PERGAMON

Journal of South American Earth Sciences 15 (2002) 553–569

Journal of
South American
Earth Sciences

www.elsevier.com/locate/jsames

Sedimentary facies and palynofacies assemblages in an Eocene perennial lake, Lumbrera formation, northwest Argentina

C. del Papa[a,*], V. García[b], M. Quattrocchio[b]

[a]*Facultad de Ciencias Naturales, CONICET: Universidad Nacional de Salta, Casilla de Correo 24-Correo Central, Buenos Aires 177, 4400 Salta, Argentina*
[b]*CONICET: Universidad Nacional del Sur, San Juan 670-8000 Bahía Blanca, Argentina*

Received 1 July 2001; accepted 1 December 2001

Abstract

The combined application of sedimentary facies and palynofacies analyses constitutes a valuable method for paleoenvironmental and paleoclimatic reconstructions, especially in continental strata in which fossil information is scarce or absent. In this paper, we present an integrated model based on this methodology for the Eocene lacustrine rocks of the Lumbrera Formation in northwest Argentina. The new data contribute to the understanding of the evolution of the final post-rift stage of the Salta Group in northwest Argentina.

The lacustrine deposits of the Lumbrera Formation are named Faja Verde I and Faja Verde II. In the Alemanía area, the Faja Verde II consists of green claystones and mudstones interbedded with sandstones and deposited in a perennial lake and fluvio-dominated delta complex. In addition, there are two major cycles that are separated by a flooding surface. The basal cycle is a retrogradational parasequence set, and the upper cycle is a progradational parasequence set. The palynofacies analysis and organic matter analytical data (TOC and Pyrolysis Rock-Eval) of each sedimentary facies are closely related to the dynamics of the depositional environment. Proximal prodelta (Palynofacies association I), distal prodelta (Palynofacies association II), lacustrine (Palynofacies association III), and interdistributary bay fill (Palynofacies association IV) subenvironments are differentiated. Each is characterized by a definitive relationship of phytoclasts, amorphous, palynomorphs, fluorescence index, quality, and quantity of the organic matter. The variation of occurrence of the *Pediastrum–Botryococcus* algae reflects fluctuations in the level of water related to identified cycles of shallowing.

Keywords: Lacustrine; Palynofacies; Organic matter; Eocene; Lumbrera formation; Northwest Argentina

Resumen

El uso combinado del análisis de facies sedimentarias y palinofacies brinda una herramienta válida para las reconstrucciones paleoambientales y paleoclimáticas de una cuenca, especialmente en secuencias continentales donde la información a partir del registro fósil es escasa o está ausente. En este trabajo se presenta un modelo sedimentario que surge de la integración de ambos métodos llevado a cabo en las rocas de origen lacustre de la Formación Lumbrera en el noroeste argentino. Finalmente los nuevos datos contribuyen al conocimiento general sobre la evolución del estadio final de post-rift del Grupo Salta en el noroeste argentino.

La Formación Lumbrera (Eoceno) argentino presenta en su tercio inferior una intercalación de depósitos lacustres, denominados Faja Verde I y Faja Verde II. En la localidad de Alemania la Faja Verde II, está formada por arcilitas y limolitas verdes y grises, con intercalaciones de areniscas, depositados en un lago perenne y delta fluvio-dominado. Se reconocieron dos ciclos estratigráficos mayores separados por una superficie de inundación. El ciclo basal formado por parasecuencias con arreglo retrogradante y el superior integrado por parasecuencias progradantes. El análisis de palinofacies y los datos analíticos de materia orgánica (COT y Pirólisis Rock-Eval) de cada facies sedimentaria identificada, está en estrecha relación con la dinámica del ambiente deposicional. Se diferenciaron los siguientes subambientes: Prodelta proximal (asociación de palinofacies I), Prodelta distal (asociación de palinofacies II), lacustre (asociación de palinofacies III) y bahía interdistributaria (asociación de palinofacies IV) cada uno caracterizado por una determinada relación de fitoclastos, amorfos, palinoformos, índice de fluorescencia, calidad y cantidad de la materia orgánica. Ha sido observado que las variaciones en la relación de las algas *Pediastrum–Botryococcus* reflejan fluctuaciones del nivel de agua relacionadas con los ciclos de somerización identificados.

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[*] Corresponding author. Tel.: +54-387-425-5386; fax: +54-387-439-4020.
E-mail addresses: delpapac@unsa.edu.ar (C. del Papa), delpapac@aol.com (C. del Papa), vmgarcia@criba.edu.ar (V. García), mquattro@criba.edu.ar (M. Quattrocchio).

PII: S0895-9811(02)00081-0

1. Introduction

During the Cretaceous and Paleogene, an intracontinental rift basin developed in northwest Argentina. Mainly continental sedimentary rocks accumulated in the basin and have been designated the Salta Group. This Group has been described by Salfity (1980, 1982, 1985), Gómez Omil et al. (1989) and Salfity and Marquillas (1994, 1999), and others. During the Paleogene, an extensive sag basin developed. These deposits were named the Santa Bárbara Subgroup (Moreno, 1970), which is made up of the Mealla, Maíz Gordo, and Lumbrera Formations.

The Lumbrera Formation is the thickest formation in the Santa Bárbara Subgroup, ranging from 300 to 450 m, and represents the end of the sedimentation of the Salta Group depositional cycle. The depositional environment defined for the Lumbrera Formation includes proximal to distal meandering river systems and lakes (del Papa and Salfity, 1999). The lacustrine system is interpreted to be of regional extent with predominantly clastic sedimentation and organic rich shales. The lacustrine deposits have been identified informally as the 'Faja Verde' by Hagerman (1933) and have chronostratigraphic value (Cazau et al., 1976). This sequence could be correlated with the *Tricolpites*(*Psilatricolpites*) *lumbrerensis* Zone, as well as with the Informal Climatic Zones (ICZ) of temperate-humid and of Eocene age (Quattrocchio et al., 2000).

In the Alemanía area, two levels of green, fine-grained sediments of lacustrine origin interbedded in the Lumbrera Formation have been recorded, the lower one named 'Faja Verde I' (Carbajal, 1974) and the upper one called 'Faja Verde II'. The first lacustrine episode is restricted in area, and its water system was holomictic. The second lacustrine episode has a regional spread and represents a deeper lake. Its thickness ranges from 20 to 40 m. Recently, del Papa (1999) pointed out that the two Fajas Verdes represent a unique lacustrine event that developed through time in a complex way. The Faja Verde has provided diverse palynomorphs studied by Quattrocchio (1978a,b) and Quattrocchio and Volkheimer (1990).

This paper summarizes work carried out in Faja Verde II of the Lumbrera Formation in the Alemanía section. This area is situated 100 km south of Salta City and is part of the Valle de Lerma in the Cordillera Oriental region (Fig. 1). The objective of this work was to establish the relationship between the sedimentary environment and subenvironments and the palynofacies types and thereby to propose an integrated model. In contrast with palynostratigraphical analysis, which uses the palynomorph content of a rock sample to determine its age, palynofacies analysis deals with the total acid-resistant organic residue. Integration of sedimentary facies data with palynofacies interpretations can be used to determine the environment of deposition. An understanding of the sedimentary context of a particular palynofacies is therefore essential if an environmental interpretation is to be more than broadly based (Batten, 1987, p. 12). To introduce the information and for description purposes, the palynofacies are presented in each sedimentary facies association; however, a final consideration about the palynological results are discussed

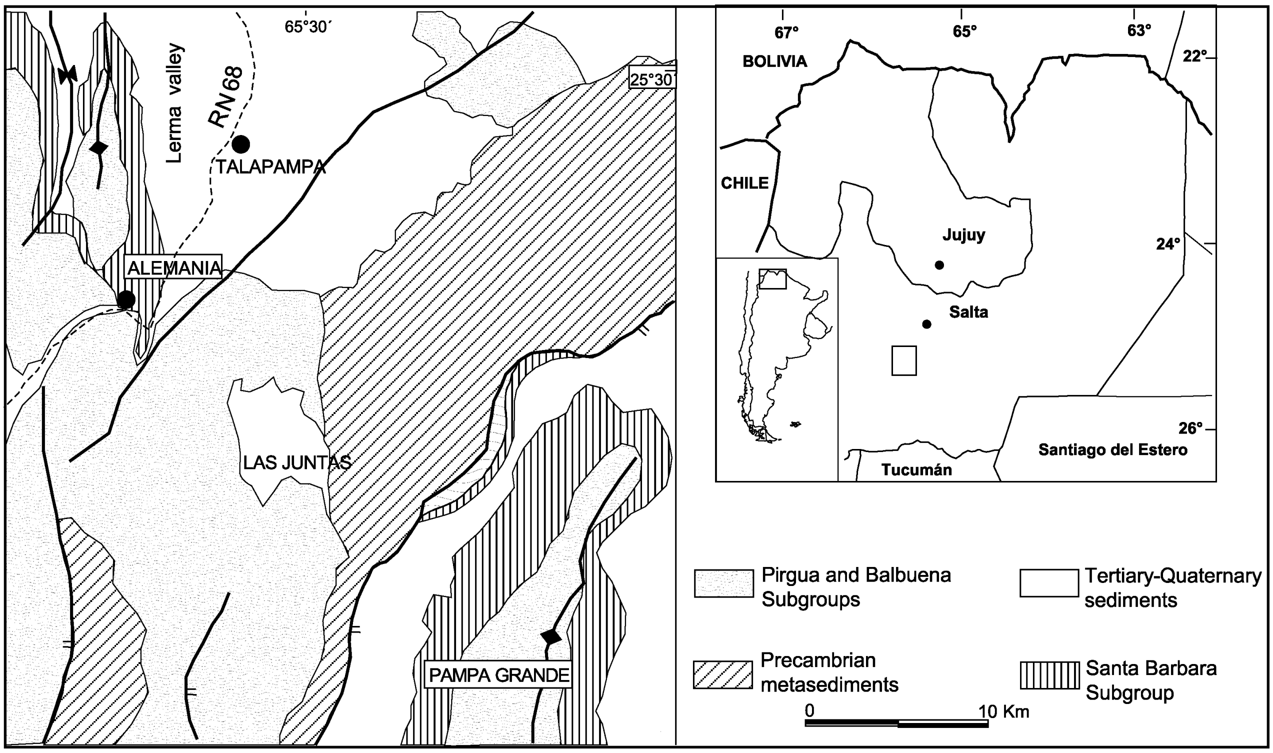

Fig. 1. Location map.

