A late proterozoic–early paleozoic magmatic cycle in Sierra de la Ventana, Argentina

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Abstract

Late Proterozoic–Early Paleozoic intrusive and volcanic rocks of Sierra de la Ventana can be grouped into two magmatic assemblages: the Meyer and Cochenleufú suites. The older Meyer suite (700–570 Ma) is composed of S-type quartz-monzodiorites, synogranites, and monzogranites associated with andesites and rhyolites and related to volcanic arc and postcollisional settings. The younger Cochenleufú (540–470 Ma) corresponds to highly fractionated homogeneous A-type monzogranites, linked to final plutonic events during postorogenic extension in collisional belts. Strong similarities between Sierra de la Ventana magmatic rocks and the S- and A-type granites of the Cape granite suite in South Africa allow for positive correlation. In both areas, primitive volcanic arcs or collisional orogens are recognized. Continuous transpressional shearing between the Swartland and Tygerberg terranes in the Saldania belt may have triggered the generation and emplacement of both suites.

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1. Introduction

Located in southeastern Buenos Aires province, Argentina, Sierra de la Ventana is a 180 km long sigmoidal mountain belt, composed of basement and sedimentary cover (Fig. 1). The basement consists of Late Precambrian–Early Paleozoic deformed granites, rhyolites, and andesites. The Paleozoic sedimentary sequences can be divided into three groups. Conglomerates and quartzites compose the Curamalal (Ordovician–Silurian) and Ventana (Silurian–Devonian) Groups. The Pillahuincó Group (Upper Carboniferous–Permian) is composed of glacial deposits, black shales, and sandstones. Deformational episodes occurred during the Upper Devonian and Permian.


In this paper, we present new petrographical and geochemical data about the intrusive and volcanic rocks of Sierra de la Ventana. These are integrated with regional geological data to postulate the magmatic source of the rocks and propose a model for the Late Proterozoic–Early paleozoic tectonomagmatic evolution of this part of Gondwana.

2. Field relationships and petrography of the igneous rocks

Igneous rocks crop out at La Mascota, La Ermita, Agua Blanca, Pan de Azucar, Cerro del Corral, San Mario, and

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Cerro Colorado (Fig. 1). Most are exposed on the western side of the Sierra de la Ventana due to tectonic transport to the northeast by thrust faults (Cobbold et al., 1986).

The outcrops at Cerro Colorado, La Ermita, and Agua Blanca are granitic and rhyolitic rocks overlain by Quaternary sediments. Those at San Mario, Pan de Azucar, and Cerro del Corral show tectonic contacts with the Paleozoic sedimentary cover (Fig. 1).

According to field relationships in the San Mario, Pan de Azucar, and Cerro del Corral granites, as well as in the Cerro del Corral rhyolite and the Pan de Azucar andesite, these rocks can be grouped into the Meyer suite. Strong ductile deformation and a typical geochemical signature, as reported subsequently, characterize this suite.

The Cochenleufu´ suite consists of the Agua Blanca and Cerro Colorado granites and the La Ermita rhyolite. They are slightly deformed and characterized by a distinctive magmatic fabric.

2.1. Meyer suite

2.1.1. Pan de Azucar

In Pan de Azucar (Fig. 2a), the greenschists, metaquartzites, basic bodies, and mylonitized granites described by Cuerda et al. (1975) underlie the Paleozoic sequence (Pan de Azucar Formation). Schiller (1930) and Cucchi (1966) infer a tectonic contact, whereas von Gosen et al. (1990) find no evidence of intrusive contact. Cobbold et al. (1986) suggest a dextral overthrust to the northeast. Our interpretation, based on the presence of ultramylonitic belts (344°/61°SW) in the granitic rocks, is a NE-vergent overthrust.

