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## Carboniferous outcrops at La Herradura Creek, San Juan Province (Western Argentina), revisited: age of the transgressions

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**ABSTRACT.** At the outcrops of the Tupe Formation in the La Herradura Creek, San Juan Province, two transgressive events are recorded, which range from few meters to tens of meters in thickness. These strata correspond to the stratotype of the faunal *Tivertonia jachalensis-Streptorhynchus inaequiornatus* Biozone. An evaluation of the timing of the two marine transgressions is made on the basis of palynological assemblages and available radiometric ages. A short-lived transgression is recorded in the latest Bashkirian-early Moscovian, and then a substantial sea level fall took place forming an irregular incision surface. Later, a major high eustatic sea-level occurred during the middle Moscovian resulting in a more important marine ingression. The palynological assemblages associated to the older transgressive event indicate the presence of the *Raistrickia densa-Convolutispora muriornata* (DM) Biozone (Subzone B). Palynofloras referred to the Subzone C of the DM Biozone characterize the strata of the younger transgression that also bear marine fauna of the *Tivertonia jachalensis-Streptorhynchus inaequiornatus* Biozone. Correlations with other Pennsylvanian outcrops in the region give support to the stratigraphic scheme here proposed.

*Keywords:* Pennsylvanian, Argentina, Transgressions, Palynology.

**RESUMEN. Afloramientos carboníferos en la quebrada La Herradura, provincia de San Juan (oeste de Argentina), revisados: edad de las transgresiones.** En los afloramientos de la Formación Tupe en la quebrada de La Herradura, provincia de San Juan, se registran dos eventos transgresivos, cuya magnitud varía desde unos pocos metros a decenas de metros de espesor. Estos estratos corresponden al estratotipo de la biozona faunística *Tivertonia jachalensis-Streptorhynchus inaequiornatus*. En esta contribución se presenta una evaluación y ajuste de la edad de las dos transgresiones marinas, sobre la base de las asociaciones palinológicas y las dataciones radiométricas disponibles. Una transgresión de corta duración se registró en el Bashkiriano tardío-Moscoviano temprano, a la que siguió una sustancial caída del nivel del mar, y originó una superficie de incisión irregular. Posteriormente, significativas condiciones de mar alto se produjeron durante el Moscoviano medio, lo que resultó en una más importante ingresión marina. Las asociaciones palinológicas relacionadas con el evento más antiguo pueden ser asignadas a la Subzona B de la Biozona *Raistrickia densa-Convolutispora muriornata* (DM). Palinofloras referidas a la Subzona C de la Biozona DM caracterizan los estratos de la transgresión más joven, donde también se reconoce la fauna marina de la Biozona *Tivertonia jachalensis-Streptorhynchus inaequiornatus*. Las correlaciones con otros afloramientos pennsylvanianos en la región dan soporte al esquema estratigráfico aquí propuesto.

*Palabras clave:* Pennsylvanian, Argentina, Transgresiones, Palinología.

## 1. Introduction

Changes of sea levels have been determined for the Carboniferous and Permian in Gondwana (Veevers and Powell, 1987; Visser, 1997; Limarino *et al.*, 2006; López Gamundí, 2010), but an accurate history of sea levels is still pending. Evaluation of the timing of individual sea-level events was problematic to estimate accurately in Argentinian northwestern basins.

The Paganzo Basin is one of the best known and most extensive late Paleozoic depositional areas of Argentina, characterized by continental sedimentation punctuated by short Pennsylvanian marine transgressions. The Paganzo Group includes the upper Paleozoic deposits of the Paganzo Basin and comprises, from base to top, the Guandacol, Tupe and Patuía formations. An important approach to constrain the age of the transgressive events in the Carboniferous successions of the Paganzo Basin was given by the definition of several biozones based on marine invertebrates. The marine deposits of the Tupe Formation contain a key invertebrate fauna referred to the *Tivertonia jachalensis-Streptorhynchus inaequiornatus* (TS) Biozone by Sabattini *et al.* (1990) who suggested a late Carboniferous age for the assemblage. The outcrops of the La Herradura Creek were proposed as the holostratotype of the biozone and its Pennsylvanian age was accepted by different authors (González, 1993; Sabattini *et al.*, 1990; Taboada, 1997, 2010). However, the age of the biozone was a matter of debate and a Cisuralian age was proposed for the fauna (Archbold *et al.*, 2004; Cisterna *et al.*, 2002, 2005, 2011).

Recently, Gulbranson *et al.* (2010) obtained an U-Pb zircon age of  $312.82 \pm 0.11$  Ma for a tonstein from shallow marine deposits at the nearby locality of La Ciénaga. These transgressive deposits at La Ciénaga were considered coeval of the transgressive event recognized at La Herradura Creek (Desjardins *et al.*, 2009). Another Pennsylvanian age was obtained at the Río del Peñón section (parastratotype of the TS Biozone), where an absolute U-Pb date of  $310.63 \pm 0.07$  Ma was provided by Gulbranson *et al.* (2010) from an ignimbrite closely related to the TS Biozone. Therefore, the transgressive deposits that contain the *Tivertonia jachalensis-Streptorhynchus inaequiornatus* Biozone were assigned to the Moscovian by Césari *et al.* (2011) and Gulbranson *et al.* (2010).

The emergence of a radiometric control on the age of many palynological biozones and sedimentary units of the Paganzo Basin (Gulbranson *et al.*, 2010; Césari *et al.*, 2011) encourages the application of palynostratigraphic control in key stratigraphic sections. Given the importance of the upper Paleozoic succession exposed at the La Herradura Creek (Fig. 1), where two transgressive events are recorded, a revision of the palynological content of the succession is presented. The aim of this study is to provide a detailed stratigraphic context and to highlight the biostratigraphic correlations of the strata with their equivalents in the Paganzo Basin in order to clarify how recent radiometric ages may be used to constrain the age of the marine transgressions. For this purpose, fifteen palynological samples corresponding to different stratigraphic horizons are studied and compared with previous information. Moreover, a sedimentary section of the stratotype is provided in which seven facies associations are described and interpreted.

## 2. Geological and paleontological setting

The transgressive deposits of the Tupe Formation at La Herradura Creek yield abundant marine fossils since the first works by Frenguelli (1946) and Leanza (1946). Initially the marine and megaflorescent assemblages were considered Viséan in age (Frenguelli, 1946; Leanza, 1946) but later studies by Sabattini *et al.* (1990) and González (1997) relocated in the late Carboniferous these associations. Indeed, Sabattini *et al.* (1990) proposed the La Herradura Creek outcrops as the stratotype of the *Tivertonia jachalensis-Streptorhynchus inaequiornatus* (TS) Biozone. A Late Pennsylvanian age was suggested for this biozone by Sabattini *et al.* (1990); González (1997); Taboada (1997); Kelly *et al.* (2001) and Dineen *et al.* (2012). However, Archbold *et al.* (2004) and Cisterna *et al.* (2002, 2006, 2011) assigned the *Tivertonia jachalensis-Streptorhynchus inaequiornatus* Biozone to the early Permian based on brachiopod correlations with similar species of Australia. The assignment to the Permian of the TS Biozone is not consistent neither with recent chronostratigraphic information (Gulbranson *et al.*, 2010) nor regional biostratigraphic schemes based on plant remains (Césari *et al.*, 2011).

Therefore the outcrops of the La Herradura Creek are key for determining the stratigraphy of



FIG. 1. Location map showing the main upper Paleozoic basins from western Argentina and the location of the main stratigraphic sections mentioned in the text. Darker areas represent paleotopographic highs (Limarino *et al.*, 2006). Asterisk show the location of the studied stratigraphic section.

the Pennsylvanian transgressions. In order to analyze the stratigraphic position of the fossiliferous levels and to establish the sedimentary pattern of the Late Paleozoic deposits, a detailed stratigraphic study was carried out in the La Herradura Creek. First, a regional geologic reconnaissance was done, a geologic map of the region was surveyed, (Fig. 2) and a detailed section of the late Paleozoic sequence was logged (Fig. 3). This information allowed defining seven facies associations (5 in the Tupe Formation and two in the Patquía Formation, Table 1). Moreover all the upper Paleozoic section was sampled for palynological studies with the purpose of establishing the correlation between palynological and invertebrates zones.

### 3. Description of the La Herradura Creek stratotype

Frenguelli (1946) described for the first time the outcrops of the La Herradura Creek, identifying at the base the 'Estratos de Guandacol' (300-400 m in thickness, Guandacol Formation), overlain by the 'Estratos del Tupe' (180-200 m, Tupe Formation) and the 'Estratos de Patquía' (200 m, Patquía Formation) at the top. The middle section, 'Estratos del Tupe' was divided by Frenguelli (1946) into four

sections: **1.** Sandstones with *Calamites*; **2.** shales with *Lepidodendron*; **3.** shales with *Syringothyris* and **4.** limestone beds included in shales and sandstones in the upper part. Frenguelli (1946) mentioned the presence of the plant species: *Calamites peruvianus* Gothan, *Lepidodendron australe* M'Coy, *Rhacopteris circularis* Walton, *Aneimites robusta* Walkom, *Macrosphenopteris* sp. and *Samaropsis* sp.

