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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.

Keywords: Argentina; Late proterozoic–Early paleozoic magmatism; Sierra de la ventana

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.

Keidel (1916) correlated the Sierra de la Ventana sequences with the Karoo basin in South Africa, and Du Toit (1937) integrated both areas in the Samfrau geosyncline. Andreis (1964), Andreis et al. (1989), Borrello (1962) and (1964), Buggisch (1987), Harrington (1947), (1970), (1972) and (1980), Iñiguez Rodríguez and Andreis (1971), Kilmurray (1968a,b) and (1975), Kilmurray et al. (1985), Llambías and Prozzi (1975), Sellés Martínez (1989), Varela (1973) and (1978) and von Gosen et al. (1990), (1991) and (2002), among others, carried out geological studies in Sierra de la Ventana. In addition, Grecco et al. (1984) and (1999), Grecco and Gregori (1993), Varela (1985), Rapela and Pankhurst (2002), and Rapela et al. (2001) and (2003) studied its petrography, geochemistry, and geochronology and reported preliminary geotectonic interpretations of the igneous rocks.

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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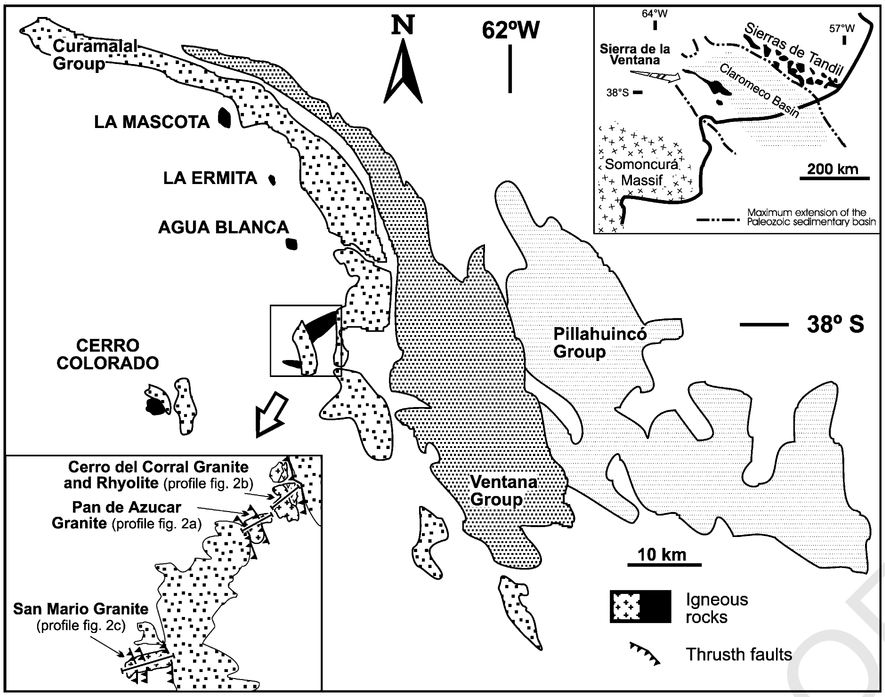

Fig. 1. Major tectonic domains in SE Buenos Aires. The box in the upper right hand shows the location of Sierra de la Ventana, as expanded in the main area of the figure. The location of the studied igneous rocks is clarified in the lower left-hand box.

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 Cochenleufú 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 (An_{26-33}), 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, biotite, 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 (An_{10-15}), and K-feldspar fenocrysts in a groundmass of micsrocrystalline 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 (An_{20-23}) shows alteration to