As shown in Fig. 2a, the eastern flank of the Cerro Pan de Azucar consists of deformed plutonic and volcanic rocks. Plutonic rocks exhibit isogranular to ultramylonitic textures. The former are composed of quartz, twinned K-feldspar, plagioclase (An26–33), and biotite. Plagioclase is replaced by sericite, epidote, and calcite. In the QAP modal triangle (Fig. 2a), these rocks plot in the synogranite and monzogranite fields. In protoclastic and protomylonitic varieties, quartz, plagioclase, and K-feldspar were disrupted to produce porphyroclasts with patchy extinction and fracturing. In the mylonitic granites, a fine-grained matrix composed of quartz, sericite, and chlorite wraps around rotated porphyroclasts of quartz, plagioclase, and K-feldspar. The ultramylonitic granites display a few strongly fractured porphyroclasts of K-feldspar in a fine-grained matrix of quartz, muscovite, and chlorite with minor calcite and biotite.

Basic and acidic volcanic rocks also are recognized in this profile. Acidic rocks consist of a 1 m thick belt of porphyritic rocks with 30% euhedral quartz, plagioclase (An10–15), and K-feldspar fenocrysts in a groundmass of microcrystalline quartz, alkaline feldspar, and fine micas. Quartz shows embayment, whereas plagioclase contains agglomerates. Its microscopic characteristics and QAP diagram classification correspond with a rhyolite.

Basic vulcanites appear as a 10 m thick, 90 m long body with notable coarse fenocrysts of plagioclase. Kilmurray (1968b) first described these rocks as diabases. The groundmass displays a pilotaxitic texture with laths of plagioclase and elongated crystals of tremolite, epidote, and quartz. The plagioclase (An20–23) shows alteration to
epidote and sericite. Oscillatory zoning and lamellar twinning are common. On the basis of these characteristics, the rocks are classified as andesites.

2.1.2. Cerro del corral

Cerro del Corral is located 100 m east of Pan de Azucar, and together they constitute the core of a large overturned anticline. Ductile shear zones and belts of mylonites and phyllonites on the eastern side of Cerro del Corral are related to overthrusting on the Paleozoic sequences. Protoclastic, protomylonitic, and mylonitic granites appear on the western flank of the Cerro del Corral (Fig. 2b). They are coarse- to medium-sized grains with fractured quartz, K-feldspar, and twinned plagioclase (An8–10). Secondary quartz, biotite, and muscovite appear in veins or disseminated crystals. On a QAP diagram, these rocks plot in the synogranite and monzogranite fields.

Volcanic rocks display porphyritic, protomylonitic, and mylonitic textures. Porphyritic varieties are composed of 20% quartz, alkali feldspar, and plagioclase phenocrysts. Quartz appears as subhedral phenocrysts with embayment and shadowy extinction. The alkali feldspars are euhedral and exhibit simple twinning and flame-like pertites. The scarce plagioclase phenocrysts (An10–12) have diffuse lamellar twinning. The matrix consists of muscovite, biotite, calcite, subhedral quartz, and plagioclase (An10). They are petrographically classified as rhyolites.

Fig. 2. Profiles at (a) Pan de Azucar, (b) Cerro del Corral, and (c) San Mario. (d) QAP diagram for the Cochenleufú suite.
Micaceous-rich, coarse bands of quartz and alkali feldspar compose the mylonitized rhyolites. The original igneous quartz and alkali feldspar represent porphyroclasts or augens surrounded by a deformed matrix.

### 2.1.3. Cerro San Mario

In San Mario, an E–W, elongated, granitic body (600 m long, 150 m wide) is overthrust on conglomerates of the Curumalal Group. The San Mario granite is a medium to coarse-grained biotite monzogranite with protoclastic to protomylonitic textures (Fig. 2c). The mineralogy consists of quartz, K-feldspar, plagioclase, and biotite. Plagioclase ranges from An15–33 in synorogenic to An26–40 in monzogranites. Large alkali feldspar is usually perthitic and shows shadowy, crosshatched twinning.

Several foliated belts cut the granite N–S (353°/66°SW). Minor aplite and pegmatite dikes crosscut the granites. Delpino and Dimieri (1992) recognize two deformational events. The first is evidenced by a regional NNW schistosity, and NE shear planes represent the second.

