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Provenance and paleogeography of the Devonian Durazno Group, southern Parana Basin in Uruguay

N.J. Uriz [a], C.A. Cingolani [a, b, *], M.A.S. Basei [c], G. Blanco [d], P. Abre [d], N.S. Portillo [a], A. Siccardi [a, b]

[a] División Geología Museo de La Plata, Paseo Del Bosque S/n, La Plata, Argentina
[b] Centro de Investigaciones Geológicas (UNLP-CONICET), La Plata, Argentina
[c] CPGeo, Instituto de Geociências, Universidade de São Paulo, Brazil
[d] Polo de Desarrollo Universitario, Geología y Recursos Minerales, Universidad de La República (CURE), Simón Del Pino 1132, Treinta y Tres, Uruguay

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ABSTRACT

A succession of Devonian cover rocks occurs in outcrop and in the subsurface of central-northern Uruguay where they were deposited in an intracratonic basin. This Durazno Group comprises three distinct stratigraphic units, namely the Cerrezuelo, Cordobés and La Paloma formations. The Durazno Group does not exceed 300 m of average thickness and preserves a transgressive-regressive cycle within a shallow-marine siliciclastic shelf platform, and is characterized by an assemblage of invertebrate fossils of Malvinokaffric affinity especially within the Lower Devonian Cordobés shales. The sedimentary provenance of the Durazno Group was determined using petrography, geochemistry, and morphological studies of detrital zircons as well as their U–Pb ages. Sandstone petrography of Cerrezuelo and La Paloma sequences shows that they have a dominantly quartz-feldspathic composition with a minor contribution of other minerals. Whole-rock geochemical data indicate that alteration was strong in each of the three formations studied; chondritic-normalized REE patterns essentially parallel to PAAS, the presence of a negative Eu-anomaly, and Th/Sc and La/Hf ratios point to an average source composition similar to UCC or slightly more felsic. Within the Cerrezuelo Formation, recycling of older volcano-metasedimentary sources is interpreted from Zr/Sc ratios and high Hf, Zr, and REE concentrations. U–Pb detrital zircon age populations of the Cerrezuelo and La Paloma formations indicate that the principal source terranes are of Neoproterozoic age, but include also minor populations derived from Mesoproterozoic and Archean-Paleoproterozoic rocks. A provenance from the Cuchilla Dionisio-Dom Feliciano, Nico Pérez and Piedra Alta terranes of Uruguay and southern Brazil is likely. This study establishes an intracratonic extensional tectonic setting during Durazno time. Considering provenance age sources, regional paleo-current distributions and the established orogenic history recorded in SW Gondwana, we suggest that the basin fill was derived from paleohighs located in what is currently SE Uruguay.

1. Introduction

The great Paraná basin covered southeastern Brazil and eastern Paraguay from the Silurian through the Devonian, later extending across northeastern Argentina and central-northern Uruguay as the Chaco-Paraná basin (Fig. 1). It is characterized by a thick sedimentary succession deposited in several sub-basins that locally compartmented the epicontinental ocean. The age span of the entire succession is Late Ordovician to Late Cretaceous.

In a general tectono-stratigraphic framework Milani et al. (1998, 2007) and Milani and Zalan (1999), studied several depocenters in the largest Paraná basin, recognizing six unconformity-bounded sedimentary supersequences; namely Río Ivaí (Ordovician-Silurian), Paraná (Devonian), Gondwana I (Carboniferous – Lower Triassic), Gondwana II (Middle to Upper Triassic), Gondwana III (Upper Jurassic to Lower Cretaceous) and Bauru (Upper Cretaceous). The first two of these supersequences are related to transgressive-regressive marine cycles of early-middle Paleozoic age. The Rio Ivaí Supersequence developed mainly in western

* Corresponding author. Centro de Investigaciones Geológicas (UNLP-CONICET), Diag. 113 n. 275, La Plata, Argentina.
E-mail addresses: nuriz@fcnym.unlp.edu.ar (N.J. Uriz), carloscingolani@yahoo.com, ccingola@cig.museo.unlp.edu.ar (C.A. Cingolani).

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Fig. 1. Gondwana paleogeographic reconstruction showing South American Silurian-Devonian basins (after Torsvik et al. 2012; Torsvik and Cocks, 2013) and the location of the study area.

Paraguay and southeastern Brazil. It is composed of Upper Ordovician conglomerates and arenites which are covered by Hirnantian diamictites, and above this a regional drape of fossil-rich marine pelites. The second sedimentation cycle, the Devonian Paraná Supersequence, occurs in the eastern part of Paraguay, southeastern Brazil and central-northern Uruguay. In southern Brazil, the principal outcrops occur along the so called Ponta Grossa arch trend where the Devonian siliciclastic sequences overlie either Río Ivaí Group or igneous-metamorphic basement rocks.

In central-northern Uruguay, the Paraná Supersequence is recognized both in outcrop and subsurface, forming the rift-related intracratonic Durazno basin (Bossi, 1966). Malvinokaffric invertebrate fossil assemblages suggest an Early Devonian age (Méndez-Alzola, 1934, 1948; Terra Arocena and Méndez-Alzola, 1939; Ferrando and Andreis, 1986; Bossi and Navarro, 1988; Figueiras, 1991; Sprechmann et al., 1993; Gaucher et al., 1996; Bossi et al., 1998; Veroslavsky et al., 2006). The subsidence/uplift pattern of cratonic basins reveals the evolution of the sedimentary environments through time, and the terrigenous grains provide important clues about the composition, age, and tectonic setting of the source areas, in addition to information about the paleoclimatic conditions and sedimentary transport processes (*e.g.*, Dickinson et al., 1983; McLennan et al., 1993). Cratonic basins were often considered to be formed after a continent assembly and controlled

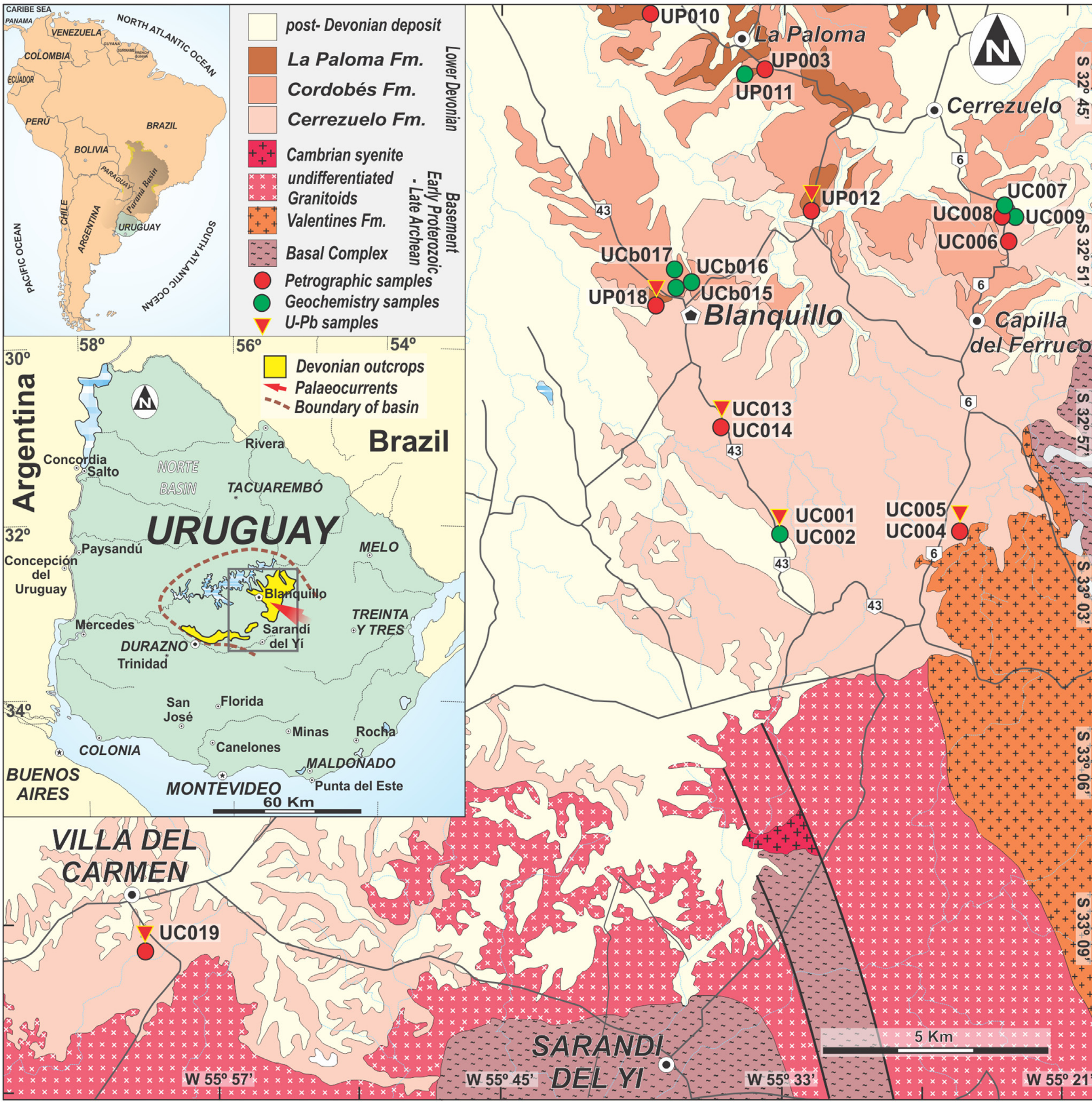


Fig. 2. General geologic sketch map of central Uruguay showing location of sample sites for all three formations examined (based on Geologic Map of Uruguay, 1:500.000, DINAMIGE, Preciozzi et al., 1985).

by subsequent tectonic evolution, as in the case of the Paraná (Milani and Ramos, 1998; Cawood et al., 2003).

Therefore, this paper aims to determine the provenance of the Durazno Group basin fill exposed in central Uruguay, to gain insights in the paleogeography and tectonic evolution of SW Gondwana during the Devonian. Provenance proxies were obtained using several techniques such as petrography, whole-rock geochemistry, morphological studies of detrital zircons and their U–Pb (LA-ICP-MS) ages. Known paleocurrents as well as the geological framework of the units studied help to constrain the sources determined in this study confirming the intracratonic extensional tectonic setting of the basin. Preliminary U–Pb results were anticipated by Uriz et al. (2013, 2014).

2. Geological setting

Outcrops of Devonian rocks occur in several localities in Durazno Department, Uruguay. They are assigned to the Durazno Group which has a threefold subdivision attributed to three prominent phases of basin deepening. From the base upwards, these episodes of basin filling are the Cerrezuelo, Cordobés and La Paloma formations (Bossi, 1966). The Durazno Group is interpreted as a transgressive-regressive siliciclastic sequence that was deposited on a cold-water shallow marine platform, evidence for

