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The Cordon del Portillo Permian magmatism, Mendoza, Argentina, plutonic and volcanic sequences at the western margin of Gondwana

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ABSTRACT

The Cerro Punta Blanca, Cerro Bayo and Cerro Punta Negra stocks, parts of the Cordillera Frontal Composite Batholith, cropping out in the Cordón del Portillo, records the Gondwana magmatic development of the Cordillera Frontal of Mendoza, in western Argentina. In this area, the San Rafael Orogenic phase, that represents the closure of the Late Carboniferous–Early Permian marine basins, begins at 284 Ma, and ceased before 276 Ma. The Cerro Punta Blanca, Cerro Bayo and Cerro Punta Negra stocks represent a post-orogenic magmatism and are equivalents to the Choiyoi Group. The Gondwana magmatic activity in the Cordón del Portillo area can be divided into two stages. The Cerro Punta Blanca stock (*c.a.* 276 Ma) represents an early post-orogenic, subduction-related magmatism similar to the basic-intermediate section of the Choiyoi Group (*c.a.* 277 Ma). The late post-orogenic second event was recorded by the Cerro Bayo (262 Ma) and Cerro Punta Negra stocks which represent a transition between subduction-related and intra-plate magmatism. This event represents the intrusive counterpart of the acidic facies of the upper section of the Choiyoi Group (c.a. 273 Ma). This extensional condition continued during the Triassic when the Cacheuta basin developed.

1. Introduction

The Cordillera Frontal of Argentina is a mountain belt more than 800 km in length, situated in western Argentina between 27° and 36°46′ S. It is composed by a string of Permian granitic bodies of the Cordillera Frontal Composite Batholith and related Permo-Triassic volcanic rocks (Choiyoi Group).

The Gondwana rocks intrude Vendian–Lower Paleozoic metamorphic rocks and Upper Paleozoic sedimentary rocks. The Cordillera Frontal has been partially covered by Cenozoic sedimentary and volcanic rocks, and experienced tectonic rejuvenation as a result of the Andean Orogeny during the Oligocene.

Previous studies of the Permian intrusive rocks include those of Rossi (1947), Polanski (1958, 1964, 1972), Caminos (1965, 1979), Dessanti and Caminos (1967), Caminos et al. (1979, 1982), Llano et al. (1985), Olivares et al. (1985), Varela et al. (1993), Petford and Gregori (1994), Gregori et al. (1996) and Orme et al. (1996). In the Cordillera Frontal of Chile, rocks of similar age have been studied by Nasi et al. (1985, 1990), Mpodozis and Cornejo (1988) and Mpodozis and Kay (1992).

The tectonic setting of the Gondwana magmatism along the Andean Cordillera has been the subject of much debate. The first hypothesis was published by Zeil (1981), who postulated that the volcanic and intrusive rocks (the Choiyoi Group and the Cordillera Frontal Composite Batholith) are the result of significant continental crust break-up after deformation in the Late Paleozoic. Magma genesis was related to anatexis of the continental crust during a 20–25 Ma period of rupture and extension.

However, studies of the Cordillera Frontal in Argentina by Llambías and Sato (1995) and in Chile by Mpodozis and Kay (1992) suggest a more complex magmatic evolution. Mpodozis and Kay (1992) proposed a Carboniferous to Early Permian magmatism related to a first stage of subduction (Elqui Complex) followed by a second stage of collisional magmatism. Late Permian–Early Triassic plutonism is represented by post-collisional granitoids, possibly associated with gravitational collapse of the oceanic plate after the collisional event (Ingaguás Complex).

In the Cordillera Frontal of the San Juan province, Llambías and Sato (1995) also recognized two stages in the evolution of the Colangüil Batholith. The first includes the Carboniferous Tabaquito and Las Piedritas granodiorites related to a magmatic arc during the cessation of a subduction process. The second is constituted by post-orogenic granites linked to the orogen uplift.

Gregori et al. (1996) recognized that most granitic stocks cropping out at Cordón del Plata and Cordón del Portillo in the Cordillera Frontal of Mendoza, are I-type. They were generated during partial melting of mafic high-K calc alkaline rocks located in the

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lower crust during an extensional stage after the San Rafael Orogenic phase.

The aim of this paper is to contribute in the understanding of the tectonic setting of the magmatic bodies belonging to the Cordillera Frontal Composite Batholith based on geological mapping, sampling, carried out on the Permian granites cropping out in the eastern area of the Cordón del Portillo.

In view of that, comparisons with equivalent rocks of similar age from the Cordillera Frontal of Chile and Argentina are made to model the evolution of this sector of the Gondwana continental margin. It also suggests that there was no Carboniferous magmatic arc based on more accurate dating.

1.1. Regional geology: The Cordillera Frontal and the Cordón del Portillo

The Cordillera Frontal is composed of mountain ranges identified as 'cordones', which exceed an altitude of 5000 m above sea level (Fig. 1). In the Province of San Juan, the Cordillera Frontal includes the Cordón de Ansilta, Cordón del Tigre, and Cordón de Colangüil, while in the Province of Mendoza includes the Cordón del Plata, Cordón del Portillo and Cordón del Carrizalito. Located in the central part of the Province of Mendoza, the Cordón del Portillo was selected for this study because of the magnificent exposures of the granitic bodies.

The Cordón del Portillo consists of a N–S belt of metamorphic rocks (Polanski, 1964, 1972) assigned by López et al. (1999) to the Guarguaraz Complex. On angular unconformity lie the Gondwana marine sedimentary rocks of the Totoral, Las Balas, Alto Tunuyán and Las Peñas formations (González Díaz, 1958; Polanski, 1958). These units reach about 1000 m thick and are composed of dark pelites, greywackes and sandstones with subordinate conglomerates. Fossil remains such as *Linoproductus cora* d'Orb., *Septosyringothyris keideli* Harr., *Aviculopecten* sp. cf. *Aviculopecten barrealensis* Reed, *Orthoceras* sp., *Spirifer* sp. and *Orbiculoide* sp. indicate an Late Carboniferous–Early Permian age.

Resting on the metamorphic rocks and marine sediments there is a thick sequence of Permian volcanic rocks of the Choiyoi Group, which comprises of andesitic, dacitic and rhyolitic lava flows, tuff and ignimbrites.

These units are intruded by the Permian Cordillera Frontal Composite Batholith (Polanski, 1958), which includes the Cordón del Portillo, Cerro Bayo, Cerro Punta Blanca, Cerro Punta Negra, and Las Yaretas stocks (Fig. 2). The metamorphic rocks form a near-horizontal roof pendant in which the effects of thermal contact with the granitic rocks are evident (Fig. 3A).

The Andean cycle is represented by the Yaretas Volcanic Complex (Pérez and Korzeniewski, 1999) and La Paloma Agglomerates (Polanski, 1964). The former includes Miocene andesites and basaltic andesites of a magmatic arc, while the latter are typical synorogenic deposits related to Andean imbrication and deformation.

1.2. Local geology

1.2.1. Guarguaraz Complex (Ediacaran–Cambrian)

The Guarguaraz Complex comprises low to medium grade regionally metamorphosed rocks, mainly phyllites and mica schists, with less frequent amphibolites, marbles and meta-quartzites (Fig. 2). López (2005) found acritarchs and cyanobacteria suggestive of an Ediacaran–Early Cambrian age.

1.2.2. Choiyoi Group (Early Permian)

The Choiyoi Group (Rolleri and Criado Roqué, 1968) is composed by volcanic rocks that crops out in the eastern side of the Cordón del Portillo. These rocks are distributed widely throughout the Cordillera Frontal and are more than 2 km thick in the southern Precordillera. The lowermost part of the Choiyoi Group comprises a 150 m thick layer of conglomerates and sandstones interbedded with thin basaltic and andesitic lava flows. They represent an intermediate to mafic subduction-related magmatism. The upper part is mainly acidic, with an intra-plate signature (Strazzere and Gregori, 2005, 2007).

1.2.3. Stocks of the Cordillera Frontal Composite Batholith in the eastern area of the Cordón del Portillo

1.2.3.1. Cerro Punta Blanca stock. The Cerro Punta Blanca stock crops out on the left side of the Arroyo Grande valley, reaching an altitude of 4500 m at Cordón del Pómez where an impressive roof pendant of metamorphic rocks can be observed (Fig. 2). The eastern side of the stock is incised by the Arroyo del Guindo valley, in which the intrusive contact between the stock and the metamorphic basement is exposed. The western side of the stock has been eroded by the Arroyo de las Guanaquitas glacial valley, which removed a significant portion of the metamorphic roof pendant. Thick glacial deposits obscure the relationship of the Cerro Punta Blanca stock with the Cordón del Portillo (Gregori et al., 1996) and Las Yaretas stocks (Gregori, 2000).

The intrusive relationship between the Cerro Punta Blanca and the Cerro Punta Negra stocks can be observed in the left margin of the Arroyo Grande valley. There, the rocks of the first one are intruded by massive rocks of the second. In the upper part of the slope of the valley, the granitic rocks of the Cerro Punta Negra stock thrust on the rocks of the Cerro Punta Blanca stock (Fig. 3B). Basic dykes are limited to a few occurrences, although a 1.5 m wide dyke intruding the granite has been identified near the confluence of the Arroyo de las Guanaquitas and the Arroyo Grande. Its contact with the Cerro Punta Blanca stock is sharp, with a WSW–ENE orientation and a near-vertical dip. The dyke is composed of a greenish rock with plagioclase laths and chloritized amphibole and biotite.