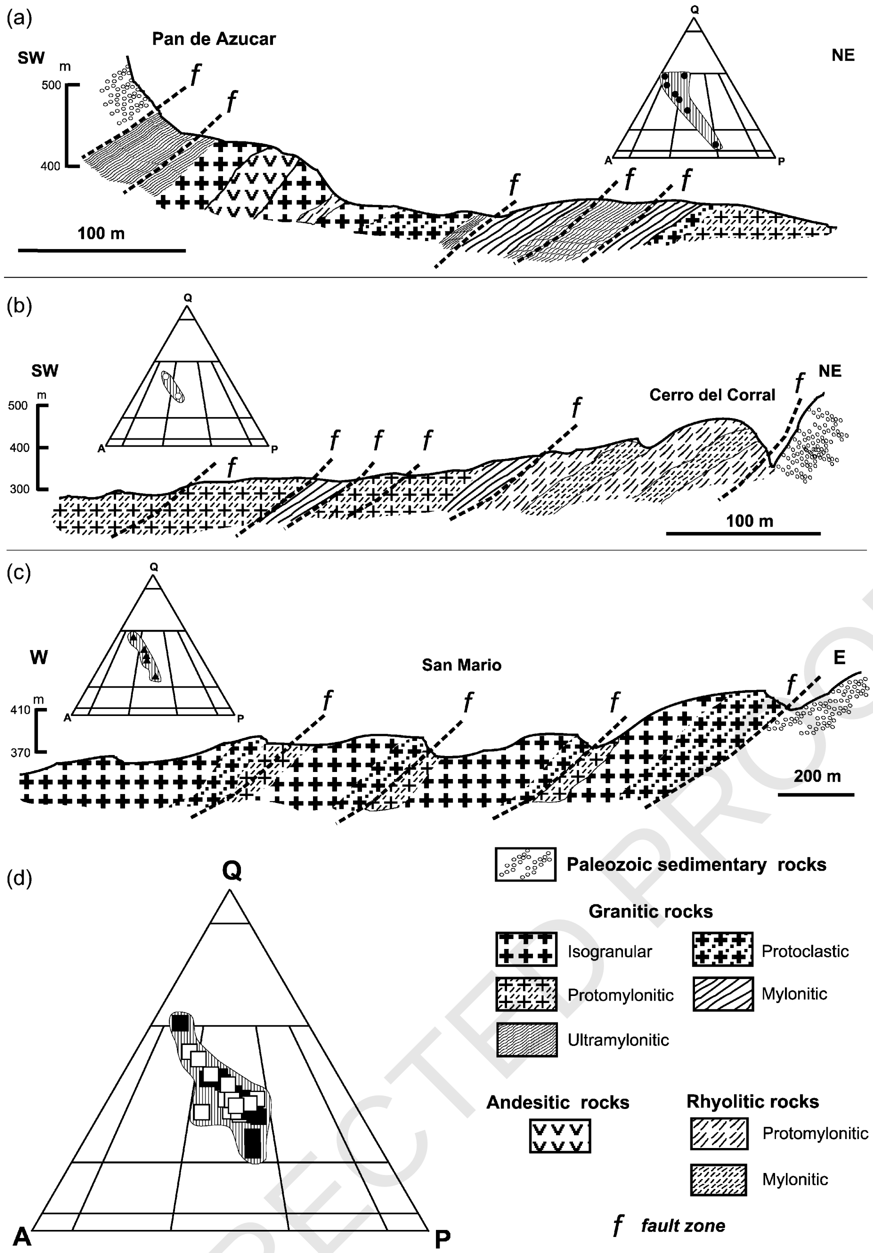

Fig. 2. Profiles at (a) Pan de Azucar, (b) Cerro del Corral, and (c) San Mario. (d) QAP diagram for the Cochenleufú suite.

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 (An_{8-10}). Secondary quartz, biotite, and muscovite appear in veinlets 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 (An_{10-12}) have diffuse lamellar twinning. The matrix consists of muscovite, biotite, calcite, subhedral quartz, and plagioclase (An_{10}). They are petrographically classified as rhyolites.

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 Curamalal 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 An_{15-33} in synogranites to An_{26-40} 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. Cochenleufú 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 Quartz appears as isolated phenocrysts, whereas plagioclase (An_{0-5}) is subhedral to euhedral. Biotite with strong pleocroism and muscovite are scarce. Fluorite is present as disseminated crystals or veinlets in the microcline (Grecco, 1990). Most samples from the Agua Blanca granite plot on the monzogranite field in a QAP diagram (Fig. 2d). Dimieri et al. (1990) describe kink bands, deformational twinning, and flexures in microcline and biotite crystals, which suggests ductile deformation during the solid-state stage (Simpson, 1985; Paterson et al., 1989).

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 microporphyritic textures with quartz and K-feldspar phenocrysts. Quartz is anhedral and presents undulose extinction and parallel deformational bands. The groundmass is completely recrystallized to fine-grained quartz. Fluorite and iron oxides appear as disseminated crystals. These rocks are classified as rhyolites.

2.2.3. Cerro colorado

Cerro Colorado is located 20 km W of Cerro San Mario The predominant lithology is a medium to coarse granite (Fig. 2d). Microcline, quartz, and plagioclase are the most abundant minerals; biotite, muscovite, fluorite, zircon, apatite, and magnetite are accessory minerals. Quartz appears as small to medium clusters between the microcline or as large phenocrysts. Microcline appears as large (3–5 cm) euhedral to subhedral crystals. Plagioclase (An_{6-10}) is euhedral with crystals up to 10 mm long, often twinned with albite and albite-carlsbad. Micaceous minerals are pleochroic biotite and kink-banded muscovite flakes. Fluorite appears as disseminated crystals in K-feldspar, irregular veinlets, and small lenses.

The western side of Cerro Colorado contains a foliation marked by the orientation of K-feldspar megacrysts (3–5 cm long) and mica flakes. The K-feldspar megacrysts are aligned in two trends: L1 (55–65°/N300–120°) and L2 (55–65°/N20–200°). Biotites display a 289°/44°SW to 340°/35°SW foliation. Biotite cumulates also follow this 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: SiO_2, TiO_2, Al_2O_3, FeO, MnO, MgO, CaO, Na_2O, K_2O, P_2O_5, 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 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

3.1.1. Major elements

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 TiO_2, Al_2O_3, Fe_2O_3, MgO (Fig 3a–d), and CaO and increasing K_2O with increasing fractionation, thus implying a comagmatic origin for these rocks. SiO_2 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 K_2O (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.