### 2.2. Cochenleufu’ duite

#### 2.2.1. Agua blanca

The Agua Blanca granite occurs 10 km north of Pan de Azucar. It is a porphyritic to aplitic granite, composed of microcline, anorthoclase, quartz, and plagioclase. Plagioclase (An0–5) is subhedral to euhedral. Biotite with strong quartz appears as isolated phenocrysts, whereas plagioclase microcline, anorthoclase, quartz, and plagioclase.

Fluorite and iron oxides appear as disseminated crystals. Fluorite is present as disseminated crystals or veinlets in the microcline (Fig. 2d). Dimieri et al. (1990) describe similar features in the Agua Blanca granite.

#### 2.2.2. La Ermita

La Ermita is located 10 km NNW of Agua Blanca. It consists of a N–S, 500 m long hill with no relationship to the Paleozoic cover. These rocks display fluidal and foliation. Orientations of feldspar and micas form an angle of 20–40° and display a S–C foliation. This fabric was developed during a submagmatic stage (Miller and Paterson, 1994; Tribe and D’Lemos, 1996). Dimieri et al. (1990) describe similar features in the Agua Blanca granite.

### 3. Geochemistry systematics

Major, trace, and rare earth elements (REE) geochemical data for both suites appear in Tables 1 and 2. X-ray fluorescence was used to determine major, minor, and trace elements: SiO2, TiO2, Al2O3, FeO, MnO, MgO, CaO, Na2O, K2O, P2O5, Ba, Cl, Co, Cr, Cu, Ga, Nb, Pb, Rb, Sr, Th, U, V, Y, Zn, and Zr. International geostandards, including AC–E, MA–N, GS–N, GA, and GH granitoids, were used for instrumental calibration. The analyses were carried out at the University of Barcelona. Instrumental neutron activation analyses were carried out on 31 selected samples to determine the REE, Ta, Hf, Sc, Cs, and Sn at ACTLABS.

#### 3.1. Meyer suite

The granitoids of the Meyer suite are the most mafic of the Sierra de la Ventana igneous rocks, ranging in composition from monzonite to granite (Table 1). Harker diagrams of major elements display decreasing TiO2, Al2O3, Fe2O3, MgO, and CaO and increasing K2O with increasing fractionation, thus implying a comagmatic origin for these rocks. SiO2 concentrations are between 57 and 77 wt% in the Pan de Azucar granite, 67–76 wt% in the Cerro del Corral granite, and 68–76 wt% in San Mario. The granitoids are characterized by high K2O (Cerro del Corral and Pan de Azucar: 6.29 wt%, San Mario: 5.28 wt%) and fall in the shoshonitic and high-K calc-alkaline fields of Pecerrillo and Taylor (1976) classification.

The AFM diagram (not shown) indicates a calc-alkaline evolution, with A ranging from 55 to 85 and evolving from the Pan de Azucar andesite to the Cerro del Corral rhyolite. The granitic rocks occupy the transitional terms of this series. All samples are subalkaline.
Table 1
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D.A. Gregori et al. / Journal of South American Earth Sciences xx (0000) xxx–xxx

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### Table 2

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The ASI index ranges 0.83–2.3 for the Cerro Corral and Pan de Azucar granites and 1.9–1.1 for San Mario; for the Pan de Azucar andesite, it is 1.3, and for the Cerro del Corral rhyolites, it ranges 1.0–3.0. This range plots in the peraluminous field on Shand (1943) diagram (not shown).

The normative corundum reaches 8.9% in the Cerro del Corral granite, 9.4% in Pan de Azucar, and 7.1% in San Mario, though modal corundum was not recognized. On the basis of their petrographical and geochemical characteristics, the Cerro del Corral, Pan de Azucar, and San Mario granites are interpreted as S-types. The Cerro de Corral rhyolites plot in the peraluminous field of Shand (1943) diagram and in the banakite and high-K rhyolite field of Pecerrillo and Taylor (1976) classification.

