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Article

Petrographical and geochemical features of the granite-pegmatite transition in the Velasco Pegmatitic District, NW Argentina

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With 5 figures and 2 tables

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Abstract: The Carboniferous post-orogenic Huaco and Sanagasta granites are located in the central sector of the Velasco Range, northwestern Argentina, and host rare-element (Be) pegmatites. They are highly fractionated peraluminous granites with porphyritic textures having variable sizes and abundances of K-feldspar megacrysts. Two different types of parental granites are recognized: a Regional Porphyritic Granite (RPG), distant from the Be-pegmatites, and an Adjacent Porphyritic Granite (APG) surrounding the Be-pegmatites. At the pegmatite margins, aplites (MA), or more rarely equigranular leucogranites, are in contact with the APG. The granite-to-pegmatite transition is characterized by a decreasing biotite/muscovite ratio and TiO_2-$Fe_2O_3{}^t$-MgO contents, which is consistent with fractional crystallization of biotite, and also by decreasing megacryst and grain size. A continuous magmatic crystallization trend from the RPG to the APG is observed, whereas the MA constitutes the earliest stage of pegmatite formation, characterized by depletion in ferro-magnesian elements, calcium and some trace elements (Ba, Sr, Y, Nb, Ce, Zr, Th). However, the granite-pegmatite evolution occurred by differentiation from a common magma source.

Key words: Fertile granites, Be-pegmatites, marginal aplites, granite–pegmatite transition, Velasco Pegmatitic District, NW Argentina.

Introduction

Pegmatites containing rare-element (e.g. Li, Cs, Ta, Nb, Y, F and Be) minerals are genetically associated with granites that have specific petrological, mineralogical and geochemical features. Be-pegmatites are generally associated with late- to post-orogenic, epizonal, peraluminous, biotite-muscovite granites (CERNÝ 1991a, 1991b). Field observations and geochemical data of both whole rock and minerals (mostly K-feldspar and muscovite) suggest that granitic pegmatites of the rare-element class derive from fertile granitic bodies following fractional crystallization processes (CERNÝ et al. 1985, 2005; CERNÝ 1991b, 1992; ZHU et al. 2006). Some experimental models support such an assumption, which can also explain the origin of zonation in granitic pegmatites, usually including marginal aplites (JAHNS & TUTTLE 1963; JAHNS & BURHAM 1969; revision by LONDON 2005).

The Pampean Pegmatitic Province is one of three pegmatitic provinces in South America; the other two are the Eastern Brazilian and the Northeastern Brazilian (or Borborema) provinces. The Pampean Pegmatitic Province is located in NW Argentina between latitudes 24º 30' S and 33º 30' S, and comprises more than 95% of the pegmatitic mineral resources of the country (GALLISKI 1994a). The first classification of the pegmatites from this province was

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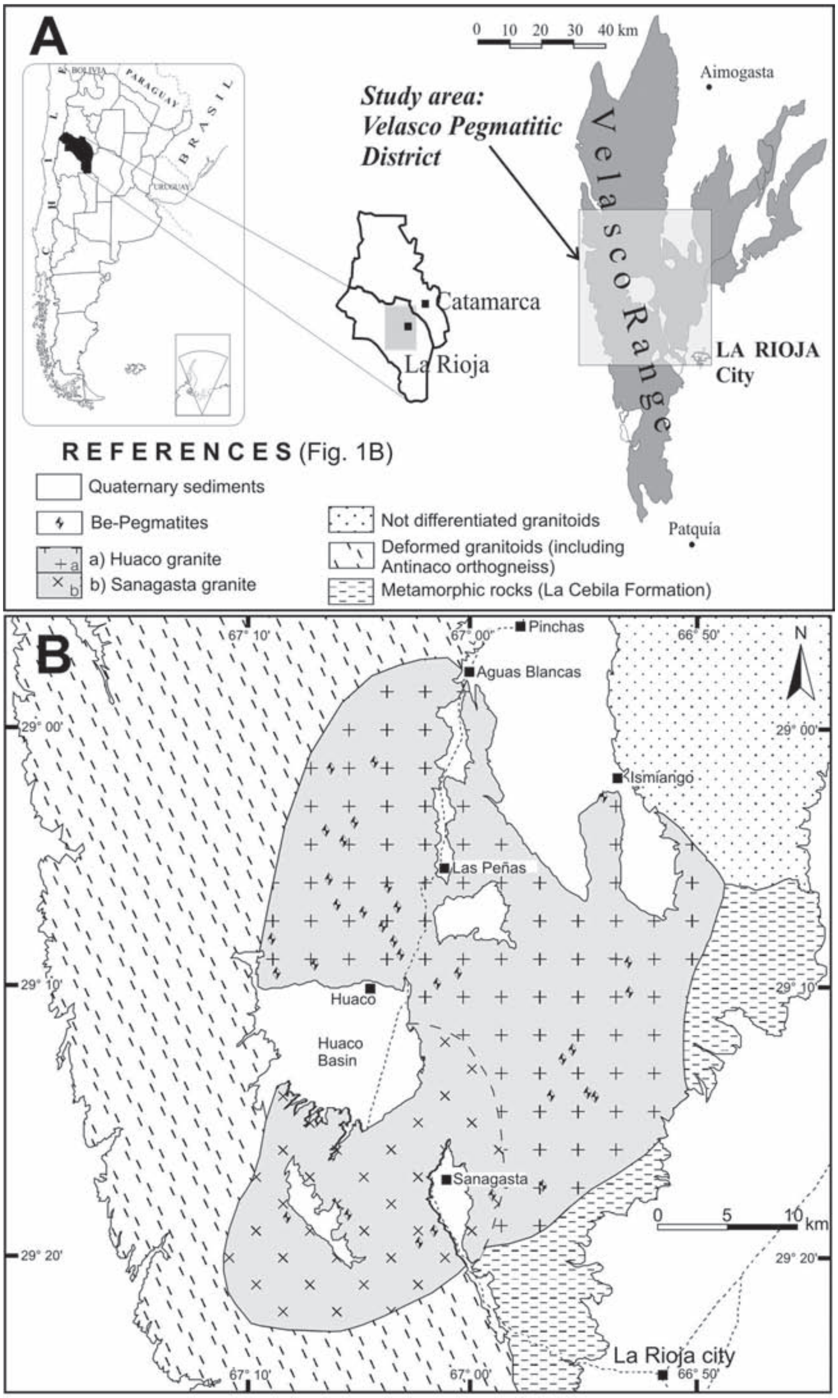

