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Linkages between the southern Patagonia Pre-Permian basements: new insights from detrital zircons U-Pb SHRIMP ages from the Cerro Negro District

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ABSTRACT

The Patagonian basement rocks are dominated by Precambrian to Early Paleozoic metamorphic rocks intruded by Paleozoic granitoids. Recently discovered basement rocks in the Cerro Negro District are characterized mainly by quartz-muscovite-chlorite schists; the metamorphic grade reaches greenschist facies (biotite-garnet grade) with a regional S_1 schistosity subparallel to the original sedimentary structure S_0 and a secondary non-penetrative S_2 foliation. New detrital zircon U-Pb geochronology shows that maximum depositional ages for detrital zircons are Devonian, ages of 379 ± 4Ma. These results suggest that the Cerro Negro basement rocks are the youngest basement in the Deseado Massif, overlapping some detrital zircon ages in the eastern Andean Metamorphic Complex in the Andean region. Most of detrital zircons are igneous in origin with a major peak around ~396Ma, probably sourced from the Devonian granitoids of the Río Deseado Complex (El Laurel and Bahía Laura granites) and equivalent northern Patagonia granitoids (*e.g.* Colan Conhué and Lago Lolog granites). Secondary peaks correspond to Ordovician to Silurian ages, being the Río Deseado Complex and La Modesta Formation (and their igneous contributors) the possible sources of the zircons. The minor oldest peaks yield Cambrian-Neoproterozoic; Mesoproterozoic and Paleoproterozoic-Archean ages, evidencing a common source from the interior of Gondwana. The results provide new insights about the relationships between the pre-Permian metasedimentary rocks of the extra-Andean and Andean region during Mid-Paleozoic ages.

KEYWORDS **Patagonia. Deseado Massif. Basement. U-Pb SHRIMP. Cerro Negro.**

INTRODUCTION

The Patagonia region comprises a vast area South from the Río Colorado river (39°-40°S), extending between the Pacific to the Atlantic coasts (65-72°W) in the southern portion of South America (Ramos, 2008). Patagonian basement outcrops are mainly exposed along the eastern side of the Andes, and can be grouped in two distinct massifs: the Somún Cura to the North and Deseado to the South; separated by Jurassic to Tertiary basins (Fig. 1). Both massifs are characterized by an extensive volcanic/sedimentary cover of Mesozoic and pos-Mesozoic age. Most of the previous studies were performed in the Somún Curá Massif, in northern Patagonia (*e.g.* Pankhurst *et al.*, 2003; Varela *et al.*, 2005; Pankhurst *et al.*, 2006; Varela *et al.*, 2007) where pre-Mesozoic basement outcrops are more widespread. Unlike the northern Patagonia, in the Deseado Massif pre-Permian basement rocks crop out in restricted and relatively small areas. Here, geochronological studies were focused mainly in the eastern metamorphic-igneous basement exposures formally grouped into the Río Deseado Complex (Figs. 1; 2) of Neoproterozoic to Late Paleozoic age (Viera and Pezucchi, 1976; Pankhurst *et al*., 2003).

During the last 20 years many authors argued about the geological origin and tectonic evolution of Patagonia in terms of its autochthous or allochthonous nature with respect to the Gondwana supercontinent (see Pankhurst *et al*., 2003; Ramos, 2008). The reconstruction of the plate tectonic history of Patagonia during the Paleozoic shows the existence of several episodes of fragmentation and rifting, convergence and accretion, renewed periods of rifting and re-accretion to the Gondwana margin (Ramos, 2008). Furthermore, this author proposes two magmatic arcs for Patagonia during Paleozoic ages: the Western (>401-320Ma) and the northern (310-285Ma). The first obliquely crosses the entire southern Patagonia from North to South through the Deseado Massif, and is represented by the Río Deseado Complex rocks. In the southern Patagonia, at the western side of this arc, several forearc/foreland diachronic basins were developed on continental crust beginning in the East with La Modesta Formation and continuing to the west with the Eastern Andean Metamorphic Complex (EAMC, partly developed over the ocean floor) from Early Paleozoic to Cretaceous times. Such metasediments became part of the accretionary prism of SW Gondwana during Late Paleozoic times (Hervé *et al*., 2000; Giacosa and Márquez, 2002; Moreira *et al*., 2005).

This article provides the characterization of a new non-outcropping basement occurrence at the Cerro Negro district, westward of the Paleozoic proposed arc, in the Deseado Massif, and presents a new U-Pb SHRIMP dating of detrital zircons for a previously unknown Devonian basin. The results are compared with other basement units from both, the extra-Andean and the Andean region of southern Patagonia, and providing a geochronological and geotectonic constrain for the evolution of Patagonia during Mid-Paleozoic times.

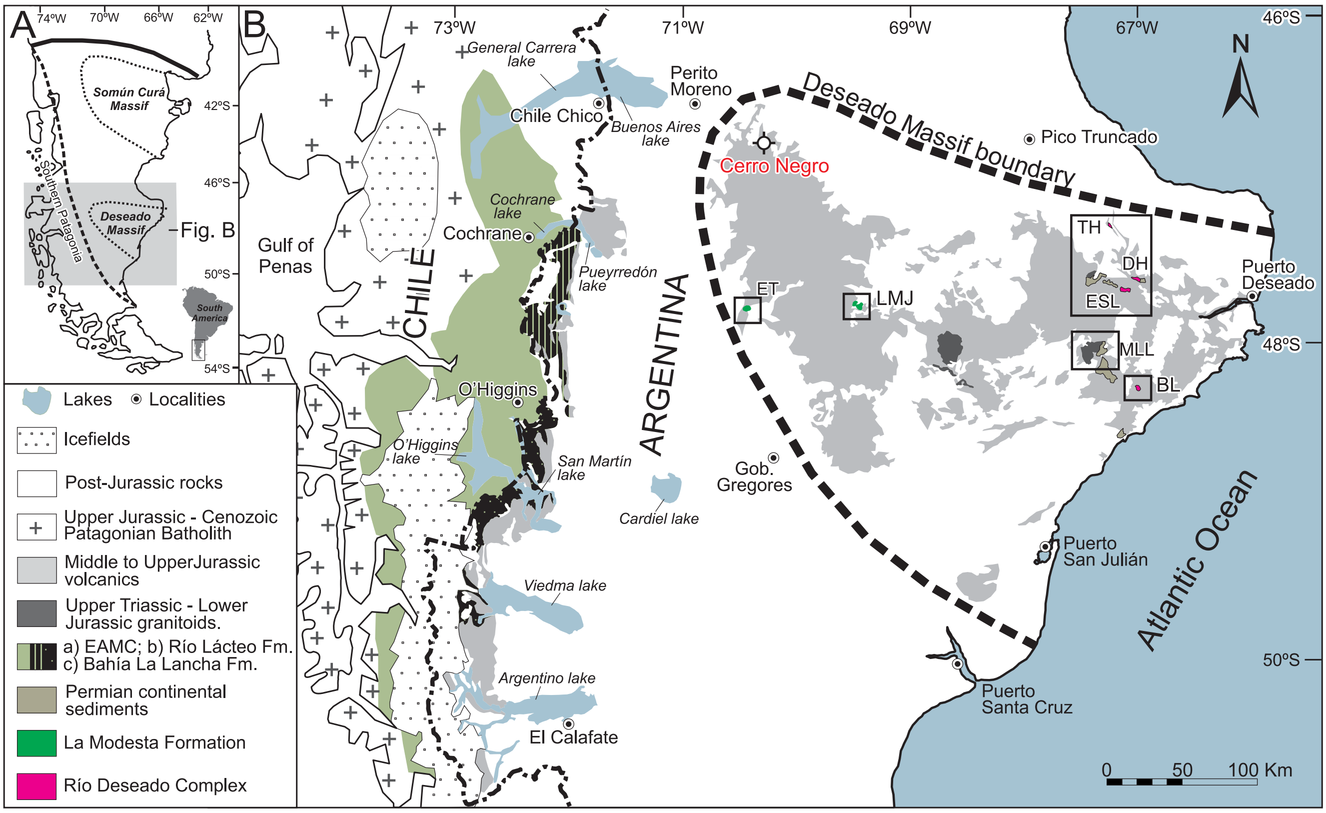

FIGURE 1. A) Location of Patagonia within South America (below right) and the position of the Deseado Massif. B) Simplified geological map of the southern Patagonia region (latitude 46ºS to 51ºS) with the location of the Cerro Negro drill-hole and the other basement outcrops, modified from Moreira *et al.* (2013). BL: Bahía Laura area, DH: Dos Hermanos area, ESL: El Sacrificio-El Laurel area, ET: El Tranquilo-La Bajada area, LMJ: La Modesta-La Josefina area, MLL: Mina La Leona area, TH: Tres Hermanas area. Fm: Formation. The framed areas are enhanced in Figure 2.

