Andean Geology 43 (1): 86-104. January, 2016
doi: 10.5027/andgeoV43n1-a05

Andean Geology
www.andeangeology.cl

Non-pegmatitic beryl related to Carboniferous granitic magmatism, Velasco Range, Pampean Province, NW Argentina

***Fernando Sardi[1], Adriana Heimann[2], Pablo Grosse[3]**

[1] *Instituto Superior de Correlación Geológica - Consejo Nacional de Investigaciones Científicas y Tecnológicas (INSUGEO-CONICET), Miguel Lillo 205, C.P. 4000, San Miguel de Tucumán, Argentina.*
fgsardi@csnat.unt.edu.ar

[2] *Department of Geological Sciences, East Carolina University, 101 Graham Building, Greenville, NC 27858, USA.*
heimanna@ecu.edu

[3] *Consejo Nacional de Investigaciones Científicas y Tecnológicas (CONICET) and Fundación Miguel Lillo, Miguel Lillo 205, C.P. 4000, San Miguel de Tucumán, Argentina.*
pablogrosse@yahoo.com

* *Corresponding author: fgsardi@csnat.unt.edu.ar*

ABSTRACT. The specialized leuco-monzogranite of the La Chinchilla Stock is a small Carboniferous stock located in the center of the Velasco Range, Pampean Province, La Rioja, Argentina. It is highly evolved and locally F- and Be-bearing, and has the potential for hosting U mineralization. Three different facies can be identified in the granitoid: border, porphyritic and equigranular facies. In all three facies the main minerals are quartz, microcline, plagioclase, biotite, and muscovite. Accessory minerals present in all facies include fluorite, zircon, and apatite. In addition, monazite, rutile, and uraninite occur as accessory minerals in the equigranular facies. Secondary minerals are muscovite, sericite, kaolinite, and opaque minerals. Secondary uranophane occurs in the equigranular and border facies. In localized areas, the equigranular facies contains small, green idiomorphic crystals of beryl ($Be_3Al_2Si_6O_{18}$) as accessory mineral. One of these beryl crystals was chemically analyzed for major and minor element contents using an electron microprobe and this information, along with fractional crystallization models and comparison with compositions of non-pegmatitic beryl from the literature, were used to understand the degree of evolution of the granitic melt. The chemical formula of beryl from the La Chinchilla Stock can be written as: $^{C}(Na_{0.014\text{-}0.033}, K_{0.001\text{-}0.002}, Ca_{0.001\text{-}0.004})$ $^{T(2)}(Be_{2.978\text{-}2.987}, Li_{0.016\text{-}0.022})$ $^{O}(Al_{1.889\text{-}1.967}, Fe_{0.045\text{-}0.103}, Mg_{0.001\text{-}0.007}, Mn_{0.001\text{-}0.007})$ $^{T(1)}(Si_{5.994\text{-}6.040}O_{18})$. The alkali contents are low (Na_2O<0.18 wt%; K_2O<0.02 wt%), while FeO_t is dominant among the divalent cations that substitute trivalent aluminum in the octahedral position of the mineral (FeO_t/(MgO+MnO)>6; FeO_t<1.27 wt%). In a longitudinal geochemical profile, Al enrichment is observed at the border while the highest Na content is found in an internal point. In a transversal geochemical profile, the highest concentration of Al is seen in an internal point while Na remains almost invariable. Ferromagnesian elements vary randomly within the crystal. This indicates compositional changes in the magma for Al, ferromagnesian elements, and Na. The FeO_t content of the analyzed beryl is within the compositional range of other disseminated beryl from granitoids but slightly higher than that of beryl from hydrothermal veins and greisens. It contains similar to slightly lower amounts of FeO_t, MgO, and Na_2O than beryl from medium to little evolved granitic pegmatites. Overall, the composition of beryl in the La Chinchilla Stock is quite similar to that from medium to poorly evolved granitic pegmatites of the nearby Velasco Pegmatite District. The formation of beryl in the La Chinchilla Stock is attributed to precipitation from a F-bearing, highly fractionated, Al- and Si-rich melt saturated in BeO. A fractional crystallization model using Rb and Ba suggests that the beryl-hosting rock crystallized from the parent melt after extreme fractionation and 75% crystallization. The occurrence of beryl as a magmatic accessory mineral in the equigranular facies of the La Chinchilla Stock is indicative of a very high degree of fractionation of the parental magma.

Keywords: Non-pegmatitic beryl, Carboniferous granite, La Chinchilla Stock, Velasco Range, Pampean Province, Argentina.

RESUMEN. Berilo no pegmatítico relacionado con el magmatismo granítico Carbonífero de la sierra de Velasco, Sierras Pampeanas, NW de Argentina. El leuco-monzogranito especializado del Stock La Chinchilla es un pequeño cuerpo carbonífero ubicado en el centro de la sierra de Velasco, Provincia de Sierras Pampeanas, La Rioja, Argentina. Es altamente evolucionado y localmente rico en F y Be, y tiene una importante potencialidad por contener mineralización de U. Pueden ser identificadas tres facies en el granitoide: facies de borde, facies porfírica y facies equigranular. En todas las facies, los principales minerales son cuarzo, microclino, plagioclasa, biotita y muscovita y los minerales accesorios incluyen fluorita, circón y apatito. Además, monacita, rutilo y uraninita ocurren como minerales accesorios en la facies equigranular. Los minerales secundarios son muscovita, sericita, caolinita y minerales opacos. Uranofano secundario aparece en las facies equigranular y de borde. En determinadas áreas, la facies equigranular contiene pequeños cristales idiomorfos de berilo de color verde ($Be_3Al_2Si_6O_{18}$) como mineral accesorio. Uno de estos cristales de berilo fue analizado químicamente por elementos mayores y menores utilizando una microsonda electrónica, y a partir de esta información, conjuntamente con modelos de cristalización fraccionada y la comparación de la composición con otros berilos no pegmatíticos disponibles en la literatura, fueron usados para comprender el grado de evolución del magma. La fórmula química del berilo del Stock La Chinchilla puede ser escrita como: $^{C}(Na_{0.014\text{-}0.033}, K_{0.001\text{-}0.002}, Ca_{0.001\text{-}0.004})\ ^{T(2)}(Be_{2.978\text{-}2.987}, Li_{0.016\text{-}0.022})\ ^{O}(Al_{1.889\text{-}1.967}, Fe_{0.045\text{-}0.103}, Mg_{0.001\text{-}0.007}, Mn_{0.001\text{-}0.007})\ ^{T(1)}(Si_{5.994\text{-}6.040}O_{18})$. El contenido de elementos alcalinos es bajo (Na_2O < 0.18 wt%; K_2O < 0.02 wt%), mientras que el FeO_t es dominante entre los cationes divalentes que sustituyen al aluminio trivalente en la posición octaédrica del mineral (FeO_t/(MgO+MnO) >6; FeO_t <1.27 wt%). En un perfil geoquímico longitudinal se observa un enriquecimiento de Al en el borde mientras que los contenidos más altos en Na se encuentran en un punto interno. En un perfil geoquímico transversal, la más alta concentración de Al aparece en un punto interno, mientras que el Na permanece casi invariable. Los elementos ferromagnesianos varían erráticamente dentro del cristal. Esto sugiere cambios composicionales en el magma en Al, elementos ferromagnesianos y Na. El contenido de FeO_t del berilo analizado está dentro del rango composicional de otros berilos diseminados en granitoides pero es levemente más alto que en otros berilos de venas hidrotermales y greisens. Contiene similar a levemente más bajas cantidades de FeO_t, MgO y Na_2O que berilos de pegmatitas graníticas medianamente a poco evolucionadas. En general, la composición del berilo del Stock La Chinchilla es bastante similar al de las pegmatitas graníticas medianamente a pobremente evolucionadas del vecino Distrito Pegmatítico Velasco. La formación del berilo en el Stock La Chinchilla es atribuida a la precipitación a partir de un fundido altamente fraccionado, rico en F, Al y Si, y saturado en BeO. Un modelo de cristalización fraccionada usando Rb y Ba sugiere que la roca portadora del berilo habría cristalizado a partir de un fundido después de un extremo fraccionamiento y 75% de cristalización. El berilo como un mineral accesorio en la facies equigranular del Stock La Chinchilla es indicativo de un muy alto grado de fraccionamiento del magma parental.

Palabras clave: Berilo no pegmatítico, Granito Carbonífero, Stock La Chinchilla, Sierra de Velasco, Sierras Pampeanas, Argentina.

