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Palynological Evidence for the Paleoenvironmental History of the Miocene Llanos Basin, Eastern Colombia

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ABSTRACT

The distal Llanos foreland basin was influenced by subsidence events since the Cretaceous until the Pliocene. Although this area has been extensively explored and is considered a potential oil reservoir, few studies of its stratigraphy and depositional environments have been conducted. This basin exhibits a geological section of Miocene age and the core Saltarin-1A, analyzed in this study, is the first and most complete drilling coreof this section with 680 meters. It represents to Carbonera, Leon and Guayabo Formations. Based on palynological data, this work has as its main aims to review the biostratigraphy, to identify the depositional environments, including those produced by marine incursions and to understand the history of the vegetation of the basin. A total of 115 palynological samples was counted, with a minimum of 300 palynomorphs per slide when possible. The core was dated from 22 to 5 My based on the graphic correlation and Maximum likelihood methods. Carbonera and the base of Leon Fms were deposited during the lower Miocene, Leon and Guayabo Fms (units 1, 2 and 3), during the middle Miocene, and the top of Guayabo Fm (units 4, 5) during the upper Miocene. In addition, three mayor marine incursions were detected during Miocene. Coeval marine transgressions have been also documented in the Central Llanos Foothills, Caribbean and Amazonia during the lower and middle Miocene. During the upper Miocene, the palynological composition indicates a change in the rate of sedimentation and in the drainage of the basin indicating possible formation of the Orinoco river. At this time the pollen showed and increase in the open vegetation. These data support previous works, which indicate an increase in the rates of deformation of the basin as well as erosion at the end of the Miocene. Finally, the palynoflora suggests the presence of a wet forest during the Miocene instead of the biomes that characterize the basin nowadays. These new data are important to understand the evolution of the Llanos Basin in relation with Andean uplift and the evolution of the Neotropics.

Keywords: Miocene, Llanos Basin, Marine incursions

INTRODUCTION

Palynology is a useful tool for evolutionary, ecological and biostratigraphic studies (Germeraad, et al., 1968; Muller, 1981; Traverse, 2007; Jaramillo et al., 2010), because the palynomorphs (pollen, spores and dinoflagellates) are the most abundant fossil group found in sedimentary rocks(Pardo-trujillo et al., 2003; Traverse, 2007; Jaramillo et al., 2010; Rodríguez-Forero et al., 2012). They have a wide age range, from millions of years ago (My) until now and they are present in all kind of environments (e.g. fresh-water lacustrine, deposits to deep-marine sediments), representing past environments spacing (e.g. Forests, grasslands) (Boucot, 1999; Olson and Thompson, 2005;Traverse, 2007). In Cenozoic rocks from Northern South America, palynology is frequently used to describe rock successions, to determinate the age and paleoecolgical nature of stratigraphic sequences and to correlate geological events in time and space (Jaramillo and Dilcher, 2001; Helenes and Cabrera, 2003; Pardo-trujillo et al., 2003; Jaramillo et al., 2005, 2006, 2010; Santos et al., 2007, 2008; Bayona et al., 2008; Silva-caminha et al., 2010; Rodríguez-Forero et al., 2012). This tool is also used to identify evolutionary patterns as speciation and diversification of the species and to understand the distribution of those in tropical environments during this period (Germeraad, et al., 1968; Muller, 1981; Van der Hammen and Hooghiemstra, 2000; Jaramillo and Dilcher, 2001; Jaramillo et al., 2010; Silva-caminha et al., 2010; Rodríguez-Forero et al., 2012).

The stratigraphic sequences that encompass palynological records are sets of layers of sedimentary rocks. Each layer records aspects of a depositional environment that is related with the type of sediment and level of preservation of the fossil record, consisting of mainly palynomorphs (Traverse, 2007; Gomez et al., 2009; Parra et al., 2009; Ji et al., 2011). The characteristics of each depositional environment are the result between the interaction of internal factors such as chemical and physical properties with external factors such as climate fluctuations and plate tectonics (Birks and Birks, 1980; Tucker, 2001; Nichols et al., 2007; Mora et al., 2008; Parra et al., 2009, 2010; Ji et al., 2011). The description and classification of the depositional environments associated with stratigraphic sections is key to understanding geological changes, evolutionary and ecological dynamics, as well as climatic events (Boucot 1999, Olson and Thompson 2005; Traverse, 2007; Parra et al., 2009; Ji et al., 2011). The foreland basins are an example of the stratigraphic sections where the depositional environments reflect a clear dynamic between geological changes, climatic fluctuations and evolutions of biota.

