Common Crustal Source for Contrasting Peraluminous Facies in the Early Paleozoic Capillitas Batholith, NW Argentina

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Abstract

The Ordovician Capillitas batholith, part of the northern Pampean ranges, NW Argentina, exhibits two peraluminous granitic facies in its eastern portion: (a) coarse- to medium-grained, porphyritic mafic facies with biotite, cordierite and aluminosilicates, carrying sillimanite-, cordierite-, and andalusite-bearing migmatitic enclaves and schlieren and (b) enclave free, mica poor, coarse-grained, porphyritic felsic facies, with andalusite and sillimanite. Banded hornfels aureoles contain cordierite poikiloblasts, biotite, plagioclase and quartz. The low-P mineral assemblage in these granites, enclaves and restites, suggests partial fusion of a supracrustal protolith. The two facies plot as two separate groups in geochemical variation diagrams, suggesting that they evolved from different magma batches derived from the same source, rather than from in situ fractional crystallization. The composition of felsic facies granites corresponds to pelite and metagraywacke-derived melts, whereas cordierite-bearing mafic granites follow a trend indicating mixing of pelite-derived melts and corresponding restites. The mafic-facies granites approach more the continental crust composition than the felsic-facies ones, which display more pronounced Ba and Sr negative anomalies. The average (La/Yb)_N ~11 rules out a high pressure garnet rich source and the low normalized Sr contents, in both granitic facies, suggest a recycled metasedimentary protolith. Absence of mafic intrusives that could have assimilated pelitic schists, allow us to infer that melting took place at rather low T and under high water activity. Heat to trigger partial fusion could have been radiogenically generated and stored in the upper crust during deformation and thickening of the continental crust, with further release during decompression. The Capillitas batholith, emplaced close to an I, S-type granite boundary line in this region appears to be an Argentinean analogue of the Cooma Series supersuite in the Lachlan Fold Belt, emplaced close to the eastern Australian I, S-type granite boundary line.

Key words: Cordierite, mafic and felsic facies, Paleozoic, common source, peraluminous.

Introduction

The strongly peraluminous Capillitas batholith, north of Andalgala town, in the Pampean ranges of NW Argentina, is one of the best examples of cordierite-bearing granitoids in southern South America. In this region, early Paleozoic magmatic epidote- and cordierite-bearing granitoids were emplaced in distinct geographic areas (Fig. 1). Some of the cordierite-bearing granitoids resemble equivalent plutons of the Lachlan Fold Belt in Australia in several respects and among them, the Capillitas batholith deserves special attention for its large size (1,600 km²) and excellent exposures. This work focuses on the petrology and geochemistry of the eastern portion of this batholith with a particular emphasis on the two granitic facies (porphyritic biotite and cordierite-rich monzonic to granodioritic facies, and an equigranular, felsic cordierite-poor nonzogranitic facies), both carrying andalusite and sillimanite (Fig. 2).

For a long time, the genesis of strongly peraluminous granitoids has attracted the attention of petrologists, since it has been demonstrated that granitic melts from which aluminum silicates can crystallize, could be experimentally produced (Green, 1976; Clemens and Wall, 1981; Thompson, 1982; Miller, 1985). The problem with the petrogenesis of these rocks does not reside only in producing peraluminous melt but also in its protolith. White and Chappell (1977) advocated the incorporation of restitic material into melt of pelites, and Elburg (1996) proposed that the interaction of mafic magmas with continental crustal rocks could explain the particular composition of the S-type granites.
Although muscovite- and cordierite-bearing peraluminous granitoids can occur in the same area and have identical ages, they generally do not represent members of the same differentiation trend (Barbarin, 1996). Patiño Douce (1995, 1999) has experimentally demonstrated that fusion of muscovite schist can generate leucocratic melts through muscovite dehydration melt, but these differ from S-type melts because the latter have much higher MgO, FeO, TiO$_2$ and CaO and lower SiO$_2$ than the leucogranites. He proposed that mafic magma (50%) and continental crust rocks could interact at low pressure (≤5 kb) in a process by means of which melt compositions seem to match those of natural S-type compositions.

