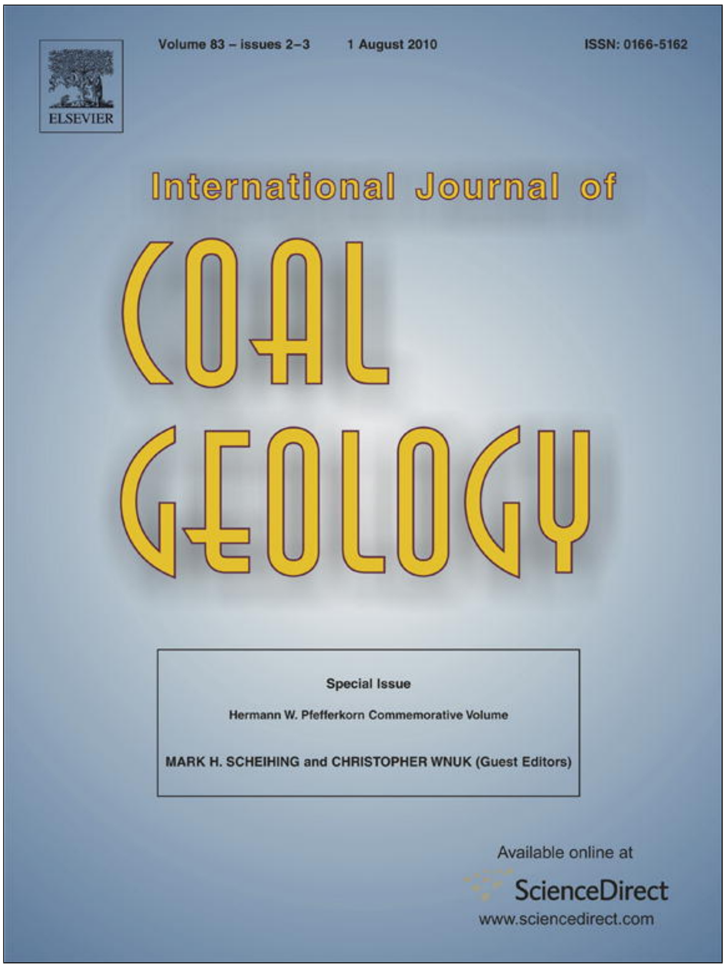
Volume 83 – issues 2–3
1 August 2010
ISSN: 0166-5162
ELSEVIER
International Journal of
COAL GEOLOGY
Special Issue
Hermann W. Pfefferkorn Commemorative Volume
MARK H. SCHEIHING and CHRISTOPHER WNUK (Guest Editors)
Available online at
ScienceDirect
www.sciencedirect.com

International Journal of Coal Geology 83 (2010) 276–291

Contents lists available at ScienceDirect

International Journal of Coal Geology

journal homepage: www.elsevier.com/locate/ijcoalgeo

Pennsylvanian and Cisuralian palynofloras from the Los Sauces area, La Rioja Province, Argentina: Chronological and paleoecological significance

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ARTICLE INFO

Article history:
Received 5 January 2009
Received in revised form 6 January 2010
Accepted 11 January 2010
Available online 20 January 2010

Keywords:
Palynostratigraphy
Paleofloras
Libertad Formation
Sauces Formation
Paganzo Basin
Gondwanan paleoclimate

ABSTRACT

Three outcrops of the Libertad and Sauces Formations from the Los Sauces area La Rioja Province, western Argentina, yielded the nine palynoassemblages studied here. Two assemblage zones are defined on the basis of the stratigraphic distribution and ranges of seventy five species of palynomorphs (42 species of spores, 32 pollen taxa and one fungus). Only thirteen species are common to both assemblages and ten species are first records for the Paganzo Basin. Assemblage 1 from the Libertad Formation is dominated by trilete spores of *Cristatisporites* (lycophyte) and *Punctatisporites* (pteridophyte). Monosaccate pollen (Coniferales/Cordaitales) is frequently present. Pteridosperms, mostly represented by *Cyclogranisporites*, are especially abundant in one level together with scarce striate bisaccate pollen grains. Assemblage 2 of the Sauces Formation is dominated by trilete spores related to the Pteridophyta (e.g., *Horriditriletes*, *Converrucosisporites*, *Granulatisporites*) and Sphenophyta. Monosaccate (Cordaitales/Coniferales) and taeniate and non-taeniate bisaccate pollen grains (Pteridospermales/Coniferales), are equally subordinated. Monosulcate pollen (Cycadophyta) and fungi (*Portalites gondwanensis*) are rare. Assemblage 1 is mainly Moscovian; assemblage 2 Asselian–Sakmarian. This interpretation is based on correlation of assemblage 1 to the DMb (Mid Pennsylvanian) and assemblage 2 to the FS (Early Cisuralian) Biozones of the Paganzo Basin (Argentina). The taxonomic composition of the *Ahrensisporites cristatus*–*Crucisaccites monoletus* (Mid–Late Pennsylvanian) and the *Protohaploxypinus goraiensis* Subzone (Asselian–Sakmarian) of the *Vittatina costabilis* (Early Cisuralian) Biozones of the Paraná Basin (Brazil) support this correlation. The continental freshwater depositional setting of this part of the Paganzo Basin is supported by the dominance of terrestrial palynomorphs and phytoclasts, the presence of coal and carbonaceous shales, and the occurrence of plant megafossils and plant debris in the sediments. The floristic changes between assemblages 1 and 2 are consistent with the interpretation of climatic amelioration associated with paleogeographic changes in Gondwana occurring during the Pennsylvanian and Cisuralian.

1. Introduction

The Carboniferous–Permian strata of the Paganzo Basin in Argentina comprise thick sedimentary sequences related to glacial and post-glacial environments. Strata display transgressive/regressive cycles preserved in the formations that comprise the Paganzo Group. Invertebrate, plant and palynomorph fossils are relatively common at many localities in these formations (see Azcuy et al., 2000). Hence, several biostratigraphic schemes have been proposed, and correlations and paleoenvironmental and paleoclimatic inferences have been updated and summarized by many authors (e.g., Archangelsky et al., 1987, 1996a,b; Azcuy et al., 1987, 2000, 2007; López Gamundi et al., 1992; Limarino et al., 1996; López Gamundi, 1997; Césari and Gutiérrez, 2001).

Palynological data are most abundant from the central and southern parts of the basin, especially from the clastic, coal-bearing Pennsylvanian strata (see Azcuy et al., 2007). In 2000, a comprehensive effort was started to gather more data about the palynology and paleobotany of the northern part of the basin. Recent results include the detailed lithostratigraphic survey of the Libertad and Sauces Formations in the Los Sauces area, La Rioja Province, Argentina (Figs. 1A and 2) published by Pieroni and Georgieff (2007). Carrizo et al. (2004) and di Pasquo et al. (2004) presented preliminary paleobotanical and palynological results supplementing the previous paleobotanical and palynological studies summarized by Vergel et al. (2000). Later, Carrizo and Azcuy in Azcuy et al. (2007) proposed the designation of the *Krauselcladus–Asterotheca*

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doi:10.1016/j.coal.2010.01.006

Zone (late Pennsylvanian–earliest Cisuralian, Fig. 1B) to replace the name of the Interval Zone of Archangelsky and Cúneo (1991). The Libertad Formation in the Los Sauces area was selected by those authors as the type section and type locality for this zone. The present contribution aims to illustrate for the first time, most of the palynomorphs obtained from nine productive samples of three sections cropping out at the Los Sauces area (Figs. 1A and 2). Comparisons with coeval palynofloras, mainly from Argentina and Brazil, support the interpreted age of the two defined assemblages, and correlations of the palynoflora across Gondwana are established. Analysis of palynomorphs and palynofacies allows paleoecological and paleoenvironmental reconstructions for Pennsylvanian and Early Cisuralian floras in this basin and consideration of the regional paleoclimatic changes that drove regional floral evolution during this time.

2. Geological and paleontological setting

The Libertad and overlying Sauces Formations are exposed on the eastern border of the Velasco Range at the Sauces Dam area 10 km to the west of La Rioja Province (Fig. 1A). This region corresponds to the northeastern part of the intracratonic Paganzo Basin, which covers over 150,000 km^2 and is bounded on the east by the Arco Pampeano Range and on the northeast by the La Puna Range (see Azcuy et al., 2000, 2007). The Libertad and Sauces Formations, which unconformably overlie a crystalline basement (Precambrian to Ordovician in age, see Aceñolaza and Bortolotti, 1981) consist of a succession of red, brown and gray sandstones and conglomerates of probable Permian age (Heim, 1946). Amos and Zardini (1963) carried out more detailed analysis of the Upper Palaeozoic deposits in this region and defined the stratigraphic succession that is currently used.

Bracaccini (1946, 1948) was the first to note the occurrence of plant fossils in these formations. Initial collections were identified by Frenguelli to be *Eremopteris whitei* Berry, *Gondwanidium argentinum* Kurtz, and *Calamites peruvianus* Goth. Azcuy and Césari (1980) recorded well-preserved plant fossils in the Libertad Formation (see Fig. 1A). These collections included *Asterotheca pianitzkyi* Frenguelli, *Cordaites* sp. and *Cordaicarpus* sp., which referred the assemblage to the latest Carboniferous Pre-*Glossopteris* Flora. Limarino et al. (1996) correlated the overlying Sauces Formation, on the basis of lithologic characteristics, to the upper section of the Paganzo Group (Patquia Formation or lower Patquia–de la Cuesta sequence, see Fig. 1B), and tentatively attributed a Permian age to this unit.

Recently, Pieroni and Georgieff (2007) re-examined this area in order to assess the lithostratigraphy and sedimentology of the northern part of the Basin, and to conduct a more comprehensive biostratigraphic palynological and paleobotanical study. These workers recognized the Upper Palaeozoic Libertad and Sauces Formations in three of the studied sections (see Figs. 1A and 2). The Libertad Formation is mainly composed of greenish gray and purple conglomerates and sandstones interbedded with pollen-rich and fossiliferous black siltstones, shales and coals. Analysis of the fossil collections from these units led to the definition of the *Krauselcladus–Asterotheca* (*KA*) Zone by Carrizo and Azcuy (in Azcuy et al., 2007). This biostratigraphic assignment is mainly due to the appearance of *Asterotheca pianitzkyi* Frenguelli and *Krauselcladus argentinus* Archangelsky (see Figs. 1 and 2). The remaining species recorded in this assemblage are: *Botrychiospsis weissiana* Kurtz emend. Archangelsky and Arrondo, *Fedekurtzia argentina* (Kurtz) Archangelsky, *Eusphenopteris sanjuanina* Césari, *Paracalamites australis* Rigby, *Cordaites riojanus* Archangelsky and Leguizamón, *Samaropsis nunezii* García emend. Archangelsky,

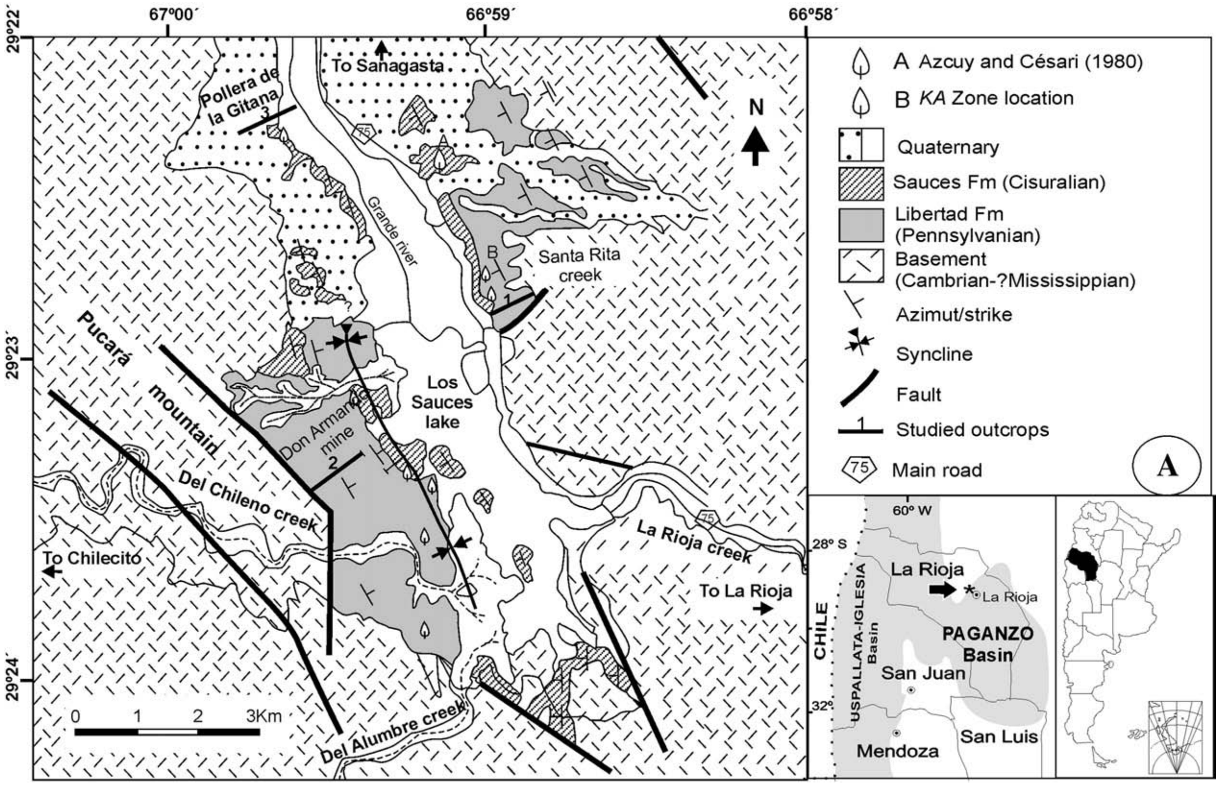


Fig. 1. A. Geologic map of Sauces Dam region, La Rioja Province, Argentina. Studied outcrops (after Pieroni and Georgieff, 2007) and other references cited in text. B. Correlation of Carboniferous and Permian stratigraphic and biostratigraphic units of Late Paleozoic basins of South America referenced in the text (after Azcuy et al., 2007; Souza et al., 2007; Césari et al., 2007; di Pasquo, 2009a, b). The Carboniferous–Permian boundary is defined here at 299 Ma after Gradstein et al. (2004). Biozone abbreviations: *Crassispora kosankei–Cystoptychus azcuyi* (KA), *Raistrickia radiosa–Apiculatasporites spinulistratus* (RS), *Dictyotriletes bireticulatus–Cristatisporites chacoparanensis* (BC), *Converrucosisporites micronodosus–Reticulatisporites reticulatus* (MR), *Marsupipollenites triradiatus–Lundbladispora braziliensis* (TB). See also references in Fig. 3.