Scalabrini Ortiz (1972) identified as formations the 'Estratos' defined by Frenguelli (1946) and measured a thickness of 204 m for the Tupe Formation in which marine deposits were described in the upper third. On the basis of marine fauna and plant remains, Leanza (1946) and Frenguelli (1946) assigned a Visean age for the deposits. The marine fauna was revised by Sabattini *et al.* (1990) and later by Cisterna *et al.* (2002) who identified at the upper section of the Tupe Formation nine fossiliferous horizons, in a stratigraphical interval of about 20 m. Unlike previously suggested by previous authors (Frenguelli, 1946 and Scalabrini Ortiz, 1972), Cisterna *et al.* (2002) proposed a thickness of about 80 m for the Tupe Formation and Cisterna *et al.* (2011) approximately 120 m (including strata here considered Patquía Formation). The marine deposits are overlain by a conspicuous marine limestone

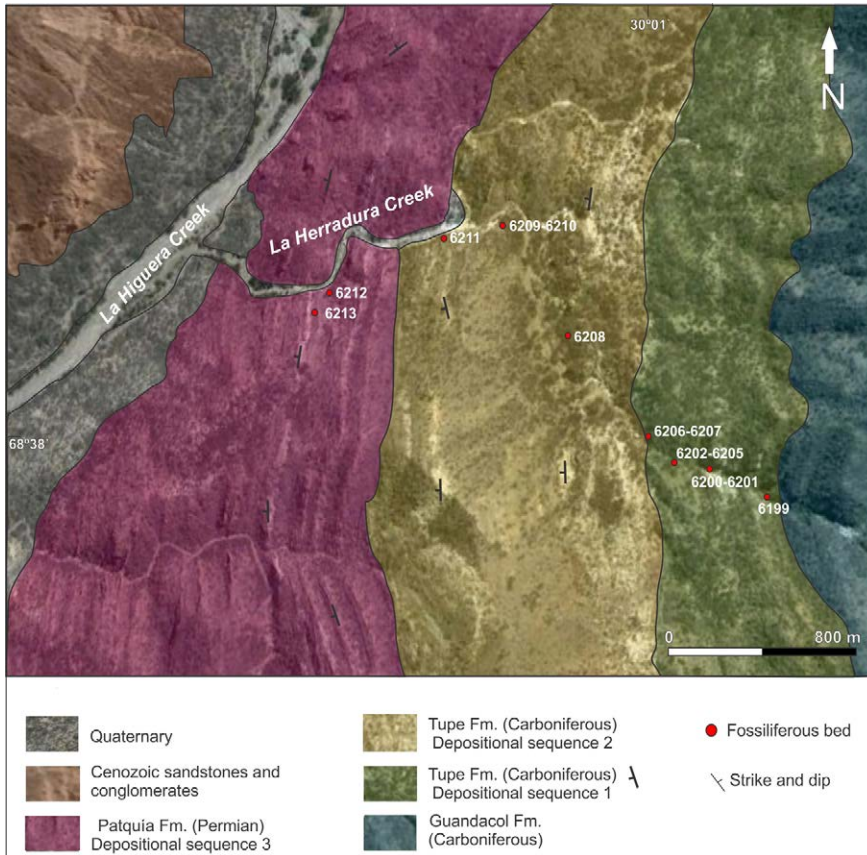


FIG. 2. Geological scheme of the La Herradura Creek showing the location of the palynological samples.

level that were considered by Frenguelli (1946) and Scalabrini Ortiz (1972) indicative of the boundary with the overlying Patquía Formation (Fig. 4). However, Cisterna *et al.* (2002) positioned much higher up the boundary between both formations, including in the Tupe Formation a rich palynological association (P9a in Cisterna *et al.*, 2002) that was recovered above the marine beds and few tens of meters above the uppermost horizon of limestone (Vergel, 2008).

In this paper, we follow the approach suggested by Frenguelli (1946) and Scalabrini Ortiz (1972) for establishing the boundary between the Tupe and Patquía formations. For characterizing the stratotype, a stratigraphic section referred to Tupe and Patquía formations, was measured at the La Herradura Creek (Fig. 3) identifying five facies associations in the former unit and two in the latter (Table 1). Each of them was sampled for palynological studies and the results are shown in Table 2. Palynological

results together with stratigraphic correlations and chronostratigraphic information allow obtaining additional evidence for the age of the TS Biozone.

### 3.1. Facies Association 1 (FA 1, coarse grained cross-bedded sandstones and conglomerates)

This facies association sits on a low-relief incision surface carved into the underlying Guandacol Formation. It comprises cross-bedded coarse-grained sandstones, gravely sandstones and some conglomerates stratified in stacked lenticular beds (38 m thick, Fig. 3, Table 1). These rocks form channel complexes bounded by five-order bounding surfaces (Miall, 1996), frequently showing downstream accretion surfaces (DA, surfaces by Miall, 1996). Fine grained-sandstones and mudstones are scarce; with the exception of a thin level of carbonaceous mudstones bearing fragmentary plant remains located 10 m above the base of the

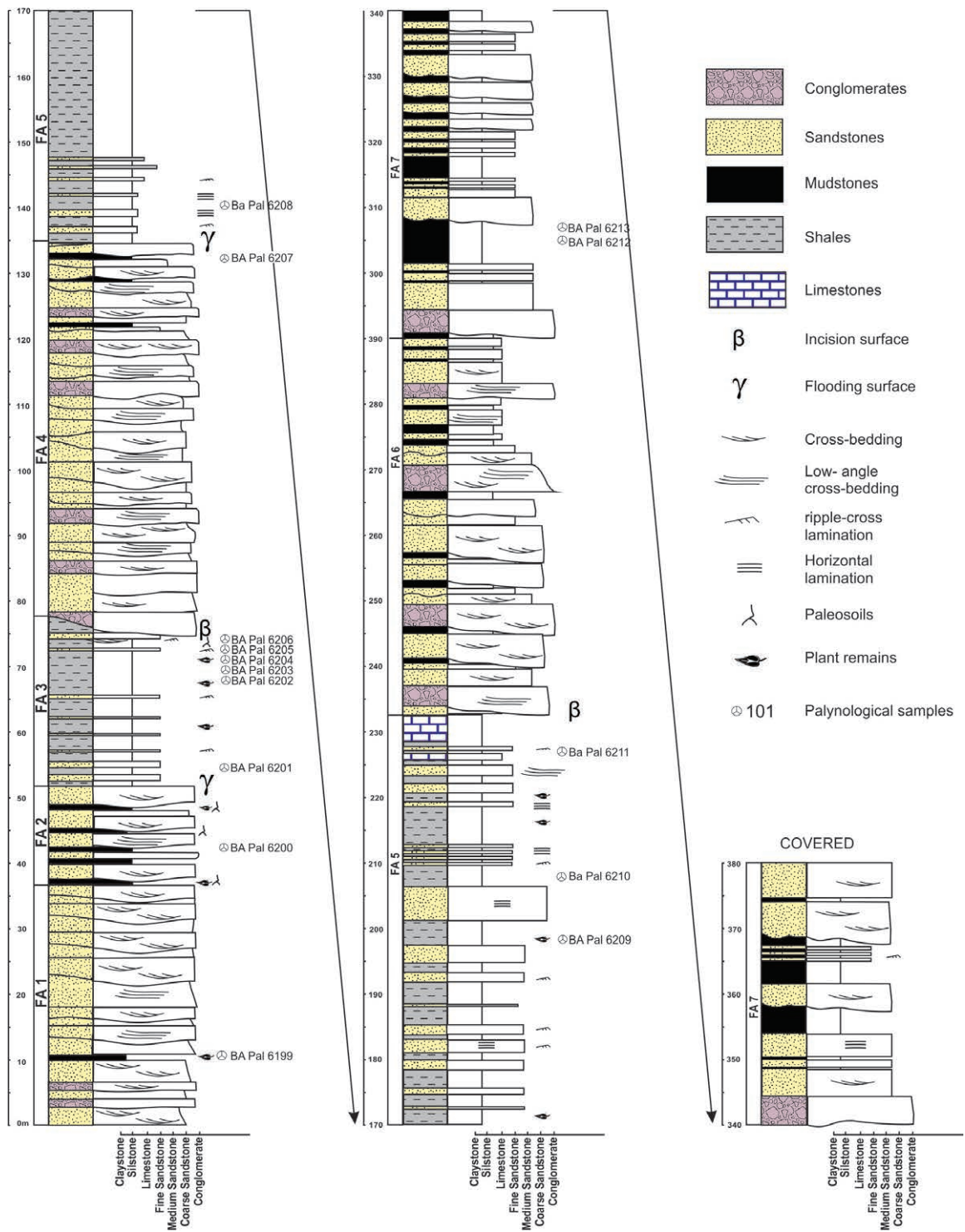


FIG. 3. Detailed sedimentological log at La Herradura Creek showing facies associations and the location of the palynological assemblages.

TABLE 1. CHARACTERISTICS, INTERPRETATION AND LITHOSTRATIGRAPHIC DISTRIBUTION OF THE FACIES ASSOCIATIONS DESCRIBED IN THIS PAPER.

Facies Association	Description	Thickness	Depositional Environment	Stratigraphic unit
7	Red mudstones and sandstones	45 m	Channel complexes separated by thick fine-grained floodplain deposits	Patquía Formation
6	Variegated crossbedded sandstones and conglomerates	35 m	Fluvial braided alluvial plains with progressive increase in floodplain deposits	
5	Fine-grained sandstones, shales and limestones	95 m	Shallow marine (Pennsylvanian transgression 2)	Tupe Formation
4	Coarse grained cross-bedded sandstones stratified in lenticular beds	85 m	Fluvial braided alluvial plains	
3	Interbedded fine-grained sandstones and carbonaceous mudstones	25 m	Estuarine (Pennsylvanian transgression 1)	
2	Coarse grained crossbedded sandstones and laminated mudstones	15 m	Multichannelized alluvial plains with abundant floodbasin deposits (high-accommodation space conditions)	
1	Coarse grained crossbedded sandstones and conglomerates	38 m	Braided alluvial plains with scarce floodbasin deposits (low-accommodation space conditions)	

Tupe Formation. Palynological assemblage from the FA 1 is composed of scarce spores (Table 2) with relatively extended stratigraphic range such as: *Apiculatasporites parviapiculatus* Azcuy (Fig. 5D), *Apiculatisporis variornatus* di Pasquo, Azcuy and Souza (Fig. 5E), *Verrucosisporites andersonii* (Anderson) Backhouse (Fig. 6N), *Apiculiretusispora alonsoi* Ottone (Fig. 5F) and *Lundbladisporea braziliensis* (Pant and Srivastava) Marques-Toigo and Pons emend. Marques-Toigo and Picarelli (Fig. 5CC).