A variety of isotopic ages (348 ± 35 Ma Rb/Sr, 337 ± 15 Ma K/Ar, 291 ± 10 Ma and 264 ± 8 Ma Rb/Sr and K/Ar) for the Cerro Punta Blanca stock have been obtained by Caminos et al. (1979) and Llambías and Caminos (1987), while an age of 276.29 ± 0.79 Ma (U/Pb using conventional zircon) was determined by Orme et al. (1996).

1.2.3.2. Cerro Bayo stock. This stock (~40 km^2) is situated on the lowermost slope of the Cordón del Portillo and has an elongated shape with a NE–SW orientation (Fig. 2). The body intrudes the Guarguaraz Complex, and the rhyolites and basalts of the Choiyoi Group (Poma and Ramos, 1994).

The main lithology of this stock consists of medium to coarse-grained white granodiorite, which represents the major part of the outcrops. No mafic dykes were observed in the Cerro Bayo stock, while minor felsic intrusions are restricted to centimetric veins cutting the basalts of the Choiyoi Group at Cerro Pajaritos.

An age of 271 ± 20 Ma (K/Ar in biotite) was determined for this stock by Caminos et al. (1979), whereas Orme et al. (1996) obtained an age of 262.7 ± 3.4 Ma (U/Pb in zircon).

1.2.3.3. Cerro Punta Negra stock. The Cerro Punta Negra stock crops out on the southern side of the Arroyo Grande valley, extending more than 10 km in a W–E direction. To the south it continues to Cerro Pircas where it intrudes the Choiyoi Group. The Cerro Pircas probably represents a part of the Cerro Punta Negra stock. Near Arroyo del Guindo, on the Arroyo Grande valley slope, a 30 m thick ENE–WSW fault zone with granitic breccias represents the tectonic contact with the Cerro Punta Blanca stock. Very well exposed, the Cerro Punta Negra stock contains semi-digested blocks of dark hornfels and is capped by a remarkable roof of metamorphic rocks

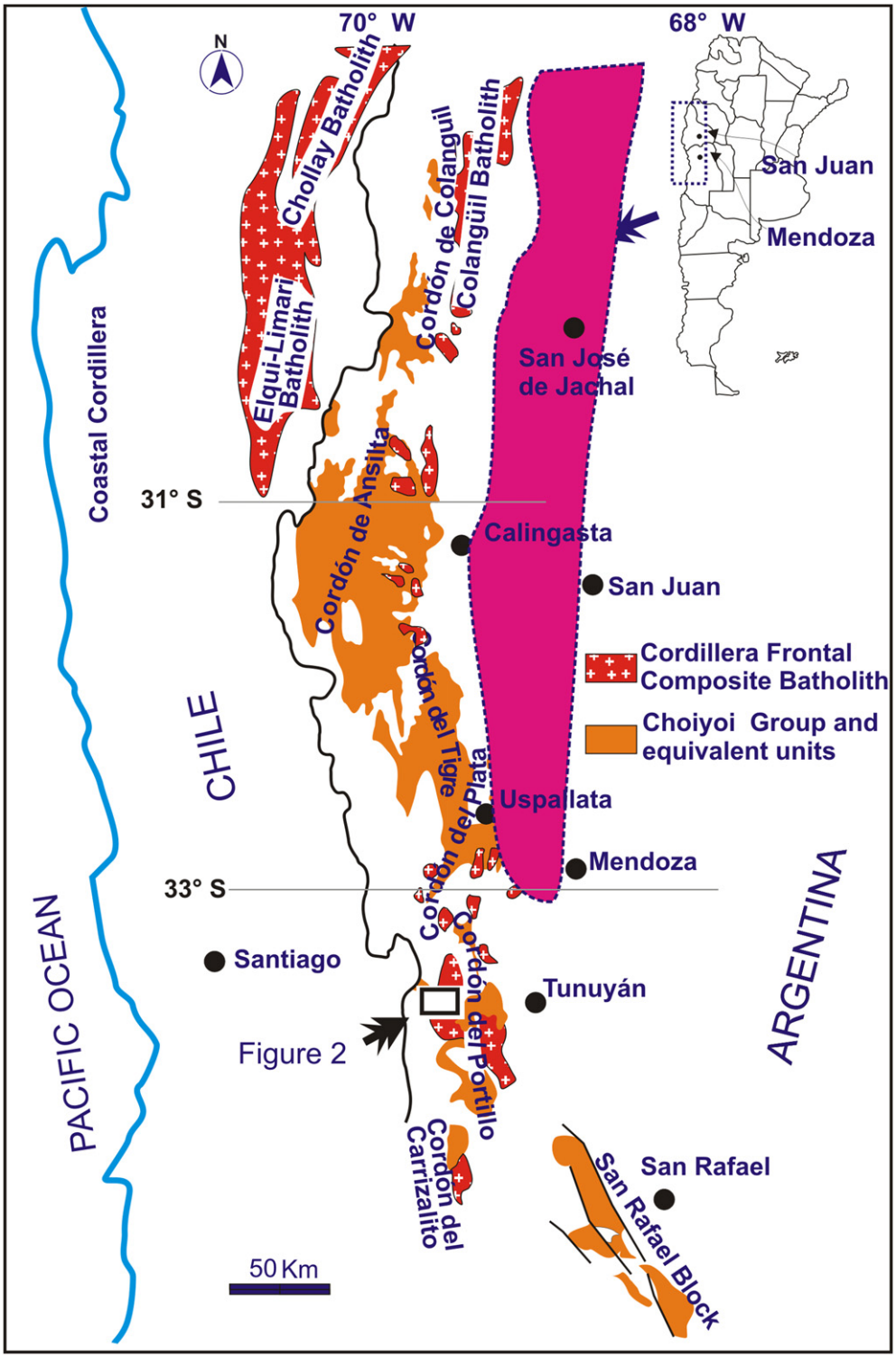

Fig. 1. Outline of the Cordillera Frontal de Chile and Argentina and San Rafael block, showing the distribution of Gondwana granitic batholiths and volcanic rocks. Location of Fig. 2 is indicated.

(Fig. 3A). The body consists of homogeneous coarse-medium grained equigranular pink granite. Radiometric dating indicated an age of 234 ± 10 Ma (whole rock K–Ar, Caminos et al., 1979).

1.2.4. Quaternary units

The older units are unconformably covered by Quaternary pyroclastic deposits consisting of juvenile vesiculated fragments, pumiceous pyroclastic flows and non-welded ash exhibiting columnar cooling joints. Unconsolidated glacial deposits appear in all valleys covering most geological contacts.

1.2.5. Structure

With the exception of the deformation of the metamorphic basement, no other ductile deformation was observed in the area.

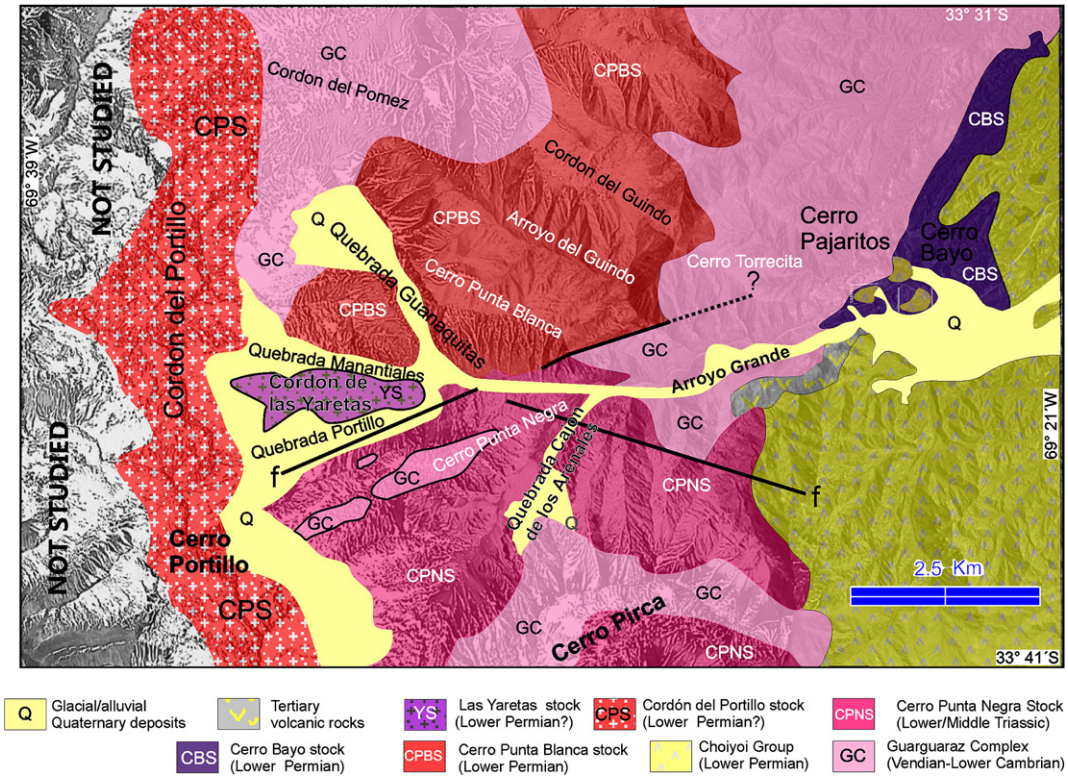

Fig. 2. Geological map of metamorphic rocks, granitic bodies and volcanic sequences on the eastern side of the Cordón del Portillo between Cerro Portillo and Cerro Pajaritos.