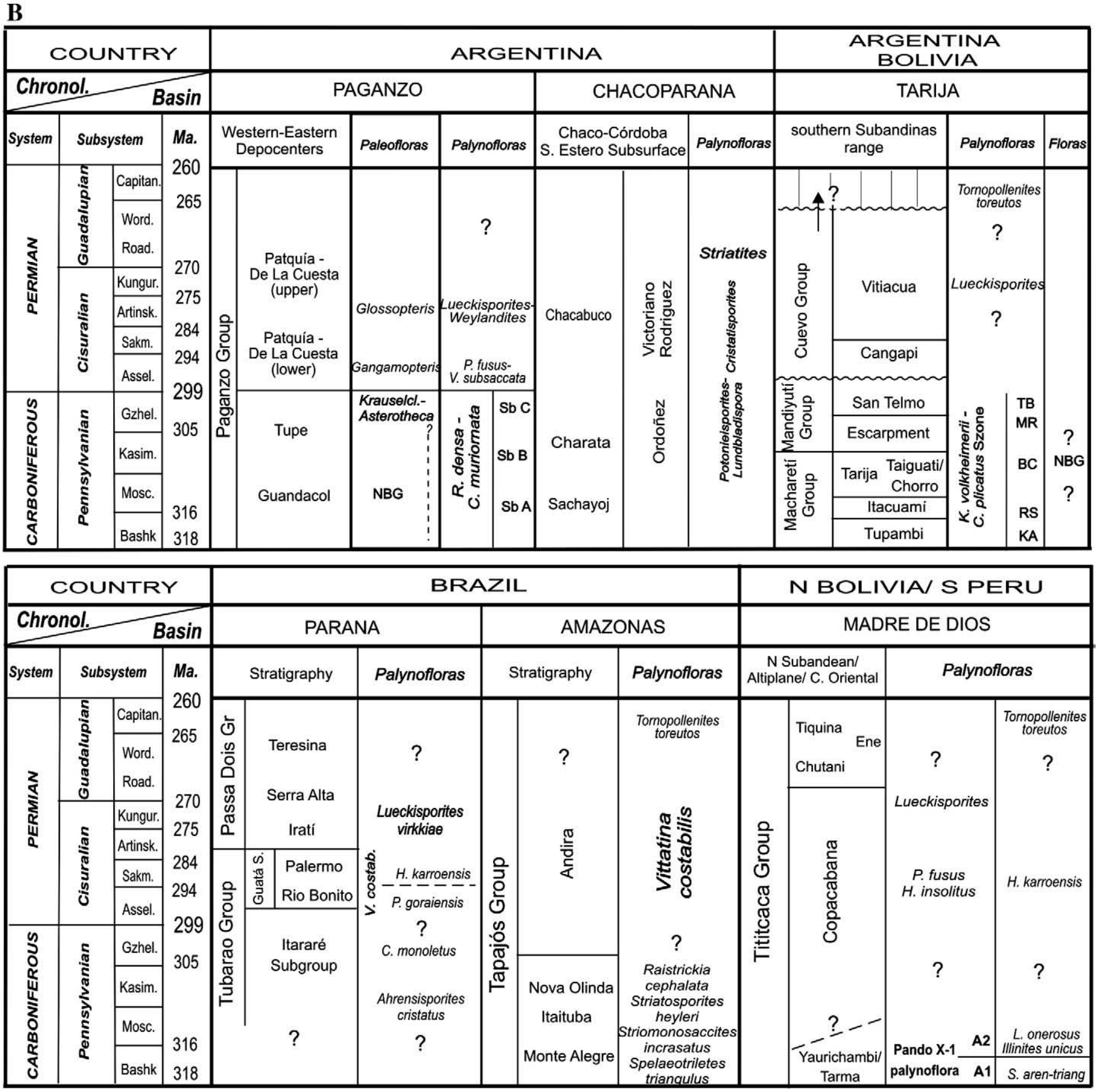


Fig. 1 (*continued*).

Cordaites sp., *Cordaicarpus* spp., and *Lycophyta* indet. The biostratigraphic importance of this assemblage will be discussed in greater detail in a later section.

The Sauces Formation either overlies the igneous basement or conformably overlies the Libertad Formation. It is chiefly composed of sandstone and reddish conglomerates (see Pieroni and Georgieff, 2007), and, for the most part, is barren of fossil remains. Only one greenish gray shale present in the Pollera de la Gitana section yielded a palynoassemblage (see Figs. 1A and 2). These units are mainly interpreted as fluvial and deltaic–lacustrine continental sequences (Pieroni and Georgieff, 2007), and are correlated to the Tupe and Patquia–de la Cuesta supersequences (see Fig. 1B) mainly based on sedimentary evidence (Andreis and Archangelsky, 1996; Azcuy et al., 2000).

3. Materials and methods

A total of 55 samples were collected for palynological investigation at the locations shown in Fig. 2. Brown, gray and black shales and siltstones and very fine-grained sandstones (some of which contained carbonized plant remains) were sampled from rocks outcropping along the three measured sections around the Los Sauces Dam (see Fig. 1A). Seven samples from the Libertad Formation and two samples from the middle part of the Sauces Formation contained

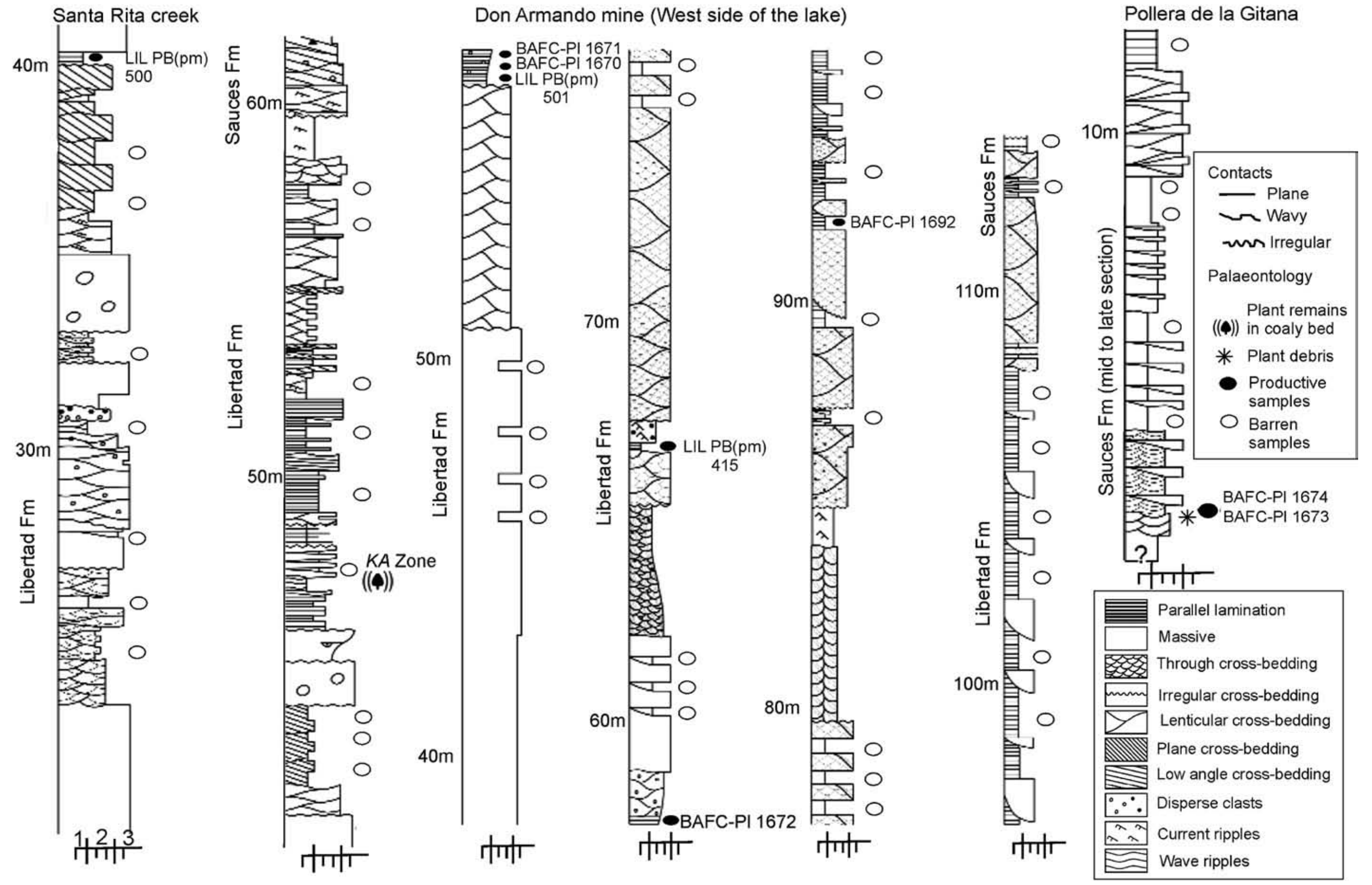


Fig. 2. Stratigraphic sections showing location of paleobotanic assemblages and palynologic samples studied (modified from Pieroni and Georgieff, 2007). Lithology is defined by column width. The lithologic references are shown at column bases and are defined as: 1 — Limestone; 2 — Sandstones (fine, medium, coarse); 3 — Conglomerates (fine, medium).

palynomorphs and phytoclasts (see Fig. 2). Samples were processed following standard palynological methods with HCl and HF to remove clastic material (e.g., Traverse, 1988). Organic residues were sieved with a metallic +25 μm filter and permanent slides of the +25 μm fraction were prepared using glycerine jelly. The −25 μm residues of all samples were observed under the microscope (×10 magnification). Rare palynomorphs were recovered from one of the −25 μm samples of the Sauces Formation (BAFC-Pl 1673). The remaining −25 μm samples were all barren and were discarded. No further treatments were applied to the samples. Slides were analyzed under transmitted-light microscopes (Orthomat Leitz, Lavobal 4 Carl Zeiss Jena and Nikon Eclipse 80i) and photomicrographs were taken with digital videocameras, Pixera (1.2 megapixels) and Motic (2.0 megapixels). Slides and residues are housed at the Laboratory of Palynology of the Department of Geology (Pure and Natural Sciences Faculty, University of Buenos Aires) and the Laboratory of Palynology of the Miguel Lillo Institute (Tucumán Province), in Argentina, under the acronyms BAFC-Pl and LIL PB(pm) respectively. Coordinates of figured specimens are indicated by the respective acronym followed by the number of the slide and the England Finder coordinate.