1. Introduction

Beryl, with an ideal formula given by $Be_3Al_2Si_6O_{18}$, is a common accessory mineral in granitic pegmatites (Tindle and Breaks, 1998; Charoy, 1999; Černý *et al.*, 2003; Alfonso and Melgarejo, 2008; Thomas *et al.*, 2009, 2011; Uher *et al.*, 2010; Rao *et al.*, 2011; Sardi and Heimann, 2014), especially those of the LCT (Li-Cs-Ta) family (based on the classification of Černý, 1991), occasionally appears associated with chrysoberyl in Be-rich pegmatites (Soman and Nair, 1985; González del Tánago, 1991), as well as in highly evolved granites (Charoy and Noronha, 1996; Charoy, 1999; Merino *et al.*, 2013). It is a source of Be, which is used primarily for alloys with other metals to achieve a lightweight and durable steel, and for nuclear and high technology applications (Barton and Young, 2002). In granitic pegmatites, the mineral can develop idiomorphic crystals from millimeter size to more than ten meters long (as occurs in some pegmatites from Madagascar; Černý, 2002). In some cases beryl develops gemological varieties of great value, such as heliodor (clear, transparent yellow beryl) and aquamarine (light green to blue with a high degree of transparency) in pegmatites (*e.g.*, Proctor, 1984). However, non-pegmatitic beryl can also represent an important source of gemstones, especially emerald and aquamarine (Barton and Young, 2002; Seifert *et al.*, 2004). In fact, beryl can occur as a mineral in other environments of varied and complex geological nature (such as metamorphic; Downes and Bevan, 2002; Novák *et al.*, 2011), and, in particular, is an accessory mineral in geochemically evolved, F-rich, metasomatized granites (*e.g.*, Černý *et al.*, 2003). Table 1 presents a summary of the types and examples of non-pegmatitic beryl (hydrothermal vein, greisen, rhyolite) occurrences worldwide.

The La Chinchilla Stock is a small granite body (3.75 km^2) outcropping in the central sector of the

TABLE 1. SUMMARY OF NON-PEGMATITIC BERYL OCCURRENCES WORLDWIDE.

i) Disseminated as magmatic accessory mineral in leucogranites, usually metasomatized ("apogranites")
- Stock La Chinchilla, Velasco Range, Argentina (Grosse *et al.*, 2005; Salvatore *et al.*, 2013) - Piedras Coloradas, Las Chacras Batholith, San Luis, Argentina** (Hurlbut and Aristarain, 1969) - Pan-African Massif, Egypt** (Abdalla and Mohamed, 1999; Abdalla, 2009) - Near to Bagdad, Arizona** (Staatz *et al.*, 1965) - Agua Verde, Pima County, Arizona** (Staatz *et al.*, 1965) - Lone Pine, California** (Staatz *et al.*, 1965) - Sheeprock Mountains, Utah, USA** (Staatz *et al.*, 1965; Barton and Young, 2002) - Mt. Antero, Colorado, USA** (Staatz *et al.*, 1965; Barton and Young, 2002) - Rosses Granite, Donegal, NW Ireland (Burke *et al.*, 1964; Hall and Walsh, 1971) - Argemela, Portugal** (Charoy and Noronha, 1996; Charoy, 1999) - Belvis de Monroy pluton, Montes de Toledo Batholith, Cáceres, Spain** (Merino *et al.*, 2013)
ii) Hydrothermal veins, essentially composed of quartz
- Mesa del Palmar, Achala Batholith, Córdoba, Argentina (Kirschbaum, 1990) - Pan-African Massif, Egypt** (Abdalla and Mohamed, 1999; Abdalla, 2009) - Rosses Granite, Donegal, NW Ireland** (Burke *et al.*, 1964; Hall and Walsh, 1971; Conliffe and Feely, 2006) - Near to Bagdad, Arizona, USA** (Staatz *et al.*, 1965) - Boomer Mine, Lake George, Colorado, USA** (Staatz *et al.*, 1965) - Elfrida, Arizona, USA** (Staatz *et al.*, 1965) - Monte Antero, Colorado, USA** (Staatz *et al.*, 1965) - Mobawk Mine, Hill City, South Dakota, USA** (Staatz *et al.*, 1965) - Black Pearl Mine, Bagdad, Arizona, USA** (Staatz *et al.*, 1965) - Lakeview Mine, Nevada, USA** (Staatz *et al.*, 1965) - Victorio Mts, Nueva México, USA** (Staatz *et al.*, 1965) - El Karit, Morocco** (Staatz *et al.*, 1965) - Triberg Granite Complex, Schwarzwald, Germany (Markl and Schumacher, 1997) - Redskin Granite, Pikes Peak Batholith, Colorado USA (Desborough *et al.*, 1980)
iii) Greisen (lenses, stockworks, or veins), usually quartz with cassiterite and/or wolframite
- Pan-African Massif, Egypt** (Abdalla and Mohamed, 1999; Abdalla, 2009) - Rosses Granite, Donegal, NW Ireland (Burke *et al.*, 1964; Conliffe and Feely, 2006) - Triberg Granite Complex, Schwarzwald, Germany (Markl and Schumacher, 1997) - Redskin Granite, Pikes Peak Batholith, Colorado, USA (Desborough *et al.*, 1980)
iv) Rhyolite rich in F (with fluorite and topaz)
- Thomas Range, Juab County, Utah, USA** (Staatz *et al.*, 1965) - Western area of USA and center area of Finland (Christiansen *et al.*, 2007)
v) Geological environment of igneous and/or metamorphic rocks of mafic to ultramafic composition, specifically for emerald variety
- Pan-African Massif, Egypt (Abdalla and Mohamed, 1999; Grundmann and Morteani, 2008; Abdalla, 2009) - Kafuru, Zambia (Seifert *et al.*, 2004; Zachariáš *et al.*, 2005) - Many worldwide localities (Groat *et al.*, 2008)

** Beryl used for comparison in figures 4 and 5.

Velasco Range (La Rioja) and within the Velasco Pegmatite District, Pampean Province, Argentina (Grosse *et al.*, 2009; Salvatore *et al.*, 2013). It is a highly evolved leucogranite that has the particularity of containing beryl as an accessory mineral in certain sectors of the stock. This stock represents one of the scarce examples of beryl-bearing granitoids (together with those found in the USA: Staatz *et al.*, 1965; central Portugal: Charoy and Noronha, 1996; Charoy, 1999; Ireland: Burke *et al.*, 1964; and central

Spain: Merino *et al.*, 2013). In addition, the stock contains elevated quantities of U mineralization, which is being explored for potential mining. However, to date, the chemical composition of beryl in this granite has not been investigated, and it provides an opportunity for understanding the relative degree of evolution of this granitoid. In this contribution we present the concentration and distribution of major and minor elements in magmatic beryl from the La Chinchilla Stock and compare them with other, similar non-pegmatitic species of magmatic (and post-magmatic) beryl to determine compositional differences and similarities, that, along with fractional crystallization models and crystallization temperatures are used to infer the relative degree of evolution of the host granitoid.

2. Geologic Setting

The Velasco mountain Range is part of the Pampean Ranges in northwestern Argentina (Fig. 1A). It is located in the "central batholitic zone", characterized mostly by large granitic batholiths and very scarce, older metamorphic rocks (Toselli *et al.*, 1986). Metapsamitic and metapelitic rocks appear as small outcrops in the central-eastern area of the Velasco Range and correlate with the La Cébila Formation of González Bonorino (1951) (Toselli *et al.*, 2000). Based on the occurrence of marine fossils, the clastic sedimentary protoliths of the metamorphic rocks were deposited during the lower Ordovician (Verdecchia *et al.*, 2007).

However, most of the rocks that make up the Velasco Range are granitoids characterized by different ages and tectono-magmatic evolution. Two main diachronic magmatic events are recognized: an early Ordovician and an early Carboniferous (Toselli *et al.*, 2000, 2005, 2007; Grosse *et al.*, 2003; Báez *et al.*, 2005). The first magmatic episode produced metaluminous to peraluminous granitoids of granodioritic and tonalitic composition, mostly now deformed. The second magmatic episode generated mostly peraluminous syenogranites to monzogranites with no deformation. The Ordovician peraluminous granitoids, with dominant porphyritic texture, crop out primarily in the northwestern and western areas of the range and have been grouped as Antinaco orthogneisses (Rossi *et al.*, 2000, 2002). These were affected by NNW-SSE shear zones that produced deformation of variable intensity and, in many cases, mylonites of regional extent (*e.g.*, López *et al.*, 1996, 2006; Höckenreiner *et al.*, 2003). Uranium-Pb zircon dating yielded early Ordovician crystallization ages (Pankhurst *et al.*, 2000; Rapela *et al.*, 2001; Báez, 2006), whereas Sm-Nd dating yielded a late Silurian-early Devonian age for the deformation event (Höckenreiner *et al.*, 2003).