PRE-PERMIAN BASEMENT ROCKS OF SOUTHERN PATAGONIA

Extra-Andean region

Basement rocks in the extra-Andean region of the southern Patagonia are exposed in the Deseado Massif geological province (60,000km^2, Fig. 1). These exposures are small and scattered occupying less than 0.1% of the total area of the Massif (~50km^2) mostly covered by extensive Jurassic volcanism of the Chon Aike magmatic province (Pankhurst *et al*., 2000). In the eastern part of the Deseado Massif, five dispersed occurrences has been gronped in as Río Deseado Complex (Figs. 1; 2A-C). Guido *et al*. (2004) described the main Río Deseado Complex lithologies distinguishing low to high grade metamorphic rocks (phyllites, quartzites, amphibole and mica schists, amphibolites, marbles, gneisses, and migmatites) which had been intruded by granitic and gabbro-dioritic. Available geochronogical data for the metamorphic rocks of the Río Deseado Complex are scarce. Pankhurst *et al*. (2003) obtained U–Pb SHRIMP detrital zircon age of ~565Ma from low grade metamorphic rocks from the Dos Hermanos phyllites. These rocks also records Mesoproterozic detrital zircon ages associated with the Gondwana construction though protoliths from older basement rocks possibly correlated with the Malvinas plateau (Ramos, 2008). It has been considered that regional metamorphism occured during the Neoproterozoic-Cambrian periods (540 ± 20Ma amphibole K-Ar ages; Pezzuchi, 1978).

Recent U-Pb geochronology has yielded early Paleozoic to Carboniferous ages for the plutonic rocks crosscutting the metamorphic rocks (Loske *et al*., 1999; Pankhurst *et al*., 2001; 2003; Guido *et al*., 2005). Guido *et al*. (2004) defines four major igneous cycles: i) a medium to upper Ordovician cycle represented by granite cobbles within the Permian La Golondrina Formation (with U-Pb zircon ages of 472 and 454Ma), and by the Dos Hermanos granite intrusion (450 ± 6Ma); ii) a Silurian cycle recorded by El Sacrificio granite intrusion (425 ± 4Ma) and the granitic dikes of the Tres Hermanas area (423 ± 3Ma); iii) a Devonian cycle evidenced by El Laurel Tonalite (395 ± 4Ma) and the Bahía Laura granite intrusions (393 ± 2Ma); iv) a Carboniferous cycle composed by the Bajo de La Leona, plutonic rocks (344 ± 4Ma).

In the western part of the Deseado Massif, La Modesta Formation is known only in restricted basement outcrops in La Modesta-La Josefina area (main locality) and in El Tranquilo-La Bajada area (Fig. 2D, E). Moreira *et al*. (2005) describes that the low-grade metamorphic rocks at La Modesta-La Josefina area are composed by alternating pelitic and psammitic muscovite-chlorite schists and meta-quartzites, with minor calc-silicate rocks, basic metavolcanics and exhalative rocks (graphitic tourmalinites, tourmaline-bearing schists and Fe-Mn nodules). The metamorphic grade rang from prehnite-pumpellyite to greenschist facies. These authors also suggest a sedimentation age for La Modesta Formation older than 413 ± 17Ma on the basis of Rb-Sr whole rock study. Recent U-Pb SHRIMP data on detrital zircons yielded 446 ± 6Ma for its maximum age of sedimentation (Moreira *et al*., 2013), suggesting that the basin closure occurred during Lower Devonian, before the exhumation of the Middle-Devonian granitoids of the Río Deseado Complex. Many of these detrital zircons record Ordovician ages, with a prominent lower Ordovician peak at approximately 473Ma. The oldest analyzed detrital zircons record minor peaks at Neoproterozoic-Cambrian and Meso to Paleoproteroic and Archean ages.

At El Tranquilo-La Bajada area, La Modesta Formation is dominated by metasediments composed of a homogeneous sequence of pelitic and psammitic quartz-muscovite-chlorite schists, with blastesis of biotite and variable amounts of carbonate, feldspar, garnet, epidote and tourmaline (Moreira *et al*., 2012). These authors indicate that the metamorphic grade corresponds to a biotite-garnet grade within greenschist facies and were interpreted as a metamorphosed pelitic and psamo-pelitic marine sedimentary succession. La Modesta Formation has a regional metamorphic foliation, S_1, subparallel to the sedimentary stratification S_0. The schistosity S_1 was deformed by a second deformational event, generating a non penetrative S_2/L_2, best evidenced in El Tranquilo-La Bajada outcrops (Moreira *et al*., 2005, 2012).

Andean region

In the southernmost Chilean and Argentine Andes, the basement of the Cenozoic mountain range is mainly composed of metasedimentary rocks of late Palaeozoic to early Mesozoic age belonging to the EAMC and equivalent units (Fig. 1; Hervé *et al*., 2000; Giacosa *et al*., 2012).

To the North (~48°30'S, Pueyrredón and Belgrano lakes) the basement rocks are characterized by low-grade metamorphic rocks of the Río Lácteo (Argentina) and Lago General Carreras (Chile) formations (Riccardi, 1971; Leanza, 1972). These units are composed of phyllites, metagreywackes and metasandstones. To the South (~48°50'S, lake San Martín) the basement rocks are defined of the Bahía La Lancha (Argentina-Chile) and Cochrane (Chile) formations, including alternating greywackes and pelites (Riccardi, 1971). The whole EAMC sequence has been interpreted as metamorphosed and deformed turbiditic deposits (Augustsson and Bahlburg, 2008).

EAMC have been assigned an Upper Devonian to Lower Carboniferous age based on biostratigraphic ages estimated