3.1.2. Trace and REE

Granites of the Meyer suite display significant variations in trace element contents (Table 1). Fractional crystallization is well represented by the K/Rb ratio, which decreases from 401 to 184 in the Pan de Azucar granite, from 261 to 189 in the Cerro del Corral granite, and from 252 to 197 in the San Mario granite. With increasing fractionation, Ba, Sc, Mn, and Zr decrease and Ga, Ta, Nb, and Y increase (Fig. 3e–h). This indicates fractional crystallization of plagioclase and K-feldspar in the melt, with enrichment of Rb and depletion of Sr in later stages (Grecco et al., 1999).

The total REE reaches 539 ppm in Pan de Azucar, 195 ppm in Cerro del Corral, and 180 ppm in San Mario. Chondrite-normalized spider diagrams of Pan de Azucar (Fig. 4a) indicate strong enrichment of LREE. The LaN/LuN between 16 and 100 suggests that garnet remained as a residual phase during the melting of the parental rocks. The patterns for Cerro del Corral (Fig. 4b) also display important LREE enrichments, though not as high as those of Pan de Azucar. Their LaN/LuN relationships between 16 and 100 suggests that garnet remained as a residual phase during the melting of the parental rocks.

The patterns for San Mario (Fig. 4c) display similar LREE enrichments. The REE concentration reaches 83 ppm, with LaN/LuN of 5.35 and Eu/Eu* of 0.82 (Fig. 4d).

The Cerro del Corral rhyolite has a high concentration of silica and alkalies, thus classifying it as a high-K subalkaline (Leat et al., 1986). The total REE concentration reaches 164 ppm. Chondrite-normalized diagrams (Fig. 4b) display severe negative Eu anomalies (Eu/Eu* = 0.097–0.42), which indicate that plagioclase was strongly fractionated.

3.2. Cochenleufu´ suite

3.2.1. Major elements

The Agua Blanca and Cerro Colorado granites present very restricted chemical compositions (Table 2) with...
SiO$_2$ = 73–77 wt%, Al$_2$O$_3$ = 11–17 wt%, and K$_2$O = 3.84–6.36 wt%. Fractional crystallization is not evident from the Harker diagrams (Fig. 3a–d). The Agua Blanca and Cerro Colorado granites are peraluminous and subalkaline with 6.8 and 4.4 wt% corundum normative, respectively.

3.2.2. Trace and REE

The Agua Blanca and Cerro Colorado granites present restricted trace element concentrations, with Rb, Y, Nb, and Ga concentrations higher than those of the Meyer suite, whereas the Sr, Zr, and Ba concentrations are lower (Fig. 3e–h). Logarithmic plots of Rb–Sr and Ba–Rb indicate restricted fractional crystallization of plagioclase and K-feldspar (Grecco et al., 1999). Total REE concentrations are between 104 and 177 ppm in Cerro Colorado and between 98 and 370 ppm in Agua Blanca. The chondrite-normalized diagram for the Cochenleufú suite indicates enrichments of 60–150 times in Cerro Colorado and 50–400 times in Agua Blanca (Fig. 4e and f). Both bodies have strong negative Eu anomalies with Eu/Eu* = 0.049–0.094 in Agua Blanca and 0.051–0.127 in Cerro Colorado. These anomalies indicate that plagioclase was severely fractionated from the original magma.
4. Previous geochronological studies

Previous radiometric ages (Borrello and Venier, 1967; Cazeneuve, 1967; Cingolani and Varela, 1973; Varela and Cingolani, 1975; Rapela et al., 2001, 2003) using K/Ar, Rb/Sr, and U–Pb SHRIMP data have been determined for the granitic and volcanic rocks of Sierra de la Ventana (Fig. 5). Late Proterozoic ages were obtained for the Cerro del Corral rhyolite (671 ± 35, 655 ± 30, 638 ± 30 Ma), Cerro del Corral granite (612.3 ± 5.3, 607 ± 5.2 Ma), Pan de Azucar andesite (603 ± 30 Ma), and Pan de Azucar granite (598 Ma).

Cingolani and Varela (1973) also constructed a Rb/Sr isochron using samples from both the San Mario and Agua Blanca granites to obtain an age of 574 ± 10 Ma. Lower Paleozoic ages were obtained for the Cerro Colorado granite (487 ± 15, 407 ± 21, 529.6 ± 3.3, 531.1 ± 4.1 Ma), Agua Blanca granite (492 Ma), San Mario granite (524.3 ± 5.3, 526.5 ± 5.5 Ma), and La Ermita rhyolite (509 ± 5.3 Ma).