In the present work it is suggested, based on geological relationships, mineral composition, textures, nature of enclaves in the granites, as well as geochemical data, that the granitic magmas under consideration resulted from partial fusion of continental crustal rocks, at low pressure (≤5 kb), without a visible contribution of a mafic magma. This work also provides petrological and geochemical information on a representative S-type granitoid of NW
Argentina for comparison with similar S-type granitoids of the Lachlan Fold Belt (e.g., Cooma supersuite) in a Paleozoic Gondwana reconstruction.

**Previous Work**

The first complete petrographic and geological descriptions of the Sierra de Capillitas granitoid rocks were provided by González Bonorino (1950a, 1951a, b) who undertook a detailed petrographic-structural work in the Aconquija range and surrounding areas. Aceñolaza et al. (1982) mapped the geologic and structural lineaments in the region north of Andalgalá. Indri (1979, 1986) and Toselli and Indri (1984) reported, for the first time, the presence of cordierite and aluminum silicates as accessory phases in this batholith, providing descriptions of the main geological and petrographic features of the Cuesta de Capillitas and its basement. They also distinguished an equigranular and a porphyritic facies. Toselli et al. (1996) carried out a petrographic and geochemical research on

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the two granitic facies and concluded that crustal metasedimentary rocks were probably the source for the peraluminous magmas.

Geochronological work performed by McNutt et al. (1975) provided a Rb-Sr age of 413 Ma (Sr₀ = 0.7146), while K-Ar ages on biotite and muscovite range between 365 and 471 Ma (Caelles et al., 1971; Linares and González, 1990). Rapela et al. (1999) obtained a U-Pb SHRIMP age of 470±3 Ma on a porphyritic biotite-rich monzogranite. These age data suggest that the granitic magmatism in this area took place from the Ordovician to the late Silurian, assuring that the Capillitas batholith was emplaced during the Famatinian magmatic cycle (Aceñola et al., 1973).

**General Geology**

According to González Bonorino (1950a, 1950b) and Aceñola et al. (1982), the Capillitas batholith extends from the Aconquija range to beyond the Quebrada de Belén to the west, forming a huge granitic area. With a surface of about 1,600 km², the Capillitas batholith encompasses the southwestern portion of the Aconquija, Capillitas, Santa Bárbara ranges, Bola del Atajo Hill, and, to the west, it continues to the Ovejería range and to the region to the south of it (Fig. 2). This huge granitic area is interrupted by gravity faults (roof pendants of the Pampean ranges in general, while the Quebrada del Potro and Quebrada de Villavil (Fig. 2). The felsic granitic facies corresponds to the porphyritic facies IV, and the modal composition for these rocks is found in table 1, where divergences between the two granitic facies are clearly seen: felsic granites have 90%, on average, of feldspars + quartz and 10%, on average, of micas (biotite + muscovite), being muscovite > biotite; while the mafic facies shows 65% in average of feldspars + quartz and 35%, in average, of biotite + muscovite + cordierite, with biotite > muscovite. The mafic granites constitute minor domains in the Capillitas batholith, and the contact between the two granitic facies, according to González Bonorino (1951a), is transitional.

In the western portion of the batholith, two granitic facies have been identified: (a) a mafic facies very rich in cordierite and biotite that predominates in the Capillitas range-Santa Bárbara area, cropping out along the hillside to the west of the Negro Hill and including a major N-S structure known as the Amanao-Visvis fault and (b) a felsic mica-poor facies, with representative outcrops in the Quebrada del Potro, Toma de Agua, and Quebrada de Villavil. (Fig. 2). The felsic granitic facies corresponds to the porphyritic facies IV, and the modal composition for these rocks is found in table 1, where divergences between the two granitic facies are clearly seen: felsic granites have 90%, on average, of feldspars + quartz and 10%, on average, of micas (biotite + muscovite), being muscovite > biotite; while the mafic facies shows 65% in average of feldspars + quartz and 35%, in average, of biotite + muscovite + cordierite, with biotite > muscovite. The felsic granites constitute minor domains in the Capillitas batholith, and the contact between the two granitic facies, according to González Bonorino (1951a), is transitional.

Mafic, biotite-rich, porphyritic monzogranite forms the largest outcrops of the batholith. Lens-shaped xenoliths of country rocks (schists, minor calc-silicates and hornblende schists) are restricted to the marginal zones of the mafic porphyritic monzogranites and may be several meters long.

