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Paleoenvironmental interpretation and palynology of outcrop and subsurface sections of the Tarija Formation (Upper Carboniferous), northwestern Argentina

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Abstract

The Tarija Formation of the Macharetí Group has been studied sedimentologically and palynologically at Zanja Honda Creek and the Zanja Honda x-1 well to assess the paleoenviromental and paleoclimatic evolution of the southern portion of the Tarija Basin. In addition, new palynological data and their implications are presented. The Tarija Formation consists mainly of thick diamictites interbedded with sandstone and mudstone layers; for the first time, a varves succession is described from the cores of the ZH x-1 well. Fifty-six spore species, 18 monosaccates, 1 praecolpate pollen grain, 4 paleophytoplankton species, and much phytodebris are recorded. The indigenous miospores are assigned to the middle portion of the *Dictyotriletes bireticulatus–Cristatisporites chacoparanensis* (BC) Biozone di Pasquo of early Late Carboniferous (Westphalian) age. Moreover, abundant reworked palynomorphs occur in both assemblages, recording erosion of Silurian–Early Carboniferous rocks. Some Late Carboniferous species such as *Crassispora kosankei* (Potonié and Kremp) Bhardwaj emend. Smith and Butterworth, *Cristatisporites rollerii* Ottone, and *Cystoptychus azcuyi* di Pasquo, exclusive of the KA Biozone, and *Raistrickia radiosa* Playford and Helby of the RS Biozone di Pasquo are interpreted as reworked from the lower Tupambi and Itacuamí formations. A fluviolacustrine setting is interpreted for the Tarija Formation on the basis of the presence of glacial varves, continental algae such as *Botryococcus braunii* Kützing, and overall facies associations. A hiatus between the fluviodeltaic interglacial Tupambi–Itacuamí depositional cycle ("Cycle I") and the fluviolacustrine, glacially influenced Itacuamí–Tarija depositional cycle ("Cycle II") is suggested by the sedimentary and palynologic data. This interpretation is confirmed by short-ranged species with biostratigraphic value, as well as the recognition of useful lithological and palynological differences helpful for characterizing both similar superposed sedimentary cycles.

Resumen

Se realiza el análisis integrado de aspectos sedimentológicos, palinológicos y estratigráficos de la Formación Tarija (Grupo Macharetí) en el perfil de Zanja Honda y en el pozo Zanja Honda x-1 con los objetivos de arribar a la interpretación paleoambiental y evolución paleoclimática de la porción austral de la cuenca Tarija. Adicionalmente, se dan a conocer nuevos datos palinológicos y sedimentológicos cuyos alcances se discuten. La Formación Tarija está compuesta por diamictitas grises, macizas y estratificadas con intercalaciones de areniscas fluviales; por primera vez se describe una sucesión de varves reconocida en coronas del pozo ZH x-1. Se identificaron cincuenta y seis especies de esporas, dieciocho especies de granos de polen monosacado y uno praecolpado, cuatro especies de fitoplancton y gran cantidad de fitodetritos. Las miosporas autóctonas son asignadas a la parte media de la Biozona *Dictyotriletes bireticulatus-Cristatisp-*

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orites chacoparanensis (BC) di Pasquo perteneciente al Carbonífero Tardío temprano (Wesphaliano). Además se determinaron palinomorfos retrabajados provenientes del sustrato silúrico a carbonífero temprano. Algunas especies del Carbonífero Tardío como *Crassispora kosankei* (Potonié y Kremp) Bhardwaj emend. Smith y Butterworth, *Cristatisporites rollerii* Ottone y *Cystoptychus azcuyi* di Pasquo, exclusivas de la Biozona KA y *Raistrickia radiosa* Playford y Helby de la Biozona RS di Pasquo, son interpretadas como retrabajadas de las Formaciones Tupambi e Itacuamí subyacentes. En base a la presencia de varves, algas como *Botryococcus braunii* Kützing y al conjunto general de las asociaciones de facies, se interpreta un ambiente fluvio-lacustre para la Formación Tarija. Los datos sedimentológicos y palinológicos indican la presencia de una discontinuidad sedimentaria entre la secuencia interglacial fluvio-deltaica Tupambi-Itacuamí "(Ciclo I)" y la secuencia glacialmente dominada fluvio-lacustre Itacuamí-Tarija ("Ciclo II"). Esta interpretación se ratifica con la presencia de especies de corto biocrón así como por la identificación de diferentes rasgos sedimentológicos y palinológicos que sirven de guía para la diferenciación de respectivos ciclos sedimentarios similares y superpuestos.

Keywords: Glacioterrestrial; Sedimentation; Palynology; Tarija Formation; Late Carboniferous; Northwestern Argentina

1. Introduction

The Tarija Formation (White in Padula and Reyes, 1958) is the most characteristic stratigraphic unit of the Tarija Basin due to the prevalence of grey diamictites that provide a record of the glaciation on the western part of the Gondwana paleocontinent during the Westphalian. This unit covers the geological provinces of the Eastern Cordillera and Subandean Ranges of northern Argentina and southern Bolivia, extending eastward in the Chaco–Salta plain subsurface. Together with the Tupambi and Itacuamí formations, it forms the Macharetí Group in Argentina (Reyes, 1972; see also Azcuy and di Pasquo, 2000a).

The Tarija Formation is composed of a monotonous succession of massive diamictites with minor intercalations of sandstones. These sedimentological characteristics, the scarce fossil record (e.g., di Pasquo and Azcuy, 1999a; Azcuy and di Pasquo, 2000a), and the complex evolution of the basin made environmental interpretation and regional correlations difficult. Thus, dissimilar appraisals are not uncommon (see López Gamundi, 1984, 1986, 1987; Starck et al., 1993a; del Papa and Martínez, 2001; di Pasquo, 2003; Buatois and del Papa, 2003).

On the basis of detailed work on outcroppings, Starck et al. (1993b) describe the presence of two paleovalleys with E-W trends carving the Devonian substrate, and Villa et al. (1984) cite one for the basal unconformity in the subsurface. Furthermore, Schulz et al. (1999) and Starck and del Papa (in press) mention the presence of paleovalley structures in both the basal unconformity and intra-Tarija deposits. The carving of these structures led to the continuous erosion of important sedimentary thicknesses, reflected in successive surfaces of unconformities, which are often difficult to identify in outcroppings due to the superposition of similar sedimentary facies. In turn, the filling of these paleovalleys produced lenticular to irregularly shaped lithosomes.

This complexity notwithstanding, when detailed stratigraphic, sedimentological, and palynological analyses are conducted, the paleoenvironmental changes, stratigraphic surfaces, and diverse palynological associations become evident. These findings make it possible to establish, in some measure, a chronostratigraphic evolutionary scheme for the Tarija Basin.

di Pasquo (2003) formally proposes a biostratigraphic scheme composed of five first-appearance biozones gathered in a Superzone named *Kraeuselisporites volkheimerii*-*Circumplicatipollis plicatus* (VP). The correlation of surface and subsurface profiles studied by di Pasquo (1999) is based on biostratigraphic results found in the Subandean Ranges and the Chaco–Salta plain. Previous systematic and/or stratigraphic studies were published by di Pasquo and Azcuy (1997a,b, 1999a), Azcuy and di Pasquo (2000b), di Pasquo et al. (2001), and di Pasquo (2002). These studies enhance our knowledge of the age of Macharetí and Mandiyutí microfloras. One of the first three biozones of Superzone VP has been attributed to the early Late Carboniferous and the remaining two to the late Late Carboniferous on the basis of selected key species, their stratigraphic rank, and the position of the biozones in the stratigraphic succession (di Pasquo, 2003). This attribution is further supported by the presence of conspicuous common South American—especially Argentinean and Brazilian—Late Carboniferous species. Many long-lived forms registered in Superzone VP support the interpretation of relatively continuous sedimentation, in which the unconformities recognized in the units of the Macharetí and Mandiyutí groups may not represent important periods (e.g., Starck, 1995).

del Papa and Martínez (2001) identify two major sedimentary cycles in the Tarija Formation on the basis of significant changes in the assemblages of sedimentary facies and the presence of unconformities recognized in outcrops. Starck et al. (2002) present a correlation of the lower Tupambi and Itacuamí formations of the Macharetí group on the basis of the depositional cycles distinguished in the subsurface.

The data offered in this present contribution provide concrete enhancements of existing information regarding the northwestern Argentine Tarija Basin and reinforce the need to apply multidisciplinary methodologies. Our purpose is to (1) document the presence of varve deposits for the first time and consider their environmental implications for this unit; (2) discuss the sedimentological and biostratigraphical differences between the Itacuamí Formation and the base of the Tarija Formation; and (3) offer a correlation proposal for the Tarija Formation, based on the main cycles defined by del Papa and Martínez (2001) and the integration of recently acquired sedimentological data. In addition, we provide palynological information regarding an outcrop and a subsurface profile for the southern area of the basin to contribute to paleoenvironmental interpretations.

2. Materials and methods

2.1. Studied area

The outcrops of the Tarija Formation in Zanja Honda Creek on the eastern slope of Sierra Aguaragüe were studied. This hill represents the easternmost part of the southern Subandean Ranges (Fig. 1). To the east, the Chaco–Salta plain is developed, on whose surface thrust faulting causes characteristic gentle hilly ridges; greater structural complexity is underground. The wells analyzed herein were drilled by Yacimientos Petrolíferos Fiscales in the 1960s and 1970s in Zanja Honda (St. ZH x-1) and Tartagal (St. Ta. x-2), both in the Salta province (Fig. 1).

We compare the results obtained with an analysis of the Fortín Alegre well (FA. x-1) (di Pasquo, 2002), close to the studied area (Fig. 1). We analyze the sedimentary facies, facies associations, and stratigraphic contacts in both outcrops and subsurface (from cores, cutting descriptions, and geoelectric logs) and consider the different stratigraphic arrangements and contact characteristics the basis for cycle subdivision. Eyles et al.'s (1983) sedimentary facies code describes the glacial environments. A detailed description of all lithofacies identified in the Tarija Formation at Aguaragüe Range may be found in del Papa and Martínez (2001, p.65).