The south of the Velasco Range is characterized by metaluminous to weakly peraluminous granitoids (granodiorite and tonalite) with accessory biotite, hornblende, titanite, and magnetite (Bellos *et al.*, 2002; Bellos, 2005). Recent U-Pb zircon SHRIMP dating of these granitoids also yielded early Ordovician crystallization ages (480-442 Ma; Bellos *et al.*, 2015), which indicates that they are correlated with granitoids from the neighboring Famatina (*e.g.*, Aceñolaza *et al.*, 1996) and Chepes (*e.g.*, Pankhurst *et al.*, 1998) Ranges that are similar, geochemically as well as in age.

Undeformed, peraluminous granitoids of Carboniferous age are located in the central and northwestern part of the Velasco Range. Based on field relationships as well as relative and absolute ages, these granitoids were grouped as Aimogasta Batholith, composed of several post-tectonic intrusions (Toselli *et al.*, 2006). Lithologically they are both two-mica syenogranite and monzogranite, commonly exhibiting porphyritic texture. Age dating (U-Pb) on zircon and monazite yielded ages between 358 and 340 Ma (Báez *et al.*, 2004; Dahlquist *et al.*, 2006; Grosse *et al.*, 2009).

The La Chinchilla Stock granitoid corresponds to the latter magmatism, based on U-Pb dating of monazite (344.5±1.4 Ma; Grosse *et al.*, 2009). First defined by Grosse *et al.* (2005), it is a small body of ~2x2 km, of monzogranitic composition, that intruded into the Huaco Granite (350-358 Ma). The contacts between the two bodies have sub-vertical as well as sub-horizontal dips, with the La Chinchilla Stock below and the Huaco Granite upwards, suggesting proximity to the stock roof (Grosse *et al.*, 2005). The monzogranite is characterized by three textural facies: border, porphyritic, and equigranular facies. Pegmatite dikes are abundant in the equigranular facies (Salvatore *et al.*, 2013).

The Huaco Granite is also Carboniferous in age and has an A-type affinity (Dahlquist *et al.*, 2006, 2010; Grosse *et al.*, 2009). It is classified as a syeno- to monzogranite with biotite and muscovite as main accessory minerals. Based on whole-rock geochemistry, it is a peraluminous granite rich in SiO_2 and

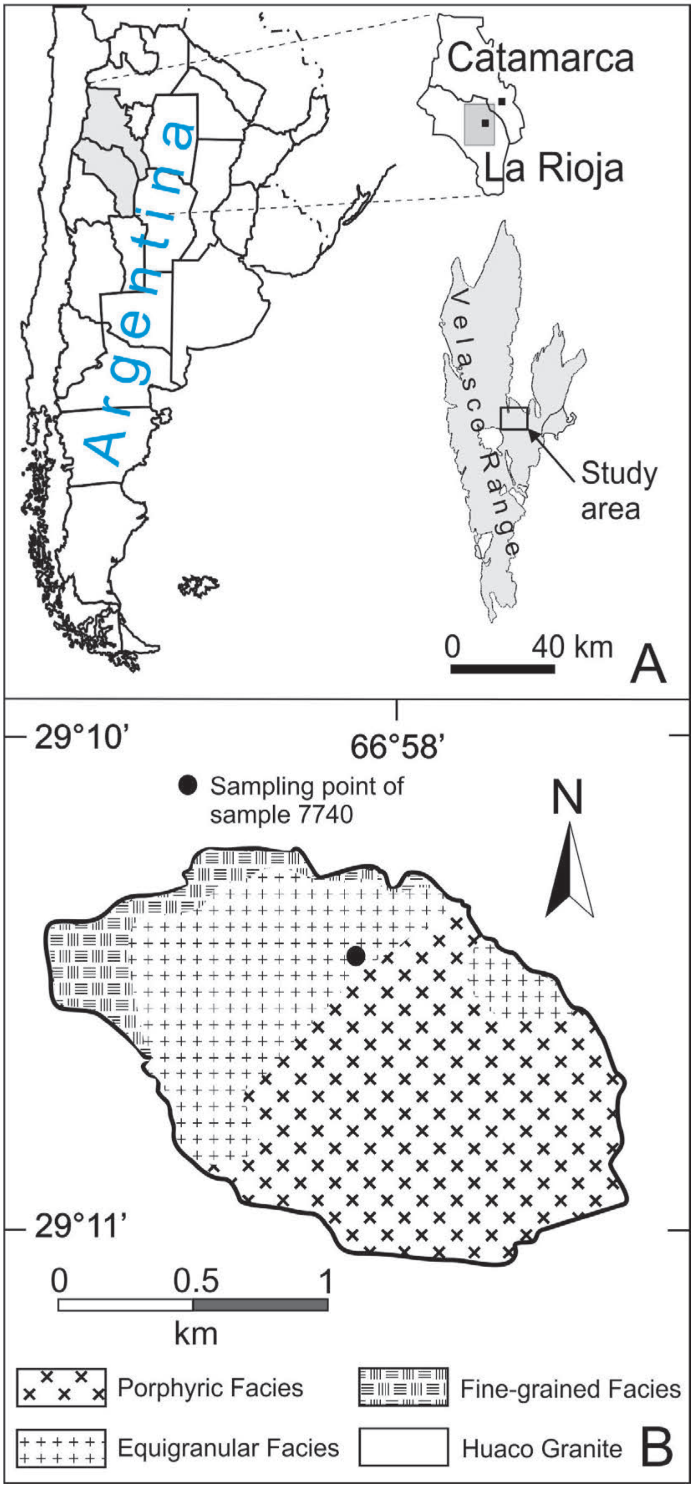

FIG. 1. **A.** Geographic location of the La Chinchilla Stock, in the Velasco Range, Pampean Province, Argentina; **B.** Simplified geologic map of the La Chinchilla Stock. Petrographic facies after Salvatore *et al.* (2013). Location of the beryl-bearing sample (7740) is shown in the map.

alkalis (Grosse *et al.*, 2009). Whole-rock major- and trace-element geochemistry and mineral chemistry (on biotite mainly), field observations, and isotopic studies indicate that the La Chinchilla Stock is an A-type granitoid with mixtures of a mantle-derived component and some crustal sources (Grosse *et al.*, 2009; Dahlquist *et al.*, 2010). Although both granitoids were generated during a post-orogenic period in a within-plate setting, no genetic relationship has been ascribed between them, since, based on isotopic studies the La Chinchilla Stock presumably derived from a more primitive source than that of the Huaco Granite (Grosse *et al.*, 2009). Recent mapping and a detailed structural study, including magmatic fabrics of the La Chinchilla Stock and the host Huaco Granite, as well as dike orientations, indicate that the La Chinchilla Stock was emplaced in the shallow crust by a mechanism that involved brittle fracturing and block displacement suggestive of magmatic stoping during the late stage of evolution of the magma chamber (Macchioli Grande *et al.*, 2015).

3. La Chinchilla Stock

3.1. Petrography

The La Chinchilla Stock is a medium-grained, equigranular to slightly porphyritic leuco-monzogranite with up to 10% K-feldspar megacrystals (Grosse *et al.*, 2006, 2009). Based on detailed mapping and according to textural and mineralogical characteristics, Salvatore *et al.* (2013) defined three granitic facies with meter-scale transitions between them: fine-grained border facies, porphyritic facies, and equigranular facies, all of similar monzogranitic composition (Fig. 1B). Overall, major minerals consist of quartz (37-42%), plagioclase (25-33%), K-feldspar (19-34%), and biotite (4-9%), while accessory minerals are muscovite, fluorite (up to 1%), zircon, monazite, opaque minerals, and scarce apatite (Grosse *et al.*, 2006, 2009). The K-feldspar is microcline and occurs as crystals that reach 4 cm long in places exhibiting rapakivi texture. Plagioclase is almost pure albite (An_{1-2}) and reaches 3 mm. Biotite is discolored and pleochroic (very light brown to reddish-brown), small (<3.5 mm), and chemically corresponds to zinwaldite. Primary muscovite is scarce and found mainly as inclusions in microcline and quartz. Fluorite occurs as small (0.3-0.5 mm), anhedral, interstitial, clear to violet crystals.