A foreland basin is the space of accommodation resultant from the interaction between a compressed orogen and its craton by subsident (Bayona et al., 2007, 2008; Parra et al., 2010). The development of stratigraphic sequences is controlled by the thrust-flexural deformations, which is influenced by the tectonic subsidence over rate of deposition and accommodation of the sediments (Dickinson, 1974; Karner & Watts, 1983; Bayona et al., 2007; Parra et al., 2009; Ji et al., 2011). As a result, the distribution of the sequences in the basin is asymmetric and each one records or proxies describes a set of sedimentary depositional environments (Dickinson, 1974; Karner & Watts, 1983; Ji et al., 2011).

The Llanos Basin, located in the east of Colombia, has been defined as a foreland basin (Cooper et al., 1995; Bayona et al., 2007, 2008; Person et al., 2012) so the influence by subsidence from the Cretaceous to the Pliocene by the uplift Andes mountains (Cooper et al., 1995; Bayona and Thomas, 2003; Holbrook et al., 2006; Jaramillo et al., 2011; Person et al., 2012). During this period of time the Llanos Basin presented high rates of continental and marine sediments accumulation unlike that of the present time, when the rates of sedimentation are low, (Jaramillo and Munoz, 2005; Bayona et al., 2007, 2008; Jaramillo et al., 2009; Rodriguez et al., 2008).

Stratigraphic sequences formed from the Cretaceous to the middle Miocene in the Eastern Llanos of Colombia are considered potential oil producers. Most of the studies in this region have been focused on mineral and seismic exploration of drill cuttings and short cores (Cooper et al., 1995; Bayona et al., 2007, 2008; Parra et al., 2009, 2010; Jaramillo et al., 2011; Person et al., 2012). However, few studies present information about the vegetation history, the depositional environments and the stratigraphy to support interpretations of shore cores (Branquet et al., 2002; Jaramillo et al., 2006 , 2010, 2011; Bayona et al, 2007, 2008; Santos et al., 2007). Currently, this area is dominated by savanna vegetation. However, during the Miocene, studies suggest that the area was a tropical rainforest, because climate was warmer than today (Zachos et al., 2001; You et al., 2009; Herold et al., 2011, 2012; Pound et al., 2012; Jaramillo and Cárdenas, 2013) and the expansion of vegetation associated with dry and/or cold conditions started during the upper Miocene (MacFadden and Higgins, 2004; Edwards and Smith, 2010; Arakaki et al., 2011; Lehmann et al., 2011; Edwards, 2012).

Debates exist over the interpretation of the depositional environments from the Miocene in Northern South America, and there are generally two hypotheses about the depositional history in this region. The first hypothesis reconstructs the environment with marine incursions (Von Ihering, 1927; Hoorn, 1993a; b; Räsänen et al., 1995; Marshall & Lundberg, 1996; Rull, 1997; Monsch, 1998; Helenes and Cabrera, 2003; Gomez et al., 2009; Jaramillo et al., 2010). The second interprets the environment with the occurrence of floodplains without marine influence (Webb, 1995; Campbell et al., 2006; Kaandorp et al., 2006; Wesselingh et al., 2006; Bayona et al., 2007, 2008; Hoviskoski et al, 2008; Latrubesse et al., 2007; Gomez et al., 2009).

To solve this debate, most studies have been focused on the Pebas Fm of the Amazon region, but the sedimentary section is too short for the interval of time and the fossil record presents several gaps of information.