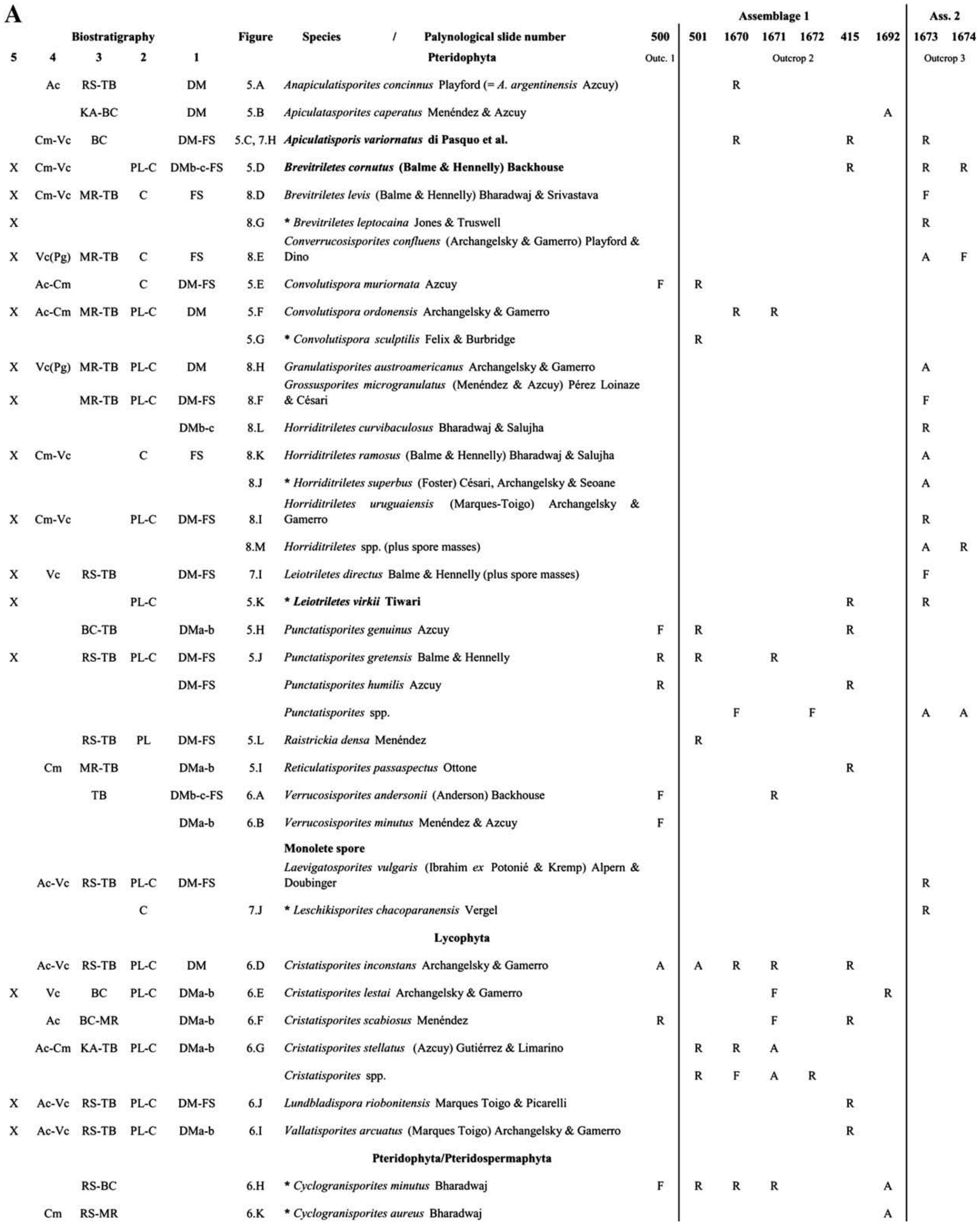
4. Palynology

4.1. General characteristics of the assemblages

Most of the samples processed, whether barren or productive, yielded phytoclasts, i.e. tracheids, cuticles, and amorphous brown or black carbonaceous particles. Phytoclasts typically comprised a significant percentage of each sample (between 60–90% of total phytoclast + palynomorph material in productive levels). The recovered pollen grains range from well-preserved to broken. Sometimes, only the sacs were preserved, especially in some levels of the Libertad Formation. The relative frequency and stratigraphic distribution of the seventy five species (42 spore taxa, 32 pollen taxa and one fungus) are summarized in Fig. 3. Two assemblages are recognized. As shown in Fig. 4, the two assemblages are distinguished by substantive differences in the overall composition and percentage abundance of the dominant plant groups (based on palynomorph affinities after Balme 1995, and Elsik, 1996, see Fig. 3). Ten of the taxa identified constitute first records from the Paganzo Basin. Thirteen species are common to both the Libertad and Sauces Formations (see Fig. 3). Most of the recorded species are illustrated in Figs. 5–9 which are arranged in alphabetical order by assemblage and botanical affinity (see Fig. 3). These species are widely described in the literature as indicated in the selected references listed in Fig. 10. Synonymy lists are provided in these references and are followed in this report.

4.1.1. Assemblage 1

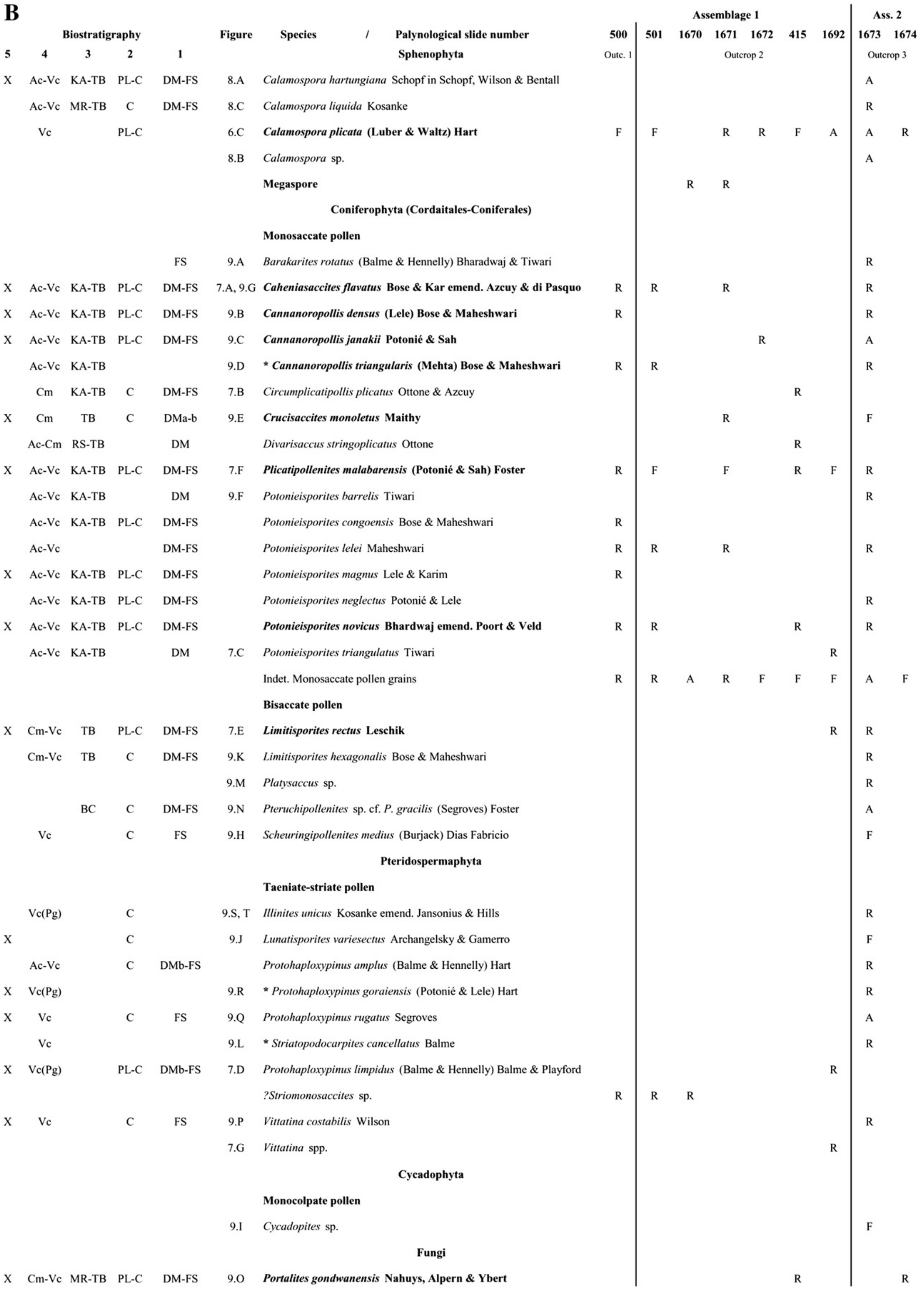
The Libertad Formation (see Figs. 2–4) yielded assemblages dominated by the trilete spores *Cristatisporites* and *Punctatisporites* respectively of lycophyte and pteridophyte affinity. Monosaccate pollen grains of the Coniferales/Cordaitales (gymnosperms) are also frequently present in all levels. The pteridosperms are mostly represented by *Cyclogranisporites*, which is especially abundant in BAFC-Pl 1692 together with scarce striate bisaccate pollen grains (Fig. 3). The thermal alteration index (TAI), is mainly around dark



A

		Biostratigraphy			Figure	Species / Palynological slide number	Assemblage 1							Ass. 2	
							500	501	1670	1671	1672	415	1692	1673	1674
5	4	3	2	1		**Pteridophyta**	Outc. 1	Outcrop 2						Outcrop 3	
	Ac	RS-TB		DM	5.A	*Anapiculatisporites concinnus* Playford (= *A. argentinensis* Azcuy)			R						
		KA-BC		DM	5.B	*Apiculatasporites caperatus* Menéndez & Azcuy							A		
	Cm-Vc	BC		DM-FS	5.C, 7.H	***Apiculatisporis variornatus* di Pasquo et al.**			R			R		R	
X	Cm-Vc		PL-C	DMb-c-FS	5.D	***Brevitriletes cornutus* (Balme & Hennelly) Backhouse**						R		R	R
X	Cm-Vc	MR-TB	C	FS	8.D	*Brevitriletes levis* (Balme & Hennelly) Bharadwaj & Srivastava								F	
X					8.G	* *Brevitriletes leptocaina* Jones & Truswell								R	
X	Vc(Pg)	MR-TB	C	FS	8.E	*Converrucosisporites confluens* (Archangelsky & Gamerro) Playford & Dino								A	F
	Ac-Cm		C	DM-FS	5.E	*Convolutispora muriornata* Azcuy	F	R							
X	Ac-Cm	MR-TB	PL-C	DM	5.F	*Convolutispora ordonensis* Archangelsky & Gamerro			R	R					
					5.G	* *Convolutispora sculptilis* Felix & Burbridge		R							
X	Vc(Pg)	MR-TB	PL-C	DM	8.H	*Granulatisporites austroamericanus* Archangelsky & Gamerro								A	
X		MR-TB	PL-C	DM-FS	8.F	*Grossusporites microgranulatus* (Menéndez & Azcuy) Pérez Loinaze & Césari								F	
				DMb-c	8.L	*Horriditriletes curvibaculosus* Bharadwaj & Salujha								R	
X	Cm-Vc		C	FS	8.K	*Horriditriletes ramosus* (Balme & Hennelly) Bharadwaj & Salujha								A	
					8.J	* *Horriditriletes superbus* (Foster) Césari, Archangelsky & Seoane								A	
X	Cm-Vc		PL-C	DM-FS	8.I	*Horriditriletes uruguaiensis* (Marques-Toigo) Archangelsky & Gamerro								R	
					8.M	*Horriditriletes* spp. (plus spore masses)								A	R
X	Vc	RS-TB		DM-FS	7.I	*Leiotriletes directus* Balme & Hennelly (plus spore masses)								F	
X			PL-C		5.K	*** *Leiotriletes virkii* Tiwari**						R		R	
		BC-TB		DMa-b	5.H	*Punctatisporites genuinus* Azcuy	F	R				R			
X		RS-TB	PL-C	DM-FS	5.J	*Punctatisporites gretensis* Balme & Hennelly	R	R		R					
				DM-FS		*Punctatisporites humilis* Azcuy	R					R			
						Punctatisporites spp.			F		F			A	A
		RS-TB	PL	DM-FS	5.L	*Raistrickia densa* Menéndez		R							
	Cm	MR-TB		DMa-b	5.I	*Reticulatisporites passaspectus* Ottone						R			
		TB		DMb-c-FS	6.A	*Verrucosisporites andersonii* (Anderson) Backhouse	F			R					
				DMa-b	6.B	*Verrucosisporites minutus* Menéndez & Azcuy	F								
						Monolete spore									
	Ac-Vc	RS-TB	PL-C	DM-FS		*Laevigatosporites vulgaris* (Ibrahim *ex* Potonié & Kremp) Alpern & Doubinger								R	
			C		7.J	* *Leschikisporites chacoparanensis* Vergel								R	
						Lycophyta									
	Ac-Vc	RS-TB	PL-C	DM	6.D	*Cristatisporites inconstans* Archangelsky & Gamerro	A	A	R	R		R			
X	Vc	BC	PL-C	DMa-b	6.E	*Cristatisporites lestai* Archangelsky & Gamerro				F			R		
	Ac	BC-MR		DMa-b	6.F	*Cristatisporites scabiosus* Menéndez	R			F		R			
	Ac-Cm	KA-TB	PL-C	DMa-b	6.G	*Cristatisporites stellatus* (Azcuy) Gutiérrez & Limarino		R	R	A					
						Cristatisporites spp.		R	F	A	R				
X	Ac-Vc	RS-TB	PL-C	DM-FS	6.J	*Lundbladispora riobonitensis* Marques Toigo & Picarelli						R			
X	Ac-Vc	RS-TB	PL-C	DMa-b	6.I	*Vallatisporites arcuatus* (Marques Toigo) Archangelsky & Gamerro						R			
						Pteridophyta/Pteridospermaphyta									
		RS-BC			6.H	* *Cyclogranisporites minutus* Bharadwaj	F	R	R	R			A		
	Cm	RS-MR			6.K	* *Cyclogranisporites aureus* Bharadwaj							A		

Fig. 3. A–B. Stratigraphic distribution of species identified in assemblage 1 of the Libertad Formation, at Santa Rita creek (outcrop 1) and Don Armando Mine (west side of lake) section (outcrop 2) and the assemblage 2 of the Sauces Formation, at Pollera de la Gitana section (outcrop 3). For location of samples see Fig. 2. Palynomorphs are arranged in alphabetical order, after their more probable parent plant group. Species registered for the first time in the Paganzo Basin are marked with an asterisk (*). Relative abundance of species (based on counting up to 250 specimens in different randomly selected slide fields) is as follows: A. Abundant (>10%), F. Frequent (5–10%), Rare (<5%). Columns to the left include figure illustrations and biostratigraphic distribution of taxa through Pennsylvanian to Early Cisuralian (Asselian–Sakmarian) after the following references (see also Fig. 10): 1: Paganzo Basin (Argentina), *Raistrickia densa–Convolutispora muriornata* (DM) and *Pakhapites fusus–Vittatina subsaccata* (FS) Zones of Césari and Gutiérrez (2001) and later records of Gutiérrez and Barreda (2006), Balarino and Gutiérrez (2006), Gutiérrez and Limarino (2006), Vergel (2008). 2: Chacoparaná Basin (Argentina), *Potonieisporites–Lundbladispora* (P–L) and *Cristatisporites* (C) Zones after Archangelsky and Vergel (1996). 3: Tarija Basin (Argentina), *Dictyotriletes birreticulatus–Cristatisporites chacoparanensis* (BC) Zone and *Nothorhacopteris–Botrychiopsis–Ginkgophyllum* (NBG) Zone, di Pasquo (2003, 2009a), del Papa and di Pasquo (2007). 4: Paraná Basin (Brazil), *Ahrensisporites cristatus* (Ac), *Crucisaccites monoletus* (Cm) and *Vittatina costabilis* (Vc) Zone and *Protohaploxypinus goraiensis* Subzone (Pg) of Souza and Marques-Toigo (2005) and Souza (2006) and later records of Premaor et al. (2006). 5: Paraná Basin (Uruguay), early Cisuralian, Beri et al. (2006), Gutiérrez et al. (2006). See also Fig. 10.