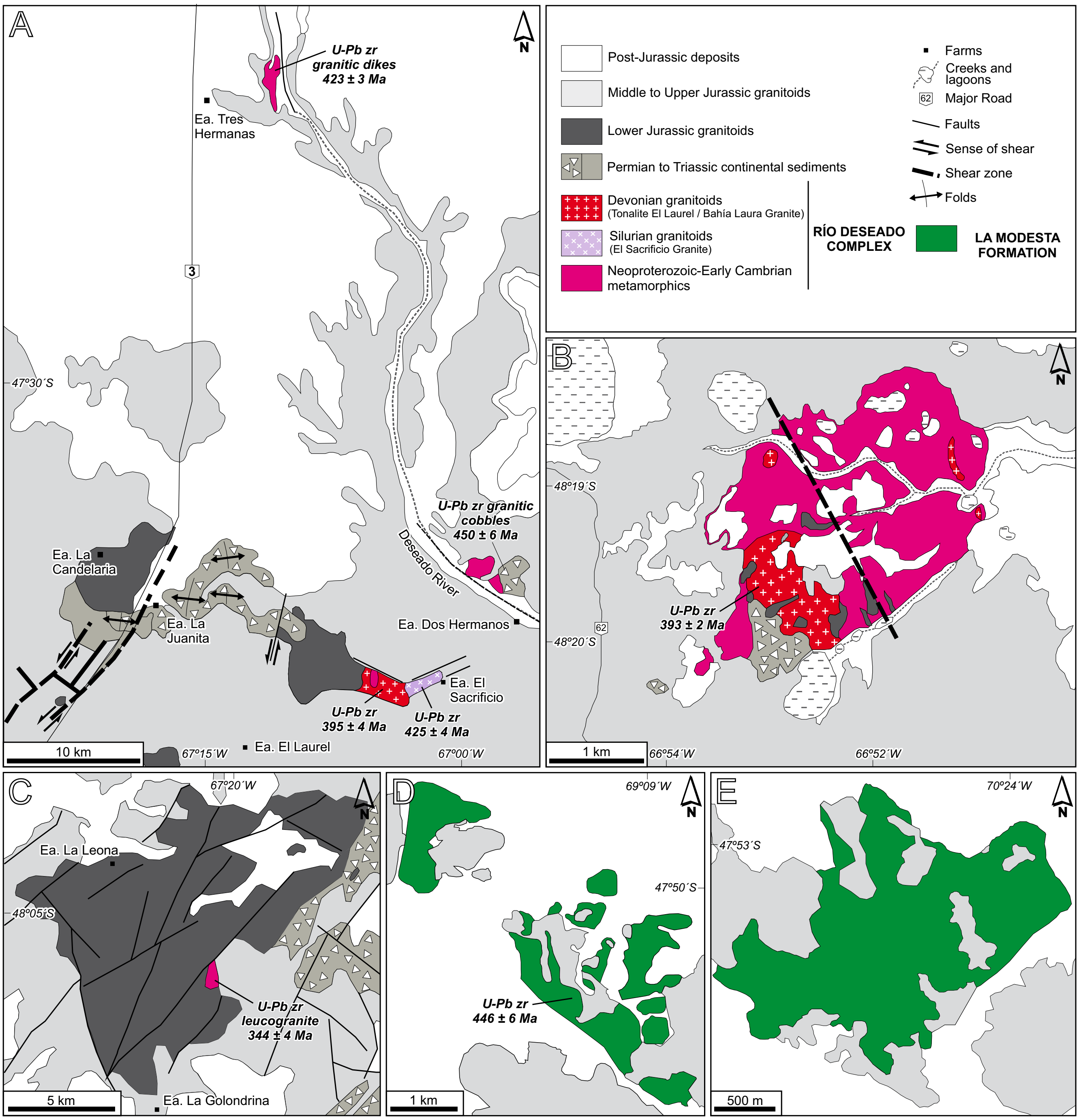

FIGURE 2. Simplified geological maps of the igneous-metamorphic basement outcrops from the Deseado Massif with U-Pb geochronological data. A) Tres Hermanas – Dos Hermanos – El Sacrificio area, modified after Fracchia and Giacosa (2006). B) Bahía Laura area, modified after Guido *et al.* (2004). C) Mina La Leona area, modified after Giacosa et al. (2002). D) La Modesta-LaJosefina area, modified after Moreira *et al.* (2013). E) La Modesta-El Tranquilo area, modified after Moreira *et al.* (2013). Note: zr: zircon age.

for the Bahía La Lancha Formation (Riccardi, 1971). U-Pb SHRIMP dating for detrital zircons had confirmed that their protolith (EAMC, easternmost samples) was mainly deposited during the Late Devonian to Carboniferous times (Faúndez *et al.*, 2002; Hervé *et al.*, 2003). A more recent study reveals that the EAMC metasediments were deposited before and during the development of a Late Carboniferous-Permian magmatic arc along Gondwana margin (Augustsson and Bahlburg, 2008).

The maximum sedimentation ages obtained from EAMC units are between ~330 and ~385Ma (Cochrane and Bahía La Lancha formations; Augustsson *et al.*, 2006; Augustsson and Bahlburg, 2008). Nevertheless, the oldest maximum sedimentation age recorded for the EAMC, and determined by Hervé *et al.* (2003), drops by Ordovician age (VS11A: 457Ma). VS11A sample, is located in the easternmost area, and could correspond to La Modesta Formation rocks incorporated in EAMC by tectonic processes (Moreira *et al.*, 2013); it is noted that the oldest detrital zircons yielded a typical Gondawanan signature with a wide range of ages of provenance with prominent peaks in the Cambrian to Neoproterozoic, Mesoproterozoic, and minor Paleoproterozoic and Archean ages. The southern Patagonia metasediments were tectonically included into subduction complexes that were accreted to the margin of Gondwana in late Palaeozoic to late Mesozoic time (~267Ma zircon fission-track ages, Thompson and Hervé, 2002).

ANALYTICAL METHODS

A representative sample of Cerro Negro basement rocks was selected for this study. The U-Pb SHRIMP geochronology on detrital zircons was performed at the Research School of Earth Sciences, Australian National University, Canberra, Australia. The whole-rock (X-ray fluorescence) and trace element (ICP-MS) geochemistry was carried out by the ALS laboratory (www.alsglobal.com).

Zircon grains were separated using standard crushing, washing, heavy liquid (Sp. Gr. 2.96 and 3.3) and paramagnetic procedures. The zircon-rich heavy mineral concentrates were poured onto double-sided tape, mounted in epoxy together with chips of the reference zircons (FC1 Duluth Gabbro), sectioned approximately in half, and polished. The grains were photographed in reflected and transmitted lights, and cathodoluminescence (CL) images were produced in a scanning electron microscope in order to define suitable regions for the analysis. Zircons on the mount were analyzed sequentially and randomly until a total of at least 60-70 grains for the sample was reached. Crystal rims were preferentially analyzed, to date the last growth stage of each zircon. Each analysis consisted of 4 scans through the mass range, with the FC1 reference zircon analyzed for every five unknown zircon analyses; SHRIMP analytical method follows Williams (1998, and references therein). The data have been reduced using the SQUID Excel Macro of Ludwig (2001). The U/Pb ratios have been normalized relative to a value of 0.01859 for the FC1 reference zircon, equivalent to an age of 1099Ma (see Paces and Miller, 1993). Uncertainties given for individual analyses (ratios and ages) are at the one sigma level. For zircons older than 800Ma, $^{207}Pb/^{206}Pb$ values were used for age calculation. Because of the small variability of $^{207}Pb/^{206}Pb$ in the Phanerozoic age range, $^{206}Pb/^{238}U$ ages were generally preferred for younger zircons. The $^{207}Pb/^{206}Pb$ ages were corrected for common Pb using the measured $^{204}Pb/^{206}Pb$ ratio in the normal manner, whereas $^{206}Pb/^{238}U$ ages were corrected based on ^{207}Pb as outlined by Williams (1998). Tera and Wasserburg (1972) concordia plots, probability density plots with stacked histograms and weighted mean $^{206}Pb/^{238}U$ age calculations were carried out using ISOPLOT/EX (Ludwig, 2003).

ANALYTICAL RESULTS

Basement mineralogy and structure

Basement rocks were collected from several drill holes (*e.g.* VDD-11009, 70º15'W, 46º52'S) below a 50 to 150 meters thick cover of Jurassic volcanic rocks during a mining exploration campaign carried out in the district during 2011. The main rock type is essentially a homogeneous sequence of schists (Fig. 3A).

At hand specimen scale the schists preserve relict sedimentary bedding as primary foliation (S_0) formed by the intercalation of siliciclastic packages of different color and grain-size. S_1 is parallel to subparalell respect to S_0 and is characterized by tight harmonic folds of centimeters scale.

Schists are composed of quartz, muscovite and chlorite with minor biotite and garnet and variable amounts of K-feldspar, plagioclase, carbonate, epidote/zoicite, and apatite and zircon as accessory minerals. They include quartz veins concordant to schistosity (Fig. 3B). They also show a porfiroblastic texture defined by euhedral to subhedral garnet, K-feldspar and plagioclase crystals with widespread inclusions (Fig. 3C, D).

Matrix exhibits lepidoblastic to granolepidoblastic texture, with two superposed fabrics: a S_1 penetrative schistosity composed by muscovite + chlorite + quartz alignment with minor biotite and a S_2 axial plane foliation that produces a crenulation cleavage, accompanied by biotite blastesis with some retrograde chlorite at the edges (Fig. 3D). Quartz has undulate extinction and has a polygonal granoblastic texture. Detrital K-feldspar and plagioclase present fragile to fragile-ductile deformation evidences such as intergranular pressure solution and reprecipitation in pressure shadows.