Fig. 1. Location of the study area.
A. Regional location of the Velasco Range.
B. Geological map of the Velasco Pegmatitic District, NW Argentina.
Simplified from SARDI & GROSSE (2005).

carried out by HERRERA (1968) using structural and mineralogical criteria. The granitic pegmatites of the Pampean Pegmatitic Province are mostly of the LCT petrogenetic family (GALLISKI 1994b). Their host rocks consist of Paleozoic metamorphic and granitoid rocks of variable composition, evolution and age. Twenty districts have been recognized in the province by GALLISKI (1994b). The Velasco Pegmatitic District, located in central-eastern Velasco Range, La Rioja, is one of these districts (Fig. 1).

The present contribution is a detailed study on the compositional and textural features and their spatial variations found at granite-pegmatite transitions of the Velasco Pegmatitic District in NW Argentina. Given are field, petrographical and geochemical data of granites and pegmatite-border rocks (usually aplites), as well as a discussion on the evolution of the granitic to early pegmatitic magmas.

Geological setting of the Velasco range

The Velasco Range is located within the Sierras Pampeanas geological province, NW Argentina (Fig. 1A). It is part of the "Central Batholitic Zone" defined by Toselli et al. (1986) and characterized by large post-tectonic batholiths of granitic and granodioritic composition, and equigranular to porphyritic textures.

Metamorphic basement rocks are present only in small outcrops on the eastern slopes of the range (Fig. 1B). They are low- to very low-grade metapelites and metapsammites. This basement can be correlated with the La Cébila Formation, defined by Gonzalez Bonorino (1951), which has recently been assigned to the Lower Ordovician based on the discovery of marine fossils at a neighboring locality to the northeast of the study area (Verdecchia et al. 2007).

The Velasco range is formed essentially by granitoids with different tectono-magmatic evolution and age (e.g. Toselli et al. 2000, 2005; Grosse et al. 2003; Báez et al. 2005). Three main types of granitoids can be recognized: (1) Ordovician peraluminous meta-granitoids; (2) Ordovician (?) metaluminous to weakly peraluminous meta-granodiorites and meta-tonalites; and (3) Carboniferous undeformed peraluminous granites.

The peraluminous meta-granitoids outcrop mainly along the northwestern and western flanks of the range and have been grouped together as the Antinaco Orthogneiss (Fig. 1B) (Rossi et al. 2000, 2005). They contain Al-bearing minerals such as muscovite, cordierite, garnet and/or sillimanite. These granitoids have been affected by several NNW-SSE trending mylonitic shear-zones of regional extension (e.g. López et al. 1996; Höckenreiner et al. 2003). U-Pb-dating on zircon indicates Lower Ordovician crystallization ages between 469 and 481 Ma (Pankhurst et al. 2000; Rapela et al. 2001; Báez 2006), while the age of deformation is not well constrained.

The metaluminous to weakly peraluminous meta-granodiorites and meta-tonalites outcrop in the southern part of the range. They contain biotite, hornblende, titanite, allanite and magnetite (Bellos et al. 2002; Bellos 2005). Although their age has not been dated yet, they can be considered Ordovician based on their similarity with Ordovician metaluminous granitoids of the neighboring Famatina region (e.g. Aceñolaza et al. 1996) and Chepes Range (e.g. Pankhurst et al. 1998).