According to Salvatore *et al.* (2013), the fine-grained border facies contains essential quartz (44%), plagioclase (33%), and microcline (23%), accessory muscovite, biotite, opaque minerals, zircon, and apatite, scarce fluorite, and secondary kaolinite and uranophane. Sericite is the most abundant secondary phase. The porphyritic facies contains megacrystals of potassium feldspar (~ 4 cm) in a medium- to coarse-grained equigranular matrix. Essential minerals are quartz (32%), microcline (36%), plagioclase (26%), and biotite-muscovite (5-6%). Muscovite, zircon, fluorite, and apatite are the accessory minerals.

The equigranular facies in the northwestern sector of the body has a special interest due to the occasional occurrence of small, disseminated crystals of green beryl among other accessory minerals. This equigranular facies has a hypidiomorphic granular texture, and is mostly pink and occasionally gray due to alteration phenomena. Essential minerals are quartz (36-38%), microcline (28-33%), plagioclase (28-30%), and biotite+muscovite (5-6%), fluorite, zircon, monazite, and opaque minerals are accessory phases, and beryl occurs as occasional mineral. In addition, Salvatore *et al.* (2011) emphasized the presence of accessory uraninite, and as secondary minerals muscovite, sericite, kaolinite, uranophane, and Fe-Ti oxides. Furthermore, Morello and Aparicio González (2013) identified the presence of an uranium-niobium-tantalum oxide, which is distributed in the form of pale to bright yellow powder aggregates and forming transparent to translucent prismatic crystals. Salvatore *et al.* (2013) also described beryl as a major constituent mineral, and Lira *et al.* (2015) reported amazonite, both in syn-magmatic pegmatites and miarolitic cavities within this facies.

3.2. Geochemistry

Geochemical studies performed by Grosse *et al.* (2009) indicate that the La Chinchilla leuco-monzogranite is very rich in SiO_2 (75.4-76.2 wt%) and weakly peraluminous (ASI=mol Al_2O_3/mol (Na_2O+K_2O+CaO)=1.05-1.13). However, Salvatore *et al.* (2013) obtained a wider range of ASI values (0.88-1.17) for the overall intrusion that indicate a slightly metaluminous to highly peraluminous affinity, including ASI values indicative of a metaluminous character in some samples of the equigranular facies. The equigranular sample containing beryl analyzed in the present study is peraluminous (ASI=1.06).

Overall, the granitoid has very low Ca, P, Fe, and in particular Mg contents. It is strongly enriched in several trace elements, particularly Li, Rb, Nb, Ta, U, Th, Y, and heavy rare-earth elements. The equigranular sample that contains the beryl analyzed in this study (sample 7740) has 80 ppm Be (Grosse *et al.*, 2009), representing the highest Be contents measured in the La Chinchilla Stock (7-80 ppm Be; Grosse *et al.*, 2009; Dahlquist *et al.*, 2010) as well as in its country rock (Huaco Granite; <21 ppm; Grosse *et al.*, 2009; Dahlquist *et al.*, 2010). The equigranular facies reaches higher Be contents (12-80 ppm Be) than the porphyritic facies (15-17 ppm Be; Grosse *et al.*, 2009; Dahlquist *et al.*, 2010). Its high Rb/Sr (16-72) and low K/Rb (54-98) ratios indicate that the La Chinchilla Stock represents an evolved magma (Grosse *et al.,* 2009). Very strong negative Eu anomalies indicate prior extensive crystallization of plagioclase and reflect the high degree of evolution of the magma (Grosse *et al.,* 2009).

In addition, Grosse *et al.* (2009) emphasized U enrichment, with 18-69 ppm, much higher than U values of common granites (4 ppm; Rogers and Adams, 1969), which has led to U exploration in the La Chinchilla Stock (Salvatore *et al.*, 2011, 2013; Parra *et al.*, 2011; Morello and Aparicio González, 2013). A prospecting study on the most favorable areas of the body resulted in inferred resources of 803 tons at a grade of 161 ppm U (Parra *et al.*, 2011). This U enrichment also evidences the highly evolved character of the La Chinchilla Stock.

3.3. Mineralogical features of beryl

The crystal structure of beryl consists of layers of rings with 6 Si-O tetrahedra, which are linked vertically and laterally by Be-O tetrahedra and Al-O octahedra (Bragg and West, 1926; Gibbs *et al.*, 1968; Hawthorne and Huminicki, 2002). For crystallochemical reasons, Be may be substituted by Li, and Al by Fe, Mg, Mn and other minor elements (Staazt *et al.*, 1965; Černý, 2002). The centers of the rings are called "channels", which are mainly occupied by water and alkalis, which in order of importance are Na, Cs, K, and Rb (Hawthorne and Černý, 1977; Aurisicchio *et al.*, 1988; Hawthorne and Huminicki, 2002).

Beryl is a casual magmatic accessory mineral in the La Chinchilla Stock. In hand sample it is visible to the naked eye and can reach about 1 cm. It occurs as idiomorphic crystals, often exhibiting hexagonal sections, with a green color or green with a slight yellowish tint (Fig. 2A, B). It commonly appears disseminated in the granite, but it also occurs in very small "pegmatitic pockets" (not exceeding 15 cm) accompanied by quartz, K-feldspar, and muscovite (Salvatore *et al*., 2013). The presence of beryl was corroborated by X-ray diffraction analysis (Grosse *et al*., 2005). Under the microscope, it is colorless, has low to moderate relief (but lower than quartz), and low interference color (first-order yellow). It may contain inclusions of K-feldspar and quartz, and more rarely biotite.

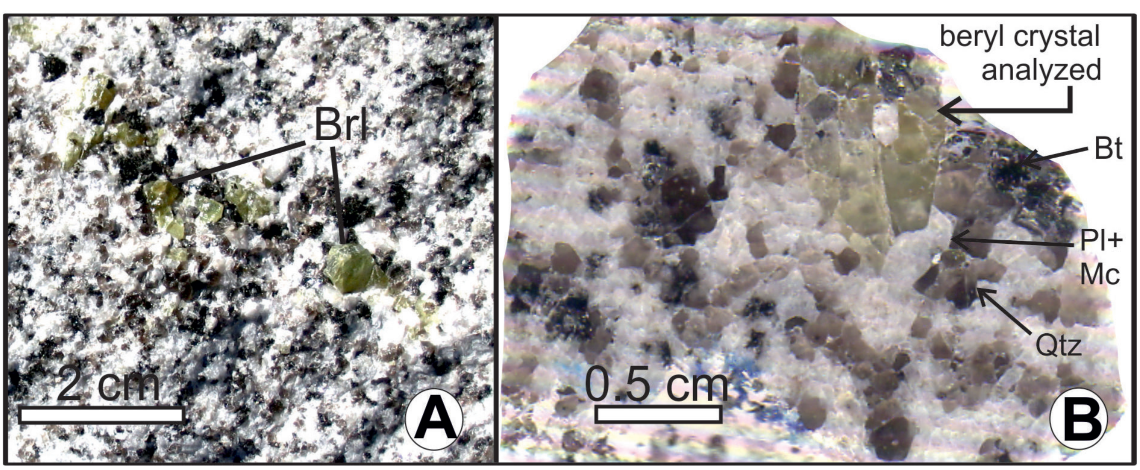

FIG. 2. **A.** Macrophotography showing the occurrence of beryl (Brl) from the La Chinchilla Stock (from Grosse *et al.*, 2005); **B.** Close up view of *a* showing the studied crystal. Dark grey: quartz (Qtz); white: plagioclase (Pl) and microcline (Mc); black: biotite (Bt); green-yellow: beryl.

4. Results

Ten individual chemical analyses were obtained by electron microprobe on a longitudinal polished crystal of beryl from the La Chinchilla Stock measuring ~1.3 cm long. Original polished-thin sections were made in the laboratory at the INSUGEO (Tucumán, Argentina), and the final polishing was performed at Vancouver Petrographics (Canada). Electron microprobe analyses were performed using a JEOL JXA-8530F Hyperprobe in the Department of Natural Sciences at Fayetteville State University (NC, USA). Operating conditions were an accelerating voltage of 15 kV, emission current of 10 nA, counting time of 10 s, and a beam diameter of 1 micrometer. Eight components were analyzed using synthetic and natural mineral standards, including albite (Na), almandine (Si, Al, Fe, Mg), bustamite (Ca, Mn), and sanidine (K).