The protolith has been recognized as a pelitic and psamo-pelitic marine sedimentary succession, with a metamorphic grade reaching the greenschist facies (biotite-garnet grade).

Whole rock and trace element composition

One selected sample of the homogeneous sequence was analyzed for whole rock major and trace elements

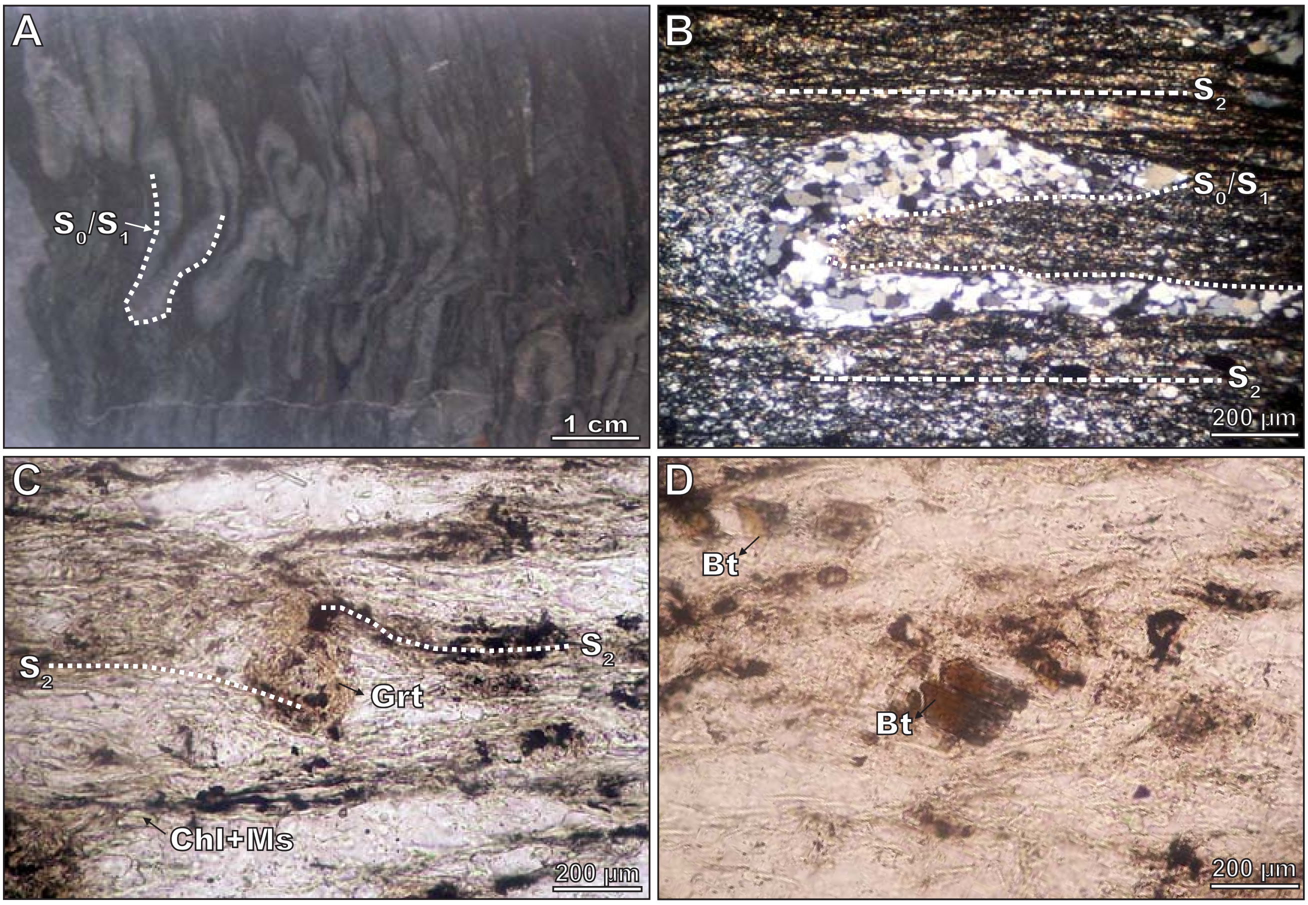

FIGURE 3. A) Hand specimen of Cerro Negro dark-greenish schists with folded bedding (S_0) composed of quartz rich layers. B) Crenulation cleavage with S_0/S_1 and the relationship with anastomosing S_2 foliation. Crossed nicols photomicrograph. C) Porphyroblastic texture defined by euhedral to subhedral garnet with curved inclusion pattern. Un-crossed nicols photomicrograph. D) Porphyroblastic texture defined with biotite by some retrograde chlorite at the edges. Un-crossed nicols photomicrograph. Notes: Grt: garnet, Bt: biotite; Chl: chlorite; Ms: muscovite.

characteristics. Results for major element were: SiO_2= 62.8wt.%; Al_2O_3= 16.2wt.%; Fe_2O_3= 6.79wt.%; MgO= 2.27wt.%; CaO= 1.30wt.%; Na_2O= 1.96wt.%; K_2O= 3.01wt.%; TiO_2= 0.76wt.%; P_2O_5= 0.17wt.%; MnO= 0.08wt.%; Cr_2O_3= 0.01wt.%. Trace elements yielded values in μg/g of Ba= 623; Sc= 18; Co= 17; Cs= 8.93; Ga= 21.80; Hf= 5.10; Nb= 13.90; Rb= 144; Sr= 71.3; Ta= 1.10; Th= 13.0; Tl= 0.80; U= 3.92; V= 162; Zr= 166; Y= 28.8; La= 37.9; Ce= 77.4; Pr= 8.93; Nd= 33.4; Sm= 6.88; Eu= 1.38; Gd= 6.99; Tb= 1.06; Dy= 5.81; Ho= 1.17; Er= 3.29; Tm= 0.48; Yb= 3.12; Lu= 0.48. The results were plotted in discrimination diagrams for provenance, recycling and tectonic setting and compared with available data from La Modesta Formation and the easternmost samples of the EAMC (Fig. 4).

Detrital zircon U-Pb ages

U-Pb ages were determined for a total of 70 zircon spots (Table 1). CL images revealed that most of the analyzed zircon grains have euhedral to subhedral shapes, with sizes ranging from 50 to 150μm (Fig. 5). The most relevant population (about 50%) corresponds to euhedral grains with zoned textures ranging from a well-developed oscillatory zonation to broad and faint growth zones (Fig. 5A-D). Only 30% of the total zircon crystals are broken. Length to width ratios ranges from 0.9 to 3.5 (*e.g.* Fig. 5A, B), reflecting mainly different crystallization velocities, whereas changes in temperature and composition of the melt cannot be completely ruled out (Corfu *et al.*, 2003). Some of the grains develop a more complex zonation pattern characterized by a complex oscillatory core truncated at the rim; with an orientation that does not conform with the external shape of the crystal (Fig. 5E). Other grains are made of homogeneous to complex core region overgrown by an oscillatory-zoned rim or a thin homogeneous rim. It is important to note that most of homogeneous broken grains correspond predominantly to Proterozoic ages.