Granitic rocks display numerous joint sets and fractures, but only two faults affecting these bodies were recognized during fieldwork. On the left side of the Arroyo Grande, a 30 m wide fault zone strikes from Arroyo del Guindo to Quebrada Portillo. Another fault is located on the right side of this valley, cutting the north side of the Cerro Punta Negra and the metamorphic roof pendant along a N310° strike. Both faults seem to be the result of the Andean Orogeny.

2. Results

2.1. Petrography of the granitic rocks

2.1.1. Cerro Punta Blanca stock

The Cerro Punta Blanca stock consists of medium- to coarse-grained hypidiomorphic rocks including sub- to euhedral plagioclase laths (49–53%) 1–5 mm in length with albite twinning. Quartz (13–27%) is found in the form of either 1–4 mm interstitial patches that represent earlier periods of slow cooling or small rounded grains (~0.5 mm) that formed during a late stage of rapid crystallization.

Alkali feldspar (10–15%) occurs as an interstitial phase, with grains up to 2 mm long. It is often poikilitic, enclosing crystals of plagioclase, biotite, and amphibole. Limited exsolution suggests minor subsolidus fluid interaction.

The large (1–7 mm long) euhedral hornblendes (2.5–5%) are aligned in the groundmass, suggesting a soft magmatic foliation (Paterson et al., 1989). Alteration varies from slight to moderate, with replacement by biotite and chlorite.

Primary biotite (5–14%), 1–2 mm long, is sub- to euhedral, is altered to chlorite and prehnite (Fig. 3C). Accessory phases include euhedral apatite (~0.4%), small euhedral zircon grains, primary titanite and magnetite (~0.7%).

2.1.2. Cerro Bayo stock

Most of the outcrops consist of medium- to coarse-grained, hypidiomorphic white monzogranite to monzodiorite, although a porphyritic phase was occasionally observed near Cerro Pajarito.

The mineralogy consists of large gray plagioclase laths (40%), anhedral interstitial grains of quartz (~20%), gray alkali feldspar (~20%), biotite (10–15%) and amphibole (5–10%). Accessory minerals are euhedral apatite (0.9%), small grains of euhedral zircon, large (0.5 mm long) apatite, euhedral zoned allanite and subhedral primary titanite, ilmenite and magnetite (Fig. 3D).

Euhedral laths of plagioclase (An_{21-49}) have well developed twinning and oscillatory zoning, while alkali feldspar (2 mm) is interstitial, with minimal exsolution of microperthite. Quartz forms anhedral interstitial pools of rounded sub-grains. The first generation of biotite consists of small (0.25–1 mm long) sub- to anhedral grains, whereas the second one appears to be crystallized from late hydrothermal fluids. Amphibole occurs as two distinct generations: small (1–2 mm) subhedral primary grains of hornblende and a second generation of large actinolite clots.

2.1.3. Cerro Punta Negra stock

The Cerro Punta Negra stock comprises medium to coarse-grained (Fig. 3E) hypidiomorphic rock with plagioclase (11–31%), quartz (24–43%), alkali feldspar (30–43%) and biotite (0.2–4%). It grades from monzogranite to syenogranite. Accessory phases include infrequent euhedral apatite, small grains of euhedral zircon, allanite, anhedral fluorite and magnetite.

Sub- to euhedral laths (~2 mm long) of plagioclase with albite twinning and slight oscillatory zoning range in composition from An_3 to An_{13}. Most grains are rimmed by an outer mantle of unaltered albite, thought to be formed during late-stage crystallization. A similar feature was observed in the Cacheuta and Médanos stocks, located few kilometers north-eastwards, in southern Precordillera.

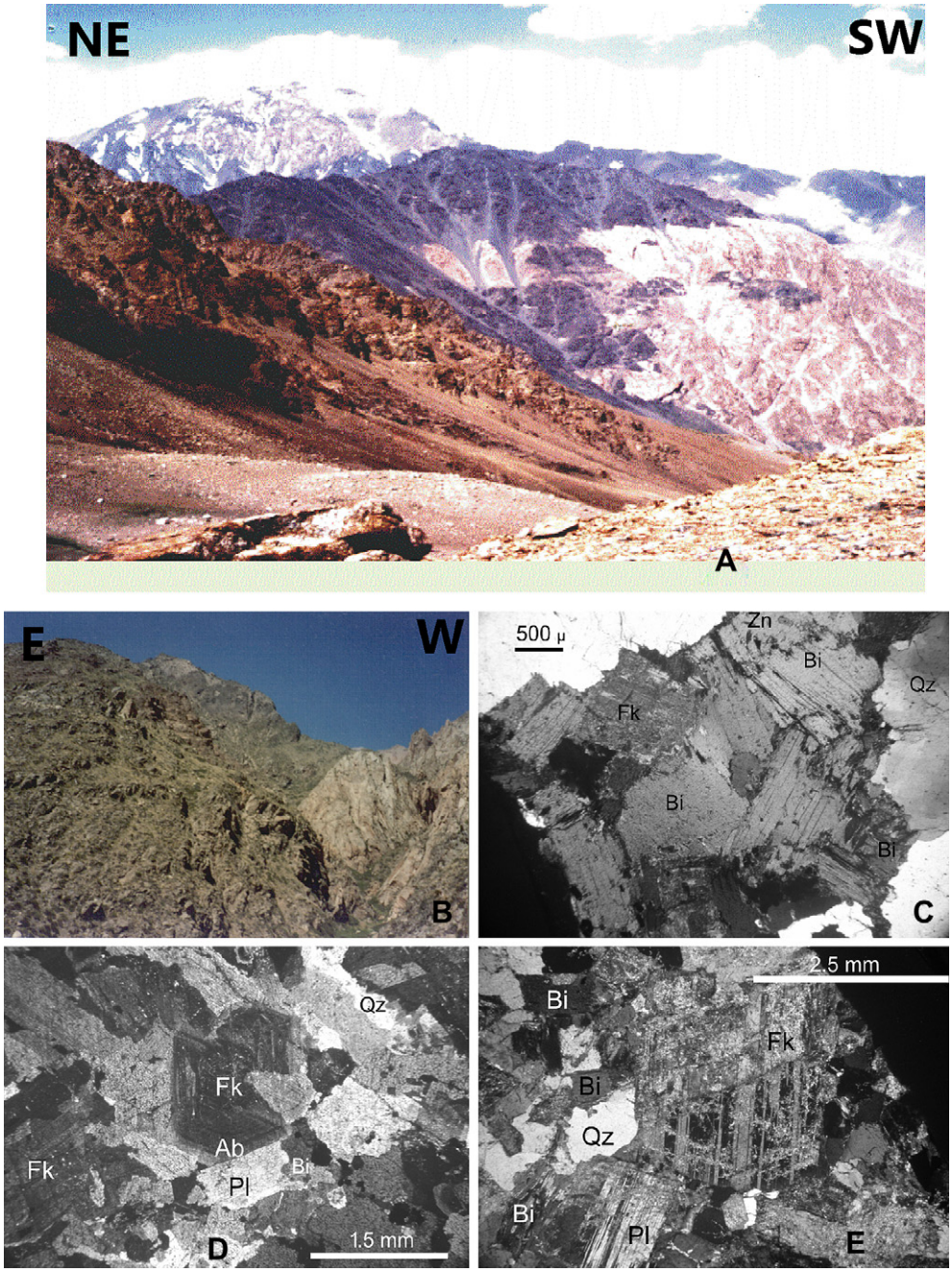

Fig. 3. A) The Cerro Punta Negra stock, its roof pendant and the included angular blocks of the metamorphic rocks, as viewed from the Arroyo Guanaquitas. In the background can be seen the Cerro Pirca, an apophysis of the Cerro Punta Negra stock. B) Rocks of the Cerro Punta Blanca stock (left) intruded by the Cerro Punta Negra stock (right) along the Arroyo Grande valley. C) Coarse-grained hypidiomorphic texture of the Cerro Punta Blanca stock composed of albite-twinned plagioclase, quartz, alkali feldspar, biotite, and amphibole. D) Medium- to coarse-grained, hypidiomorphic texture of the Cerro Bayo stock composed of plagioclase laths, anhedral interstitial grains of quartz, coarse alkali feldspar and biotite. E) Medium- to coarse-grained, hypidiomorphic texture of the Cerro Punta Negra stock formed of plagioclase, quartz, alkali feldspar and biotite. Grains of feldspar are rimmed by an outer mantle of unaltered albite, formed during late-stage crystallization.

Alkali feldspar forms large (up to 1 cm) interstitial rounded grains that show variable exsolution and cross-hatched twinning of microcline, which is typical of K-feldspar found in highly differentiated granites (Parsons, 1978).

Quartz occurs as large interstitial polycrystalline groups up to 8 mm in diameter, consisting of several sub-grains separated by consertal boundaries. It also forms discrete equant grains. Interstitial grains of biotite (2–3 mm) poikilitically enclose grains of K-feldspar and plagioclase, suggesting late-stage crystallization. Other mafic phases include rare amphibole (<1%), whereas accessory phases include zircons, scarce needle-like apatite, subhedral allanites, small grains of magnetite and anhedral patches of fluorite.