The undeformed peraluminous granites are located in the central and northern sectors of the Velasco Range. They are two-mica syeno- and monzogranites, commonly with porphyritic textures. Toselli et al. (2006) have recently grouped these granites as the Aimogasta Batholith based on their similar field relationships and absolute ages, which indicate they are post-tectonic intrusions. U-Pb on zircon and monazite ages constrain this post-tectonic activity to the Lower Carboniferous, between 334 and 353 Ma (Báez et al. 2004; Dahlquist et al. 2006; Grosse et al. 2009; Söllner et al. 2009).

The Velasco Pegmatitic District

The Velasco Pegmatitic District is located in the vicinity of the Huaco Basin in the central-eastern sector of the Velasco Range (Fig. 1A). The host rocks of the Be-pegmatites in this district are the Huaco and Sanagasta granites (Fig. 1B) (Toselli et al. 2000; Báez et al. 2005; Grosse & Sardi 2005; Grosse et al. 2009). Intrusive relationships and clear contacts between both granites have not been observed; thus a gradational contact is suggested. The Huaco granite covers a greater area than the Sanagasta granite (~620 and ~240 km^2 respectively) and contains considerably more Be-pegmatites (Fig. 1B). Both granites intrude the Ordovician peraluminous meta-granitoids and the low-grade metamorphic rocks of the La Cebila Formation (Fig. 1B). Existing crystallization ages for these granites are 350-358 Ma for the Huaco granite and 353 ± 1 Ma for the Sanagasta granite (U-Pb on monazite, Grosse et al. 2009), 345 ± 6 Ma for the Huaco granite and 349 ± 5 Ma for the Sanagasta granite (U-Pb LA-ICP-MS on zircon, Söllner et al. 2009).

Both granites are syeno- to monzogranitic and are characterized by a porphyritic texture of idiomorphic perthitic microcline megacrysts immersed in a coarse- to medium-grained groundmass. Megacryst sizes vary between 1.5 and 12 cm, most commonly between 2.5 and 4.5 cm. Their abundance ranges between 25 and 45% (Grosse & Sardi 2005). The megacrysts are predominantly white in the Huaco granite and pink in the Sanagasta granite. Granophyric textures are common in the Huaco granite; Rapakivi-like mantle textures are frequent in the Sanagasta granite. The Huaco granite contains biotite and muscovite, while

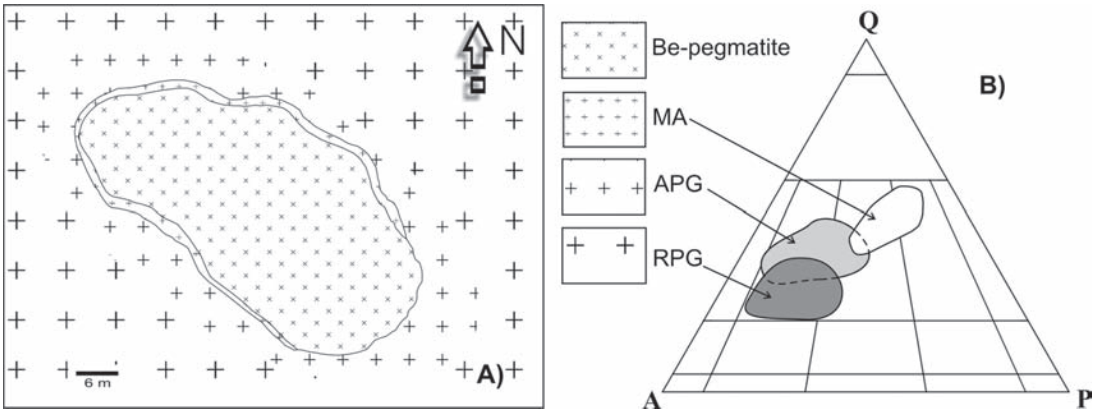

Fig. 2. A. Geological map of the "Cora Vivi" pegmatite from the Velasco Pegmatitic District (NW Argentina) showing the two different types of parental granites (RPG and APG) and the marginal aplitic zone of the pegmatite (MA). **B.** QAP diagram (Streckeisen 1976).

the Sanagasta granite contains generally only biotite. Accessory minerals present in both granites are apatite, monazite and zircon, all usually included in biotite.

The Be-pegmatites located within the Huaco and Sanagasta granites have irregular or ellipsoidal shapes and rather small sizes, with the main axis less than 350 m long. Based on their textures and mineralogy, three main zones can be recognized in the pegmatites (Sardi 2005): a marginal-external zone formed by aplites or more rarely by medium-grained leuco-granites; an intermediate zone composed of feldspars (microcline-perthite and plagioclase) and quartz in variable proportions, accompanied by accessory minerals such as beryl, triplite, muscovite, biotite, tourmaline, F-apatite (Sardi et al. 2006) and spodumene (Morteani et al. 1995); and a quartz core, which can also contain scarce tourmaline, muscovite and/or beryl. The gem-quality of some yellow and light-blue beryls (heliodor and aquamarine respectively), rock-crystals and rose-quartzes are the main economic value of these pegmatites (Sardi 2008). Sardi & Grosse (2005) classify these pegmatites following the nomenclature of Cerný (1991a) as rare-element class, beryl type, beryl-columbite-phosphate subtype, hybrid LCT-NYF family.