The analytical data was plotted on Tera-Wasserburg diagrams as total ratios, uncorrected for common Pb (Fig. 6A). Most of the data plot close to the concordia curve and

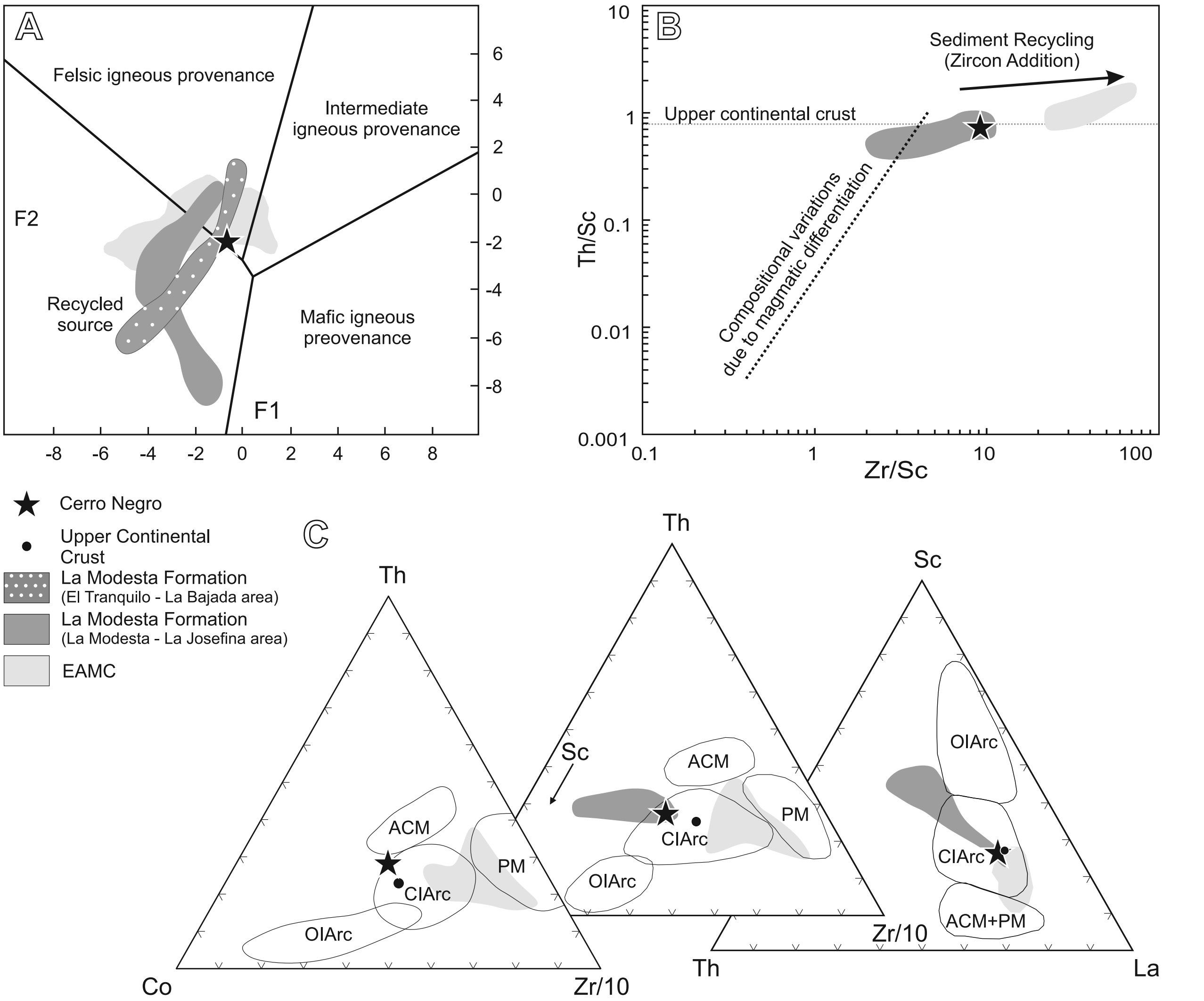

FIGURE 4. Geochemical diagrams from the Cerro Negro basement rocks compared with southern Patagonia metasediments. A) Discriminant function diagram for the provenance signature using major elements (after Roser and Korsch, 1988). D1= $1.773TiO_2 + 0.607Al_2O_3 + 0.76Fe_2O_3T - 1.5MgO + 0.616CaO + 0.509Na_2O - 1.224K_2O - 9.09$; D2 = $0.445TiO_2 + 0.07Al_2O_3 - 0.25Fe_2O_3T - 1.142MgO + 0.438CaO + 1.475Na_2O - 6.861$. B) Th/Sc vs. Zr/Sc discrimination plot after McLennan et al. (1993). C) Trace elements discrimination fields for greywackes from different tectonic environments from Bhatia and Crook (1986). ACM: active continental margin; CIArc: continental island arc, OIArc: oceanic island arc, PM: passive margin. EAMC data from Augustsson and Bahlburg (2008), La Modesta Formation data from Moreira et al. (2013). Note: Upper Continental Crust according to Rudnick and Gao (2003).

so the areas analyzed are dominated by radiogenic lead. Some of the analyzed grains are variably enriched with common Pb, and so the total ratios plotted on Figure 6A are above the concordia curve. This does not indicate that the areas analyzed are discordant, only that they are enriched with common Pb. In addition, Figure 6B shows the relative probability density plots, with stacked histograms of the detrital zircon radiogenic ages for the Cerro Negro sample. The $^{206}Pb/^{238}U$ ages of the 70 analyzed detrital grains range from about 2500 to 370Ma. About 47% of the ages are Devonian and are distributed between 368 ± 4 and 411 ± 5Ma with a unimodal peak at ~369Ma. The results of 10 analyses (14%) yielded Silurian ages ranging between 420 ± 5 and 444 ± 6Ma, with two secondary peaks at ~430 and ~444Ma. Ordovician ages are recorded in 11 analyzed zircons (16%) ranging from 446 ± 6 to 477 ± 6Ma, with a secondary peak at 473Ma. Only one zircon shows a Cambrian age of 504 ± 7Ma. The remaining grains (16%) indicate Proterozoic ages between 595 ± 7 and 1870 ± 9Ma, with scattered smaller peaks or single analyses peaks at 595, 746, 1153, 1397 and 1874Ma. The oldest analyzed grain gives Archean ages of 2635 ± 7Ma.

The six younger zircons were taken into consideration to estimate the maximum time of sedimentation, resulting on an age of 379 ± 4Ma (Mean Square Weighted Deviation, MSWD= 0.40). The analyzed spots on individual zircons come from the edges of the crystals reflecting their youngest ages. The youngest single grain analyzed from the sample has a $^{206}Pb/^{238}U$ age of 368 ± 4Ma was omitted

TABLE 1. Summary of the U-Pb SHRIMP results for analyzed zircons. oz: oscillatory zoning; fz: faint zoning; bz: broad zoning; coz: complex oscillatory zoning; hcor: homogeneous core with oscillatory rim; ccor: complex core with oscillatory rim; hcr: homogeneous core with rim; ccr: complex core with rim; ocr: oscillatory core with rim; h: homogeneous