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Table 1
Chemical analyses of the Meyer suite (major elements in w%, trace, and REE in ppm)

Sample	CR0590	CR0190	PA 0991	PA 0491	PA0891	PA2191	PA2291	PA1891	PA0291	PA0791	PA1691	SM 0292	SM 0492	SMO2	SM 0192	SM 0392	PA 1991	CR0791	CR0690	CR0391
Locality	Corral granite		Pan Azucar									San Mario					Azucar Andesite	Corral Rhyolite		
SiO_2	67.96	68.44	72.93	72.54	74.81	61.59	60.75	57.01	67.53	69.93	65.05	68.36	76.09	72.89	70.67	68.21	60.71	76.49	74.58	73.05
TiO_2	0.68	0.54	0.56	0.52	0.35	0.55	0.63	0.91	0.43	0.73	0.80	0.33	0.21	0.27	0.30	0.52	0.78	0.09	0.07	0.07
Al_2O_3	16.47	15.37	15.79	16.26	13.98	15.85	15.79	17.44	15.91	15.81	16.29	15.51	14.75	14.78	15.16	16.35	16.41	13.36	13.01	17.15
FeO	4.24	2.80	1.99	1.60	1.35	4.28	4.30	6.45	4.42	2.66	3.56	2.34	1.08	1.19	1.94	3.05	5.81	0.78	1.11	1.46
MnO	0.05	0.04	0.02	0.02	0.03	0.14	0.11	0.24	0.15	0.03	0.04	0.06	0.01	0.03	0.06	0.05	0.25	0.07	0.02	0.01
MgO	1.27	0.92	0.76	0.63	0.78	2.05	2.10	1.51	1.43	1.18	1.32	0.49	0.38	0.34	0.76	1.35	1.46	0.13	0.06	0.44
CaO	0.67	0.46	0.13	0.32	1.73	1.82	1.68	1.79	2.05	0.56	2.32	1.52	0.24	0.89	0.87	3.15	2.88	1.23	0.24	0.00
Na_2O	0.87	2.50	0.77	0.14	0.57	4.59	6.99	3.89	0.26	1.75	1.57	3.24	1.02	2.23	2.40	0.31	0.10	0.34	3.60	0.24
K_2O	4.91	5.32	5.95	5.59	3.99	4.35	4.04	6.29	5.13	5.50	5.12	5.28	5.21	5.11	5.10	4.53	6.05	4.89	5.10	4.91
P_2O_5	0.24	0.17	0.17	0.09	0.09	0.16	0.18	0.14	0.05	0.12	0.20	0.13	0.06	0.05	0.13	0.06	0.10	0.01	0.02	0.02
LOI	1.93	2.93	1.37	2.00	2.34	3.12	2.06	3.45	1.98	1.32	3.00	2.32	1.82	1.57	1.18	1.90	4.74	1.89	1.19	2.05
Cr	8	10	5	5	17	27					23	18	13	21	14	48	410	6	2	12
Co	44	57	55	72	73	46					64	67	86	104	53	87	34	83	110	47
Sc	11	4	3	5	2	10					6	4	3	5	4		25	4	4	3
V	45	41	23	30	24	65	65	121	38	47	68	27	8	15	20	63	119	1	2	8
Rb	170	208	192	179	107	109	83	284	167	197	166	205	177	220	174	149	266	1.00	1.00	1.00
Cs	2.00	2.00	22.00	1.00	2.00	3.00					3.00	3.00	1.00	3.00	4.00		9.00	274	285	555
Ba	1441	1073	794	1416	460	650	652	1169	765	753	1064	1177	752	579	1201	427	1026	102	56	20
Sr	105	143	170	238	161	410	356	38	82	191	191	122	99	98	223	216	60	20	21	16
Ga	18	21	16	16	14	19	20	18	15	16	21	17	15	17	17	19	15	3.20	4.00	2.00
Ta	0.50	1.00	4.98	5.50	1.00	2.00					4.00	4.98	5.00	3.04	0.50	5.53	8.86	25.3	40.9	24.6
Nb	22.9	17.3	9.4	13.8	11.0	14.2	15.3	18.8	18.8	1.4	15.6	21.7	23.7	25.6	17.9	17.1	18.0	7.00	8.00	5.00
Hf	10.00	8.00	9.00	12.00	5.00	6.00					10.00	5.00	5.00	7.00	7.00		6.00	153	148	97
Zr	291	200	265	386	243	180	171	113	166	420	254	181	137	145	232	177	109	37	80	23
Y	27	9	19	22	11	10	11	21	36	21	11	22	24	31	18	11	18	26.34	41.48	18.55
Th	8.20	21.12	95.19	61.09	61.58	5.80	7.88	3.84	11.07	142.17	24.42	13.37	18.01	25.19	10.42	17.67	4.23	1.30	8.19	3.75
U	0.20	0.40	1.40	1.10	1.93	0.40					1.2	2.30	1.11	2.60	0.40		1.10	38.00	22.00	19.00
La	49.00	34.00	150.00	120.00	94.00	30.00					80.00	37.00	38.00	51.00	44.00		21.00	75.00	53.00	35.00
Ce	88.00	77.00	240.00	210.00	170.00	54.00					150.00	65.00	67.00	81.00	81.00		38.00	38.00	34.00	14.00
Nd	45.00	30.00	130.00	96.00	81.00	22.00					61.00	22.00	32.00	35.00	34.00		15.00	6.40	8.20	2.50
Sm	7.00	4.60	16.00	11.00	10.00	4.20					9.60	3.70	4.50	6.00	3.90		3.80	0.20	0.20	0.40
Eu	1.40	0.60	0.90	1.30	1.10	1.40					1.50	0.80	0.90	1.00	1.00		1.10	1.20	1.90	0.60
Tb	1.00	0.50	0.41	0.50	0.50	0.40					0.48	0.50	0.50	0.40	0.50		0.80	5.05	9.06	3.07
Yb	3.83	1.20	1.64	3.51	0.92	1.54					1.21	3.22	4.01	5.43	2.66		3.21	0.67	1.27	0.45
Lu	0.61	0.13	0.20	0.54	0.10	0.20					0.16	0.49	0.53	0.70	0.46		0.42	6.54	6.51	19.71
Cl	b.d.	40.47	14.20	14.26	13.06	26.47	27.08	7.12	11.05	33.57	18.47	17.07	58.96	97.90	32.39	26.96	17.68			