Two chemical transects, a longitudinal one (AA'; parallel to the c axis) and a transversal one (BB'; perpendicular to the c axis), were performed on the longitudinal section of the beryl crystal (Fig. 3A). The distribution of the analyzed points is shown in a sketch of the mineral observed under the microscope (Fig. 3A). The results are shown in figure 3B and Table 2, including the chemical composition and the structural formula of beryl.

The composition of beryl, expressed in averages followed by ranges, is: 62.8 wt% SiO_2 (62.1-63.3 wt%), 17.3 wt% Al_2O_3 (16.6-17.6 wt%), 0.8 wt% FeO_t (0.6-1.3 wt%), 0.03 wt% MnO (0.01-0.08 wt%), 0.02 wt% MgO (0.001-0.05 wt%), 0.02 wt% CaO (0.01-0.04 wt%), 0.13 wt% Na_2O (0.08-0.18 wt%), and 0.009 wt% K_2O (0.002-0.02 wt%). Beryllium oxide contents were calculated from stoichiometry using the Al_2O_3 and SiO_2 contents and assuming an ideal beryl formula ($Be_3Al_2Si_6O_{18}$). Average and ranges of beryllium oxide contents are 13.0 wt% BeO and 12.8-13.1 wt% BeO, respectively. Iron is dominant among the divalent cations occupying the octahedral site (FeO_t/MgO+MnO>6). The Na contents are always greater than K; therefore, the studied beryl can be classified as a sodic beryl according to the classification of Hawthorne and Černý (1977).

Geochemical profiles show a slight compositional variation. In general, for the longitudinal section (A-A'), Al is enriched at the rims of the mineral and depleted in the center (Fig. 3B, A). In the transverse across the longitudinal section of the crystal (B-B'), the highest value of Al is in an internal point of the crystal, but the variations are not consistent (Fig. 3B, B). The sum of Fe+Mg+Mn is highest in the internal part of the crystal's longitudinal profile and lowest near the edges (Fig. 3B, C, D). Sodium contents show a zigzag pattern in the longitudinal profile (Fig. 3B, E), with the lowest concentration in one of the crystal edges, whereas in the transversal profile the pattern is more or less flat, although also showing the lowest contents at the mineral rim (Fig. 3B, F). Overall, the pattern of the sum of the ferromagnesian elements follows that of Na and is the inverse of that for Al.

5. Discussion

5.1. Beryl composition and comparison with non-pegmatitic beryl worldwide

The contents of the three major mineral components are slightly lower (62.1-63.3 wt% SiO_2, 16.6-17.6 wt% Al_2O_3, 12.8-13.1 wt% BeO) than the theoretical values calculated from the theoretical formula (67.1 wt% SiO_2, 18.9 wt% Al_2O_3, 13.9 wt% BeO). Therefore, the mineral naturally contains other minor components, including FeO, MgO, MnO, alkaline elements (Na, K), and most likely H_2O (not analyzed in this study) that replace some major elements, the latter two located in the center of the channels, (*e.g.*, Andersson, 2006).

Beryl from the La Chinchilla Stock has a formula given by:

$$^{C}(Na_{0.014-0.033}, K_{0.001-0.002}, Ca_{0.001-0.004})\ ^{T(2)}(Be_{2.978-2.987}, Li_{0.016-0.022})\ ^{O}(Al_{1.889-1.967}, Fe_{0.045-0.103}, Mg_{0.001-0.007}, Mn_{0.001-0.007})\ ^{T(1)}(Si_{5.994-6.040}O_{18}).$$

For comparative purposes, the composition of beryl from the La Chinchilla Stock is plotted along with compositional data for non-pegmatitic beryl and beryl in pegmatites from the Velasco District, which are hosted in the Huaco and Sanagasta granites (Figs. 4, 5; Sardi and Heimann, 2014). A negative correlation is observed between the Al_2O_3 and FeO_t+MgO+MnO (wt%) contents in beryl from various sources (Fig. 4A). This correlation demonstrates the substitution of alumina by ferromagnesian and manganese oxides in the octahedral position of the mineral (*e.g.*, Černý, 2002). The same negative correlation can also be observed for the single crystal analyzed in this study (Figs. 3B, 4). A slightly overall

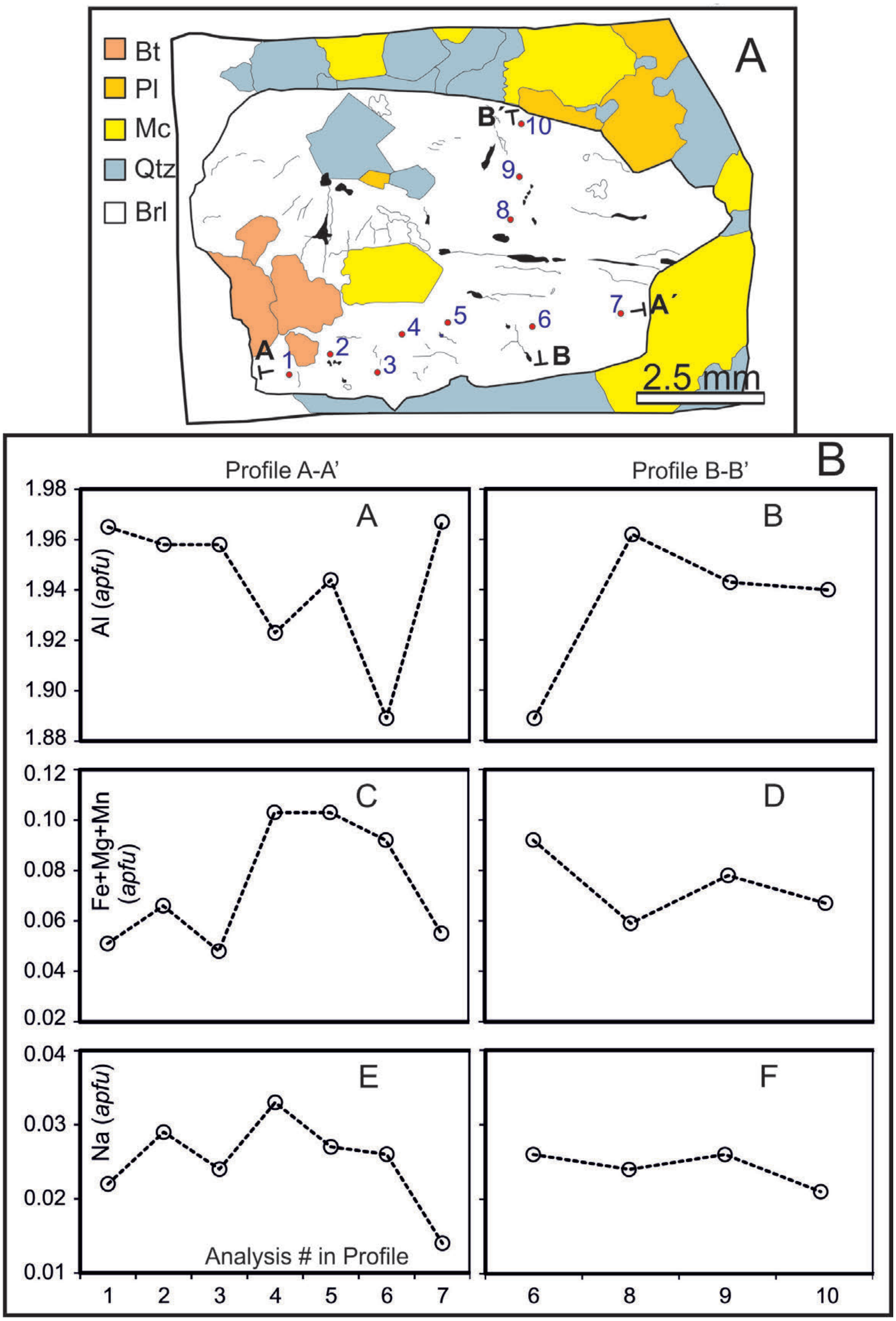

FIG. 3. **A.** Sketch of the studied beryl crystal form the La Chinchilla Stock as observed under the microscope indicating the location of the individual spot chemical analyses along two transects (A-A' and B-B'). Abbreviations: **Bt:** biotite; **Brl:** beryl; **Mc:** microcline; **Pl:** plagioclase; **Qtz:** quartz; **B.** Chemical profiles (A-A' and B-B') of the studied beryl crystal *versus* analysis number in each profile; **A-B.** Al (*apfu*). **C-D.** Fe+Mg+Mn (*apfu*). **E-F.** Na (*apfu*). ***apfu:*** atoms per formula unit, based on 18 oxygen atoms. Analyses performed via electron microprobe.