2.2. Palynologic analysis

The palynological samples that turned out to be fertile, obtained from the Zanja Honda creek, correspond to two levels of stratified diamictites (BAFC-Pl 1476 and 1477). Sample BAFC-Pl 1640 from core 2 of the Zanja Honda well, collected between 2992 and 2994 m depth, corresponds to the varves level (Fig. 2). All samples were processed by standard palynological preparation techniques of acid digestion in HCl/HF and a single treatment in hot HCl, followed by sieving at 25 μm. Kerogen residues were mounted on permanent slides with gelly-gelatine. Palynomorphs were studied with a Leitz Orthoplan

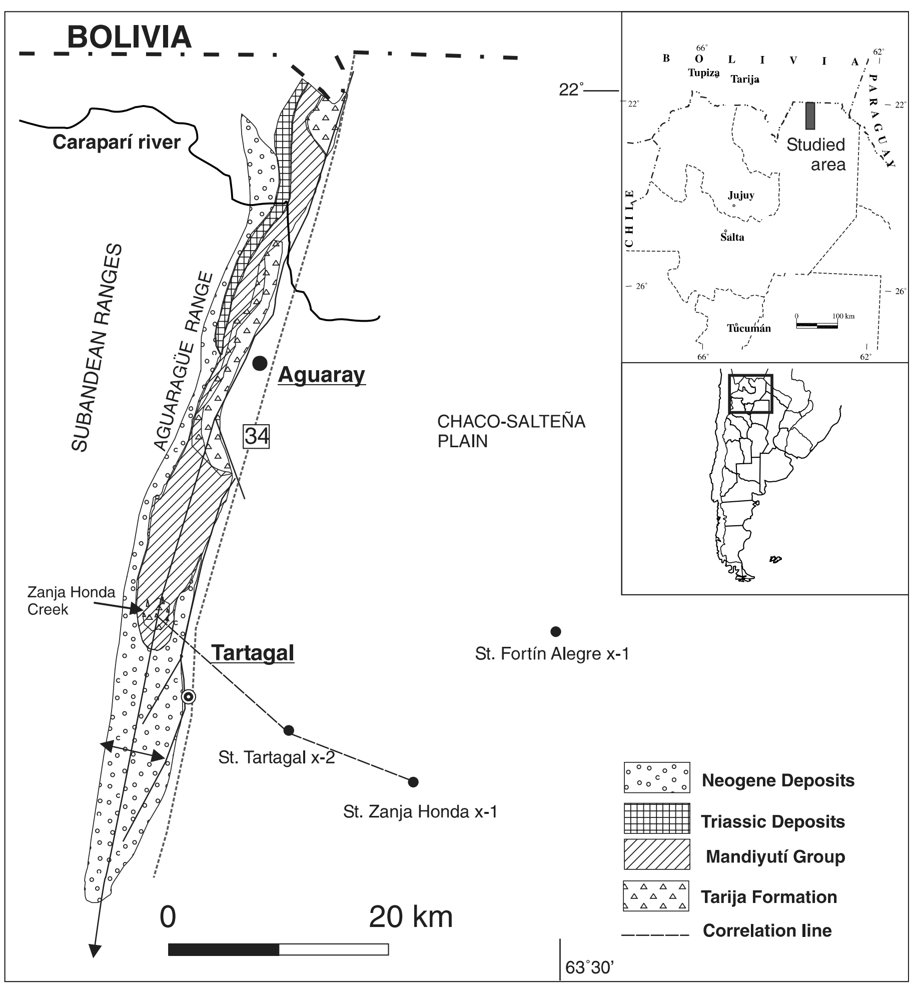


Fig. 1. Geological map showing the location of outcrops and wells studied.

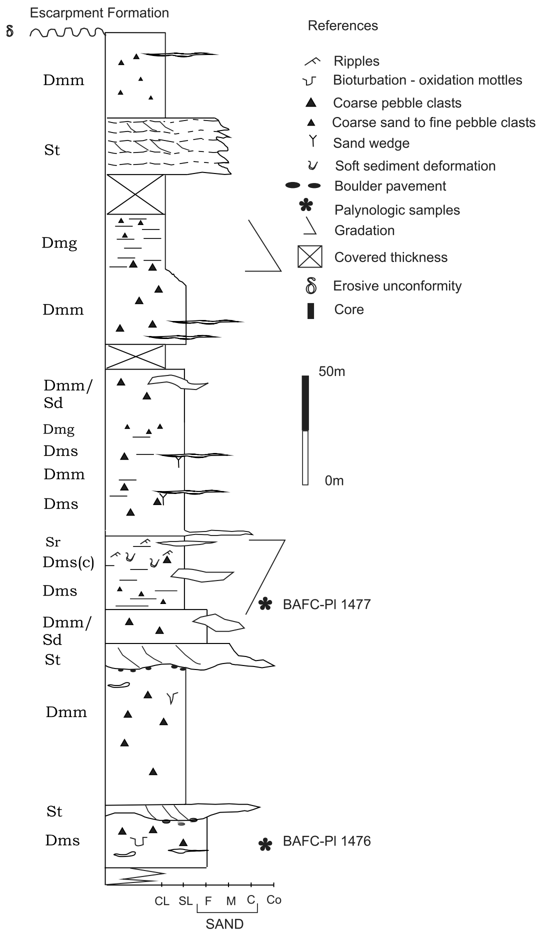


Fig. 2. Outcrop section of the Tarija Formation at Zanja Honda Creek, Aguaragüe Range.

binocular microscope with 1000× maximum magnification. Microphotographs were obtained with a Pixera digital camera with 1.2 M pixel maximum resolution, and the coordinates correspond to the universal England Finder graticule. The slides have been housed with sample numbers BAFC-Pl at the Laboratory of Palynology of the Department of Geology, Exact and Natural Sciences Faculty, Buenos Aires University.

3. Localities studied

3.1. Zanja Honda Creek (Aguaragüe Range)

The lower portion of the Tarija Formation is not exposed, because it is part of the anticline structure's nucleus. The uppermost contact is an erosive unconformity with the Escarpment Formation, which is the base of the Mandiyutí Group (see Azcuy and di Pasquo, 2000a). The partial thickness is 380 m, which corresponds to the upper reaches of the unit and coincides with "facies association III" of del Papa and Martínez (2001). It consists of massive and reworked grey diamictites and, to a lesser proportion, successions of medium to fine whitish sandstones.

3.1.1. Massive diamictite

This assemblage is characteristic of the basal and middle sections of the profile studied (Fig. 2). It principally consists of massive diamictites (Dmm), deformed sandstones (Sd), and, in minor percentages, current-reworked stratified diamictites ($Dms_{(c)}$). This profile differs from other localities, such as Iquira and Aguas Blancas to the north of Zanja Honda Creek, in that it exhibits frequent current-reworked structures ($Dm_{(c)}$) and clastic wedges (Fig. 2).

The massive diamictitic (Dmm) facies are composed of pebbly mudstones and fine, grey muddy wackes that form massive successions of 10–20 m thickness. These levels are poorly organized and consist of a mixture of completely homogenized gravel, sand, and mud (Fig. 3A). The Dmm facies correspond to feldspathic wackes (Fig. 3B) and, to a lesser degree, lithic wackes. We examine two clast populations: angular grains corresponding to a first sedimentary cycle and rounded grains pertaining to a second cycle (del Papa and Martínez, 2001).

The matrix average varies between 40% and 50%. The greater clasts (granule to boulder) are angular and subrounded. The greatest diameter observed was 25 cm (Fig. 3A), but diameters generally oscillate between 4 and 7 cm. A high percentage has polished, faceted, and frequently striated faces; in some cases, their major axes are perpendicular to the stratification. The clasts are composed of quartz, and lithic fragments of quartz sandstone, pink and grey quartz arenite, pink and white granite, and a minor proportion of grey schists are observed.

The tops of some diamictitic levels present a slight stratification and intercalation of thin, channeled levels of fine white sandstone with structures of load casts, ripples, and isolated ripples ($Dms_{(c)}$) (Fig. 3C).

The sandstones interbedded with Dmm facies are of variable thicknesses, from a few centimeters to 2 m. Their geometry is lenticular at medium scale (few meters), and their structures are deformed by load and slumps; in some cases, the layers are completely inverted.

Dmm deposits result from different processes, which occasionally work in combination: debris flow, rain out from glaciers, and resedimentation from slides (e.g., Eyles et al., 1985; Dowdeswell and Scourse, 1990; Eyles and Eyles, 2000). The presence of faceted and striated clasts points to an origin related to glacier dynamics and probably responds to combine till or tilloid resedimentation mechanisms brought about by debris flows and rain out from floating ice or the glacier front.

The presence of clasts with major axes perpendicular to stratification also suggests that some material is the direct result of massive rain out from ice rafting.

The presence of $Dms_{(c)}$ facies near the top of some beds indicates periods of lower discharge from the glacier, with consequent reworking of the diamictites by traction currents, which produce granulometric segregation and the formation of sedimentary structures.

López Gamundi (1987) posits two ruling processes for the deformed sandstones: liquefaction of the sediment after

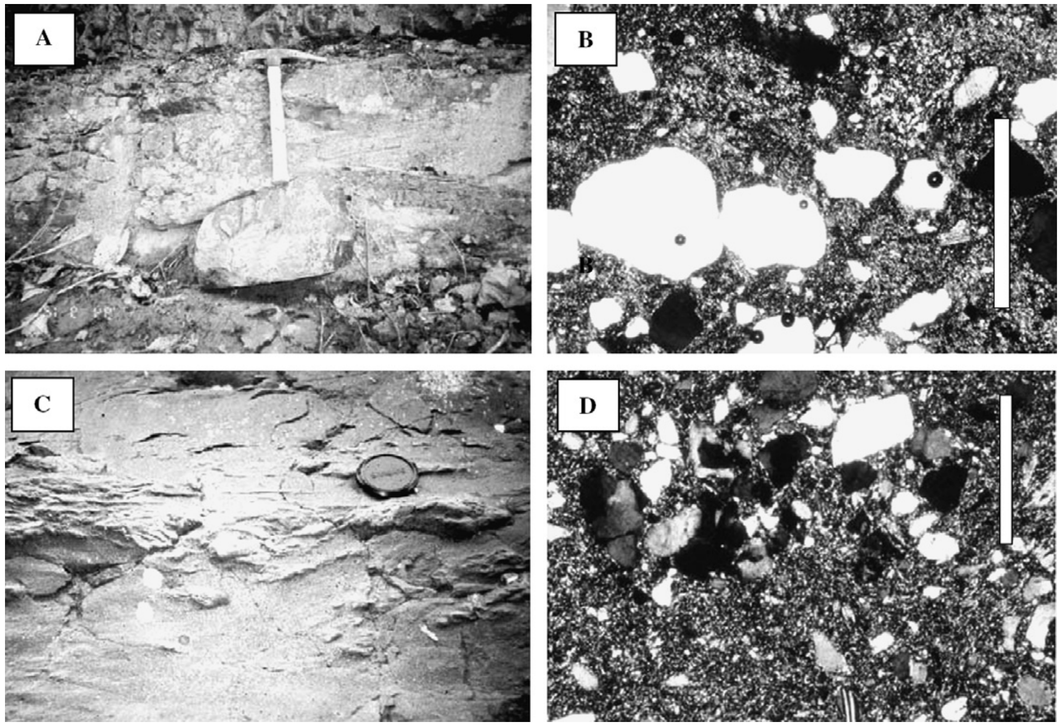


Fig. 3. (A) Coarse Dmm facies with a granitic boulder. (B) Photomicrograph of homogeneous wacke of Dmm facies, scale bar = 5 mm. (C) Field photograph of $Dms_{(c)}$ facies; note sandy segregation with rippled structure, lens cap for scale. (D) Photomicrograph of Dms facies; note weak granulometric differentiation, scale bar = 4 mm.

burial and differential compaction or lateral displacement effects of the beds. In all cases, and prior to deformation, the sandstones beds represent the filling of channels by traction currents and are interpreted as proglacial channels.

3.1.2. Stratified diamictite

These are made up of fine diamictites, are matrix supported, and composed of sand- and silt-sized detritus, with scattered conglomerate clasts. Their average thickness is 10 m, in which Dms, Dmg, and Sd facies are defined.

The stratification is indicated by: (1) changes in color, (2) granulometric gradation, and (3) slightly defined stratification surfaces. The beds are tabular, with thicknesses varying between 10 and 40 cm, massive or with weak normal gradation. The matrix consists of a mixture of very fine sand, silt, and clay. The greater clasts (granules and pebbles) immersed in the matrix are principally composed of quartz and lithic fragments of quartz arenites, feldspathic arenites, and pink granites (Fig. 3D). Clasts with perfectly polished and faceted faces are common. Their greater diameters vary from 2 to 4 cm; their axes are usually parallel and less frequently perpendicular to stratification. Some stratified levels also present normal granulometric gradation, Dmg (Fig. 2). Lenticular sandstones, a few cm thick, with load structures and slumps are common (Sd).

These diamictites result from the remobilization of sediment caused by debris flows and slides, which are occasionally responsible for the deformation of associated sandy levels (Eyles et al., 1985). Stratification is produced by the stacking of repeated subaqueous debris flows that originate from heterogeneous sediments (Eyles et al., 1985). The greater clasts with *a* axes perpendicular to stratification probably come from rafting.