B

Biostratigraphy					Figure	Species / Palynological slide number	Assemblage 1							Ass. 2	
5	4	3	2	1			500	501	1670	1671	1672	415	1692	1673	1674
						Sphenophyta	Outc. 1	Outcrop 2						Outcrop 3	
X	Ac-Vc	KA-TB	PL-C	DM-FS	8.A	*Calamospora hartungiana* Schopf in Schopf, Wilson & Bentall								A	
	Ac-Vc	MR-TB	C	DM-FS	8.C	*Calamospora liquida* Kosanke								R	
	Vc		PL-C		6.C	***Calamospora plicata* (Luber & Waltz) Hart**	F	F		R	R	F	A	A	R
					8.B	*Calamospora* sp.								A	
						Megaspore			R	R					
						Coniferophyta (Cordaitales-Coniferales)									
						Monosaccate pollen									
				FS	9.A	*Barakarites rotatus* (Balme & Hennelly) Bharadwaj & Tiwari								R	
X	Ac-Vc	KA-TB	PL-C	DM-FS	7.A, 9.G	***Caheniasaccites flavatus* Bose & Kar emend. Azcuy & di Pasquo**	R	R		R				R	
X	Ac-Vc	KA-TB	PL-C	DM-FS	9.B	***Cannanoropollis densus* (Lele) Bose & Maheshwari**	R							R	
X	Ac-Vc	KA-TB	PL-C	DM-FS	9.C	***Cannanoropollis janakii* Potonié & Sah**					R			A	
	Ac-Vc	KA-TB			9.D	*** *Cannanoropollis triangularis* (Mehta) Bose & Maheshwari**	R	R						R	
	Cm	KA-TB	C	DM-FS	7.B	*Circumplicatipollis plicatus* Ottone & Azcuy						R			
X	Cm	TB	C	DMa-b	9.E	***Crucisaccites monoletus* Maithy**				R				F	
	Ac-Cm	RS-TB		DM		*Divarisaccus stringoplicatus* Ottone						R			
X	Ac-Vc	KA-TB	PL-C	DM-FS	7.F	***Plicatipollenites malabarensis* (Potonié & Sah) Foster**	R	F		F		R	F	R	
	Ac-Vc	KA-TB		DM	9.F	*Potonieisporites barrelis* Tiwari								R	
	Ac-Vc	KA-TB	PL-C	DM-FS		*Potonieisporites congoensis* Bose & Maheshwari	R								
	Ac-Vc			DM-FS		*Potonieisporites lelei* Maheshwari	R	R		R				R	
X	Ac-Vc	KA-TB	PL-C	DM-FS		*Potonieisporites magnus* Lele & Karim	R								
	Ac-Vc	KA-TB	PL-C	DM-FS		*Potonieisporites neglectus* Potonié & Lele								R	
X	Ac-Vc	KA-TB	PL-C	DM-FS		***Potonieisporites novicus* Bhardwaj emend. Poort & Veld**	R	R				R		R	
	Ac-Vc	KA-TB		DM	7.C	*Potonieisporites triangulatus* Tiwari							R		
						Indet. Monosaccate pollen grains	R	R	A	R	F	F	F	A	F
						Bisaccate pollen									
X	Cm-Vc	TB	PL-C	DM-FS	7.E	***Limitisporites rectus* Leschik**							R	R	
	Cm-Vc	TB	C	DM-FS	9.K	*Limitisporites hexagonalis* Bose & Maheshwari								R	
					9.M	*Platysaccus* sp.								R	
		BC	C	DM-FS	9.N	*Pteruchipollenites* sp. cf. *P. gracilis* (Segroves) Foster								A	
	Vc		C	FS	9.H	*Scheuringipollenites medius* (Burjack) Dias Fabricio								F	
						Pteridospermaphyta									
						Taeniate-striate pollen									
	Vc(Pg)		C		9.S, T	*Illinites unicus* Kosanke emend. Jansonius & Hills								R	
X			C		9.J	*Lunatisporites variesectus* Archangelsky & Gamerro								F	
	Ac-Vc		C	DMb-FS		*Protohaploxypinus amplus* (Balme & Hennelly) Hart								R	
X	Vc(Pg)				9.R	* *Protohaploxypinus goraiensis* (Potonié & Lele) Hart								R	
X	Vc		C	FS	9.Q	*Protohaploxypinus rugatus* Segroves								A	
	Vc				9.L	* *Striatopodocarpites cancellatus* Balme								R	
X	Vc(Pg)		PL-C	DMb-FS	7.D	*Protohaploxypinus limpidus* (Balme & Hennelly) Balme & Playford							R		
						?Striomonosaccites sp.	R	R	R						
X	Vc		C	FS	9.P	*Vittatina costabilis* Wilson								R	
					7.G	*Vittatina* spp.							R		
						Cycadophyta									
						Monocolpate pollen									
					9.I	*Cycadopites* sp.								F	
						Fungi									
X	Cm-Vc	MR-TB	PL-C	DM-FS	9.O	***Portalites gondwanensis* Nahuys, Alpern & Ybert**						R			R

Fig. 3 (*continued*).

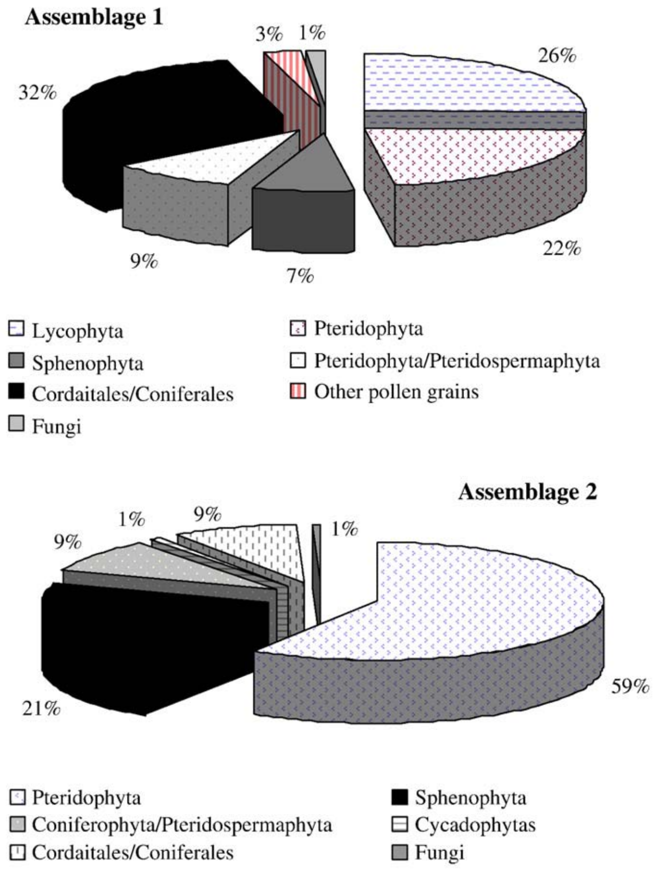


Fig. 4. Quantitative distribution of palynomorphs based on botanical affinities of major plant groups (see Balme, 1995; Elsik, 1996), for each assemblage in the Libertad and Sauces Formations.

orange to dark brown (2+ to 3) falling within the gas generation zone after Utting and Wielens (1992).

4.1.2. Assemblage 2

The Sauces Formation Assemblage (see Figs. 2–4) is dominated by trilete spores of the genera *Horriditriletes*, and *Converrucosisporites*–*Granulatisporites*, related to the Pteridophyta and Sphenophyta. The Cordaitales/Coniferales (monosaccate pollen grains) and Coniferales/Pteridospermaphyta (e.g., *Protohaploxypinus*, *Illinites*, *Pteruchipollenites*, *Vittatina*), are also common, but subordinated in abundance. Palynomorphs belonging to the Cycadophyta (*Cycadopites* sp.) and *Portalites gondwanensis* are rare (Figs. 3 and 4). The thermal alteration index (TAI) is mainly around light to medium orange (2− to 2) falling within the oil generation zone (after Utting and Wielens, 1992).

5. Age and correlation

During the last 20 years, numerous palynologic, stratigraphic and paleontologic studies increased our understanding of Carboniferous and Permian palynofloras in South America. Better biostratigraphic schemes from the different basins, augmented with radiometric dates, refined chronostratigraphic correlations (see Azcuy et al., 2007 and Césari et al., 2007 and their references). Currently, the chronostratigraphic correlations in Gondwanan Pennsylvanian–Cisuralian studies (e.g., Stephenson, 2008 and references therein) are based mainly on palynomorphs, because they are more widely distributed than datable igneous rocks. The stratigraphic distribution of the species recorded in this study from the three outcrops (see Figs. 2 and 3) and the analysis of their chronostratigraphic ranges, especially of the diagnostic species included in Fig. 10, support the definition of two assemblages: assemblage 1 of Middle to Late Pennsylvanian (Moscovian–early Kasimovian) and assemblage 2 of Early Cisuralian (Asselian–Sakmarian). The ages proposed are mostly in agreement with previous biostratigraphic schemes, especially those from the western basins of Argentina based on megafloras and palynomorphs (see Figs. 3 and 10).

Césari and Gutiérrez (2001) proposed the *Raistrickia densa*–*Convolutispora muriornata* (DM) Assemblage Biozone and correlated it to the paleofloristic *Nothorhacopteris*–*Botrychiopsis*–*Ginkgophyllum* Biozone of the Pennsylvanian of Argentina. The palynozone was subdivided into three subzones by the mentioned authors: Subzone A (DMa) characterized by the first appearance of monosaccate pollen grains such as *Plicatipollenites* and *Cannanoropollis*); Subzone B (DMb) defined by the first appearance of species of *Protohaploxypinus*, although the abundance and diversity of miospores especially cingulizonate spores such as *Cristatisporites*, *Kraeuselisporites* and *Vallatisporites* is similar in both subzones; and Subzone C (DMc) defined by the appearance of *Quadrisporites* spp., scolecodonts and acritarchs such as *Michrystridium* sp. and *Verhyachium* sp. found in marine-littoral deposits. Species from the underlying and overlying biozones are also present.

