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The basement of the Deseado Massif at Bahía Laura, Patagonia, Argentina: a proposal for its evolution

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Abstract

The Río Deseado Complex, the basement of the eastern Deseado Massif geological province of Argentina, is composed of five dispersed, small outcrops of upper Proterozoic–lower Paleozoic metamorphic and igneous rocks. We propose a possible evolution for these rocks on the basis of a detailed study of the easternmost outcrop (Bahía Laura). The Bahía Laura metamorphic rocks are metasedimentary and igneous-derived rocks formed prior to the Pampean metamorphic event. Metasedimentary schists, garnet-rich and micaceous gneisses, and the migmatite's paleosome are interpreted as marine sediments (pelites, sandstones, and limestones). The igneous-derived rocks are metaluminous and peraluminous granodiorites (hornblendic and granodioritic gneisses) and tholeiitic basalts (amphibolites) that were produced in a magmatic arc and a primitive island arc, respectively. These rocks underwent regional metamorphism during the Pampean cycle (Neoproterozoic–Paleozoic boundary), then a plutonic intrusion (Bahía Laura peraluminous monzogranite) and several granitoid injections,both of which are correlated with the Famatinian (Ordovician–Silurian) magmatic arc proposed for this region. Finally, all rocks were slightly deformed by a post-Famatinian tectonic event that may have produced the basement exhumation. According to the proposed evolution of the Río Deseado Complex in Bahía Laura, the basement of the Deseado Massif could be part of a Late Proterozoic-Mid Paleozoic orogenic belt.

Keywords: Bahía Laura; Basement; Deseado massif; Río Deseado Complex

Résumé

El Complejo Río Deseado es el basamento del sector oriental de la provincia geológica Argentina Macizo del Deseado, el mismo está compuesto de cinco pequeños y dispersos afloramientos de rocas metamórficas e ígneas de edad Proterozoico superior a Paleozoico inferior. El afloramiento más oriental (Bahía Laura) se estudió en detalle, proponiendo una evolución para estas rocas. Las rocas metamórficas de Bahía Laura son metasedimentitas y rocas ortoderivadas formadas previo al evento metamórfico Pampeano. Las metasedimentitas (esquistos, gneises granatíferos y micáceos y el paleosoma de las migmatitas) son interpretados como sedimentos marinos: pelitas, areniscas y calizas, y las rocas ortoderivadas como granodioritas metaluminosas y peraluminosas (gneises hornbléndicos y granodioríticos) y basaltos toleíticos (anfibolitas) producidos en un arco magmático y un arco de islas inmaduro, respectivamente. Estas rocas ha sufrido un metamorfismo regional durante el Ciclo Pampeano (límite Neoproterozoico–Paleozoico) y posteriormente una intrusión plutónica (monzogranito peraluminoso Bahía Laura) y varias inyecciones de granitoides correlacionadas con el arco magmático Famatiniano (Ordovícico a Silúrico) propuesto para esta región. Finalmente, todas esas rocas fueron deformadas y metamorfizadas por un evento tectónico post-Famatiniano que habría producido la exhumación del basamento. Teniendo en cuenta la evolución propuesta para el Complejo Río Deseado en el afloramiento Bahía Laura, el basamento del Macizo del Deseado podría ser parte de un cinturón orogénico del Proterozoico Superior-Paleozoico Medio.

1. Introduction

The Río Deseado Complex (Viera and Pezzuchi, 1976) is the basement of the eastern Deseado Massif geological province. It is composed of scarce, dispersed, small outcrops

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of metamorphic (phyllites, quartzites, schists, amphibolites, gneisses, and migmatites) and igneous rocks as granitoid intrusions, as well as one small stock with an assumed upper Proterozoic-lower Paleozoic age (De Giusto et al., 1980). There are five outcrops of rocks in the eastern Deseado Massif (Fig. 1): Tres Hermanas (Chebli and Ferello, 1975), Dos Hermanos (Viera and Pezzuchi, 1976), Bajo la Leona (Márquez and Panza, 1986; Panza et al., 1995), El Laurel-El Sacrificio (Giacosa et al., 1990), and Bahía Laura (Guido et al., 2000). The most important characteristics of the Río Deseado Complex rocks are summarized in Table 1.

In this article, we provide a detailed petrographic and geochemical characterization of the Bahía Laura outcrop, analyze the rocks, and compare them with other remnants of the Deseado Massif's basement to propose their preliminary evolution.

2. Geologic setting

The Deseado Massif is a 60,000 km^2 geological region located in the north of the Santa Cruz province (Fig. 1) in southern Argentinean Patagonia. The oldest rocks belong to the Río Deseado Complex and, probably, the La Modesta Formation (Di Persia, 1962; De Giusto et al., 1980). These are poorly studied, low-grade metamorphic rocks (mica and quartz-mica schists, phyllites, and metaquartzites with variable degrees of quartz injection; Giacosa et al., 2002) located in the central western Deseado Massif.

Overlying these basement rocks is a Permian–Triassic Gondwanic sedimentary sequence (La Golondrina, La Juanita, and El Tranquilo Formations), lower Jurassic plutonic rocks (La Leona Formation), and extended middle–upper Jurassic volcanic and volcano-sedimentary rocks (Roca Blanca, Cerro León, and Bajo Pobre Formations and Bahía Laura Group). More recently, upper Jurassic–Cretaceous continental pyroclastic and sedimentary rocks (Bajo Grande and Baqueró Formations) were deposited in small extensional basins. The Tertiary is mainly represented by marine (Monte León and San Julián Formations) and continental sedimentary rocks (Santa Cruz Formation); the Tertiary and Quaternary are also characterized by several basaltic flows and gravel deposits