2.2. Geochemical characterization

Geochemical investigation has been carried out by analyzing 29 samples for major and trace elements of granitic rocks. The analyses were conducted using INAA and ICP-MS at ACTLABS (Canada). International geostandards were used for calibration.

Table 1
Chemical analyses of Cordon del Portillo stocks.

Sample	6197	6297	6397	6697	6797	6897	7597	522	522b	923	5997	6097	6497	6997
Stock	Cerro Punta Negra							Cerro Punta Blanca						
SiO[2]	75.81	76.18	73.54	74.10	74.20	74.21	73.83	62.64	63.22	67.29	62.00	68.48	63.58	65.01
TiO[2]	0.07	0.06	0.22	0.19	0.14	0.17	0.05	0.53	0.50	0.57	0.77	0.42	0.50	0.46
Al[2]O[3]	12.31	12.16	13.20	13.75	13.55	13.56	12.45	15.78	15.67	14.37	16.12	14.61	17.28	16.35
FeO	0.40	0.40	0.90	0.80	0.50	0.70	0.30	3.87	3.51	3.69	3.20	1.70	2.30	1.80
Fe[2]O[3]	0.78	0.70	1.00	0.90	0.96	0.81	0.87				2.04	1.20	1.78	1.94
MnO	0.05	0.04	0.05	0.04	0.03	0.06	0.04	0.10	0.10	0.13	0.09	0.06	0.10	0.07
MgO	0.00	0.00	0.20	0.02	0.15	0.07	0.09	1.37	1.19	1.23	1.89	1.02	1.31	1.18
CaO	0.46	0.44	0.77	0.73	0.73	0.82	0.47	5.12	4.85	3.76	4.79	2.39	4.81	4.50
Na[2]O	4.19	4.25	4.23	4.40	4.53	4.22	4.70	4.55	5.66	1.98	3.40	3.28	4.08	3.87
K[2]O	4.47	4.51	4.84	4.74	4.49	4.75	4.47	4.13	3.87	4.31	2.76	4.28	2.35	2.66
P[2]O[5]	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.29	0.28	0.16	0.03	0.02	0.03	0.02
LOI	0.42	0.35	0.43	0.46	0.49	0.44	0.51	1.12	0.61	1.97	1.49	1.16	0.73	0.63
Total	98.97	99.10	99.39	100.14	99.78	99.82	97.79	99.50	99.46	99.46	98.58	98.62	98.85	98.49
Rb	153	275	220	274	345	241	398	117	134	69	125	207	178	135
Sr	6	10	65	65	55	61	5	635	585	986	495	336	580	645
Y	52	87	68	61	49	47	99	15	13	12	22	22	13	13
Zr	43	112	260	235	195	119	187	125	101	256	185	105	123	115
U	5.37	5.25	5.56	5.60	7.73	4.78	4.99	2.08	2.14	1.31	2.28	11.07	2.33	4.28
Nb	17.52	23.98	21.85	21.00	18.56	14.12	41.25	12.23	12.53	9.70	12.00	13.47	14.56	10.00
Ba	45.80	53.58	280.00	258.00	270.00	458.00	99.40	894.00	926.00	686.00	689.00	516.00	987.25	994.58
Hf	5.14	5.78	11.00	6.71	10.21	9.54	8.02	5.02	4.38	6.62	6.21	4.58	4.10	3.74
Ta	3.01	2.87	2.74	2.40	3.74	2.56	3.54	1.20	1.34	0.84	1.09	3.27	1.81	2.20
Th	21.13	18.20	22.83	19.57	31.87	18.60	24.23	9.41	7.20	5.46	10.93	17.90	8.10	7.19
Cl								273.03	235.84	223.21				
S								69	74	416				
Co								11	10	11				
V								44	50	65				
Cu									6	241				
Zn								63	84	83				
Pb								16	19	50				
Ga								20	19	17				
La	19.93	23.60	61.70	41.10	42.00	35.67	20.77	18.14	18.71	41.39	31.60	23.93	30.87	20.33
Ce	55.43	66.80	134.00	97.33	106.67	91.13	58.67	48.15	46.60	83.50	79.13	56.10	61.53	45.57
Pr	7.21	8.21	13.10	10.41	10.77	9.22	7.83	4.97	4.34	8.88	8.41	5.07	6.27	3.91
Nd	30.77	33.15	56.68	41.17	47.53	42.23	37.88	19.95	18.80	31.30	37.60	24.18	27.68	25.92
Sm	11.24	11.06	10.53	8.00	9.57	6.87	10.87	5.79	4.39	7.23	6.81	5.05	3.72	4.20
Eu			0.48	0.79	0.76	0.37		1.55	1.42	2.30	1.47	0.83	1.07	1.19
Gd	10.56	8.99	9.48	6.77	5.22	5.63	12.66	3.30	3.45	4.55	8.12	3.89	4.07	4.32
Tb	2.06	1.57	1.90	1.20	1.33	1.69	2.49	0.53	0.48	0.53	0.86	1.24	0.60	0.66
Dy	8.57	7.57	6.49	7.28	7.89	6.78	18.23	2.53	2.71	2.61	4.43	5.21	3.56	1.68
Ho	2.28	2.29	1.96	2.07	2.11	1.35	3.37	0.52	0.43	0.60	0.89	1.01	0.56	0.40
Er	8.30	6.42	7.70	5.78	5.95	4.17	8.83	1.49	1.32	0.98	2.68	2.51	1.49	1.23
Tm	1.16	1.04	0.96	1.06	1.14	0.80	1.26	0.20	0.31	0.28	0.35	0.34	0.26	0.25
Yb	7.65	7.40	6.52	6.45	8.71	6.34	9.66	1.57	2.00	1.43	2.59	3.07	1.30	1.58
Lu	1.08	0.92	0.91	1.17	1.25	0.95	1.38	0.31	0.28	0.23	0.51	0.54	0.15	0.21

Sample	7097	7197	7297	7397	7897	325	425	625	725	5397	5497	5697	5797	422	522
Stock	Cerro Punta Blanca									Cerro Bayo					
SiO[2]	65.79	65.01	65.75	66.25	65.55	66.19	68.29	69.12	67.25	61.48	61.49	55.32	66.25	61.89	62.33
TiO[2]	0.43	0.47	0.43	0.47	0.58	0.61	0.52	0.54	0.60	0.72	0.72	1.07	0.38	0.42	0.45
Al[2]O[3]	16.62	17.29	16.23	15.35	15.83	14.61	14.79	13.81	13.12	18.13	17.59	18.62	16.10	17.61	17.23
FeO	1.30	1.50	1.50	2.14	2.00	3.88	3.31	3.39	3.87	2.81	3.00	4.90	2.10	2.98	2.45
Fe[2]O[3]	2.22	2.33	2.05	1.50	2.21					1.51	1.61	1.84	1.14	1.60	2.05
MnO	0.08	0.07	0.08	0.09	0.08	0.08	0.07	0.08	0.09	0.06	0.07	0.11	0.08	0.07	0.06
MgO	1.06	1.06	1.12	1.30	1.60	1.68	1.42	1.52	1.46	1.05	1.15	2.50	0.60	1.83	2.65
CaO	4.22	4.87	4.23	3.69	3.79	4.15	3.00	2.61	4.59	3.88	3.50	6.84	2.47	3.96	3.10
Na[2]O	3.89	3.80	3.86	3.12	3.89	3.70	4.37	3.92	4.74	4.19	3.91	3.36	5.89	3.78	4.25
K[2]O	2.82	2.60	2.90	4.02	4.51	4.44	4.65	4.75	4.17	3.85	3.96	2.00	3.27	3.46	3.01
P[2]O[5]	0.02	0.02	0.02	0.02	0.02	0.21	0.21	0.25	0.25	0.02	0.02	0.03	0.02	0.02	0.03
LOI	0.61	0.62	0.69	0.63	0.71	1.10	0.46	0.53	0.84	0.63	0.55	0.89	0.50	0.51	0.45
Total	99.06	99.64	98.86	98.58	100.77	100.65	101.09	100.52	100.98	98.33	97.57	97.48	98.80	98.13	98.06
Rb	124	99	125	171	110	100	143	103	108	123	131	130	165	119	120
Sr	624	627	540	447	441	413	378	353	436	480	455	479	480	399	472
Y	14	17	11	20	22	22	18	17	20	31	40	50	62	33	52
Zr	119	154	113	145	177	163	293	324	179	539	779	490	564	458	623
U	2.15	2.36	3.78	2.71	3.15	5.25	1.39	1.97	2.61	2.20	2.11	1.94	2.27	3.50	2.57
Nb	9.78	11.10	9.79	12.40	13.21	13.70	10.40	8.30	11.10	12.80	15.40	14.60	19.58	13.58	16.75
Ba	881.00	978.23	954.67	687.00	685.00	710.00	1009.00	979.00	770.00	3478.50	3125.40	1235.50	2745.26	1596.20	2580.23
Hf	2.87	5.31	4.23	4.21	6.24	6.48	6.27	7.69	4.86	18.00	22.10	8.00	8.97	7.45	11.10
Ta	1.34	2.15	3.54	1.99	1.91	1.52	0.66	0.44	1.04	1.89	2.10	1.34	2.89	1.59	2.40
Th	5.50	7.08	8.48	9.88	10.51	19.63	5.04	7.34	15.01	9.82	11.20	4.99	14.73	10.23	8.45
Cl						198.8	204.68	300.9	292.81						

Table 1 (*continued*)