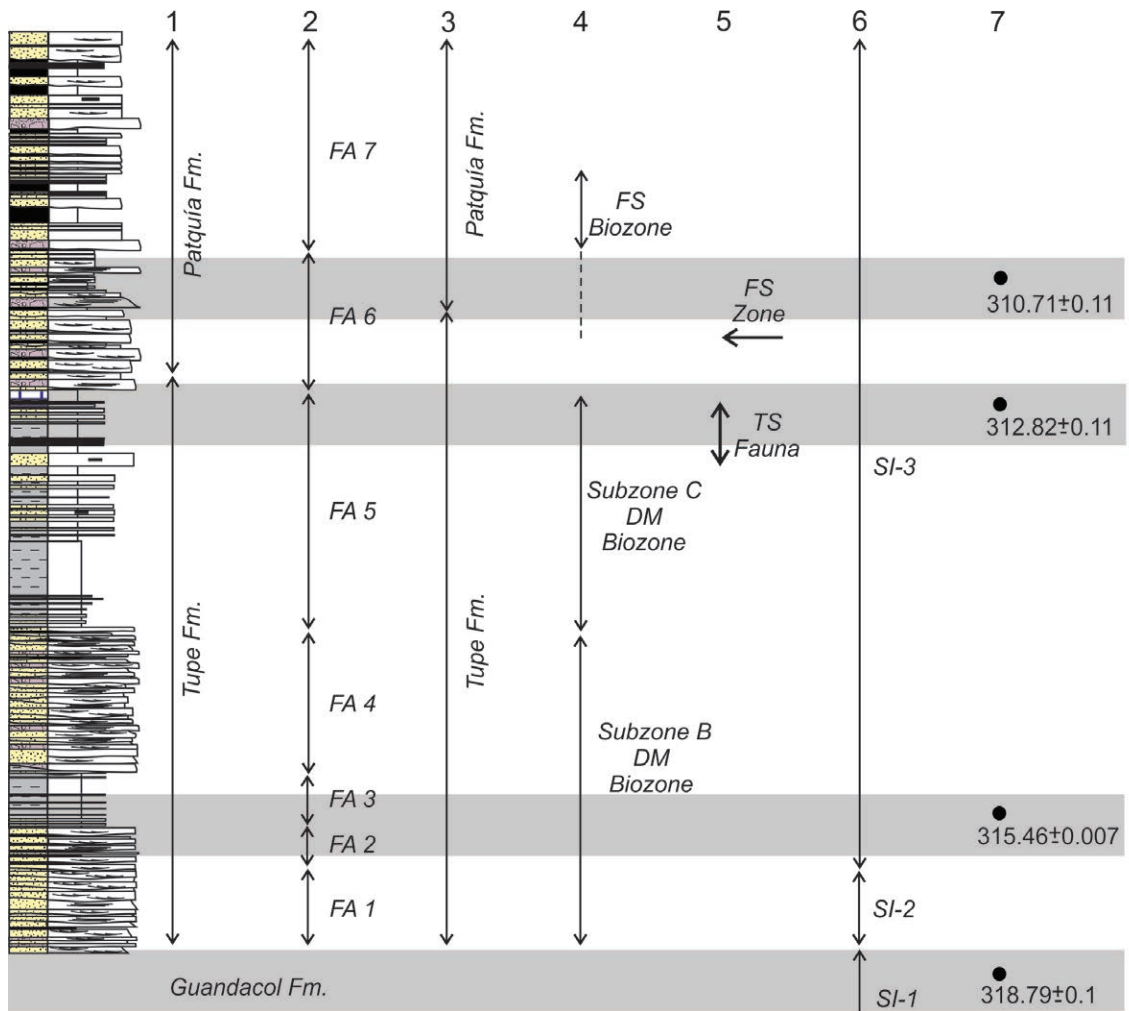
This interval is interpreted as deposited in braided alluvial plains with restricted development of floodbasins under low-accommodation space conditions. FA 1 correlates with that described by Tedesco *et al.* (2010) as FA 1 at the base of the Tupe Formation in the Huaco area which was interpreted as formed under low-accommodation conditions.

### 3.2. Facies Association 2 (FA 2, coarse grained cross-bedded sandstones and laminated mudstones)

This interval (15 m thick, Fig. 3) is similar in terms of sandstone dominance to the previously described FA 1, but differs in the presence of carbonaceous

mudstones and fine-grained sandstones as well as in the more tabular form of the beds and the occurrence of finning-upward cycles. Each cycle can be divided in two terms, the lower one comprises cross-bedded coarse-grained sandstones and fine-grained conglomerates (forming more than 80% of the cycle), overlying a low-relief erosive surface. The upper term is composed of thin beds (up to 20 cm) of mudstones and fine-grained sandstones bearing plant remains and showing paleosol structures (roots). Palynologically, monosaccate pollen is abundant in the FA 2 where more diverse spores also appear (Table 2). Some species seems to be restricted to this interval, like *Raistrickia* sp. cf. *R. paganciana* Azcuy (Fig. 6J) and *Florinites* sp. (Fig. 6AA). Other species of broader stratigraphic record, but constrained to the Tupe Formation, are: *Raistrickia densa* Menéndez (Fig. 6F), *Raistrickia rotunda* Azcuy (Fig. 6D) and *Convolutispora muriornata* Menéndez (Fig. 5O).

Probably the depositional environment was very similar to that of the FA 1, but the higher amount of fine-grained deposits indicates the presence of flood plains. A network of braided (or anastomosing) channels separated by relatively broad, vegetated



FA: Facies association  
 SI: Depositional sequence  
 ●: Radiometric age

DM: *Raistrickia densa*-*Convolutispora muriornata* Biozone  
 FS: *Pakhpites fusus*-*Vittatina subsaccata* Biozone  
 TS: *Tivertonia jachalensis*-*Streptorhynchus inaequiornatus* Biozone

FIG. 4. Synthesis of the stratigraphic, biostratigraphic, sequential-stratigraphic and chronostratigraphic models proposed for the La Herradura Creek and surrounding areas by several authors. References: 1. Stratigraphic division proposed by Frenguelli (1946) for the La Herradura Creek section (note that originally Frenguelli used the name of 'Estratos' which were later redefined as formations); 2. Facies associations identified in Tupe and Patquia Formations (this paper); 3. Stratigraphic division proposed by Cisterna (2010) for the La Herradura Creek; 4. Palynological zones recognized along the La Herradura Creek section (this paper); 5. Biostratigraphic scheme, based on faunal assemblages (Cisterna, 2010); 6. Sequential stratigraphic model proposed by Gulbranson *et al.* (2010) for the Paganzo Basin and 7. Radiometric U-Pb ages obtained for depositional sequences (column 6) in the neighboring section of Huaco (Gulbranson *et al.*, 2010). Shaded horizontal lines indicate the transgressive events.

and likely poorly-drained flood plains is inferred for FA 2. Therefore the transition from braided to anastomosing river deposits indicates an increase in the sedimentary accommodation space during the deposition of FA 2.

**3.3. Facies Association 3 (FA 3, fine-grained sandstones and carbonaceous mudstones)**

Interbedded green to dark-gray fine-grained sandstones and mudstones form a monotonous

TABLE 2. STRATIGRAPHIC DISTRIBUTION OF THE PALYNOLOGICAL SPECIES.

Formation		Tupe												Patquía		
Facies Association		FA1	FA2	FA3						FA4	FA5				FA7	
BA Pal		6199	6200	6201	6202	6203	6204	6205	6206	6207	6208	6209	6210	6211	6212	6213
Spores	<i>Verrucosiporites</i> sp. (Fig. 5Q)	X				X										
	<i>Apiculatasporites parviapiculatus</i> (Fig. 4D)	X	X	X			X	X	X	X						
	<i>Apiculiretusispora alonsoi</i> (Fig. 4F)	X	X					X					X			
	<i>Apiculatisporis variornatus</i> (Fig. 4E)	X	X	X			X	X	X	X	X		X	X		
	<i>Verrucosiporites andersonii</i> (Fig. 5N)	X	X			X	X	X	X	X				X		
	<i>Lundbladispora braziliensis</i> (Fig. 4CC)	X	X					X	X				X	X	X	X
	<i>Brevitriletes levis</i> (Fig. 4J)		X								X			X	X	
	<i>Raistrickia</i> cf. <i>R. paganciana</i> (Fig. 5J)		X													
	<i>Cristatisporites stellatus</i> (Fig. 4R)		X			X	X	X	X	X					X	
	<i>Lundbladispora riobonitensis</i> (Fig. 5A)		X													X
	<i>Spelaotriletes ybertii</i> (Fig. 5L)		X	X						X	X		X	X	X	X
	<i>Cristatisporites rollerii</i> (Fig. 4Y)		X				X		X				X			X
	<i>Cyclogranisporites microgranus</i> (Fig. 4S)		X				X		X				X			X
	<i>Grossusporites microgranulatus</i> (Fig. 4X)		X													X
	<i>Raistrickia densa</i> (Fig. 5F)		X	X					X						X	
	<i>Cristatisporites inconstans</i> (Fig. 4N)		X			X	X	X	X						X	
	<i>Convolutispora muriornata</i> (Fig. 4O)		X						X				X			
	<i>Calamospora</i> sp. (Fig. 4K)		X						X				X			
	<i>Raistrickia rotunda</i> (Fig. 5D)		X	X					X							
	<i>Vallatisporites arcuatus</i> (Fig. 5M)		X	X					X	X		X		X	X	X
	<i>Cyclogranisporites rinconadensis</i> (Fig. 4T)					X	X	X	X							
	<i>Brevitriletes leptocaina</i> (Fig. 4I)						X	X								
	<i>Verrucosiporites</i> cf. <i>V. sifati</i> (Fig. 5P)						X	X	X					X	X	X
	<i>Cristatisporites spinosus</i> (Fig. 4Q)						X						X	X	X	X
	<i>Granulatisporites austroamericanus</i> (Fig. 4V)							X	X							X
	<i>Cristatisporites chacoparanaensis</i> (Fig. 4M)						X		X	X				X	X	
	<i>Verrucosiporites menendezii</i> (Fig. 5O)							X	X					X		
	<i>Cristatisporites menendezii</i> (Fig. 4L)							X	X					X		
	<i>Anapiculatisporites concinnus</i> (Fig. 4B)						X	X	X	X	X	X		X		
	<i>Punctatisporites glaber</i>							X				X		X		



table 2 continued.

Formation		Tupe													Patquía	
Facies Association		FA1	FA2	FA3						FA4	FA5				FA7	
BA Pal		6199	6200	6201	6202	6203	6204	6205	6206	6207	6208	6209	6210	6211	6212	6213
Spores	<i>Ahrensiporites cristatus</i> (Fig. 4A)								X							
	<i>Foveosporites</i> cf. <i>F. hortonensis</i> (Fig. 4U)									X						
	<i>Microreticulatisporites punctatus</i> (Fig. 5B)										X			X		
	<i>Granulatisporites</i> cf. <i>G. varigranifer</i> (Fig. 4W)												X	X	X	X
	<i>Apiculiretusispora ralla</i> (Fig. 4G)												X	X		X
	<i>Raistrickia cephalata</i> (Fig. 5.G,I)												X	X		
	<i>Leiotriletes tiwarii</i> (Fig. 4BB)												X			
	<i>Apiculiretusispora</i> cf. <i>A. papillata</i> (Fig. 4H)													X	X	
	<i>Apiculatasporites caperatus</i> (Fig. 4C)													X	X	
	<i>Retusotriletes anfractus</i> (Fig. 5K)													X		X
	<i>Horriditriletes uruguayensis</i> (Fig. 4P)														X	X
	<i>Horriditriletes</i> cf. <i>H. tereteangulatus</i> (Fig. 4Z)														X	X
	<i>Raistrickia</i> sp. cf. <i>R. radiosa</i> (Fig. 5E)														X	
	<i>Laevigatosporites vulgaris</i> (Fig. 4AA)														X	
	<i>Lophotriletes discordis</i> (Fig. 4DD)														X	
<i>Punctatisporites gretensis</i> (Fig. 5C)													X			
Algae	<i>Navifusa variabilis</i> (Fig. 7H)													X		
	<i>Tetraporina punctata</i> (Fig. 7K)						X								X	
Pollen grains	<i>Cannanoropollis densus</i> (Fig. 5R)		X			X	X	X					X	X	X	X
	<i>Cannanoropollis janakii</i> (Fig. 5S)		X				X		X	X		X	X	X	X	X
	<i>Cannanoropollis mehtae</i> (Fig. 5U)		X	X	X	X	X	X	X	X		X	X	X	X	X
	<i>Circumplicatipollis plicatus</i> (Fig. 5Y)		X			X										X
	<i>Plicatipollenites gondwanensis</i> (Fig. 6H)		X			X	X						X		X	X
	<i>Plicatipollenites malabarensis</i> (Fig. 6O)		X						X				X	X	X	X
	<i>Plicatipollenites trigonalis</i> (Fig. 6D)		X			X	X						X	X	X	X
	<i>Limitisporites rectus</i> (Fig. 6A)		X							X			X	X		X
	<i>Potonieisporites barrelis</i> (Fig. 6C)		X				X							X	X	
	<i>Potonieisporites neglectus</i> (Fig. 6M)		X										X	X	X	
	<i>Potonieisporites methoris</i> (Fig. 6J)		X			X							X	X		
	<i>Crucisaccites monoletus</i> (Fig. 5T)		X	X	X	X	X	X	X			X	X			

table 2 continued.