In the study area, granites are not associated with migmatites, but migmatites crop out in the eastern and northwestern regions of the neighbouring Sierra de Aconquija (not shown in Fig. 2) and have been described by González Bonorino (1951a).

González Bonorino (1950a, 1951a, 1951b) found the Capillitas batholith to be a late- to post-tectonic, epizonal intrusion in phyllites and schists of the basement. These country rocks underwent low to medium grade regional metamorphism, as shown by muscovite-chlorite-quartz and muscovite-biotite-cordierite associations. The granitic intrusion developed hornfels aureoles, a static regime that generated cordierite and biotite porphyroblasts in the phyllites and schists of appropriate chemical composition. The intrusion mechanism has been attributed by González Bonorino (1950b) to a major stoping and a passive, late-to post-tectonic, emplacement. In fact, only minor deformation is observed.

The batholith is foliated at the margins, where biotite-rich schlieren and enclaves of biotite-sillimanite-andalusite-cordierite rocks and biotite-sillimanite flow bands are common. The contact relationships with phyllites and schists are sharp and subconcordant.

**Petrography**

In the western portion of the batholith, two granitic facies have been identified: (a) a mafic facies very rich in cordierite and biotite that predominates in the Capillitas range-Santa Bárbara area, cropping out along the hillside to the west of the Negro Hill and including a major N-S structure known as the Amanoa-Visvis fault, and (b) a felsic mica-poor facies, with representative outcrops in the Quebrada del Potro, Toma de Agua, and Quebrada de Villavil. The felsic granitic facies corresponds to the porphyritic facies IV, and the modal composition for these rocks is found in table 1, where divergences between the two granitic facies are clearly seen: felsic granites have 90%, on average, of feldspars + quartz and 10%, on average, of micas (biotite + muscovite), being muscovite > biotite; while the mafic facies shows 65% in average of feldspars + quartz and 35%, in average, of biotite + muscovite + cordierite, with biotite > muscovite. The felsic granites constitute minor domains in the Capillitas batholith, and the contact between the two granitic facies, according to González Bonorino (1951a), is transitional.

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Dark metasedimentary lens-shaped enclaves up to few decimeter-long of biotite migmatite-gneiss are abundant throughout the batholith. They contain dark, medium-grained melanosome with biotite, andalusite, cordierite and sillimanite. Enclaves with magmatic textures are rare...
to absent, but aplitic to pegmatitic narrow dykes are rather common.

Mafic, porphyritic, two-mica monzogranites are gray to pink, with coarse-grained groundmass, containing andalusite, sillimanite, cordierite, biotite, muscovite, tourmaline, zircon and apatite. Microcline megacrysts up to 15 cm long occupy 15% to 50% of the volume of the rock. Perthitic microcline is found as megacrysts and in the groundmass and exhibits inclusions of euhedral plagioclase, rounded quartz and biotite. In the equigranular facies, microcline is commonly anhedral with cross-hatch twinning. Microcline megacrysts are early-crystallized phases as already pointed out by González Bonorino (1950a). Plagioclase (An$_{30}$) is variably zoned, only rarely showing patchy zoning, where resorbed oligoclase core is surrounded by albite. Fresh and well-developed biotite showing zircon and monazite inclusions forms large flakes and, sometimes, is altered to chlorite + magnetite. Cordierite constitutes a common accessory phase usually found as very corroded anhedral grains, surrounded by micaceous material, and presenting biotite, quartz, muscovite and zircon inclusions. Quartz grains with fibrolite and isolated fibrolite are also common inclusions, while green spinel is rare. Sometimes, cordierite is altered to pinito and white mica.

Sillimanite is commonly observed in two-mica monzogranites as felted masses of fibers of fibrolite or developed from biotite, that also includes quartz, plagioclase, muscovite and cordierite. It is sometimes found as contorted fibrous aggregates associated with biotite that is also sigmoidally deformed. This form is observed surrounding plagioclase, quartz and K-feldspar grains, suggesting that these minerals pushed their borders against fibrolite aggregates during their growth. These textures are hardly believed to be magmatic ones.