Sample	7097	7197	7297	7397	7897	325	425	625	725	5397	5497	5697	5797	422	522
Stock	Cerro Punta Blanca									Cerro Bayo					
S						100	143	194	69						
Co						12	10	11	13						
V						72	52	57	69						
Cu						24	11	14							
Zn						67	124	258	67						
Pb						22	19	21	19						
Ga						18	19	18	17						
La	22.03	23.20	21.83	24.63	33.97	51.03	24.35	37.15	35.12	48.23	62.03	34.87	154.00	40.12	99.45
Ce	46.23	51.67	53.30	60.83	65.50	83.15	55.80	71.20	77.50	111.33	134.00	83.40	305.00	98.45	220.45
Pr	4.40	4.62	5.04	5.98	7.08	8.74	5.94	6.64	8.31	10.83	14.20	9.39	31.47	23.25	18.40
Nd	20.77	24.20	21.37	28.03	28.95	29.55	21.60	24.25	28.75	60.20	59.63	38.08	113.83	48.50	83.12
Sm	3.49	4.56	4.14	4.60	5.46	5.75	4.57	4.89	5.73	9.08	11.77	7.65	15.65	12.45	8.45
Eu	1.14	1.62	1.23	0.92	1.09	2.11	1.78	1.63	1.97	3.08	3.48	2.60	2.52	2.78	2.89
Gd	3.79	4.24	3.91	3.98	3.63	4.43	3.16	4.36	4.55	7.96	9.98	7.28	11.73	8.24	10.25
Tb	0.57	0.53	0.63	0.81	0.56	0.74	0.60	0.51	0.60	1.57	1.79	0.92	1.14	0.99	1.23
Dy	2.56	2.83	3.49	2.04	4.19	3.57	3.49	3.29	3.36	6.33	6.99	3.47	6.05	4.28	5.33
Ho	0.48	0.50	0.69	0.62	0.68	0.71	0.79	0.65	0.71	1.31	1.57	0.92	1.17	1.02	1.28
Er	0.78	1.67	1.93	1.81	2.41	2.29	2.06	1.85	2.34	3.61	4.85	3.24	4.23	3.50	4.53
Tm	0.17	0.39	0.26	0.31	0.36	0.26	0.37	0.38	0.37	0.61	0.90	0.38	0.69	0.48	0.72
Yb	1.30	1.35	2.10	1.40	3.15	2.37	1.85	2.10	2.40	4.28	5.24	3.30	4.48	4.10	3.80
Lu	0.29	0.25	0.36	0.31	0.50	0.53	0.27	0.29	0.37	0.61	0.76	0.35	0.48	0.51	0.68

Analyst: ACTLABS·

2.2.1. Classification of granitoids

Major, trace and rare earth element data for representative samples of granitoids are listed in Table 1. The normative ANOR vs. Q'F′ diagram (Fig. 4A) of Streckeisen and Le Maitre (1979) was used for nomenclature. In this diagram the Cerro Punta Blanca stock is characterized by a wide range of composition, with most samples classifying as diorite, monzodiorite, quartz monzonite, quartz syenite, syenogranite and quartz alkali feldspar syenite (Fig. 4A). A quartz monzonite, monzogranite and granodiorite composition is displayed in the QAP triangle (Fig. 4B). The Cerro Bayo stock is characterized by a quartz diorite composition in Fig. 4A, although in the normative QAP triangle (Fig. 4B) the stock plots in the quartz monzodiorite and granodiorite fields. The Cerro Punta Negra stock plots as monzodiorite in Fig. 4A, and as monzodiorite and quartz monzodiorite.in the QAP diagram of Fig. 4B.

The Ab–An–Or diagram (Barker, 1979) shows that the Cerro Punta Blanca stock ranges between the granite and granodiorite fields, whereas the Cerro Bayo stock samples plot in the tonalite field. Rocks of the Cerro Punta Negra stock correspond to granites and granodiorites (Fig. 4C).

All stocks are subalkaline (Irvine and Baragar, 1971) and belong to the high-K calc-alkaline series (Fig. 4D) of Pecerillo and Taylor (1976).

In terms of the A/CNK ratio (Fig. 4E) (Shand, 1927), the Cerro Bayo stock is metaluminous to weakly peraluminous, whereas both the Cerro Punta Blanca and Cerro Punta Negra stocks are metaluminous.

2.2.2. Geochemical features

2.2.2.1. Cerro Punta Blanca stock. Harker diagrams (not shown) for the major elements show decreasing trends for TiO_2, Al_2O_3, Fe_2O_3, FeO, MgO and CaO content with increasing SiO_2 (range: 62–69.12 wt %). K_2O has a positive trend, whereas Na_2O shows considerable scatter probably related to fractionation of plagioclase crystals.

Cerro Punta Blanca stock rocks have slight negative trends of Sr and Ba with increasing SiO_2, while Hf, U, Th and Zr show no specific trend of either enrichment or depletion with silica increase. There is a decline in Sr with decreasing CaO caused by minor fractionation of plagioclase, whereas the bivariate logarithmic Ba–Sr diagram shows moderate fractionation of both plagioclase and alkali feldspar (Fig. 4F).

The spider diagram normalized to primordial mantle values (Sun and McDonough, 1989) indicate that LILEs are enriched relative to HFSEs, with the Rb concentration being higher than Ba. The Nb, P and Ti show negative anomalies, while U and Th are slightly enriched (Fig. 5A).

The chondrite normalized REE diagram (Sun and McDonough, 1989) for the Cerro Punta Blanca stock is shown in Fig. 5B. Total REEs increase slightly with increasing SiO_2.

Overall, REE profiles for the Punta Blanca stock show a trend of moderate LREE enrichment and constant HREE values ($La_N/Yb_N = \sim 10$). The level of HREE enrichment with respect to chondrite suggests that phases such as garnet and hornblende were not present in the source of this stock.

2.2.2.2. Cerro Bayo stock. The Cerro Bayo stock has trends of decreasing TiO_2, Al_2O_3, Fe_2O_3, FeO, MgO and CaO with increasing SiO_2 (range: 55.32–66.25 wt%). Na_2O has a steep positive trend, suggesting either Na enrichment in the most evolved samples (porphyry) or albitization (Table 1). A not well-defined trend with increasing SiO_2 was observed for K_2O. It could be possible that alteration of the most evolved samples masked any positive trend.

Harker diagrams (not shown) for trace elements show small positive trend of increasing Th with increasing SiO_2, whereas Sr and U remain constant across the entire range of silica values. The decrease in Sr with decreasing CaO is probably caused by fractionation of plagioclase. Rb is constant with evolution to higher silica contents. The bivariate logarithmic Ba–Sr diagram shows restricted fractionation of both plagioclase and alkali feldspar (Fig. 4F).

Fig. 5C is a spider diagram normalized to primordial mantle values (Sun and McDonough, 1989). LILEs are enriched in comparison with HFSEs, reaching Ba concentrations of 3527 ppm. A significant negative Nb anomaly is apparent ($Nb_N \sim 20$), with an average Nb^*/Nb_N relationship of 5.

HFSE are fairly enriched ($\sim$70–100 times) relative to primitive mantle. Th behaves incompatibly with increasing SiO_2 and is therefore probably incorporated into the allanite present in the more evolved members. Ti decreases with increasing silica, suggesting fractionation of titanite. P is constant, but at low values of $\sim 1 \times$ primitive mantle; indicating that some apatite remained in the source after melting.