Results

Both the Huaco and Sanagasta granites show gradational variations in texture, mineralogy and geochemistry towards the associated Be-pegmatites. Two granite types can be recognized: a main 'regional' porphyritic granite - RPG - located away from the pegmatites, and a local 'adjacent' porphyritic granite – APG – located around the pegmatites (Fig. 2A). The APG is in sharp contact with the pegmatites and spans a variable area usually not wider than 6 m. The wall-rocks of the pegmatites usually consist of marginal aplites – MA – forming a thin envelope of a few centimeters to almost one meter (Fig. 2A).

Petrography

Both granite types have syeno- to monzogranitic modal compositions (Fig. 2B). The main differences between the RPG and the APG are variations in megacryst size and abundance, and in quartz and mica contents. The abundance of microcline megacrysts is generally higher in the RPG than in the APG (Table 1). The size of the megacrysts is considerably larger in the RPG, where they can reach up to 12 cm in length, while the maximum size in the APG is ~4 cm (Table 1). The quartz and muscovite contents are higher in the APG, while the biotite and apatite contents are higher in the RPG (Table 1). Thus, the biotite/muscovite ratio is higher in the RPG (Table 1).

The MA has monzogranitic to granodioritic modal compositions (Fig. 2B). They have equigranular, fine-grained textures, and contain abundant quartz and muscovite and scarce biotite (Table 1). Their biotite/muscovite ratio is much lower than in the granites (Table 1).

Table 1. Petrographical features of the studied rocks from the Velasco Pegmatitic District, NW Argentina. **tr** = trace amount.

		RPG	APG	MA
Lithology		syenogranite to monzogranite dominantly syenogranite	monzogranite to syenogranite	granodiorite to monzogranite
Microcline megacrysts	**Abundance** [%]	24.1 - 39.1 average 32.01	18.0 - 36.8 average 29.5	equi-granular texture
	Maximum size [cm]	12	4.2	fine- to medium-grained
Modal composition Average values	quartz	21.8	37.2	37.2
	microcline	48.2	36.1	24.9
	plagioclase	17.2	15.5	24.2
	biotite	7.9	6.3	2.3
	muscovite	4.0	4.5	9.9
	apatite	1.1	0.2	tr
	zircon	0.2	0.2	--
	biotite/muscovite	2.0	1.4	0.3

Geochemistry

18 samples were analyzed for major and trace (Cr, Ni, Rb, Sr, Y, Zr, Nb, Ba, Ce, Pb and Th) elements by X-ray fluorescence (XRF) at the Naruto University of Education (Japan); 6 samples are of the RPG, 7 of the APG and 5 of the MA. Glass beads from finely ground samples were prepared with a sample-to-flux ratio of 1:10 and analyzed for major elements, whereas trace elements were determined using pure press pellets. Standards were supplied by the Geological Survey of Japan (JGb1, JB2, JB3, JA2, JG1a, JG2, JG3, JR1 and JR2). The lower detection limits for the trace elements were: Zr and Ba, 10 ppm; Ce, 5 ppm; Cr, Rb, Sr and Y, 1 ppm; Nb, Ni and Th, 0.1 ppm. The results of the major and trace element analyses are given in Table 2.

The two granite types have high silica contents above 70% (except for one sample of the RPG with 68%). The APG generally have higher silica contents (70.1-74.4%, average 72.1%) than the RPG (68.1-73.5%; average 71.1%). The MA has even higher and more restricted silica contents (72.9-75.7%; average 74.3%). Both the RPG and APG are K_2O-rich (4.7-5.7%, average 5.2%; and 4.6-7.1%, average 5.5% respectively), with $K_2O/Na_2O > 1$, while the MA generally has lower K_2O (2.8-6.1, average 4.4%) and higher Na_2O contents, with variable K_2O/Na_2O ratios. The RPG has the highest ferromagnesian contents ($Fe_2O_3+MgO+TiO_2$ = 3.1-5.4%, average 3.8%) followed by the APG (2.2-4.0%, average 2.8%) and the MA (0.8-1.5%, average 1.5%). The studied rocks are peraluminous, with ASI (molar $Al_2O_3/[CaO+Na_2O+K_2O]$) values between 1.00 and 1.22 (Table 2). The average ASI values are 1.10 for the RPG, 1.14 for the APG and 1.11 for the MA.