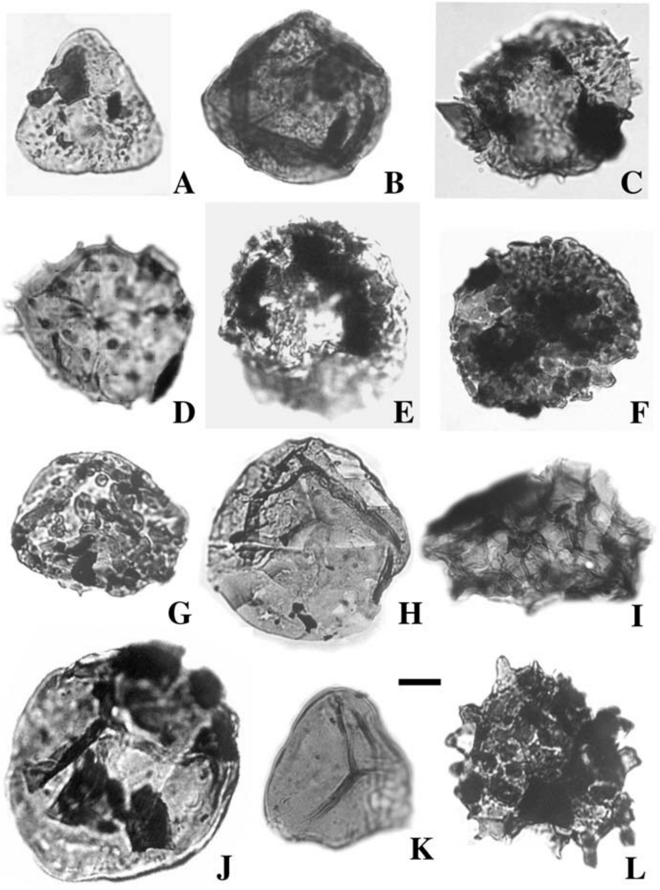


Fig. 5. Selected species of assemblage 1, Libertad Formation, Sauces Dam area, La Rioja Province, Argentina. Scale bar = 10 µm. (A) *Anapiculatisporites concinnus* Playford (=*A. argentinensis* Azcuy), BAFC-Pl 1670(2) L44/1. (B) *Apiculatasporites caperatus* Menéndez and Azcuy, BAFC-Pl 1692(1) V57/1. (C) *Apiculatisporis variornatus* di Pasquo, Azcuy and Souza, BAFC-Pl 1670(2) U30/3. (D) *Brevitriletes cornutus* (Balme and Hennelly) Backhouse, LIL-PB(pm) 500(5) E47–F47. (E) *Convolutispora muriornata* Azcuy, LIL-PB(pm) 500(c) Y56-2. (F) *Convolutispora ordonensis* Archangelsky and Gamerro, BAFC-Pl 1670(2) S24/2. (G) *Convolutispora sculptilis* Felix and Burbridge, LIL-PB(pm) 501(8) Z36. (H) *Punctatisporites genuinus* Azcuy, LIL-PB(pm) 500(2) X44-2. (I) *Reticulatisporites passaspectus* Ottone, LIL-PB(pm) 415(1) D34-3. (J) *Punctatisporites gretensis* Balme and Hennelly, LIL-PB(pm) 500(b) Z49. (K) *Leiotriletes virkii* Tiwari, LIL-PB(pm) 415(6) V36-4. (L) *Raistrickia densa* Menéndez, LIL-PB(pm) 501(8) Y37.

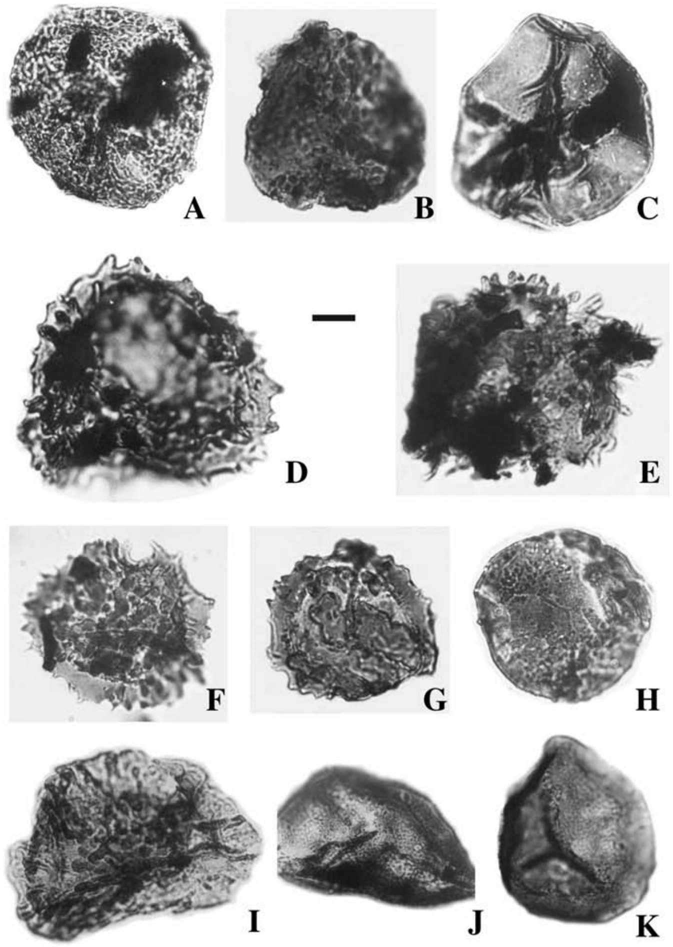


Fig. 6. Selected species of assemblage 1, Libertad Formation. Scale bar = 10 µm. (A) *Verrucosisporites andersonii* (Anderson) Backhouse, LIL PB(pm) 500(2) T30. (B) *Verrucosisporites minutus* Menéndez and Azcuy, BAFC-Pl 1671(2) S27/1. (C) *Calamospora plicata* (Luber and Waltz) Hart, LIL PB(pm) 500(2) Q41-1. (D) *Cristatisporites inconstans* Archangelsky and Gamerro, LIL PB(pm) 501(8) B52-3. (E) *Cristatisporites lestai* Archangelsky and Gamerro, BAFC-Pl 1671(2) T25/1. (F) *Cristatisporites scabiosus* Menéndez, BAFC-Pl 1671(1) Y30. (G) *Cristatisporites stellatus* (Azcuy) Gutiérrez and Limarino, BAFC-Pl 1671(2) B23. (H) *Cyclogranisporites minutus* Bharadwaj, LIL PB(pm) 500(2) S31-1. (I) *Vallatisporites arcuatus* (Marques-Toigo) Archangelsky and Gamerro, LIL PB(pm) 415(2) B55. (J) *Lundbladispora riobonitensis* Marques-Toigo and Piccarelli, LIL PB(pm) 415(5) K44-2. (K) *Cyclogranisporites aureus* Bharadwaj, BAFC-Pl 1692(1) X62.

Following this scheme, the assemblage 1 of the Libertad Formation is attributed to the DMb Subzone of Césari and Gutiérrez (see Figs. 3 and 10) based on the presence of *Verrucosisporites andersonii* in Santa Rita creek (LIL PB(pm) 500) and Don Armando mine (at BAFC-Pl 1671). The occurrence of other species exclusive to the DMb–DMc Subzones like *Brevitriletes cornutus*, *Protohaploxypinus limpidus* and *Vittatina* sp. in this sample reinforce this correlation. Samples LIL PB(pm) 501 and BAFC-Pl 1670 of the Don Armando mine section (see Fig. 2) are in close stratigraphic proximity to BAFC-Pl 1671, and could correspond to the DMb Subzone as well even though no diagnostic species have been found in either sample. On the other hand, the co-occurrence of *Krauselcladus argentinus* with *Asterotheca pianitzkyi* in the Santa Rita section (see Fig. 2), which was used by Carrizo and Azcuy (in Azcuy et al., 2007) to attribute this floral assemblage to the *KA* Zone, support a Late Pennsylvanian age for the upper Libertad Formation (see Fig. 10). Unfortunately, no productive sample was recovered above this plant level to be compared with the other palynoassemblages here studied and elsewhere.

Beyond the Paganzo Basin, assemblage 1 is correlated to the *Potonieisporites–Lundbladispora* Zone of Archangelsky and Gamerro (see Vergel, 1993; Archangelsky and Vergel, 1996) of the Chacoparaná Basin, which is characterized by abundant trilete spores (especially species of the genera *Punctatisporites*, *Convolutispora*, *Verrucosisporites*, *Cyclogranisporites*, *Lundbladispora*, *Cristatisporites*, *Vallatisporites*), monosaccate pollen grains and rare taeniate pollen belonging to the genera *Protohaploxypinus* and *Vittatina*.

In the Tarija Basin (Argentina), five zones were defined by di Pasquo (2003). Assemblage 1 likely correlates to the Basin's late Bashkirian–Moscovian *Dictyotriletes birreticulatus–Cristatisporites chacoparanensis* (BC) Zone (see Figs. 1B and 3) on the basis of several species common to both and especially based on several species exclusive to both zones (*Apiculatisporis variornatus*, *Cristatisporites scabiosus*, *C. lestai*, *Pteruchipollenites gracilis*). Recently, new records from this palynozone (see del Papa and di Pasquo, 2007) were collected in association with the first record of plant remains from the Tarija basin (*Samaropsis nunezii*, *Cordaicarpus cesariae*, *Ginkgophyllum diazii*, *Cordaites riojanus*, *Paracalamites australis*). These megafloras are assigned to the NBG Zone by di Pasquo (2009a) reinforcing age correlation with assemblage 1.

Several assemblage 1 species are shared with the *Ahrensisporites cristatus* and *Crucisaccites monoletus* Zones (Souza, 2006) in the Paraná Basin of Brazil (e.g., *Cristatisporites stellatus*, *Anapiculatisporites concinnus*, *Crucisaccites monoletus*, *Protohaploxypinus amplus*, see Figs. 1B, 3 and 10). The age of assemblage 1 is also supported by the presence of species restricted to the Pennsylvanian floras of Argentina, Brazil and Bolivia (e.g., *Cristatisporites stellatus*, *Apiculatasporites caperatus*, *Anapiculatisporites concinnus*, *Verrucosisporites minutus*, *Cyclogranisporites minutus*, *Cyclogranisporites aureus*, see Fig. 10). It is interesting to note that coeval palynofloras (Moscovian s.l.) are known from Peru, northern Bolivia and northern Brazil (e.g., Playford and Dino, 2000a,b; Azcuy et al., 2002; di Pasquo, 2009b; see Fig. 1B). Notable qualitative differences are observed between the palynofloras of northern and southern South America. Striate monosaccate and bisaccate pollen grains are common to abundant in palynofloras from northern South America while spore and non-striate pollen grains dominate palynofloras from southern Bolivia, southern Brazil and Argentina. Elsewhere in Gondwana, *Anapiculatisporites concinnus*, *Brevitriletes cornutus*, *Punctatisporites gretensis*, *Verrucosisporites andersonii* and *Vallatisporites arcuatus* together with similar species of *Cristatisporites* and *Cyclogranisporites* and monosaccate pollen grains have been found in the late Pennsylvanian OSPZ1 Assemblage from Oman and Saudi Arabia (Stephenson, 2004; Penney et al., 2008).

The Early Cisuralian biostratigraphic framework for the Paganzo Basin is referred to the *Pakhapites fusus–Vittatina subsaccata* (FS) Interval Biozone. Its boundary with the underlying DM Zone is marked by the first appearance of both eponymous species and an increase in striate pollen grains. Other taxa typical of this biozone include *Hamiapollenites insolitus*, *Hamiapollenites fusiformis*, *Striatoabieites multistriatus*, *Marsupipollenites striatus*, *Latusipollenites quadrisaccatus*, *Barakarites rotatus*, *Converrucosisporites confluens*, *Granulatisporites* sp. cf. *G. trisinus*, *Kraeuselisporites sanluisensis*, *Lophotriletes rarus*, *L. cursus* and *Brevitriletes cornutus*. The base of the FS Zone coincides with the base of the *Gangamopteris* megafloristic Zone (Césari and Gutiérrez, 2001; see Fig. 10 and its references), although plant megafloras akin to this zone have not been discovered in this area yet (see Pieroni and Georgieff, 2007). The species exclusive to the FS Zone and present in assemblage 2 are *Brevitriletes levis*, *Converrucosisporites confluens*, *Horriditriletes ramosus*, *Barakarites rotatus*, *Scheuringipollenites medius*, *Protohaploxypinus rugatus* and *Vittatina costabilis* (see Figs. 3 and 10). Recently, Vergel (2008) found *Converrucosisporites confluens* and *Vittatina costabilis* in the uppermost Tupe Formation (see Fig. 1B) exposed at La Herradura creek in San Juan Province (Argentina). These key taxa are present with other taxa in assemblage 2, thus reinforcing its age and correlation.