Formation		Tupe												Patquía		
Facies Association		FA1	FA2	FA3						FA4	FA5				FA7	
BA Pal		6199	6200	6201	6202	6203	6204	6205	6206	6207	6208	6209	6210	6211	6212	6213
Pollen grains	<i>Florinites</i> sp. (Fig. 5AA)		X													
	<i>Caheniasaccites elongatus</i> (Fig. 5X)				X							X	X	X	X	
	<i>Tuberisaccites varius</i> (Fig. 6R)					X	X					X				
	<i>Potoneisporites brasiliensis</i> (Fig. 6Q)						X						X	X	X	X
	<i>Potoneisporites magnus</i> (Fig. 6F)						X							X	X	X
	<i>Potoneisporites densus</i> (Fig. 6G)							X	X					X	X	
	<i>Caheniasaccites ovatus</i> (Fig. 5V)							X				X	X	X	X	
	<i>Caheniasaccites densus</i> (Fig. 5W)								X				X	X	X	
	<i>Limitisporites monosaccoides</i> (Fig. 6I)										X		X	X	X	
	<i>Potoneisporites triangulatus</i> (Fig. 6N)										X			X		X
	<i>Cannanoropollis trilobatus</i> (Fig. 5Z)											X				
	<i>Tuberisaccites</i> sp. (Fig. 6S)											X	X			X
	<i>Trisaccate</i> indet. (Fig. 7F)											X	X	X		
	<i>Gondwanopollis</i> sp. (Fig. 5BB)												X			
	<i>Limitisporites hexagonalis</i> (Fig. 6E)												X			
	<i>Potoneisporites marleniaei</i> (Fig. 6L)												X			
	<i>Limitisporites</i> sp. cf. <i>L. luandensis</i> (Fig. 6B)													X	X	
<i>Potoneisporites novicus</i> (Fig. 6P)													X	X	X	
<i>Bisaccate</i> indet. (Fig. 6K)															X	
Striate pollen grains	<i>Protohaploxylinus</i> cf. <i>P. haigii</i> (Fig. 7B)										X			X	X	X
	<i>Protohaploxylinus limpidus</i> (Fig. 7C)											X	X	X		
	<i>Striatoabietes multistriatus</i> (Fig. 7A)												X			X
	<i>Hamiapollenites insolitus</i> (Fig. 7D, E)													X	X	X
	<i>Protohaploxylinus amplus</i> (Fig. 7N)													X	X	X
	<i>Illinites unicus</i> (Fig. 7J, L)														X	X
	<i>Vittatina costabilis</i> (Fig. 7M)														X	
	<i>Vittatina wodehousei</i> (Fig. 7G)														X	
	<i>Vittatina subsaccata</i> (Fig. 7I)														X	

BA Pal: Museo Argentino de Ciencias Naturales palynological collection.

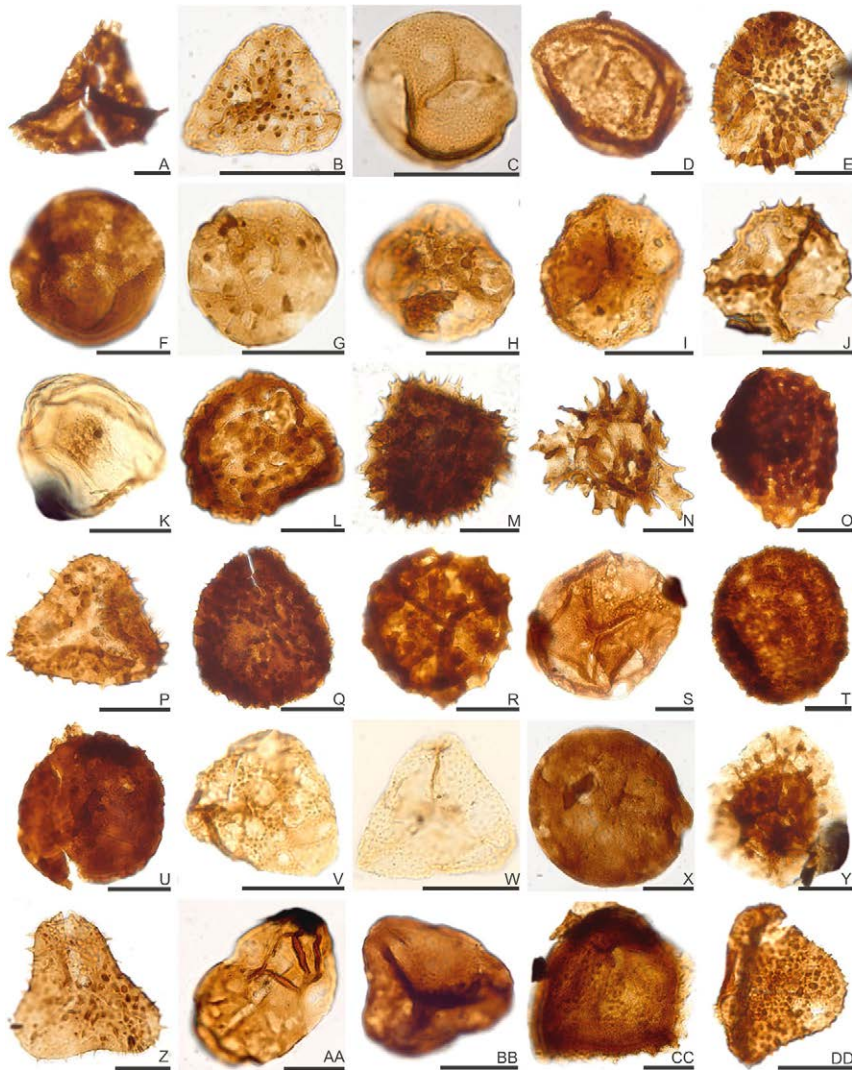


FIG. 5. **A.** *Ahrensisporites cristatus* Playford and Powis, BA Pal 6206-2:T26/3; **B.** *Anapiculatisporites concinnus* Playford, BA Pal 6205-4:Q25/3; **C.** *Apiculatasporites caperatus* Menéndez and Azcuy, BA Pal 6212-7:N38/4; **D.** *Apiculatasporites parvicapiculatus* Azcuy, BA Pal 6202-2:N31/1; **E.** *Apiculatisporis variornatus* di Pasquo, Azcuy and Souza, BA Pal 6200-2:Y36/1; **F.** *Apiculiretusispora alonsoi* Ottone, BA Pal 6200-5:W38/1; **G.** *Apiculiretusispora ralla* (Menéndez and Azcuy) Menéndez and Azcuy, BA Pal 6211-2:X54/3; **H.** *Apiculiretusispora* sp. cf. *A. papillata* Menéndez and Azcuy, BA Pal 6211-1:P47/4; **I.** *Brevitriletes leptocaina* Jones and Truswell, BA Pal 6203-4: T34/2; **J.** *Brevitriletes levis* (Balme and Hennelly) Bharadwaj and Srivastava, BA Pal 6211-2:X41/4; **K.** *Calamospora* sp., BA Pal 6200-2:F34/3; **L.** *Cristatisporites menendezii* (Menéndez and Azcuy) Playford, BA Pal 6211-2:F26/3; **M.** *Cristatisporites chacoparanaensis* Ottone, BA Pal 6203-4:K45/1; **N.** *Cristatisporites inconstans* Archangelsky and Gamarro, BA Pal 6206-1:Z44/4; **O.** *Convolutispora muriornata* Menéndez, BA Pal 6200-1:G32/0; **P.** *Horriditriletes uruguayensis* (Marques-Toigo) Archangelsky and Gamarro, BA Pal 6212-3:P20/4; **Q.** *Cristatisporites spinosus* (Menéndez and Azcuy) Playford, BA Pal 6210-3:M23/1; **R.** *Cristatisporites stellatus* (Azcuy) Gutiérrez and Limarino, BA Pal 6200-2:W53/2; **S.** *Cyclogranisporites microgranus* Bhardwaj, BA Pal 6213-1:M31/4; **T.** *Cyclogranisporites rinconadensis* Césari and Limarino, BA Pal 6202-1:H40/1; **U.** *Foveosporites* sp. cf. *F. hortonensis* (Playford) Azcuy, BA Pal 6207-1:F49/2; **V.** *Granulatisporites austroamericanus* Archangelsky and Gamarro, BA Pal 6205-1:E40/3; **W.** *Granulatisporites* sp. cf. *G. varigranifer* Menéndez and Azcuy, BA Pal 6210-3:Y56/0; **X.** *Grossusporites microgranulatus* Pérez Loinaze and Césari, BA Pal 6213-1:P20/4; **Y.** *Cristatisporites rollerii* Ottone, BA Pal 6206-4:H54/4; **Z.** *Horriditriletes* sp. cf. *C. tereteangulatus* (Balme and Hennelly) Backhouse, BA Pal 6212-3:X39/0; **AA.** *Laevigatosporites vulgaris* (Ibrahim) Ibrahim, BA Pal 6212-1:T31/3; **BB.** *Leiotriletes tiwarii* Saxena, BA Pal 6210-1:P34/1; **CC.** *Lundbladispota braziliensis* (Pant and Srivastava) Marques-Toigo and Pons emend. Marques-Toigo and Picarelli, BA Pal 6200-4:Z31/0; **DD.** *Lophotriletes discordis* Gutiérrez and Césari, BA Pal 6212-1:J54/2. Scale bar: 20  $\mu$ m.