Grain Spot	Zircon Morphology	U (ppm)	Th (ppm)	Th/U	^{206}Pb* (ppm)	Ages (Ma)					Grain Spot	Zircon Morphology	U (ppm)	Th (ppm)	Th/U	Pb* (ppm)	Ages (Ma)				
						^{206}Pb/^{238}U	±	^{207}Pb/^{206}Pb	±	Disc (%)							^{206}Pb/^{238}U	±	^{207}Pb/^{206}Pb	±	Disc (%)
1.2	oz	257	190	0.74	16	437	6				36.1	hcr	165	43	0.26	24	1001	12	1115	23	10
2.1	ccr	767	184	0.24	50	474	5				37.1	coz	217	98	0.45	14	446	6			
3.1	oz	335	122	0.36	19	406	5				38.1	ochr	438	232	0.53	24	386	4			
4.1	bz	132	118	0.90	7	382	6				39.1	oz	502	244	0.49	34	477	5			
5.1	coz	220	182	0.83	12	399	6				40.1	hcr	40	25	0.64	8	1342	23	1386	35	3
6.1	hcor	648	413	0.64	34	377	4				41.1	h	29	15	0.53	7	997	58	1368	1512	27
7.1	hcr	241	38	0.16	61	1676	18	1842	28	9	42.1	oz	477	661	1.39	26	382	4			
8.1	oz	648	493	0.76	38	420	5				43.1	h	54	39	0.71	5	621	11			
9.1	hcr	292	206	0.70	16	390	5				44.1	bz	427	213	0.50	23	387	5			
10.1	hcr	294	105	0.36	122	2543	25	2635	7	3	45.1	oz	282	172	0.61	17	399	5			
11.1	hcr	548	171	0.31	58	752	8	887	30	15	46.1	fz	238	90	0.38	51	1429	15	1401	14	-2
12.1	hcr	504	446	0.89	27	393	4				47.1	coz	278	125	0.45	16	386	5			
13.1	oz	465	94	0.20	49	746	8				48.1	bz	578	292	0.51	36	431	5			
14.1	oz	617	165	0.27	34	394	4				49.1	h	128	40	0.32	7	408	6			
15.1	bz	551	335	0.61	30	395	4				50.1	oz	741	533	0.72	47	426	5			
16.1	ccor	433	227	0.53	28	467	5				51.1	oz	267	276	1.03	15	396	5			
17.1	fz	442	167	0.38	25	404	5				52.1	bz	439	280	0.64	24	382	4			
18.1	ccr	118	13	0.11	8	474	7				53.1	oz	522	334	0.64	29	388	4			
19.1	oz	340	181	0.53	97	1854	19	1870	9	1	54.1	hcor	142	99	0.70	8	402	6			
20.1	bz	567	119	0.21	35	433	5				55.2	fz	229	183	0.80	13	400	5			
21.1	h	40	13	0.33	6	986	20	1063	85	7	56.1	fz	339	208	0.61	30	595	7			
22.1	coz	327	268	0.82	21	446	5				57.1	oz	322	228	0.71	22	472	6			
23.1	oz	378	208	0.55	20	380	4				58.1	hcr	365	454	1.25	20	396	5			
24.1	bz	239	181	0.76	15	433	6				59.1	hcor	256	123	0.48	15	403	5			
25.1	bz	410	173	0.42	28	477	6				60.2	bz	127	93	0.73	7	394	6			
26.1	coz	176	125	0.71	11	444	6				61.1	coz	190	103	0.54	12	458	6			
27.1	fz	152	100	0.66	9	438	6				62.1	fz	486	283	0.58	29	411	5			
28.1	hcr	306	166	0.54	16	375	5				63.1	bz	330	24	0.07	33	679	17			
29.1	fz	103	108	1.05	17	1156	16	1098	62	-5	64.1	ccr	173	41	0.24	12	472	6			
30.1	hcor	173	110	0.63	12	504	7				65.1	bz	741	730	0.98	44	421	5			
31.1	coz	488	341	0.70	31	449	5				66.1	hcor	520	248	0.48	31	425	5			
32.1	h	192	58	0.30	11	386	5				67.1	coz	125	107	0.86	7	404	6			
33.1	oz	282	148	0.52	16	399	5				68.1	oz	352	223	0.63	20	402	5			
34.1	oz	278	123	0.44	57	1378	16	1400	14	2	69.1	hcor	1414	628	0.44	74	368	4			
35.1	oz	205	119	0.58	11	392	5				70.1	oz	735	274	0.37	42	403	4			

Notes:

1. Uncertainties given at the one σ level.
2. Error in Temora reference zircon calibration was 0.55% for the analytical session (not included in above errors but required when comparing ^{206}Pb/^{238}U data from different mounts).
3. For areas older than ~800 Ma correction for common Pb made using the measured ^{204}Pb/^{206}Pb ratio.
4. For areas younger than ~800 Ma correction for common Pb made using the measured ^{238}U/^{206}Pb and ^{207}Pb/^{206}Pb ratios following Tera and Wasserburg (1972) as outlined in Williams (1998).
5. For % Disc, 0% denotes a concordant analysis.

from this calculations due to enhanced radiation damage and subsequent Pb-loss (see Dickinson and Gehrels, 2009).

DISCUSSIONS

Depositional age and correlations

Linkages between the different outcrops of Paleozoic metasediments of southern Patagonia, were mentioned by numerous authors (*e.g.* Giacosa *et al.*, 2002; Hervé *et al.*, 2003; Augustsson *et al.*, 2006; Augustsson and Bahlburg, 2008; Ramos, 2008; Moreira *et al.*, 2012, 2013).

The U-Pb SHRIMP detrital zircon age for the Cerro Negro basement rocks reveals a maximum depositional age of 379 ± 4Ma (Upper Devonian). This result infers that the Cerro Negro basement rocks represent a younger stratigraphic position than La Modesta Formation (U-Pb SHRIMP 446 ± 6Ma) its main locality (~120km southeast), and overlaps the oldest EAMC ages (~330 and ~385Ma; Figs. 1; 7) and equivalent units.

The absence of Devonian ages toward the southeast of Cerro Negro district suggests no zircons supply of La Modesta Formation (Moreira *et al.*, 2013). Nevertheless, it is important to point out that the mentioned ages cannot be completely ruled out for zircons of La Modesta Formation at El Tranquilo-La Bajada area where the lithology and structure agreed with the Cerro Negro features (see Moreira *et al.*, 2005; 2012).

Hervé *et al.* (2005) reported late Devonian ages in detrital zircons in metasediments of the Esquel and Cushamen formations, located in southwestern part of the Somún Curá Massif (U-Pb SHRIMP ~335-372Ma, Fig. 7). These authors correlate these units with equivalent units of the EAMC, and propose a common source area and depositional basin, although the former displays a higher metamorphic grade (amphibolite facies). Those units also preserved Devonian to Early Carboniferous detrital zircons of probable early Paleozoic magmatic rocks (Hervé *et al.*, 2005; Ramos, 2008).

So far, the Cerro Negro basement rocks do not record their metamorphism ages. However, the metamorphic event could have occurred before Permian ages, based on the metamorphism ages proposed for EAMC by Thompson and Hervé (2002) and Augustsson *et al.* (2006). These data are consistent with the Carboniferous to Early Permian metamorphism ages proposed by Hervé *et al.* (2005) for the equivalent units found in the southwestern Somún Curá Massif.

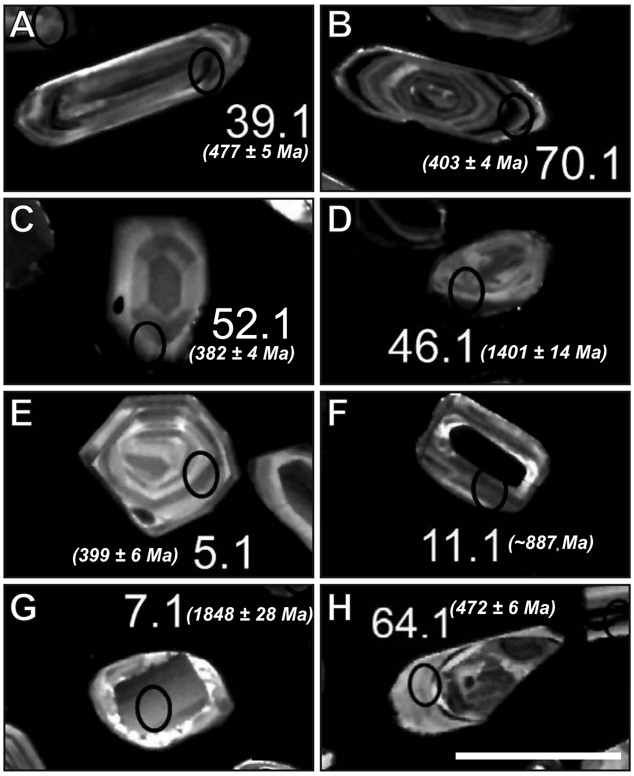

FIGURE 5. Representative CL images of grains analyzed from Cerro Negro sample showing the location of the SHRIMP analysis and the radiogenic age. A-B) Euhedral zircon with oscillatory zoning internal structure. C) Euhedral zircon with broad zoning internal structure. D) Rounded zircon with faint zoning internal structure. E) Euhedral zircon with complex oscillatory zoning internal structure. F) Rounded zircon with homogeneous core rounded by faint zoning rim. G) Rounded zircon with homogeneous core rounded by homogeneous rim. H) Complex core zircon with rim. Scale bar (in H): 100µm. Note: The number (e.g. 39.1) is the grain spot number in Table 1.