Table 1
The main criteria used for describing and classifying amorphous organic matter according to Tyson (1995, Table 20.2, p. 352)

Property	Lustre			Color			Heterogeneity (in white light)				Heterogeneity (under fluorescence)		Form and relief (under fluorescence)			
Characteristic	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Description	Hyaline	Glossy	Matt	Yellow–orange–red	Orange brown	Grey to grey brown	Homogeneous	With small opaque speckles	Clotted, lumpy structure	With inclusions	Relatively homogeneous	Clearly heterogeneous	Flat, irregular sheets	Irregular with crystal imprints	Granular to spherulitic	Pelletal
Palynofacies/ samples																
12			×			×			×			*		×		×
11		×	×	×	×		×		×	×		*	×			
10B			×	×	×	×			×	×		*				
10		×	×		○	×			×	×		*	×			
9	○	×	×	×	×		×		▨	×	*		×			
8B	○	×	×	×	×		×		▨	×	*		×	×		
8		×	×		×	○			▨	×		*		×		
7			×	×	×	○			×	×		*	×			
6			×	×	×	○			○		*	*	×			
5		○	▨	×	×	○			▨	×		*			×	×
4			▨	▨		○			×	×		*	×		×	
3		○	▨	×		○			×	×		*			×	
2			▨	○	○	▨			×	×		*			▨	
1			▨		×	○			×	×		*			×	

Property	Form and relief (under fluorescence)				Cohesiveness		fluorescence characteristics (green–yellow colours)				Pyrite content			Typical association		
Characteristic	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
Description	Rounded, bead-like	Rounded, low relief grains	Globular and fluffy	Relatively angular laths	Forms coherent particles	Tends to disintegrate finely dispersed	Particle matrix no fluorescent	Particle matrix weak-moderate fluorescence	Particle matrix strong fluorescence	Uniformly highly fluorescence	Pirite inclusions absent	Pirite inclusions rare	Pirite inclusions abundant	Kerogen phyt./ spormorphs dominated	Kerogen assemblage mixed	'AOM' dominated kerogen assemblage
12					○	▨	*				*					
11		×			○	▨	*				*			*		
10B			×		×	×		*				*				*
10			×		×	×		*				*				*
9			×		×	×			*		*					*
8B			×		×	×			*		*					*
8			×		×	×			*							*
7			×		×	▨		*			*					*
6			×		×	▨		*			*					*
5			×		×	▨		*			*					*
4			×		×	▨		*			*					*
3			×		○	▨		*			*					*
2			▨		○	▨		*			*					*
1			×		×	▨		*			*					*

▨: abundant; ×: common; ○: rare; *: present.

Table 2
The main criteria used for describing and classifying phytoclast particles. The criteria used are those presented by Tyson (1995) in Table 20.4, p. 350

Property	Edge translucency		Translucent colors		Fluorescence			Microstructure					Form/symmetry						Angularity			Outline				Size	
Characteristic	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
Description	Opaque	Translucent	Orange–brown	Yellow	Moderate strong	Weak	Absent	One cell	Several cell	Pits-ribs	Fibrous	None	Acicular	Laths	Equant	Planar	Irregular	Thin	Angular	Rounded	Irregular	Sharp	Frayed	Corroded	Pseudo-amorphous	Variable	Smaller than other phytoclast
Palynofacies/samples																											
12	○	▨	▨				×			▨	▨	×			×		▨			○	▨			▨	×	×	×
11	○	▨	▨				×			▨		×				▨			×		×			▨	×	×	×
10B	○	▨	▨				×					×		○	○		▨		×		×		×	▨	○		
10	×	×	×				×			×		×					▨				×			×	×		
9	○	×	×				×							×	×				×	×			×	×	×	×	
8B	×	▨	×				×					×					×						×	×	×		
8	○	▨	×						×	×	▨						×		×				×	×	×		
7	×	×	×							×	×	▨			×		○						×	×			
6	×	▨	▨	×						▨	▨			○			×				×		▨	▨	×		×
5		×	×	×		×			▨	▨	▨						×				▨		▨	▨	×		
4	×	▨	▨	×						▨	▨			×			×		×	×	▨		▨	▨	×		
3	○	▨	▨	○			×			○	○			○						×	×			▨	×	×	
2	○	▨	▨				×			×	×						×							▨	×		
1	○	▨	×	×			×					×					×		×		×			▨	×		×

▨: Abundant; ×: Common; ○: Trace.

separately. In addition, information about hydrogen and carbon richness is provided by the total organic carbon (TOC) and Pyrolysis Rock-Eval analyses.

2. Material and methods

Fieldwork included sedimentological and palynological sampling of Faja Verdes II at the Alemanía section. The excellent outcrops show a complete transition between marginal and central deposits and oxic–anoxic cycles. Sedimentary facies and facies association were identified to determine the environment and subenvironments, whereas total and clay-fraction X-ray diffraction analyses were made to identify the mineralogical composition. The analyses were performed on RIGAKU D/Max.-IIC (2.0 K) equipment, LANAIS-Universidad Nacional de Salta.

Physical and chemical extraction of the 14 stratigraphical samples was performed using standard palynological processing techniques (Volkheimer and Melendi, 1976), which involve treatment with hydrochloric and hydrofluoric acids. No oxidation by nitric acid was performed because it affects the fluorescence of the hydrogen-rich particles. Between 20 and 30 g of the sample were weighed, and five tablets of *Lycopodium* sp. (containing 11.267 spores each) were added to determine the pollen concentration. The mounting medium used to prepare the palynological slides was NOA 61 (Norland Products Incorporated, USA), which appears to be the best medium for fluorescence work because it provides a dark green background. Slides were systematically examined in normal transmitted and incident blue light to identify the palynofacies (Combaz, 1980). Observation of the samples in blue light fluorescence is very helpful in classifying the nature of unoxidized, thermally immature to mature oil source rocks.

The comparative observations are based on a standard magnification (i.e. × 20). Under transmitted and fluorescent light, the palynofacies content comprises three categories of organic matter: palynomorph, phytoclast, and amorphous (Tyson, 1995), according to Tyson's qualitative preservation scale (1995, Table 20.2, p. 347). The scale is based on the apparent, visually assessed, relative fluorescence intensity, as well as partly on the fluorescence color of unoxidized, immature kerogen. The main criteria used for describing and classifying amorphous particles are presented in Table 1 and those for the most common types of phytoclasts in Table 2. The criteria used are given by Tyson (1995) in Tables 20.2 (p. 352) and 20.4 (p. 350). The probable origin of the amorphous matter and phytoclast types recognized by white and blue light fluorescence are provided in Tables 3 and 4 (Tyson, 1995, pp. 351 and 353).

The TOC of eleven samples and Rock-Eval Pyrolysis of six selected samples were performed in SPT-Synergic Petroleum Technologies S.A. Laboratory, Buenos Aires. Not all rocks were analyzed because of the low organic content visually observed in many hand samples.Petroleum source

Table 3
Important common types of amorphous organic matter recognized in transmitted white light and incident blue light fluorescence (Tyson, 1995 in Table 20.7, p. 353)

Characteristics	Probable origin
1–2, 4–5, 7, 11, 17/20, 21, 26, 27, 30	Resin particles
2, 4–5, 8–10, 12, 15/16/19, 21, 24–25, 28–29, 31–32	Well-preserved plankton/ bacterial-derived 'AOM.'. Varies with actual source and preservation state
3, 6, 8–10, 12, 13–14, 22 > 21, 23, 27–28, 30–32	Degraded plankton/bacteria-derived 'AOM'
3 > 2, 4–5, 7, 11, 18, 21, 23, 27–28, 30	Liberated particles of cell-filling gels (e.g. corpo-huminites, often from root or bark material)
2, 4–5, 7, 11, 13, 21, 25, 26, 27–29, 32	Well-preserved bacterial mat 'AOM'

rocks are evaluated according to their carbon richness by TOC in weight percent (wt%) and their hydrogen richness or quality using Rock-Eval Pyrolysis. The latter method provides several measurement parameters: $S1$, $S2$, $S3$, T_{max}, and HI. $S1$ represents the milligrams of hydrocarbons that can be thermally distilled from one gram of rock (mg HC/g rock). $S2$ represents the milligrams of hydrocarbons generated by pyrolythe degradation of the kerogen in one gram of rock (mg HC/g rock). $S3$ represents the milligrams of carbon dioxide generated from one gram of rock during temperature programming up to 390 °C (mg CO_2/g rock). The hydrogen index (HI) corresponds to the quantity of pyrolyzable hydrocarbon (HC) from $S2$ relative to the TOC (mg HC/g C_{org}) in the sample. T_{max} is the temperature at which the maximum amount of $S2$ hydrocarbons is generated.