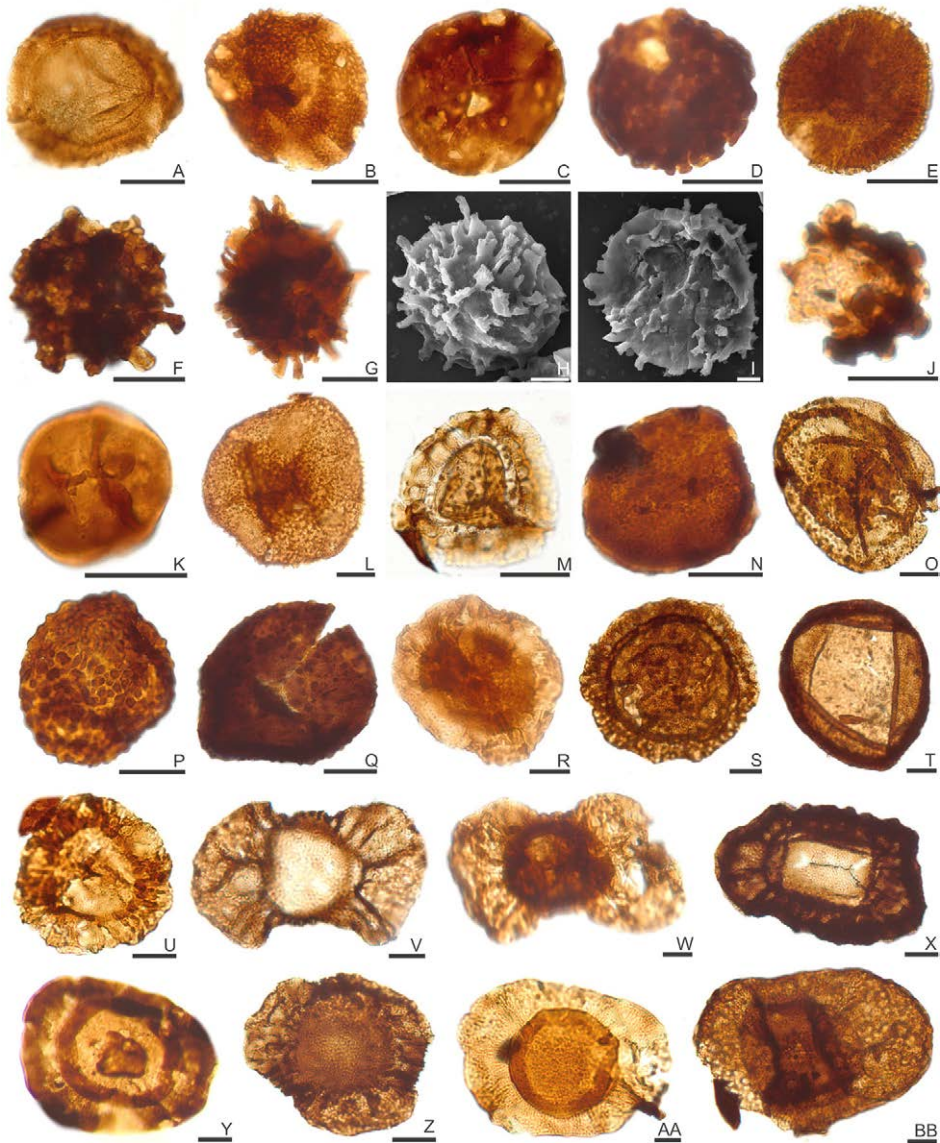


FIG. 6. **A.** *Lundbladispora riobonitensis* Marques-Toigo and Picarelli, BA Pal 6200-5:L34/3; **B.** *Microreticulatisporites punctatus* Knox, BA Pal 6211-1:H33/3; **C.** *Punctatisporites gretensis* Balme and Hennelly; BA Pal 6211-2: S40/1; **D.** *Raistrickia rotunda* Azcuy, BA Pal 6200-5:Q58/1; **E.** *Raistrickia* sp. cf. *R. radiosa* Playford and Helby, BA Pal 6212-8:A37/4; **F.** *Raistrickia densa* Menéndez, BA Pal 6205-1:W31/1; **G-I.** *Raistrickia cephalata* Bharadwaj, Kar and Navale ; **G.** BA Pal 6211-2:T23/0; **H.** MEB ; **I.** MEB ; **J.** *Raistrickia* sp. cf. *R. paganciana* Azcuy, BA Pal 6200-1:K39/0; **K.** *Retusotriletes anfractus* Menéndez and Azcuy, BA Pal 6213-1:S43/2; **L.** *Spelaeotriletes ybertii* (Marques-Toigo) Playford and Powis emend. Playford, Dino and Marques-Toigo, BA Pal 6213-1:V51/2; **M.** *Vallatisporites arcuatus* (Marques-Toigo) Archangelsky and Gamarro, BA Pal 6200-5:V50/0; **N.** *Verrucosisporites andersonii* (Anderson) Backhouse, BA Pal 1988, BA Pal 6205-2:S41/1; **O.** *Verrucosisporites menendezii* Archangelsky and Gamarro, BA Pal 6205-4:R50/3; **P.** *Verrucosisporites* sp. cf. *V. sifati* (Ibrahim) Smith and Butterworth, BA Pal 6203-3:F33/1; **Q.** *Verrucosisporites* sp., BA Pal 6199-3:W54/2; **R.** *Cannanoropollis densus* (Lele) Bose and Maheshwari, BA Pal 6211-2:V53/2; **S.** *Cannanoropollis janakii* Potonié and Sah, BA Pal 6210-2:M32/0; **T.** *Crucisaccites monoletus* Maithy, BA Pal 6209-3:J27/2; **U.** *Cannanoropollis mehtae* (Lele) Bose and Maheshwari, BA Pal 6211-2:Q47/2; **V.** *Caheniasaccites ovatus* Bose and Kar emend. Archangelsky and Gamarro, BA Pal6209-2:J52/0; **W.** *Caheniasaccites densus* Lele and Karim emend. Gutiérrez, BA Pal6211-1:O29/2; **X.** *Caheniasaccites elongatus* Bose and Kar, BA Pal 6209-1:H46/3; **Y.** *Circumpliatipollis plicatus* Ottone and Azcuy, BA Pal 6200-5:B33/4; **Z.** *Cannanoropollis trilobatus* (Höeg and Bose) Gutiérrez, BA Pal 6209-2:U52/1; **AA.** *Florinites* sp., BA Pal 6200-4:U37/2; **BB.** *Gondwanopollis* sp., BA Pal 6210-2:N53/3. Scale bar: 20  $\mu$ m.

sequence up to 25 m thick. Mudstones, frequently organic-rich, are composed of laminated siltstones (less frequently claystones) stratified in tabular beds, up to 10 cm thick, showing poorly preserved plan remains. Fine-grained sandstones appear in tabular beds exhibiting current and wave ripple-cross lamination, heterolithic structures and more rarely small-scale cross-bedded sets. Several pollen species appear for the first time in the FA 3: *Caheniasaccites elongatus* Bose and Kar (Fig. 6X), *C. ovatus* Bose and Kar emend. Archangelsky and Gamarro (Fig. 6V), *C. densus* Lele and Karim emend. Gutiérrez (Fig. 6W), *Tuberisaccites varius* Lele and Makada (Fig. 7R), *Potoneisporites brasiliensis* (Nahuys, Alpern and Ybert) Archangelsky and Gamarro (Fig. 7Q), *P. magnus* Lele and Karim (Fig. 7F) and *P. densus* Maheshwari (Fig. 7G). Palynological samples from the FA 3 are characterized by the exclusive presence (Table 2) of *Ahrensia* *crustatus* Playford and Powis (Fig. 5A), *Cyclogranisporites rinconadensis* Césari and Limarino (Fig. 5T) and *Brevitriletes leptocaina* Jones and Truswell (Fig. 5J), the last record of *Raistrickia rotunda*, and the presence of *Tetraporina punctata* (Tiwari and Navale) Kar and Bose (Fig. 8K).

Fossil plants were collected from the upper levels of the FA 3 and are preserved as imprints of foliage and molds of stems. *Botrychiopsis weissiana* Kurtz emend. Archangelsky and Arrondo is the most abundant species in the assemblage. This species is represented by bipinnate fragments characterized by pinnules obliquely inserted, decurrent, subopposite to alternate, spatulate to obovate (Fig. 9E). Distal pinnules are spatulate to oval with rounded margin and venation open and dichotomous (Fig. 9A, C). A long stem mold of lycophyte, 33 cm in length and 4 cm in diameter, exhibits rhomboidal leaf cushions in spiral arrangement (Fig. 9F). Its imprint on the host rock shows the rhomboidal leaf cushions, about 0.8 cm in width, lacking details about leaf scar or ligule (Fig. 9D). Probably these specimens correspond to the ones described by Frenguelli (1946) as *Lepidodendron australe* Mc Coy, but their preservation hampers to confirm this assignment. According to the observed characteristics in other Gondwanan lycophytes, outline and size of the leaf cushions vary on axes of different orders in the same species (Souza de Faria et al., 2009).

Several sphenopsid stems of small diameter (0.8-12 mm) are also present and probably represent herbaceous plants (Fig. 9B).

The presence of wave ripple cross-lamination, heterolithic structures and the dominance of fine-grained rocks suggest a restricted (estuarine?) marine depositional environment. FA 3 corresponds to a short-lived early Moscovian marine transgression which is represented by shallow marine and estuarine deposits. Invertebrate remains were not recognized in these levels.

### 3.4. Facies Association 4 (FA 4, coarse-grained lenticular sandstones)

The base of the FA 4 is marked by an incision surface carved into FA 3 which is in turn covered by coarse-grained sandstones, conglomerates, and thin beds of fine-grained sandstones and mudstones (Table 1). FA 4, 85 m thick, is mainly composed of tabular and trough cross-bedded coarse-grained sandstones and conglomerates stratified in lenticular beds. Thin beds (up to 25 cm) of laminated fine-grained sandstones and carbonaceous mudstones appear towards the top of this facies association. Only one palynological sample was recovered from this facies association; its composition is similar to the underlying assemblages (Table 2).

The irregular topography recorded by the incision surface was initially filled by braided river deposits which initially did not preserve fine-grained sediments of the flood plain area. Nevertheless, flood-plain accumulations were becoming more important towards the top of the facies, to the extent that the accommodation space increased.