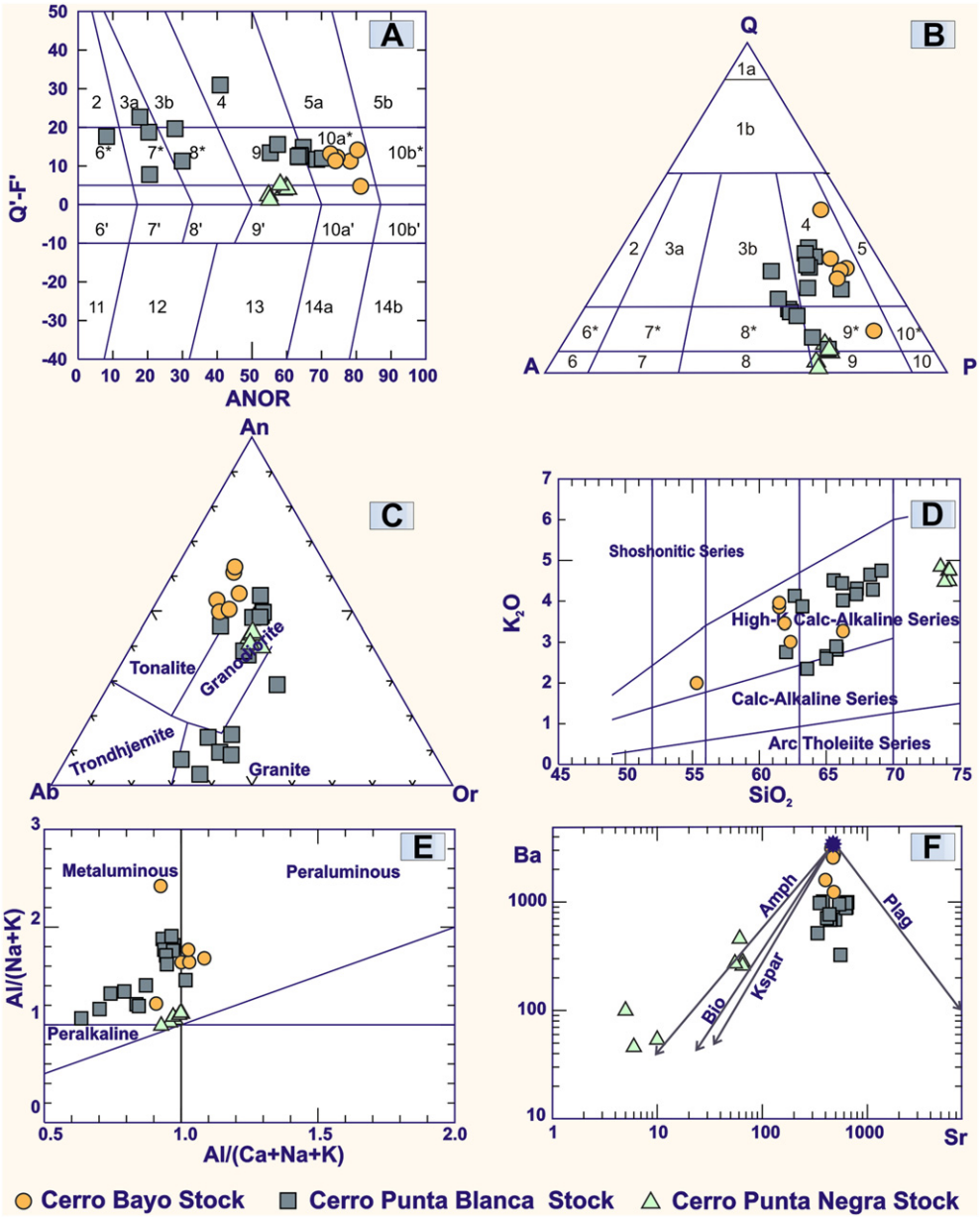

Fig. 4. A) Normative ANOR vs. Q′F′ diagram of Streckeisen and Le Maitre (1979). Samples of the Cerro Punta Blanca (■) and Cerro Bayo stocks (●) display a wide dispersion from diorite to alkali feldspar granite, whereas those of the Cerro Punta Negra stock (Δ) are grouped in the monzodiorite field. B) QAP diagram indicating the composition of the stocks. C) Ab–An–Or diagram showing the typical compositions identified during field investigation. D) Pecerillo and Taylor (1976) diagram displaying a high-K calc alkaline trend typical of continental magmatic arcs. Note again the extreme differentiation of Cerro Punta Negra stock (Δ) samples. E) A/CNK vs. A/NK diagram indicating that most samples are metaluminous, in concordance with their I-type mineralogy. The Cerro Punta Negra stock (Δ) samples plot away from the trend of the Cerro Punta Blanca-Cerro Bayo stocks. F) Ba vs. Sr diagram showing restricted fractionation of plagioclase and alkali feldspar in the Cerro Punta Blanca (■) and Cerro Bayo (●) stocks, and extensive fractionation of hornblende and biotite in the Cerro Punta Negra stock (Δ).

Fig. 5D shows REE diagram normalized to chondrite in which an increase in total REE concentration with increasing SiO_2 is evident due to incompatibility in the melt and concentration in the most evolved units.

Only the most evolved porphyritic facies has a negative Eu anomaly, consistent with fractionation of plagioclase. The MREEs to HREEs show no specific trend of enrichment/depletion with silica increase, suggesting that hornblende and zircon were not fractionating phases. The level of HREE enrichment ($La_N/Yb_N = \sim 14$) with respect to chondrite suggests that phases such as garnet and hornblende were not present in the source of this stock.

2.2.2.3. Cerro Punta Negra stock. Harker diagrams (not shown) for the major elements reveal a restricted range of SiO_2 (73.54–76.18 wt%), accompanied by steep negative trends with increasing SiO_2 for TiO_2, Al_2O_3, FeO and Fe_2O_3. Data points for MgO, CaO, Na_2O and K_2O are too clustered for any trends to be discerned.

Harker diagrams for trace elements (not shown) indicate that Th, U and Hf are nearly constant and Ba, Zr, and Sr strongly decrease with increasing SiO_2.

Decreasing Sr with decreasing CaO, and decreasing Sr with Ba imply fractionation of both hornblende and biotite (Fig. 4F).

The spider diagram shown in Fig. 5E displays more negative Ba, Sr, P and Ti anomalies when compared with the Cerro Bayo and

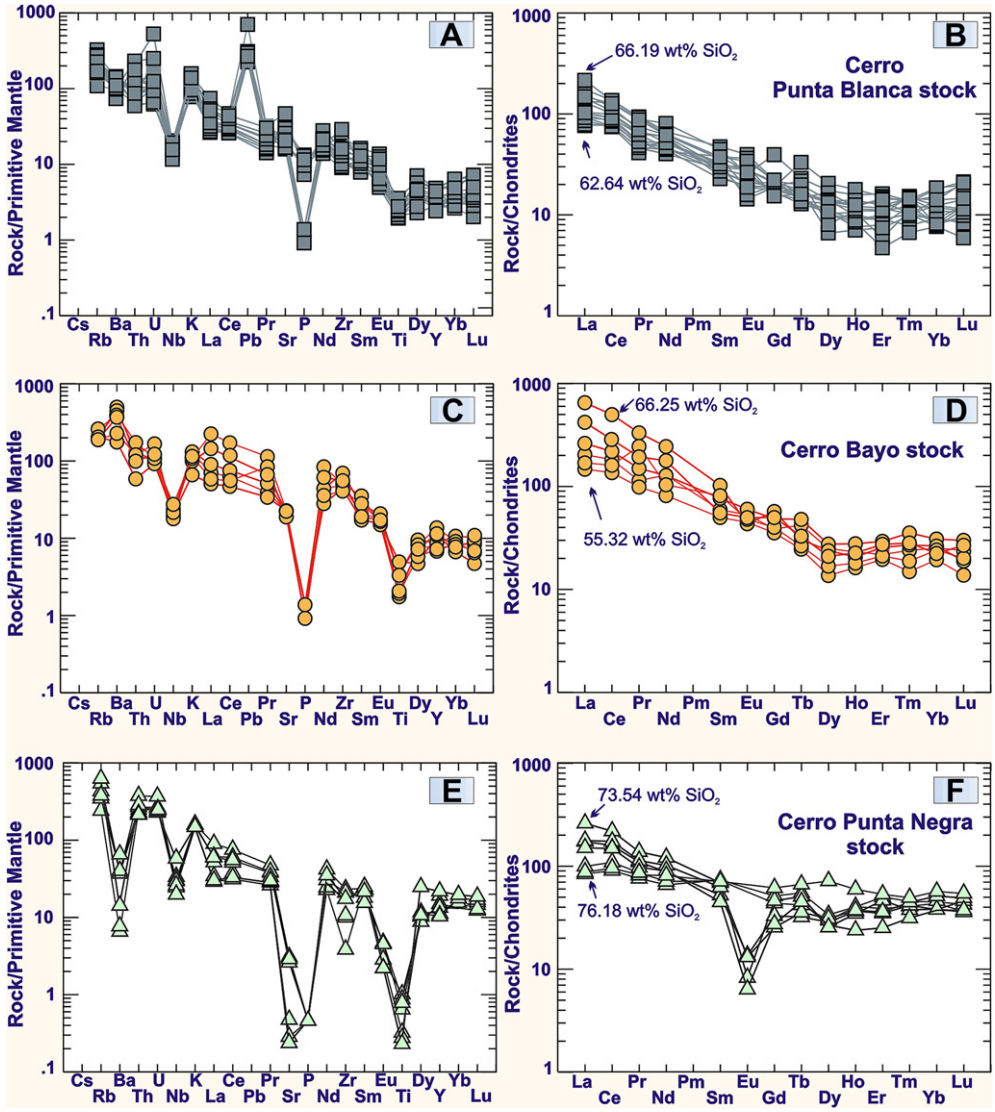

Fig. 5. A) Normalized to primordial mantle (Sun and McDonough, 1989) diagram of the Cerro Punta Blanca stock (■), in which a significant negative Nb anomaly can be identified. B) Chondrite normalized REE diagram (Sun and McDonough, 1989) of the Cerro Punta Blanca stock (■) samples, showing small positive Eu anomalies indicative of plagioclase abundance. Flat HREE illustrate that garnet was not involved during melting of the Cerro Punta Blanca stock parental magma. C) Diagram as A) for the Cerro Bayo stock (■), in which a less negative Nb anomaly can be recognized. D) Diagram as B) for the Cerro Bayo stock (●). No Eu anomalies can be identified, although the La/Lu ratio is similar to that of Cerro Punta Blanca samples. Again, there is no indication of garnet and hornblende in the parental rocks. E) Normalized to primordial mantle diagram of the Cerro Punta Negra stock (Δ), presenting strongly negative anomalies of Ba, Sr and Ti. The Nb anomaly is also smaller than in the other stocks. F) Chondrite normalized REE diagram of the Cerro Punta Negra stock (Δ) displaying a nearly flat La/Lu ratio, with a significant negative Eu anomaly.

the Cerro Punta Blanca stocks. The negative Nb anomaly is also significant, but lies in the range of the previously described stocks. According to Pearce (1983) negative Nb anomalies are indicative of the strong participation of a continental crust component. Nb and Zr concentrations are in the range of subduction-related magmatism.