In levels with low organic carbon content, the palynofacies studies contribute information about the origin of organic matter and the degradation processes.

3. Palynofacies analysis

A palynofacies is 'a body of sediment containing a distinctive assemblage of palynological organic matter thought to reflect a specific set of environmental conditions, or to be associated with a characteristic range of hydrocarbon-generating potential' (Tyson, 1995). In addition, palynofacies analysis is 'the palynological study of depositional environments and hydrocarbon source rock potential based upon the total assemblage of particulate organic matter' (Tyson, 1995).

Each sedimentary facies is characterized by its palynological organic matter content (amorphous organic matter, phytoclasts [translucent and opaque], and palynomorphs) as recognized in transmitted white light and incident blue light fluorescence. Organic matter is transported similarly to detritus grains. Thus, the results of a particulate organic matter study should be correlated with the results of a sedimentary study.

The degree of alteration of the palynological assemblages can be evaluated by examination of the state of preservation of palynomorphs in sediment samples ('deterioration classes', Delcourt and Delcourt, 1980). The following criteria are used to characterize palynological results:

- Biological provenance of the particles;
- Uniformitarianism, or the high degree of correspondence between the fossil algae and modern freshwater algae that strengthens the degree of certainty of the taxonomic and ecological relationships for each individual taxon (Zippi, 1998); and
- The ecological diagnosticity of the species (e.g. *Pediastrum* vs. *Botryococcus*)

For example, *Pediastrum* prefers higher nutrient loading. Thus, a change in the trophic state of a lake from oligotrophic to eutrophic usually results in a decrease of the *Botryococcus*:*Pediastrum* ratio. Salinity appears to be a significant factor, with *Botryococcus* being euryhaline and *Pediastrum* stenohaline.

Prolonged oxidation of organic matter lowers the hydrogen content and decreases both autofluorescence and source rock potential, prior to its complete destruction (Livingstone and Melack, 1984).

Two other criteria are used to characterize palynological results:

- Any recognizable difference in the degree of organic maturation of any particle species within the assemblage (correlation between fluorescence preservation scale and hydrogen index), pyrolysis (TOC, $S1$, $S2$, $S3$), and the amorphous organic matter characterized under incident blue light, and
- Fluorescence properties, which are affected by the state of preservation and the source of organic matter. The level of fluorescence exhibited by the matrix of 'AOM' particles is generally constant within any sample and reflects the general redox status of the depositional environment (Tyson, 1995).

4. Sedimentological and palynological analysis

The Alemanía section of the Faja Verde II is 18 m thick. It is characterized by clastic sedimentation and from fine- to medium-grained sandstones with siltstones, mudstones and shales. Limestones and evaporitic layers have not been recorded in the Alemanía section, but discrete levels of stromatolites were observed in lateral positions. The depositional environments vary from delta to inner lake, including all the transitions between them (Fig. 2).

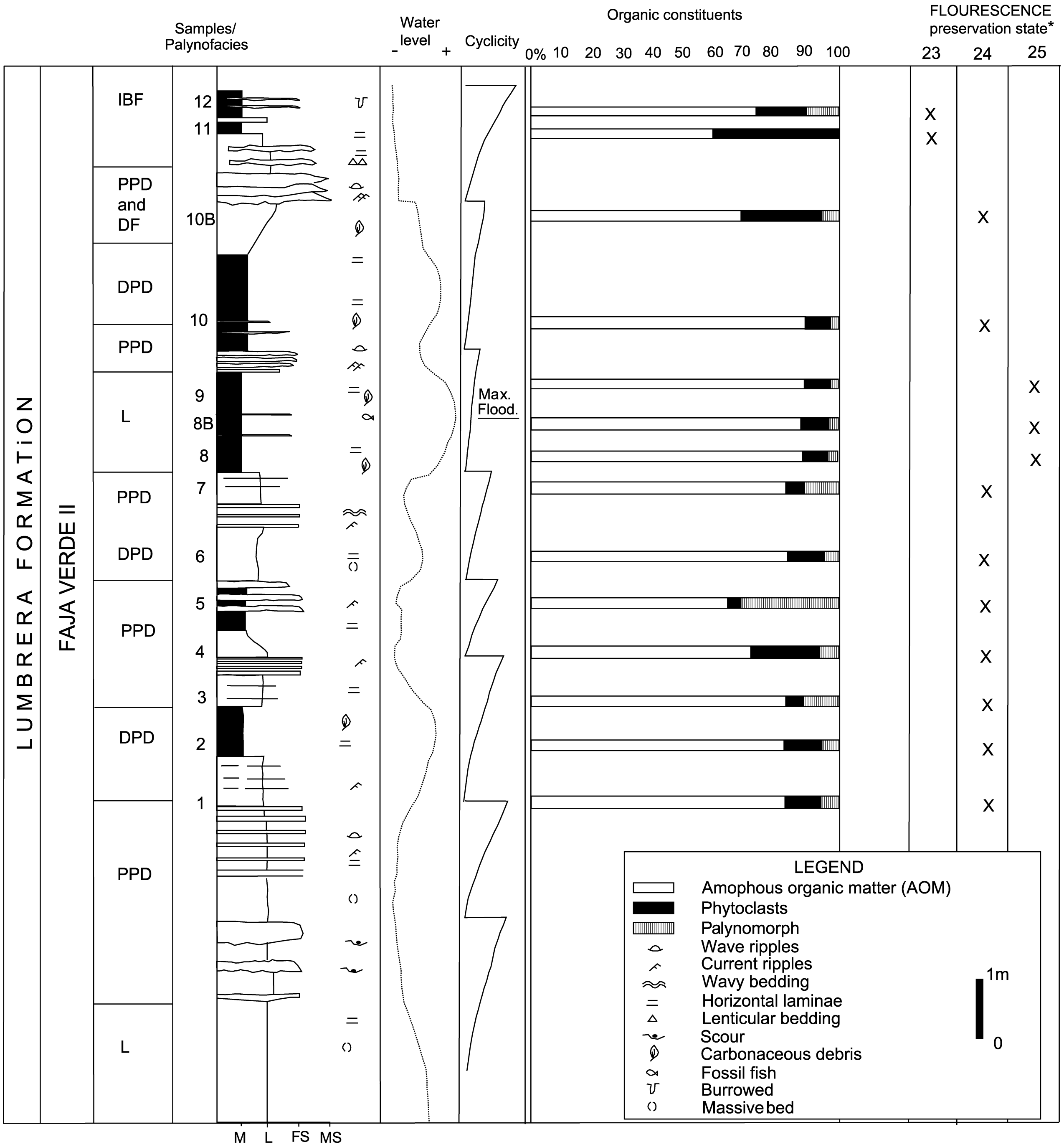

Fig. 2. Stratigraphic section showing the inferred water level fluctuation, cyclicity, organic constituents, and fluorescence of each sample. L: lake, PPD: proximal prodelta, DPD: distal prodelta, DF: delta front, and IBF: interdistributary bay fill. (*) Preservation state according to Tyson (1995).

Using sequence stratigraphy, a fourth-order cyclicity has been established by field observation. It constitutes two major cycles, the first with a retrogradational pattern of parasequences and the second with a progradational pattern. A flooding surface divides both cycles and represents the maximum depth of the lake at Alemanía (Fig. 2).

The sedimentary facies were grouped into the following four main facies associations to differentiate the sedimentary processes and organic matter contents.

4.1. Proximal prodelta facies association; palynofacies association I (Fig. 2)

Heterolithic levels composed of medium to fine sandstones and mudstones characterize this facies association. The sandstone layers are feldspathic arenite and tabular with broad erosive bases. Parallel lamination (Sh) and climbing ripples (Sr) of type A (Jopling and Walker, 1968) and linguoid in plane view are the common structures. Fine levels

Table 4
Important common phytoclast types recognized in transmitted white light and incident blue light fluorescence (Tyson, 1995 in Table 20.5, p. 351)

Characteristics	Probable origin
1, 7, 10, 14, 19 > 20/21, 22, 26	Carbonized tracheid debris
1, 7, 10, 14–15, 19–20, 22, 24, 26–27	Worn and transported oxidized or carbonized wood
2, 3, 7, 10, 14, 19, 22, 26	Tracheid (wood) debris
2, 3, 7, 12, 14/17, 19–21, 22–25, 26	Gelified plant tissue
2, 3, 7, 9, 14/15/17, 21, 23, 26	Poorly lignified cortex tissues
2, 4 > 3, 5, 8, 16–17, 19, 22, 26	Cuticle (epidermal tissues)
2, 4, 5–6, 12, 16–17, 19, 22/24, 26	Membranous material (often degraded cuticle)
2, 3, 7, ±8, 18, 22, 27	Fungal hyphae
2, 3, 6, 12, 14–17, 19–21, 24–25, 26	Poorly lignified tissues bacterially modified under subaqueous reducing conditions

of mud (Fm) drape the sandstone layers. The mudstones layers (Fl) are interbedded with siltstones and very fine sandstones. Fl facies are moderate yellowish brown and pale olive and constitute a rhythmic deposit. Each couple consists of clear and dark laminae. The clear laminae have a mean thickness of 6 mm and are formed by clay minerals. The dark laminae have a mean thickness of 3 mm and are integrated by coarse siltstone with muscovite laminae. The Fm facies are yellowish gray and have common oxic motling and organic matter remains. Both Fl and Fm facies are integrated by detrital quartz, feldspar, and muscovite. The clay minerals are illite and kaolinite in lower proportions. Analcime is the common diagenetic mineral. Trace-fossils and vertical and subvertical burrows in sandstone layers and different kind of trails in mudstones layers are quite frequent in this facies association. These rocks are characterized by a low percentage of organic matter. The TOC value varies between 0.17 and 0.45% (Table 5).