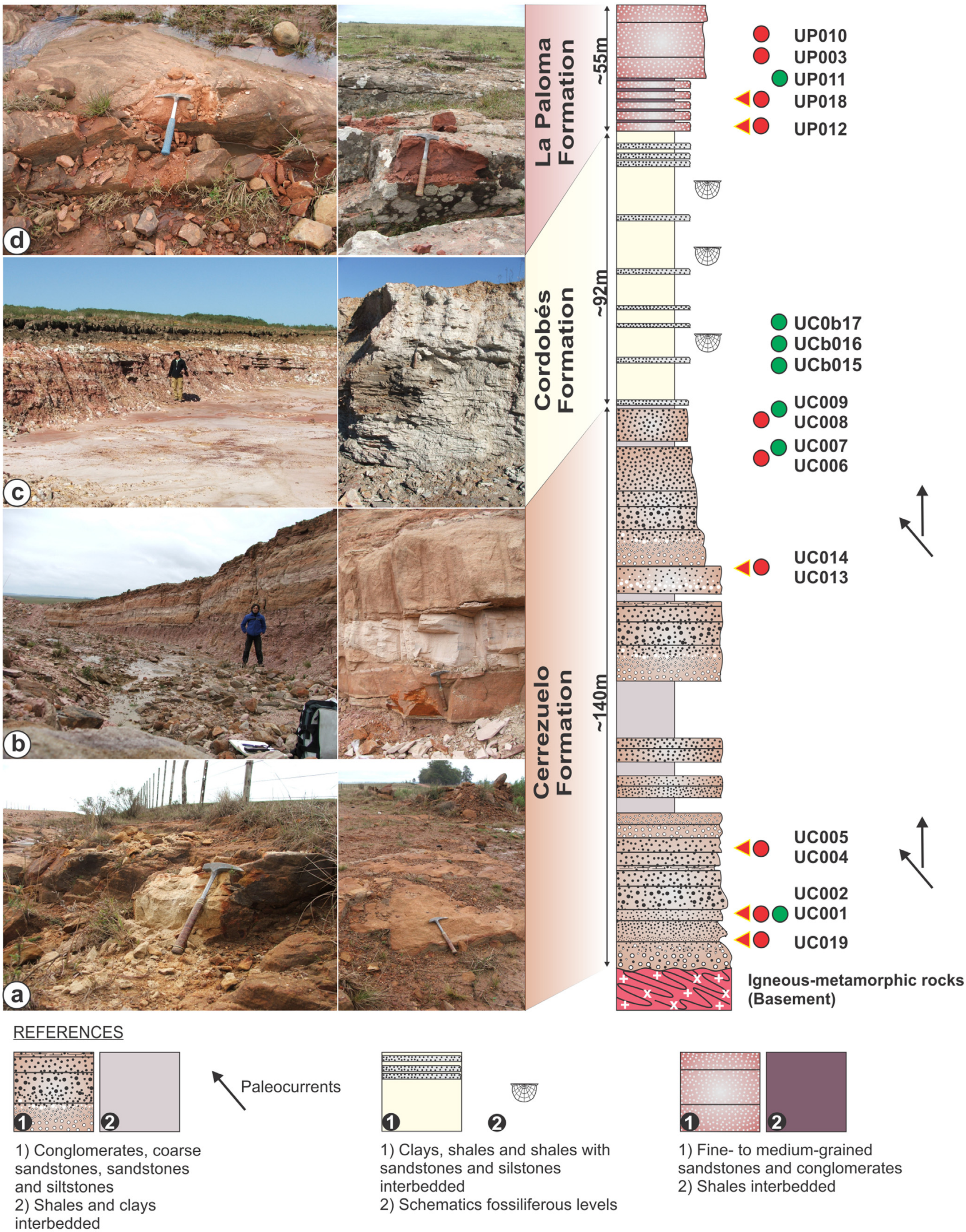


Fig. 3. Schematic lithostratigraphic section of Durazno Group (modified after Veroslavsky et al., 2006) with stratigraphic position of sampled levels **a-b)** Outcrops of the Cerrezuelo Formation showing base and top respectively. **c)** Outcrops of the Cordobés Formation in quarries near Blanquillo. **d)** Outcrops of the La Paloma Formation in the vicinity of the homonymous locality.

which comes from South American high latitude paleogeographic reconstructions (Torsvik and Cocks, 2013). Overall, the stratigraphy is subhorizontal. Subsurface lithofacies of the Devonian basin shows a north-northwestward deepening and deposition occurred within an extensional subsidence sedimentary regime. Outcrops occur within the bedrock and banks of modern streams, quarries, road-cuts, and as small isolated exposures in the undulating landscape. Fossils found mainly in the kaolinite-rich shales of the Cordobés Formation broadly constrain the age to Early Devonian (Sprechmann et al., 1993; Gaucher et al., 1996).

The basal unit of the Durazno Group uncomformably overlies basement rocks of the Piedra Alta (Paleoproterozoic) and Nico Pérez (Archean to Neoproterozoic) terranes. Towards the east, the Cuchilla Dionisio terrane or Dom Feliciano belt consists of calc-alkaline rocks corresponding to a continuous granitic belt spanning southern Brazil and Uruguay, the Arachania magmatic arc which was active during the Neoproterozoic and was tangentially accreted to the Río de la Plata craton at ca. 530 Ma (Blanco et al., 2009; Gaucher et al., 2009; Frimmel et al., 2013). The eastern domain of the Cuchilla Dionisio terrane is composed of Mesoproterozoic (Stenian) and Cryogenian polydeformed rocks and supracrustal rocks of the Ediacaran Rocha Group that were probably part of the Kalahari craton (Preciozzi et al., 1999, 2003; Basei et al., 2005, 2011; Frimmel et al., 2013, Blanco et al., 2014a). The Durazno Group is unconformably covered either by latest Carboniferous-earliest Permian glaciogenic sediments of the San Gregorio Formation, locally forming deeply incised channels, or by younger units (Fig. 2).

Within the Durazno Group, the pre-Early Devonian *Cerrezuelo Formation* is arkosic, composed of feldspathic-quartz sandstones with abundant muscovite (Andreis and Ferrando, 1988, 1991). It is a fining-upwards sequence that grades into the overlying pelitic Cordobés Formation (Fig. 3a and b). Maximum recorded thickness of the Cerrezuelo, encountered in the La Paloma IGU-186 borehole, is about 140 m. The sedimentary facies are attributed to coastal, littoral and sub-littoral processes with local fluvial influence. Sedimentological studies indicate paleocurrents directed uniformly towards the NW and N (Andreis and Ferrando, 1988; Da Silva et al., 1991; Sprechmann et al., 1993; Veroslavsky et al., 2006). Fossils are comparatively rare in the Cerrezuelo Formation because of the coarse nature of the sediments, which does not favor preservation. However, trace fossils and plant remains have been observed. In a palynological study, Grahn (2003) compares assemblages of chitinozoans with the better studied section of the Chaco-Paraná basin, from which he suggests a Pridoli to early Pragian age for the lower Cerrezuelo. Supporting this interpretation are U–Pb zircon dates of 417.5 and 407.9 Ma for the basal arkosic rocks of the Lolén Formation in the neighboring Ventania depocenter (Uriz et al., 2011). Furthermore, the occurrence of diverse invertebrate assemblages in the overlying Cordobés Formation indicates that there may be a substantial hiatus that excludes the late Pragian. In this context, two samples (UC019 and UC001) from the lowermost Cerrezuelo Formation display a dominance of kaolinite attributed to intense diagenetic alteration (Figs. 3 and 5), characteristics typical of an unconformity. In this respect, the upper Cerrezuelo may be early Emsian.

There are differences in the paleogeographic interpretation of the Cerrezuelo Formation lithofacies (Preciozzi et al., 1985; Andreis and Ferrando, 1991; Sprechmann et al., 1993; Veroslavsky, 1994). However, the presence of diagenetic alteration of coarse grained fluvial arkoses at the base of the unit, encountered in some exploration wells, suggests that reworking was not substantial (Preciozzi et al., 1985; Da Silva et al., 1991). The upper part of this formation has the characteristics of marine platform sedimentation, such as tempestites and sporadic bioturbation (Sprechmann et al., 1993), indicating marine inundation. This interpretation of shallow marine platform sedimentation is supported by petrographic analysis which shows an increase in the proportion of detrital quartz up section.

The overlying *Cordobés Formation* is composed of white-greyish kaolinitic shales (Zalba et al., 1988), subordinate illitic shales, and isolated siltstone beds (Fig. 3 c). Ferruginous levels are common, comprising diagenetic hematite and limonite. Maximum thickness recorded at the mentioned borehole is 92 m. The Cordobés Formation is attributed to a maximum flooding transgressive event. It is a marine succession with a rich invertebrate fauna, including brachiopods, gastropods, bivalves, and trilobites, typical of the Malvinokaffric realm in SW Gondwana and suggesting a likely Early Devonian Emsian age (Sprechmann et al., 1993; Gaucher et al., 1996; A. Tankard, personal communication). A broader Pragian-Emsian age range is provided by various studies of palynomorphs, including acritarch and spore assemblages, identified from outcrop and well samples (Martínez Macchiavelo, 1968; Pöthe de Baldis, 1977; Da Silva, 1991; Oliveira, 1997; Grahn, 2003; Daners et al., 2013). Other fossils include an Acanthoid-like fish (Botella et al., 2003) and a new taxon of fossil plant (Morel et al., 2015).

Table 1
Coordinates of sample locations and technique applied.

Units	Samples	GPS	Methodologies
La Paloma Formation	UP018	32°52′35.50″S – 55°37′48.30″W	Petrography, Zr Morphology, U–Pb
	UP012	32°49′40.20″S – 55°31′43.80″W	Petrography, U–Pb
	UP011	32°44′41.00″S – 55°34′19.00″W	Geochemistry
	UP010	32°42′18.80″S – 55°37′4.00″W	Petrography
	UP003	32°44′36.30″S – 55°33′9.20″W	Petrography
Cordobés Formation	UCb017	32°51′45.70″S – 55°37′18.60″W	Geochemistry
	UCb016	32°52′43.50″S – 55°37′9.10″W	Geochemistry
	UCb015	32°52′43.50″S – 55°37′9.10″W	Geochemistry
Cerrezuelo Formation	UC019	33°15′37.90″S – 55°59′51.60″W	Petrography, U–Pb
	UC014	32°56′42.10″S – 55°35′40.40″W	Petrography, Zr Morphology
	UC013	32°56′42.10″S – 55°35′40.40″W	Petrography, Zr Morphology, U–Pb
	UC009	32°49′51.40″S – 55°23′5.60″W	Geochemistry
	UC008	32°49′51.40″S – 55°23′5.60″W	Petrography
	UC007	32°49′51.40″S – 55°23′5.60″W	Geochemistry
	UC006	32°50′56.50″S – 55°23′17.80″W	Petrography
	UC005	33° 0′25.90″S – 55°25′22.60″W	Petrography, U–Pb
	UC004	33° 0′25.90″S – 55°25′22.60″W	Petrography
	UC002	33° 1′0.00″S – 55°33′8.30″W	Geochemistry
	UC001	33° 1′0.00″S – 55°33′8.30″W	Petrography, U–Pb

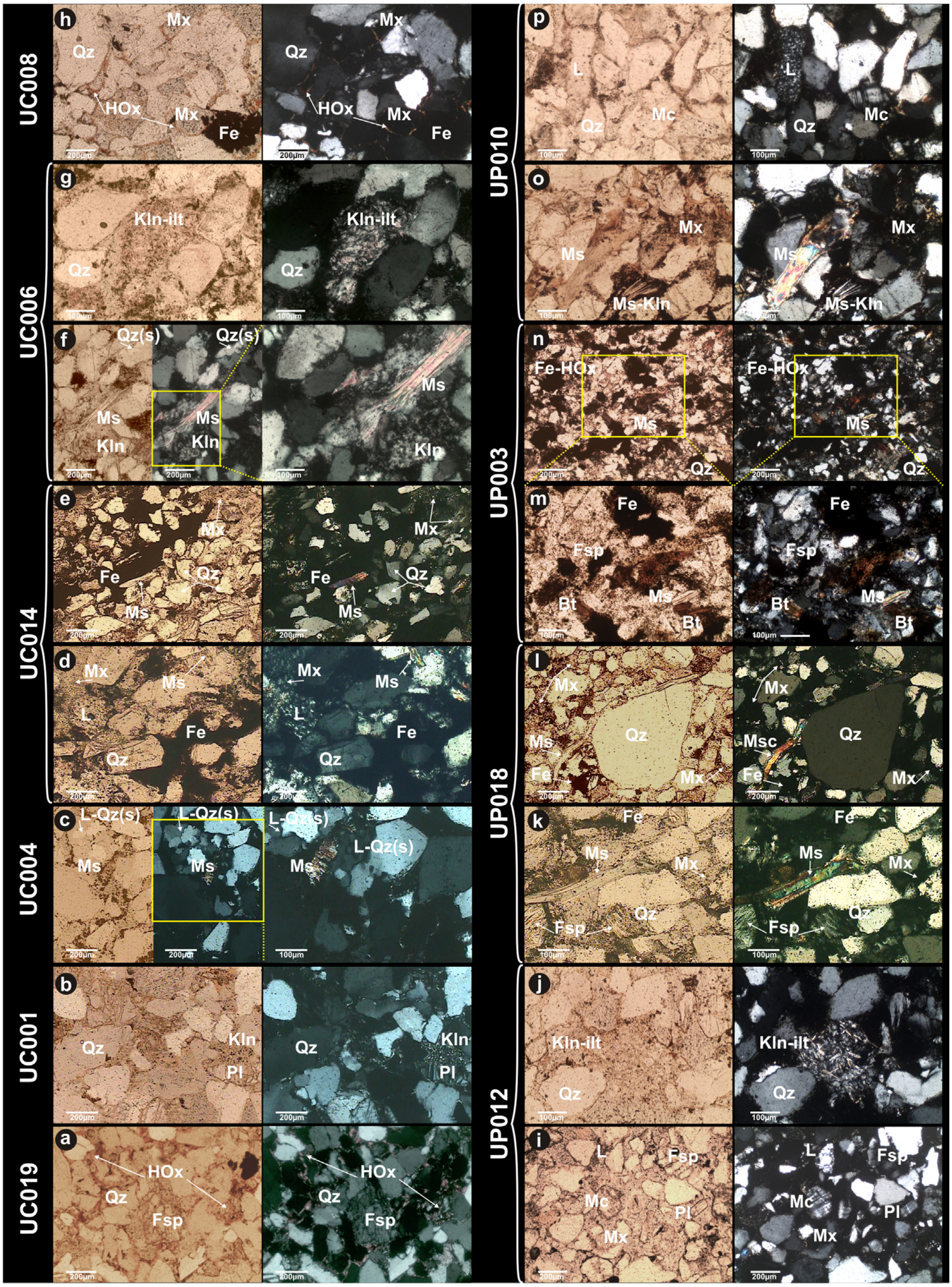


Fig. 4. Thin sections from Cerrezuelo (a, b, c, d, e, f, g, h) and La Paloma (i, j, k, l, m, n, o, p) units in stratigraphic order. Qz: Quartz; Qz(s): sutured Quartz; Ms: Muscovite; L: Lithic; Fe: Iron oxides; HOx: Hydroxides; Mx: Matrix, Kln: Kaolinite; ilt: Illite; Fsp: Feldspars; Mc: Microcline; Pl: Plagioclase: Bt: Biotite.//nicols on the left, X nicols on the right.