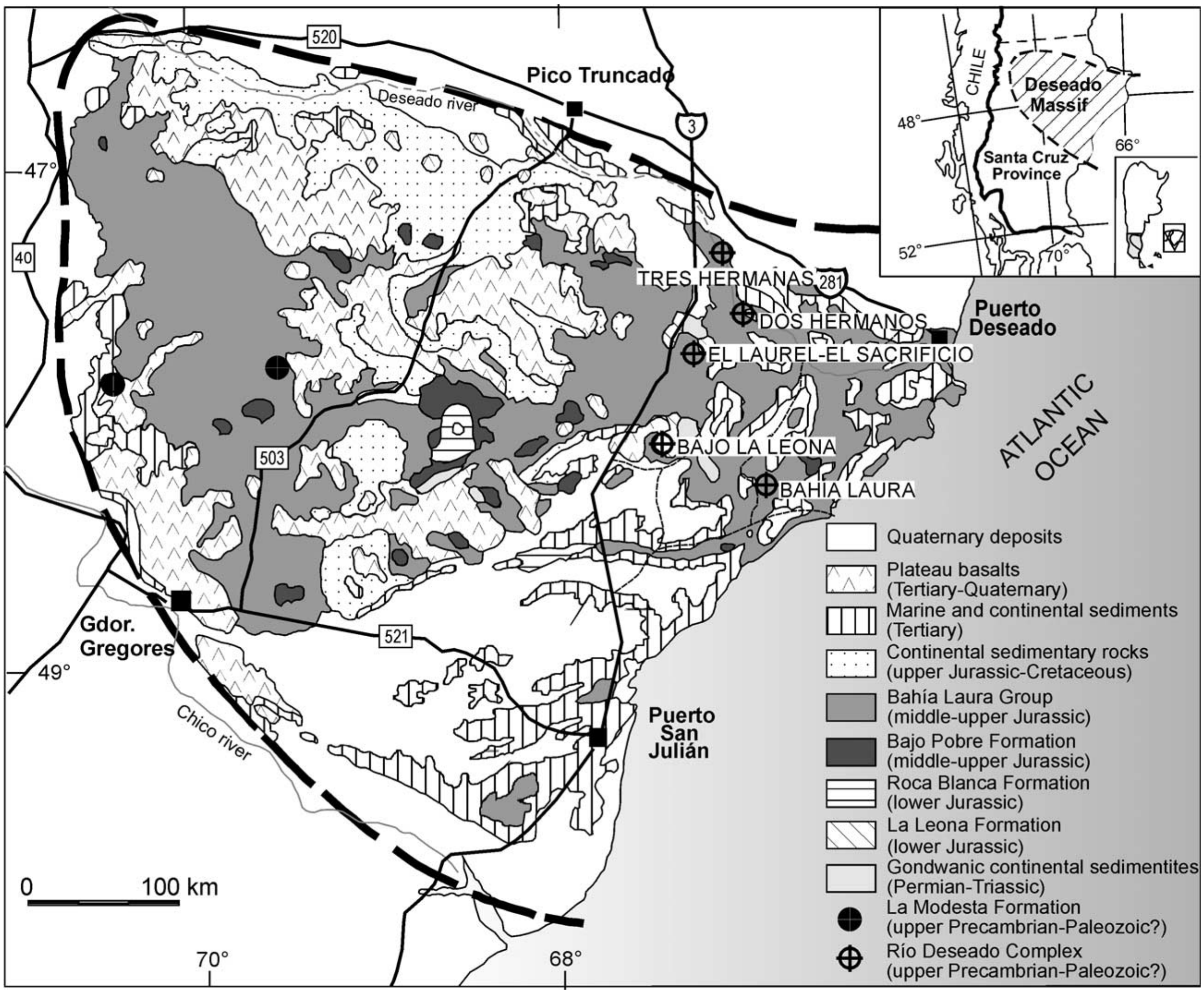


Fig. 1. Geological map of the Deseado Massif. Río Deseado Complex outcrops are enhanced.