Fig. 5F shows the chondrite normalized REE diagram for the Cerro Punta Negra stock. Samples with the highest SiO_2 values have minor quantities of total REEs. The REE profiles display a trend of slight LREE enrichment and constant level of HREEs, with $La_N/Yb_N = 3$. The depletion of LREEs, especially La, Ce and Nd, with evolution suggests fractionation of allanite, which is present in these rocks. Concentrations of Eu in the most evolved samples show a trend of depletion with evolution consistent with plagioclase fractionation. The level of HREE enrichment with respect to chondrite suggests that phases such as garnet and hornblende were not present in the source of this stock. HREE values do not show any trends consistent with the fractionation of any particular phase.

2.3. Tectonic discrimination

The Rb vs. Y + Nb tectonic diagram (Pearce et al., 1984) enables discrimination between arc, within-plate, collisional and orogenic granites. As displayed in Fig. 6A, the Cerro Bayo stock plots between volcanic arc and within-plate granites. In this diagram the Cerro Punta Blanca stock plots in the volcanic arc granites field, while the Cerro Punta Negra stock samples fall completely in the within-plate granites field. The Hf–Rb/30–Ta*3 discrimination diagram (Harris et al., 1986) shows that rocks of the Cerro Bayo stock plot in the volcanic arc and late – post-collisional fields, whereas the Cerro Punta Blanca and Cerro Punta Negra stocks plot mostly in the volcanic arc and late- to post-collisional field (Fig. 6B). In the Y–Nb–Ce diagram (after Eby, 1992), most samples plot in the A2

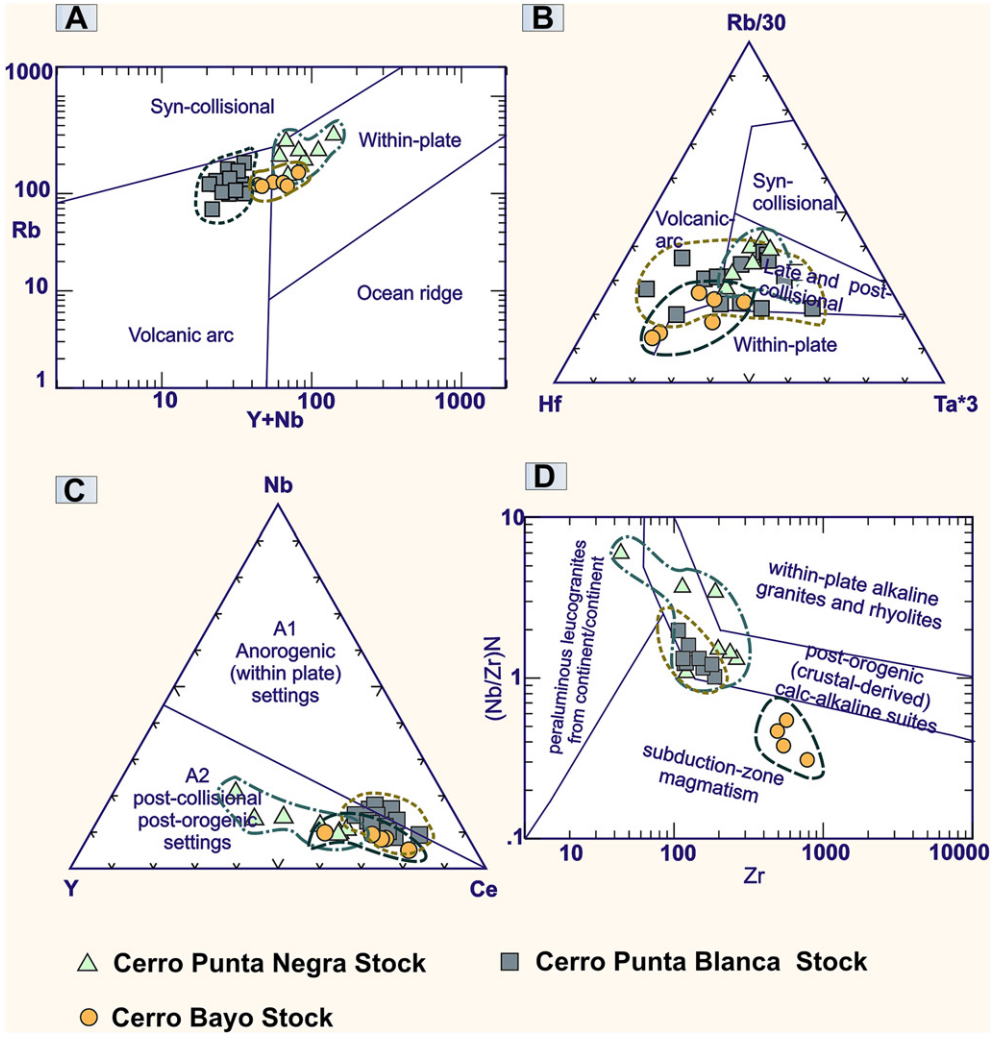

Fig. 6. A) Y + Nb vs. Rb diagram (Pearce et al., 1984) showing evolution from volcanic arc granite to within-plate granite. B) Rb/30–Hf–Ta*3 diagrams (Harris et al., 1986) showing that most samples plot in the volcanic arc and late/post collisional fields. C) Y–Nb–Ce diagram (Eby, 1992) in which most samples plot in the volcanic arc and post-orogenic tectonic setting. D) Zr vs. (Nb/Zr)N diagram of Thiéblemont and Tegyey (1994). Cerro Bayo stock samples (●) plot in the subduction-zone magmatic rocks field, whereas those of the Cerro Punta Blanca (■) and Cerro Punta Negra (Δ) stocks plot in the field of post-orogenic rocks.

field, corresponding to a post-orogenic tectonic setting (Fig. 6C), with a few samples plotting in the within plate field.

In the Zr vs. $(Nb/Zr)_N$ diagram (Thiéblemont and Tegyey, 1994), samples of the Cerro Bayo stock plot in the field of subduction-zone magmatic rocks, while the Cerro Punta Blanca and Cerro Punta Negra stocks plot in the field of post-orogenic zone rocks (Fig. 6D).

3. Discussion

As above indicated, the Gondwana volcanic and plutonic activity in the Cordillera Frontal de Argentina and Chile was considered as the result of a 20–25 Ma period of tectonic activity associated with anatexis of the crust.

Early studies by Mpodozis and Kay (1992), and Poma and Ramos (1994) have demonstrated that the early stages of this magmatism were subduction-related.

Indeed, it has argued that the basaltic–andesitic facies of the Choiyoi Group at the Cordillera Frontal of Mendoza was part of a subduction-related volcanic arc (Llambías et al., 1993; Sato and Llambías, 1993; Japas and Kleiman, 2004; Strazzere and Gregori, 2007; Strazzere et al., 2006; Kleiman and Japas, 2009 among others). In the Cordillera Frontal of Chile, Mpodozis and Kay (1992) assigned the first stage of plutonism – the Guanta and Cochiguás plutons (Late Carboniferous–Permian, 308–251 Ma, K/Ar and Rb/Sr ages) to a continental calc-alkaline I-type magmatism related to an oblique subduction. This event preceded a Late Permian (260–242 Ma) uplift-collision event in the Elqui Cordillera of Chile.

In the Cordón de Colangüil, located in the Province of San Juan, the Tabaquito Granodiorite (326–329 ± 1 Ma, Llambías and Sato, 1995) was also related to a magmatic arc due to subduction.

In the Cordón del Portillo area, the Cerro Punta Blanca stock was assigned to the Carboniferous magmatic event by Caminos et al. (1979), mainly due to its older age (337 ± 15 Ma K/Ar, 348 ± 35 Ma Rb/Sr). However more recent zircon dating (276.29 ± 0.79 Ma) by Orme and Atherton (1999) suggests that the existence of a Carboniferous magmatic event can be discarded. Therefore, the age of the San Rafael Orogenic phase at the Cordón del Portillo should be older than 276 Ma, if the studied stocks are considered as post-orogenic, as no evidence of synorogenic deformation is observed in these plutons.

The first volcanic event of the Choiyoi Group, marked by the basaltic–andesitic facies, was dated at 277 ± 3.0 Ma (U/Pb conventional zircon) by Strazzere and Gregori (2011), in coincidence with the age of the Cerro Punta Blanca stock. This volcanic