Figures 3 and 4 present major and trace element variation diagrams with $1/TiO_2$ as a differentiation index. This index is better than SiO_2 for these lithologies because of their limited silica range and because Ti is less easily remobilized by secondary effects (e.g. Förster et al. 1999). TiO_2 contents are generally higher in the RPG than in the APG, while the TiO_2 contents in the MA are much lower. Thus, the $1/TiO_2$ index approximately separates the less differentiated RPG from the APG and clearly separates

Table 2. Chemical compositions of the studied rocks from the Velasco Pegmatitic District, NW Argentina. Total iron as Fe_2O_3; major elements in wt%; trace element in ppm; **n. a.** = not analyzed. **n. d.** = not defected.

SAMPLE	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MgO	MnO	CaO	Na_2O	K_2O	P_2O_5	ASI	Cr	Ni	Rb	Sr	Y	Zr	Nb	Ba	Ce	Pb	Th
RPG																						
6650	72.48	0.43	13.48	3.36	0.49	0.06	1.10	3.01	4.69	0.34	1.12	3.2	5.4	390	60.0	38.6	309	36.4	203	84.2	20.5	36.6
6746	68.06	0.53	14.31	4.31	0.60	0.09	1.22	3.14	4.92	0.40	1.13	19.0	6.1	480	54.4	44.2	288	43.8	187	82.4	19.4	35.4
6748	70.94	0.28	14.85	2.54	0.28	0.06	0.86	3.43	5.32	0.26	1.15	13.9	4.4	412	52.4	36.2	185	32.1	204	58.8	23.2	20.3
6846	70.92	0.29	14.26	2.54	0.26	0.07	1.12	3.35	5.65	0.27	1.04	12.1	4.0	361	66.2	34.6	217	27.7	256	56.7	27.3	25.5
6847	70.86	0.31	14.27	2.67	0.39	0.06	0.75	2.95	5.63	0.31	1.16	18.5	5.9	429	50.5	37.7	193	32.7	208	55.9	23.6	25.0
7319	73.48	0.35	12.50	2.68	0.37	0.05	0.98	3.11	5.15	0.18	1.00	n.d.	6.2	332	63.9	42.3	224	25.2	248	72.2	24.6	33.5
Average	*71.12*	*0.37*	*13.95*	*3.02*	*0.40*	*0.07*	*1.01*	*3.17*	*5.23*	*0.29*	*1.10*	*13.3*	*5.3*	*401*	*57.9*	*38.9*	*236*	*33.0*	*218*	*68.4*	*23.1*	*29.4*
APG																						
6657	73.23	0.19	13.94	1.87	0.24	0.05	0.62	3.11	5.32	0.22	1.16	22.5	5.8	420	43.2	35.7	134	29.3	169	40.7	24.4	17.4
6738	70.06	0.35	14.63	3.25	0.41	0.09	0.97	3.45	5.25	0.37	1.11	12.8	6.5	487	56.0	43.3	239	38.9	213	65.5	23.6	25.1
6744	73.12	0.30	13.86	2.57	0.32	0.06	0.85	3.34	4.60	0.21	1.15	5.4	4.3	393	48.5	35.8	200	33.3	181	41.4	23.5	26.3
6842	72.44	0.24	14.30	1.84	0.16	0.06	0.27	2.20	7.07	0.20	1.22	7.1	6.8	658	43.0	43.8	198	29.6	254	56.0	25.8	24.9
6924	74.34	0.21	13.20	2.04	0.20	0.09	0.74	2.94	4.50	0.12	1.19	6.1	10.1	447	37.1	38.7	117	41.9	166	41.0	20.5	21.7
7122	70.60	0.25	14.18	2.38	0.32	0.06	0.80	3.28	5.94	0.30	1.07	26.4	5.5	485	n.a.	40.1	182	30.1	223	83.0	31.2	26.3
7129	70.99	0.22	14.39	2.16	0.28	0.05	0.89	3.52	5.86	0.23	1.05	1.5	5.7	403	55.6	36.3	154	27.2	200	42.1	28.2	20.0
Average	*72.11*	*0.25*	*14.07*	*2.30*	*0.28*	*0.07*	*0.73*	*3.12*	*5.51*	*0.24*	*1.14*	*11.7*	*6.4*	*470*	*47.2*	*39.1*	*175*	*32.9*	*200*	*52.8*	*25.3*	*23.1*
MA																						
7121A	75.01	0.07	14.07	0.72	0.09	0.05	0.60	5.35	3.02	0.26	1.07	2.8	4.6	327	16.6	25.2	1.7	24.2	54.8	15.3	11.9	9.0
7121B	73.99	0.06	14.83	0.81	0.09	0.04	0.56	5.22	2.76	0.26	1.18	28.5	4.8	376	13.9	26.1	7.4	33.9	65.9	30.5	7.1	5.8
7121C	72.93	0.09	15.01	0.87	0.10	0.04	0.49	4.39	4.39	0.26	1.17	9.2	6.4	434	25.0	29.5	0.7	28.2	82.7	16.3	16.6	6.6
7312	73.87	0.12	13.18	1.23	0.10	0.05	0.56	2.99	6.10	0.14	1.05	4.6	8.1	608	44.4	43.8	75.9	16.0	210	37.4	32.0	17.2
7320	75.69	0.07	12.80	0.65	0.06	0.03	0.35	3.07	5.58	0.13	1.09	18.4	5.1	413	33.0	30.4	26.2	12.5	101	2.9	28.8	4.2
Average	*74.30*	*0.08*	*13.98*	*0.86*	*0.09*	*0.04*	*0.51*	*4.20*	*4.37*	*0.21*	*1.11*	*12.7*	*5.8*	*431*	*26.6*	*31.0*	*22.4*	*23.0*	*103*	*20.5*	*19.3*	*8.6*