Regionally, such diverse assemblages of marine taxa occur in lower Emsian strata, such as the Ponta Grossa Formation of the Paraná basin and Lower Icla Formation of the Devonian basin of Bolivia. Although tenuous, we suggest an early Emsian age for the Cordobés Formation.

The *La Paloma Formation* is a sandy-pelitic to conglomeratic upward-coarsening succession, recording the final phase of basin deepening and over filling. It is reddish to purple in color with a muscovite-rich quartz-feldspathic composition (Fig. 3d). Maximum thickness recorded in the Rincón del Bonete borehole is 55 m, compared with just 36 m in the La Paloma well. The formation was deposited during the regressive phase of the Devonian sea, expressed in littoral sedimentation. The Malvinokaffric invertebrate fauna has largely disappeared, and only trace fossils and few

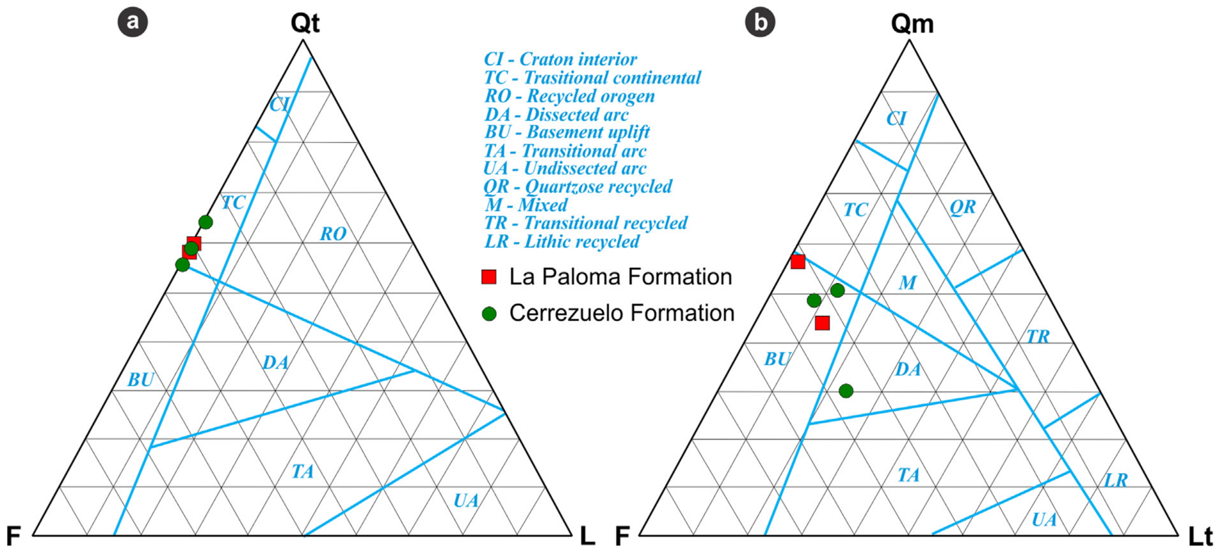


Fig. 5. Provenance ternary diagrams after Dickinson et al. (1983) from Durazno Group sandstones. Abbreviations: K: feldspars, Qt: total quartzs, Lt: total lithoclasts (including polycrystalline quartz), Qm: monocrystalline quartz, L: Lithoclasts.

Table 2
Major oxides (in %) and trace elements (expressed in ppm) of silstones and shales from Durazno Group.

Sample	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	Cr_2O_3	LOI	Sum	Ni	Sc	Ba
	%	%	%	%	%	%	%	%	%	%	%	%	%	ppm	ppm	ppm
UC002	69.86	14.6	5.25	0.5	0.1	0.08	2.53	0.93	0.04	0.01	0.008	5.8	99.76	43	12	532
UC007	45.29	35.09	1.99	0.23	0.11	0.04	0.72	1.65	0.18	<0.01	0.018	14.4	99.71	48	19	376
UC009	52.87	30.04	1.02	0.08	0.06	0.04	0.15	2.34	0.08	<0.01	0.022	13.1	99.81	28	14	159
UCB-015	53.99	26.38	3.42	0.98	0.19	0.09	3.69	0.98	0.11	<0.01	0.018	9.9	99.78	47	21	466
UCB-016	51.32	26.05	2.1	0.75	0.2	0.1	2.86	0.99	0.11	<0.01	0.019	15.3	99.75	27	19	421
UCB-017	55.36	26.47	1.61	0.96	0.15	0.12	3.91	1.08	0.1	<0.01	0.018	10	99.76	40	21	484
UP-011	58.62	18.84	7.22	0.83	0.27	0.19	4.32	0.99	0.14	0.06	0.01	8.3	99.78	<20	16	477
Sample	**Be**	**Co**	**Cs**	**Ga**	**Hf**	**Nb**	**Rb**	**Sn**	**Sr**	**Ta**	**Th**	**U**	**V**	**W**	**Zr**	**Y**
	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
UC002	2	13.9	5.6	20.1	12	19.5	98.8	5	71.3	1.6	19.8	3	157	3.1	454.1	40.1
UC007	4	7.5	5.4	44.1	8.6	35.1	49.9	7	315.4	2.5	37.8	3.5	138	2.7	312.1	45.7
UC009	4	5.4	0.9	33.6	15.6	41.9	8.8	4	179.1	2.8	21.7	4	106	3.2	608.9	31.9
UCB-015	5	4.2	18	34.7	5.5	20.5	193.7	6	204.4	1.4	22.7	4.5	178	2.9	173.1	41
UCB-016	4	4.5	14.5	33	5	20.4	161.7	6	210.7	1.5	20.5	6.7	143	2.5	152.4	29.3
UCB-017	3	2.8	17.4	32	5.2	21.4	199.3	6	190.2	1.6	19.5	4.5	157	2.6	179.9	33.4
UP-011	3	6.8	5.9	20.7	6.5	19.8	161.3	5	106.6	1.4	17.9	2.7	151	2.5	228.4	42.2
Sample	**TOT/C**	**TOT/S**	**Mo**	**Cu**	**Pb**	**Zn**	**Ni**	**As**	**Cd**	**Sb**	**Bi**	**Ag**	**Au**	**Hg**	**Tl**	**Se**
	%	%	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppb	ppm	ppm	ppm
UC002	<0.02	<0.02	4	12.9	14.1	80	33.9	6.6	<0.1	0.1	0.2	<0.1	1.5	<0.01	<0.1	<0.5
UC007	0.02	0.03	0.5	5.6	10.1	16	11.1	1.6	<0.1	<0.1	0.1	<0.1	<0.5	<0.01	<0.1	<0.5
UC009	<0.02	<0.02	0.1	3.5	3	7	6.5	<0.5	<0.1	<0.1	<0.1	<0.1	<0.5	<0.01	<0.1	<0.5
UCB-015	0.09	<0.02	0.8	55.2	24.4	36	23.1	4.2	<0.1	0.2	0.7	<0.1	<0.5	0.02	0.2	<0.5
UCB-016	3.87	0.12	0.7	307.9	9.9	16	19.1	1.6	<0.1	<0.1	0.6	0.7	<0.5	0.15	<0.1	1.8
UCB-017	0.07	<0.02	<0.1	12.9	16.9	15	14.4	<0.5	<0.1	<0.1	0.4	<0.1	<0.5	0.03	0.2	<0.5
UP-011	<0.02	<0.02	0.9	15.7	4.4	22	13.3	3.8	<0.1	0.5	0.4	<0.1	<0.5	<0.01	0.2	<0.5

Table 3
Rare earth elements data (expressed in ppm) of siltstones and shales from Durazno Group.

REE (ppm)		La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Sum
Samples	UC002	51.2	121.3	11.89	42.6	7.57	1.32	6.59	1.13	6.64	1.36	4.09	0.65	4.41	0.65	261.4
	UC007	182.3	409.2	37.23	128.7	19.78	4.02	15.81	2.02	9.61	1.59	4.26	0.6	3.67	0.49	819.28
	UC009	72.9	125	17.86	66.7	11.73	2.51	9.48	1.31	6.62	1.13	3.29	0.45	2.84	0.46	322.28
	UCB015	55.2	109.1	14.92	57.7	10.13	2.17	9.26	1.53	8.33	1.65	4.95	0.76	4.85	0.73	281.28
	UCB016	55.9	113.1	14.93	56.3	9.38	1.93	7.52	1.16	5.75	1.14	3.37	0.52	3.67	0.52	275.19
	UCB017	51.2	97.5	13.06	51.1	10.43	2.13	8.56	1.23	6.22	1.19	3.81	0.62	3.99	0.59	251.63
	UP011	49.6	95.7	12.7	49.4	9.41	1.98	8.32	1.33	7.54	1.55	4.67	0.69	4.47	0.66	248.02
	UCC Rudnick and Gao (2003)	31	63	7.1	27	4.7	1	4	0.7	3.9	0.83	2.3	0.3	2	0.31	148.14

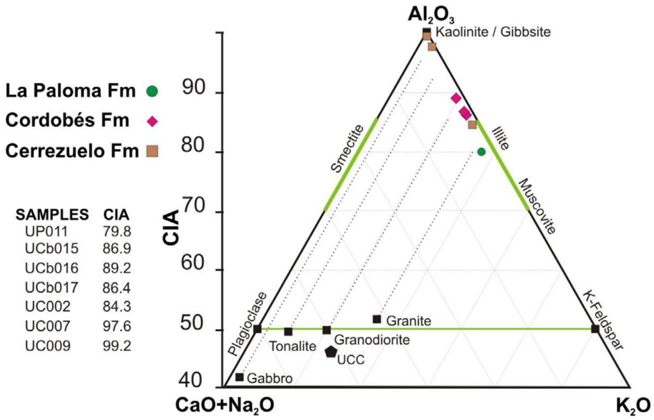


Fig. 6. A-CN-K diagram for the Durazno Group. UCC (upper continental crust), idealized mineral compositions and crystalline rocks values are according to Taylor and McLennan (1985). Lines indicate the predicted weathering trend for the average rocks composition (Nesbitt and Young, 1984, 1989). Note that the lower part of the diagram with A < 40 is not shown. The left side of the figure shows the range of CIA values.

