous granitoids (7 kbar; Parada *et al.*, 1999), whereas the Famatinian metaluminous granitoids of the Sierra de Chepes had low emplacement pressures (2.7-3.6 kbar). It is also important to emphasise that the pistacite value of the magmatic Ep found in the Ordovician granitoids (average Ps=28) sharply contrasts with the pistacite value of the magmatic Ep exhibited by the Carboniferous Andean batholiths (average Ps=24).

According to these observations, the occurrence of magmatic epidote might be related to different sources of the Orodvician Famatinian granitoids and the Carboniferous Andean batholiths. The Famatinian granitoids were derived mainly from melting of a high-fo_2 old continental lithosphere (~1700 Ma) (Pankhurst *et al.*, 1998, 2000; Rapela, 2000), while the Carboniferous Andean metaluminous granitoids resulted mainly from different degrees of mixing between crustal- and mantle- derived magmas (Parada *et al.*, 1999).

This may mean that the presence of magmatic epidote in calc-alkaline rocks does not always require high pressures, but is source-dependent. This imprints a typical signature of fo_2, a_{H_2O}, P_{H_2O}/P_{Total} on the primordial magma.

The presence/absence of these suites characterised also by the abundant accessory minerals (*e.g.*, Aln, Ttn, Ap, Zrn, Mag; Dahlquist, 2000), can help to better define the magma sources and to understand the geotectonic environment in which the Ep magmas occur. If the relationship of magmatic Ep-bearing granitoids to the characteristics of the source is confirmed in future studies can help to better define the magma sources and to understand the geotectonic environment in which the Ep magmas occur.

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