The palynofacies association I consists of palynofacies 1, 3, 4, 5, 7, and 10B (Fig. 2). Amorphous organic matter (Table 1) varies from 65% in palynofacies 5 to 85% in palynofacies 1, 3, and 7. They are dominated by finely dispersed, membranaceous or spongy, granular to spherulitic, amorphous organic matter. It shows weak to moderate fluorescence, orange to pale orange color, and scale point 4 (Tyson, 1995). Scale point 4 is commonly equivalent to Type II kerogen. The probable origin is degraded plankton or bacterially derived AOM. The presence of incompletely altered remains enables the determination of subordinate amorphous matter of land-plant origin (Table 3, Figs. 3 and 4A and B).

The phytoclasts vary from 5% in palynofacies 7 to 25% in palynofacies 10B (Fig. 2). Abundant translucent phytoclasts are orange-brown or dark brown and structured or structureless. Scarce opaque phytoclasts consist of black or almost black equidimensional structureless material (Table 2). The probable origins, according to the abundance of phytoclasts, are worn and transported oxidized or carbonized wood, tracheid (wood) debris, gelified plant tissue and poorly lignified cortex tissues, fungal hyphae, cuticle, and degraded aqueous plant material (Table 4).

The palynomorphs vary from 5% in palynofacies 1, 4, and 10B to 30% in palynofacies 5 and are *Smilacipites saltensis* (Quattrocchio, 1980), *Pediastrum* and *Botryococcus* (fresh water algae), fungal spores, algal filaments, and circular bodies (of algal origin?). Palynofacies 5 is characterized by the relatively high frequency (30%) of *Botryococcus* with degraded masses of this alga. In palynofacies 3 and 7, the increase of *Pediastrum* is associated with an increase in the abundance of palynomorphs (*S. saltensis* in palynofacies 3)

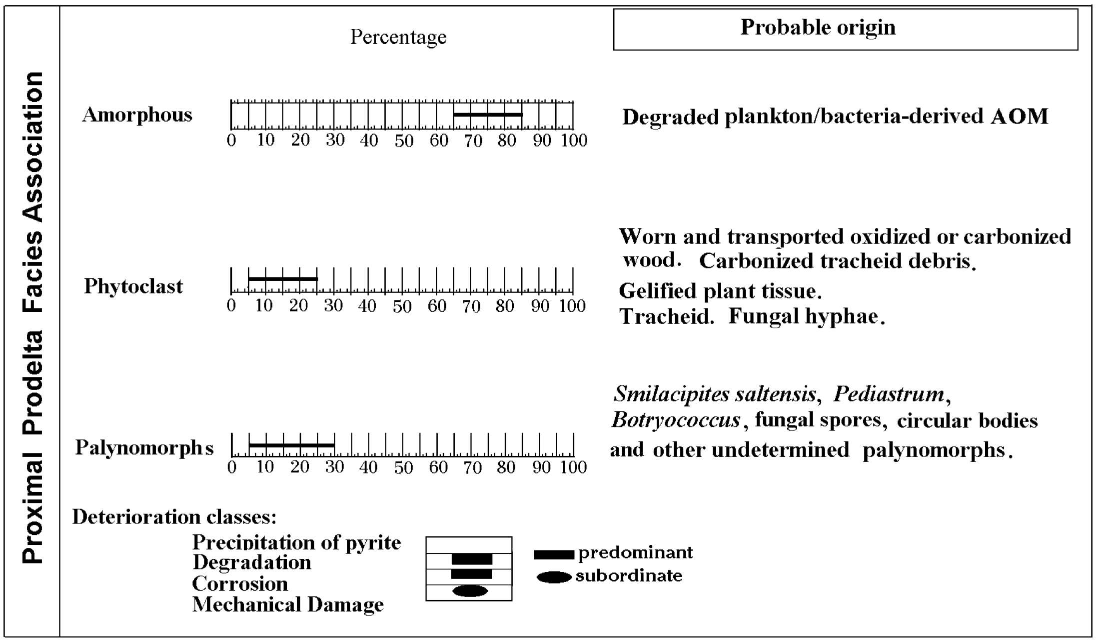

Fig. 3. Palynofacies association I.

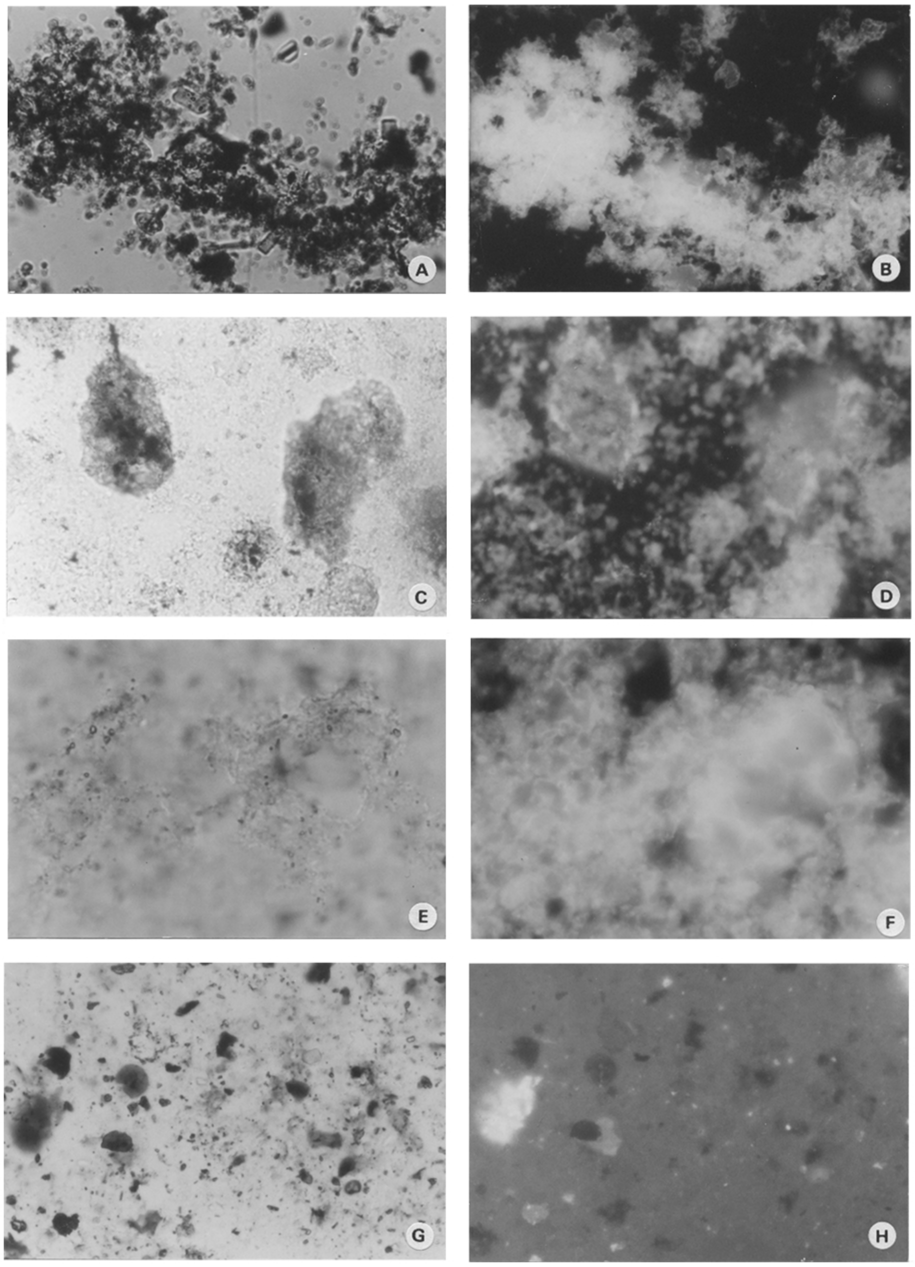

Fig. 4. (Magnification 400 ×). (A and B) Sample M3. Clotted and lumpy amorphous organic matter with inclusions and amorphous finely dispersed. (A) Seen in transmitted white light. (B) Seen under incident blue light fluorescence. Membranaceous and spongy AOM shows moderate fluorescence, yellow to orange, scale point 4. (C and D) Sample M10. Spongy, granular to spherulitic and finely dispersed AOM. (C) Seen in transmitted white light. (D) Seen under incident blue light fluorescence. It shows moderate fluorescence and yellow to grey-green fluorescing colors, scale point 4. (E and F) Sample M8b. Spongy, granular to spherulitic amorphous organic matter. The amorphous matter is deformed and imprinted by the growth of analcime crystals as craters in the kerogen. (E) Seen in transmitted white light. (F) Seen under incident blue light fluorescence. Well-preserved AOM shows strong green yellowish fluorescing colors, scale point 5. (G and H) Sample M11. The amorphous matter consists of abundant finely dispersed material and lower proportion of clotted and lumpy structure. (G) Seen in transmitted white light. Notice the presence of fungal spores and small phytoclasts. (H) Seen under incident blue light fluorescence. The particle matrix is not fluorescent (scale point 3).

and phytoclasts (in Palynofacies 1, 4, and 10B; Fig. 2), which indicate fluvio-deltaic influence. *Pediastrum* and circular bodies (algae?) often occur together in these samples. The predominant modes of pollen grain deterioration are degradation and corrosion, and the mechanical damage is subordinate.