Provenance

The most prominent detrital zircon peaks in the Cerro Negro sample record a Lower Devonian age (~396Ma). Possible source areas for this age correspond to the youngest granitoids of the Río Deseado Complex in the Deseado Massif (Figs. 1; 2; 7; El Laurel, 395 ± 4Ma; Bahía Laura, 393 ± 2Ma) included in the Western Magmatic Arc outlined by Ramos (2008, Fig. 7). Devonian ages were also registered along this magmatic arc in northern Patagonia (Fig. 7, Varela *et al.*, 2005; Pankhurst *et al.*, 2006) including the Colan Conhué (394 ± 4Ma) and Lago Lolog granites (395 ± 4Ma) dated by Pankhurst *et al.* (2003). These authors also propose a major Devonian S-type granitoid belt extending from North Patagonia to with equivalent ages at the Antarctic Peninsula.

The second peak reveals Upper Ordovician to Silurian ages at ~444Ma and ~430Ma. Those zircons could be coming from the Río Deseado Complex plutonic rocks such as the Dos Hermanos granite (450 ± 6Ma); El Sacrificio granite (425 ± 4Ma) and Tres Hermanas granitic dikes (423 ± 3Ma). The third peak of ~473Ma is consistent with the most prominent peak for La Modesta Formation being a possible Ordovician source for the Cerro Negro basement. Moreira *et al.* (2013) suggest that the most provable sources would be cobbles of magmatic rocks from Permian conglomerate and Middle-Upper Ordovician granites from the Río Deseado Complex and also from the Somún Curá Massif plutonic rocks. Thereby, these sources could have also contributed to the Cerro Negro basement rocks.

The reminding minor older peaks, of Cambrian to Neoproterozoic ages (503, 595 and 746Ma);

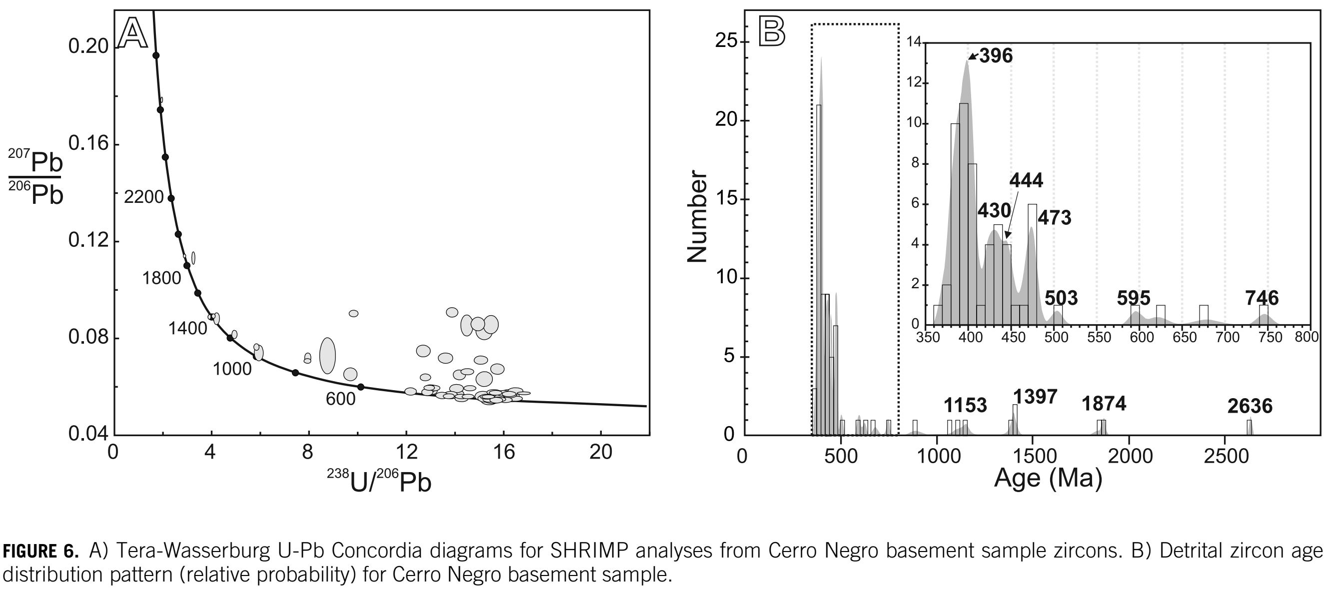

FIGURE 6. A) Tera-Wasserburg U-Pb Concordia diagrams for SHRIMP analyses from Cerro Negro basement sample zircons. B) Detrital zircon age distribution pattern (relative probability) for Cerro Negro basement sample.

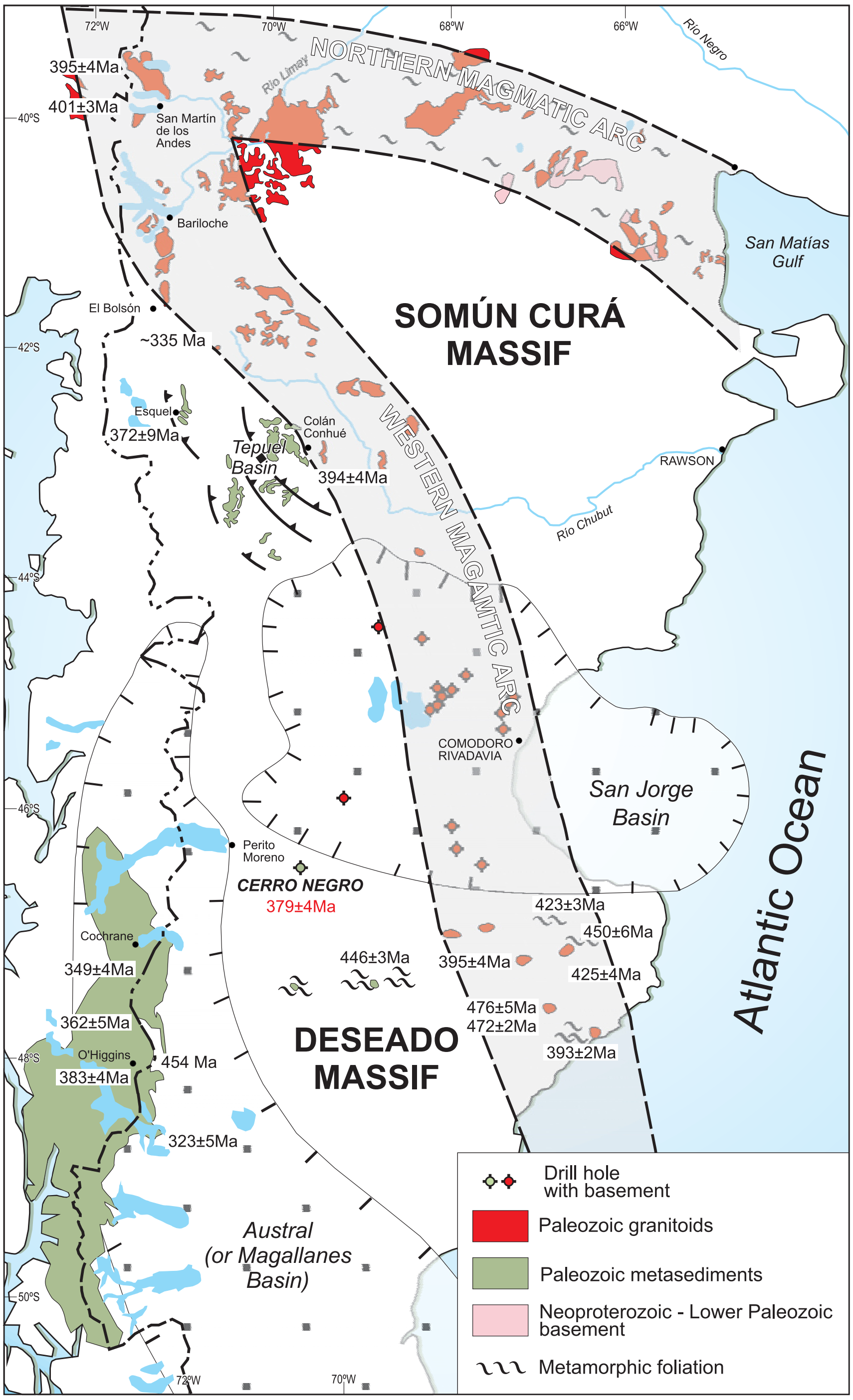

FIGURE 7. Sketch map of the igneous-metamorphic basement from Patagonia adapted from Ramos (2008), with the location of Cerro Negro drill-hole and the possibly related ages proposed in this paper. See discussion in the text.