Table 2
Chemical analyses of the Cochenleufú suite (major elements in w%, trace, and REE in ppm)

Sample	AB 02	AB 09	AB 15	AB 14	AB 03	AB 17 g	AB 1884	AB 2284	AB 17r	AB 1722	AB 1384	AB 0884	AB 0384	CC 02	CC 04	CC 05	CC 08
Locality	Agua Blanca													Cerro Colorado			
SiO_2	75.89	74.33	75.31	73.26	74.35	75.33	76.32	74.37	74.18	76.37	73.03	77.01	76.23	77.18	77.36	75.49	76.09
TiO_2	0.04	0.05	0.03	0.12	0.02	0.05	0.02	0.02	0.05	0.02	0.05	0.02	0.06	0.08	0.11	0.10	0.11
Al_2O_3	12.85	13.95	13.29	14.30	13.29	13.89	13.36	12.94	13.35	13.77	13.64	13.84	13.84	11.95	11.63	12.99	12.34
FeO	1.35	1.09	1.63	1.01	1.29	1.75	0.36	0.91	1.25	0.77	1.20	0.49	0.63	0.85	0.93	1.04	1.22
MnO	0.23	0.19	0.10	0.08	0.09	0.49	0.33	0.10	0.49	0.09	0.11	0.08	0.04	0.01	0.01	0.01	0.03
MgO	0.15	0.04	0.42	0.03	0.06	0.19	0.02	0.01	0.11	0.01	0.12	0.06	0.09	0.10	0.10	0.10	0.10
CaO	0.70	0.10	0.21	0.70	0.90	0.16	0.29	0.37	0.13	0.39	0.15	0.11	0.50	0.10	0.17	0.26	0.28
Na_2O	3.20	4.43	4.34	4.22	3.79	3.68	2.37	6.00	3.68	0.59	5.46	2.80	2.75	3.27	3.17	3.65	3.48
K_2O	4.64	4.26	4.20	4.14	4.45	4.26	5.33	4.80	4.26	4.82	5.10	4.76	4.79	5.73	4.68	5.25	4.88
P_2O_5	0.03	0.03	0.01	0.02	0.01	0.01	0.00	0.00	0.01	0.00	0.00	0.01	0.01	0.01	0.02	0.01	0.02
LOI	0.87	0.50	0.52	0.40	0.60	0.21	1.54	0.25	0.50	0.64	0.45	0.63	0.79	0.62	0.27	0.32	0.32
Cr							350			15	47	360	310				
Co							4			97	78	3	4				
Sc									3	10	17	6	5				
V									4	1	9	4	1				
Rb					440	490	524	783		773	558	533	455				
Cs							9.00			23.00	3.00	6.00	5.00				
Ba							110	7		240	47	170	30				
Sr					8	5	20	1	27	2	8	8	5				
Ga							24	26	15	28	22	24	20				
Ta									5.00	7.93	4.00	4.00	5.00				
Nb					51.0	46.0	52.5	57.3	51.0	58.5	52.3	52.9	72.9				
Hf							3.00			16.00	14.00	6.00	6.00				
Zr					74	152	30	133	64	132	85	67	75				
Y					64	150	63	173	101	184	87	169	93				
Th							29.46	42.95	15.00	45.83	52.92	24.85	62.48				
U							3.14		4.50	4.10	4.00	2.00	3.50				
La									18.00	14.00	110.00	13.00	16.00				
Ce									49.00	54.00	170.00	33.00	37.00				
Nd									17.00	16.00	71.00	25.00	23.00				
Sm									6.70	9.40	13.00	7.70	7.60				
Eu									0.20	0.20	3.10	0.30	0.20				
Tb									2.10	2.60	0.20	2.20	1.80				
Yb									10.90	29.70	3.59	18.70	11.60				
Lu									1.32	3.90	0.53	2.73	1.66				
Cl							100.70	30.68	31.40	35.01	33.59	68.00	39.58				

Sample	CC 20	CC 23	CC 24	CC 26	CC 1683	CC 1983	CC 2283	CC 3183	CC 0183	CC 02b	CC 03
Locality	Cerro Colorado										
SiO_2	76.45	74.01	74.75	76.91	75.98	76.59	77.40	77.50	77.80	74.27	76.18
TiO_2	0.06	0.06	0.08	0.04	0.09	0.07	0.06	0.06	0.10	0.08	0.05
Al_2O_3	12.29	13.32	13.65	12.75	13.05	13.05	13.56	12.86	13.37	13.07	12.52
FeO	0.86	1.40	1.22	0.43	1.16	0.77	0.89	0.99	1.13	1.17	1.22
MnO	0.01	0.01	0.01	0.01	0.03	0.01	0.01	0.02	0.01	0.01	0.01
MgO	0.10	0.06	0.09	0.20	0.09	0.07	0.05	0.03	0.22	0.12	0.01
CaO	0.10	0.87	0.50	0.54	0.38	0.59	0.40	0.32	0.10	0.10	0.46
Na_2O	4.00	3.49	3.83	3.97	3.22	3.58	1.71	2.40	1.50	2.90	4.07
K_2O	4.83	4.88	4.91	4.33	5.12	4.96	5.17	5.12	5.30	6.36	3.84
P_2O_5	0.02	0.02	0.02	0.02	0.01	0.01	0.00	0.00	0.01	0.02	0.01
LOI	0.10	0.51	0.21	0.37	0.68	0.17	0.64	0.53	0.32	0.32	0.19
Cr					2	3	6	5	4		
Co					4	3	3	1	4		
Sc					4	4	4	3	5		
V					10	5	6	2	2		
Rb					394	423	467	262	352		
Cs					17.00	17.00	9.00	5.00	9.00		
Ba					67	51	45	140	126		
Sr					8	7	9	16	7		
Ga					23	24	24	19	20		
Ta					3.00	5.00	4.00	3.00	2.00		