both granite types from the highly differentiated MA, recording a gap between the granites and the pegmatite-margin aplites (Figs. 3 and 4). The samples of both granite types define clear and steep negative differentiation tendencies for $Fe_2O_3^t$, MgO, CaO and P_2O_5. In contrast, the MA samples define sub-horizontal tendencies for these oxides, except for P_2O_5 which show scatter. SiO_2 contents from the two granite types follow a rough and steep positive tendency, whereas they show a weak positive tendency in

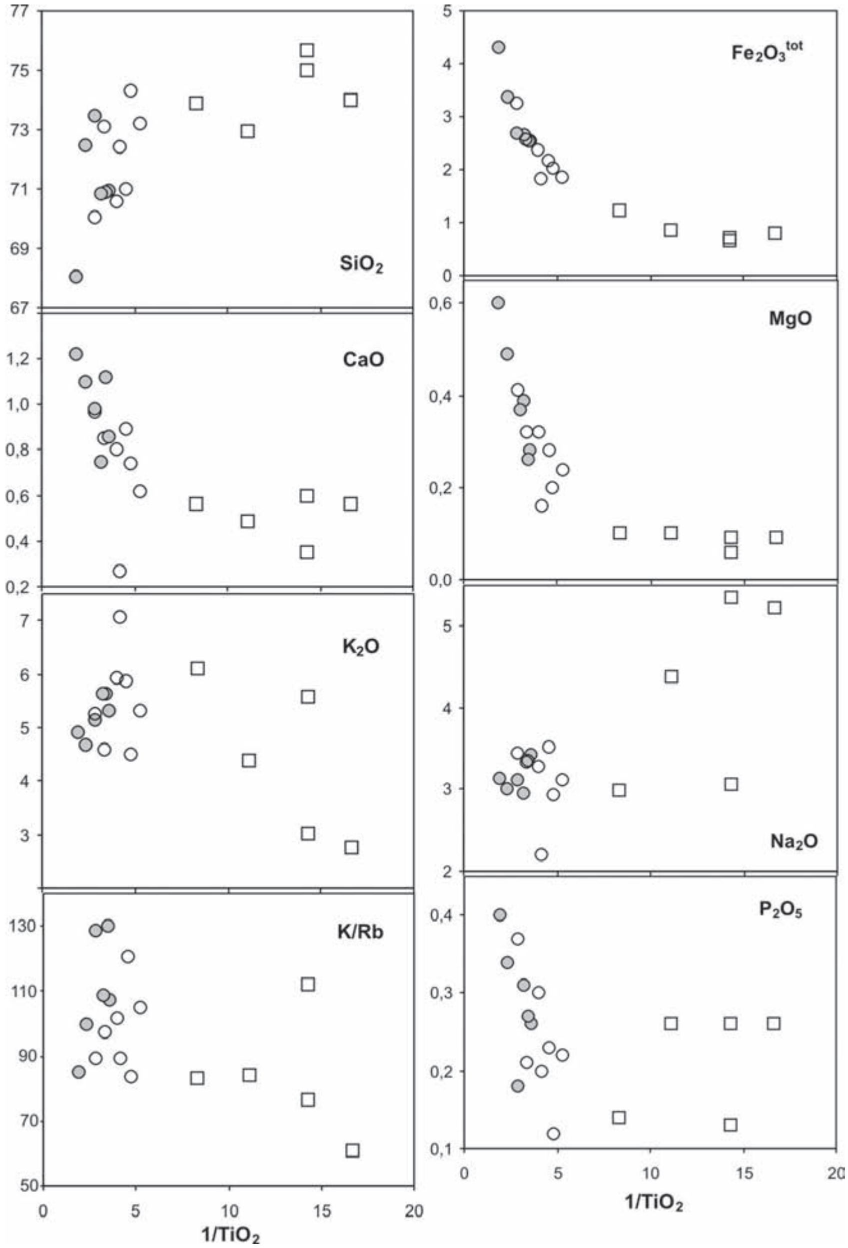

Fig. 3. Geochemical variation of major elements of samples from the RPG (**filled circle**), the APG (**empty circle**) and the MA (**square**). Values in wt%.

the MA. K_2O and Na_2O contents in the RPG and APG samples are scattered and do not define any tendency, whereas the MA samples define a rough negative tendency for K_2O and a rough positive tendency for Na_2O.