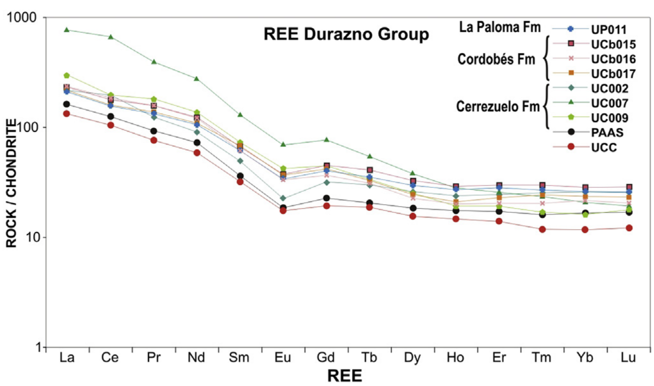


Fig. 7. Chondritic-normalized REE patterns from the Durazno Group. PAAS: Post-Archean Australian Shales (Nance and Taylor, 1976); UCC: upper continental crust (Rudnick and Gao, 2003). Chondritic normalization values from Sun and McDonough (1989).

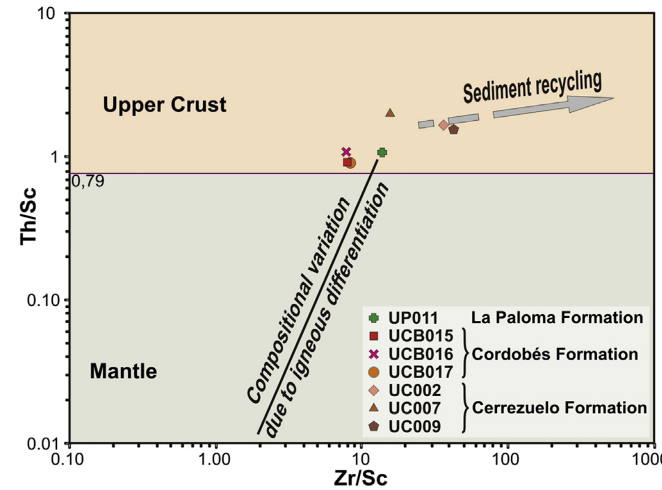


Fig. 8. Th/Sc versus Zr/Sc diagram after McLennan et al. (2003).

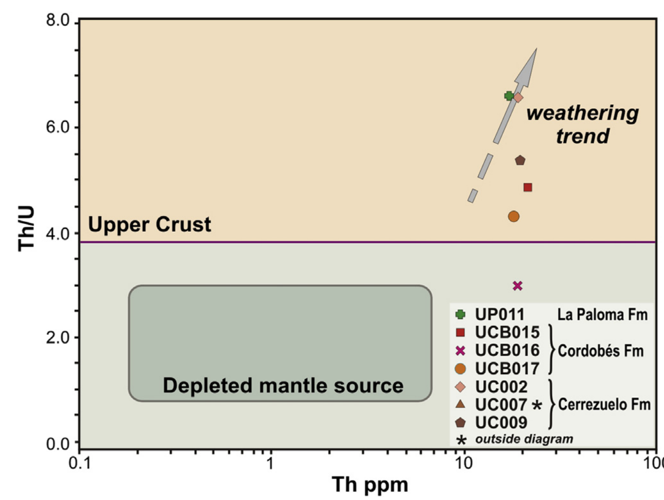


Fig. 9. Th/U vs Th after McLennan et al., (1993).

Table 4
Selected element ratios of Durazno Group.

Sample	Th/U	Th/Sc	Zr/Sc	La/Th	Eu_n/Eu^*
UC002	6.60	1.65	37.84	2.59	0.57
UC007	10.80	1.99	16.43	4.82	0.69
UC009	5.43	1.55	43.49	3.36	0.73
UCB-015	5.04	1.08	8.24	2.43	0.68
UCB-016	3.06	1.08	8.02	2.73	0.70
UCB-017	4.33	0.93	8.57	2.63	0.69
UP-011	6.63	1.12	14.28	2.77	0.68

tentaculitids are known (Sprechmann et al., 1993). In the Paraná basin, Bosetti et al. (2012) record a substantial turnover or extinction of Malvinokaffric taxa during the latest Emsian. On the basis of stratigraphic correlation with the better studied Bokkeveld Group of South Africa, A. Tankard (personal communication) suggests a late Emsian to early Eifelian age. Likewise, there is a marked reduction in diversity at the transition to the Upper Icla Formation of Bolivia. Together, these suggest a late Emsian to earliest Eifelian age for the La Paloma Formation.

In the subsurface, the Devonian section was recognized in the so called Uruguayan Norte basin (Fig. 2); key exploration wells are Rincón del Bonete, La Paloma, Cuchilla Zamora, Achar, Salsipuedes (Daners et al., 2013). Seismic data show several extensional depocenters, possibly reflecting basin compartmentalization. It is probably these structural units that preserve what is believed to be pre-Carboniferous organic-rich black shales which have been the

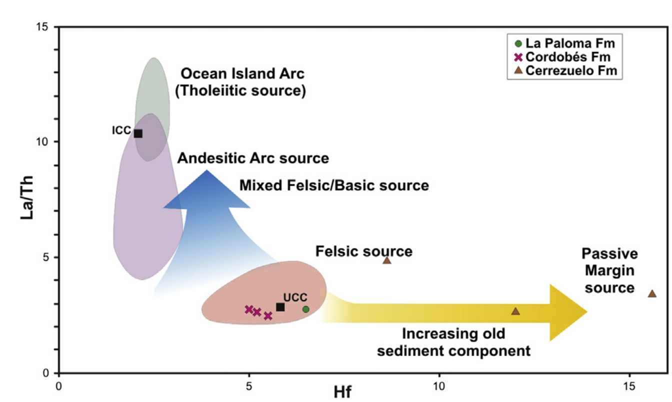


Fig. 10. La/Th vs Hf diagram (based on Floyd and Leveridge, 1987; Gu et al., 2002) to determine average source composition of the Durazno Group. ICC: lower continental crust; UCC: upper continental crust.

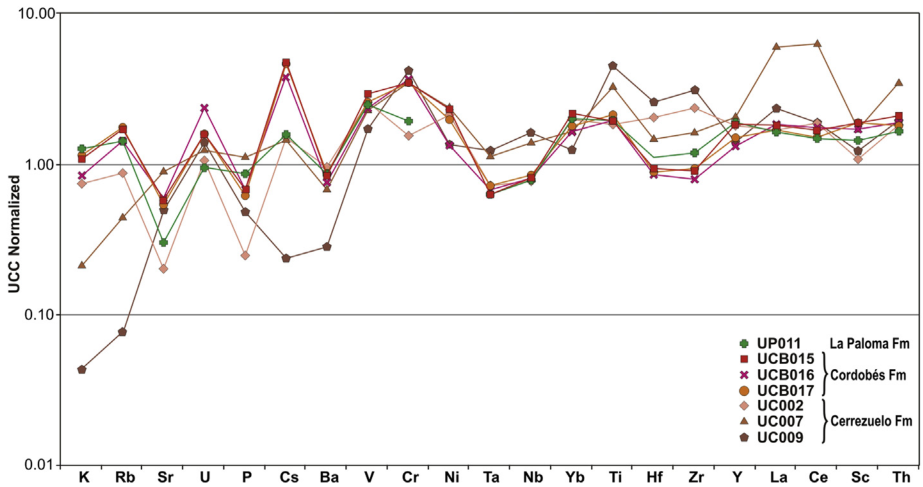


Fig. 11. Upper continental crust-normalized multi-element patterns (Floyd et al., 1991); elements are arranged from left to right in order of decreasing ocean residence time and comprise a relatively mobile group (from K to Ni) and a more stable group (from Ta to Th). Normalization values are from Taylor and McLennan (1985), except for P and Yb which are from McLennan et al. (2006).

targets for hydrocarbon exploration (de Santa Ana, 1989; de Santa Ana et al., 2008).

3. Analytical technique and sampling

Measured sections of the Cerrezuelo, Cordobés and La Paloma formations in outcrop are located in the vicinity of Blanquillo, Villa del Carmen, Capilla Ferruco, Cerrezuelo and La Paloma (Figs. 2 and 3). All lithological types along the stratigraphic succession were sampled (Zimmermann et al., 2015). Table 1 summarizes the GPS locations and the methodology applied to each sample. Six sandstones sampled in the Cerrezuelo Formation are homogeneous quartz sandstones with grain size varying between 100 and 200 μm. From the base upwards, they are designated as: UC019, UC001, UC004, UC005, UC006 and UC008. Four sandstone samples from the La Paloma Formation, grain size varying from 300 to 600 μm, are labeled from bottom up as: UP018, UP012, UP003 and UP010.

Twelve thin sections were examined using a Zeiss optical microscope to determine the textural and optical properties of minerals as well as paragenetic associations. For whole-rock geochemistry, seven pulp samples were prepared and sent to ACME Labs, Canada, for analysis. Major elements were obtained by inductively coupled plasma element spectroscopy (ICP-ES) on fusion beads. Loss on ignition (LOI) was determined by igniting a sample split and measuring the weight loss. Rare earth elements (REE) and certain trace elements were analyzed by ICP-MS. The morphology of detrital zircons from samples of the Cerrezuelo (UC013 and UC014; n = 30 grains) and La Paloma (UP018; n = 24 grains) formations was examined using a scanning electron microscope (SEM-JEOL JSM 6360 LV) at the Museum of La Plata, Argentina. A total of 385 detrital zircon grains were measured by U–Pb method from six quartz sandstones of the Cerrezuelo (UC001, UC019, UC005 and UC013; n = 257 grains) and La Paloma (UP018 and UP012; n = 128 grains) Formations. No zircons were found in silt-shale samples from the Cordobés Formation. Detrital zircons were obtained after crushing and sieving about 3–5 kg of each sample. The fractions retained in less than 140-micron mesh were separated using hydraulic processes to obtain heavy mineral preconcentrates. These were treated with bromoform to obtain the complete heavy mineral spectra. Methylene iodide was used to achieve a fraction enriched in zircons, followed by an electromagnetic separation with Frantz Isodynamic equipment when necessary. The final selection of crystals, mounted in 2 cm diameter epoxy resin and polished, was examined under a binocular microscope. The grains were photographed in reflected and transmitted light, and cathodoluminescense (CL) images were produced in order to investigate the internal structures of the zircon crystals as well as to characterize different populations. U–Pb age determinations by LA-ICP-MS were carried out at the Institute of Geological Sciences, University of Sao Paulo, according to standard procedures (Sato et al., 2010). Choice of spot sites was guided by CL imaging. All LA-ICP-MS zircon data are shown in supplementary Tables. The U–Pb isotope analyses were performed on zircon grains using a Thermo-Fisher Neptune laser-ablation multicollector inductively coupled plasma mass spectrometer equipped with a 193 Photon laser system. For the operating conditions and instrument settings of the NEPTUNE instrument and laser ablation system during analytical sessions see Sato et al. (2010). For interpretation of the detrital zircon ages, only analyses less than 10% discordant were considered. The data are portrayed in Concordia or Tera-Wasserburg diagrams generated with the programme Isoplot/Ex (Ludwig, 2001). The analytical routine follows a procedure that starts with 3 measures of GJ standard, followed by measurements of two blanks. After these steps a sequence of 13 analyses of unknown zircons is performed. These data are reduced with the aid of Python software at University of Sao Paulo, Brazil.