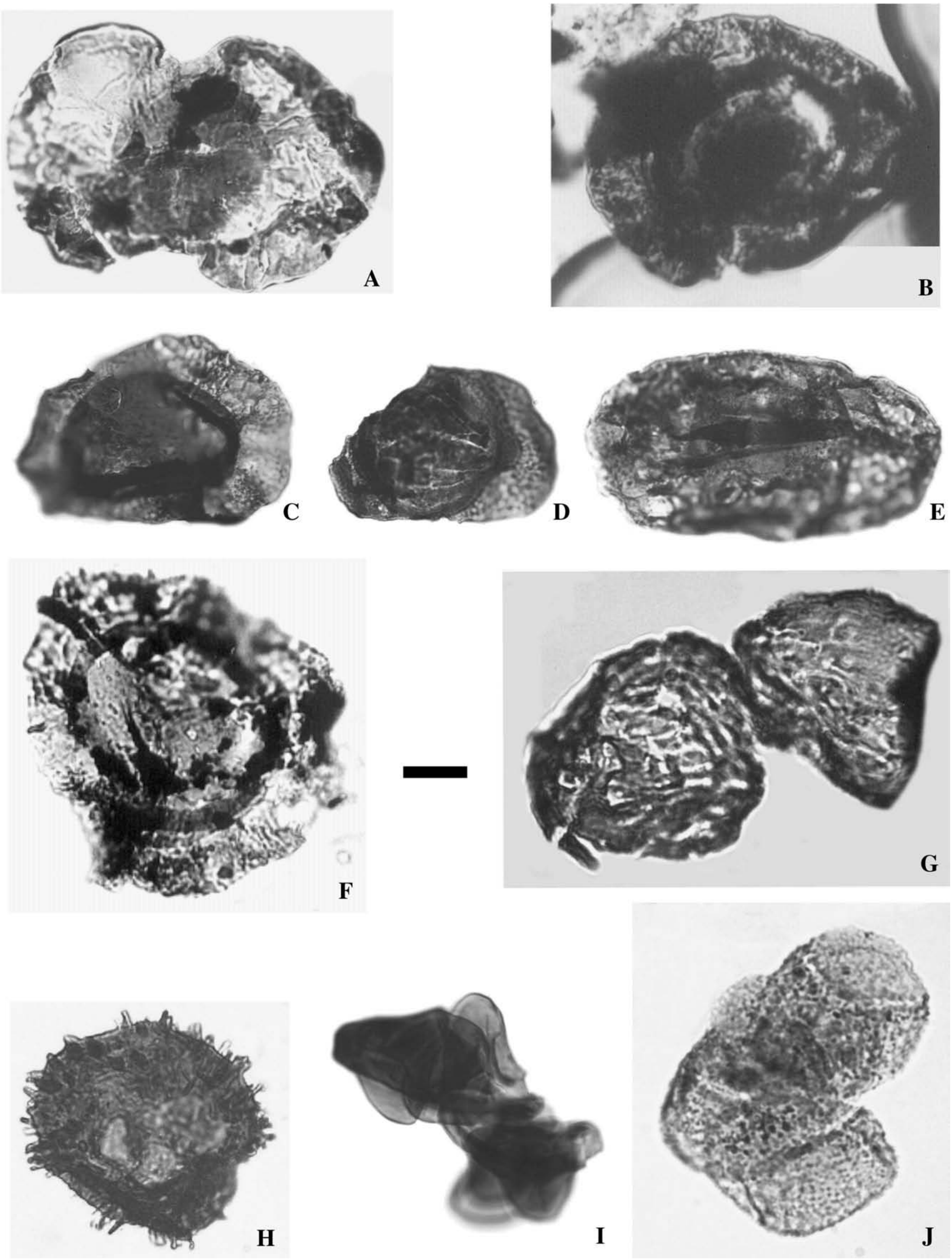


Fig. 7. (A–G) Selected species of assemblage 1, Libertad Formation and (H–J) of the assemblage 2, Sauces Formation. Scale bar = 20 µm except for G–J = 10 µm. (A) *Caheniasaccites flavatus* Bose and Kar emend. Azcuy and di Pasquo, BAFC-Pl 1671(1) Y47/1. (B) *Circumplicatipollis plicatus* Ottone and Azcuy, LIL PB(pm) 415 (3) R42. (C) *Potonieisporites triangulatus* Tiwari, BAFC-Pl 1692(1) T32. (D) *Protohaploxypinus limpidus* (Balme and Hennelly) Balme and Playford, BAFC-Pl 1692(1) O56/2. (E) *Limitisporites rectus* Leschik, BAFC-Pl 1692(2) S53. (F) *Plicatipollenites malabarensis* (Potonié and Sah) Foster, LIL PB(pm) 500 (1) L49. (G) *Vittatina* spp., BAFC-Pl 1692(2) N53/1. (H) *Apiculatisporis variornatus* di Pasquo et al., BAFC-Pl 1673(2) W52. (I) *Leiotriletes directus* Balme and Hennelly (spore mass), BAFC-Pl 1673(2) N28/4. (J) *Leschikisporites chacoparanensis* Vergel, BAFC-Pl 1673(3) S56.

The Cisuralian *Cristatisporites* (C) Zone (see Figs. 1B and 3) in the Chacoparaná Basin is recognized by an increase in striate pollen grains, especially of the genus *Vittattina*, and the first appearance of *Granulatisporites confluens*, *Protohaploxypinus perfectus* and *Marsupipollenites striatus* (see Vergel, 1993; Archangelsky and Vergel, 1996; Azcuy et al., 2007 and references therein). *Brevitriletes levis*, *Converrucosisporites confluens*, *Horriditriletes ramosus*, *Scheuringipollenites medius*, *Illinites unicus*, *Lunatisporites variesectus*, *Protohaploxypinus rugatus*, *Vittatina costabilis* and *Leschikisporites chacoparanensis* are the most important species exclusive to the C Zone shared with assemblage 2 (see Fig. 3).

The Asselian–Sakmarian *Protohaploxypinus goraiensis* Subzone of the Early Cisuralian *Vittatina costabilis* (Vc) Zone of Souza and Marques-Toigo (2005) in the Paraná Basin also contains several species in common with assemblage 2 (e.g., *Brevitriletes levis*, *Granulatisporites austroamericanus*, *Protohaploxypinus rugatus*, *Striatopodocarpites cancellatus*). Because of the presence of *Protohaploxypinus goraiensis* (see Figs. 1B, 3 and 10), a more accurate age can be proposed. A very similar assemblage from the Early Cisuralian subsurface of Uruguay (San Gregorio Formation, see Fig. 1B) was recently described by Beri et al. (2006) and Gutiérrez et al. (2006). Many species are shared with the assemblage 2 including *P. goraiensis* (see Fig. 3) supporting our proposed age determination and allowing correlation between these two occurrences. Finally, the lower *Vittatina costabilis* Zone (see Fig. 1B) of the Amazonas Basin in northern Brazil (Playford and Dino, 2000a, 2000b), shared a few species with assemblage 2 like *Vittatina costabilis*, *Illinites unicus*, *Portalites gondwanensis* and species of *Striatopodocarpites* and monosaccate pollen grains.

Elsewhere in Gondwana, assemblages with species common to South America and with quantitatively similar taxonomic compositions to South America palynofloras have been recognized in Africa (e.g., MacRae, 1988), Antarctica (e.g., Lindström, 1995), Australia (e.g., Jones and Truswell, 1992), Oman and Saudi Arabia (e.g., Stephenson and Filatoff, 2000). However, correlations are not precise as discussed by Stephenson (2008), who analyzed the timing of species appearances (whether coeval or slightly diachronous) of some index taxa with regard to their use in establishment of late Pennsylvanian and Cisuralian palyno-correlations across Gondwana. He recognized that *Granulatisporites confluens* is an index species of the Early Cisuralian (Asselian), although an older record is known from the latest Pennsylvanian in northern Argentina (di Pasquo, 2003; see Fig. 3) and younger appearances (Sakmarian) in Australia and Arabia (see Stephenson, 2008). The genus *Vittattina* is another example. Some records of *Vittatina subsaccata* are known from the late Pennsylvanian of the Chacoparaná Basin (see Archangelsky and Vergel, 1996). Indeterminate species from northern Bolivia (di Pasquo, 2009b) and scarce specimens in assemblage 1 (see Fig. 3) also date to the Pennsylvanian, even though most of its species appeared in the Asselian in most of the rest of the World (see Playford and Dino, 2000b, 2002; Dunn, 2001; Gutiérrez et al., 2006). Similar interpretation issues relate to the appearance of *Lunatisporites variesectus* in assemblage 2 and in the middle part of the *Cristatisporites* Zone in the Chacoparaná Basin (see Fig. 1B; Playford and Dino, 2002). This taxon marks the lower limit of the *Lueckisporites virkkiae* Zone in Paraná Basin (see Souza and Marques-Toigo, 2005), which is correlated to the Striatites Zone in the Chacoparaná Basin (see also Azcuy et al., 2007). Such subtle differences in the ranges of taxa are common throughout Gondwana. Assemblage 2 most closely correlates to the Early Cisuralian Lidkvarvet palynoflora from northern Heimefrontfjella (Antarctica, Lindström, 1995), the *Converrucosisporites confluens* Zone of Foster and Waterhouse (1988) in Australia and the OSPZ2 Zone of Stephenson et al. (2003) in Oman and Saudi Arabia, based on the presence of *Converrucosisporites confluens*, *Protohaploxypinus amplus*, *P. limpidus*, *P. goraiensis*, *Horriditriletes ramosus*, *Brevitriletes cornutus*, *B. levis* and *Punctatisporites gretensis*.

6. Paleoecology and taphonomy for paleoenvironmental interpretation

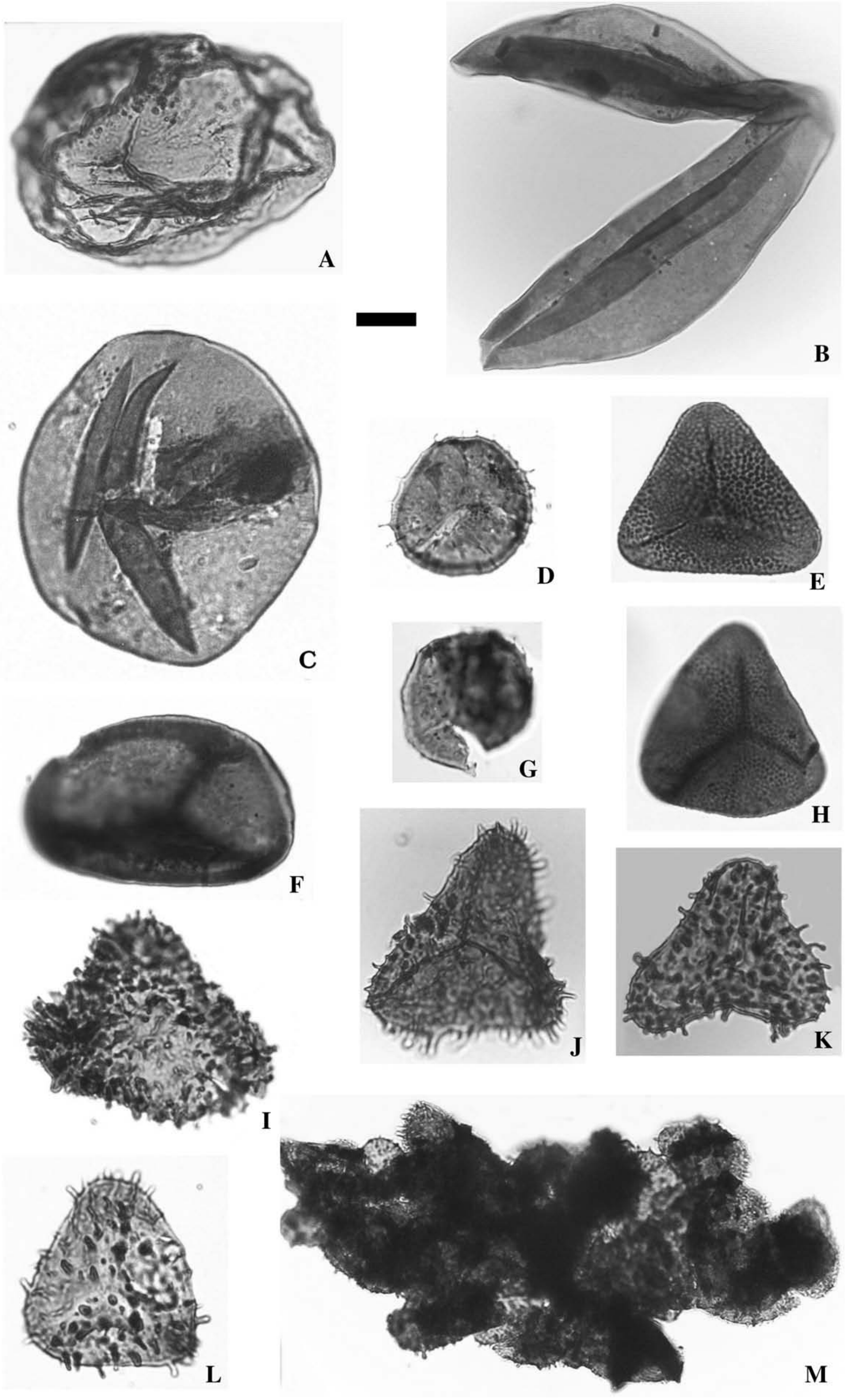
Assemblages 1 and 2 are composed of terrestrial palynomorphs (see Figs. 3 and 4) and, several characteristics of the organic remains, as discussed below, support the conclusion that both units were deposited under continental paleoenvironment conditions, in agreement with Pieroni and Georgieff (2007, and references therein). For example, *Portalites gondwanensis*, is interpreted as a fungus after Elsik (1996), which is frequently recorded in coal beds from the Late Palaeozoic of Argentina, Brazil and Uruguay (see Souza, 2003; Souza and Callegari, 2004). Pitting by fungal activity and cracking by hydratation–dehydration processes (see Cameron et al., 1989; Tyson, 1995) of the phytoclasts and palynomorphs is also highly suggestive of their terrestrial origin. Phytoclasts (mainly tracheids and brown and black unstructured particles and less frequently cuticles) are registered abundantly in almost all samples (10% in barren samples and between 60–90% of total phytoclasts + palynomorphs in productive samples) from the three outcrops (see Fig. 2). The inertinite (or black to brown particles) and other amorphous plant-derived particles (see Tyson, 1995; Batten, 1996) are rounded or irregular in shape. These particles are present in all samples, but generally, only one shape is dominant (e.g., rounded phytoclasts in BAFC-Pl 1672; irregular phytoclasts in BAFC-Pl 1671, see Fig. 2). This characteristic could be interpreted as an indication of variable transport regimen, i.e. longer vs. shorter transport distance or higher vs. lower flow with associated turbulence. However, phytoclast shape may also relate to the source of the clasts and the biological and chemical degradation processes that acted on them during transport.