Nb	40.9	46.8	46.2	39.1	37.1	29.0
Hf	11.00	10.00	7.00	4.00	6.00	
Zr	140	121	79	34	104	107
Y	96	129	98	77	53	79
Th	66.17	64.18	46.37	53.75	33.56	
U	4.06	9.66	3.50	1.90	3.30	
La	29.00	26.00	19.00	15.00	39.00	
Ce	77.00	79.00	53.00	43.00	81.00	
Nd	34.00	30.00	22.00	23.00	39.00	
Sm	12.00	14.00	9.30	9.80	9.00	
Eu	0.30	0.40	0.20	0.20	0.40	
Tb	3.20	3.40	2.70	2.20	1.90	
Yb	13.90	18.20	12.90	10.30	6.13	
Lu	1.67	2.26	1.67	1.26	0.88	
Cl	32.87	33.28	32.75	30.27	35.15	

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 La_N/Lu_N 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 La_N/Lu_N relationships vary between 8.6 and 28.0 with small Eu anomalies, reflecting some plagioclase fractionation. San Mario displays patterns similar to those of Cerro del Corral, with La_N/Lu_N relationships varying between 7.6 and 10.2 (Fig. 4c).

The Pan de Azucar andesite is classified by Winchester and Floyd (1977) as andesite and alkaline basalt. The total REE concentration reaches 83 ppm, with La_N/Lu_N 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. Cochenleufú suite

3.2.1. Major elements

The Agua Blanca and Cerro Colorado granites present very restricted chemical compositions (Table 2) with