3.1.3. Channeled sandstones

These are organized into packages with thicknesses varying from 6 to 32 m, fining and thinning upward. They consist of St and Sr facies of submature, coarse to fine sandstones with conglomeradic lags. The strata are medium to thick, lenticular to tabular in shape with very gently to highly eroded scour surfaces. The most frequent sedimentary structures are trough cross-stratification, tabular cross-stratification, and current ripples with mud drapes. Two channel levels covered with striated boulders appear close to the exposed base of the unit, interpreted as boulder pavements (del Papa and Martínez, 2001).

The sandstones are arkoses and lithic arkoses, with subangular and angular grains and moderately sorted and closed fabric; 5–10% is represented by silt-sized matrix. The lithic fragments consist of quartz arenites, schists, and granites.

The geometry of the facies successions and sedimentary structures points to channel-fill deposits from traction currents. The sequence presents gently lenticular geometry, and the fill consists of superposed sand beds dominated by aggradational processes. They are interpreted as subaqueous distributary channels related to deltaic systems.

3.2. Zanja Honda well (St. ZH x-1)

This well is located in the Chaco–Salta plain (Fig. 1). The drilling goes through Tertiary deposits, which in this area are constituted by the Subandean Tertiary Tranquitas Formation and Conglomerado Galarza (Arigós and Vilela, 1949), to Carboniferous deposits, represented by the Tarija Formation, and reaches the Devonian substratum at a depth of 3087 m. The Tarija Formation overlays Los Monos Formation (Devonian) in discordant contact. The upper contact with the Conglomerado Galarza is also discordant (Fig. 4).

The sedimentary facies conforming the Tarija Formation, obtained from cores and cutting descriptions are as follows: massive diamictites (Dmm), grey stratified diamictites (Dms), fine green and violet-brown sandstones (Sm and St), and levels of laminated mudstones with dropstones (Fld).

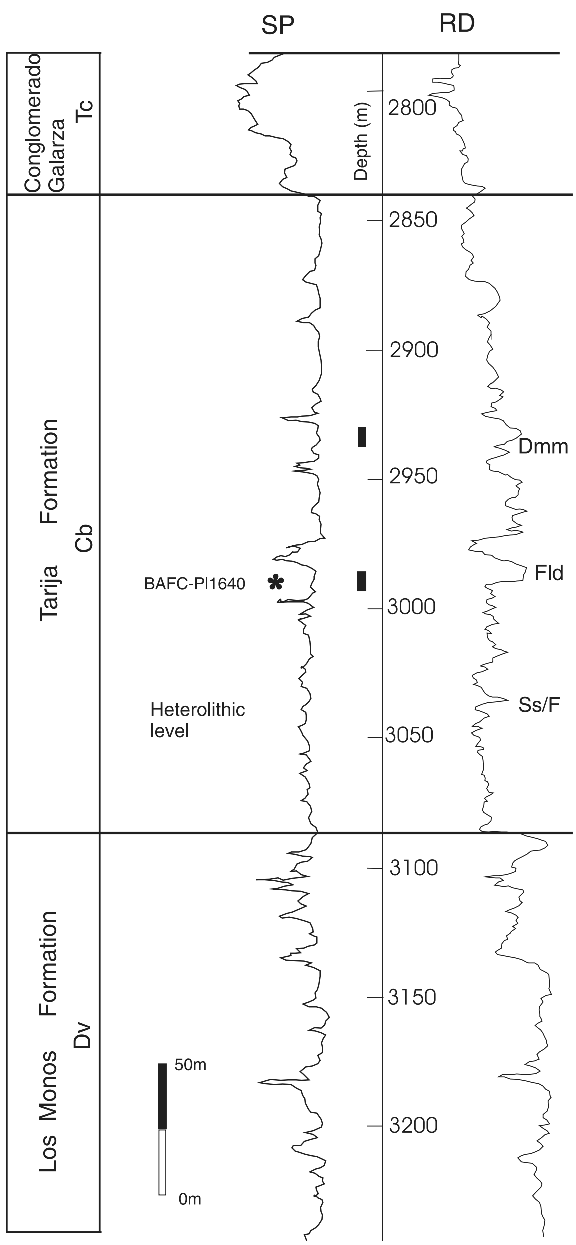


Fig. 4. Geologic logs of Tarija Basin at St. Zanja Honda x-1 well (see Fig. 1 for location).

3.2.1. Laminated mudstones with dropstones (Fld)

Core 2 from Zanja Honda well, taken at 2992–2994 m depth (Fig. 4), consists of alternating claystones and fine, dark grey to black siltstones with fine white sandstones in thin (mm) layers (Fig. 5A). Layers of greenish, cm-thick sandstones are randomly intercalated with rippled stratification and isolated ripples with flattened tops. Coarse sand- and granule-sized quartz clasts, interpreted as dropstones, appear in both the laminated levels and the sandstones.

The laminated levels consist of two layers: (1) lower, light sandy silty and (2) upper, dark, and clayey. They constitute a pair of lamellae 0.9–1 mm thick. Contact between each pair is sharp and erosive; between each lamina, the contact is in some cases sharply defined and gradational in others.

The light sandy silty lamella consists of fine sand and siltstone. Its thickness varies from 0.3 to 0.5 mm, with normal (type 1) or inverse-normal (type 2) gradation (Fig. 5B). The sand grains are subangular to subrounded, and their borders show evidence of corrosion with pervasive matrix incursion. They consist of quartz (mostly with fluid inclusions) and other polycrystalline grains, plagioclase, and potash feldspar. Clayey intraclasts are also found. Silty material is observed, composed of micas (principally muscovite and illite) and organic matter lying parallel to the lamination.

The darker, clayey lamella (Fig. 5C) consists of clays, micas, and organic matter, markedly laminated and parallel to the surface of the contact with the light lamella. This layer is homogeneous, and no gradation is observed. The clays determined by X-ray diffraction are illite, smectite, and kaolin. This layer has a higher content of organic matter than the light one.

The evidence of dropstones altering and deforming lamination is clear, especially in the silty and clayey levels (Fig. 5D), including those with their *a* axes perpendicular to stratification.

Moreover, thin layers of coarse sands are randomly intercalated, eroding and altering the described lamination. These layers represent the episodic entrance of more vigorous streamfloods. Macroscopic sampling does not show evidence of bioturbation either perpendicular to lamination or on the stratification planes; however, subtle disturbances in lamination, which may have resulted from organic activity, are observed in thin sections.

Glacial varves form as a consequence of seasonal variations in the provision of sediment to the basin (Ashley, 1975; Sturm and Matter, 1978). During spring and summer, coarse detritus (sand and coarse silt) comes in through under- and interflows and is deposited from nearer areas to the inner basin, whereas finer detritus (inter- and

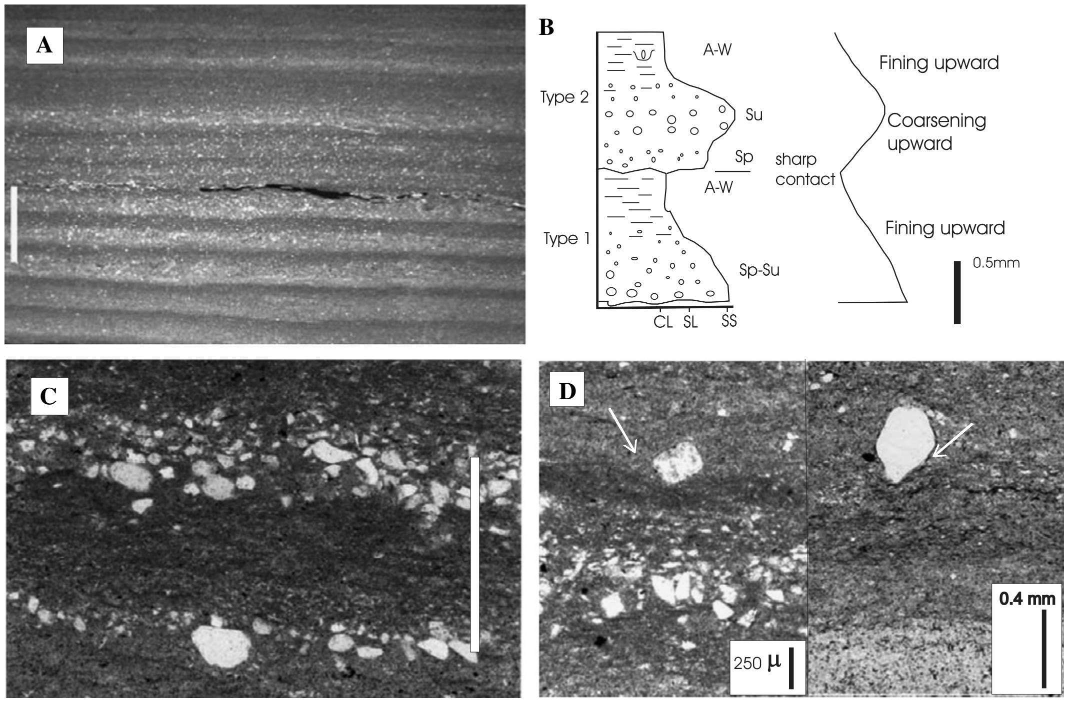


Fig. 5. (A) Hand-polished sample of rhythmic deposits, composed of light sandy lamina and dark clayey lamina, scale bar = 3 mm. (B) Schematic logs of two types of varves identified in the Tarija Formation. Su, summer; A, autumn; W, winter; Sp, spring. (C) Normal, gradational contact between siltstones (upper coarse lamina) and organic matter–rich claystones (dark lamina) (plane-polarized light, PPL), scale bar = 0.9 mm. (D) Dropstones bending the lamination (arrows) (PPL).

overflows) remains in suspension. Thus, the summer deposit (light-colored layer) is thicker and may present normal, inverse, or no gradation and laterally shows a tendency to thinning and granulometric gradation (proximal–distal). At the end of autumn, when the water begins to cool toward total freezing in winter, the provision of detritus ceases, and the suspended clay slowly settles down, depositing a fine, dark layer that coats all bottom irregularities.

Therefore, the laminated deposits analyzed here constitute rhythmites, which are interpreted as glaciolacustrine varves. This interpretation is based on (1) the characteristics described, including thickness, normal gradation, and sharply defined contact between lamellae, coinciding with those mentioned by Smith and Ashley (1985); (2) their close association with glaciogenic diamictites; and (3) the presence of dropstones suggesting ice-rafting processes associated with the rhythmites. Likewise, the characteristics differ from those described for glaciomarine varves (e.g., symmetrical tendency of the varves; see Milana and López, 1998). This evidence indicates an origin related to glacier dynamics in a continental environment. Preservation of the varvic stratification is controlled by the thermocline position and, consequently, by oxygen deficiency or even anoxia at the bottom (Sturm and Matter, 1978). The absence of trace fossils, found in other sites of the basin (see Buatois and del Papa, 2003), attests to this anoxia.

It is likely that the isolated disturbances observed in the lamination and interpreted as organic activity represent periods of thermocline instability, moments in which there was a complete overturn of water. This characteristic is common in glacial lakes, which generally go through periods of dimictic circulation. In nonstratification water periods, the consequent good oxygenation of the bottom would have favored the temporary installation of bentonic fauna.

4. Palynologic results

Two of the samples taken in the Zanja Honda Creek profile, from the middle to upper section of the Tarija Formation, turned out to be fertile; some 150 species were identified. Only one sample core from the well section was processed from the middle of the formation (see Fig. 4). Furthermore, as constantly occurs in Tarija Basin deposits, a significant number of these species (roughly 50%) correspond to reworked forms, principally Devonian and Early Carboniferous. Figs. 6A and B show, for each species, the number of specimens found in the three samples examined. Indigenous forms are alphabetically ordered according to their most probable botanical affinities, and the major groups of reworked palynomorphs are gathered according to their most probable stratigraphic range in Panynological literature. Figs. 7–9 illustrate the most representative indigenous group species in the associations examined, which make it possible to define the stratigraphic location of these levels according to the biostratigraphic chart proposed by di Pasquo (2003).