TABLE 2. CHEMICAL COMPOSITION OF BERYL FROM THE LA CHINCHILLA STOCK, VELASCO RANGE (ARGENTINA).*

	1	2	3	4	5	6	7	8	9	10
SiO_2	63.21	62.61	63.26	62.78	62.05	62.45	63.18	62.71	62.90	62.72
Al_2O_3	17.58	17.36	17.51	17.05	17.09	16.58	17.59	17.41	17.28	17.18
FeO_t	0.56	0.79	0.59	1.22	1.27	1.05	0.60	0.60	0.94	0.80
BeO**	13.10	12.97	13.10	12.95	12.84	12.82	13.10	13.00	13.01	12.96
MnO	n.d.	0.01	0.01	0.03	n.d.	0.03	0.08	0.04	0.02	0.04
MgO	0.04	0.02	n.d.	0.02	n.d.	0.03	0.01	0.05	0.01	0.00
CaO	0.04	0.01	0.03	n.d.	n.d.	n.d.	0.02	n.d.	0.02	n.d.
Na_2O	0.12	0.15	0.13	0.18	0.14	0.14	0.08	0.13	0.14	0.11
K_2O	0.00	n.d.	0.00	0.02	0.02	0.00	0.01	n.d.	0.01	0.01
apfu based on 18 oxygen atoms										
Si^{T1}	5.999	5.997	6.005	6.007	5.993	6.04	5.997	5.999	6.003	6.013
Be	2.987	2.984	2.987	2.978	2.979	2.979	2.987	2.987	2.983	2.985
Li**	0.013	0.016	0.013	0.022	0.021	0.021	0.013	0.013	0.017	0.015
Σ^{T2}	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000
Al	1.965	1.958	1.958	1.923	1.944	1.889	1.967	1.962	1.943	1.94
Fe^{++}	0.045	0.063	0.047	0.098	0.103	0.085	0.047	0.048	0.075	0.064
Mn	-	0.001	0.001	0.002	-	0.002	0.007	0.004	0.001	0.003
Mg	0.006	0.002	-	0.003	-	0.005	0.001	0.007	0.002	-
Σ^{O}	2.016	2.024	2.006	2.026	2.047	1.981	2.022	2.021	2.021	2.007
Ca	0.004	0.001	0.003	-	-	-	0.002	-	0.002	-
Na	0.022	0.029	0.024	0.033	0.027	0.026	0.014	0.024	0.026	0.021
K	-	-	-	0.002	0.002	-	0.001	-	0.001	0.001
Σ^{C}	0.026	0.030	0.027	0.035	0.029	0.026	0.017	0.024	0.029	0.022

* Analyses by EMP. *apfu*, atoms per formula unit. BeO** calculated by stoichiometry considering an ideal beryl formula and using the measured values of SiO_2 and Al_2O_3. Li** calculated as Li= 3-Be (Wang *et al.*, 2009). ^{T1}: tetrahedral position 1; ^{T2}: tetrahedral position 2; ^{O}: octahedral position; ^{C}: channel; n.d. and **- :** not detected.

positive correlation can also be suggested between Na_2O and FeO_t+MgO+MnO (wt%; Fig. 4A) for beryl data available from the literature, as well as for beryl from the La Chinchilla Stock. These correlations suggest that Na compensates the electrostatic imbalance generated by the very limited substitution of divalent elements by trivalent aluminum, which is consistent with the results obtained in previous studies (*e.g.*, Černý, 2002; Aurisicchio *et al.*, 2012).

Overall, beryl from the La Chinchilla Stock has FeO_t+MgO+MnO and Al_2O_3 values that fall within the compositional range of other non-pegmatitic beryl as well as of beryl from granitic pegmatites from the Velasco District (Fig. 4A, B). These values, however, are among the lowest for alumina, and less so for FeO_t+MgO+MnO. The sodium content of beryl from the La Chinchilla Stock is the lowest among all non-pegmatitic beryl used for comparison (Fig. 4B). However, compared with beryl in pegmatites from the Velasco District (Sardi and Heimann, 2014), the studied beryl has higher FeO_t+MgO+MnO values and similarly low Na_2O contents.

Compositional differences and similarities can be seen among beryl from the La Chinchilla Stock, beryl from the Velasco District pegmatites, and beryl from other geological environments, including

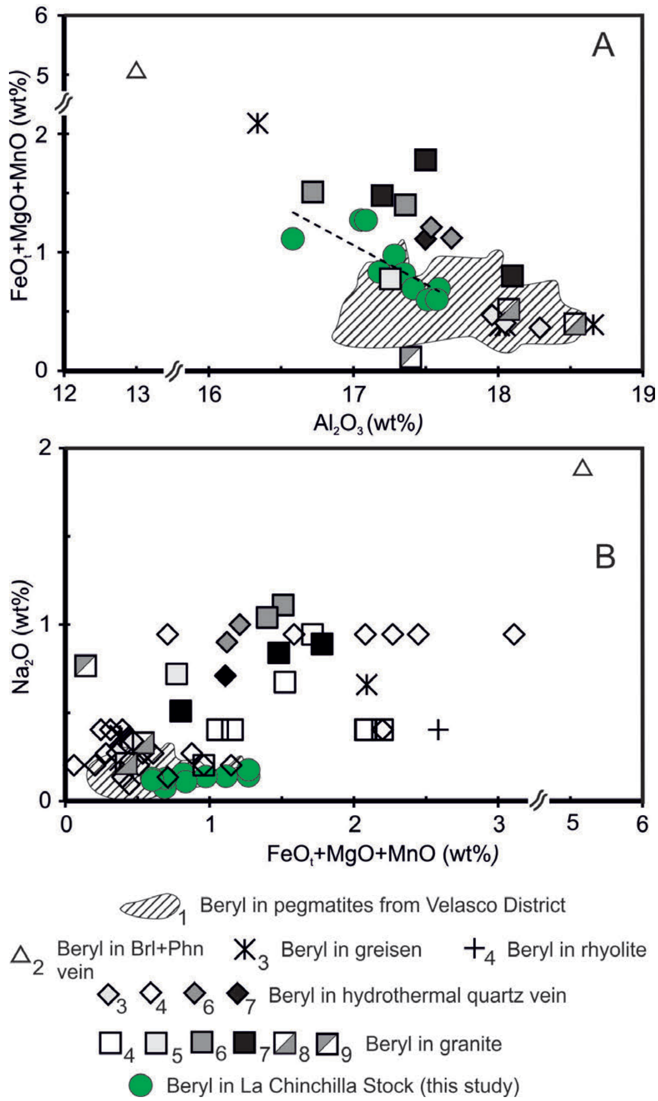

FIG. 4. Compositional variation diagrams of beryl from the La Chinchilla Stock and beryl from diverse igneous and hydrothermal environments. **A.** Al_2O_3 (wt%) *versus* FeO_t+Mg+MnO (wt%); **B.** FeO_t+Mg+MnO (wt%) *versus* Na_2O (wt%). References: **1** Sardi and Heimann (2014); **2** Abrecht and Hänni (1979); **3** Abdalla and Mohamed (1999); **4** Staatz *et al.* (1965); **5** Hurlbut and Aristarain (1969); **6** Hall and Walsh (1971); **7** Abdalla (2009); **8** Merino *et al.* (2013); **9** Charoy (1999). Abbreviations: **Brl:** Beryl; **Phn:** Phenakite.

accessory magmatic beryl in granitic and felsic rocks (commonly metasomatized), hydrothermal quartz veins, greisen bodies (with parageneses of Sn±W), and a rhyolite (Fig. 5; Table 1).