The facies association suggests that the plume of sediments entered into the lake as stratified inflows. The fine sandstones and coarse silts were deposited by density underflow, whereas the mudstones settled down from overflow and interflow during periods of calm water. The massive beds and trace fossils are indicative of organic activity. The cleaner cross-bedded sand (Sh, Sr) represents depositions that are closer to distributary-mouth bars in the

Table 5
Analytical data for samples studied (see Fig. 2 for location)

Samples/palynofacies	TOC (wt%)	$S1$	$S2$ (mg HC/g)	$S3$ (mg HC/g)	T_{MAX} (°C)	HI (mg HC/g TOC)	OI (mg CO_2/g TOC)
4	0.44						
5	0.45						
6	0.59						
7	0.17						
8	9.75	2.55	64.53	1.3	435	661	13
8B	4.25	0.61	22.73	1.93	432	534	45
9	3.93	0.92	25.21	0.83	434	641	21
10	2.04	0.28	8.54	1.32	432	418	64
10B	0.4						
11	1.66	0.66	1	1.1	439	60	66
12	1.52	0.04	1.43	0.59	444	38	38

delta front (Kanes, 1970). The underflows lose velocity in a short distance when they reach the foot bar. As a consequence, good grain gradation occurs. The frequent fluvial structures, similar to unidirectional current ripples and cross-bedding, are common in sandy fronts and prodeltas of fluvio-dominated deltas (Bhattacharya and Walker, 1992).

The palynofacies association I (Fig. 3) has been recorded in green-grey (muscovitic) siltstones (partially laminated) and laminated grey claystones (Facies Fl and Fm). The abundance of amorphous organic matter (65–85%) is characteristic of stagnant bottom conditions. The presence of algae and palynomorphs suggests a freshwater environment relatively close to the terrestrial input. The latter is supported by the presence of abundant translucent phytoclasts (5–25%). Pyrite is not present, which suggests that the environment could have been freshwater with a low concentration of sulphate.

Diagenetic processes such as degradation, corrosion, and the absence of pyrite indicate that the bottom alternated between aerobic and dysaerobic conditions. These alternations may reflect cyclic events, including cycles of deepening and shallowing (*Pediastrum* and *Botryococcus* abundance) combined with subsequent processes such as mechanical breakdown and oxidation, which led to the destruction of fossil pollen.

4.2. Distal prodelta facies association; palynofacies association II (Fig. 2)

This facies association includes shales (facies Fl), massive mudstones (facies Fm), and very fine laminated sandstones (facies Sh); it comprises heterolithic levels with mud dominance. The facies Fl are yellowish grey and pale olive, composed of poorly to well-laminated siltstones and claystones. The muscovite in siltstones is aligned and marks the lamination. The Fm facies associated with Fl are structureless; rare levels of very fine sand with starve ripples are also present (facies Sh, Sr). The mineralogical composition is analcime, quarz, feldspar, and muscovite. X-ray analysis determined the presence of illite as a unique clay. The organic content increases in comparison with palynofacies association I; the TOC values vary from 0.5 to 2.04% (Table 5).

Palynofacies association II consists of palynofacies 2, 6, and 10 (Fig. 2). Its amorphous organic matter (Table 1) varies from 85% in palynofacies 2 and 6 to 90% in palynofacies 10. It consists of finely dispersed AOM, that is, spongy, granular to spherulitic, structureless material. It is characterized by weak to moderate fluorescence, yellow to pale orange fluorescing colors, and scale point 4 (Tyson, 1995). Scale point 4 is commonly equivalent to Type II kerogen. The intensity of fluorescence and hydrogen index (HI) (Fig. 5) and TOC and $S2$ (Fig. 6, Table 5) of sample 10 also indicate the same type of kerogen. The probable origin is degraded plankton or bacterially derived AOM. In lower proportions, it is often possible to determine amorphous material of land plant origin; its affinity is estimated by the presence of incompletely altered remains and orange to red fluorescing colors (Table 3, Fig. 4C and D).

The phytoclasts (Table 2) vary from 7% in palynofacies 10 to 10% in palynofacies 2 and 6. There are abundant translucent phytoclasts of small structureless material (<10 μm). Structured phytoclasts are mainly translucent, yellow to orange, and with planar and irregular form.

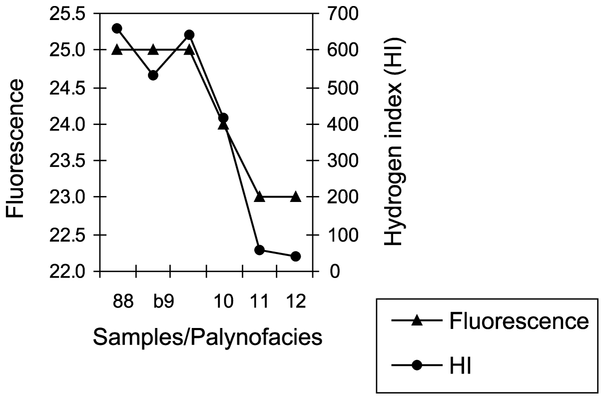

Fig. 5. Correlation between fluorescence index and hydrogen index.

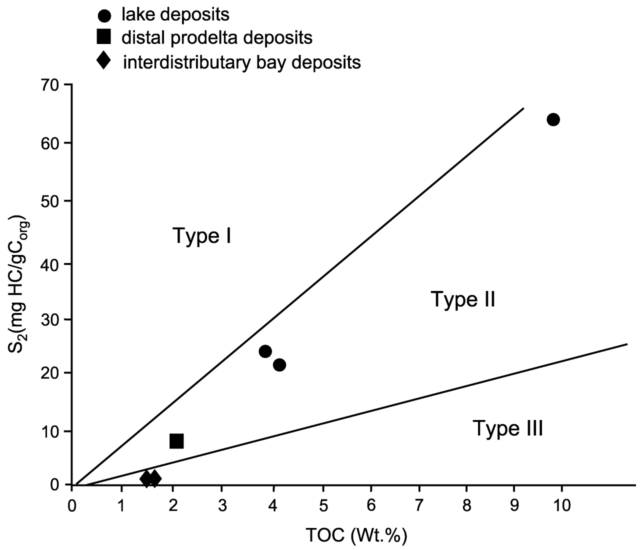

Fig. 6. TOC–S_2 diagram showing type I, II and III kerogen.

Opaque phytoclasts are less abundant. The probable origins, according to the abundance of phytoclasts, are tracheid (wood) debris, cuticle (epidermal tissues), fungal hyphae, worn and transported oxidized or carbonized wood, gelified plant tissue, and poorly lignified cortex tissues (Table 4).

The palynomorphs vary from 3% in palynofacies 10 to 5% in palynofacies 2 and 6. In palynofacies 2, *Pediastrum* is associated with circular bodies. In palynofacies 6, *Botryococcus* is associated with fungal spores. In palynofacies 10, only undetermined palynomorphs and fungal spores are associated with pyrite.

The predominance of fine material is indicative that settling was the main process of sedimentation and that the bottom current was subordinate. The preservation of lamination in the shale suggests scarce burrowing. However, the underflows would keep the bottom oxygenated. The clay and siltstones interlayers may have been produced by differential settling from the water column, due to seasonal variation. The increase in clay content is indicative of lateral distance from the distributary mouth and combination with lake sedimentation processes. This facies association is characteristic of distal prodelta settings.

The Palynofacies association II (Fig. 7) has been recorded in grey muscovitic laminated siltstones and massive grey claystones (facies Fl and Fm). The abundance of amorphous organic matter (85–90%) is characteristic of stagnant bottom conditions. Probably, the AOM matrix was partially degraded in the water column but finally was preserved in a dysoxic reducing environment. The phytoclasts are scarce (7–10%), which suggests a distal depositional setting. The presence of algae indicates a freshwater environment. Diagenetic processes such as degradation and corrosion are present. The precipitation of pyrite is subordinate. Crystals of pyrite or marcasite in the samples indicate that bottom conditions were anoxic–dysoxic.

4.3. Lacustrine facies association; palynofacies association III (Fig. 2)

The facies association includes shales (Fl), mudstones (Fm), and fine sandstone layers (Sh). Laminated claystones with dark yellowish brown and grey colors characterize the Fl facies. Fm layers are interbedded with Fl facies with millimetric thickness. Analcime, quartz, and plagioclase are the dominant minerals. The clay mineral is illite.