Trace element contents are quite variable (Fig. 4). Negative tendencies from the RPG towards the APG are found for Ce, Zr, Th and Sr; the MA roughly follows these negative trends, although tending to flatten out. The two granite types have similar Nb, Y and Ba contents, while Rb contents roughly increase from the RPG towards the APG. Ba and Y contents in the MA are lower than in the granites and show a rough negative trend; Rb also follows a negative tendency but its concentrations are similar to those in the granites; Nb contents are quite variable and are similar or lower than in the granites.

The studied rocks can be classified as "highly differentiated granites" according to the Ba-Rb-Sr triangular diagram of El Bouseily & El Sokkary (1975) (Fig. 5). In this diagram, differentiation towards the Rb vertex is observed as a sequence from RPG to APG to MA.

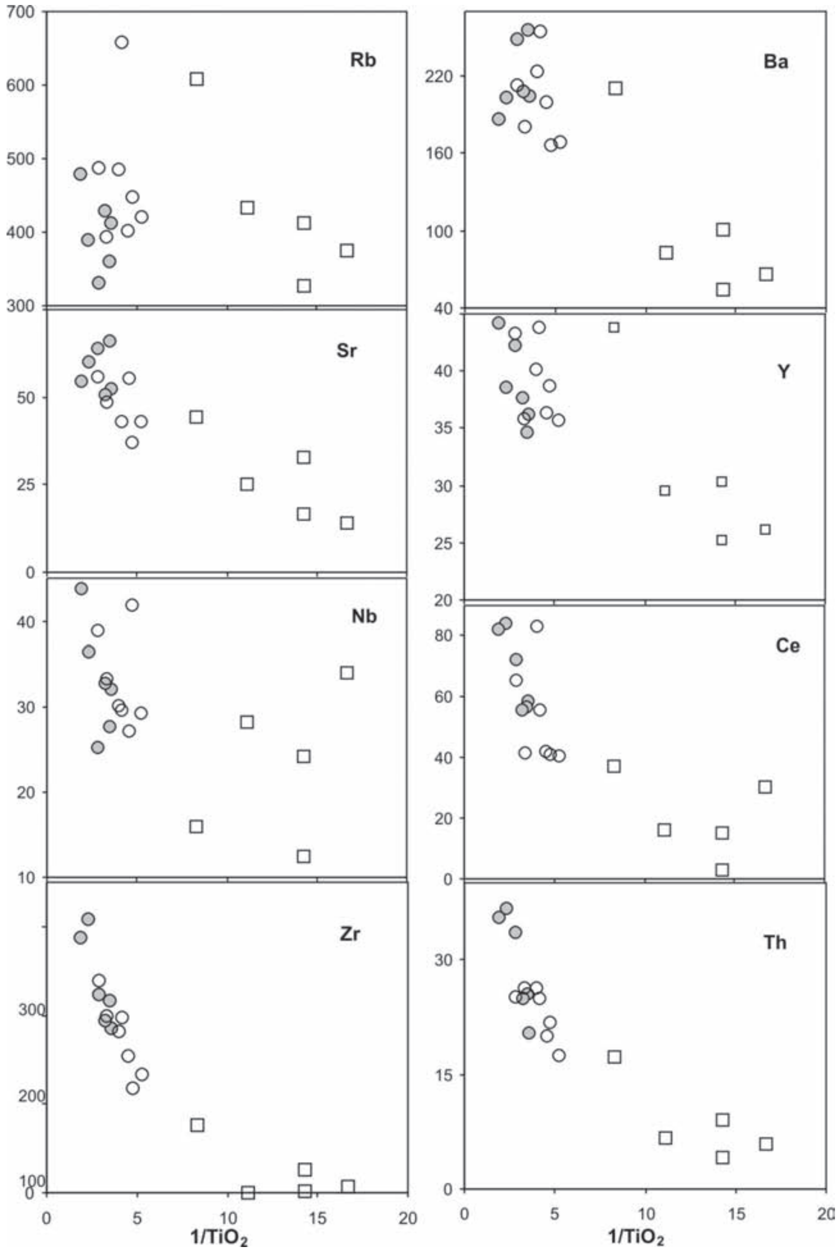

Fig. 4. Geochemical variation of trace elements of samples from the RPG (**filled circle**), the APG (**empty circle**) and the MA (**square**). Values in ppm; TiO_2 in wt%.