The felsic, porphyritic, and equigranular monzogranite is white to reddish, medium-to coarse-grained, with muscovite and biotite. The fine-grained, almost aplitic muscovite-rich facies carries abundant tourmaline. Quartz is found in the groundmass or as sub-rounded inclusions in biotite and cordierite. Plagioclase (albite-oligoclase, An >10) is usually unzoned, and occurs as albite-carlsbad twinned hypidiomorphic laths. Andalusite is generally found as anhedral to subhedral grains or prismatic with visible cleavage, pink to colorless weak pleochroism, sometimes exhibiting patchy zoning. It usually occurs as relics within muscovite flakes that represent its alteration product. As in the case of coexisting cordierite, andalusite may not be of magmatic origin, but may be partially derived from fibrolite-andalusite-cordierite-bearing enclaves. Enclaves of such a composition probably originated in deep-seated rocks (migmatitic melanosomes) or they are restites, since this is a virtually absent assemblage in the surrounding metamorphic country rocks. Black tourmaline is found as interstitial, isolated, subhedral crystals.

### Table 1. Modal mineralogy of the felsic and mafic granitic facies and enclaves of the Capillitas batholith.

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<th>Plagioclase</th>
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<th>Biotite</th>
<th>Muscovite</th>
<th>Cordierite</th>
<th>Sill/andalusite</th>
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Xenoliths and Enclaves

Xenoliths are lens-shaped, usually centimeter to decimeter long, restricted to the marginal zones of the batholith and many of them are clearly derived from the wall rocks. Most show fine, equigranular hornfels-like textures. Those derived from psamopelitic rocks are composed of quartz-biotite-plagioclase and rare potash feldspar and muscovite. Fine-grained cordierite is present in small amount.

Calc-silicate xenoliths are very fine-grained showing plagioclase, epidote and garnet. Hornfelsic xenoliths with hornblende, biotite, plagioclase and quartz are less abundant. All of them show sharp contacts and no assimilation effect with their host granitic rocks.

Enclaves have an appearance of melanosome of metasediments, are intermediate- to coarse-grained, foliated, very rich in biotite and have very rare muscovite. They are often found as lenses several decimeter long and also with disaggregate aspect forming schlieren bands in the cordierite granitoids. Two compositional types are recognized in these enclaves: (a) melanosomes with biotite, plagioclase, quartz, andalusite, sillimanite, cordierite, without potassic feldspar and melanosome with biotite, quartz, andalusite, sillimanite, cordierite lacking both potassic feldspar and plagioclase. In any case, garnet or any higher pressure-assemblage or indication of higher metamorphic grade has not been observed.

The microgranular enclaves, of unclear origin, are tonalitic in composition, with igneous texture, usually rounded, fine- to intermediate-grained, up to few decimeter long. They are less abundant than the metasedimentary enclaves.

The Capillitas batholith resembles, in several respects, the Cooma granodiorite in the Lachlan Fold Belt of Australia. As in the Capillitas batholith, the Cooma granodiorite is massive, medium- to coarse-grained and rich in biotite and cordierite crystals up to 10 cm across, according to Chappell et al. (1991). The inclusions in this pluton are all of sedimentary derivation, most are biotite-rich and some are rich in sillimanite. They are considered to be residual material from partial melting (restite). The most distinctive chemical features of the Cooma pluton are the very low CaO (average 3.3%) and NaO (average 2.2%) contents. Similar chemical behavior is observed in the mafic facies of the Capillitas batholith. Likewise, the modal abundances of biotite (about 20%), andalusite (2.5%), and muscovite (4%) observed in the Cooma pluton are similar to abundances of these phases in the mafic facies of the Capillitas batholith. The Cooma pluton is situated near the S/I line boundary in Australia and the Capillitas batholith, next to the eastern border of the central zone batholiths that perhaps represent a S/I-type granite boundary line in Argentina (cordierite-bearing/epidote-bearing granitoids; Sial et al., 1999).

Geochemistry

Major, trace and rare-earth element (REE) analyses of 33 representative samples of the felsic, mafic granitoids and enclaves are found, respectively, in tables 2, 3 and 4.