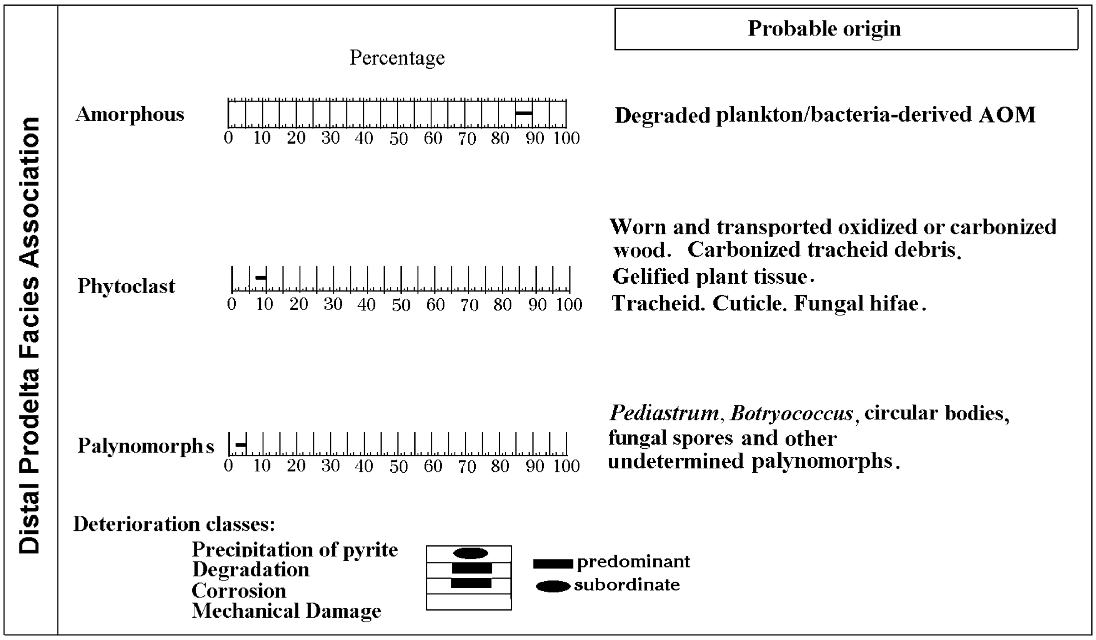

Fig. 7. Palynofacies association II.

No bioturbation evidence is present; instead, frequent fossils fishes (Malabarba et al., 1999) and organic remains were identified. Lenticular flat lens shapes or continuous beds of siltstones and very fine sandstones (Sh facies) are interbedded. Isolated micro-ripples (Reineck and Singh, 1975) are also present. Lake deposits have the highest organic contents, ranging from 4 to 9.75% TOC (Table 5).

Palynofacies association III consists of palynofacies 8, 8B, and 9 (Fig. 2). The amorphous organic matter is 90% (Table 1), consists of abundant, well-preserved AOM, and is spongy, granular to spherulitic, with low proportions of finely dispersed matter. The origin of the granules is uncertain. The amorphous matter is deformed and imprinted by the growth of diagenetic analcime crystals as craters in the kerogen, which impart a pseudocellular appearance to the AOM (Tyson, pers. comm.) (Figs. 4E and F and 8A–D), as illustrated by Tyson (1995 in Plate D5 and D6 from a sample of a dysoxic–anoxic lacustrine laminite rich in fish remains). Sample 8B (Fig. 2) also presents well-preserved fossil fishes. Well-preserved AOM provides strong green-yellowish fluorescing colors, and its overwhelming dominance in the samples suggests Type I/II kerogen composition (scale point 5; Tyson, 1995). This is confirmed by high hydrogen indices (Fig. 5) and TOC and *S*2 values (Fig. 6). The probable origins are degraded plankton, bacterially derived AOM, and subordinate amorphous organic matter of cuticular origin (Table 3).

The phytoclasts vary from 5% in palynofacies 8 to 7% in palynofacies 8B and 9. Irregular in shape, opaque, and translucent phytoclasts are present in similar proportions

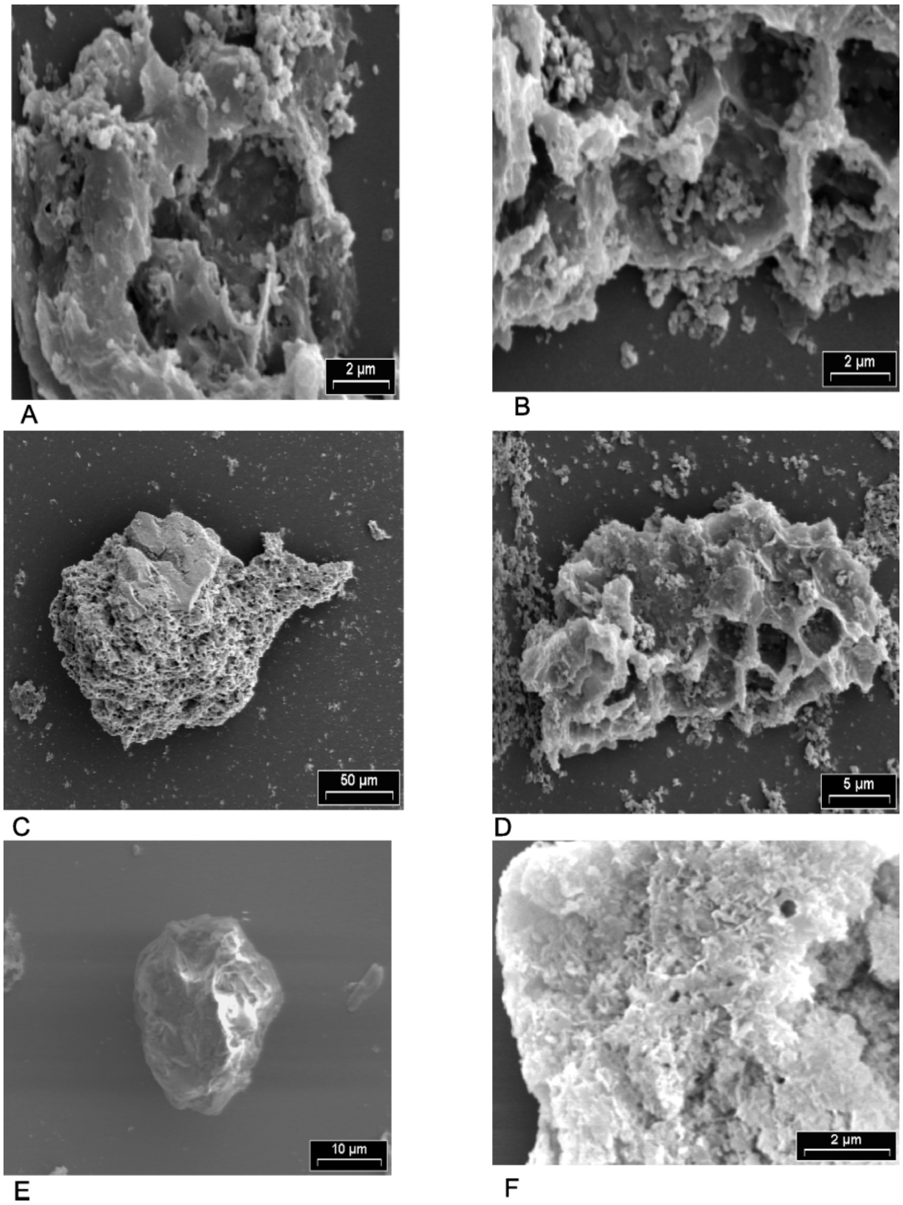

Fig. 8. All samples seen in SEM. (A–D) Sample M8, non-filamentous? microbial/cyanobacterial mat. The amorphous matter is imprinted by the growth of analcime crystals imparting a pseudocellular appearance. (E and F) Sample M8b. (E) Circular body? (F) Cyanobacterial mat.

(Table 2). Biostructured phytoclasts of cuticular origin are also recognized. The probable origins, according to abundance data, are cuticle, worn and transported oxidized or carbonized wood, gelified plant tissue, and fungal hyphae (Table 4).

The palynomorphs vary from 3% in palynofacies 8B and 9 to 5% in palynofacies 8. The palynomorphs consist of phytoplankton dominated by *Pediastrum*, indeterminate palynomophs, circular bodies, algae filamentous (Fig. 8E and F), and fungal spores. *Pediastrum* and degraded masses of this algae show very high fluorescence. The predominant modes of pollen grain deterioration are degradation and corrosion.

This facies association was deposited in an open perennial lake. The deposition of fine-grained sediments and organic matter were below the wave base in a stratified column water environments with anoxic–dysoxic bottom conditions (Sagri et al., 1989; Talbot and Livingstone, 1989; Roger and Astin, 1991). The coarse material represents deposits from turbidity currents triggered by sporadic storm floods. These currents provoked a turbulence in the bottom setting with resulting oxygenation. The palynofacies association III (Fig. 9) has been recorded from dark grey shales (facies Fl). The high abundance of well-preserved, plankton/bacterial-derived AOM (90%) represents low energy, stagnant, oxygen-depleted paleoenvironments (Boulter and Riddick, 1986; Bryant et al., 1988; Van der Zwan, 1990; Gorin and Steffen, 1991; Tyson, 1995). Such paleoenvironments are usually located near the depocenter (Whitaker et al., 1992).