Table 1
Main characteristics of the Río Deseado Complex

Outcrop	Pampean metamorphic rocks	Metamorphic grade	Protolith	Metamorphism age	Famatinian plutonic rocks	Plutonism age
Bahía Laura (Guido et al., 2000; this work)	Mica, quartz, and serpentine-rich schists (injected by leucogranitic veins); amphibolites; injected gneisses (micaceous, garnet-rich, and hornblendic); migmatites.	Low (greenschist facies), medium (amphibolite facies), to high grade in migmatites.	Metasediments (marine sequence) and igneous protoliths.		Bahía Laura granite, granodioritic-tonalitic injections. Aplitic and pegmatitic differentiations.	
Tres Hermanas (Chebli and Ferello, 1975; Giacosa, 1999; Giacosa et al., 2002).	Micaschists; amphibolites; amphibolic schists; metaquartzites; calc-schists; marbles and migmatites.	Medium grade (Epidote amphibolite facies).	Metaquartzites and amphibolic schists are metasediments.	U/Pb (detritic zircon from metaquartzite): 903 Ma (Loske et al., 1999).	Tectonically folded and foliated granitic injections (granitic orthogneisses). Aplite and pegmatite differentiations.	Rb/Sr one sample (leucogranite injection): 406 ± 10 Ma (Chebli et al., 1976). U/Pb (granodioritic injection): 424 Ma (Loske et al., 1999). U/Pb (discordant granitic dike): 423 ± 6 Ma (Pankhurst et al., 2001).
Dos Hermanos (Viera and Pezzuchi, 1976; Pezzuchi, 1978; Palma, 1991; Giacosa, 1999; Giacosa et al., 2002).	Phyllites; micaschists; quartzites; amphibolites; amphibolic schists; migmatites and quartz injections.	Low to medium grade (greenschist to epidote amphibolite facies).	Quartz-rich sand to pelitic sequences with marl intercalations. Amphibolites have igneous protolith, but amphibolite schists are metasediments.	K/Ar (amphibolite whole rock): 540 ± 20 Ma (Pezzuchi, 1978). Sm/Nd (detritic zircons from metamorphite): 1200 Ma (Pankhurst et al., 1994). U/Pb SHRIMP (detritic zircons from phyllite): 508–1370 Ma, with highs at 580, 640, 800, and 1100–1200 Ma (Pankhurst et al., 2001).	2 M granite (Dos Hermanos granite), gabbro-diorite sills, late muscovite granite with pegmatite facies and Siluric dacite.	U/Pb (altered muscovite granite from Permian conglomerate clast): 454 and 472 Ma (Loske et al., 1999). Rb/Sr (Dos Hermanos granite): 395 ± 30 Ma minimum age (Pankhurst et al., 2001). U/Pb (Dos Hermanos granite): 460 ± 6 Ma doubtful age (Pankhurst et al., 2001).
Bajo La Leona (Panza et al., 1995; Giacosa, 1999).	Quartz-feldspar and micaschists; metaquartzites; gneissic rocks (obliterated by Mesozoic intrusions) and quartz injections.	Low to medium grade (greenschist to epidote amphibolite facies).	Sandstone sequence with scarce pelite rocks. Also, volcanic porphiritic and tuffaceous rocks.		Postkinematic granitic intrusions and syntectonic tonalites.	K/Ar (Godeas, 1985), Rb/Sr (Pankhurst et al., 1993), and U/Pb SHRIMP (Pankhurst et al., 2001) on leucogranite: 350 ± 10, 350 ± 22 and 346 ± 4 Ma, respectively.
El Sacrifio-El Laurel (Giacosa et al., 1990, 1998, 2002).	Quartz-feldspar schists (injected by leucogranitic veins) and amphibolites as xenoliths in the plutonic rocks.	Medium grade (amphibolite facies).	Metasediments.		Hornblendic El Laurel tonalite stock, intruded by foliated 2 M El Sacrificio granite and late leucocratic granite.	U/Pb (granodiorite): 420 Ma (Loske et al., 1999). U/Pb (El Laurel Tonalite): 402–407 Ma (Loske et al., 1999) and 405 ± 6 Ma (Pankhurst et al., 2001). U/Pb SHRIMP (El Sacrificio granite): 412 ± 11 and 419 ± Ma (Pankhurst et al., 2001).

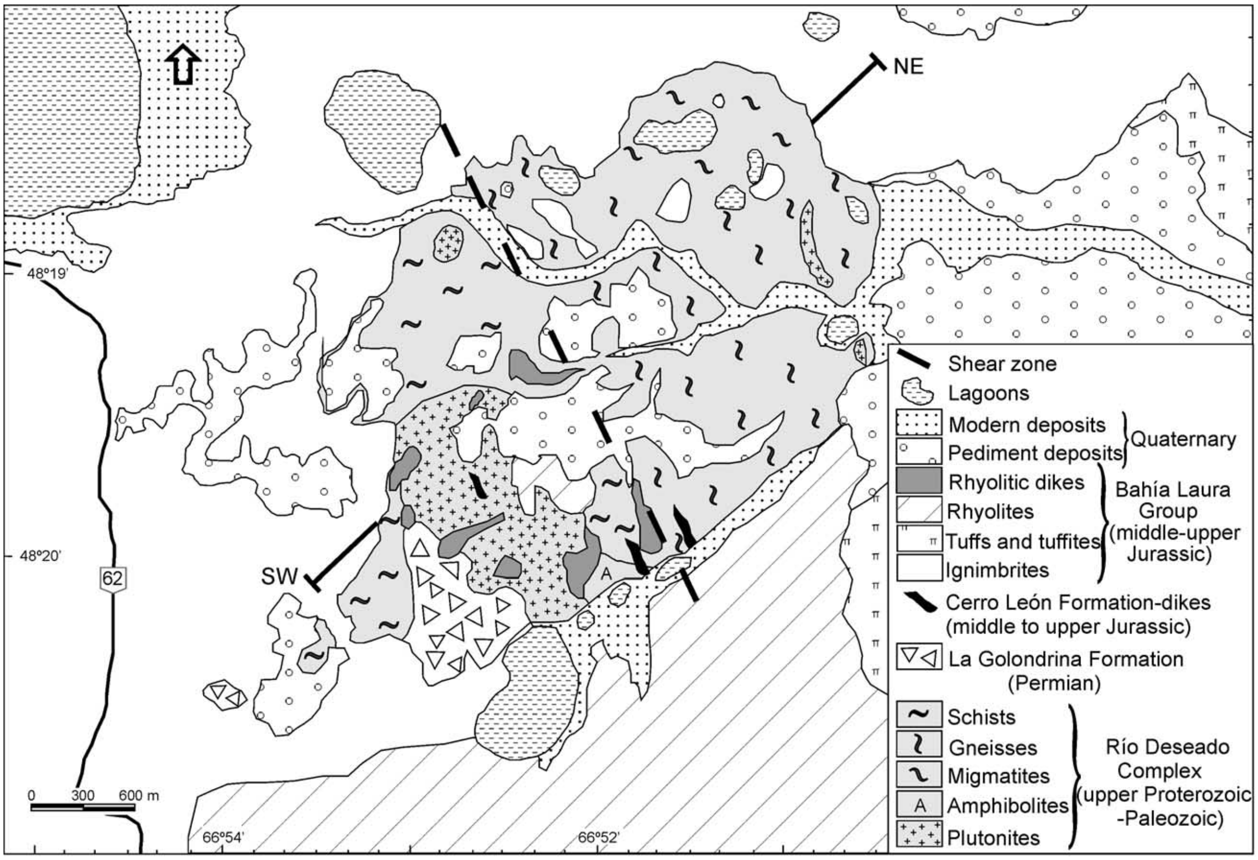
(Rodados Patagónicos) that overlie most of the Deseado Massif region and produce a typical tableland landscape.