### 3.5. Facies Association 5 (FA 5, fine-grained sandstones, shales and limestones)

This interval, from 75 to 95 m thick, is easily identified by the dominance of fine-grained rocks, including mudstones, shales, fine-grained sandstones and interlaminated successions of very fine-grained sandstones and mudstones. The lower part of the FA 5 (about 15 m thick) comprises a retrogradational sequence of medium- and fine-grained sandstones interbedded with mudstones being coarse-grained sandstones very scarce and restricted to the base of the succession. The middle part is mainly composed of dark gray shales and massive mudstones, frequently showing poorly preserved plant remains, together with centimetric lenses of massive marls. Finally, the upper part (70 m thick) is made up by

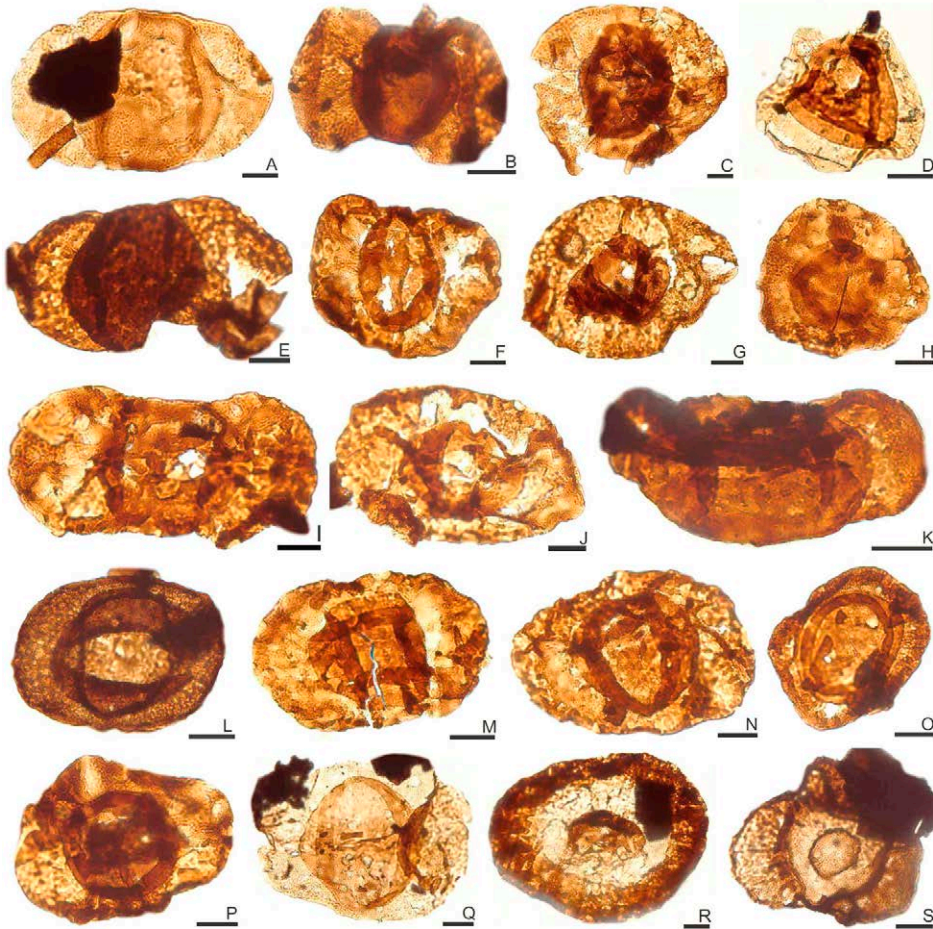


FIG. 7. **A.** *Limitisporites rectus* Leschik, BA Pal 6213-2:B52/3; **B.** *Limitisporites* sp. cf. *L. luandensis* Bose and Maheswari, BA Pal 6212-4:Y56/3; **C.** *Potonieisporites barrelis* Tiwari, BA Pal 6211-1:B36/2; **D.** *Plicatipollenites trigonalis* Lele, BA Pal 626212-8:H60/4; **E.** *Limitisporites hexagonalis* Bose and Maheswari, BA Pal 6210-2:S56/2; **F.** *Potonieisporites magnus* Lele and Karim, BA Pal 6211-4:Z35/1; **G.** *Potonieisporites densus* Maheswari, BA Pal 6211-2:J31/4; **H.** *Plicatipollenites gondwanensis* (Balme and Hennelly) Lele, BA Pal 62011-1:Z27/2; **I.** *Limitisporites monosaccoides* Bose and Maheswari, BA Pal 6211-1:Y49/1; **J.** *Potonieisporites methoris* (Hart) Foster, BA Pal 6211-2:M43/1; **K.** Bisaccate indet., BA Pal 6213-7:F41/4; **L.** *Potonieisporites marleniaei* Playford and Dino 2000, BA Pal 6210-2:J43/3; **M.** *Potonieisporites neglectus* Potonié and Lele, BA Pal 6211-3:R48/3; **N.** *Potonieisporites triangulatus* Tiwari, BA Pal 6208-1:Z45/4; **O.** *Plicatipollenites malabarensis* (Potonié and Sah) Foster, BA Pal 6213-1:G24/4; **P.** *Potonieisporites novicus* Bhardwaj, BA Pal 6211-2:R37/4; **Q.** *Potonieisporites brasiliensis* (Nahuis, Alpern and Ybert) Archangelsky and Gamarro, BA Pal 6212-5:P49/0; **R.** *Tuberisaccites varius* Lele and Makada, BA Pal 6203-3:B45/2; **S.** *Tuberisaccites* sp., BA Pal 6209-3:D43/2. Scale bar: 20  $\mu$ m.

an upward-coarsening and thickening succession composed of shales, mudstones and fine- to medium-grained sandstones which finishes with a level of limestone (3 m thick) at the top of the succession. Sandstones frequently show horizontal lamination, ripple-cross lamination and ripple (both symmetrical and asymmetrical) at the top of the beds. Samples from the FA 5 contain *Navifusa variabilis* Gutiérrez and Limarino (Fig. 8H) as exclusive species and

the first appearances of *Raistrickia cephalata* Bhardwaj, Kar and Navale (Fig. 6G, I), *Limitisporites monosaccoides* Bose and Maheswari (Fig. 7I), *Cannanoropollis trilobatus* (Höeg and Bose) Gutiérrez (Fig. 6Z), *Potonieisporites marleniaei* Playford and Dino (Fig. 7L), *Protohaploxylinus* sp. cf. *P. haigii* Foster (Fig. 8B), *Protohaploxylinus limpidus* (Balme and Hennelly) Balme and Playford (Fig. 8C), *Striatoabieites multistriatus* (Balme and

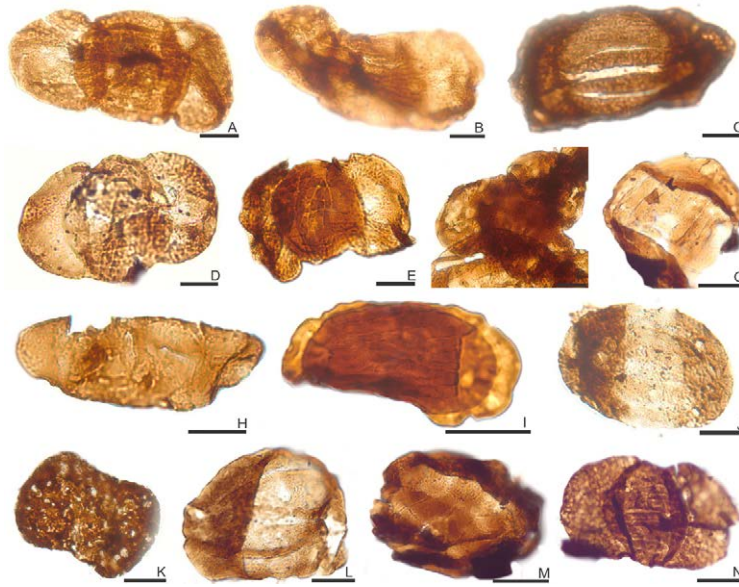


FIG. 8. **A.** *Striatoabietes multistriatus* (Balme and Hennelly) Hart, BA Pal 6212-2:M47/1; **B.** *Protohaploxylinus* sp. cf. *P. haigii* Foster, BA Pal 6211-2:R33/0; **C.** *Protohaploxylinus limpidus* (Balme and Hennelly) Balme and Playford, BA Pal 6209-4:G37/4; **D-E.** *Hamiapollenites insolitus* (Bharadwaj and Saluha) Balme; **D.** BA Pal 6212-2:P51/0; **E.** BA Pal 6212-2:M47/1; **F.** *Trisaccate* indet., BA Pal 6211-2:Z51/4; **G.** *Vittatina wodehousei* (Jansonius) Hart, BA Pal 6212-4:Z24/0; **H.** *Navifusa variabilis* Gutiérrez and Limarino, BA Pal 6211-2:R43/1; **I.** *Vittatina subsaccata* Samoilovich, BA Pal 6212-8:045/4; **J, L.** *Illinites unicus* Kosanke emend. Jansonius and Hills; **J.** BA Pal 6213-2:T48/3; **K.** *Tetraporina punctata* (Tiwari and Navale) Kar and Bose, BA Pal 6211-2:C36/1; **L.** BA Pal 6213-3:H49/3; **M.** *Vittatina costabilis* Wilson emend. Tschudy and Kosanke, BA Pal 6212-2:D43/4; **N.** *Protohaploxylinus amplus* (Balme and Hennelly) Hart, BA Pal 6211-4:U45/1. Scale bar: 20 µm.



FIG. 9. **A, C, E.** *Botrychiopsis weissiana* Kurtz emend. Archangelsky and Arrondo; **B.** Sphenopsid stem; **D, F.** Lycophyte stem. Scale=1cm.

Hennelly) Hart (Fig. 8A), *Hamiapollenites insolitus* (Bharadwaj and Saluha) Balme (Fig. 8D, E) and *Protohaploxypinus amplus* (Balme and Hennelly) Hart (Fig. 8N). Abundance of taeniate pollen varies from 0.3% to 0.7%.

There is little doubt that FA 5 records the Pennsylvanian transgression and seems to be a key level for regional correlation between the upper Paleozoic sequences of the western Paganzo Basin and Río Blanco Basin (Limarino *et al.*, 2006). The above described lower and middle parts of the facies association represent transgressive systems tract deposits while the upper part corresponds to sedimentation under highstand conditions. The TS Biozone studied by Cisterna *et al.* (2002, 2011) was recovered from these levels. The fossiliferous levels are located immediately below the thicker package of limestones and a few meters over the thinner package of limestones (see figure 2 in Cisterna *et al.*, 2002).