The palynofacies association is very lean in phytoclast content (3–7%), and translucent phytoclasts are of dominant cuticular origin. The cuticles are derived from leaves. The preservation of entire leaves in sediments is associated with low energy fluvio-deltaic and lacustrine environments (Gastaldo and Huc, 1992 in Batten (1996, p.1034)). *Pediastrum* is the only genus present.

4.4. Interdistributary bay facies association; palynofacies association IV (Fig. 2)

This facies association is made up of laminated and massive mudstones (Fm and Fl facies). The sedimentary signatures of these deposits are intense bioturbation, moderately rich organic matter clay (1.66 and 1.59% TOC, Table 5), and the presence of mudcrack structures. Facies Fl is mainly dark colored, pale brown, and dark gray with illite as the main clay mineral and analcime, quartz, and plagioclase in subordinate proportions. Thin levels of massive (Sm) and rippled (Sr) sandstones with wavy and lenticular bedding are also present.

Palynofacies association IV consists of palynofacies 11 and 12 (Fig. 2). Its amorphous organic matter varies from 60% in palynofacies 11 to 75% in palynofacies 12. The amorphous group (60–75%) consists of abundant, finely dispersed material and lower proportions of clotted and lumpy structures with inclusions (Table 1, Fig. 4G and H). The particle matrix is not fluorescent (scale point 3; Tyson, 1995), which is equivalent to Type III kerogen. Fig. 5 shows the same results but with a lower HI value. A similar relationship is present in the TOC and *S*2 diagram (Fig. 6). The probable origin is continental-plant derived (humic) amorphous organic matter and a low proportion of amorphous organic matter of algal/bacterial origin (Table 3).

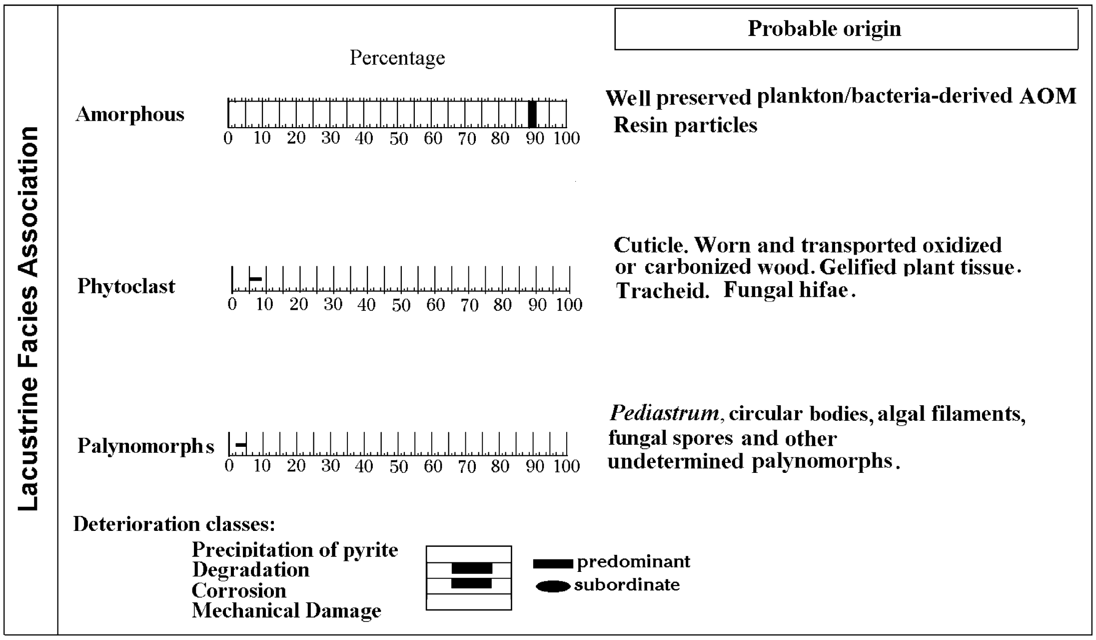

Fig. 9. Palynofacies association III.

The phytoclasts vary from 15% in palynofacies 11 to 38% in palynofacies 12. Abundant proportions of structureless translucent phytoclasts are orange brown and irregular in shape (Table 2). Opaque phytoclasts are rare. The probable origins, according to the importance of phytoclasts, are poorly lignified cortex tissues, worn and transported oxidized or carbonized wood, tracheid (wood) debris, gelified plant tissue, fungal hyphae, and cuticle (Table 4).

The palynomorphs vary from 2% in palynofacies 11 to 10% in palynofacies 12. They are very rare and have been grouped as undetermined filamentous algae and circular bodies. The palynomorphs show dull fluorescence.

The fine-grained material settled from the fluvial overbanks during flood stages. Gould (1970) used the term 'delta-flank depressions' to describe zones among the main fluvial scours that are occupied by shallow lakes. The sandstones are brought in during floods and represent crevasse deposits (Elliot, 1974). This facies association is characteristic of well-drained interdistributary zones. The burrowed mottled sediments and lack of peat material distinguish this environment from marshes (Donaldson et al., 1970). Sedimentary structures are indicative of a very shallow water level in which periods of subacqueous sedimentation alternated with periods of subaereal exposure.

The palynofacies association IV (Fig. 10) has been recorded in the bioturbated dark grey mudstones and black shales (Facies Fl). The abundance of amorphous organic matter derived from land plants characterizes this palynofacies. The high proportion of phytoclasts (15–38%) is characteristic of environments in which traction and suspension processes occur rapidly. The studied samples are characterized by intense bioturbation and relative low organic carbon content (TOC < 1.66 wt%), which indicate oxic depositional conditions. Diagenetic processes, such as degradation, corrosion, and the absence of pyrite, also indicate aerobic conditions.

5. Correlation between sedimentary facies and organic matter contents

The high percentage of illite in the matrix in all samples leads us to assume that $S2$ values are minimum; according to Dembicki et al. (1983), more than 85% of the pyrolyzate organic matter can be retained in the clay structure. The correlation schemes between the hydrogen index and relative fluorescence intensity of amorphous organic matter and richness of TOC yield good to excellent correlations with hydrocarbon source rocks (Figs. 5 and 6). To correct the 'matrix effect', $S2$–TOC data are plotted (Langford and Blanc-Valleron, 1990), and in Fig. 6, a correlation between TOC and the $S2$ parameter is shown. The TOC percentage changes according to the environmental dynamics and evolution.

Although inner lake facies are rich in organic content, this content decreases progressively as the clastic input and agitation of water increases. The inner lake samples are characterized by high HI values, strong fluorescence intensity, and the highest TOC content. Samples 8, 8B, and 9, with high contents of organic matter, have high $S2$ values, and the kerogen types are determined as Type I/II and Type II (Tyson, 1995) (Figs. 5 and 6). Sample 10, with moderate HI and fluorescence intensity, represents the sedimentation in a distal prodelta environment in which

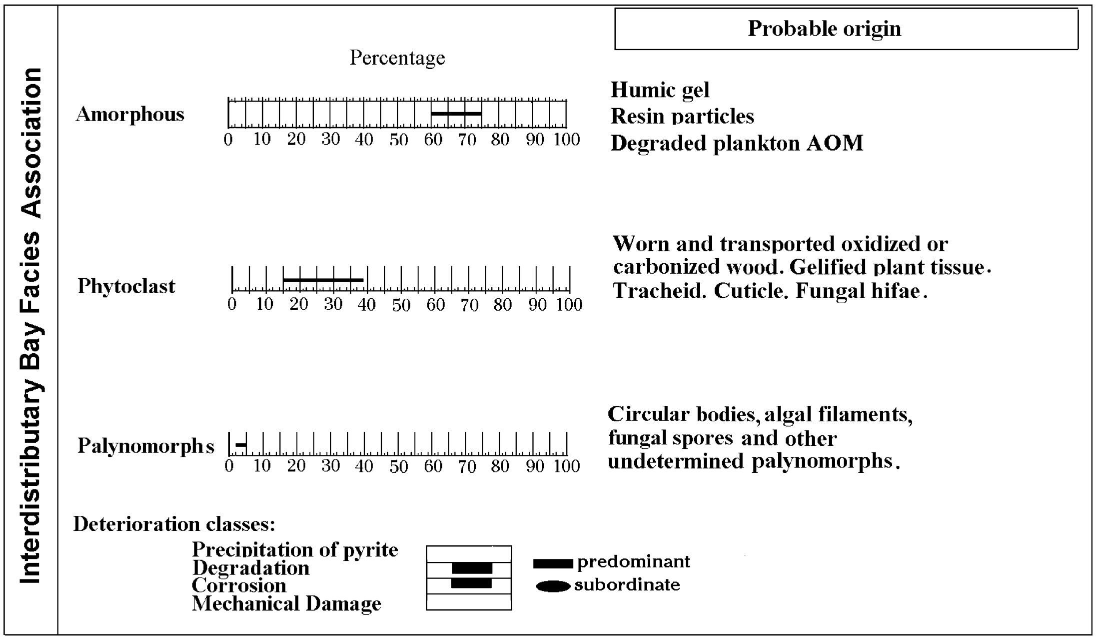

Fig. 10. Palynofacies association IV.

underflow currents are subordinate to lake settling in an oxygenated bottom. The kerogen of samples plotted in Types I and II coincide with a plankton/bacterial origin. Type II probably results from the mixing of Type I (degraded algal material) and Type III (terrigenous material) (Cornford, 1984). This mixing is observed in lake deposits with algae *Pediastrum* and leaves of higher plants.