4. Results

4.1. Petrographic examination

Petrographical analysis of sedimentary rocks has proved useful as an aid to determining provenance (Dickinson et al., 1983), but the resolution can be enhanced by the addition of geochemical and isotopic data. Sandstone petrography (Fig. 4) of both units (Cerrezuelo-La Paloma) shows that the sequences have a dominant quartz-feldspathic composition with a minor component of other minerals such as muscovite, as well as accessory minerals including opaque specimens and zircons. Lithoclasts of igneous-metamorphic and sedimentary compositions are also recognized. Quartz grains usually have undulating extinction, and polycrystalline quartz is also present; quartz grains with triple points and engulfment are recognized and could be derived from metamorphic rocks. An igneous provenance is also suggested by the presence of K-feldspar (microcline) showing perthite textures. The

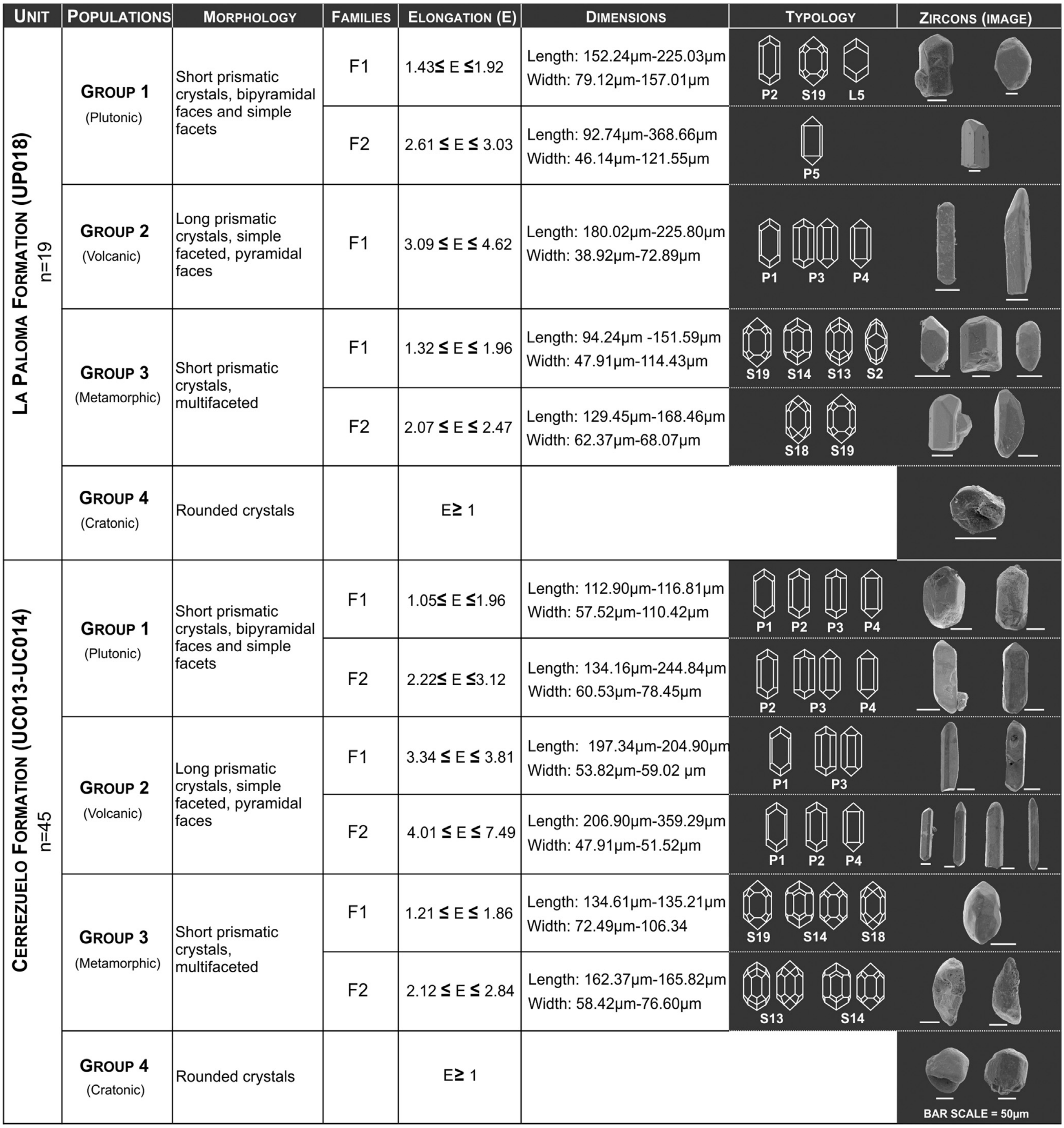


Fig. 12. Zircon populations identified according to Pupin (1980). On the right some SEM images are shown.

alkaline feldspars and plagioclases are altered to illite and kaolinite clays. Within the samples with homogeneous grain size, the quartz and feldspar fragments are angular to sub-angular, but in the poorly sorted samples the finer grains are sub-rounded. Lithoclasts are rounded to sub-rounded and the general texture is clast-supported. The Cerrezuelo Formation (Fig. 4a–h) has a poor clay matrix composed of kaolinite and illite. In comparison, the matrix of the La Paloma Formation (Fig. 4i–p) is more abundant and besides kaolinite and illite it also contains elongated and oriented quartz, feldspar and muscovite. Iron oxide cement has been observed in both units. The petrographical description is consistent with previous sedimentological analyses (Zalba et al., 1988).

Five samples were selected for point-counting under the microscope. They are composed of 50–60% quartz and 30–40% feldspar, classifying as arkosic arenites. In the Q-F-L diagram (Fig. 5a) samples from La Paloma and Cerrezuelo Formations cluster within the transitional continental block provenance, while in the Qm-F-Lt diagram (Fig. 5b) their distribution is more dispersed due to differences in the Qp content, although a provenance from a continental block is supported, and can be related to an intracratonic rift basin (Dickinson et al., 1983).

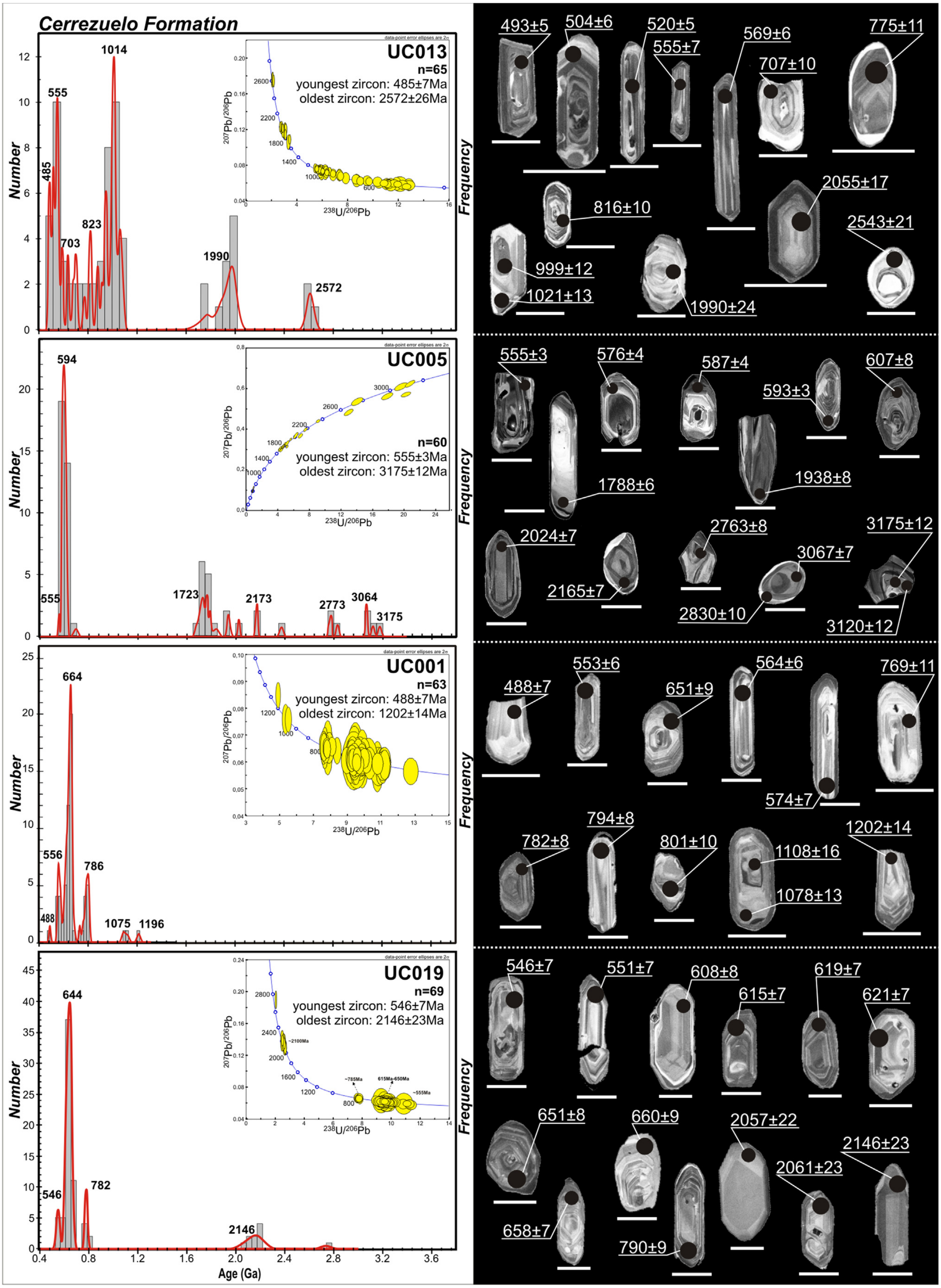


Fig. 13. Frequency histograms and probability curves of detrital zircon ages from sampled levels of the Cerrezuelo Formation. Insets show Concordia and Tera-Wasserburg diagrams. Data obtained by ICP-LA-MS methodology. Right: cathodoluminescence images of selected zircon grains. Scale bar 100 mμ, ages and errors in Ma.

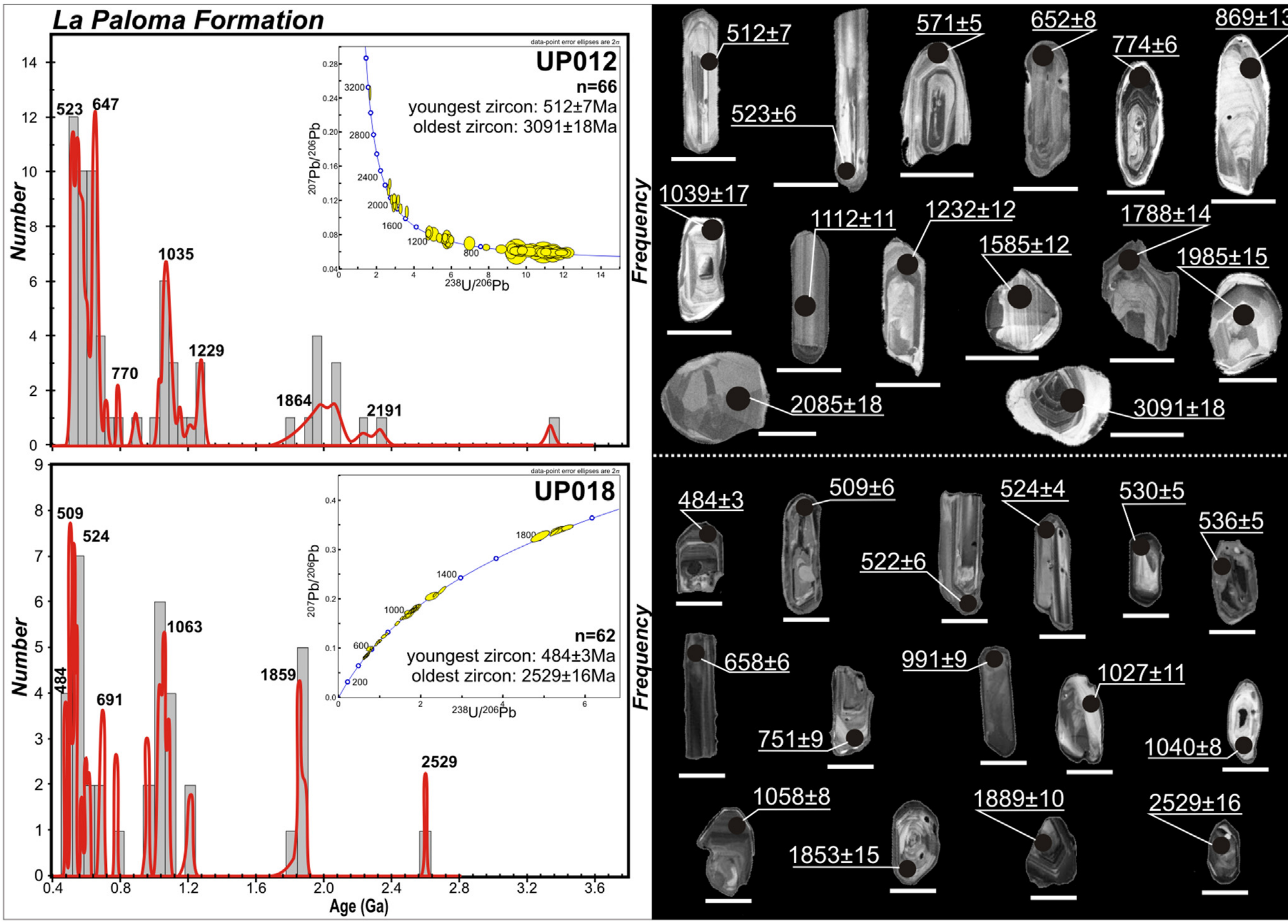


Fig. 14. Frequency histograms and probability curves of detrital zircon ages from sampled levels of the La Paloma Formation. Insets show Concordia and Tera-Wasserburg diagrams Data obtained by LA-ICP-MS methodology. Right: cathodoluminescence images of selected zircon grains. Scale bar 100 mμ, ages and errors in Ma.