Scarce, badly preserved indigenous and reworked palynomorphs were obtained from the dark mudstones of

A

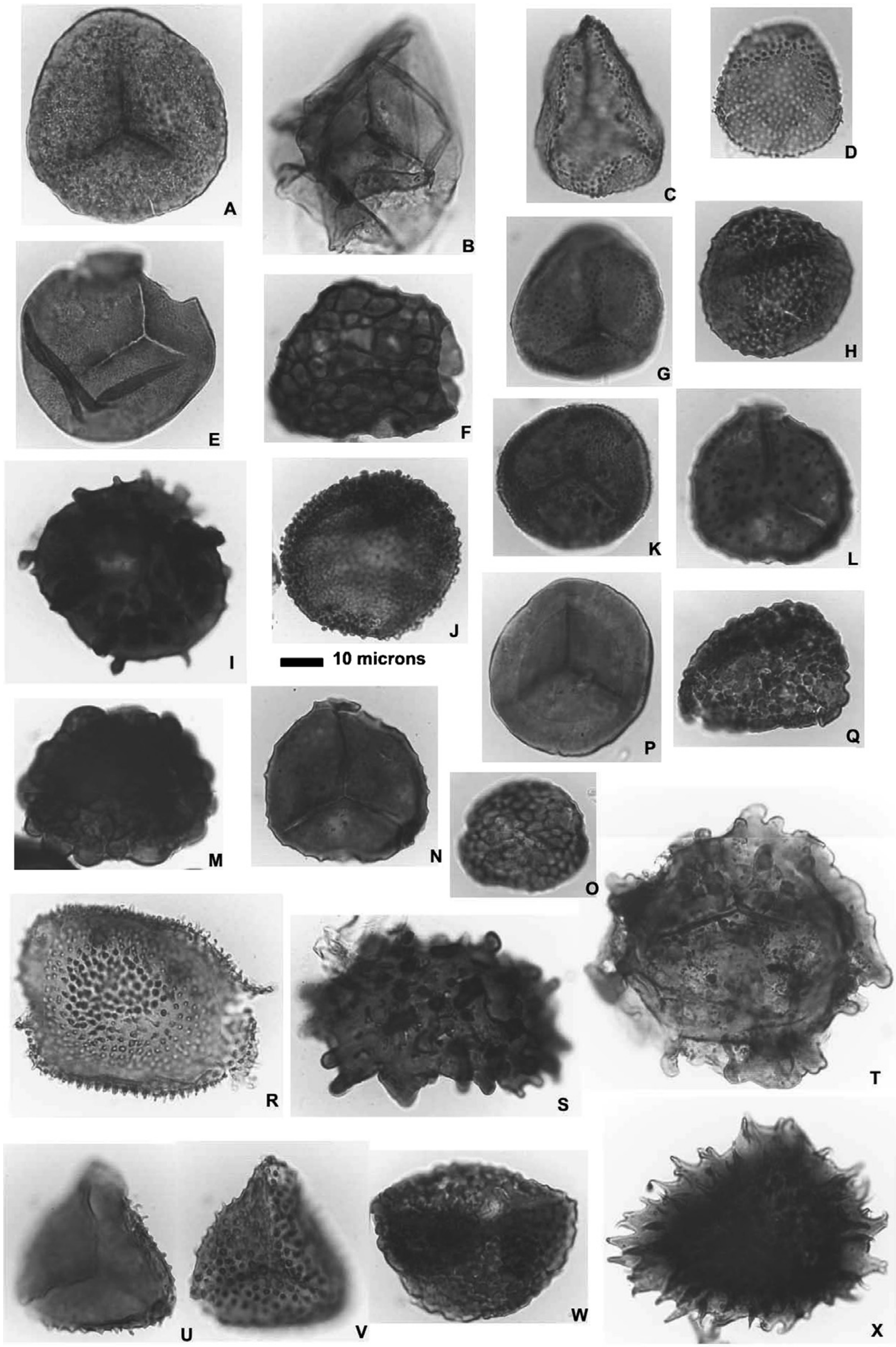
Plate, fig.	Sample number (BAFC-PI) / Indigenous palynomorphs	1640	1476	1477
	Pteridophyte spores			
Fig. 7, G	*Anapiculatisporites* sp. cf. *A. argentinensis* Azcuy 1975			1
	Anapiculatisporites spp.		1	
	Apiculatasporites caperatus Menéndez and Azcuy 1969		3	2
	Apiculatasporites parviapiculatus Azcuy 1975		2	
Fig. 7, I	**Apiculatisporis* sp. cf. *A. variornatus* di Pasquo et al. 2003		3	
Fig. 7, F, O	*Dictyotriletes bireticulatus* (Ibrahim) Potonié and Kremp emend. Smith and Butterworth 1967	1	5	10
	Leiotriletes spp.		3	1
Fig. 7, H	**Microreticulatisporites punctatus* Knox 1950		2	1
	Punctatisporites glaber (Naumova) Playford 1962			1
	Punctatisporites gretensis Balme and Hennelly 1956			1
Fig. 7, A	**Punctatisporites pseudofoveosus* Azcuy 1975		3	
	Punctatisporites spp.		10	6
Fig. 7, S	*Raistrickia densa* Menéndez 1965		1	1
	Raistrickia radiosa Playford and Helby 1968		2	
Fig. 7, T	*Raistrickia verrucosa* Menéndez 1965		1	1
	Reticulatisporites polygonalis (Ibrahim) Loose 1934		1	
Fig. 7, Q	**Verrucosisporites morulatus* (Knox) Potonié and Kremp emend. Smith and Butterworth 1967			1
Fig. 7, J	*Verrucosisporites patelliformis* (Menéndez) Gutierrez 1988		4	5
Fig. 7, M	*Verrucosisporites quasigobbettii* Jones and Truswell 1992		3	1
	**Verrucosisporites* sp.		3	1
	Pteridophyte - Pteridospermaphyte spores			
	Cyclogranisporites aureus (Loose) Potonié and Kremp 1955		1	
Fig. 7, E	*Cyclogranisporites minutus* Bharadwaj 1957		2	7
	Cyclogranisporites spp.		1	
	Granulatisporites parvus Azcuy 1975		1	
Fig. 7, C	*Granulatisporites varigranifer* Menéndez and Azcuy 1971		3	
	Lycophyte spores			
Fig. 8, O	**Crassispora kosankei* (Potonié and Kremp) Bhardwaj emend. Smith and Butterworth 1967			1
Fig. 8, B	*Cristatisporites chacoparanensis* Ottone 1989		2	1
Fig. 7, X	*Cristatisporites crassilabratus* Archangelsky and Gamerro 1979		1	3
Fig. 8, A	*Cristatisporites inconstans* Archangelsky and Gamerro 1979			1
Fig. 8, D	*Cristatisporites menendezii* (Menéndez and Azcuy) Playford 1978 emend. Césari 1985		2	
Fig. 8, C	**Cristatisporites rollerii* Ottone 1991		1	
Fig. 8, H	*Cristatisporites scabiosus* Menéndez 1965		2	2
Fig. 8, E	*Cristatisporites spinosus* (Menéndez and Azcuy) Playford 1978 emend. Césari 1985		1	1
	Cristatisporites stellatus (Azcuy) Gutierrez y Limarino 2001			1
	Cristatisporites spp.		16	3
Fig. 8, L	*Endosporites rhytidosaccus* Menéndez and Azcuy 1973		3	1
Fig. 7, P	*Endosporites zonalis* (Loose) Knox 1950		3	1
Fig. 7, W	**Foveosporites hortonenesis* (Playford) Azcuy 1975		1	
Fig. 8, I	*Lundbladispora riobonitensis* Marques Toigo and Picarelli 1984		1	4
Fig. 8, G	*Vallatisporites arcuatus* (Marques Toigo) Archangelsky and Gamerro 1979		14	6
Fig. 8, F	*Vallatisporites ciliaris* (Luber) Sullivan 1964		3	3
Fig. 8, N	*Vallatisporites vallatus* Hacquebard 1957		1	2
	Vallatisporites spp.		6	3
	Sphenophyte spores			
Fig. 7, K	*Apiculiretusispora alonsoi* Ottone 1989		3	2
Fig. 7, L, N	**Apiculiretusispora tuberculata* Azcuy 1975		2	1
Fig. 7, B	*Calamospora hartungiana* Schopf en Schopf, Wilson and Bentall 1944	1	3	5
	Retusotriletes anfractus Menéndez and Azcuy 1969		1	
	**Retusotriletes nigritellus* (Luber) Foster 1979		5	
	***Incertae sedis* spores**			
Fig. 8, J	**Cristatisporites* sp. cf. *Bascaudaspora canipa* Owens 1983		1	
Fig. 7, D	*Dibolisporites disfacies* Jones and Truswell 1992	1	6	1
Fig. 7, U, V	**Didecitriletes ericianus* (Balme and Hennelly) Venkatachala and Kar 1965		3	
Fig. 7, R	**Didecitriletes* sp. cf. *D. ericianus* (Balme and Hennelly) Venkatachala and Kar 1965		2	1
	**Knoxisporites stephanophorus* Love 1960		1	
Fig. 8, M	**Rugospora cortaderensis* (Césari and Limarino) Gutiérrez and Limarino 2001		3	1
	Spelaeotriletes ybertii (Marques Toigo) Playford and Powis 1979			1
Fig. 8, K	*Velamisporites australiensis* (Playford and Helby) di Pasquo et al. 2003		7	4
	Undetermined		18	11
	Gymnospermous pollen grains	None		
	Caheniasaccites flavatus Bose and Kar emend. Azcuy and di Pasquo 2000		2	
	Cannanoropollis densus (Lele) Bose and Maheshwari 1968		1	
	Cannanoropollis janakii Potonié and Sah 1960		1	1
	Cannanoropollis triangularis (Mehta) Bose and Maheshwari 1968		1	
Fig. 9, B	*Crucisaccites latisulcatus* Lele and Maithy 1964			1
Fig. 9, I	**Cystoptychus azcuyi* di Pasquo 2002		3	1
	Divarisaccus stringoplicatus Ottone 1991		1	1
Fig. 9, E	*Plicatipollenites malabarensis* (Potonié and Sah) Foster 1975		3	2
	Plicatipollenites trigonalis Lele 1964		2	1
	Potonieisporites barrelis Tiwari 1965		2	
	Potonieisporites brasiliensis (Nahuys, Alpern and Ybert) Archangelsky and Gamerro 1979		1	
	Potonieisporites congoensis Bose and Maheshwari 1968		2	
Fig. 9, C	*Potonieisporites densus* Maheshwari 1967		2	
Fig. 9, D	*Potonieisporites magnus* Lele and Karim 1971			1
	Potonieisporites neglectus Potonié and Lele 1961		1	2
Fig. 9, F	*Potonieisporites novicus* Bhardwaj 1954 emend. Poort and Veld 1996		4	4
	Potonieisporites triangulatus Tiwari 1965			1
	Undetermined		17	8
	Medullosaceae praecolpate prepollen grain			
Fig. 9, A	**Schopfipollenites ellipsoides* Potonié and Kremp 1954			1
	Chlorophycean algae			
Fig. 9, H	*Botryococcus braunii* Kützing 1849		25	20
Fig. 9, G	*Brazilea scissa* (Balme and Hennelly) Foster 1975	4	6	4
Fig. 9, K	*Quadrisporites horridus* Hennelly ex Potonié and Lele 1961		3	1
Fig. 9, J	*Tetraporina punctata* (Tiwari and Navale) Kar and Bose 1976		3	3

Fig. 6. Number of specimens registered in the studied samples. (A) Indigenous miospores arranged according to their probable parent plant group. The species registered for the first time in the Tarija Formation are marked with an asterisk. (B) Main reworked palynomorph groups ordered by their probable stratigraphic range.