3. Bahía Laura

Bahía Laura (Fig. 2) is located 30 km west of the Bahía Laura Bay in the No Te Admires (previously named La Juanita) farm and between approximately 48°18′10″ and 48°20′30″ S and 66°50′30″ and 66°53′30″ W. The area is characterized by low hills that alternate with plains and mesetas of minimal topographical differences. Outcrops are small, partially covered, and discontinuous, and the best exposures appear in the steep margins of creeks and lagoons. As the easternmost remnant, Bahía Laura has the highest metamorphic degree of the Deseado Massif's basement outcrops and provides the best area to recognize the deformation of the Río Deseado Complex.

The basement rocks appear in a lensoid-shaped area of approximately 10 km^2, elongated in a northeastern direction. Bahía Laura is composed of metamorphic and igneous rocks (Table 2) and divided in half (western and eastern) by a shear zone. The metamorphic rocks show a marked lithological diversity: mica, quartz- and serpentine-rich schists, four types of gneisses (micaceous, garnet-rich, granodioritic, and hornblendic), migmatites, amphibolites, and minor calc-silicate rocks. All rocks are intensely foliated NW strike (N300°–N340° azimuth and 20°–26° NE dip), and the amount of igneous intrusions and metamorphic grade increase to the NE. The metamorphic rocks show a prograde metamorphism, from low-grade schists at the southwest to migmatites at the northeast border, and pass through low- to medium-grade amphibolites and medium-grade gneisses.

Igneous rocks are composed of granitoid injections (with scarce aplite and pegmatite facies) arranged concordant and



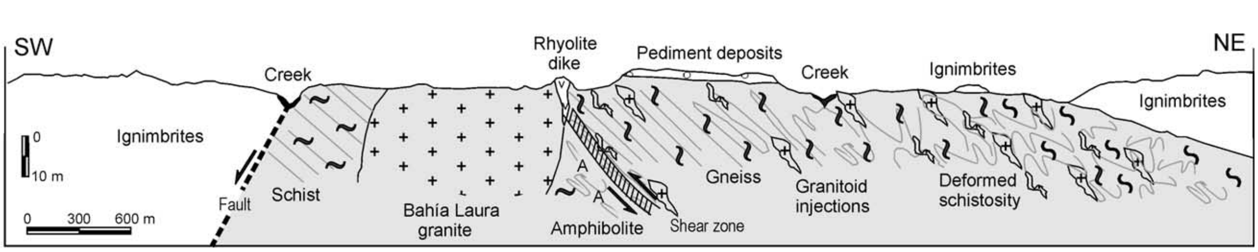


Fig. 2. Bahía Laura geological map, with interpretative SW–NE cross-section and large vertical exaggeration.

Table 2
Summary of the petrographical data from the Bahía Laura basement rocks

Rock	Texture	Mineralogy	Metamorphic grade
Metasedimentites			
Schists (mica and quartz-rich)	Lepidoblastic to granolepidoblastic	qz + Kf + pl + bt ± mu ± cl ± to ± ap ± zr	Greenschist facies (low)
Gneisses (M: micaceous, G: garnet-rich)	Granoblastic to granolepidoblastic	M: qz + Kf + pl + bt + cl ± mu ± sph ± ap ± zr; G: qz + pl + bt + mu + ga ± ap ± zr	Amphibolites (medium)
Migmatites (L: leucosome, Ml: melanosome, Ms: mesosome)	L: granoblastic; Ml: lepidoblastic; Ms: foliated	L: qz + Kf + pl ± ap; Ml: qz + bt ± zr; Ms: qz + pl + Kf + bt + mu ± ap ± zr ± op	High amphibolites (high)
Ortoderived			
Amphibolites (mineralogical associations A and B)	Granonematoblastic	am + pl + qz ± sph ± ap ± zr (A) ± ep, (B) ± ga	(A) Greenschist facies (low) (B) Amphibolites (medium)
Gneisses (H: hornblendic, Gd: granodioritic orthogneiss)	Granoblastic to granolepidoblastic	H: qz + pl + Af + am ± bt ± ep ± sph ± ap ± zr; Gd: qz + pl + Af + bt + mu ± ap ± zr	Amphibolites (medium)
Plutonic rocks			
Bahía Laura granite	Inequigranular to porphyroid	qz + mi + pl + mu + bt ± ap ± zr ± mica enclaves	
Granitoid injections	Granular (also pegmatoid and aplitic)	qz + mi + pl ± bt ± mo ± ap ± zr	

qz: quartz, Kf: K feldspar, pl: plagioclase, bt: biotite, mo: muscovite, cl: chlorite, to: tourmaline, ap: apatite, zr: zircon, sph: sphene, ga: garnet, op: opaque minerals, am: amphibole, Af: alkaline feldspar, ep: epidote, and mi: microcline.

discordant to the foliation. A 1 km diameter stock of foliated biotite–muscovite granitoid (Bahía Laura granite) intrudes the schists. Both types of igneous rocks show slight deformational textures.

The geological sequence also includes continental sedimentary rocks of the La Golondrina Formation (fanglomerate facies), basic dikes of the Cerro León Formation, volcanic rocks of the Bahía Laura Group (ignimbrites, rhyolitic lava flows, rhyolitic dikes, tuffs, and tuffites), pediment, and modern alluvial-colluvial deposits.

3.1. Schists

Three varieties of schists are located in the western sector of the outcrop area: mica, quartz, and subordinately serpentine-rich. Micaschists are black, gray, or green rocks that have a penetrative NW schistosity (N340°/NE dip) with crenulation cleavage. They comprise quartz and quartz-feldspar veins, concordant and discordant to schistosity. In addition, they have a lepidoblastic to granolepidoblastic texture with two superposed fabrics: a S1 foliation that typically is anastomosed and planar with a strong decrease in grain size (probably due to a mylonitic origin), and a S2 axial plane foliation that produces the crenulation cleavage, accompanied by muscovite blastesis over the flanks of the microfolds (Fig. 3A). Micaschists are composed of quartz, K feldspar, plagioclase, biotite, muscovite, chlorite, and sporadic iso-oriented crystals of tourmaline, as well as apatite and zircon as accessory minerals. Quartz has undulate extinction and forms polycrystalline lenses of mortar quartz where the crystals are aligned in a parallel manner. Feldspars are scarce, and micas bind the quartz lenses. Mineral paragenesis indicates a low metamorphic grade in greenschist facies with a progressive increase in the grain size to the northeast.