4.2. Whole-rock lithogeochemistry

Whole rock geochemical analyses of sedimentary rocks are useful for provenance determinations, particularly when accompanied by petrographic studies and geochronological data of detrital heavy minerals. Weathering analysis and geochemical classifications are based on major elements, while certain trace elements (such as REE) and their ratios are used to characterize the composition of the source(s) (Tables 2 and 3).

4.2.1. Chemical Index of Alteration (CIA)

Because bulk chemical composition of detrital rocks is often affected by weathering and diagenesis which obscures the original composition of the source(s), it is important to evaluate the extent of these processes. The degree of primary material transformation due to weathering can be estimated using the Chemical Index of Alteration: CIA $= \{Al_2O_3/(Al_2O_3 + CaO_{(s)} + Na_2O + K_2O)\} \times 100$, where $CaO_{(s)}$ refers to the calcium associated with silicate minerals and the index is calculated by using mole fractions (Nesbitt and Young, 1982).

Several factors may affect CIA values in sedimentary rocks, such as grain size, mineral reactions during diagenesis (McLennan et al., 1993), mineral selection and mass loss during transport (Nesbitt and Young, 1982), mixture of detritus from different sources each with a different or unique weathering history (McLennan et al., 1993) and potassium metasomatism (Fedo et al., 1995). Generally, CIA values reflect the mobility of Ca^{+2}, Na^{+1} and K^{+1} with respect to Al^{+3} and Ti^{+2} (Nesbitt and Young, 1982). Index values between 50 (CIA value for unweathered crystalline rocks) and 60 are indicative of a low degree of weathering, values between 60 and 80 indicate moderately weathered rocks, while CIA values above 80 represent strongly weathered material (Fedo et al., 1995).

The Durazno Group is characterized by high CIA values, ranging from 82 to 99 for the Cerrezuelo Formation, from 86 to 89 for the Cordobés unit, and a value close to 80 for the La Paloma Formation sample. On a SiO_2 vs CIA diagram, despite SiO_2 dispersion, we observe strong weathering for all samples of the Durazno Group.

4.2.2. A-CN-K diagram

An A-CN-K display (Fig. 6) shows that most of the samples from the three formations plot towards the A-K line and around the illite composition, implying that most Ca and Na have been removed during the strong alteration that affected the units. Two samples from the Cerrezuelo Formation are grouped towards A, indicating dominance of kaolinite as a result of even more intense alteration. Samples follow a normal weathering path for UCC (upper continental crust), except that from the La Paloma Formation which might indicate a source composition more felsic (*i.e.* granite) than average UCC. Because of the conspicuous feldspar alteration observed in sandstone thin-sections of well and outcrop samples, together with the presence of a cold-climate Malvinokaffric fauna, it seems very likely that the high CIA values for the Durazno Group, and the Cerrezuelo Formation in particular, reflect post-depositional alteration.

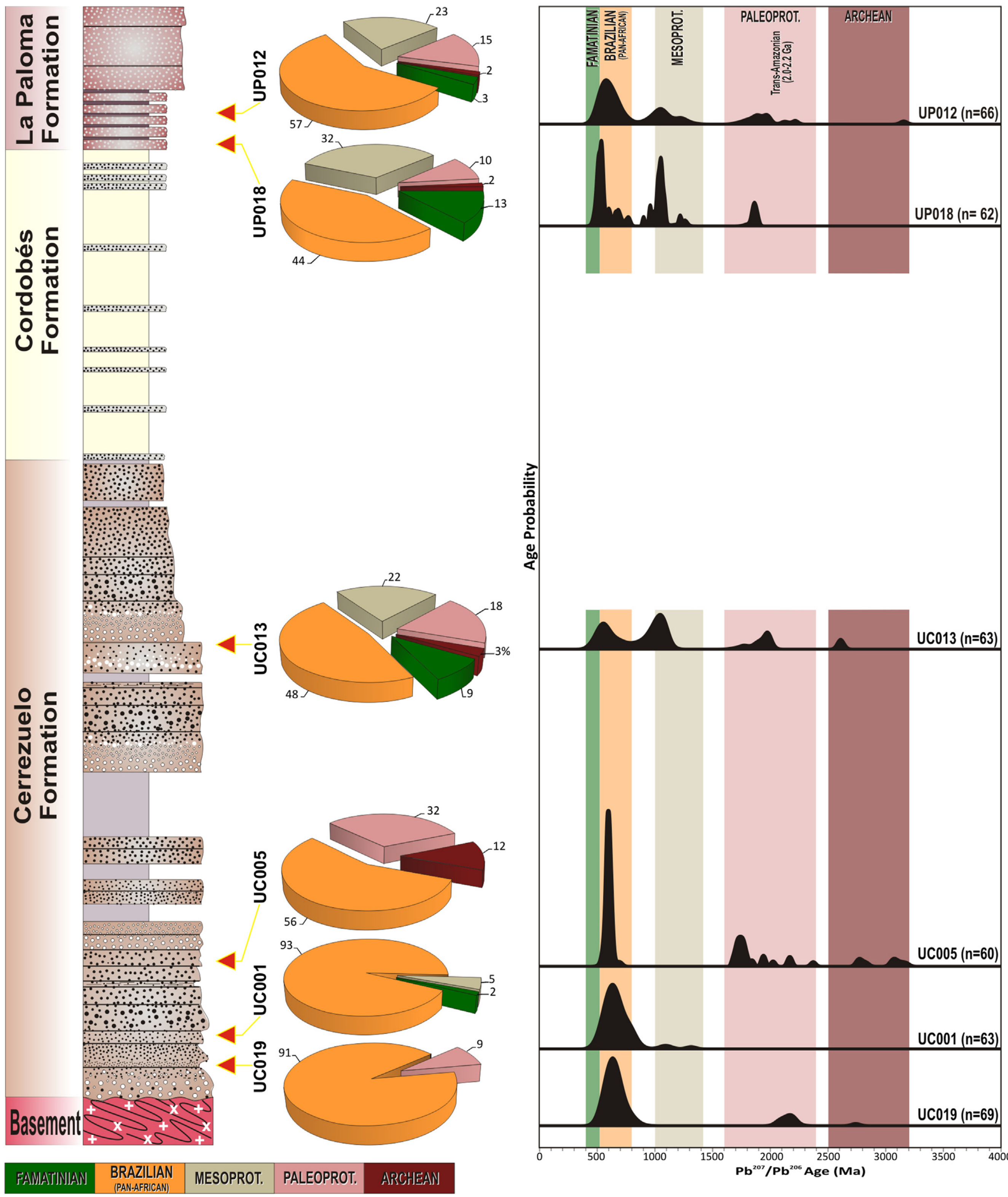


Fig. 15. Stratigraphic column showing the obtained U–Pb ages of the detrital zircons represented in percentage 'pie-diagrams'. On the right, the probability density distribution diagrams for each sample are shown. Different colors are from recognized South American orogenic cycles: Archean to Paleoproterozoic; Mesoproterozoic, Brazilian (Neoproterozoic-Early Cambrian) and Famatinian (Middle Cambrian-Devonian). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

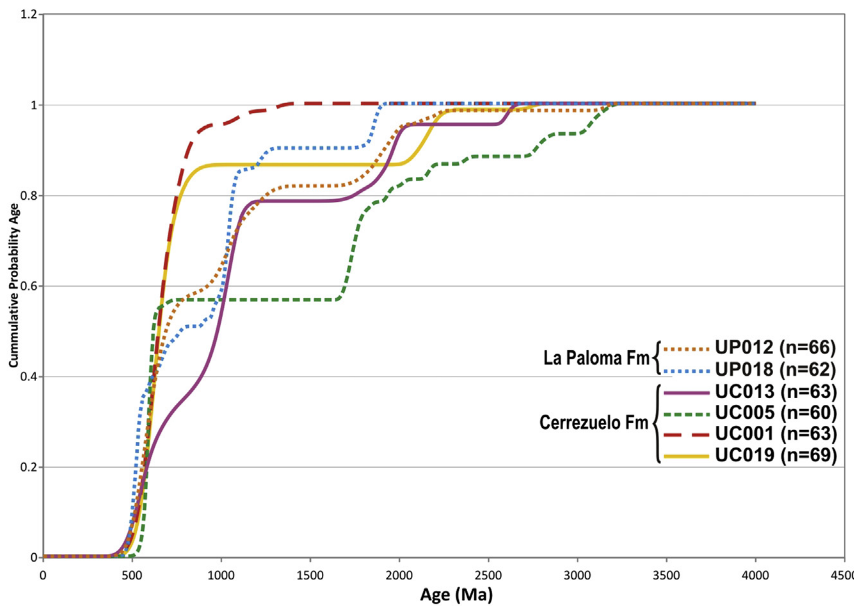


Fig. 16. Kolmogorov–Smirnov (K–S) sample test.

Table 5
Results of statistical Kolmogorov–Smirnov (K–S test, with error CDF) for all samples analyzed. a) Values P: Blank, P < 0.05; Yellow: P > 0.05. b) Values D.

a)	K-S P-values using error in the CDF					
Sample	**UC019**	**UC001**	**UC005**	**UC013**	**UP018**	**UP012**
UC019		**0.563**	0.006	0.000	0.001	0.015
UC001	**0.563**		0.000	0.000	0.000	0.001
UC005	0.006	0.000		0.013	0.002	0.037
UC013	0.000	0.000	0.013		**0.222**	**0.111**
UP018	0.001	0.000	0.002	**0.222**		**0.648**
UP012	0.015	0.001	0.037	**0.111**	**0.648**	
b)	**D-values using error in the CDF**					
Sample	**UC019**	**UC001**	**UC005**	**UC013**	**UP018**	**UP012**
UC019		0.135	0.298	0.462	0.340	0.265
UC001	0.135		0.433	0.537	0.420	0.348
UC005	0.298	0.433		0.285	0.335	0.252
UC013	0.462	0.537	0.285		0.187	0.210
UP018	0.340	0.420	0.335	0.187		0.131
UP012	0.265	0.348	0.252	0.210	0.131	

4.2.3. Trace elements

Trace elements, including rare earth elements (REE) and their ratios, are useful to determine recycling, weathering and average composition of the source mix. Chondritic normalized REE diagrams (normalization values from Sun and McDonough, 1989) of the Durazno Group reveal patterns essentially parallel to PAAS (Post-Archean Australian Shales; Nance and Taylor, 1976) and UCC (Rudnick and Gao, 2003), despite a general enrichment in both LREE and HREE, which is more evident for sample UC007 of the Cerrezuelo Formation and is probably related to selective concentration of heavy minerals such as zircon and allanite (Fig. 7; Table 3). All samples display the Eu-anomaly, typical for UCC derived detrital sedimentary rocks. Eu_N/Eu^* values ranging from 0.57 to 0.73 are in accordance with derivation from average UCC ($Eu_N/Eu^* = Eu_N/(0.67\ Sm_N + 0.33\ Tb_N)$) (Table 4).

On a Th/Sc vs Zr/Sc diagram (Fig. 8; Table 4), some samples from the Cerrezuelo Formation show recycling, reflecting the increasing sedimentary component shown by higher Hf concentrations. These, together with very high Zr, Th, REE concentrations of shales from the Cerrezuelo Formation (see Table 2), as well as the presence of rounded zircons in the coarser fractions are interpreted as evidence of reworking of older sedimentary units that lead to selective concentration of heavy minerals. Th/Sc ratios above UCC values not accompanied by high Zr/Sc ratios might indicate a sediment supply from a source more felsic than average UCC.

The Th/U vs U display (McLennan et al., 1993) provides a tool to estimate the amount of weathering and/or recycling of sedimentary rocks, since there is a tendency for an increase of Th/U ratios above upper crustal values of 3.8–4.0 as a result of alteration. As deduced using the CIA, Th/U ratios well above average values of the upper continental crust shown by most samples of the Durazno Group indicate intense weathering (Fig. 9; Table 4). Only one sample of the Cordobés Formation reflects U enrichment (6.7 ppm; Table 2).