In contrast, samples 11 and 12 of the interdistributary bay show low HI values and a lack of fluorescence (Figs. 5 and 6). Sedimentary rocks show lower TOC percentages and low *S*2 parameters, characteristic of Types III and IV kerogen. Although these samples contain up to 1.5 wt% TOC, they respond weakly to pyrolysis. The palynofacial analysis shows that much of the organic matter was supplied from higher plants, and the AOM in these levels is probable recycled (Peters, 1986).

In proximity to fluvial-deltaic environment (prodeltaic and interdistributary bay deposits), sediments are characterized by burrowing, relative low organic carbon content, and particularly abundant translucent phytoclasts, which indicate of oxic conditions (Bombardiere and Gorin, 1998). The translucent/opaque phytoclast percentage in the environment was similar; consequently, no differentiation could be obtained. This facies association shows palynomorphs with mechanical damage, degradation, and corrosion. The most conspicuous differences are in the type of degradation. In the delta deposits (facies associations I, II, and IV), the main degraded processes are mechanical damage and corrosion in aerobic conditions. In lacustrine facies association, degradation and corrosion by anaerobic microbial alteration prevail.

6. Discussion

The depositional environment of Faja Verde II is represented by a fluvio-dominated delta, which episodically prograded into a perennial freshwater lake (Fig. 11). Temporarily, the lake became stratified with anoxic hypolimnion. The passage of silty prodelta facies into delta, top trough, thin sandy facies represents a delta with a finger sandy shoal of delta front (Walker and Harms, 1971; Bhattacharya and Walker, 1992). The seasonal input variation probably produces the progradation of the delta complex and the shift of marginal facies basinward. The bloom of *Botryococcus* and *Pediastrum* algae was a consequence of these periods. However, *Botryococcus* and *Pediastrum* do not occur together in the studied samples, which suggests that they have somewhat different ecological preferences.

Mohammed and Bonnefille (1991) indicated that, for Lake Langeno (Ethiopia), the relative content of *Pediastrum* seems to increase during more humid intervals, when AOM and organic-rich laminated sediments (5–7% TOC) were deposited. Similar relationships could have existed in this study, for which *Pediastrum* is the dominant species in lacustrine facies association (sample M8) with 9.75% TOC (Table 5). In Lake Victoria (Africa), *Botryococcus* was abundant when lake levels fell and conditions were probably more saline. However, with a reexpansion and deepening of the lake, *Pediastrum* became the dominant form (Tyson, 1995, p. 316). Similar relationships were observed in this study; whereas *Botryococcus* is dominant in samples from proximal prodeltaic deposits (*palynofacies association I*, palynofacies 5), *Pediastrum* is dominant in inner lacustrine deposits (*palynofacies association III*, palynofacies 8) (Fig. 11).

Ancient *Botryococcus* colonies are often poorly preserved, granular in appearance, and lacking fluorescence, which indicates survival despite oxidation and a possible penecontemporaneous reworking (Hutton et al., 1980). Prolonged oxidation lowers the hydrogen content and decreases both autofluorescence and source rock potential prior to complete destruction (Tyson, 1995, p. 313). In this study, the abundance of *Botryococcus* reported from proximal deposits (*palynofacies association I*, palynofacies 5) presents these mentioned characteristics.

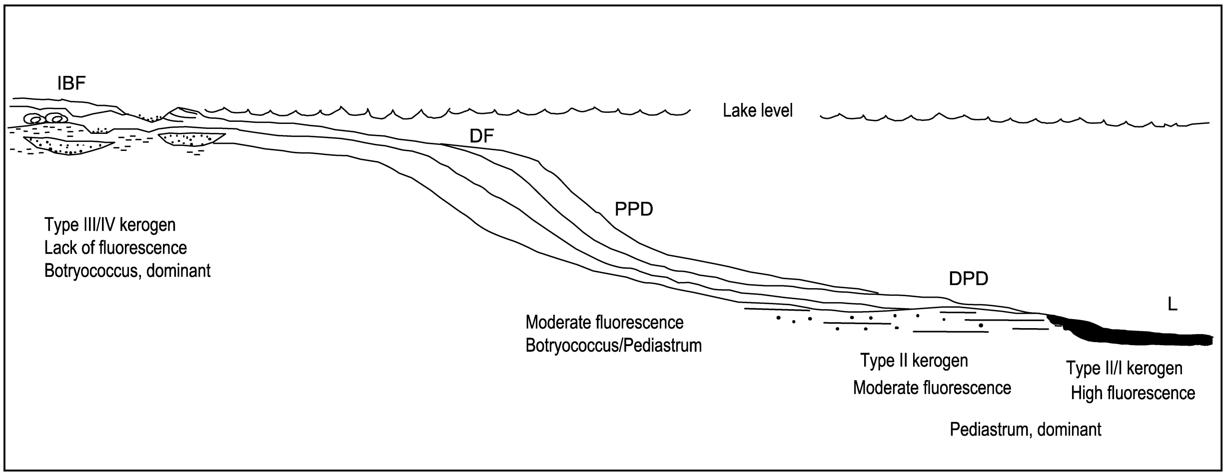

Fig. 11. Types of kerogen and organic matter distribution according to paleoenvironment interpretation. Scheme without scale.

Colonies of *Botryococcus* are common in littoral areas where they accumulate in quiet and wind-protected sections (Tyson, 1995).

In the Maíz Gordo Sequence (Late Paleocene–Early Eocene), the amorphous organic matter dominates the laminated limestones facies associated with nonmarine dinoflagellate cysts. This palynofacies indicates an increase of salinity in the water body (Quattrocchio and del Papa, 2000). We assume, because of the absence of dinoflagellate cysts in our succession, that the conditions are not as saline as is Maíz Gordo's lake.

The agents forming lacustrine strata essentially respond to many physical factors that control the rate of accommodation (Oviatt et al., 1994), and they must be considered in the application of sequence stratigraphy in lake deposits. Variation in lake levels substitutes for the relative sea level changes of marine environments (Shanley and McCabe, 1994). Organic-rich, lacustrine-condensed sections occur when rising water levels and biological productivity are sufficient, oxygenation is low, and mineral input is constrained (Jacobson, 1991). Palynofacies 8, 8B, and 9 represent this situation and are characterized by anoxic conditions.

Two main cycles divided by the flooding surface are determined. The lower is composed of five parasequences that show a retrogradational stacking pattern (Van Wagoner et al., 1990) and represent the progressive flooding of the basin (Fig. 2). This transgressive episode is interpreted as climatically controlled. The maximum lake level depth is represented by a maximum flooding surface (palynofacies 8B and 9). Immediately above this surface, a progradational parasequences set began (Fig. 2). The characteristics and fluorescence intensity of the amorphous organic matter are the most conspicuous figures that demonstrated the shallowing upward cycles.

Temperate and humid conditions were inferred for Fajas Verdes I and II in Alemanía subbasin at Pampa Grande locality (situated 24 km to the southeast, Fig. 1). The assemblages are dominated by elements characteristic of humid montane paleocommunities (e.g. Gymnospermae, Gunneraceace, Hamamelidaceae, and Lycopodiaceae). Elements from swamps include Oenotheraceae, Marsileaceae, and Combretaceae (Quattrocchio et al., 2000). Similar conditions are proposed for the studied section. Syn- or postdepositional factors could have affected pollen grain preservation in this section. Also, the presence of analcime in the sediments suggests alkaline conditions, which could explain the destruction of the palynomorphs (Volkheimer, 1972).

7. Conclusions

Our goal has been to gain insight into the lacustrine basins and particularly the lacustrine facies of the Lumbrera Formation by applying combined sedimentary facies and palynofacies analyses. We conclude that

- The Faja Verde II of the Lumbrera Formation at Alemanía represents a fluvio-deltaic succession that prograded into a perennial freshwater lake.
- Four main subenvironments exist, each of which is characterized by a distinctive sedimentary facies and palynofacies association: lacustrine, distal prodelta, proximal prodelta, and interdistributary bay (Fig. 11).
- The variation of the occurrence of *Botryococcus* and *Pediastrum* algae reflects the lake level fluctuation. Whereas *Botryococcus* is dominant in periods of lake level fall, *Pediastrum* is dominant in periods of lake level rise.
- The variation of the fluorescence intensity of the AOM also reflects the lake level fluctuation and constitutes an instrument in the interpretation of sequence stratigraphy.
- The main characteristics identified in the organic components of Faja Verde II are in close relationship with the environment. A slight variation in the dynamic of the system (e.g. clastic input, water level, overturn, salinity) produces an imprint on the organic matter and regulates its quantity and quality.
- Palynofacies in combination with sedimentary facies correlate with paleoenvironments and paleosubenvironments and provide information for sequence stratigraphic analysis.

Acknowledgments

We thank Dr Richard Tyson and Alfredo Disalvo for their comments. This research was supported by CONICET (PIP 0883/98 and PIP 4788/96), Consejo de Investigación de Universidad Nacional de Salta (grant no. 966), and Secretaría General de Ciencia y Tecnología, Universidad Nacional del Sur. We are very grateful for helpful reviews by Helen Martin and an anonymous referee.

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