### 3.6. Facies Association 6 (FA 6, variegated sandstones and conglomerates)

Fine-grained marine deposits are abruptly covered by fluvial coarse-grained sandstones and conglomerates reaching 35 in thickness which rest over an important incision surface carved into the marine deposits. While conglomerates are gray in color, sandstones are light gray to purple at the base of the facies association and pass upward to pink and red in color. Arkosic sandstones are stratified in cross-bedded lenticular channelized beds whereas conglomerates are mainly massive and composed of quartz, k-feldspar, granite and metamorphic clasts. Despite the fact that fine-grained rocks are missing in the first meters of the facies association, red mudstones appear from the middle part and increase progressively their participation towards the top.

The lowermost levels of the described succession are interpreted as deposited by braided rivers whilst a progressive increase in flood plain deposits occurs towards the top of the facies. It is possible that the growth in the amount of flood plain deposits reflects a change in the type of fluvial system from braided to wandering. The erosive surface that separates FA 5 and 6 in the La Herradura Creek correlates with an important incision surface of regional expression, which points out the Pennsylvanian sea-level fall in the Late Paleozoic basins of western Gondwana.

### 3.7. Facies Association 7 (FA 7, red mudstones and sandstones)

The top of the upper Paleozoic sequence, 45 m thick in the La Herradura Creek, is a classical red-bed succession composed of channel complexes separated by thick flood plain deposits. Channel complexes reach up to 5 m in thickness and comprise coarse-grained cross-bedded sandstones and conglomerates stratified in amalgamated beds. Flood plain accumulations can be divided in two major types: **1.** monotonous successions (up to 5 m thick) of horizontally laminated or ripple cross-bedded mudstones likely deposited in flood-basin areas and **2.** upward-coarsening sequences of interbedded mudstones and sandstones probably corresponding to crevasse splay progradation within the floodplain.

FA 7 is interpreted as deposited in anastomosing fluvial plains indicating an increase in the accommodation space from the FA 6 to FA 7. Palynological assemblages from this facies association (Patquía Formation) are distinguished by an increase of taeniate pollen (up to 2.5%) and include the first records of *Illinites unicus* Kosanke *emend.* Jansonius and Hills (Fig. 8J, L), *Vittatina costabilis* Wilson *emend.* Tschudy and Kosanke (Fig. 8M), *Vittatina wodehousei* (Jansonius) Hart (Fig. 8G) and *Vittatina subsaccata* Samoilovich (Fig. 8I). Spores species such as *Horriditriletes uruguayensis* (Marques-Toigo) Archangelsky and Gamarro (Fig. 5P), *Horriditriletes* sp. cf. *H. superbus*, *Raistrickia* sp. cf. *R. radiosa* Playford and Helby (Fig. 6E), *Laevigatosporites vulgaris* (Ibrahim) Ibrahim (Fig. 5AA), *Lophotriletes intermedius* and *Lophotriletes discordis* Gutiérrez and Césari (Fig. 5DD) are exclusive of these palynological samples (Table 2).

## 4. Previous palynological studies

Vergel (2008) described three palynological associations, P(1a), P(1b) and P(9a) (see Cisterna *et al.*, 2002, Fig. 2). The sample P(1a) was located at the base and the P(1b) in the middle part of Tupe Formation, while the sample P(9a) comes from the top levels of the Tupe Formation (Cisterna *et al.*, 2002) or the lower part of the Patquía Formation according to stratigraphic boundaries followed here (Fig. 4).

The palynoflora P(1a) from the lower part of the Tupe Formation was characterized by Vergel



(2008) by the presence of: *Caheniasaccites* spp., *Cristatisporites inconstans* Archangelsky and Gamero, *Cristatisporites menendezii* (Menéndez and Azcuy) Playford, *Cyclogranisporites microgranus* Bhardwaj, *Foveosporites hortonensis* (Playford) Azcuy, *Lundbladispota braziliensis*, *Lundbladispota irregularis* (Menéndez) Césari, *Lundbladispota riobonitensis* Marques-Toigo and Picarelli, *Plicatipollenites gondwanensis* (Balme and Hennelly) Lele, *Portalites gondwanensis* Nahuys, Alpern and Ybert, *Potonieisporites brasiliensis*, *Potonieisporites novicus* Bhardwaj, *Punctatisporites gretensis* Balme and Hennelly, *Raistrickia densa*, *Spelaeotriletes ybertii* (Marques-Toigo) Playford and Powis emend. Playford, Dino and Marques-Toigo, and *Vallatisporites ciliaris* Sullivan. Vergel (2008) referred this assemblage to the DM Biozone (Césari and Gutiérrez, 2001) and assigned a late Carboniferous age. Vergel (2008) noted that all these species are common with other associations of the Tupe Formation, and equivalent units, in other localities.

The palynoflora from the middle part of the succession, P(1b), just below the marine beds, yielded a taxonomically impoverished and poorly preserved assemblage including: *Apiculatisporites caperatus* Menéndez and Azcuy, *Cristatisporites inconstans*, *Foveosporites hortonensis*, *Lundbladispota braziliensis*, *Lundbladispota irregularis*, *Lundbladispota riobonitensis*, *Punctatisporites gretensis*, *Spelaeotriletes ybertii*, and *Vallatisporites ciliaris*. Vergel (2008) remarked that the poor preservation of the palynoflora made impossible to suggest a precise age for the bearing strata.

The sample from Patquía Formation, P(9a), contains taeniate pollen (5%) and was characterized by Vergel (2008) by the presence of: *Converrucoisporites confluens* (Archangelsky and Gamero) Playford and Dino, *Pseudoreticulatispora pseudoreticulata* (Balme and Hennelly) Bharadwaj and Srivastava, *Horriditriletes ramosus* (Balme and Hennelly) Bharadwaj and Salujha, *Anapiculatisporites tereteangulatus* (Balme and Hennelly) Playford and Dino, *Laevigatosporites colliensis* (Balme and Hennelly) Venkatachala and Kar, *Marsupipollenites triradiatus* Balme and Hennelly, *Protohaploxypinus seawardii* (Virkki) Hart and *Pakhapites fusus* (Bose and Kar) Menéndez. Vergel (2008) accurately mentioned that the palynoflora recovered from beds above the marine horizon includes species never before recorded from the Tupe Formation. The

author proposed correlations with assemblages from western Argentina and other Gondwanan regions suggesting an early Permian age (not older than Asselian-Sakmarian) for the palynoflora.

## 5. Palynological results and comparisons

The palynological analysis of the Tupe and Patquía formations at the La Herradura Creek was performed on 15 samples collected from almost all the facies associations except the FA 6 that resulted palynologically unproductive. Several palynological associations comparable to those analyzed here have been described for central western Argentina successions. The palynological content of the FA 1, FA 2, FA 3, and FA 4 are equivalent to those included in the Subzones A and B of the DM Biozone defined for the Carboniferous of Argentina (Césari and Gutiérrez, 2001). Both subzones were characterized by the presence of monosaccate pollen grains and the appearance of *Protohaploxypinus* spp. in the Subzone B which was defined on the basis of palynofloras from the Tupe and other coeval units of the Paganzo Basin (e.g., Loma Larga, Trampeadero formations, the upper member of the Agua Colorada Formation and the lower parts of the Santa Máxima Formation) and the El Imperial Formation (San Rafael Basin, Fig. 10). The percentages of taeniate pollen in those palynofloras, is always lower than 1.5%.

Palynological assemblages from FA 5 are distinguished by the presence of *Navifusa* (a marine marker) and taeniate pollen, suggesting a correlation with the Subzone C of the DM Biozone. Subzone C was originally recognized in marine deposits of the El Imperial, Santa Máxima and Agua Negra Formations (Fig. 10). The palynofloras from the upper part of the 'Estratos de Mascasin' (Pérez Loinaze and Césari, 2004), the Libertad Formation (di Pasquo *et al.*, 2010) in the Paganzo Basin and the upper part of the Río del Peñón Formation (*sensu* Gutiérrez and Limarino, 2006) in the Río Blanco Basin are characterized by some species of *Protohaploxypinus* and the first records of *Vittatina* but lack key species as *Pakhapites fusus* (Bose and Kar) Menéndez, indicative of the overlying FS Biozone. Libertad Formation at Los Sauces locality (Fig. 1) also bear plant remains of the Interval Biozone (defined by Archangelsky *et al.*, 1987) confirming the relation between this biozone and the Subzone C.

Biozone	San Rafael Basin	Río Blanco Basin	Paganzo Basin						
			Southwestern area	Southeastern area	Northeastern area	Sierra de Maz	Sa. de los Llanos	Famatina area	Huaco area
FS	El Imperial Fm.	Río del Peñón Fm. 310.63 ± 0.07Ma★	Santa Máxima Fm.	Bajo de Véliz/Tasa Cuna Fm.	Los Sauces Fm.				
					Libertad Fm.	Tupe Fm.		Loma Larga Fm.	Agua Colorada Fm.
DM	C								
	B								

FIG. 10. Correlation of the main stratigraphic units bearing palynological assemblages mentioned in the text. Palynological biozones are based on Césari and Gutiérrez (2001). Radiometric ages are based on Gulbranson *et al.* (2010).

Two samples from the Patquía Formation at La Herradura Creek provided palynological assemblages characterized by many species identified in underlying strata together with the incoming of *Illinites unicus*, *Vittatina costabilis*, *Vittatina wodehousei* and *Vittatina subsaccata* (Table 2). Vergel (2008) also recognized specimens of *Pakhapites fusus* in these stratigraphic levels which were included in the Tupe Formation by Cisterna *et al.* (2002). Thus, palynological assemblages from the Patquía Formation can be compared with those recovered from the Bajo de Véliz and Tasa Cuna formations (Paganzo Basin) and the upper part of the El Imperial Formation. Palynological content of the Bajo de Véliz and Tasa Cuna formations was studied by Menéndez (1971), Gutiérrez and Césari (2000), Césari *et al.* (1999) and Balarino and Gutiérrez (2006). Palynofloras from both units share the taeniate pollen: *Hamiapollenites fusiformis* Marques-Toigo emend. Archangelsky and Gamero, *Protohaploxypinus* spp., *Pakhapites fusus* and *Vittatina* spp. García (1996) analyzed palynological assemblages from the upper section of the El Imperial Formation and identified taeniate pollen such as *Protohaploxypinus* spp., *Pakhapites fusus*, *Hamiapollenites fusiformis* and *Vittatina* sp. All these palynofloras, were included in the FS Biozone (Césari and Gutiérrez, 2001) and are associated with plant remains of the *Gangamopteris* flora (Archangelsky and Cúneo, 1984; Césari *et al.*, 2007).