On a La/Th vs Hf diagram, a UCC provenance composition for the Durazno Group is shown by La/Th ratios between 2.43 and 4.82. Except for the Cerrezuelo Formation, Hf concentrations are typical of felsic source, which shows an increasing sedimentary component probably related to sedimentary recycling (Fig. 10; Table 4).

The same scenario may be observed in upper continental crust-normalized multi-element patterns (Fig. 11; Table 2; Floyd et al., 1991), where the Cerrezuelo Formation shows a depletion of the more mobile elements following strong post-depositional alteration. This is demonstrated by high CIA values and petrographic observations, and enrichment in elements located towards the right of the diagram, implying the influence of heavy mineral concentration. The La Paloma Formation displays the least differentiated pattern of all units of the Durazno Group with respect to the UCC.

4.3. Zircons morphology and Th/U ratios

Following Pupin (1980) and Gärtner et al. (2013), parameters used to identify population differences are size, shape, habit, crystal elongation and roundness. Several zircon groups are identified that represent plutonic, volcanic, metamorphic and recycled sources. Groups and families determined are shown in Fig. 12.

Four groups were recognized for each formation as cratonic, metamorphic, volcanic and plutonic grains. Many zircon grains show subhedral to euhedral morphologies, indicating a near-source provenance, but others are rounded, indicating a recycling by cannibalism, or particular hydrodynamic sedimentary conditions (Gärtner et al., 2013).

Most zircons have oscillatory zoning, with Th/U ratios mostly >0.1 (only six grains show low ratio) implying that the great majority of zircons were derived from igneous sources (Table 4, Table. S5–S9). In general, low Th/U (< 0.1) in zircon grains can be an indication of metamorphic origin, however metamorphic zircons with high Th/U exist, particularly in high grade rocks (Rubatto, 2002; Harley et al., 2007). The younger zircon grain ages from all studied samples show ratios between 0.43 and 1.1.

4.4. U–Pb detrital zircon ages

The analysis of detrital zircons has been widely used as a guide to the mechanisms of growth and recycling of the continental crust (Fedo et al., 2003). Interpreting zircon provenance helps our understanding of the geological history by including evidence of all sources and their relationship to each other. Despite some limitations, the almost ubiquitous presence of zircon grains in sedimentary deposits makes them a target for precise U–Pb age dating and the possibility of establishing the maximum depositional age of any sequence or unit (Fedo et al., 2003). However, the provenance of detrital zircons, their origin, erosion, transport and deposition depend of various factors which should be considered when interpreting zircon age patterns (Moecher and Samson, 2006).

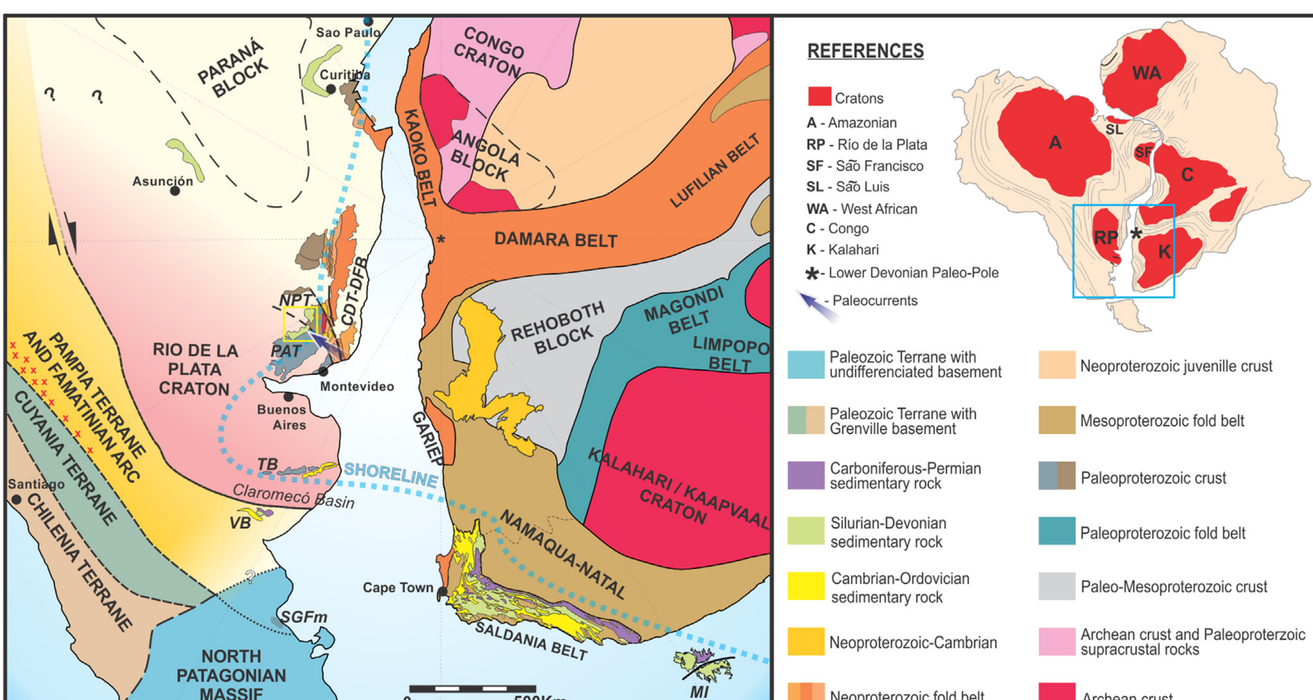


Fig. 17. SW Gondwana paleogeographic sketch map during Early Devonian time (based on Torsvik et al., 2012). The shoreline is after Linol et al. (2015). PAT: Piedra Alta terrane; NPT: Nico Pérez terrane; CDT-DFB: Cuchilla Dionisio-Dom Feliciano belt; TB: Tandilia belt; VB: Ventania belt.

Data from the detrital zircons analyzed in this study are presented in Tables S5–S10 and Figs. 13 and 14 are described below.

4.4.1. Cerrezuelo formation

Samples UC001 and UC019 are characterized by a dominance of Neoproterozoic detrital ages (91 and 94% respectively), ranging from 800 to 546 Ma. Furthermore, almost 5% of ages measured in sample UC001 (63 grains) are Mesoproterozoic (M3) with a range of ages between 1200 and 1078 Ma, as well as a Late Cambrian age of 488 ± 7 Ma derived from a single zircon. Sample UC019 (n = 69) also displays 9% of Paleoproterozoic ages between 2146 and 2057 Ma.

The main peak of detrital zircon ages in sample UC005 (n = 60) is Neoproterozoic with an age range 694–555 Ma (~57%), a prominent Paleoproterozoic peak with ages between 1796 and 1680 Ma (P4: 20%), 2024 and 1844 Ma (P3: 6.7%), 2372 and 2165 Ma (P2: 5%). Neoarchean zircons with ages ranging from 2778 to 2763 Ma are scarce (3.3%), and Mesoarchean (3175–2830 Ma) ages are also present (8.3%).

Data acquired from 65 zircons in sample UC013 still show the predominance of Neoproterozoic ages between 999 and 543 Ma (~45%), but not as abundant as in samples from the lower levels of the formation. Other peaks present are of Mesoproterozoic age between 1090 and 1000 Ma (M3: 21.5%), Paleoproterozoic age between 2469 and 1659 Ma (P4: 3.1%, P3: 12.3%, P2: 1.54% and P1: 1.5%), and Neoarchean age 2572–2543 Ma (3.1%). This sample also records the youngest detrital zircons with Cambrian to Early Ordovician ages (531 and 485 Ma).

4.4.2. La Paloma formation

Sample UP018 (n = 62) shows a dominance of Neoproterozoic ages ranging from 991 to 546 Ma (25.8%); Early Cambrian ages between 540 and 520 Ma are also frequent (17.7%). Mesoproterozoic zircons represent 32% of all data, whereas 27.4% belong to the M3 with ages between 1088 and 1001 Ma while 4.8% has an age distribution between 1266 and 1200 Ma (M2). Middle Cambrian detrital zircons represent 11.3% (511–501 Ma) and Paleoproterozoic zircons between 1889 and 1820 Ma (9.7%; P3). The youngest zircon was found in this sample, an Early Ordovician age of 484 ± 3 Ma. The oldest zircon in this sample has a Neoarchean age of 2529 ± 16 Ma.

Sample UP012 produced an Early-Middle Cambrian dataset, with ages between 541 and 512 Ma (~12%), a dominance of Neoproterozoic detrital grains (48%) with ages ranging from 998 to 542 Ma, a Mesoproterozoic contribution between 1585 and 1020 Ma (M3: 16.7%, M2: 4.5% and M1: 1.5%), Paleoproterozoic ages ranging from 2085 to 1726 Ma (P4: 3%, P3: 10.6%, P2: 1.5%), and one zircon grain of Mesoarchean age 3091 Ma.

5. Discussion

5.1. Provenance patterns and K–S test

A visual comparison of the probability density distribution diagrams of the dated samples (Fig. 15) allows differentiating of sets with specific provenance patterns.

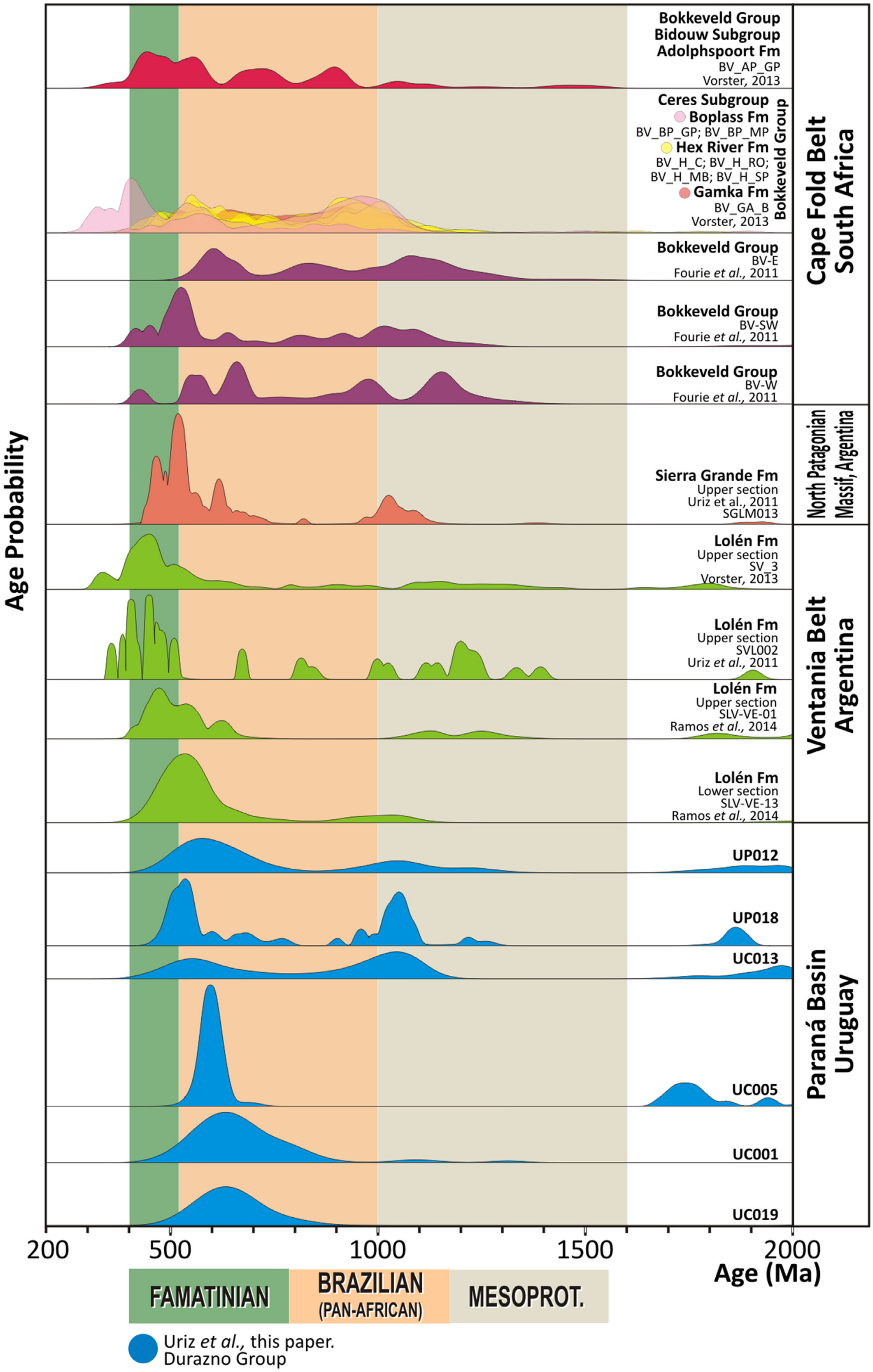
To assess the heterogeneity of the age distributions, the Kolmogorov–Smirnov (K–S) two-sample test was applied (Berry et al., 2001) (Fig. 16; Table 5). This test provides a means to compare mathematically two detrital zircon age distributions to determine if there is a statistically significant difference between them. The method is independent of any assumptions about the probability distribution of a sample and allows comparison of both age values (peak locations) and distributions (peak shapes) using the parameter P (DeGraaff-Surpless et al., 2003). According to the above mentioned parameters, a good correlation between samples of the Durazno Group is observed. Ages of the younger detrital zircon grains across all formations of the Durazno Group are similar, pointing to broadly similar ages of sediment deposition. The maximum sedimentation age of the Cerrezuelo Formation (488–485 Ma) is within error identical to that obtained for the La Paloma Formation (Upper Cambrian-Lower Ordovician boundary).