Mesoproterozoic (1153 and 1397Ma), and Paleoproterozoic to Archean ages (1874 and 2543Ma) could be interpreted as inherited igneous zircons coming from the eastern Deseado Massif basement. These oldest zircons were also known in the northern Patagonia and EAMC metasediments, indicating a widespread source area from SW Gondwana to these basins (see González *et al.*, 2002, 2011; Pankhurst *et al.*, 2006; Naipauer *et al.*, 2010; Varela *et al.*, 2011; Uriz *et al.*, 2011; Chernicoff *et al.*, 2013; Ramos *et al.*, in press).

The obtained geochemical analyses in Figure 4 are compositionally comparable with the geochemistry found at La Modesta Formation (Moreira *et al.*, 2013) and EAMC (Augustsson and Bahlburg, 2008). However, the analyzed basement rocks indicate that the Cerro Negro paleobasin received higher amounts of igneous recycled materials from nearby sources because of poor sediment recycling processes.

Geotectonic setting

Detrital zircon age distribution patterns offer a powerful tool to determine the tectonic setting of the basin in which they were deposited (Cawood *et al.*, 2012). The overall spread of ages is a function of the nature of the source and the area of the distributive province, with large hinterlands more likely to provide a variety of source ages.

The Cerro Negro basement rocks present an unimodal detrital pattern with a major peak close to the estimated maximum sedimentation age, most likely reflecting a forearc and trench basin characteristics according to the scheme of Cawood *et al.* (2012). Moreover, these authors proposed a tectonic setting discrimination diagram based on the difference between the measured crystallization age (CA) for a detrital zircon grain and the depositional age (DA) of the succession in which it occurs. The Cerro Negro basement sample shows a detrital zircon pattern falling within a convergent field with a high proportion of detrital zircons (generally greater than 50%) and ages close to the depositional age (Fig. 8). When compared to La Modesta Formation (Moreira *et al.*, 2013) and EAMC (Hervé *et al.*, 2003; Augustsson and Bahlburg, 2008), the latter tends to show also a convergent setting, but with a higher proportion of older ages with respect to sedimentation age (Fig. 8).

This results lead to a forearc or foreland hypothesis for the tectonic setting of the Cerro Negro basement rocks in terms of Patagonia during Devonian times, that later on were accreted to the SW margin of Gondwana. The geochemistry also supports this hypothesis, as most all trace elements suggest a continental island margin in a similar way as La Modesta Formation, whereas the EAMC displays a more complex signature (Fig. 4C).

This idea was already proposed by Moreira *et al.* (2013) for La Modesta Formation during Ordovician times. Nevertheless, a few thinks should be taken into consideration. The first one is that the arc position during Devonian ages is not well constrained. On this matter, Pankhurst *et al.* (2003) propose a possible continuity of the Devonian magmatism from northern Patagonia into the Deseado Massif. These authors also point out that the lack of geochemical data for this magmatic suite precludes the assignment of a clear tectonic environment, although some εNdt and Sm/Nd age models suggests subduction-related arc magmatism. Furthermore, Guido *et al.* (2005) describe the Bahía Laura Granite as a peraluminous, two-mica monzogranite, interpreted as post-collisional granite. Augustsson and Bahlburg (2008) analyzed the EAMC in terms of provenance, and concluded that the northern EAMC (~48°S) metasediments (with Devonian to Carboniferous depositional ages) were derived from the metasedimentary country rocks of the evolving magmatic arc.

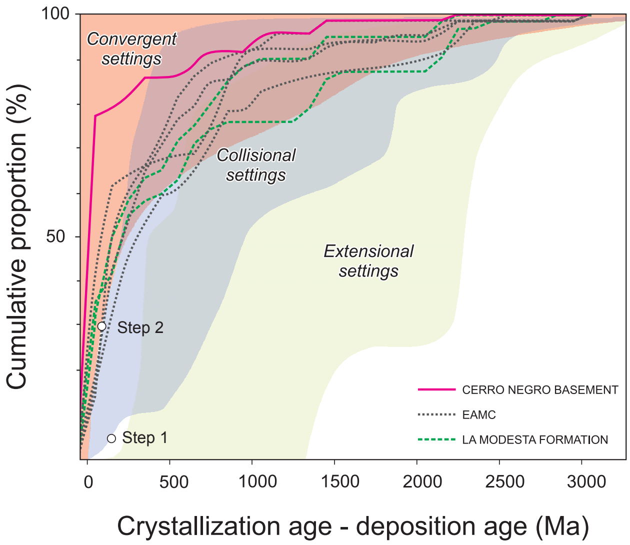

FIGURE 8. Cumulative proportion curves of the southern Patagonia as a function of the difference between the measured crystallization age (CA) for a detrital zircon grain and the depositional age (DA), after Cawood et al. (2012). Extensional (including intracra- tonic) settings have CA – DA greater than 150Ma in the youngest 5% of the zircons (step 1), and all convergent settings have CA – DA less than 100Ma in the youngest 30% of zircons (step 2). EAMC data from Augustsson *et al.* (2006) and Hervé *et al.* (2003), La Modesta Formation data from Moreira *et al.* (2013).

Finally, the available data show that the possible igneous sources of Devonian age for the Cerro Negro basement rocks are located at least 200 to 250 kilometers away from the paleobasin (Fig. 7). For such distances, a major proportion of hinterland zircon sources and rounded and/or broken crystals should be expected in the Cerro Negro paleobasin. Thus, one possibility is that the Devonian arc was closer to the studied depocenter, now hidden below the widespread Jurassic Chon Aike volcanics defined by Pankhurst *et al.* (2000). This hypothesis could be supported by basement fragments (schists and granites) of unrevealed age found within Jurassic ignimbrites and lavas located in the central to western Deseado Massif (Echeveste *et al.*, 2001; Páez *et al.*, 2010).

Another hypothesis is that selective pathways deposited major arc-derived zircons into the Cerro Negro depocenter, whereas major reworked cratonic sources fed the northern EAMC and equivalent units in a similar way as described by Korsch *et al.* (2009) for the New England Orogen, Eastern Australia. Further detrital zircon analysis should be conducted on all basement occurrences within the Deseado Massif in order to clarify this hypothesis.

CONCLUDING REMARKS

Reported low grade metamorphic rocks of Cerro Negro, record U-Pb ages from detrital zircons of Upper Devonian times (379 ± 4Ma, maximum depositional age), being the youngest basement occurrence described in the Deseado Massif and overlapping the Devonian-Carboniferous ages of the EAMC and equivalent units. The detrital zircon age pattern reveals a tectonic setting related with a convergent margin such as a forearc for Devonian times, that is supported by the geochemical signature.

Most of detrital zircons are igneous in origin with a major peak around ~396Ma that could corresponds to Devonian granitoids of the Río Deseado Complex and equivalent northern Patagonia granitoids. Secondary peaks are coincident with La Modesta Formation (and their igneous contributors) being a possible sources for the Cerro Negro basement from Ordovician to Silurian zircons. Minor older peaks yielded Cambrian-Neoproterozoic; Mesoproterozoic and Paleoproterozoic-Archean ages, indicating a SW Gondawana cratonic source such as the Paleozoic basements of Patagonia.

These results confirm the generation of diachronic basins mentioned by Moreira *et al.* (2005), developed on the continental crust close to the magmatic arc, during the Paleozoic, getting progressively younger toward the west.

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