## 6. Age and discussion

Palynological assemblages of the FA 1 to FA 4 are correlative of the Subzones A and B of the DM Biozone. These subzones were constrained to the Late Serpukhovian-Bashkirian according with radiometric data (Césari *et al.*, 2011). Plant remains of the NBG Biozone (*Nothorhacopteris-Botrychiopsis-Ginkgophyllum*) supported the age assigned to the fossiliferous strata. The short-lived transgression, represented by FA 3, is characterized by palynological assemblages of those subzones without evidence of taeniate pollen. Invertebrate remains were not recognized in this interval, but regional correlation with fossiliferous localities in the west of the basin is possible. This short transgressive event may be constrained approximately to the latest Bashkirian-early Moscovian by  $^{206}\text{Pb}/^{238}\text{U}$  age of  $315.46\pm 0.07$  Ma obtained from a tonstein included in coal bed of flood plain deposits of the Tupe Formation at the near locality of Huaco (Gulbranson *et al.*, 2010). Thus, there is a strong correlation with strata bearing the *Marginovatia-Maemia* fauna (formerly known as *Balakhonia peregrina-Geniculifera tenuiscostata*) that characterizes the Río Blanco and Calingasta-Uspallata Basins (Taboada, 1999; Taboada, 2010), which was considered late Bashkirian-earliest Moscovian in age according to worldwide records of the homonym species (Taboada, 1997, 2010).

The main transgression, represented by FA 5, is characterized at La Herradura Creek by the oldest faunal assemblages of the TS fauna (Cisterna *et al.*, 2011). Palynological assemblages here analyzed from the same beds bearing marine invertebrates confirm the original Pennsylvanian age assigned to the TS Biozone by Sabattini *et al.* (1990). Palynofloras recovered from the AF5, characterized by the presence of several species of *Protohaploxypinus* genus, are referred to the Subzone C of the DM Biozone. This subzone is referred to the Moscovian (Césari *et al.*, 2011).

Although an scarce fauna was recognized in marine beds from the easternmost records of the transgression at La Ciénaga locality (17 km to southeast of the La Herradura Creek), these horizons were correlated with the marine interval identified in the middle part of the La Herradura Creek by Desjardins *et al.* (2009) and Cisterna *et al.* (2011). A sample of a tonstein from shallow marine deposits at La Ciénaga (facies association VII by Desjardins *et al.*, 2009) yields a  $^{206}\text{Pb}/^{238}\text{U}$  age of  $312.82 \pm 0.11$  Ma. Thus, as was suggested by Césari *et al.* (2011), radiometric ages discard an early Permian age for the top of the Tupe Formation. Moreover, the palynoflora (P9a) described by Vergel (2008) some tens of meters above the transgressive deposits (Fig. 4) and referred to the Asselian-Sakmarian suggests just that the underlying fauna would be not younger than this age.

The middle-upper part of the Río del Peñón Formation (Río Blanco Basin, Fig. 1) contains faunal assemblages described by (Cisterna and Sabattini, 1998; Cisterna and Simanaukas, 2000), one of them referred undoubtedly to the TS Biozone. The marine fossiliferous interval of 38 m in thickness was located approximately at 600 m above the base of the unit (Cisterna *et al.*, 2011). Therefore, although thickness variations are considered accompanying the paleogeography, the TS Biozone is recognized above the radiometric  $^{206}\text{Pb}/^{238}\text{U}$  dating of  $310.63 \pm 0.07$  Ma provided by Gulbranson *et al.* (2010) from an ignimbrite in fluvio-deltaic deposits, approximately at the level 'F' described by Gutiérrez and Limarino (2006) that contain palynological assemblages of the DM Biozone. A Moscovian age for the TS Biozone in the Río del Peñón Formation is also proposed by Dineen *et al.* (2012).

Radiometric K-Ar age of  $307.2 \pm 5.2$  Ma from the middle part of the Agua de Jagüel Formation (Mendoza Province) where Lech (2002) recognized the presence of the TS Biozone, also constrains its age range.

The faunal assemblages of the nearby La Delfina Creek were also correlated by Cisterna *et al.* (2006) with those from La Herradura Creek, located 10 km to northwestern (Fig. 1). According to Cisterna (2010) and Cisterna *et al.* (2011) the TS Biozone in the Tupe Formation at La Delfina Creek is located above horizons that contain diagnostic species of the Carboniferous NBG and Interval megafloristic biozones and *Raistrickia densa-Convolutispora muriornata* palynological Biozone described by Coturel and Gutiérrez (2005) and Gutiérrez *et al.* (2005). Cisterna *et al.* (2011) noted that the faunal association is dominated by *Costatumulus* Waterhouse and *Orbiculoidea* d'Orbigny and is compositionally comparable to the fauna described in the lowest marine horizon of the Tupe Formation at La Herradura Creek.

The FA 7 considered here part of the Patquía Formation contains palynofloras assigned to the FS Biozone. The age of this biozone was originally considered early Cisuralian (Césari and Gutiérrez, 2001), but recently Césari *et al.* (2011) proposed its possible beginning in the latest Pennsylvanian. Some species present in this facies association, that usually were considered markers of Carboniferous-Permian in Gondwana include: *Convurrencosporites confluens*, *Vittatina* spp., *Pakhapites fusus*, among others. Although *Vittatina* species are abundant in Permian sequences, the genus is also known from the Moscovian of Arabia (Owens and Turner, 1995), the Stephanian B of Western Europe (Clayton *et al.*, 1977) and the section slightly below the Carboniferous-Permian boundary stratotype in Kazakhstan (Dunn, 2001) and the late Bashkirian-early Moscovian of the Subangara area (Zhu *et al.*, 2005). Moreover, di Pasquo (2009) has recorded well-calibrated *Vittatina* species in the Moscovian of Bolivia.

*Convurrencosporites confluens* is a good index of the latest Carboniferous-earliest Permian in Australia, Antarctica, Brazil, India, Oman, Saudi Arabia, South Africa and South America. Stephenson (2009), proposed the incoming of *C. confluens* in the Gzhelian or Kasimovian based on palynological assemblages from the Ganigobis Shale Member of Namibia, radiometrically dated as  $302.0 \pm 3.0$  Ma. The difficulty in detecting good specimens of *C. confluens* in sparse assemblages has rendered its identification uncertain in most palynofloras of the Paganzo Basin.

Previous records of taeniate pollen recovered from glossopterid sporangia have revealed that

*Protohaploxypinus* spp. (especially *P. limpidus*) and *Striatopodocarpidites cancellatus* (Balme and Hennelly) Hart are species not useful for high resolution biostratigraphic analysis since they have been found in a single sporangium (Lindström *et al.*, 1997 and cites therein). The same coincidence of the two pollen types was advertised in Angaraland pollen organs (Zavialova and van Konijnenburg-van Cittert, 2011) and primitive *Protohaploxypinus* (1%) were reported in the early Bashkirian of the Subangara area (Zhu *et al.*, 2005).

The upper part of the Río del Peñón Formation also provided palynological assemblages (levels G-L in Gutiérrez and Limarino, 2006) with up to 2% of *Vittatina* (see page 703 in Gutiérrez and Limarino, 2006). Those authors suggest the presence of the *Pakhapites fusus-Vittatina subsaccata* (FS) Biozone by the occurrence of *Vittatina* sp., *Barakarites rotatus* and *Polarisaccites bilateralis*. Cisterna *et al.* (2011) add new palynological species, although the precise stratigraphic range of the new records (*e.g.*, *Pakhapites fusus*) is not given throughout the succession. The illustrated specimens are poorly preserved casting doubt on some of the assignments, *e.g.*, *B. rotatus* and *P. fusus* (Cisterna *et al.*, 2011, fig. 4.1, 4.2). If the presence of the biozone can be confirmed, it would have begun in the late Pennsylvanian according to the radiometric age obtained by Gulbranson *et al.* (2010) for the Río del Peñón Formation.

The FS Biozone was correlated by Césari and Gutiérrez (2001), Césari (2007) and Césari *et al.* (2011) with the Brazilian *Vittatina costabilis* (VcZ) Interval Zone Souza and Marques-Toigo (2003), characterized by the abundance and diversity of taeniate pollen grains and registered in the upper Itararé Subgroup and Río Bonito Formation (Marques-Toigo, 1991). Guerra-Sommer *et al.* (2005) obtained a time of deposition based on ID-TIMS U-Pb zircon ages ranging from 299±2.6 to 296±1.4 Ma for tonsteins located in the middle section of the Río Bonito Formation. A similar age (298.5±2.6 Ma) was obtained by Rocha-Campos *et al.* (2006, 2008) for the same stratigraphic section. Thus, a latest Kasimovian or earliest Asselian age may be considered at least for the lower part of the VcZ in Brazil.

In summary, radiometric data in Argentina and Brazil in conjunction with palynological correlation allow to propose a Late Pennsylvanian age for the high eustatic conditions and associated TS

Biozone recognized in the Tupe Formation at the locality of La Herradura Creek. Recently, Césari *et al.* (2011) proposed a Moscovian age for the TS Biozone without discarding that can reach slightly younger ages. Although radiometric data from Brazil and Argentina suggest an age no younger than 299 Ma, a palynological revision and absolute ages in key sections bearing TS Biozone are necessary to precise the upper limit of the faunal biozone.

## 7. Conclusions

The Tupe Formation is constrained to the Pennsylvanian in contrast to the proposal that extends its chronostratigraphic range into the Permian on the basis of the faunal association located in its upper part. Two marine incursions are identified in the middle-upper part of the unit at La Herradura Creek. The lower is characterized by palynofloras of the Subzone B of *Raistrickia densa-Convolutispora muriornata* Biozone and constrained to approximately 315 Ma. The higher is more significant and the strata contain marine invertebrates of the *Tivertonia jachalensis-Streptorhynchus inaequornatus* Biozone and palynofloras referred to the Subzone C of *Raistrickia densa-Convolutispora muriornata* Biozone. Radiometric controls in near localities corroborate the presence of the *Tivertonia jachalensis-Streptorhynchus inaequornatus* Biozone at approximately 312 Ma.

Palynological samples recovered from strata above the marine deposits, in the Patquia Formation, provide palynological assemblages that allow their assignment to the *Pakhapites fusus-Vittatina subsaccata* Biozone.

Comparison of the palynofloras studied here with other described from the Paganzo Basin, suggests a gradual increase in abundance of taeniate pollen towards the Carboniferous-Permian boundary and encourages the revision of key stratigraphic sections for a better definition of the Subzone C of *Raistrickia densa-Convolutispora muriornata* Biozone and the *Pakhapites fusus-Vittatina subsaccata* Biozone.

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