Quartz-rich schists are light gray rocks, mineralogically and texturally similar to mica schists, but with a higher proportion of quartz due to protolith variation. Serpentine-rich schists are located in a NW-oriented, small (15×5 m^2) outcrop close to the northern contact between the Bahía Laura granite and the micaschists. Very altered rocks with recognizable chlorite (pennines) and serpentine (antigorite and chrisotile veins), they possess high geochemical anomalies in Cr (1813 ppm), Ni (679 ppm), and Mg (1.2%) and probably correspond to a local ultramafic metamorphosed dike.

3.2. Amphibolites

Amphibolites are located in a small (50×30 m), NW-oriented outcrop and are composed of melanocratic, black to greenish rocks. They occur in the southeast of the western half of the outcrop and have a WNW

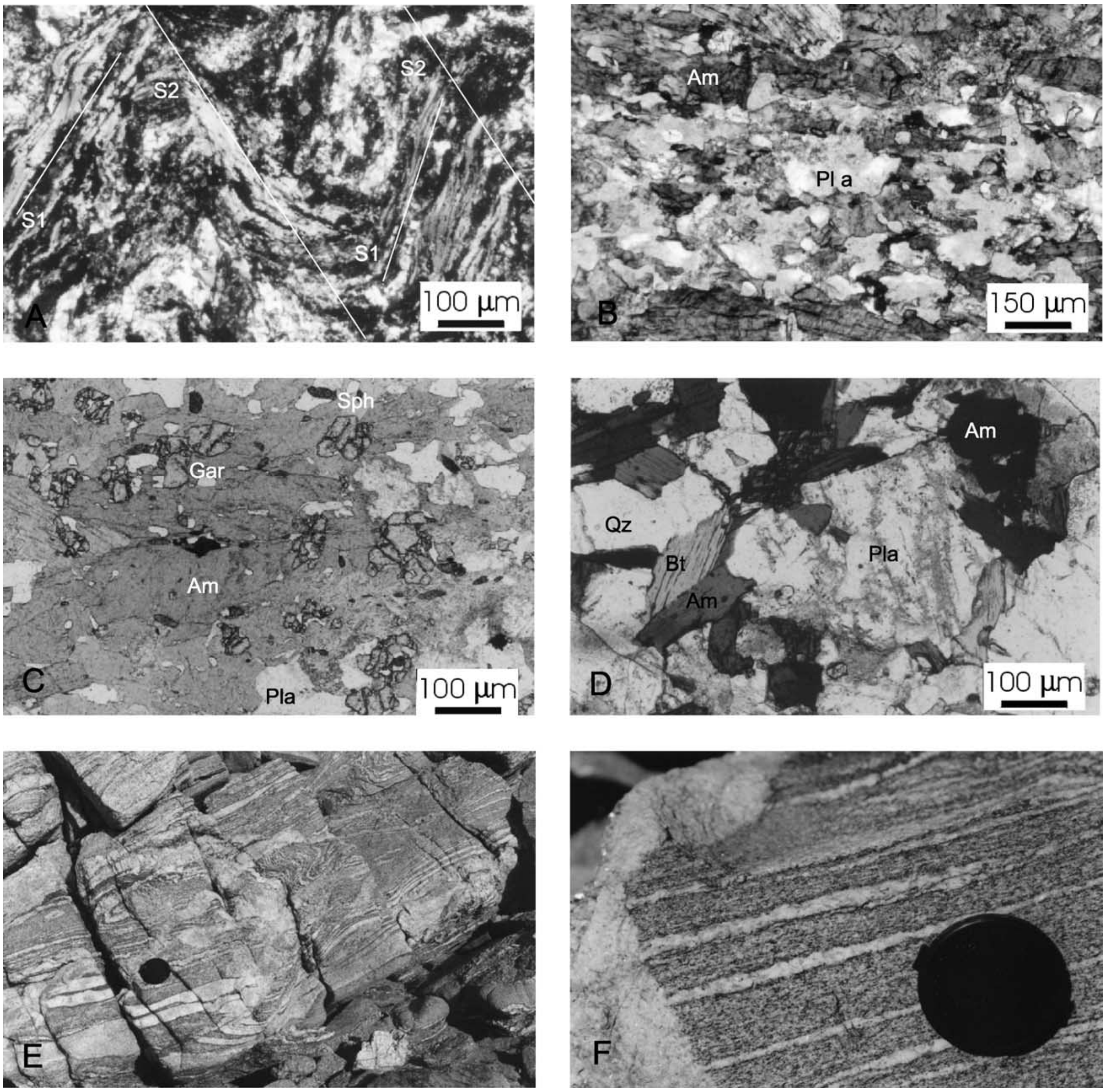


Fig. 3. (A) Mica schist fabric. (B) Low-grade amphibolite. (C) Garnet-rich amphibolite. (D) Hornblendic gneiss, with two generations of amphibole. (E) Folded, injected migmatite. (F) Banded migmatite. Notes: Am = amphibole, Pla = plagioclase, Ga = garnet, Sph = sphene, Bt = biotite, and Qz = quartz.

foliation (N300°) with a 25° NE dip. They are injected, in fashions both concordant and discordant to foliation, by quartz and calcite veins. Their texture is granonematoblastic, composed of alternating 2–5 mm thick bands of oriented amphiboles and thinner (less than 1 mm) bands of plagioclase and quartz. In the two mineralogical associations: amphibole; plagioclase; quartz; clinozoicite (Fig. 3B) and amphibole; plagioclase; quartz; garnet (Fig. 3C). Apatite, sphene, and minor zircon are accessory minerals. The former mineral association indicates low-grade metamorphism in greenschist facies, and the latter suggests medium-grade metamorphism in amphibolites facies with garnet blastesis at the expense of chlorite and epidote.