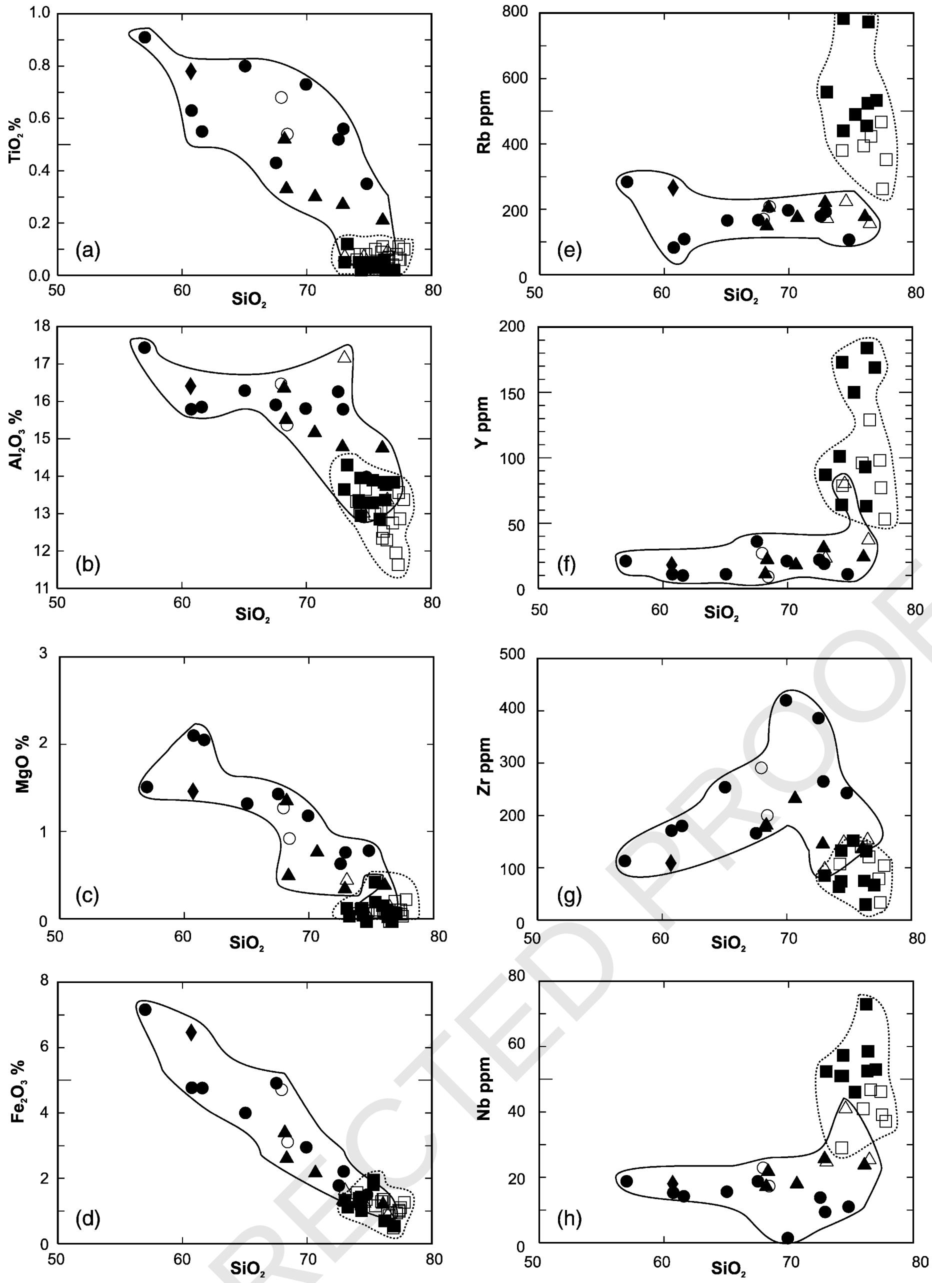

Fig. 3. Harker diagrams for the Meyer and Cochenleufú suites. Pan de Azucar granite •, Cerro del Corral granite ●, San Mario granite ▲, Cerro del Corral rhyolite △, Pan de Azucar andesite ◆, Agua Blanca granite □, and Cerro Colorado granite □.

$SiO_2 = 73–77$ wt%, $Al_2O_3 = 11–17$ wt%, and $K_2O = 3.84–6.36$ 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.

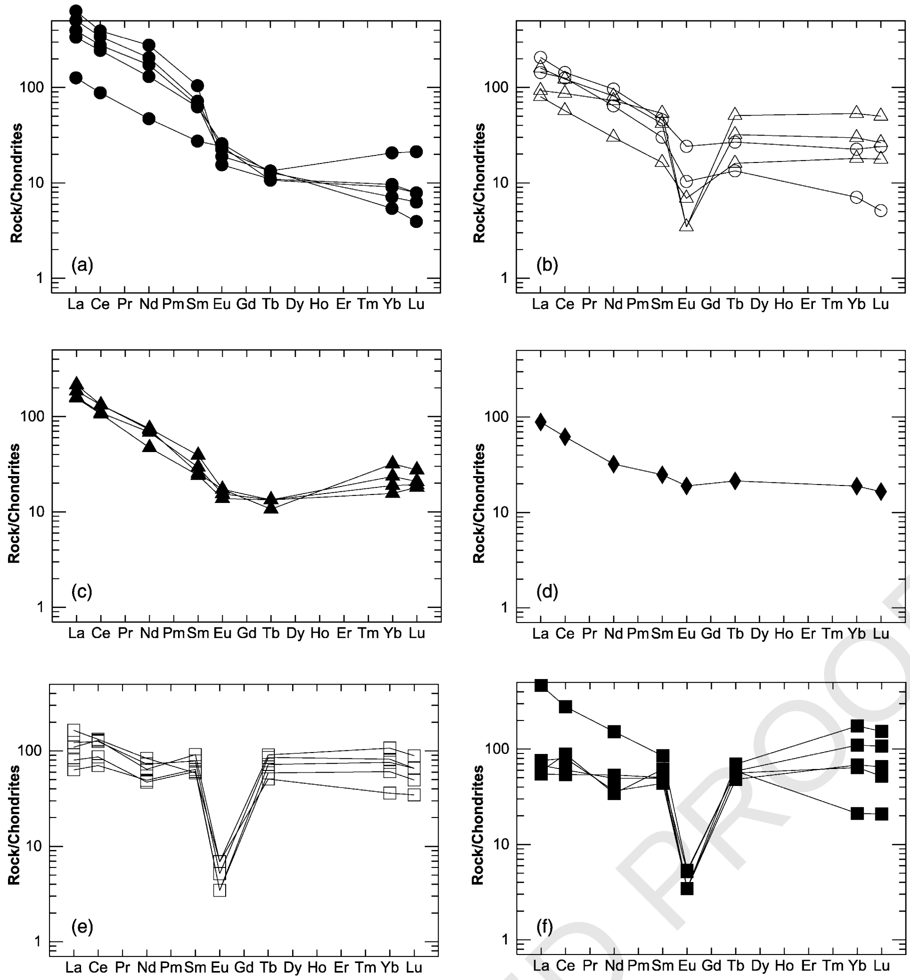

Fig. 4. Chondrite-normalized spider diagrams for (a) Pan de Azucar granite, (b) Cerro del Corral granite and rhyolites, (c) San Mario granite, (d) Pan de Azucar andesite, (e) Cerro Colorado granite, and (f) Agua Blanca granite. Symbols as in Fig. 3.

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 syncollisional granites. In the Y + Nb versus Rb diagram (Fig. 6a),