Discussion

The Huaco and Sanagasta granites show transitional spatial variations towards the Be-pegmatites in terms of texture, mineralogy and geochemistry: (1) megacryst abundance and size decrease; (2) quartz and muscovite contents increase, and biotite and apatite contents decrease; (3) ferromagnesian, calcium and phosphorous contents decrease, while silica increases slightly; and (4) Ce, Zr, Th and Sr contents decrease, and Rb roughly increases. The modal and chemical variations are consistent with a continuous fractional crystallization process within the granites in the direction of the Be-pegmatites, characterized essentially by biotite and apatite (and possibly zircon and monazite) fractionation, and progressive increase in silica (i.e. quartz) and incompatible elements such as Rb. The decrease in megacryst abundance and size can be attributed to progressively lower temperature conditions, which would cause lower growth rates and

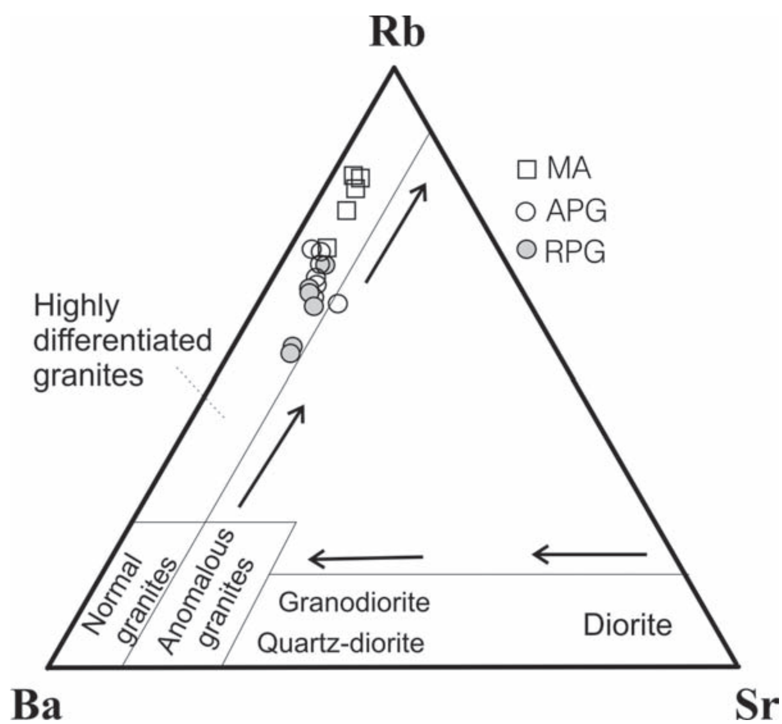

Fig. 5. Triangular diagram of Ba-, Rb- and Sr-contents of samples from the RPG, the APG and the MA (diagram after El Bouseily & El Sokkary 1975). **Arrows** indicate differentiation increase of igneous rocks.

hence crystallization of smaller K-feldspar megacrysts (e.g. Vernon 1986).

The pegmatite-margin aplites are the first crystallizing zone of the Be-pegmatites and thus record the earliest evolution of the pegmatite melts. In comparison with the surrounding granites, the MA are characterized by smaller grain-size; higher plagioclase and muscovite contents and lower K-feldspar, biotite and apatite contents; higher silica and sodium concentrations and lower ferromagnesian, calcium, potassium, phosphorous and trace element contents. These differences are quite notable, and in general no chemical continuity with the granites can be clearly observed; i.e. the compositions of the MA generally do not follow the granite major and trace element trends. This discontinuity suggests that the MA were generated as a first crystallizing phase of the pegmatitic system, rather than as a final crystallization phase of the granitic magma. The geochemistry of the MA suggests that the pegmatite-forming melts were highly evolved, peraluminous, poor in ferromagnesian and calcium elements, and that the first phase in the pegmatite evolution was the crystallization of Na-rich and sterile (i.e. low trace element contents) aplites (e.g. Jahns & Tuttle 1963; London 2005).

Biotite is the main ferromagnesian-bearing mineral in the studied rocks and is the host of trace elements such as Rb. The decrease in TiO_2, MgO and $Fe_2O_3^t$ contents from the RPG-APG (granites) to the MA (border-pegmatite) is probably consistent with biotite fractionation during the crystallization process (e.g. Zhu et al. 2006). On the other hand, the increase in CaO contents and slight increase in Na_2O contents from the RPG-APG to the MA can be attributed to fractional crystallization of Ca-rich and Na-poor plagioclase respectively.

The textural, mineralogical and geochemical granite-pegmatite transition, evidenced by the presence of the APG around the Be-pegmatites, indicate that the pegmatite-forming melts were derived from the granitic magmas. The irregular and sometimes globular shapes of the pegmatites are consistent with a genetic link between the granites and the pegmatites.

Conclusions

The bulk compositions of the RPG and APG are consistent with a continuous magmatic crystallization trend within the Huaco and Sanagasta granites towards the pegmatites. Shortly after this granitic event, final residual water-saturated and rare-element-rich pegmatite-forming melts derived from the granites crystallized as Be-pegmatites in cavities located in the consolidated (or mostly consolidated) granite mass, producing a pegmatitic event. Aplites, or more rarely equigranular leucogranites, located at the

margins of the Be-pegmatites constitute the earliest stage of the pegmatitic event. Both events are related, and the granite-to-pegmatite evolution occurred by differentiation from a common magma source.
The early history of the pegmatitic event is characterized by the scarce (to null) crystallization of biotite and depletion in ferromagnesian elements, calcium and trace elements (Ba, Sr, Y, Nb, Ce, Zr, Th) compared to the granitic event.

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