The mafic cordierite granites have average SiO₂ contents of 66.45% and the felsic ones, 73.8%. The CaO, MgO, Fe₂O₃, and TiO₂ contents are higher in the cordieritic mafic granitoids with CaO = 1.21% and MgO + Fe₂O₃ + TiO₂ = 6.36%, while the felsic granites have CaO = 0.59% and MgO + Fe₂O₃ + TiO₂ = 1.85%. These differences in the major element oxides can be easily observed in the elemental variation diagrams, that show a distinct behavior of the two granite facies (Figs. 3a, b) and in the alumina saturation index (ASI = 1.3 and 1.2, respectively) that show a higher peraluminosity of the mafic cordieritic granitoids. This range of composition is similar to that of other peraluminous cordieritic granitoids in the Pampean ranges (Rapela et al., 1997, 1998). These oxide variations are also similar to those reported for S-type, cordierite-bearing granites in the Lachlan Fold Belt, Australia (e.g., Cooma supersuite, Chappell et al., 1991).

Trace elements like Zr, Sr, Ba and Rb also show these differences in both granites, with higher Zr, Sr and Ba contents in the mafic granites and higher Rb contents in the felsic ones (Figs. 3c,d,e and f). The average REE content is higher in the mafic granites (162 ppm), while in the felsic ones the average is 50 ppm.

In the Debon and Le Fort (1983) diagram (Fig. 4a), the typology of the peraluminous granitoids is well defined, where the felsic granitoids lie in the field of muscovite-rich leucogranites (field 1) while the mafic ones lie in the
Table 2. Major and trace element analyses of the felsic facies of the Capillitas batholith. ACNK = molar Al₂O₃/(CaO+Na₂O+K₂O); n.d. = not determined.

<table>
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<th>Sample</th>
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<th>1825</th>
<th>2124</th>
<th>2387</th>
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<th>2396</th>
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<td>71.80</td>
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<td>0.10</td>
<td>0.10</td>
<td>0.13</td>
<td>0.10</td>
<td>0.10</td>
<td>0.18</td>
<td>0.19</td>
<td>0.18</td>
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<td>0.31</td>
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<td>Fe₂O₃</td>
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<td>2.20</td>
<td>1.56</td>
<td>1.68</td>
<td>2.09</td>
<td>1.84</td>
<td>1.72</td>
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<td>1.67</td>
<td>1.84</td>
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<td>1.13</td>
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<td>0.07</td>
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<td>0.07</td>
<td>0.07</td>
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<tr>
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<td>0.25</td>
<td>0.22</td>
<td>0.22</td>
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<td>99.54</td>
<td>99.36</td>
<td>99.45</td>
<td>100.10</td>
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<td>99.62</td>
<td>99.37</td>
<td>99.44</td>
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<td>99.57</td>
<td>100.81</td>
<td>100.12</td>
<td>100.25</td>
<td>99.09</td>
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</table>

EARLY PALEOZOIC CAPILLITAS BATHOLITH, NW ARGENTINA 331

field for biotite-rich leucogranites (field II). The felsic granites show, in general, a variable depletion of REE, a characteristic common to the most fractionated granites that show a marked positive correlation between Rb/Ce and Rb (Fig. 4b). The high Rb/Sr = 11 and Rb/Ba = 4.7 suggest, but are not proof of an evolution through fractional crystallization, once the possibility of different pulses of melt from a similar source cannot be ruled out.

In the A-B diagram of figure 5 (Debon and Le Fort, 1983; modified by Villaseca et al., 1998), samples from the felsic, cordierite-free, granitoids lie in the F-P field which is reserved for the felsic peraluminous granites, while samples from the mafic, cordierite-bearing granites tend to follow mostly the trend defined by highly peraluminous granitoids of the Cooma supersuite, Australia, or the Hercynian Layos granite, Spain (respectively Co and Ly trends in the H-P field of Fig. 5).

Higher REE concentration is observed in the mafic granitoids due, among other factors, to a high concentration of accessory phases like zircon, monazite and apatite. In both types, a pronounced negative Eu anomaly can indicate an important feldspar fractionation at the residue of partial melting in the source or a chemical characteristic of the source itself (Fig. 6a). For both granites, the average (La/Yb)n = 11 is interpreted as the absence of garnet at the source. This characteristic is very common to many strongly peraluminous granitoids in the Pampean ranges (Rapela et al., 1996).