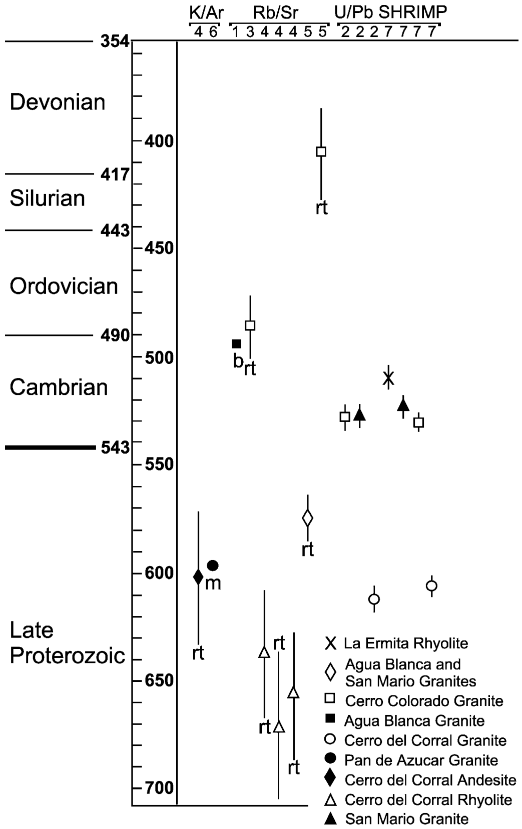

Fig. 5. Radiometric ages obtained from Sierra de la Ventana. (1) Borrello and Venier, 1967; (2) Rapela et al., 2001; (3) Varela et al., 1990; (4) Varela and Cingolani, 1975; (5) Cingolani and Varela, 1973; (6) Cazeneuve, 1967; and (7) Rapela et al., 2003. rt = whole rock, b = biotite, and m = muscovite.

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 SiO_2 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 A_1-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 TiO_2–MnO*10-P_2O_5*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. Cochenleufú suite

Samples from the Cochenleufú 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 SiO_2, $Na_2O + K_2O$, Ga/Al, Zr, Nb, Ga, Y, and Ce and low CaO.

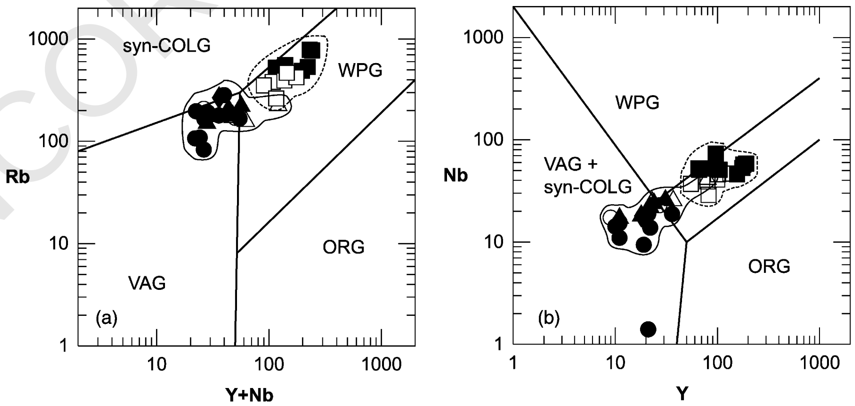

Fig. 6. (a) Rb versus Y + Nb diagram (Pearce et al., 1984) and (b) Y versus Nb diagram for the Meyer and Cochenleufú suites. Symbols as in Fig. 3.