The age population indicates two magmatic cycles at 700–560 and 530–470 Ma, which are concordant with the field-, petrographical-, and geochemical-based separation into two suites. Discrepancies arise when the younger age of the San Mario granite is compared with other members of the Meyer suite. However, zircon cores with ages that vary between 600 and 540 Ma and the Pb loss registered at 500 Ma suggest that the obtained age is not completely reliable, especially considering the strong similarities in the geochemistry, petrography, and deformation of the San Mario, Pan de Azucar, and Cerro del Corral granites. On this basis, the San Mario granite is included in the Meyer suite.

Equivalent magmatic cycles have been recognized in South Africa, where they constitute the Cape granite suite (Scheepers, 1995; Scheepers and Poujol, 2002).

5. Tectonic discrimination

5.1. Meyer suite

Pearce et al. (1984) subdivide the granitoids, according to their tectonic setting, into intrusion in ocean ridge, volcanic arc, within plate, orogenic, and synollisional granites. In the Y + Nb versus Rb diagram (Fig. 6a),
samples plot dominantly in the volcanic arc field, whereas in the Y versus Nb diagram, they plot in both the volcanic arc and syncollisional fields (Fig. 6b).

Whalen et al. (1987) discriminate between A-type granites and most orogenic granitoids (M-, I-, and S-types) using the Ga/Al relationships and Y, Nb, and Zr concentrations. In Whalen et al.’s (1987) discrimination diagrams, the Meyer suite granites plot in the S- and I-type granite fields (Fig. 7). These results indicate that the Meyer suite consists of S-type granites, as defined by Chappell and White (1974).

Harris et al. (1986) recognize four groups of granitic rocks in the Himalayan, Alpine, and Hercynian belts: (1) precollisional, calc-alkaline, dioritic to granodioritic plutons associated with volcanic arcs; (2) syncollisional, peraluminous leucogranites; (3) late- or postcollisional, calc-alkaline, biotite-hornblende tonalite to granodioritic plutons; and (4) postcollisional alkaline rocks. In the triangular diagram Rb/30-Hf–Ta*3 (Fig. 8a), samples plot in the precollisional (volcanic arc) and the late- or postcollisional fields, though a few appear in the within-plate field. In the SiO2 wt% versus Rb/Zr diagram (not shown), most samples plot in the VAG field. In the Y–Nb–Ce and Y–Nb–3*Ga diagrams of Eby (1992), most samples plot in the A1-type granite field (Fig. 9a and b).

Rocks with geochemical and petrologic characteristics emplaced during a subduction-collision event have been recognized in the Karakoram Axial batholith of northern Pakistan (Baltoro plutonic unit, Hunza leucogranite; Crawford and Windley, 1990), the Pan-African belt of the Arabian shield (Jackson et al., 1984), the Homrit Waggat complex of Egypt (Hassanen, 1997), and the Qinling belt of China (Mattauer et al., 1985).

Through plotting in TiO2–MnO*10–P2O5*10, Ti/100–Zr–Y*3, and Th/Yb–Ta/Yb discriminant diagrams (Pearce and Cann, 1973; Pearce, 1982; Mullen, 1983), the Pan de Azucar andesite is classified as a calc-alkaline basalt that erupted at active continental margins (not shown).

5.2. Cochenleufu` suite

Samples from the Cochenleufu suite plot in the within-plate granite field (Fig. 6) of Pearce et al. (1984) diagrams. They also fall in the A-type granite field in trace elements versus 10000 Ga/Al discrimination diagrams (Fig. 7). This result agrees with the A-type granite characteristics of these rocks, namely, the high SiO2, Na2O + K2O, Ga/Al, Zr, Nb, Ga, Y, and Ce and low CaO.
In the Rb/30-Hf–Ta*3 diagram (Harris et al., 1986), the samples plot in the syn- to postcollisional fields (Fig. 8b); in the SiO2 wt% versus Rb/Zr diagram (not shown), they are classified in the syncollisional field.