The continental crust-normalized REE patterns for the mafic granites and enclaves show very similar patterns...
and remarkable superposition among them, with a more REE-enriched restitic enclave showing more pronounced Eu anomaly (Fig. 6b). Multi-element patterns normalized to the continental crust are also similar, enriched in relation to the continental crust, with Ba and Nb troughs approaching the corresponding continental crust values, and an important Sr trough indicative of a weathered source (Fig. 6c).

To compare the compositions of both granitic facies to those of melts experimentally produced by partial fusion of pelites (e.g., Vilizetz and Holloway, 1988; Patiño Douce and Johnston, 1991 and Patiño Douce, 1999), we have plotted (Fig. 7) the percentage of CaO/(FeO + MgO) against Al₂O₃ against TiO₂ against Al₂O₃ + CaO + Na₂O + K₂O. The data for the felsic granitic facies lie in the field for melts obtained from the partial fusion of muscovite schists overlapped with that for graywackes, while the mafic granitic facies data lie near the restite-melt R mixing line in a pelitic system without the contribution of a basaltic component melt (Figs. 7a and b).

**Discussion and Conclusions**

The conditions for generation of a granitic magma from a H₂O-undersaturated mafic pelite (biotite metapelitic) under low pressure (<5 kb) are produced by dehydration fusion of biotite. The experimental data indicate that, at minimum temperatures of fusion around 800°-850°C, the
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Fig. 4. (a) Diagram A-B from Debon and LeFort (1983). A = Al - (K + Na + 2Ca) and B = Mg + Fe + Ti for the mafic and felsic granites, (b) Rb/Ce versus Rb diagram for felsic granites. Fields I to VI are from Debon and Lefort (op. cit).

Fig. 5 A-B diagram (modified from Debon and Le Fort, 1983) for different series: Central Spain Hercynian Belt (Layos granite, Barbero and Villaseca, 1992), Lachlan Fold Belt series: Co (Cooma series; Chappell et al., 1991), other granites: To (Tourem, Holtz and Barbey, 1991), TS (Trois Seigneurs; Wickham, 1987); this work (symbols as in Fig. 2). Fields are: H-P (highly peraluminous), M-P (moderately peraluminous), I-P (low peraluminous) and F-P (felsic peraluminous). I/S stands for the I, S-type granite boundary line.

geochemical and geological evidence that this was not the case: (1) the interaction between mafic magma and metamorphic rocks of the upper crust to produce a hybrid S-type magma as that in Capillitas, requires that a large volume of mafic magma ascended and has been emplaced in the upper crust. There is no evidence for the existence of a mafic magma in the area of outcrop of the granitic pluton (over 1,600 km²); (2) enclaves in the cordieritic granite are metamorphic in the majority (metapelites to metapsammites) in which we can distinguish well those that were derived from the wall rocks, while the biotite-rich ones with sillimanite, andalusite, quartz and cordierite represent restites of incomplete unmixing or melanosomes of migmatites incorporated, assimilated and partially disaggregated in the granitic magma; (3) the geochemistry of these enclaves is in favor of a restitic composition, for they are enriched in REE, MgO, Fe₂O₃ and TiO₂; (4) when the oxide contents are plotted in appropriate diagrams of experimentally-obtained melts, the compositions of cordieritic granites and their enclaves lie on or very close to the pelitic melt-restite mixing line (Patiño Douce, 1999), while the felsic granites lie in the field of pure crustal melts.

The necessary temperature for the fusion and formation of large volumes of granitic magmas could have resulted from radiogenic heat stored during crustal deformation and thickening by K, Rb, Th and U, as proposed by England and Thompson (1984). Gerdes et al. (2000) proposed a
model for the batholith of South Bohemia in the Variscan orogen in Europe, in which they demonstrated the feasibility of crustal heat production by radioactive element decay during and after crustal thickening, enough to explain the thermal evolution with time and crustal melt volumes. The lack of a study in Argentina that has quantified crustal deformation and thickening during the early Paleozoic in the Pampean ranges, as well as limited isotopic data available for this area, preclude us from exploring this possibility.

Alternatively, mafic plutonism underplating could have supplied the necessary heat to trigger melting of metapelites in the crust in a similar fashion to what happened in the Lachlan Fold Belt. This is a hypothesis that deserves consideration in future work.

Acknowledgments

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