3.3. Gneisses

Gneisses are the most extensive metamorphic rocks occurring in the eastern part of the outcrop and are represented by micaceous gneisses, garnet-rich gneisses, hornblendic gneisses, and granodioritic orthogneisses. They have a conspicuous NW foliation (N335° with variable NE dip) and are densely injected by granitoids veins. Their texture is granoblastic to granolepidoblastic.

Micaceous gneisses are gray to pink rocks composed of undulate extinction quartz, K feldspar, plagioclase, biotite, chlorite, and scarce muscovite and sphene, with apatite and zircon as accessories. The garnet-rich gneisses are gray rocks composed of postkinematic and poikilitic garnet that is discordant with the planar fabric and are represented by anastomosed ribbons of micas (biotite and muscovite) and binding ribbons of quartz and plagioclase. A second generation of kinking muscovites crosscuts the planar fabric at a 45° angle.

Hornblendic gneisses are black to greenish rocks formed by lobulated and undulate extinction quartz, plagioclase with relict zonation, scarce alkaline feldspar, biotite, epidote, and two generations of hornblende: The first is green to blue and has tabular shape. The second is brown to green and is frequently in basal sections, discordantly to the fabric. Accessory minerals consist of sphene, apatite, and zircon (Fig. 3D). The green to blue hornblende and the plagioclase (An_{25}–An_{28}) indicate a medium to high metamorphic grade. Finally, granodioritic orthogneisses are pink to gray rocks composed of lobulated quartz, xenoblastic plagioclase and alkaline feldspar, biotite, and muscovite, and apatite and zircon as accessory minerals. Quartz has undulate extinction and mortar texture; K feldspar occasionally has perthites. In addition, there are two types of biotite, prismatic and xenoblastic.

3.4. Migmatites

Migmatites are defined following Mehnert (1968) and Johannes (1983). Located at the northeastern border of the outcrop with the injected gneisses, they are intensely deformed, folded, and injected by granitoids (Fig. 3E). Their stromatitic and banded structure contains leucosome, melanosome, and mesosome on the centimeter scale (Fig. 3F). Leucosome is composed of regular bands of quartz (with lobulated grains, undulate extinction, and subgrain formation), K feldspar (with occasionally micropertitic texture), and plagioclase (with inequigranular granoblastic texture and antiperthites). Melanosome provides 1–2 mm bands with lepidoblastic texture that bind the leucosomes and is composed of biotite and some quartz. Mesosome has a foliated texture of lobulated and undulate extinction quartz, plagioclase, K feldspar (with mirmequites), biotite (two types), muscovite, apatite, zircon, and opaque minerals. These rocks represent an incipient migmatization event that can be generated only by high-grade metamorphic conditions (high amphibolites facies).

The Bahía Laura granite has an inequigranular to porphyroid texture composed of quartz with undulate extinction and lobate grain boundaries, microclines that sometimes reach 5 cm, perthites, plagioclase, muscovite, biotite, apatite and zircon as accessories, and mica enclaves. In some places close to the shear zone, quartz has a mortar texture, plagioclases show curved polisintetic twins, and micas reveal kinking bands.

The granitoid injections are parallel to or discordant with the foliation of the metamorphic rocks. They have a coarse granular texture with anhedral minerals and are composed of lobulated, undulate extinction, and mortar quartz, microcline, plagioclase, and scarce oriented micas. As accessories, zircon and opaque minerals appear. These injections also have pegmatoid and aplitic facies.

4. Stratigraphy and geochronology

Feruglio, 1949 noted that the metamorphic rocks from the Deseado Massif belonged to the pre-Devonian metamorphic event. Ugarte (1966) later gave an Eo-Paleozoic age to the La Modesta outcrops. Subsequently, Lesta and Ferello (1972) identified two metamorphic belts (oriental and occidental), called 'Sustrato Preantracolitico.' Pezzuchi (1978) then correlated the Deseado Massif basement rocks with the metamorphic rocks from the Somuncurá Massif and Sierras Pampeanas and thereby located them in Precambrian–lower Paleozoic times.

Radiometric data of the Río Deseado Complex are scarce and do not clearly define the age of metamorphism. As summarized in Table 1, the ages range from 1200 to 402 Ma. The age of metamorphism can be assumed Neoproterozoic–Early Cambrian (Pampean), considering the 540 ± 20 Ma age determined by Pezzuchi (1978) in Dos Hermanos and the 529 ± 8 Ma (U/Pb, Söllner et al., 2000) and 523 ± 4 Ma (U/Pb SHRIMP, Pankhurst et al., 2003) ages given by a granodioritic orthogneiss from a bore hole in Tierra del Fuego. The sedimentation age for the metasedimentary rocks may be 580–540 Ma (Loske et al., 1999; Pankhurst et al., 2001, 2003), though protoliths from older basement rocks range from 580 to 1200 Ma and possibly are correlated with the Malvinas plateau (Ramos, 2002). Plutonism affecting the metamorphic rocks is well studied; the U/Pb and U/Pb SHRIMP ages vary between 346 and 472 Ma (Loske et al., 1999; Pankhurst et al., 2001).

These data define at least three Famatinian igneous events and a single plutonic event in the Carboniferous. The three Famatinian plutonic events are the medium Ordovician (454–472 Ma) Dos Hermanos granite, the middle to late Silurian (412–424 Ma) Tres Hermanas granitoids and El Sacrificio granite, and the early Devonian (402–407 Ma) El Laurel Tonalite. A Carboniferous age has been proposed for the Bajo La Leona leucogranite, which corresponds to the 350 Ma age determined by three different methods.