B

Reworked palynomorphs Sample number (BAFC-Pl)	1640	1476	1477
Silurian/Devonian Spores			
Laeovolancis divellomedium (Chibrikova) Burgess and Richardson 1991		3	4
Devonian Spores			
Acinosporites acanthomammillatus Richardson 1965		1	
Acinosporites ledundae Ottone 1996	1		1
Acinosporites spp.		3	
Ancyrospora spp		4	1
Apiculiretusispora brandtii Streel 1964 (= *A. nitida* Owens 1971)	1	2	1
Archaeozonotriletes columnus Allen 1965			1
Auroraspora macra Sullivan 1968		4	2
Dibolisporites spp.		2	
Emphanisporites rotatus (McGregor) McGregor 1973	1	4	2
Endosporites longiradiatus Menéndez and Pöthe de Baldis 1967		2	1
Geminospora lemurata Balme 1962 emend. Playford 1983	1	3	4
Grandispora protea (Naumova) Moreau-Benoit 1980		1	
Grandispora pseudoreticulata (Menéndez and Pöthe de Baldis) Ottone 1996		4	1
Grandispora permulta (Daemon) Loboziak, Streel and Melo 1999		2	1
Grandispora spp.		15	4
Hystricosporites spp.		2	
Retispora lepydophyta (Kedo) Playford 1976		7	6
Samarisporites triangulatus Allen 1965		1	5
Vallatisporites pusillites (Kedo) Dolby and Neves 1970		3	
Verrucosisporites scurrus (Naumova) McGregor and Camfield 1982		1	1
Verrucosisporites premnus Richardson 1965		1	1
Early Carboniferous spores			
Colatisporites decorus (Bharadwaj and Venkatachala) Williams in Neves et al. 1973		7	2
Convolutispora circumvallata Clayton 1971		3	
Cordylosporites marciae Playford and Satterthwait 1985		3	
Densosporites anulatus (Loose) Schopf, Wilson and Bentall 1944		2	1
Kraeuselisporites explanatus (Naumova) Azcuy and di Pasquo 2003		1	1
Pustulatisporites gibberosus (Hacquebard) Playford 1963		2	
Tumulispora rarituberculata (Luber) Potonié 1966			2
Spinozonotriletes uncatus Hacquebard 1957		2	
Velamisporites minutus (Neves and Ioannides) Ravn 1991		1	
Verrucosisporites nitidus (Naumova) Playford 1963		1	
Undetermined	15	45	23
Devonian Prasinophyceae			
Cymatiosphaera pavimenta (Deflandre) Deflandre 1954			1
Cymatiosphaera spp.	1	7	1
Dictyotidium torosum Playford 1981			1
Dictyotidium spp.			1
Duvernaysphaera kraeuselii (Stockmans and Willière) Stockmans and Willière 1962			2
Hemiruptia legaultii Ottone 1996		10	10
Leiosphaeridia spp.		6	2
Maranhites insulatus Burjack and Oliveira 1989			1
Maranhites mosesii (Sommer) Brito emend. Burjack and Oliveira 1989			1
Maranhites spp.		8	10
Pterospermella reticulata Loeblich and Wicander 1976		1	
Pterospermella spp.		4	1
Tasmanites spp.		4	1
Silurian Acritarcha		6	
Devonian Acritarcha			
Ammonidium garrasinoi Ottone 1996		1	1
Arkonites bilixus Legault 1973		2	
Baltisphaeridium triangulare Stockmans and Willière 1962		1	1
Estiastra barbata Downie 1963		3	
Estiastra improcera Loeblich 1969		4	5
Estiastra spp.			2
Exochoderma arca Wicander and Wood 1981		2	1
Exochoderma triangulata Wicander and Wood 1981		2	
Gorgonisphaeridium discissum Playford 1981		2	1
Gorgonisphaeridium ohioense (Winslow) Wicander 1974		1	1
Gorgonisphaeridium winslowiae Staplin et al. 1965		1	1
Gorgonisphaeridium spp.	1	8	6
Muraticavea munificus Wicander and Wood 1981		2	1
Navifusa bacilla (Deunff) Playford 1977	1	1	1
Umbellasphaeridium companulatum Oliveira y Burjack 1997		1	
Umbellasphaeridium saharicum Jardiné et al. 1972		3	1
Umbellasphaeridium deflandreii (Moreau-Benoit) Jardiné et al. 1972			1
Verhyachium colemanii Playford 1981		1	1
Verhyachium polyaster Staplin 1961		1	1
Verhyachium trispinosum (Eisenack) Deunff 1954		1	1
Verhyachium spp.		5	5
Undetermined Acritarcha		15	12
Devonian Chlorophycean algae			
Chomotriletes sp.			1
Chomotriletes vedugensis Naumova 1953		2	
Silurian/Devonian Chlorophycean algae			
Quadrisporites granulatus (Cramer) Ströther 1991		6	2
Quadrisporites variabilis (Cramer) Ottone and Rossello 1996		6	2

Fig. 6 (*continued*)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the varves level in Zanja Honda core 2 (BAFC-Pl 1640) in contrast to the result obtained from diamictite facies in Zanja Honda Creek (BAFC-Pl 1476 and 1477).

Sample BAFC-Pl 1640 shows scarce, very badly preserved palynomorphs, in which reworked Devonian elements prevail, as may be seen in Figs. 6A and B and Table 1. *Dibolisporites disfacies* and *Dictyotriletes bireticulatus* are prominent among the indigenous palynomorphs. These species appear in other locations of the Tarija Basin in the base of the *Dictyoriletes bireticulatus*-*Cristatisporites chacoparanensis* (BC) di Pasquo Biozone. According to di Pasquo (2003), this biozone is recognizable from the medium to upper portion of the Tarija Formation to the lower portion of the Escarpment Formation. In the Tuyunti stream profile, the base of the biozone is approximately 40 m above the boundary with the Itacuamí Formation (di Pasquo, 2003). The characteristics mentioned for this assemblage permit their assignment to a lower portion of Biozone BC, which corresponds stratigraphically with the lower to middle portion of the Tarija Formation. The scarce record of palynomorphs and the absence of *Botryococcus*, pollen grains, and lycophytes in the indigenous group (Fig. 6A) suggest critical climatic conditions at deposition (possibly glaciated area surrounding the lake during autumn–winter). These critical conditions, possibly in combination with the lack of nutrients (e.g., N_2) in the water during the cold season, would have impeded the development of algae, especially *Botryococcus*. The absence of pollen grains is difficult to explain but might be due to either an inefficient dispersal mechanism or their catchment in farther areas.

In addition, the poor preservation of the palynomorphs may be due to their time of residence in the water column and slow settling to the bottom. This scenario would have favored bacterial degradation under partially oxygenated conditions, which probably continued through the action of bacteria in sub-oxic conditions after they were deposited. Another indigenous component present is *Brazilea scissa*, a zygospore that could confirm a lacustrine depocenter (Colbath and Grenfell, 1995). Nevertheless, taphonomic processes and the provenance of the unique sample analyzed could be explanations of the scarcity of palynomorphs recorded, so more sampling is needed to define the weight of each process in this interpretation.

Samples BAFC-Pl 1476 and 1477 show a great number of mostly well-preserved indigenous and reworked species. The right columns of Table 1 show the percentages of major palynomorph groups obtained by counting up to 250 specimens in different, randomly selected slide fields. These were averaged with those from the group of samples 1476–1477 presented in Figs. 6A and B. The values for each particular association, obtained from this figure, appear on the left. Comparison of the final column with the percentages of group 1476–1477 provides very similar values.

Sample BAFC-Pl 1476 (Fig. 2) contains abundant phytoclasts (about 50% of the palynomorph total), principally represented by gelified vegetable detritus (30%), cuticles, tracheids, and resinites (20%) of various sizes (poor selection). The remaining 50% consists of miospores and phytoplankton, in which two groups are recognizable: an indigenous (45%) group consisting of 26% trilete spores, 10% monosaccate pollen grains, 7% *Botryococcus*, and 2% other algae (e.g., *Brazilea*, *Tetraporina*), and another group of reworked forms (33% spores, 22% palaeomicroplankton) of Siluro-Devonian age (e.g., *Laevolancis divellomedium*, *Quadrisporites variabilis*, *Eupoikilofusa striatifera* (Cramer) Cramer, *Dactylofusa maranhensis* Brito and Santos), from the Devonian s.l. (Fig. 6B) and the Early Carboniferous (e.g., *Colatisporites decorus*, *Cordylosporites marciae*, *Densosporites anulatus*). In general, the organic matter shows varied exine maturation colors (related to the thermal history originally attained by the different layers). These colors point to different stratigraphic origins: The thin-walled indigenous spores are generally orange brown to yellowish orange (TAI about 2, Batten, 1996), whereas most of the reworked spores are riper (dark brown, TAI approximately 3). The Devonian acritarchs are partially pyritized, though they are generally light brown to yellowish orange; the Siluro-Devonian are dark brown and ill preserved.

Sample BAFC-Pl 1477 displays very similar characteristics, with varied exine maturation colors but a slightly higher proportion of phytoclasts (gelified vegetable detritus

Fig. 7. Characteristic palynomorphs from *Dictyotriletes bireticulatus*-*Cristatisporites chacoparanensis* Biozone registered in Tarija Formation at Zanja Honda Creek (BAFC-Pl 1476, 1477) and Zanja Honda x-1 well (BAFC-Pl 1640). Scale bar = 10 μm. (A) *Punctatisporites pseudofoveosus* Azcuy 1975, BAFC-Pl 1476(1) K62/4. (B) *Calamospora hartungiana* Schopf en Schopf, Wilson and Bentall 1944, BAFC-Pl 1476(1) X56. (C) *Granulatisporites varigranifer* Menéndez and Azcuy 1971, BAFC-Pl 1476(1) U62. (D) *Dibolisporites disfacies* Jones and Truswell 1992, BAFC-Pl 1476(2) S22. (E) *Cyclogranisporites minutus* Bharadwaj 1957, BAFC-Pl 1476(1) Y55. (F) *Dictyotriletes bireticulatus* (Ibrahim) Potonié and Kremp emend. Smith and Butterworth 1967, BAFC-Pl 1476(2) W39/3. (G) *Anapiculatisporites* sp. cf. *A. argentinensis* Azcuy 1975, BAFC-Pl 1477(1) G31/4. (H) *Microreticulatisporites punctatus* Knox 1950, BAFC-Pl 1477(1) O58/4. (I) *Apiculatisporis* sp. cf. *A. variornatus* di Pasquo et al. 2003, BAFC-Pl 1476(1) J38/4. (J) *Verrucosisporites patelliformis* (Menéndez) Gutierrez 1988, BAFC-Pl 1476(2) P63/1. (K) *Apiculiretusispora alonsoi* Ottone 1989, BAFC-Pl 1477(1) L32. (L) *Apiculiretusispora tuberculata* Azcuy 1975, BAFC-Pl 1476(1) L53. (M) *Verrucosisporites quasigobbettii* Jones and Truswell 1992, BAFC-Pl 1476(1) H58. (N) *Apiculiretusispora tuberculata* Azcuy 1975, BAFC-Pl 1476(1) L53. (O) *Dictyotriletes bireticulatus*, BAFC-Pl 1477(1) L33/4-L34/3. (P) *Endosporites zonalis* (Loose) Knox 1950, BAFC-Pl 1477(1) M30. (Q) *Verrucosisporites morulatus* (Knox) Potonié and Kremp emend. Smith and Butterworth 1967, BAFC-Pl 1477(1) L30/1. (R) *Didecitriletes* sp. cf. *D. ericianus* (Balme and Hennelly) Venkatachala and Kar 1965, BAFC-Pl 1476(1) R32/2. (S) *Raistrickia densa* Menéndez 1965, BAFC-Pl 1476(1) V16/4. (T) *Raistrickia verrucosa* Menéndez 1965, BAFC-Pl 1477(1) Z29/3. (U and V). *Didecitriletes ericianus* (Balme and Hennelly) Venkatachala and Kar 1965, BAFC-Pl 1476(1) G46. (W) *Foveosporites hortonensis* (Playford) Azcuy 1975, BAFC-Pl 1476(2) S21/4. (X) *Cristatisporites crassilabratus* Archangelsky and Gamerro 1979, BAFC-Pl 1477(1) D21/1.