5.2. Rock sources and paleogeography in broader SW Gondwana context

Fig. 15 presents an overview of the main detrital zircon populations found in the Durazno Group, indicating that three main sources are responsible for the vast majority of observed ages. The main peak corresponds to *Neoproterozoic ages* around 600 Ma that could have been derived from the Cuchilla Dionisio terrane (Bossi and Gaucher, 2004) or Dom Feliciano magmatic belt (Basei et al., 2008, 2011), which is developed in the southeastern part of Brazil and Uruguay, or even granitic rocks located in the Nico Pérez terrane. A second group of sources is characterized by *Mesoproterozoic ages* between 1000 and 1150 Ma that may confirm partial derivation from the easternmost domain of the Cuchilla Dionisio terrane (or Punta del Este terrane after Basei et al., 2011) developed in the southeastern part of Uruguay and, by extension, the Namaqua belt in South Africa (Eglington, 2006) (Fig. 17). The third group of ages is characterized by *Paleoproterozoic* and *Archean zircons* that may have been derived from basement underlying the Durazno Group, represented by the Piedra Alta and Nico Pérez terranes. The Nico Pérez terrane includes the Archean La China Complex (3.5–3.1 Ga; Hartmann et al., 2001; Gaucher et al., 2011), the Valentines Formation (2.6–2.1 Ga; Bossi et al., 2001) and the Paleoproterozoic Rapakivi Illescas batholith (1.8 Ga; Oyhantcabal et al., 2011). All these units are spatially closely related to the main exposure of the Cerrezuelo Formation which, together with petrographical characteristics, paleoenvironment conditions and paleocurrent distributions, suggests short distances of sediment transport.

Fig. 18 shows the distribution of detrital zircon ages, between 2000 and 200 Ma that compares the Durazno Group with other Gondwanian Devonian successions such as the Lolén Formation of the Ventania Belt, the Sierra Grande Formation of the North Patagonian Massif and the Bokkeveld Group of South Africa. As already stated, samples from the bottom section of the Cerrezuelo Formation (UC019, UC001 and UC005) have a similar sedimentary provenance, displaying age peaks at 600–650 Ma (Brazilian) and a minor contribution of Cambrian zircons (Famatinian). These patterns are different from both the upper part of the Durazno Group as well as the other Devonian units here considered. In contrast, the upper section of the Cerrezuelo Fm (UC013) and the La Paloma Formation (UP018, UP012) show greater variability of provenance ages indicating changes in the sedimentary supply. However, Fig. 18 shows conspicuous dissimilarities between their age patterns and those of the Lolén and Sierra Grande formations (Uriz et al., 2011; Uriz, 2014). Moreover, compared to the Bokkeveld Group, similarities in the provenance ages are found only in some of the samples recorded by Fourie et al. (2011) and Vorster (2013). The scarcity of both Ordovician detrital zircon ages and zircon ages older than 1300 Ma within the whole Durazno Group is remarkable.

Detrital zircon patterns are similar to those associated with sedimentary rocks of the Neoproterozoic-Cambrian Arroyo del Soldado Group (Blanco et al., 2009), implying recycling of older platformal sequences, an interpretation supported by the whole-rock geochemistry. Because the 550–484 Ma zircon population is too young to be assigned to the Cuchilla Dionisio-Dom Feliciano belt, we suggest that it is likely derived by cannibalism from


Bokkeveld Group
Bidouw Subgroup
Adolphspoort Fm
BV_AP_GP
Vorster, 2013
Ceres Subgroup
Boplass Fm
BV_BP_GP; BV_BP_MP
Hex River Fm
BV_H_C; BV_H_RO;
BV_H_MB; BV_H_SP
Gamka Fm
BV_GA_B
Vorster, 2013
Bokkeveld Group
Bokkeveld Group
BV-E
Fourie et al., 2011
Bokkeveld Group
BV-SW
Fourie et al., 2011
Bokkeveld Group
BV-W
Fourie et al., 2011
Cape Fold Belt
South Africa
Sierra Grande Fm
Upper section
Uriz et al., 2011
SGLM013
North Patagonian
Massif, Argentina
Lolén Fm
Upper section
SV_3
Vorster, 2013
Lolén Fm
Upper section
SVL002
Uriz et al., 2011
Lolén Fm
Upper section
SLV-VE-01
Ramos et al., 2014
Lolén Fm
Lower section
SLV-VE-13
Ramos et al., 2014
Ventania Belt
Argentina
UP012
UP018
UC013
UC005
UC001
UC019
Paraná Basin
Uruguay
Age Probability
200
500
1000
1500
2000
Age (Ma)
FAMATINIAN
BRAZILIAN
(PAN-AFRICAN)
MESOPROT.
Uriz et al., this paper.
Durazno Group

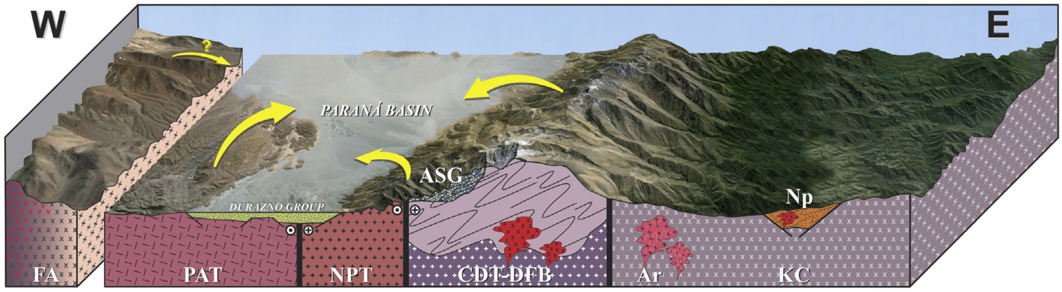


Fig. 19. Block diagram showing the Devonian Durazno depocenter as a part of the great Paraná basin developed over the Piedra Alta-Nico Pérez terranes as most probable sources of detritus. The highlands located in E and SE record the Neoproterozoic arc and supracrustal rocks. Ar: Arachania belt; ASG: Arroyo del Soldado Group; CDT-DFB: Cuchilla Dionisio terrane-Dom Feliciano belt; FA: Famatinian arc; KC: Kalahari craton; Np: Neoproterozoic sediments (Nama Group); NPT: Nico Pérez terrane; PAT: Piedra Alta terrane.

metasedimentary sequences, such as the Arroyo del Soldado Group, or perhaps the post-orogenic granitic magmatism of the Damara, Kaoko and Gariep belts (Miller and Frimmel, 2009), thus indicating the exhumation of these granitic rocks during the Devonian. A less likely possibility is a provenance of magmatic rocks of Late Cambrian to Devonian age that occur within the Famatinian arc west of the Durazno basin in central Argentina (Fig. 19).

Particularly conspicuous in our U–Pb detrital zircon results of the Devonian Durazno Group is the paucity of metamorphic supracrustal rocks of Mesoproterozoic Calimmian age (1600–1400 Ma) such as is exposed at the southern edge of the Nico Pérez terrane (Sánchez Betucci et al., 2009; Gaucher et al., 2011).

5.3. Tectonic setting of the Durazno basin

Neoproterozoic magmatism in the Cuchilla Dionisio-Dom Feliciano belt took place in older continental crust. Its tectonothermal evolution has much in common with the western Kalahari craton (Frimmel et al., 2011; Blanco et al., 2011, 2014b), and is markedly different to that of the Río de la Plata craton (Basei et al., 2000, 2005; Bossi and Gaucher, 2004). This led Gaucher et al. (2009) to propose a long and narrow continental fragment they name 'Arachania', the westernmost part (in present-day coordinates) of the ancestral Kalahari craton that split off during break-up of Rodinia (Frimmel et al., 2011, Fig. 19).

We attribute subsidence of the Durazno basin to an episode of extensional tectonism that reactivated pre-existing crustal fabrics. We base this interpretation on: (1) the immature or arkosic composition of the sandstones (abundant feldspar altered to kaolinite) at the base, evolving to a platformal sequence dominated by detrital quartz sedimentation; (2) differences in the patterns of the zircon age populations are probably the result of basin-margin or rift-flank uplift and denudation of the basement collages that make up the Río de la Plata craton and the Cuchilla Dionisio terrane; (3) there is no evidence, such as from geochemical and petrographic provenance proxies, of contemporaneous orogenic tectonism during the time of Durazno accumulation; (4) an extensional interpretation is consistent with that of the conjugate Bokkeveld basin of South Africa which has a decidedly extensional or transtensional overprint (Tankard et al., 2009). The pre-Durazno transpressional tectonism between the Río de la Plata craton and the Cuchilla Dionisio terrane was already completed by Devonian time. This collisional episode dates to the Cambrian, followed by a long period of thermal relaxation and post-orogenic magmatism that is documented in SW Gondwana (Frimmel et al., 2013).

6. Final remarks

a. Petrographical and geochemical data show that alteration was strong for all studied units of the Durazno Group, and point to an average source composition similar to UCC or slightly more felsic. Recycling of older volcano-metasedimentary sources can be deduced for the lower section of the basin fill.
b. The U–Pb detrital zircon data provided evidence of a significant contribution from Neoproterozoic sources to the entire Devonian succession. Evidence of a Mesoproterozoic source first appears in the upper part of the Cerrezuelo Formation and continues through La Paloma Formation. From the present assessment it is clear that contributions from Archean to Paleoproterozoic sources such as the Río de la Plata and Kalahari cratons were rare; implication regarding source areas evolution is that both cratons were covered by younger sedimentary sequences shedding the bulk of detritus to the Devonian basin.
c. Detrital zircon patterns suggest a main derivation from the Cuchilla Dionisio terrane (or Dom Feliciano belt), which formed a paleohigh as a result of its accretion to the Río de la Plata craton during the Brazilian (Pan-African) orogeny. Contributions from the cratonic Nico Pérez and Piedra Alta terranes are subordinate. Even though the Durazno and the Bokkeveld basins show similar subsidence/extensional tectonic history, comparison between them is rather difficult to achieve since they represent different depocenters separated by the above mentioned paleotectonic high.
d. In a SW Gondwana paleogeography, these provenance age patterns show high exhumation and erosion rates for the Cuchilla Dionisio-Dom Feliciano belt and, conversely, low exhumation and erosion rates for the cratonic areas during Devonian time.
e. Malvinokaffric invertebrate fossil assemblages, sparse palynological data and stratigraphic correlation indicate an Early Devonian age for basin subsidence and sedimentation. Further supporting this, the maximum sedimentation age is defined by scarce Ordovician detrital zircons of 485 and 484 Ma for the Cerrezuelo and La Paloma formations respectively.

Fig. 18. Comparison of the probability density distribution diagrams from Durazno Group (this paper) with other Gondwanian Devonian sequences (Uriz et al., 2011 for Lolén and Sierra Grande Fms; Fourie et al., 2011 for Bokkeveld Group; Vorster, 2013 for Lolén Fm and Bokkeveld Group; Ramos et al., 2013 for Lolén Fm), restricted to ages in between 2000 and 200 Ma.

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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.2016.01.002.

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