In Bahía Laura, as in the rest of the eastern Deseado Massif, the Río Deseado Complex is pre-upper Permian, because it underlies sedimentary rocks of the La Golondrina Formation. Although there are no geochronological data for these rocks, they can be correlated with the geochronological data available, assuming the metamorphism is close to the Proterozoic–Paleozoic boundary and the plutonism as Famatinian in age.

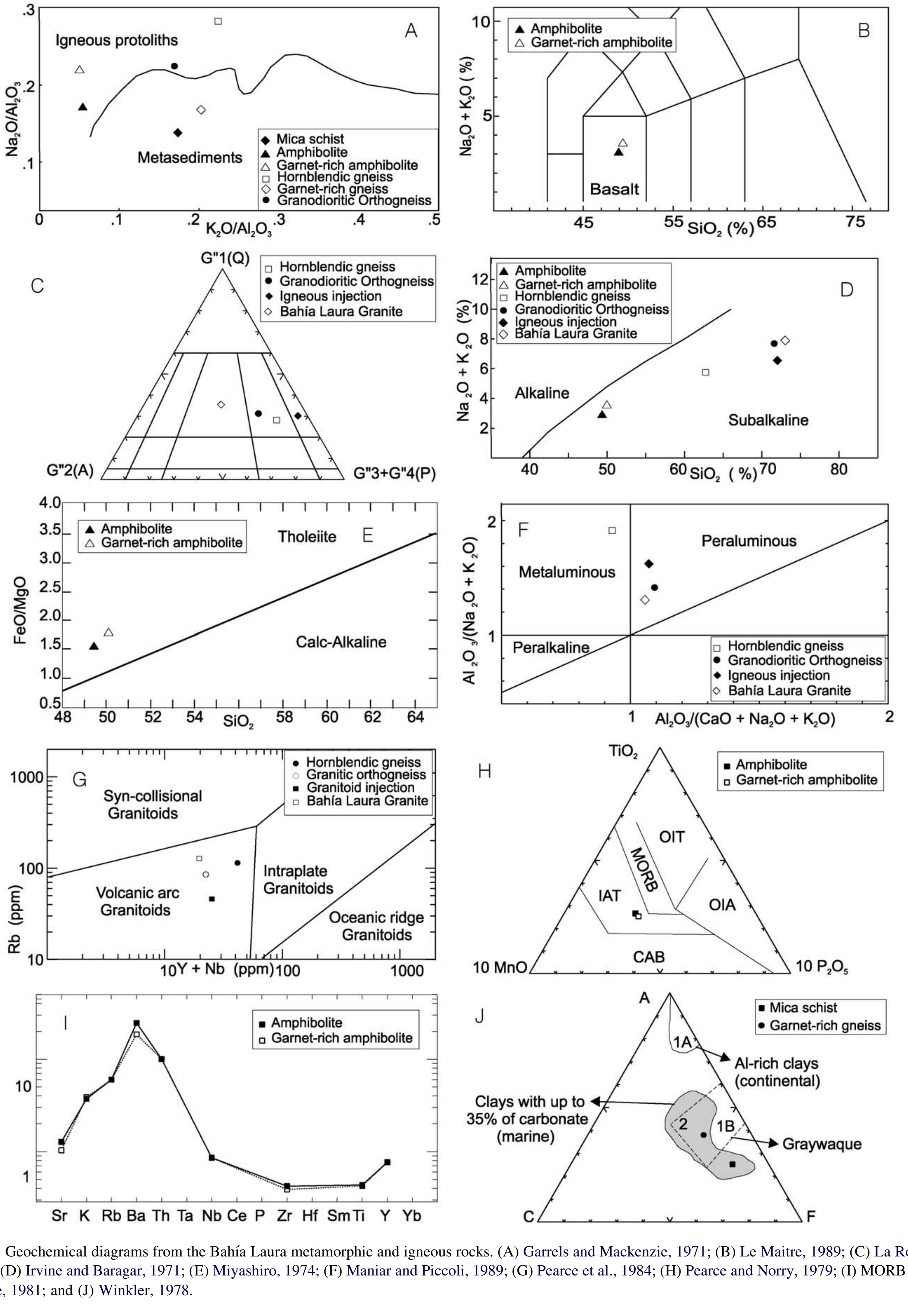


Fig. 4. Geochemical diagrams from the Bahía Laura metamorphic and igneous rocks. (A) Garrels and Mackenzie, 1971; (B) Le Maitre, 1989; (C) La Roche, 1992; (D) Irvine and Baragar, 1971; (E) Miyashiro, 1974; (F) Maniar and Piccoli, 1989; (G) Pearce et al., 1984; (H) Pearce and Norry, 1979; (I) MORB after Pearce, 1981; and (J) Winkler, 1978.

5. Geochemistry

The most representative samples of Bahía Laura were analyzed in the XRF Laboratory of Salta University and plotted in geochemical diagrams (Fig. 4). Analytical results appear in Table 3. All metamorphic rocks, except migmatites and injected micaceous gneisses, are plotted in Fig. 4A, in which the metasedimentary rocks (micaschists and garnet-rich gneisses) are separated from the igneous-derived rocks (amphibolites, hornblendic gneisses, and granodioritic orthogneisses). The TAS (Fig. 4B) diagram and cationic homologue of the QAP (Fig. 4C) diagram classify both the igneous-derived and the plutonic rocks. The amphibolites appear in the basalt field, the granodioritic orthogneisses and hornblendic gneisses as granodiorites, the Bahía Laura granite as monzogranite, and the igneous injection in the tonalite field.

According to the diagram in Fig. 4D, the igneous-derived and plutonic Río Deseado Complex rocks belong to the subalkaline series. The amphibolites rocks have tholeiitic affinities (Fig. 4E), and the granitoids are peraluminous, except for the hornblendic gneisses, which has metaluminous affinities (Fig. 4F).