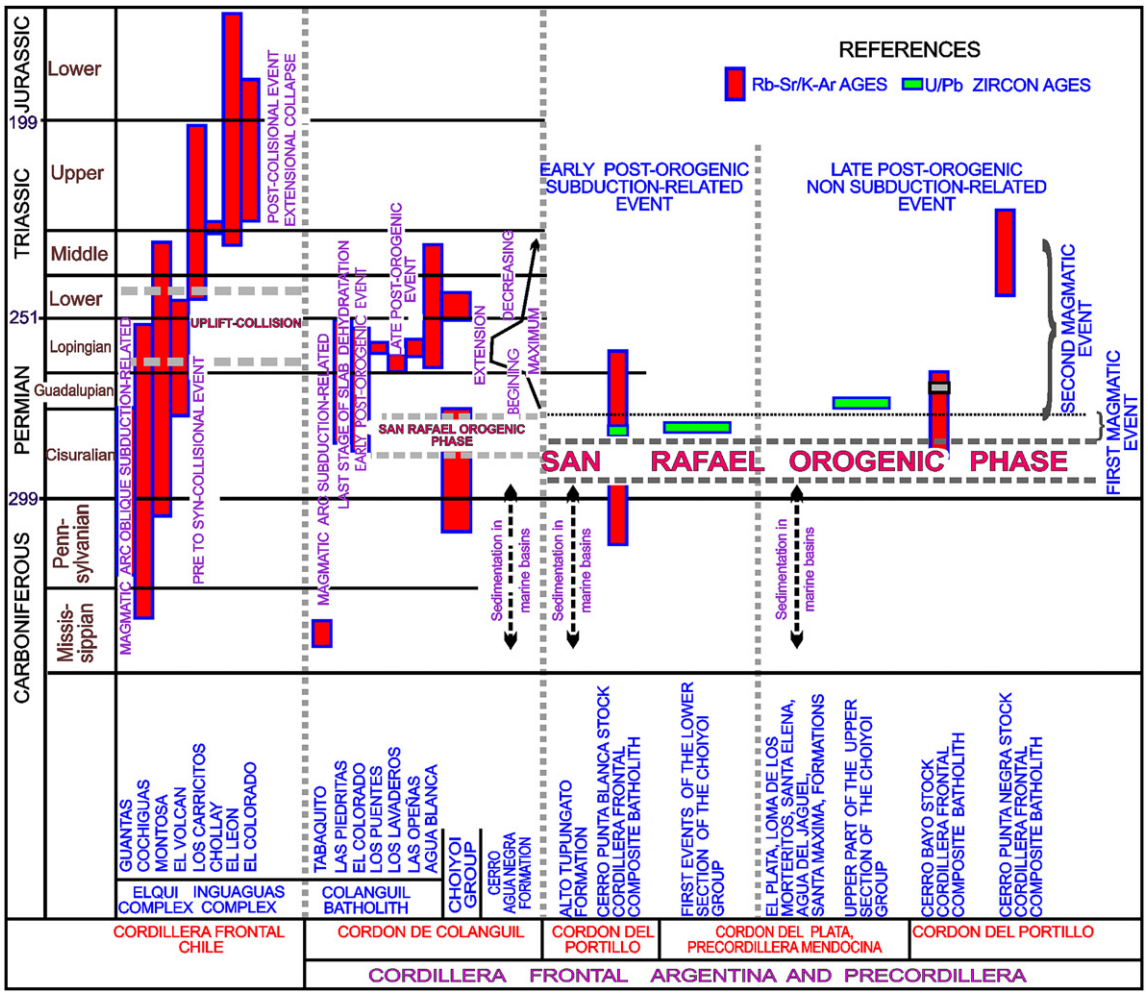

Fig. 7. Geochronological chart of magmatism, basin development and diastrophic events in the Cordillera Frontal of Chile and Argentina and Mendoza Precordillera. K/Ar and Rb/Sr ages are shown in black, with zircon dating in gray. Estimated errors are also represented. Left-hand column shows radiometric ages of the Elqui and Inguaguás Complexes in the Cordillera Frontal of Chile. Data are from Nasi et al. (1985), Ribba et al. (1988), Brook et al. (1986), Mpodozis and Cornejo (1988), and Mpodozis and Kay (1992). The tectonic settings of the granites are also indicated. The Cordón de Colangüil (Cordillera Frontal of San Juan province) data (Rb/Sr) were obtained from Sato and Llambías (1993) and Llambías and Sato (1995). The ages of the Choiyoi Group, San Rafael diastrophic phase and the end of sedimentation in the marine basin (Cerro Agua Negra formation) are displayed. An estimate of the amount of extension occurring during magmatism (Llambías and Sato, 1995) is schematically represented. Old K/Ar and Rb/Sr ages from Cordón del Portillo (Cordillera Frontal de Argentina) were taken from Caminos et al. (1979) and new U/Pb zircon ages from Orme and Atherton (1999). Age of the marine sedimentation is based on fossil remains (Pagani and Sabattini, 2002; Taboada, 2001). Age determination (U/Pb, ICP MS LA) of the Choiyoi Group in the Precordillera area is taken from Strazzere and Gregori (2011). The age of the San Rafael diastrophic phase is also indicated. Data from Cordón del Plata are from Caminos (1965) and Polanski (1972).

event, that show no evidence of compressional deformation, lies on angular unconformity over the marine sequences assigned to the Carboniferous that contain fossil remains of *Lissochonetes* sp., *Cancrinella* sp., *Neospirifer* sp., *Spirifer* sp., and *Orbiculoidea* sp. (Aparicio, 1966). The age was considered as Late Carboniferous–Early Permian. According to Pagani and Sabattini (2002), sedimentation extended until the Sakmarian–Kungurian ages (~295–270 Ma) or according to Taboada (2001) until the Asselian–Sakmarian (~299–284 Ma). Therefore the age of the San Rafael Orogenic phase must be restricted to the Artinskian with a time span of 7 Ma (~284–277 Ma) for the Cordón del Portillo area of the Cordillera Frontal of Argentina. The time span of the San Rafael Orogenic phase in the Cordón de Colangüil was considered to be around 10 Ma, lasting from 280 to 272 Ma as indicated by Llambías and Sato (1995).

Although the ages are nearly coincident and its duration is similar, a diachronic development of the San Rafael Orogenic phase along western Argentina must be not discarded. For different interpretations about the San Rafael Orogenic phase in the San Rafael and Chadí Leuvú blocks and Sierra de la Ventana refer to Kleiman and Japas (2009), Llambías et al. (2003) and Tomezzoli and Vilas (1999) respectively.

The Cerro Punta Blanca stock could represent an early post-orogenic magmatic event, if compared with the magmatic evolution of the Colangüil Batholith. There, the Las Piedritas and Los Puentes stocks were assigned to a post-orogenic event by Llambías and Sato (1995). The geochemistry of Cerro Punta Blanca stock is comparable with those of the Las Piedritas and Los Puentes stocks and therefore, as above indicated a subduction-related magmatism.

The Cerro Bayo stock geochemistry shows an attenuation of subduction components, indicative of a transition to a non subduction-related magmatism. The characteristics of subduction-related magmatism are almost lost in the Cerro Punta Negra stock, and its geochemistry is more similar to an A-type granite.

Both stocks are related to extensional tectonic conditions due to their transitional and alkaline compositions, which are comparable to the acidic section of the Choiyoi Group and the late stage in the Colangüil Batholith (Figs. 5 and 7).

In the Colangüil Batholith, the Los Lavaderos, Las Opeñas and Agua Blanca stocks represent the maximum expansion during

extensional conditions in the Late Permian–Early Triassic times (Sato and Llambías, 1993).

The age of 234 ± 10 Ma of the Cerro Punta Negra stock seems to be too young when compared with the age of Cerro Bayo (262 Ma) and the upper part of Choiyoi Group, but this is due to the radiometric method used (K–Ar whole rock, Caminos et al., 1979).

Sediments in the Triassic Cacheuta basin, located 50 km east of Cordón del Portillo contain blocks of the Permian granitic intrusions. Therefore, the age of the Cerro Punta Negra stock must be early that the sedimentation of the Triassic rift, and may be comparable with the upper part of Choiyoi Group and the Cerro Bayo stock. Indeed their geochemical features are analogous.

The last magmatic event recorded in the Choiyoi Group in the Uspallata area, represented by the acidic volcanic and subvolcanic facies, was dated at 273 ± 1.3 Ma (U/Pb, conventional zircon) by Strazzere and Gregori (2011), constraining the unit to a period of 8.3 Ma. This magmatic association was generated in an intraplate environment, which also is represented by the Cerro Punta Negra stock, and partially by the Cerro Bayo stock.

The climax of the extension, associated with rifting structures, appears to be of Early Triassic age (Rolleri and Fernandez Garrasio, 1979; Kokogian et al., 1993; Giambiagi and Martinez, 2008) with the development of the continental Cacheuta basin. Tuffaceous material interbedded in the upper part of the Río Mendoza Formation was dated at 243 ± 3 Ma (U/Pb, zircon, Ávila et al., 2006).

4. Conclusion

The Cerro Punta Blanca, Cerro Bayo and Cerro Punta Negra stocks, located in the Cordón del Portillo, are a part of the Cordillera Frontal Composite Batholith, records part of the evolution of Gondwana magmatism of central western Argentina.

In this area, the San Rafael Orogenic phase start approximately at 284 Ma, which is the age suggested for the end of the Carboniferous marine sedimentation.

This orogenic phase must have ceased before 276 Ma, because the Cerro Punta Blanca stock and other granitic intrusives of this area show no evidences of coetaneous deformation during their intrusion. Therefore they are considered as post-orogenic intrusives.

In the Cordón del Portillo area two stage of Gondwana magmatic activity were recognized. The first was recorded by the Cerro Punta Blanca stock (276 Ma) which represents a subduction-related magmatism. Similar genetic considerations can be done for the basic-intermediate section of the Choiyoi Group, which indicate an age of 277 ± 3.0 Ma.

The second event was recorded by the Cerro Bayo (262 Ma) and Cerro Punta Negra stocks which are the result of a transition between subduction-related and intra-plate magmatism. This event is equivalent with the development of the acidic facies of the upper section of the Choiyoi Group.

Extensional conditions therefore prevailed on the Cordillera Frontal during the Carboniferous, with compressional conditions between ~284 and 277 Ma. Early post-orogenic intrusive activity related to subduction developed between 277 and 273 Ma. The Late post-orogenic intrusive activity non-related to subduction developed between 273 and 262 Ma. This extensional condition seems to be continued until the Triassic when the Cacheuta basin developed.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jsames.2012.07.010.

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