Lycophytes and pteridophytes are the dominant groups in most collections from the assemblage 1 zone except for a sample (BAFC-Pl 1692) where species of *Cyclogranisporites* of pteridosperm affinity are dominant, together with the ever present cordaitalean/coniferalean non-striate monosaccate pollen grains (see Figs. 3 and 4). This composition is in agreement with data collected from the coaly horizon *KA* Zone that contain identifiable plant fossils within the Libertad Formation in this area (see Figs. 2 and 10). Pieroni and Georgieff (2007) interpreted the Libertad Formation to have evolved from an alluvial fan system to an alluvial system associated with the development of temporary lakes during humid conditions based on their sedimentary analysis together with the paleontological information provided by Carrizo et al. (2004) and di Pasquo et al. (2004).

Only one very productive sample was recovered from a thin gray claystone bed in the mid-part of the Sauces Formation (see Fig. 2). This sample contains an abundance of pteridophyte spores (see Fig. 4), especially the spore masses of *Leiotriletes directus* (Fig. 7I) and *Horriditriletes ramosus* (Fig. 8M), which, because of their monospecific nature, are interpreted as sporangial contents (see Glasspool, 2000). This productive bed is interpreted to have developed in a floodplain/backswamp environment that accumulated during a more humid interval during the deposition of the Sauces Formation in the Early Cisuralian, although, Pieroni and Georgieff (2007) present a contrasting interpretation — that the red and yellow beds of the Sauces Formation were continental deposits that accumulated under arid conditions.

7. Floral evolution related to paleoclimatic changes

The major vegetational turnover that occurred across Gondwana and the other floral provinces at the transition from the Pennsylvanian to the Cisuralian are linked to worldwide paleoclimatic trends (see Fig. 10). Locally, this turnover is reflected by the qualitative and the quantitative differences between assemblages 1 and 2 (see Figs. 3 and 4). Though this transition is recognized among coeval palynofloras across Gondwana (as described in Section 5), the exact timing of this event is diachronous. In addition, the presence of endemic taxa in various basins suggests that local microclimates controlled by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paleolatitude and regional paleogeography affected the exact timing of the transition (e.g., Gastaldo et al., 1996). Consequently, the Moscovian s.l. palynofloras of Peru, northern Bolivia and northern Brazil containing abundant or frequent striate monosaccate and bisaccate pollen grains (e.g., Playford and Dino, 2000a, 2000b; Azcuy et al., 2002; di Pasquo, 2009b), are qualitatively different from the palynofloras of southern Bolivia and western Argentina dominated by spores and non-striate pollen grains. These differences are interpreted to have been caused by paleolatitudinal position that affected the rate and timing of paleoclimatic changes. The paleobiogeographical consequences were discussed by Gastaldo et al. (1996), Iannuzzi and Rösler (2000), Playford and Dino (2000b) and di Pasquo (2009b) among others.

The main paleobotanical groups identified in assemblage 1 are trilete spores belonging to various lycophytes and pteridophytes and mainly non-striate monosaccate–bisaccate pollen grains of cordaitalean and coniferalean affinity. Scheffler et al. (2003), presented a paleoclimatic curve for the Moscovian to Sakmarian in Gondwana corrected for the higher latitudinal position of Southern Gondwana. The assemblage 1 palynoflora is consistent with this curve and indicates a generally humid, temperate climate (see Fig. 10). Moreover, in the framework of paleoclimatic phases described by Césari and Gutiérrez (2001 and references therein) for the western basins of Argentina (see Fig. 10), the Moscovian Assemblage 1 should be correlated to the Paleoclimatic Sub-phase IIIb. Phase III is divided into two sub-phases: Sub-phase IIIa is related to deglaciation and is represented by a marine post-glacial transgression bearing palynofloras of the DMa Zone and NBG Zone deposited in lacustrine and fiord environments. Sub-phase IIIb is characteristic of humid temperate (or cold temperate) climates, which were favorable for the accumulation of the coal beds and carbonaceous mudstones found in the Libertad Formation in the study area. Palynofloras from this paleoclimatic phase are referred to DMb Subzone. The floras are still related to the NBG Zone but, in addition, are characterized by the first appearance of arborescent lycophytes and sphenophytes (see Césari and Gutiérrez, 2001). Although many of the same groups found in the DMa Zone persisted in these palynofloras, some differences in the dominance of trilete spores related to pteridophytes and significant qualitative and quantitative changes in the pollen assemblages probably reflect a warming trend which followed the end of glacial conditions and a progressive increase of the diversity of plant communities (e.g., the first appearance of many striate pollen grains related to new pteridosperms groups). The upper part of the Libertad Formation up to the Sauces Formation, is likely equivalent to the upper parts of the Tupe sequences (see Fig. 1B; Vergel, 2008), where paleofloristic assemblages are characterized by true ferns (Filicales), Cordaitales, Equisetales and abundant conifers and with the appearance of species such as *Asterotheca pianitzkyi* and *Krauselcladus argentinus* (see Fig. 10). However, the equivalent palynofloras of DMc Subzone are quite similar to the DMb Subzone, dominated by species referred to lycophytes together with the coniferophytes, pteridophytes and sphenophytes. Additionally, marine and brackish species occur in strata of the Uspallata–Iglesia in the westernmost part of the Paganzo Basin. In its eastern part (see Fig. 1), only continental species are recognized (see Césari et al., 2007).

The paleoclimatic Phase IV after Césari and Gutiérrez (2001) is characterized by transitional features between humid–temperate (Phase IIIb) and arid (Phase V) conditions. This phase corresponds to the Early Cisuralian FS and *Gangamopteris* Zones recognized in the Bajo de Véliz and Tasa Cuna Formations (correlated to the lower Patquía–de la Cuesta sequence, see Fig. 1B). The latter flora is defined by the incoming of the Glossopteridales indicated by the dominance of striate–taeniate pollen grains among the new groups of pteridosperms (e.g., glossopterids and peltasperms, the parent plants of species of *Vittatina*, *Alisporites*–*Pteruchipollenites* and *Pakhapites*). New groups of lycophytes, pteridophytes, and sphenophytes characterized Cisuralian palynofloras in Gondwana, together with an abundance of Cordaitales and Coniferales mono- and bisaccate pollen grains (see Balme, 1995; Cúneo, 1996; Césari and Gutiérrez, 2001; Balarino and Gutiérrez, 2006). Some of these groups of plants are more typical of warmer and semiarid paleoenvironments linked with the Gondwana movement to lower latitudes (see Gastaldo et al., 1996; Scotese et al., 1999; McLoughlin, 2001; Iannuzzi and Souza, 2005; Césari et al., 2007). The assemblage 2 showed a dominance of Pteridophyta and Sphenophyta trilete spores of the genera *Horriditriletes*, *Converrucosisporites*–*Granulatisporites*, over the subdominance of Cordaitales/Coniferales (monosaccate pollen grains) and Coniferales/Pteridospermaphyta (e.g., *Protohaploxypinus*, *Illinites*, *Pteruchipollenites*, *Vittatina*) (see Fig. 4). This composition reflects the transitional Phase IV paleoclimate, between humid–temperate conditions (Phase IIIb) and more arid Phase V conditions, which are better indicated by the red-beds of the upper Sauces Formation. The paleoclimatic evolution of the study area is in agreement with a general trend of milder climates across western Gondwana as explained by Scheffler et al. (2003), during the Asselian–Sakmarian (see Fig. 10).

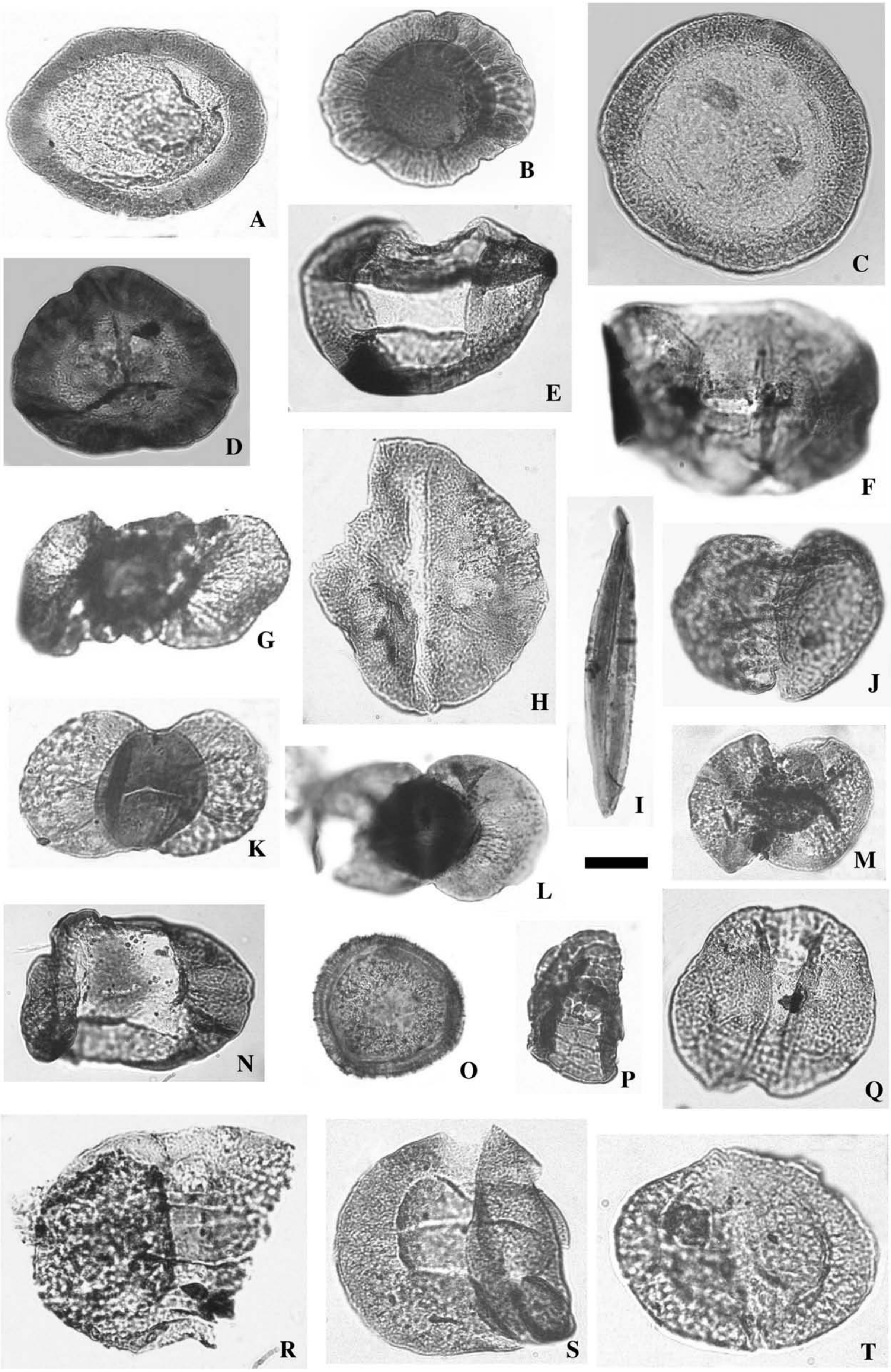
8. Conclusions

The palynology of the Libertad and Sauces Formations exposed in the northwest of the Paganzo Basin, La Rioja Province, have been investigated. Fifty-five claystone, siltstones and very fine-grained sandstones samples (many containing abundant plant debris) were collected from both units. Nine of the samples were productive, yielding seventy five species of well-preserved palynomorphs (42 spores, 32 pollen grains and one fungus). Two biostratigraphic assemblages are defined, and only thirteen taxa are shared between them. Assemblage 1 is recognized in seven samples from the Libertad Formation. It is dominated by spores with lycophyte (*Cristatisporites*) and pteridophyte (*Punctatisporites*) affinities (55%) and monosaccate pollen grains (32%) derived from Coniferales/Cordaitales parent plants (*Cannanoropollis*, *Potonieisporites*, *Plicatipollenites*). The assemblage 2 of the Sauces Formation is dominated by trilete spores (80%) mainly related to Filicopsida (*Horriditriletes* spp., *Converrucosisporites confluens*, *Granulatisporites austroamericanus*) and Sphenopsida (*Calamospora*). Pollen grains, including taeniate and non-taeniate pollen grains (e.g., *Limitisporites*, *Platysaccus*, *Pteruchipollenites*, *Protohaploxypinus*, *Illinites*, *Striatopodocarpites*, *Vittatina*) are more diverse but subordinate (19%).

Ten species constitute first records from the Paganzo Basin: *Convolutispora sculptilis*, *Cyclogranisporites minutus* and *Cyclogranisporites aureus* are exclusive to assemblage 1 and *Brevitriletes leptocaina*, *Horriditriletes superbus*, *Leschikisporites chacoparanensis*, *Protohaploxypinus goraiensis*, *Striatopodocarpites cancellatus* only register in assemblage 2. *Leiotriletes virkii* and *Cannanoropollis triangularis* are present in both assemblages.