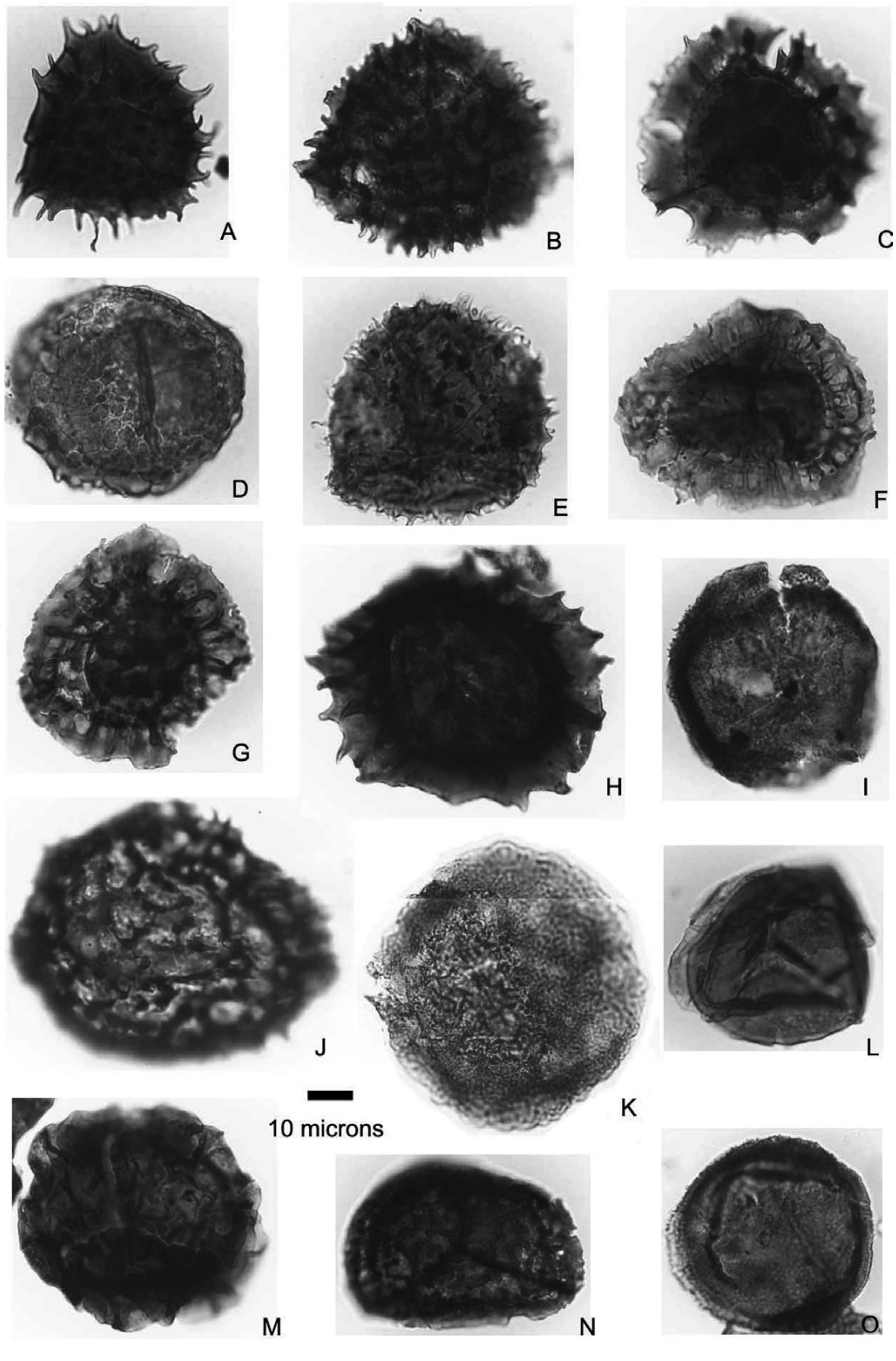

Fig. 8. Characteristic palynomorphs from *Dictyotriletes bireticulatus-Cristatisporites chacoparanensis* Biozone registered in Tarija Formation at Zanja Honda creek (BAFC-Pl 1476, 1477) and Zanja Honda x-1 well (BAFC-Pl 1640). Scale bar = 10 μm. (A) *Cristatisporites inconstans* Archangelsky and Gamerro 1979, BAFC-Pl 1476(1) J60/2. (B) *Cristatisporites chacoparanensis* Ottone 1989, BAFC-Pl 1476(2) C36/3. (C) *Cristatisporites rollerii* Ottone 1991, BAFC-Pl 1476(2) X37/3. (D) *Cristatisporites menendezii* (Menéndez and Azcuy) Playford 1978 emend. Césari 1985, BAFC-Pl 1476(2) C54. (E) *Cristatisporites spinosus* (Menéndez and Azcuy) Playford 1978 emend. Césari 1985, BAFC-Pl 1477(1) U35. (F) *Vallatisporites ciliaris* (Luber) Sullivan 1964, BAFC-Pl 1477(1) W36. (G) *Vallatisporites arcuatus* (Marques Toigo) Archangelsky and Gamerro 1979, BAFC-Pl 1477(1) R21. (H) *Cristatisporites scabiosus* Menéndez 1965, BAFC-Pl 1476(1) W38/4. (I) *Lundbladispora riobonitensis* Marques Toigo and Picarelli 1984, BAFC-Pl 1477(1) B18/3. (J) *Cristatisporites* sp. cf. *Bascaudaspora canipa* Owens 1983, BAFC-Pl 1476(1) E62/1. (K) *Velamisporites australiensis* (Playford and Helby) di Pasquo et al. 2003, BAFC-Pl 1476(1) Y52. (L) *Endosporites rhytidosaccus* Menéndez and Azcuy 1973, BAFC-Pl 1477(1) K41/1. (M) *Rugospora cortaderensis* (Césari and Limarino) Gutiérrez and Limarino 2001, BAFC-Pl 1476(1) C63/2. (N) *Vallatisporites vallatus* Hacquebard 1957, BAFC-Pl 1477(1) J16/2-H116/4. (O) *Crassispora kosankei* (Potonié and Kremp) Bhardwaj emend. Smith and Butterworth 1967, BAFC-Pl 1477(1) K40.

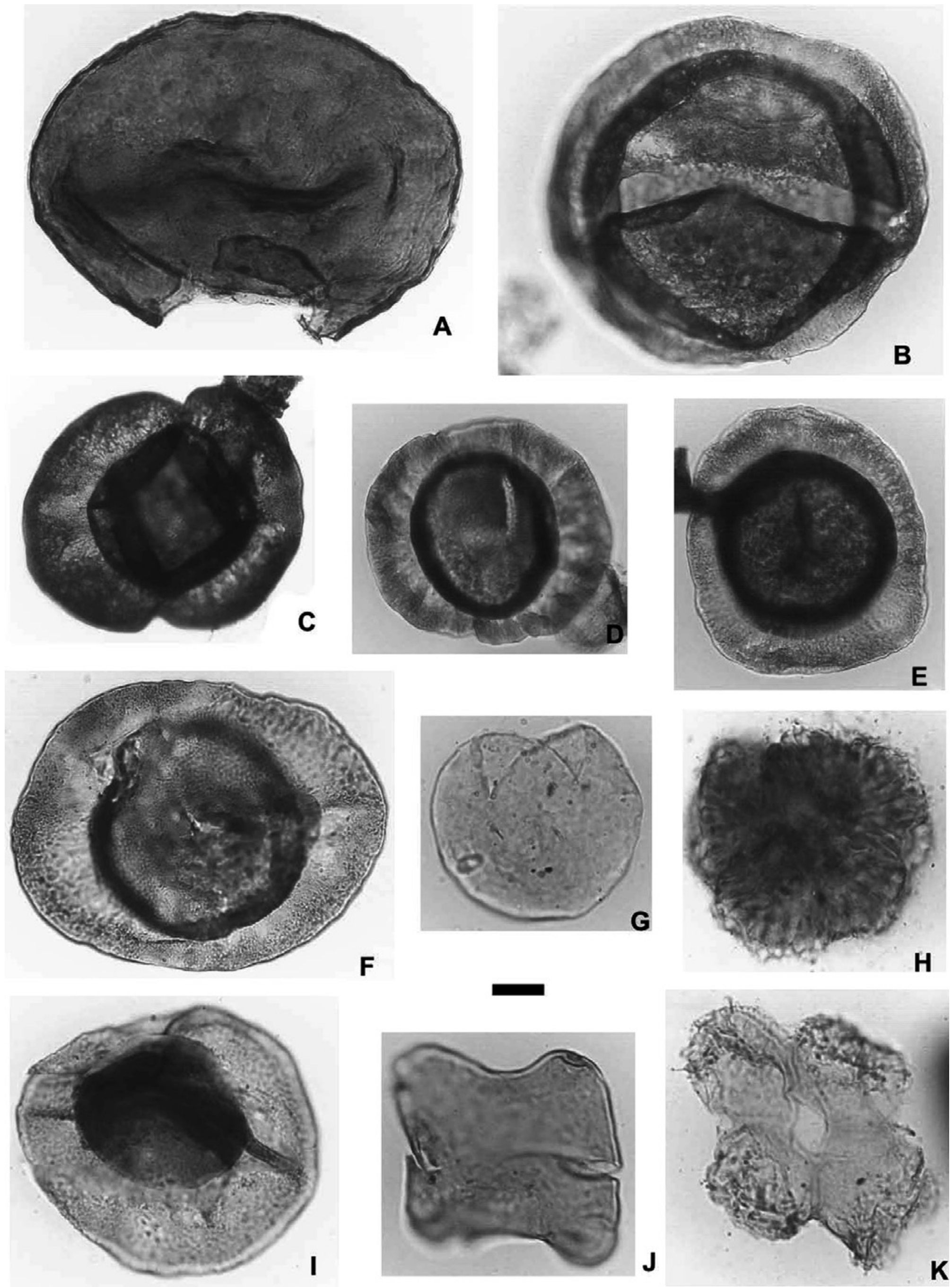

Fig. 9. Characteristic palynomorphs from *Dictyotriletes bireticulatus-Cristatisporites chacoparanensis* Biozone registered in Tarija Formation at Zanja Honda creek (BAFC-Pl 1476, 1477) and Zanja Honda x-1 well (BAFC-Pl 1640). Scale bar = 10 μm (G–H, J–K), 20 μm (A–F, I). (A) *Schopfipollenites ellipsoides* Potonié and Kremp 1954, BAFC-Pl 1477(1) H16/3. (B) *Crucisaccites latisulcatus* Lele and Maithy 1964, BAFC-Pl 1477(1) O58/4. (C) *Potonieisporites densus* Maheshwari 1967, BAFC-Pl 1476(2) R15/1. (D) *Potonieisporites magnus* Lele and Karim 1971, BAFC-Pl 1477(1) A53. (E) *Plicatipollenites malabarensis* (Potonié and Sah) Foster 1975, BAFC-Pl 1477(1) M55. (F) *Potonieisporites novicus* Bhardwaj 1954 emend. Poort and Veld 1996, BAFC-Pl 1476(1) D34. (G) *Brazilea scissa* (Balme and Hennelly) Foster 1975, BAFC-Pl 1477(1) K47/1. (H) *Botryococcus braunii* Kützing 1849, BAFC-Pl 1476(2) C35. (I) *Cystoptychus azcuyi* di Pasquo 2002, BAFC-Pl 1476(1) L43. (J) *Tetraporina punctata* (Tiwari and Navale) Kar and Bose 1976, BAFC-Pl 1476(2) B52. (K) *Quadrisporites horridus* Hennelly ex Potonié and Lele 1961, BAFC-Pl 1476(2) Y24/2-Y25/1.