In general, beryl from the La Chinchilla Stock has several chemical similarities with beryl from pegmatites of the Velasco District (Fig. 5), although some differences are also evident. The average iron content (0.84 wt% FeO_t) of beryl from the La Chinchilla Stock is slightly higher than that of beryl from pegmatites of the Velasco District (Fig. 5A). This is consistent with the findings by Staatz *et al.* (1965) and Abdalla (2009), who stated that beryl in pegmatites usually has lower Fe contents than that in granitoids. In turn, FeO_t values of beryl from the La Chinchilla Stock fall within the compositional range of beryl from leucogranites (Abdalla, 2009; Hall and Walsh, 1971), while they are usually higher

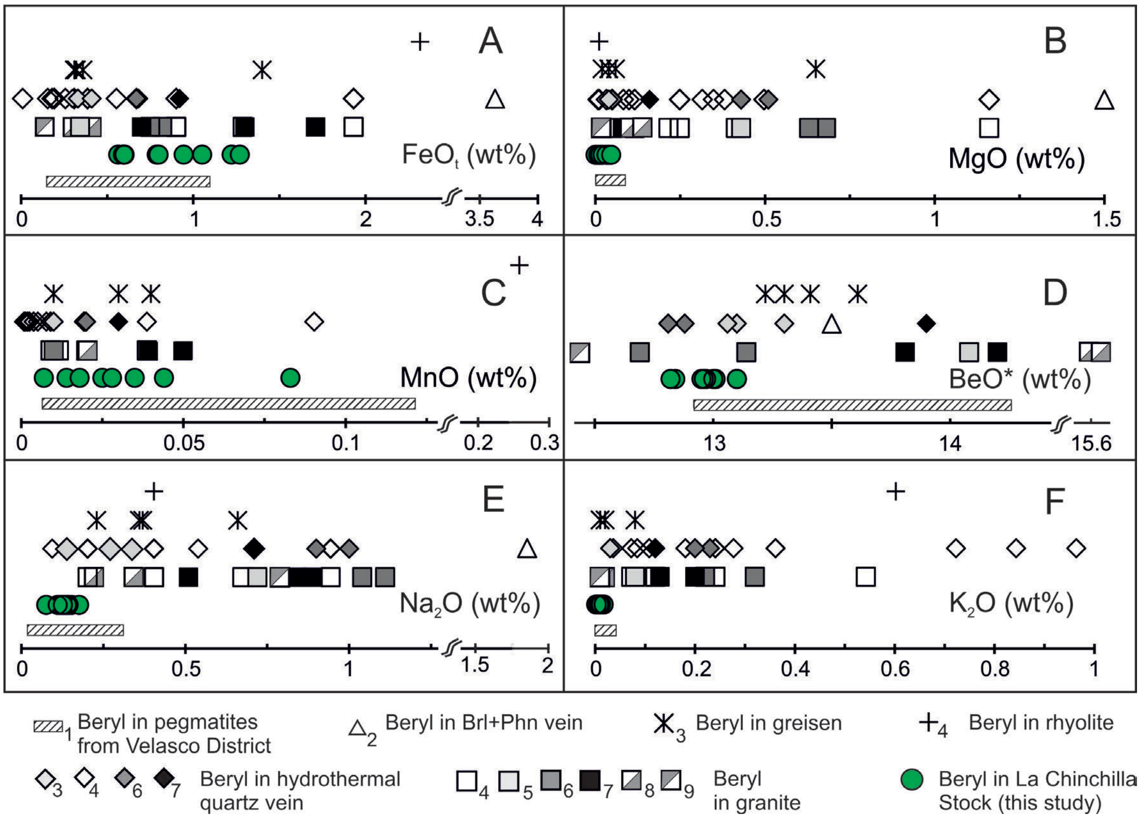

FIG. 5. Chemical variation diagrams showing the composition of beryl from the La Chinchilla Stock, non-pegmatitic beryl from different geological origins, and beryl from pegmatites of the Velasco District, Argentina. **A**. FeO_t (wt%); **B**. MgO (wt%); **C**. MnO (wt%); **D**. BeO* (wt%); **E**. Na_2O (wt%); **F**. K_2O (wt%). **BeO*** calculated from stoichiometry. References as in figure 4.

than those of beryl from hydrothermal quartz veins and greisen (Abdalla and Mohamed, 1999), with some exceptions. Notably higher Fe values can be seen in beryl from a rhyolite and in beryl+phenakite veins (3.6 wt% FeO_t; Abrecht and Hänni, 1979).

The MgO, Na_2O, and K_2O contents of beryl from the La Chinchilla Stock are very low (Figs. 5B, E, F, respectively) compared with those of beryl from other geologic origins (hydrothermal/metasomatic), fall among the lowest of beryl in other granites, and, in turn, are comparable with those of beryl from Velasco District pegmatites (Sardi and Heimann, 2014). The MnO values fall within the compositional spectrum of beryl from pegmatites of the Velasco District (Sardi and Heimann, 2014) and are very similar to those in beryl from other environments, except for beryl in the rhyolite, which reaches the highest value (0.26 wt% MnO; Fig. 5C; Staatz *et al.*, 1965).

Beryl from the La Chinchilla Stock is depleted in BeO (calculated by stoichiometry) compared with beryl from pegmatites of the nearby Velasco District as well as beryl from other origins (Fig. 5D). Even though we note that the source magma of the pegmatites from the Velasco District was likely a separate and different magma than that which generated the La Chinchilla Stock, these low Be values in beryl and the low amount of beryl present in the granitoid likely reflect a granitic magma source less rich in Be or a lower degree of differentiation of the source melt compared to the source melt of the pegmatites. Overall, the slightly higher FeO_t and lower alkali contents of beryl from the La Chinchilla Stock compared with those in beryl from the pegmatites resembles those in beryl from poorly evolved pegmatites (Trueman and Černý, 1982; Černý, 2002; Neiva and Neiva, 2005; Sardi and Heimann, 2014).

5.2. Genesis of beryl

The La Chinchilla Stock is considered a specialized granite according to Tischendorf (1977) due to its high content of rare metals, especially Rb, Li, and Be. Both, the accessory mineralogy and geochemical characteristics indicate that it is a highly evolved leucogranite (Grosse *et al.*, 2009) that contained a F-bearing fluid phase that probably acted as a complexing agent for metals and also generated accessory fluorite (Manning, 1981; Grosse *et al.*, 2005; Salvatore *et al.*, 2013). Based on isotopic studies, Grosse *et al.* (2009) considered that the La Chinchilla Stock was generated from a more primitive mantle source than that which formed its country rock, the Huaco Granite. The presence of beryl and the relatively high Be (<80 ppm) and F content of the La Chinchilla Stock can be explained by a source enriched in Be (such as metapelites) and/or a high degree of differentiation of a mixed crustal-mantle source. Metapelites are not known to exist in the country rocks of the La Chinchilla Stock. Therefore, in order to better demonstrate that the most likely process that led to the crystallization of beryl during evolution of this melt was extensive fractional crystallization of a parent melt, below we present calculated crystallization temperatures and a fractional crystallization model for the La Chinchilla Stock.

Using available chemical compositions for the granitoid, two geothermometers (Zr saturation, Watson and Harrison, 1983; REE saturation, Montel, 1993), and an estimated 5 wt% H_2O content, calculated crystallization temperatures for the beryl-bearing equigranular facies sample of the La Chinchilla Stock range from 750 to 768 ˚C. Calculated crystallization temperatures for other samples from the stock range from 740 to 778 ˚C, while the host Huaco Granite reaches higher values (740-807 ˚C). Crystallization temperatures calculated by Dahlquist *et al.* (2010) for the stock using the zircon saturation geothermometer yielded 720-757 ˚C, which are similar to the lower temperatures obtained in this study by the same method and lower than those obtained by the REE saturation geothermometer. Calculated crystallization temperatures for the beryl-bearing sample are somewhat higher than those obtained for some other beryl-bearing granitoids that contain more complex mineral assemblages, including chrysoberyl and various aluminous minerals (750-670 ˚C; Merino *et al.*, 2013), and also higher than those experimentally obtained for beryl-bearing granitic pegmatites (670-720 ˚C; Thomas *et al.*, 2009, 2011). Furthermore, recent structural studies evidence a shallow emplacement for the La Chinchilla Stock (Macchioli Grande *et al.*, 2015), which is consistent with beryl crystallization at low pressures (Černý, 1991) in the granitoid as well as in shallow, miarolitic granitic pegmatites hosted by the granitoid (Salvatore *et al.*, 2013; Lira *et al.*, 2015). Therefore, the relatively low temperatures and pressures of crystallization along with its crystal size, morphology, and associated minerals reflect beryl crystallization in the La Chinchilla Stock during the late stages of magma evolution, and that the magma was saturated in Be up to these final stages of crystallization.