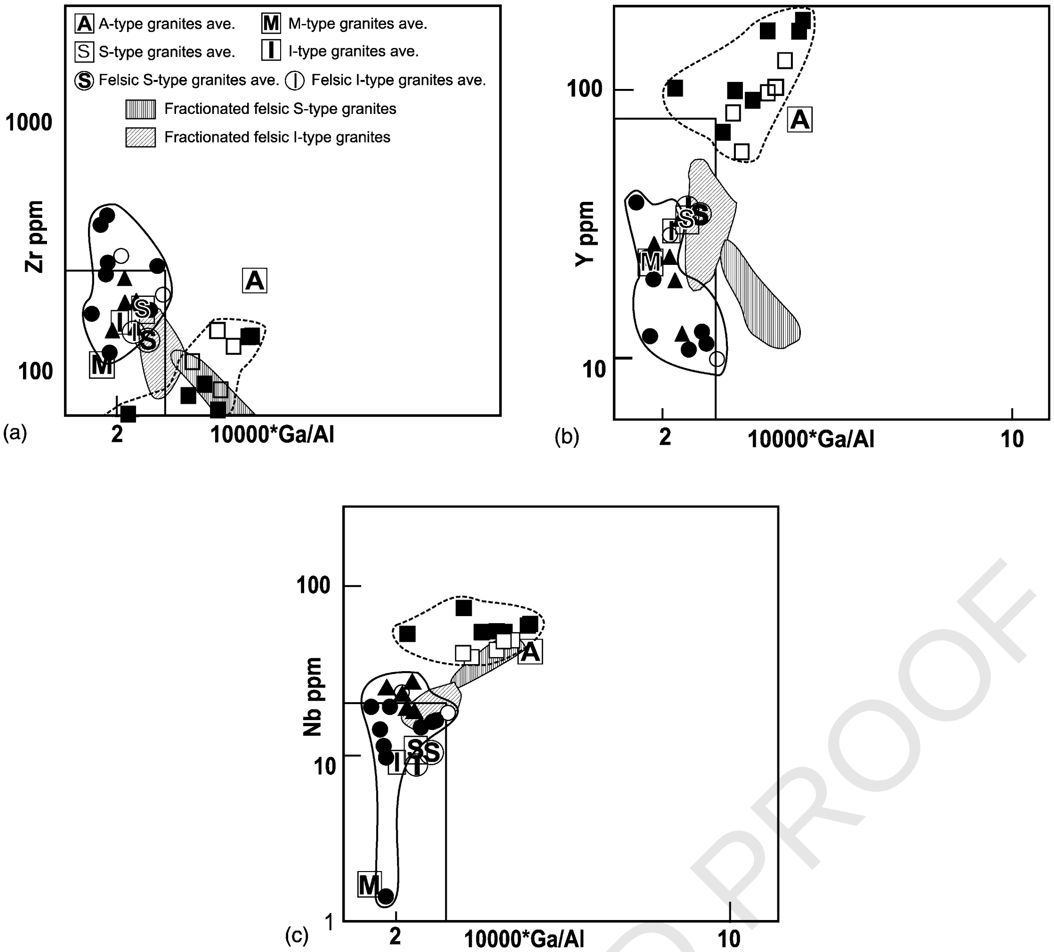

Fig. 7. (a) Zr, (b) Nb, and (c) Y versus 10000 Ga/Al diagrams (Whalen et al., 1987) for the Meyer and Cochenleufú suites. Symbols as in Fig. 3.

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 SiO_2 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

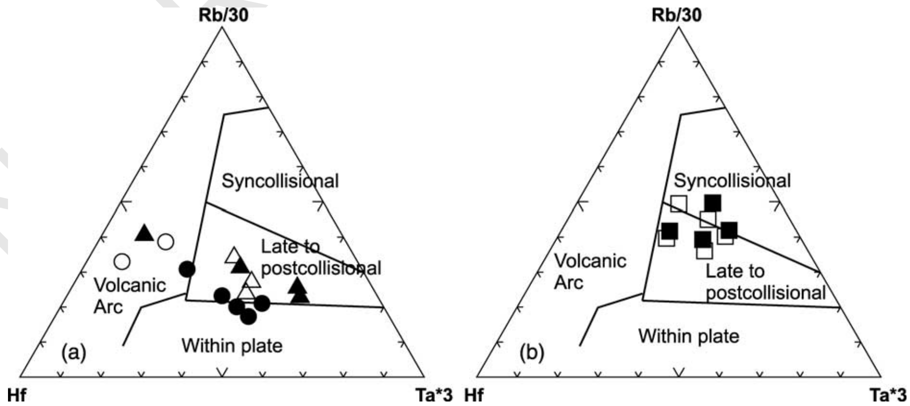

Fig. 8. Rb/30-Hf-Ta*3 diagrams (Harris et al., 1986) for the (a) Meyer and (b) Cochenleufú suites. Symbols as in Fig. 3.

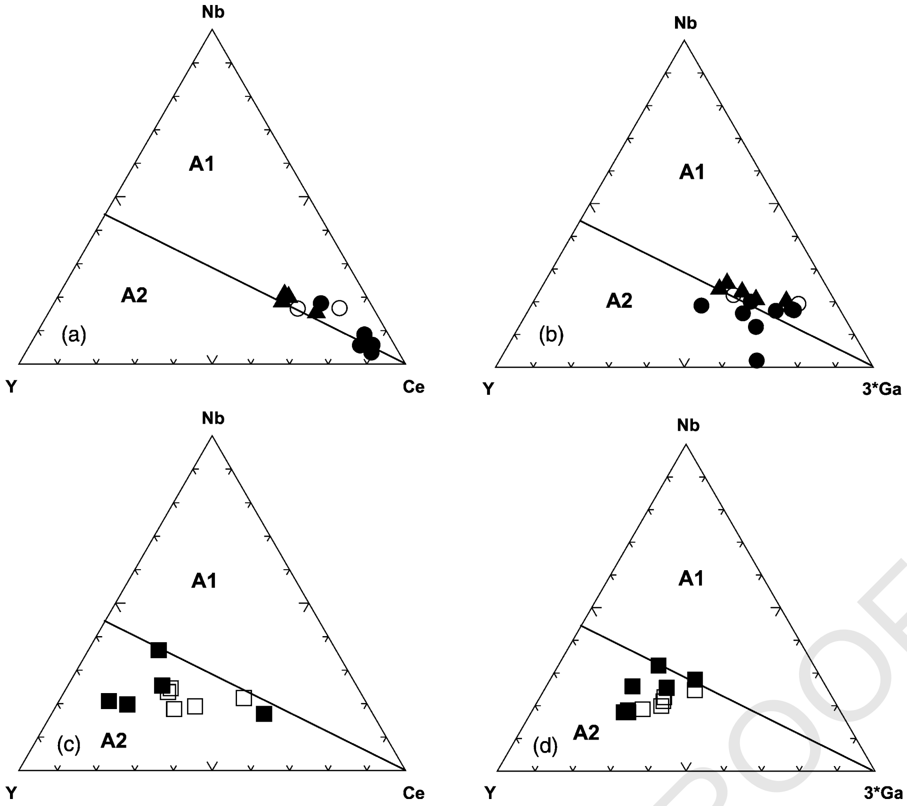

Fig. 9. (a, c) Y–Nb–Ce diagram (Eby, 1992) and (b, d) Y–Nb-3*Ga diagram for the Meyer and Cochenleufú suites. Symbols as in Fig. 3.

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 A_2 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, 1962), which was emplaced in a calc-alkaline arc. The Mid-Proterozoic-Late Cambrian history of the Transantarctic Mountains has been interpreted as a cycle of extension, continental rifting, transpression, and subduction (Moyes et al., 1993).

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 Cochenleufú suite (540–470 Ma) displays an A-type signature related to the final plutonic events during postorogenic extension in the collisional belts.

The remarkable similarities observed between the suites of Sierra de la Ventana and the Saldania belt enables 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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