59%, cuticles, tracheids, and resinites 7.5%), likewise a poor selection. The remaining 33.5% is made up of 40% indigenous and 60% reworked palynomorphs. In the first group, 26% corresponds to trilete spores, 6% to pollen grains, 7% *Botryococcus*, and 1% to other algae. The reworked palynomorphs comprise 34% of Siluro-Devonian and Early Carboniferous trilete spores (e.g., *Colatisporites decorus*, *Tumulispora rarituberculata*, *Densosporites anulatus*), 25% of Devonian palaeomicroplankton, and 1% of Siluro-Devonian acritarchs (Fig. 6B and Table 1).

Table 1
Synthesis of the quantitative results obtained from the studied samples

Grupo palinológico/No.Muestra	1640	1476	1477					1477 (%)					Sum	Prom %
Esporas autóctonas			2	1	1	4	1	6.5	5.0	3.3	20.0	3.3	38.1	7.6
Polen monosaccado			1					3.2					3.2	0.6
Botryococcus			1	1				3.2	5.0				8.2	1.6
Otras algas autóctonas														
Esporas D-Carb.			3	4	5	2	6	9.7	20.0	16.7	10.0	20.0	76.3	15.3
Acritarcas Dev.			3	4	1		3	9.7	20.0	3.3		10.0	43.0	8.6
Acritarcas Sil.														
Palinodetritos														
Cutículas					1	2				3.3	10.0		13.3	2.7
Traqueidas					1	2				3.3	10.0		13.3	2.7
Resinitas			1		1			3.2		3.3			6.6	1.3
Amorfo														
Detritos vegetales			20	10	20	10	20	64.5	50.0	66.7	50.0	66.7	297.8	59.6
			31	20	30	20	30	100	100	100	100	100	500	100

	(numero) de sistematica (porcentaje)						sin palinodetritos con palinodetritos					promedio	
Grupo palinológico/No.Muestra	1640	1476	1477	1640	1476	1477	1476	1477	1476	1477		1476	1477
Esporas autóctonas	3	155	95	10	32	33	20	21	10	7		26	27
Polen monosaccado		43	26		9	9	12	3	6	1		10	6
Botryococcus		25	20		5	7	8	6	4	2		7	6
Otras algas autóctonas	4	12	8	14	2	3	2		1			2	1
Esporas D-Carb.	19	134	66	66	28	23	40	45	20	15		34	34
Acritarcas Dev.	3	110	74	10	23	26	16	24	8	8		19	25
Acritarcas Sil.		6			1		2	1	1	1		2	1
Palinodetritos											34	100	100
Cutículas									10	3			
Traqueidas									10	3			
Resinitas										2			
Amorfo													
Detritos vegetales									30	59			
Total	29	485	289	100	100	100	100	100	100	100			

Palynomorph groups/Sample	1640 (%)	1476 (%)	1477 (%)	Assemblage 1476–1477			
				No. ej.	%	Hazard %	Mean (%)
Total Indigenous	24	45	40	399	50	35	43
Indigenous spores	10	26	27	267	34	20	27
Pteridophyte and Pteridosp.				95	12		10
Sphenophyte				22	3		2
Lycophyte				89	11		9
Incertae sedis				61	8		6
Pollen grains		10	6	66	8	8	8
Algae	14	9	7	65	8	7	8
Botryococcus		7	6	45	6		6
Other algae	14	2	1	20	2		2
Total reworked	76	55	60	394	50	65	57
Spores	66	33	34	197	25	40	32
Acritarchs-algae	10	22	26	197	25	25	25
Total assemblage	100			793		100	100

Palynomorph groups/Sample	1640 (%)	1476 (%)	1477 (%)	Assemblage 1476–1477			
				Spec.Nr.	%	Hazard %	Mean (%)
Total Indigenous	24	45	40	399	50	35	43
Indigenous spores	10	26	27	267	34	20	27
Pollen grains		10	6	66	8	8	8
Algae	14	9	7	65	8	7	7.5
Botryococcus		7	6	45	6	6	6
Other algae	14	2	1	20	2	1	1.5
Total reworked	76	55	60	394	50	65	57
Spores	66	33	34	197	25	40	32
Acritarchs-algae	10	22	26	197	25	25	25
Total assemblage	100	100	100	793	100	100	100

Another notable feature of both samples from the Zanja Honda profile, though we recognize the need for more sampling to confirm this statement, is the low proportion of charcoal and the absence of charred particles, which imply no fires happened in the surroundings during deposition. This suggestion in turn supports the theory of a humid paleoclimate with a marked rainy season (Cope and Chaloner, 1985; Wang et al., 1999; Scott, 2000). The presence of abundant phytodetritus, good general preservation of nonpyriritized indigenous material, and the great volume of relatively well-preserved reworked material correlate with the paleoenvironmental interpretation of the host rock. They also attest, as expressed by di Pasquo and Azcuy (1997b) and Azcuy and di Pasquo (2000a), to the existence on the one hand of tectonic events that generated new supply areas and, on the other, to erosion processes related to glacier dynamics that would have originated paleovalleys and lacustrine depocenters. During the Late Carboniferous, Siluro-Devonian, and Early Carboniferous, rocks were resedimented together with their palynological content principally through fluvial drainage (di Pasquo and Azcuy, 1999b) in an interglacial period. The organic matter would have reached a nearby lacustrine depocenter and rapidly settled from debris flows, which favored their preservation. Also, the presence of different types and sizes of well-preserved *Botryococcus* colonies may suggest that they settled *in situ*, confirming the continental (lacustrine) characteristics of the depocenter (Batten and Grenfell, 1996).

According to the stratigraphic distribution of Late Carboniferous species in the Tarija Basin (di Pasquo, 2003), the Zanja Honda profile samples can be attributed to the BC Biozone. The following indigenous species are found here: *Endosporites zonalis*, *E. rhytidosaccus*, *Velamisporites autraliensis*, *Reticulatisporites polygonalis*, *Cristatisporites crassilabratus*, *C. scabiosus*, *Vallatisporites ciliaris*, *Dibolisporites disfacies*, *Spelaeotriletes ybertii*, *Cucisaccites latisulcatus* and those that give the biozone its name (Fig. 6A). Sample BAFC-Pl 1476 can be correlated with samples BAFC-Pl 452/1164 of the Tuyunti stream profile, on the basis of the presence of *Endosporites rhytidosaccus*, *Cristatisporites scabiosus*, *Vallatisporites ciliaris*, *Spelaeotriletes ybertii*, and *Crucisaccites latisulcatus* and a direct comparison with the samples of that profile. The samples of the Tuyunti profile are situated in the middle portion of Tarija Formation (di Pasquo, 2003). The characteristics of assemblage BAFC-Pl 1477 suggest a correlation with sample BAFC-Pl 1165 of the Tuyunti profile, even though di Pasquo (2003) does not refer to *C. latisulcatus* at that level. Its stratigraphic rank extends at least to that level.

Furthermore, it is worth noting that the following species were discovered for the first time in the Tarija Basin (Fig. 6A): *Knoxisporites stephanophorus*, *Verrucosisporites morulatus*, *Cristatisporites* sp. cf. *Bascaudaspora canipa*, *Apiculatisporis* sp. cf. *A. variornatus*, *Retusotriletes nigritellus*, *Microreticulatisporites punctatus*, *Apiculiretusispora tuberculata*, *Didecitriletes ericianus*, *Rugospora cortaderensis*, and *Foveosporites hortonensis*. Their most frequent record is in Late Carboniferous (Westphalian) associations in Argentina and Brazil (Césari and Gutiérrez, 2001; Souza et al., 2003). Biozone BC is attributed to the middle Late Carboniferous or Westphalian (di Pasquo, 2003).

Other species registered for the first time in these associations (Fig. 6A), such as *Crassispora kosankei*, *Cristatisporites rollerii*, *Cystoptychus azcuyi*, and *Schopfipollenites ellipsoides*, are interpreted as reworked elements of Biozone KA (di Pasquo, 2003), because they are found in a reworked diamictite, which suggests potent erosion episodes that beveled the Tupambi Formation. These erosive events may have been caused by glacier action, which produced large volumes of detritus and triggered its continuous debris flow (facies Dmm and Dms). Thus, the stratigraphic value of the species, recognized as exclusive Biozone KA forms, is maintained. We note the existence of other Late Carboniferous species identified in Biozone RS is very likely; they might be found in these associations as reworked forms of the Itacuamí Formation (e.g., *Raistrickia radiosa*). Additional studies could confirm this hypothesis.

5. Correlation and stratigraphic interpretation

In spite of the general correlation between outcrops and subsurface data, certain degrees of uncertainty remain, and Fig. 10 shows our proposed correlation. This correlation is based on the stratigraphic cycles suggested by del Papa and Martínez (2001) and sedimentological data; palynology also partially contributes to this purpose due to the scarcity of samples. The sedimentary facies and facies assemblages in the Zanja Honda profile (Fig. 2) have been interpreted as evidence of a fluvioglacial environment (del Papa and Martínez, 2001) and suggest a sedimentation area close to the icecap.

The alternation of massive diamictite and stratified facies marks successive periods of glacier advance (deposition of Dmm facies with coarse clasts) and retreat with resedimentation and normal sediment gradation (Dms and Dmg). In the Zanja Honda well (St. ZH x-1) (Fig. 4), the presence of varves points to distalization of direct glacial influence toward the E-SE and the existence of a lacustrine environment with restricted water circulation (thermal stratification).

The preservation of lamination requires certain conditions: the absence of burrowing bentonic organisms that alter the primary structures, inappreciable turbidite activity to disturb the water/sediment interface, extensive flat substratum below the wave base, and low bubble generation from biogenic gas (Kelts and Hsü, 1978). These conditions are confirmed by the sequence described and jointly contributed to good rhythmite preservation.