Also, the dating of Miocene strata in Northern South America, is controversial, particularly, after the middle Miocene. These strata correspond to the upper Pebas and the Guayabo Fms. These have been dated as upper part of the middle Miocene to the Pliocene (Branquet et al., 2002; Gómez et al., 2005; Wesselingh et al., 2006; Bayona et al., 2008; Parra et al., 2010), upper Miocene to Pliocene (Cooper et al., 1995; Campbell et al., 2006; Martinez, 2006; Latrubesse et al., 2007; Bayona et al., 2008; Campbell, 2010; Horton et al., 2010; Mora et al., 2010; Montes et al., 2012) or Pleistocene (Santos and Silva, 1976; Kronberg et al., 1991; Person et al., 2012).

The distal Llanos foreland basin exhibits a geological section from the Miocene of 680 meters. From this the core Saltarin-1A, analyzed in this study, is the first and most complete drilling of this section, corresponding to Carbonera, Leon and Guayabo Fms, and will be useful in clarifying the controversial stratigraphy with palynological data as biostratigraphic markers. Identifying marine incursions in this section, as well as timing and frequency has the potential to could clarify the controversy about the sedimentary deposits in Northern South America during this period of time. Also, this study will be helpful in understanding the evolution of the Neotropical landscape, starting with the questions: Was the Llanos Basin a tropical rain forest during the Miocene? Did the expansion of the savannas occur during the upper Miocene? Finally, this work provides new data to the study of the biogeography and evolution of current and extant taxa such as the diversification of the neotropical vegetation communities during the Miocene in Northern South America.

MATERIALS AND METHODS

Study area

The Llanos Basin (figure1) is defined in the north by the Colombia-Venezuela border, in the south by Sierra de la Macarena and Vaupes Arch, by the Guaicaramo fault system in the west, and by the Guyana Shield in the east (Cooper et al., 1995; Bayona et al., 2007, 2008; Barrero et al, 2007). The Saltarin-1A core is 670m in depth, located at 70.6º W, 4.70º N, and was drilled by the oil company Hocol. Two additional short cores were drilled and correlated with Saltarin-1A. The additional cores were Saltarin-1 of 120m Saltarin-1AD of 50m of depth. Saltarin-1 core was correlated with the top of Saltarin-1A (firsts 135m) and Saltarin-1AD was correlated with the bottom of Saltarin-1A (last 50m).