Assemblage 1 is dated as Moscovian s.l. (to early Kasimovian?) on the basis of its correlation to the DMb (Mid–Late Pennsylvanian) Biozone of the Paganzo Basin, the PL Zone of the Chacoparaná Basin

Fig. 8. Selected species of assemblage 1, Sauces Formation. Scale bar = 10 μm. (A) *Calamospora hartungiana* Schopf in Schopf, Wilson and Bentall, BAFC-Pl 1673(3) X27. (B) *Calamospora* sp., BAFC-Pl 1673(3) X27. (C) *Calamospora liquida* Kosanke, BAFC-Pl 1673(2) Z34/4. (D) *Brevitriletes levis* (Balme and Hennelly) Bharadwaj and Srivastava, BAFC-Pl 1673(3) X53/3. (E) *Converrucosisporites confluens* (Archangelsky and Gamerro) Playford and Dino, BAFC-Pl 1673(3) D48/1. (F) *Grossusporites microgranulatus* (Menéndez and Azcuy) Pérez Loinaze and Césari, BAFC-Pl 1673(3) Q56/4. (G) *Brevitriletes leptocaina* Jones and Truswell, BAFC-Pl 1673(3) B48/3. (H) *Granulatisporites austroamericanus* Archangelsky and Gamerro, BAFC-Pl 1673(3) R33. (I) *Horriditriletes uruguaiensis* (Marques-Toigo) Archangelsky and Gamerro, BAFC-Pl 1673(3) W50/2. (J) *Horriditriletes superbus* (Foster) Césari, Archangelsky and Seoane, BAFC-Pl 1673(3) W49/2. (K) *Horriditriletes ramosus* (Balme and Hennelly) Bharadwaj and Salujha, BAFC-Pl 1673(3) R30/2. (L) *Horriditriletes curvibaculosus* Bharadwaj and Salujha, BAFC-Pl 1673(3) B33. (M) *Horriditriletes ramosus* (spore mass), BAFC-Pl 1673(3) H33/3.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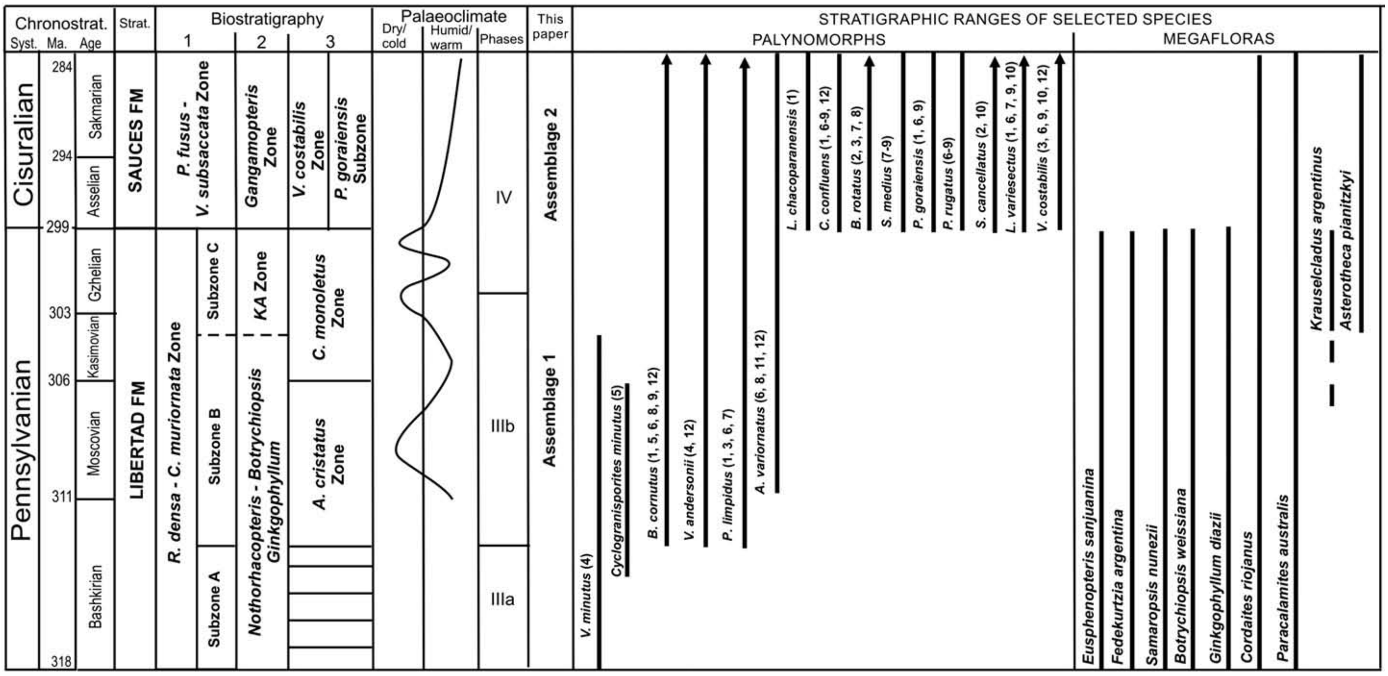

Fig. 10. Biostratigraphy and stratigraphic ranges of diagnostic species based on selected literature from Pennsylvanian and Early Cisuralian palynofloras of South America. Chronostratigraphy and absolute time dates after Gradstein et al. (2004). Palaeoclimate Phases after Césari and Gutiérrez (2001 and its references) and curve of glaciation–deglaciation for Gondwana after Scheffler et al. (2003). References: Paganzo Basin, 1. Césari and Gutiérrez (2001), 2. Azcuy et al. (2007 and references therein), Paraná Basin, 3. Souza (2006). Stratigraphic ranges: Megafloras (see Azcuy et al., 2007; di Pasquo, in press), Palynomorphs: 1. Vergel (1993), Archangelsky and Vergel (1996), Playford and Dino (2002), 2. Lindström (1995, 1996), 3. Playford and Dino (2000a,b), 4. Césari and Gutiérrez (2001), 5. di Pasquo (2003, 2009a), 6. Souza and Callegari (2004), Iannuzzi and Souza (2005), Souza and Marques-Toigo (2005), Souza (2006), 7. Balarino and Gutiérrez (2006), 8. Gutiérrez and Limarino (2006), 9. Gutiérrez et al. (2006), 10. Premaor et al. (2006), 11. del Papa and di Pasquo (2007), 12. Vergel (2008). See also Figs. 1A and 3.

and the BC Zone of the Tarija Basin in Argentina, and the *Crucisaccites monoletus* (Mid–Late Pennsylvanian) Biozone of the Paraná Basin in Brazil. This age determination is also supported by the presence of species restricted to the Pennsylvanian floras of those countries (e.g., *Cristatisporites stellatus*, *Apiculatasporites caperatus*, *Anapiculatisporites concinnus*, *Verrucosisporites minutus*, *Cyclogranisporites minutus*, *Cyclogranisporites aureus*, see Fig. 10). Overlying assemblage 1 in the Santa Rita Creek section, the taxa *Krauselcladus argentinus* and *Asterotheca pianitzkyi* (see Fig. 2) are attributed to the late Pennsylvanian *KA* Zone (see Figs. 1B and 10). Unfortunately, no productive sample was recovered above this level to be compared with the other palynoassemblages studied here and elsewhere.

Assemblage 2 is attributed to the Asselian–Sakmarian based on correlations to the FS (Early Cisuralian) Zone of the Paganzo Basin and the lower part of the C Zone of Chacoparaná Basin in Argentina and the Asselian–Sakmarian *Protohaploxypinus goraiensis* Subzone of the Vc Zone of the Paraná Basin and the lower part of the Vc Zone of the Amazonas Basins in Brazil. All these assemblages are characterized by an increase in striate pollen grains and the first appearance of *Converrucosisporites confluens*, *Scheuringipollenites medius*, *Barakarites rotatus*, *Protohaploxypinus goraiensis*, *P. rugatus*, *Lunatisporites variesectus*, *Striatopodocarpites cancellatus*, and *Vittatina costabilis* (see Fig. 3). Additionally, the base of the FS Zone coincides with the base of the *Gangamopteris* megafloristic Biozone (see Fig. 10), but the discovery of plant megafossils akin to this zone is still lacking in this area. Other correlations of both assemblages to assemblages elsewhere in Gondwana are addressed in the text.

Major vegetational turnovers from the Pennsylvanian to the Cisuralian across Gondwana and elsewhere are linked to general paleoclimatic trends (see Fig. 10). In the present study area, they are reflected by qualitative–quantitative differences between assemblages 1 and 2 (see Figs. 3, 4 and 10). The main paleobotanical groups identified in the assemblage 1 are lycophyte and pteridophyte and mainly non-striate monosaccate–bisaccate pollen grains of cordaitalean and coniferalean affinities. This palynoflora is consistent with generally temperate and humid climates occurring in the higher latitudes of Western Gondwana during the Moscovian. Moreover, in the framework of the paleoclimatic phases described for western basins of Argentina (see Fig. 10), this assemblage should be correlated to the temperate (or cold temperate) and humid climates of paleoclimatic sub-phase IIIb. Accumulation of coal beds with plant fossils and carbonaceous mudstones with plant debris and high proportions of continental origin palynomorphs and phytoclasts (between 60–90% of total phytoclasts + palynomorphs in productive levels), recognized here in the Libertad Formation, support a continental freshwater paleoenvironment.

The upper part of the Libertad Formation up to the Sauces Formation is characterized by true ferns (Filicales), Cordaitales, Equisetales

Fig. 9. Selected species of assemblage 1, Sauces Formation. Scale bar = 20 µm except for R = 15 µm and T = 10 µm. (A) *Barakarites rotatus* (Balme and Hennelly) Bharadwaj and Tiwari, BAFC-Pl 1673(2) Z37. (B) *Cannanoropollis densus* (Lele) Bose and Maheshwari, BAFC-Pl 1673(3) U30. (C) *Cannanoropollis janakii* Potonié and Sah, BAFC-Pl 1673(3) X24/2. (D) *Cannanoropollis triangularis* (Mehta) Bose and Maheshwari, BAFC-Pl 1673(3) O30/2. (E) *Crucisaccites monoletus* Maithy, BAFC-Pl 1673(3) L27/1. (F) *Potonieisporites barrelis* Tiwari, BAFC-Pl 1673(1) Z57/1. (G) *Caheniasaccites flavatus* Bose and Kar emend. Azcuy and di Pasquo, BAFC-Pl 1673(2) J29/3. (H) *Scheuringipollenites medius* (Burjack) Dias Fabricio, BAFC-Pl 1673(2) Z33/2. (I) *Cycadopites* sp. cf. *C. adjectus*, BAFC-Pl 1673(3) D55/4. (J) *Lunatisporites variesectus* Archangelsky and Gamerro, BAFC-Pl 1673(3) P35. (K) *Limitisporites hexagonalis* Bose and Maheshwari, BAFC-Pl 1673(2) X33. (L) *Striatopodocarpites cancellatus* Balme, BAFC-Pl 1673(2) Y29. (M) *Platysaccus* sp., BAFC-Pl 1673(2) Z32/3. (N) *Pteruchipollenites* sp. cf. *P. gracilis* (Segroves) Foster, BAFC-Pl 1673(2) K38/3. (O) *Portalites gondwanensis* Nahuys, Alpern and Ybert, BAFC-Pl 1674(1) Y45/1. (P) *Vittatina costabilis* Wilson, BAFC-Pl 1673(2) H26/1. (Q) *Protohaploxypinus rugatus* Segroves, BAFC-Pl 1673(2) T25/4. (R) *Protohaploxypinus goraiensis* (Potonié and Lele) Hart, BAFC-Pl 1673(2) D44/1. (S, T) *Illinites unicus* Kosanke emend. Jansonius and Hills, S. BAFC-Pl 1673(2) Z42/1–3, T. BAFC-Pl 1673(3) B60/1.

and abundant conifers and the appearance of new species such as *Asterotheca pianitzkyi* and *Krauselcladus argentinus* (see Fig. 10). Although many elements of the preexisting flora persisted in assemblage, some of the observed floral change likely reflect a warming trend following the end of glacial conditions at the end of the Pennsylvanian in this part of Gondwana. Warming resulted in increasing diversity o plant communities (e.g., the first appearance of many striate pollen grains belonging to newly colonizing pteridosperm groups). Assemblage 2 of the Sauces Formation is characterized by an abundance of pteridophytic spores (see Fig. 4) and especially, the presence of spore masses of *Leiotriletes directus* and *Horriditriletes ramosus*, which reflect the development of local humid conditions and the development of marshes and floodplains in the fluvial paleoenvironment. Cordaitales/Coniferales (monosaccate pollen grains) and Coniferales/Pteridospermaphyta (e.g., *Protohaploxypinus*, *Illinites*, *Pteruchipollenites*, *Vittatina*) were subdominant plants (Fig. 4) covering the more mesophytic to xeric areas. These floral characteristics are consistent with a transitional to Phase IV paleoclimatic conditions, i.e. conditions between the humid–temperate (Phase IIIb) and the more arid Phase V climates described for the western basins of Argentina. Locally, Phase V is interpreted from the dominance of red and yellow deposits of continental origin in the upper Sauces Formation. Therefore, a general trend of milder climates during the Pennsylvanian to the Cisuralian across western Gondwana is also evidenced by the evolution of both assemblages 1 and 2 recognized in this region of western Argentina (see Fig. 10).

Acknowledgements

The authors are grateful to Dr. Hugo Carrizo, who supplied the material for this study, and Gustavo Holfeltz for preparing most of the samples. Two anonymous reviewers and the editors of the special volume are gratefully acknowledged for their constructive suggestions and comments, as is Dr. Christopher Wnuk for correcting the English. This work was supported by research grants awarded by PIP CONICET 5518 and PICTR 0313/01 Agencia.

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