A second well, Tartagal (St. Ta. x-2), located between the sites described, was also used. Here, the Tarija Formation rests unconformably on the Tupambi Formation and

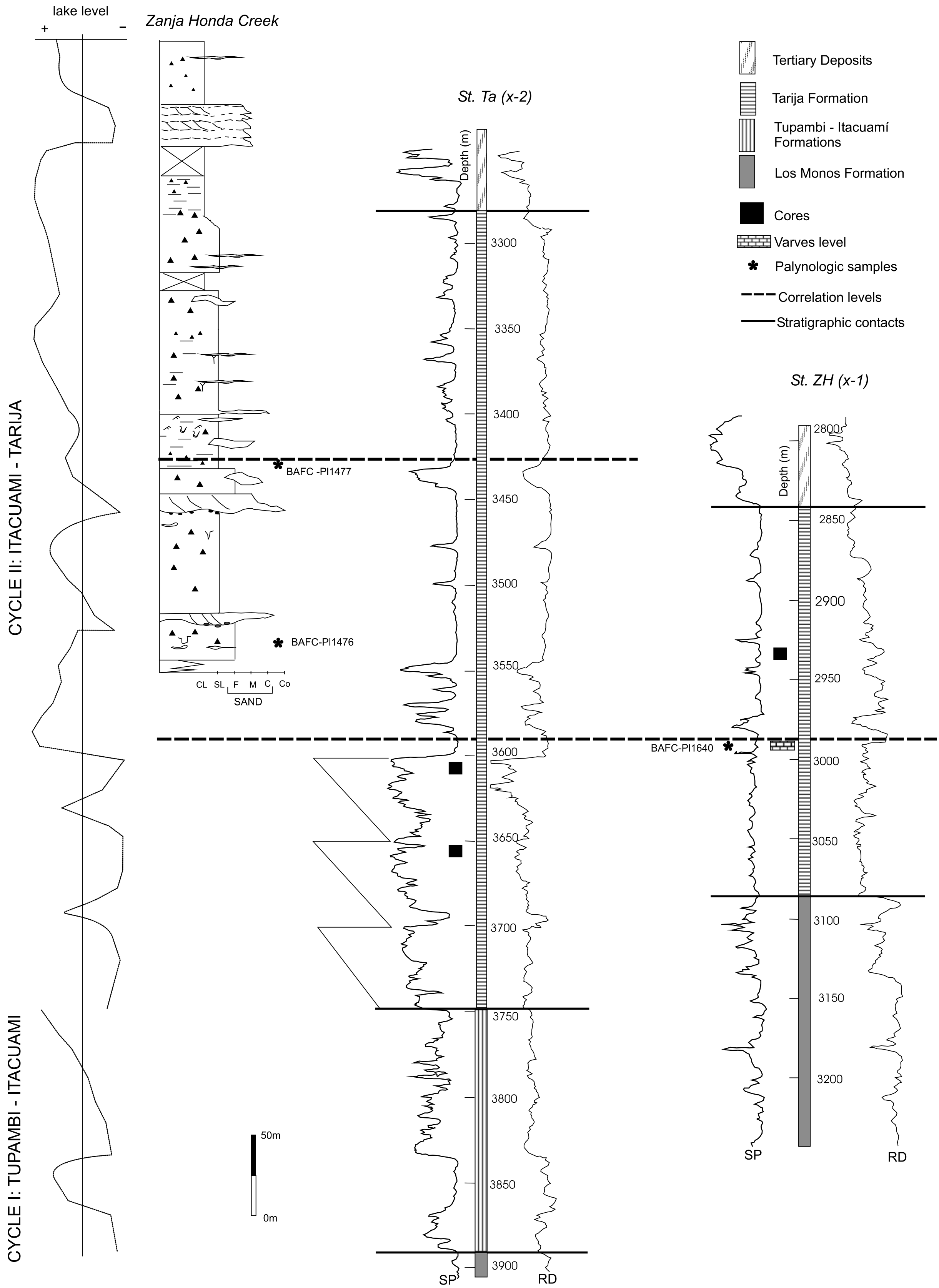

Fig. 10. Correlation proposed for the southern portion of the Tarija Basin based on paleoenvironmental analysis and biostratigraphic position of palynologic levels, according to di Pasquo (2003).

passes, also in disconformity, to the Escarpment Formation (Mandiyutí Group) (Fig. 10). The first thick pelitic level resting on the base sandstones serves as the correlation level between the well logs, according to the concepts of sequence stratigraphy (Van Wagoner et al., 1990). This level is very conspicuous in the basin, as is a common horizon of correlation (see also Schulz et al., 1999; Starck et al., 2002). In well ZH x-1, it corresponds to the varves level, which lies on a basal heterolithic sequence. Thus, the process of flooding suffered by the basin is evident in the correlation. This rise in base level would account for the generation of necessary conditions for the preservation of varvic lamination.

Under and toward the base of the well log St. Ta. x-2, the Tarija Formation begins with a succession of sandstones consisting of three stacking cycles, evident in the SP profile, with a prograding pattern on the finer levels (Fig. 10). Cores 1 and 2, taken from 3610 to 3613 and 3664 to 3665 m, respectively, reveal the presence of well-selected, fine, cross-bedded sandstones, with flaser and ripple marks toward the top of the beds. The clasts consist of quartz, feldspars, biotites, muscovites, and abundant woody material. To the SE in well St. ZH x-1, this section is represented by heterolithic facies (see SP design in Fig. 10), which rest directly on the Devonian substratum. This lateral relationship is consistent with the deepening of the basin in this direction. The sandstone section is equivalent to those found, especially in the subsurface, and named "Areniscas Palmar" by Fernández Garrasino (1978) who, with an analysis of thickness variations, points to their wedging or thinning to the north and northeast of the basin. Coarse to medium, massive and stratified diamictites interbedded with minor sandstone layers predominate above the correlation surface and toward the top of the unit in all three profiles.

Two boulder pavements designing paleochannels filled by fluvial sandstones were found in this position in Zanja Honda Creek (del Papa and Martínez, 2001). In well St. Ta. x-2, the presence of sandy beds has been interpreted as a consequence of glacier regression coinciding with the filling of the paleochannels. The proximity of the outcrops and well (15 km) allow us to consider these sandstone packets as the same level (Fig. 10). The fine deposits over the sandstone beds are interpreted as a flooding episode, employed as a second correlation level.

6. Discussion

The varve sequence here considered part of the Tarija Formation was previously interpreted as part of the Itacuamí Formation (internal YPF reports) on the basis of the pelitic composition of the levels. The paleoenvironment of the Tupambi–Itacuamí–Tarija succession has been subject to different interpretations: Fernández Garrasino (1978) and Pozzo and Fernández Garrasino (1979) find the Tupambi Formation in the Chaco–Salta subsurface and interpret its psammitic deposits as transgressions associated with littoral shoals aligned with the southern border of the basin. They consider the fine sandstones and mudstones coastal lagoons and the upper pelitic section an external platform setting.

Another paleoenvironment interpretation of the Tupambi Formation suggests deltaic systems and distributary bars, which become fluvial facies near the top. The presence of slump-produced synsedimentary deformations would be a consequence of high sedimentation rates. A probable periglacial influence has been inferred by the presence of diamictites at the base of the distributary mouth bars (López Gamundi, 1986; Starck et al., 1993a). The Itacuamí Formation mudstones are believed to have been deposited in a prodelta and shallow platform environment, associated with the deltaic deposits of the Tarija Formation (López Gamundi, 1986).

Starck et al. (1992) interpret the sandstone and mudstone sequence of the Tupambi–Itacuamí formations to be deltaic bars and lacustrine paleoenvironments, strata normally found in discordant contact on the Devonian basement. Schulz et al. (1999) propose for the Macharetí–Mandiyutí groups a cyclic filling model ruled by paleoclimatic changes related to the Carboniferous Glaciation (Carboniferous Megacycle). The Tupambi–Tarija Supercycle would be composed of an interglacial Hemisupercycle (HSC) of the Tupambi and Itacuamí formations, dominated by a fluvial setting that changed to distal fluvial, floodplain, and lacustrine facies near the top. The glacial HSC represented by the Tarija Formation is composed of diamictites with minor sandstone and mudstone intercalations of glacial and periglacial paleoenvironments in a minor amplitude advance-and-retreat context within ruling glacial conditions.

On the basis of regional subsurface studies carried out by Starck et al. (2002), as well as sedimentological and palynological evidence discussed herein, we register a stratigraphic unconformity in the deltaic-lacustrine succession that separates the Tupambi–Itacuamí cycle ("Cycle I") from the Itacuamí–Tarija cycle ("Cycle II"). The latter begins with deltaic sandstone facies, laterally associated with lacustrine mudstones (Fig. 10). Thus, two sedimentary cycles are recognized, composed of similar paleoenvironmental sediments. This similarity has led to confusion of one with the other.

Evidence attesting to this conclusion includes the following: First, the shales of Cycle I show no evidence of sedimentation from glacial processes (i.e., ice rafting, debris flows). Instead, there is evidence of glacial sedimentation in the Cycle II shales, both varve lamination and dropstones.

Second, different palynomorph associations are found in lacustrine sequences I and II. In Fortín Alegre well (FA x-1), for example, as at the base of the Tuyunti profile, di Pasquo (2002) notes Biozone *Cassispora kosankei*-*Cystoptychus azcuyi* (KA) in laminated black mudstones pertaining to Cycle I (Tupambi Formation). In addition, di Pasquo (2003) finds Biozone *Raistrickia radiosa-Apiculatasporites spinulistratus* (RS) in the outcropping sections of the Itacuamí Formation at Iquira and Tuyunti streams (Sa. Aguaragüe), Tonono well (St. To x-1) in the Argentine portion, and the Balapuca profile and southern portion of Bolivia (Fig. 1).

Third, no fossil traces were found in lacustrine Cycle I, whereas in lacustrine Cycle II, Buatois and del Papa (2003) identify *Diplopodichnus biformis*, *Diplichnites gouldi* concerning *Mermia* ichnofacies.

Fourth, in the levels studied herein (Fig. 6A), corresponding to Biozone BC, species such as *Crassispora kosankei*, *Cristatisporites rollerii*, *Cystoptychus azcuyi*, and *Schopfipollenites ellipsoides*, as well as others that might correspond to Biozone RS (e.g., *Raistrickia radiosa*), are recorded for the first time. Because they are found in a reworked diamictite, erosive episodes may have obliterated part of the underlying Cycle I deposits (Tupambi–Itacuamí Formation). Thus, the stratigraphic value of the species recognized as exclusively Biozone KA forms (di Pasquo, 2003) is maintained by our findings.

Fifth, on the basis of the sedimentary record that reflects glacier dynamics and the diversity of plant groups recognized from the palynomorphs, it appears that Tarija glaciers were temperate. The development of conspicuous vegetation, especially during the interglacial period, reflects an increase in humidity, with sphenophytes associated with a riverside paleoenvironment, lycophytes colonizing the margins of more stable water bodies, and algae attesting to a lacustrine setting (Fig. 6A). The pteridophyte spores and gymnosperm pollen grains represent somewhat higher mesophilic paleoenvironments, which coincides with the abundant reworked material supplied by the erosion of elevated areas composed of strata older than Late Carboniferous (Westphalian). Therefore, a humid, temperate paleoclimate, corresponding to a glacial retraction period, is interpreted at least for levels BAFC-Pl 1476 and 1477 of the Zanja Honda profile; the varves point to well-defined seasons with cold winters in a glacial period, in which glaciated lands on the surroundings of the depocenter may be the main cause of a decrease in the amount of indigenous palynomorphs. Nevertheless, as we stated previously, the scarcity of sampling and taphonomic processes affecting palynomorphs could be good explanations of their scarcity in the varves section. More information is needed to recognize the weight of paleoclimate over other processes in influencing the development of the flora at this time.

Sixth, consequently Cycle II began with fluvial–deltaic deposits laterally related to sandstones and mudstones of lakes of possibly shallow water (Lowstand stage). The fluvial system is later overlapped by inner lake mudstones (Transgressive and Highstand stages). This rise of the base level is noticeable in large parts of the basin and could be related to the glacial regression; it also coincides with a relative rise of the sea level on a global scale, which affected the basins during the Late Carboniferous (Golonka and Ford, 2000).

7. Conclusions

The combined sedimentological, palynological, and stratigraphic studies carried out in a portion of the Tarija Basin in Argentine enable us to:

1. Define two superposed sedimentary cycles with similar sedimentary paleoenvironments—Cycles I and II—separated by an unconformity, where both cycles correspond to the Macharetí Group in the Tarija Basin.
2. Note that Cycle I is formed by the Tupambi–Itacuamí (late Namurian) and Cycle II by the Itacuamí–Tarija (Westphalian) formations. Each cycle shows distinct sedimentary and palynological characteristics.
3. Identify varve deposits in the Tarija Formation for the first time, thus reinforcing the theory of at least a temporary lacustrine origin for this unit.
4. Offer the initial discovery, in Zanja Honda creek, of the following indigenous species of the Tarija Basin: *Knoxisporites stephanophorus*, *Verrucosisporites morulatus*, *Cristatisporites* sp. cf. *Bascaudaspora canipa*, *Apiculatisporis* sp. cf. *A. variornatus*, *Retusotriletes nigritellus*, *Microreticulatisporites punctatus*, *Apiculiretusispora tuberculata*, *Didecitriletes ericianus*, *Rugospora cortaderensis*, and *Foveosporites hortonensis*, most frequently recorded in Late Carboniferous associations of Argentina and Brazil.

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