Fractional crystallization of a magmatic melt can be modeled using the Rayleigh equation (Rollinson, 1998) to determine the behavior of an incompatible and a compatible element during the evolution of a melt that ultimately led to beryl crystallization in the La Chinchilla Stock (Fig. 6). Rayleigh fractionation considers

$$C_l/C_o = f^{D-1},$$

where C_o is the initial concentration of the element in the melt, C_l is the concentration of the element in the liquid at a given time, f is the fraction of melt remaining, and D is the global (mode-adjusted) distribution coefficient of the element between the solid and the melt. Two evolution models were calculated assuming a starting melt with 100 ppm Ba and 190 ppm Rb, distribution coefficient (K_D) values for Rb and Ba in K-feldspar, plagioclase, and biotite for peraluminous felsic melts (Arth, 1976; Rapela and Shaw, 1979; Nash and Crecraft, 1985; Icenhower and London, 1996), and modes of fractionating minerals of: **1)** 60% plagioclase, 15% K-feldspar, 10% biotite, and 15% quartz, and **2)** 26% plagioclase, 36% K-feldspar, 6% biotite, and 32% quartz. Evolution trends of the melt produced granitoid compositions that closely match the measured compositions of the various granitic facies of the La Chinchilla Stock. The compositions of the equigranular facies fall along the late stages of crystallization of the modeled melt, whereas the porphyritic and border facies plot along earlier stages of crystallization. Based on the model, an initial melt will produce a rock with

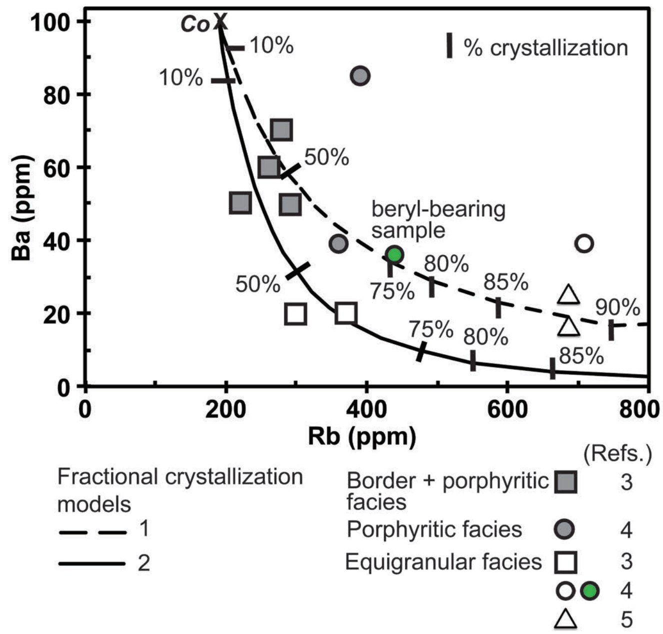

FIG. 6. Fractional crystallization models calculated for Rb and Ba using the Rayleigh equation ($C_l/C_o = f^{D-1}$; Rollinson, 1998), where C_l is the concentration of the element in the liquid at a given time, C_o is the initial concentration of the element in the melt, , *f* is the fraction of melt remaining, and *D* is the global distribution coefficient (mode-adjusted) of the element between the solid (mineral) and the melt. The curves show two evolution trends calculated assuming a starting melt with 100 ppm Ba and 190 ppm Rb, distribution coefficient (K_D) values for Rb and Ba in K-feldspar, plagioclase, and biotite for peraluminous felsic melts (Arth, 1976; Rapela and Shaw, 1979; Nash and Crecraft, 1985; Icenhower and London, 1996), and modes of fractionating minerals of: **1)** 60% plagioclase, 15% K-feldspar, 10% biotite, and 15% quartz, and **2)** 26% plagioclase, 36% K-feldspar, 6% biotite, and 32% quartz (mode of the porphyritic facies of Salvatore *et al.*, 2013). Rock compositions from: 3 Salvatore *et al.* (2013), 4 Grosse *et al.* (2009), and 5 Dahlquist *et al.* (2010).

a chemical composition similar to the equigranular facies sample that contains the studied beryl at or after ~75% crystallization.

Experimental studies of Be partitioning indicate that the formation of beryl in pegmatite melts requires a minimum Be content of about 6 ppm in the felsic parental magma together with multistage fractional crystallization (up to 80%) and removal of residual melts in order to reach the minimum beryl saturation threshold (about 70 ppm Be; London and Evensen, 2002). The highly incompatible behavior of Be in the parental granitic melt (London, 2008) would favor the gradual Be enrichment in the residual melt through progressive fractionation and crystallization of minerals. This is consistent with the results of our fractional crystallization model that suggests that 75% crystallization can explain the formation of the beryl-bearing granitoid. In addition, Be concentrations may be increased by assimilation of Be-bearing minerals such as micas and cordierite in the host rock (Armbruster and Irouschek, 1983; Evensen *et al.*, 1999; London and Evensen, 2002), and even though cordierite has not been observed in the Huaco Granite, micas are present and could explain the concentration of Be in the La Chinchilla Stock. However, because Be contents of these micas are not known, advanced, progressive fractionation of the parent melt can simply explain the increase in Be content and beryl crystallization, as indicated in previous experimental, theoretical, and case studies (*e.g.*, Shearer *et al.*, 1987; Charoy and Noronha, 1996; Evensen *et al.*, 1999; Evensen and London, 2002; Merino *et al.*, 2013). For example, in a study of a reversely zoned pluton, Merino *et al.* (2013) modeled extreme granite differentiation from a monzogranitic parent melt and showed that this can explain the presence of beryl in the latest granitic facies, which, interestingly, has lower Be contents (5-54 ppm Be) than the La Chinchilla Stock. Therefore, the presence of beryl as magmatic accessory mineral in the La Chinchilla Stock is an indicator of very high degrees of fractionation and efficient removal of residual melts (London, 2008).

The solubility and precipitation of beryl are regulated by several factors, most importantly the activities (*a*) of major mineral-forming components (BeO, Al_2O_3, and SiO_2) and possible reactions involving fluxing elements (*e.g.*, F, Li), followed in importance by temperature (Charoy, 1999; Evensen *et al.*, 1999; Barton and Young, 2002). In fact, the presence of fluxing components lowers crystallization temperatures (London, 1992; Manning and Pichavant, 1983) that, in turn, facilitate beryl saturation (Evensen *et al.*, 1999). Thus, the solubility of beryl in a silica-saturated magma such as the one of the La Chinchilla Stock likely decreased due to a high $aSiO_2$ and aAl_2O_3, and a gradual decrease in temperature, which resulted in beryl precipitation.

6. Conclusions

Beryl from the Carboniferous, specialized La Chinchilla Stock has a chemical composition consistent with the normal composition of the mineral species presented in previous studies. The sum of FeO_t, MgO, and MnO is very low, with FeO_t being dominant (FeO_t>>MgO+MnO). It is also very low in alkalis, with Na_2O>>K_2O.

Cationic substitutions of alkalis (Na, K), Fe, Mg, and Mn are minor. A negative correlation between ferromagnesian elements and Al, and a slight positive correlation between ferromagnesian elements and Na suggest minor inter-elemental exchanges.

Comparatively, beryl from the La Chinchilla Stock has slightly higher FeO_t and lower alkali (Na_2O, K_2O) contents than beryl of hydrothermal origin (quartz-veins and greisen). The MgO, Na_2O, and K_2O contents are very low compared with those of beryl from other geologic origins (hydrothermal/metasomatic granites), are among the lowest of beryl in other granites, and are comparable with those of beryl from the Velasco District pegmatites, of medium-to-low degree of evolution.

A fractional crystallization model shows evolution trends that closely match the measured compositions of the various granitic facies in the La Chinchilla Stock. The compositions of the equigranular facies, which contains beryl, fall along the late stages of crystallization of the modeled melt, whereas the porphyritic and border facies plot along earlier stages of crystallization. Based on the model, an initial melt will produce a rock with a chemical composition similar to the equigranular facies sample that contains the studied beryl at or after ~75% crystallization.

Based on the host-rock mineralogy and the characteristics of beryl, its formation in the La Chinchilla Stock is attributed to precipitation from a highly evolved, F-bearing, Be saturated magma, in which high Si and Al contents induced the stabilization of beryl during the final stages of magma crystallization.

Acknowledgements

Funding for this project was provided by the Division of Research and Graduate Studies and the Thomas Harriot College of Arts and Sciences at East Carolina University (ECU; to AH). Consejo Nacional de Investigaciones (CONICET, Argentina) is thanked for a postdoctoral scholarship (to FS) to undertake the present study at ECU, and the Department of Geological Sciences at ECU for hosting his postdoctoral stay. This study is a contribution of the project G/501 and PIP 0171 of the CIUNT and CONICET, respectively. N. Foster is thanked for help with electron microprobe analysis. J. Bitner is thanked for providing transportation to Fayetteville State University to FS. Constructive and critical reviews by E. Merino Martínez greatly helped improve the manuscript and are much appreciated. We thank editor L. Lara for handling the manuscript and for additional comments provided to improve the manuscript.

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Manuscript received: June 02, 2015; revised/accepted: October 16, 2015; available online: October 19, 2015.