Finally, in Eby (1992) Y–Nb–Ce and Y–Nb-3*Ga diagrams, most of the samples plot in the continental–continental collisional to postcollisional field (Fig. 9a and b). Examples include the Gabo and Mumbulla suites in the Lachland fold belt, Australia (Collins et al., 1982), and the Topsails complex of Newfoundland (Whalen et al., 1987).

6. Discussion

In Sierra de la Ventana, the deficiency of igneous rock outcrops, as well as the lack of field relationships with host rocks, makes it difficult to establish its tectonic
setting. However, the correlation with the African granitic suites enables us to clarify the evolution of accretional events in Sierra de la Ventana. Two igneous suites are differentiated in Sierra de la Ventana. The most basic is the Meyer suite (700–570 Ma), which displays a calc-alkaline evolution related to volcanic arc and postcollisional settings.

In the Saldania belt of South Africa, sedimentary and volcanic rocks deposited in the Boland terrane (Malmesbury Group) attest to ocean floor spreading in response to the breakup of Rodinia and the progressive opening of the proto-Atlantic (Adamastor Ocean) during 780–750 Ma (Rozendaal et al., 1999). Rocks of this age, which represent this extensional event, had not been recognized in Sierra de la Ventana, though they were found in Sierra de Tandil. A reversal of the spreading caused subduction and the closure of the Adamastor Ocean (600–570 Ma).

The presence of a suture zone at the Swartland-Boland terrane boundary supports either oblique collision or strike-slip transpressional tectonics without the development of a proper collision orogen. The Cape granite suite consists of a first and second phase of intrusion (600–520 Ma), with olivine gabbros, gabbros, diorites, and granodiorites related to subduction along an immature magmatic arc (Scheepers, 1995). S-type granitic rocks that intruded during this phase have late orogenic to postorogenic signatures. In Sierra de la Ventana, the Meyer suite represents this subduction-collision event.

The Cochenleufú suite (540–470 Ma) is considered an A-type association and plots in the within-plate, syn- to postcollisional fields in several discrimination diagrams. According to Eby (1992) classification, these rocks belong to the A₂ granitoids, which generally occur as final plutonic events during postorogenic extension in collisional belts (Crawford and Windley, 1990; Bonin, 1990).

In the Cape granite suite, the final phase of intrusion (520–500 Ma) is represented by A-type granitoids (Scheepers, 1995), which are considered anorogenic alkaline granites. The granites are related to the pressure release that occurs during a strike-slip regime, with associated uplift and extension after collision. Equivalent postcollisional granites, intruded during an oblique N–S collision of the Kalahari and Congo cratons, have been recognized in the central Damaran orogenic belt, Namibia (Gresse and Scheepers, 1993). They are related to the closure of the Adamastor Ocean.

The Swartland and Tygerberg terranes (Saldania belt), accreted in a transpressive regime to the Boland terrane (600–630 Ma), are potential candidates for the Sierra de la Ventana suites’ emplacement.

Similar structural styles, magmatism, and tectonic events have been recognized in the Saldania, Ross, and Delamarian orogens, indicating a common history (Rozendaal et al., 1999). The Ross event, responsible for major magmatism in the Transantarctic Mountains, is represented partially by the granitic Harbour intrusive complex (Gunn and Warren,
7. Conclusions

In Sierra de la Ventana, two magmatic suites are differentiated. The older Meyer suite (700–570 Ma) displays a calc-alkaline evolution related to a volcanic arc and postcollisional setting. The younger Cochenleufu’ suite (540–470 Ma) displays A-type characteristics after a major orogenesis. Geol. J. 25, 261–270.

The remarkable similarities observed between the suites of Sierra de la Ventana and the Saldania belt enable a positive correlation. In both cases, primitive volcanic arc or collisional orogens are recognized. Moreover, continuous shearing between the Swartland and Tygerberg terranes was a potential trigger for the emplacement of both suites.

8. Uncited reference

Varela and Cingolani, 1990.

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