The petrogenetic diagrams show that granitoids plot in the volcanic arc granitoid field (Fig. 4G) and amphibolites plot in the island arc tholeiite field (Fig. 4H). The pattern of the trace elements normalized to MORB shows a Ba, K, Th, and Rb enrichment for the amphibolites, typical of suprasubduction rocks and similar to primitive arc rocks (Fig. 4I). Metasedimentary rocks plotted in the ACF diagram show graywacke to marine clay protoliths (Fig. 4J).

Table 3
Geochemical results from the Bahía Laura metamorphic and igneous rocks

Sample (number)	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	MnO (%)	MgO (%)	CaO (%)	Na_2O (%)	K_2O (%)	P_2O_5 (%)	TiO_2 (%)	Ba (ppm)	Rb (ppm)	Sr (ppm)	Zr (ppm)	Y (ppm)	Nb (ppm)	V (ppm)	Th (ppm)	Co (ppm)	Ni (ppm)	Cr (ppm)	LOI (%)
Hornblendic gneiss (242)	62.68	15.45	5.69	0.11	3.29	4.60	3.24	2.54	0.23	0.72	206	111	233	164	29	12	3	12	93	41	70	0.87
Micaschist (237)	60.04	15.51	5.16	0.09	1.67	2.30	2.15	2.69	0.18	0.71	587	94	152	161	30	13	33	9	65	29	56	4.86
Garnet-rich amphibolite (8g)	49.12	13.24	13.13	0.19	6.93	10.75	2.91	0.67	0.12	1.09	491	12	153	38	23	3	128	n/d	72	76	216	1.90
Orthogneiss (244)	70.97	14.86	1.88	0.03	0.96	1.68	4.17	3.43	0.14	0.32	1411	86	995	215	16	7	127	2	110	10	8	0.74
Garnet-rich gneiss (239)	64.83	14.96	6.24	0.06	3.15	1.81	2.51	3.03	0.11	0.82	662	110	308	217	26	11	41	8	105	42	70	2.53
Amphibolite (8)	48.63	13.27	13.17	0.18	7.53	11.08	2.33	0.70	0.11	1.07	371	12	124	35	23	3	87	n/d	71	83	222	1.55
Granitoid injection (245)	71.94	16.35	0.97	0.02	0.65	2.83	5.32	1.23	0.15	0.13	346	46	989	124	24	2	114	5	119	8	4	0.53
2 M granitoid (238)	73.50	13.28	1.52	0.02	0.53	1.37	2.97	4.84	0.05	0.20	766	127	263	135	16	4	344	15	94	1	3	2.00

6. Discussion

Bahía Laura metamorphic rocks increase in metamorphic grade from low (greenschist facies) in the southwest to medium–high (high amphibolite facies) at the northeastern border, with medium grades (epidote and garnet amphibolite facies) in the gneissic area. Deformation increases from southwest to northeast and concentrates in the central area, where a shear zone, which divides low- from medium-grade rocks, is inferred (Fig. 2).

The metamorphic rocks from Bahía Laura represent metasedimentary and igneous-derived rocks. Metasediments (schists, garnet-rich and micaceous gneisses, and migmatites) are marine pelites, sandstones, and minor limestones that may have been deposited in a passive margin with detritic material of varying ages (580–1200 Ma). The metamorphosed igneous rocks are granodiorites and basalts. Whereas granodiorites are metaluminous and peraluminous rocks that may have been part of a magmatic arc, basalts are tholeiitic rocks with compositional affinities to a primitive island arc.

Plutonic rocks that intrude the metamorphic rocks are peraluminous granite (Bahía Laura granite) with several granitoid injections that mainly affect the gneisses.

The Bahía Laura granite and granitoid injections are calc-alkaline plutonic rocks, which probably formed part of an Ordovician–Silurian (Famatinian) magmatic arc, as proposed by Ramos (2002).

With these preliminary data, the following stages can be specified:

- *First stage*. Oceanic crust generation, evidenced by the tholeiitic basalts and serpentinites associated with marine sedimentation (marine pelites, sandstones, and minor limestones) and with calc-alkaline magmatic arc development (possibly island arc by oceanic-oceanic crust subduction).
- *Second stage*. Regional metamorphism, assumed at the Neoproterozoic–Paleozoic boundary, in agreement with the major orogenic activity that occurred in the Cambrian and the importance of this period for the continental crust formation of Gondwana (Rapela and Pankhurst, 2002).
- *Third stage*. Intrusion of calc-alkaline granitoids, mainly of Famatinian age.
- *Fourth stage*. Post-Famatinian deformational event, possibly correlated with the exhumation of the Deseado Massif's basement in the pre-lower Devonian (Giacosa et al., 2002).

7. Conclusion

If the age of metamorphism is assumed to be Early Cambrian, a Neoproterozoic (pre-Pampean cycle) evolution for the first stage of oceanic crust, marine sedimentation, and island magmatic arc formation is possible. The regional framework (mainly the eastern position of the mafic rocks compared with the Pampean arc magmatic rocks and migmatites) of the different lithologies described in Bahía Laura (Fig. 2) suggests northeast-dipping subduction. The regional Pampean metamorphism that occurred in the Neoproterozoic–Paleozoic boundary was mainly low to medium grade but reached high grades, as evidenced by the migmatites. Metamorphism was followed by an igneous intrusion stage of Famatinian age, represented by the Ordovician–Devonian granitoids. Scarce evidence of this plutonic activity exists, but it could be related to a Famatinian magmatic arc. Finally, a post-Famatinian deformational event may have affected the basement rocks of the Río Deseado Complex. This proposed evolution for the Río Deseado Complex agrees with the idea that the basement of the Deseado Massif is part of a Late Proterozoic-Mid Paleozoic orogenic belt.

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