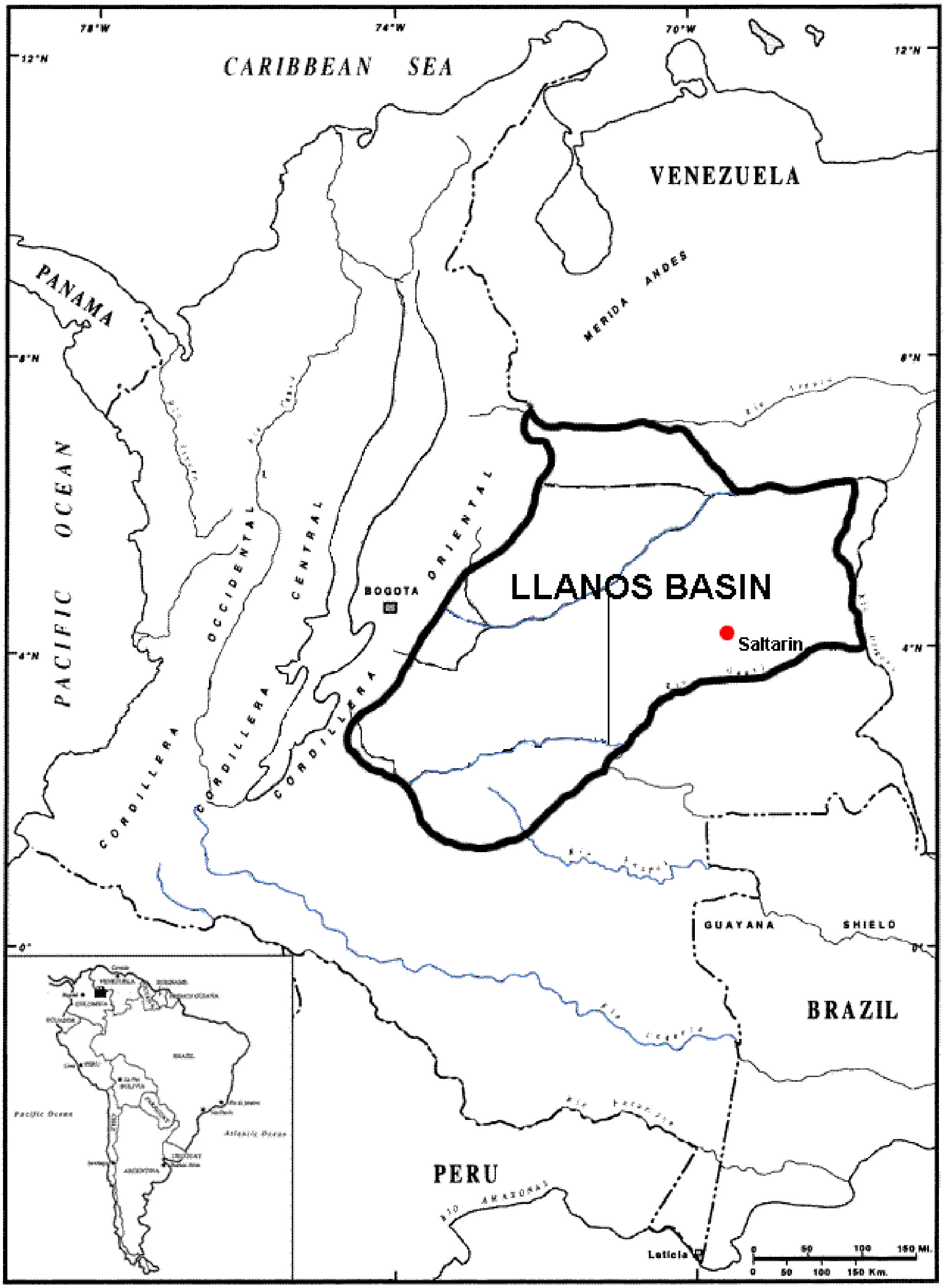

Figure 1. Map of location of the core Saltarin (black point) studied in Llanos Basin from Colombia, area delimited with a bold line.

Bayona et al. (2008) carried out sedimentological, stratigraphic, biostratigraphic and provenance analyses in each stratigraphic unit of Saltarin-1A (figure2). According to Bayona et al. (2008), the sediment composition shows that Eastern Cordillera and the Guyana field were the major source area of sediment input in the Llanos Basin. Lithological analyses indicate that the base of the core corresponds to the upper part of Carbonera Fm with three units: C1, the bottom of the section with 17m of sandstones units associated with a deltaic system; C2 is approximately 46m of mudstone unit, associated with a lacustrine system; C3 is 61m of sandstones, and has been interpreted as a fluvial system. The Leon Fm, overlying the Carbonera Fm., is a muddy sequence that has been associated with a lacustrine system. The Guayabo Fm, has six units: G1, G2 and G3 are compose of mudstones grading to sandstones sediments, whereas G1 is associate with a deltaic system, G2 has characteristics of a paleosol, and C3 accumulated under semi-oxidant conditions, possibly as a flood plains. Units G4 and G5 is comprised of sandstones, indicating a fluvio- deltaic system.

In the Llanos Basin, the Carbonera, Leon and Guayabo Fms range in age from the Oligocene to Neogene (Escalante and Rojas, 1991; Notestein et al., 1994; Albert et al., 2006; Bayona et al., 2007a, 2007b, 2008a, 2008b, 2013; Martinez, 2006; Jaramillo et al., 2007; Gomez et al., 2009; Parra et al., 2009; Ochoa et al., 2012). Biostratigraphic data (figure 2) suggest that the Saltarin section has an age from lower to upper Miocene (Bayona et al, 2008). In the Carbonera Fm, C1 and C2 units correspond to lower Miocene. The C3 unit, Leon Fm and the three first units of Guayabo Fm (G1, G2, G3) are associated with the middle Miocene. The last two units of Guayabo Fm, have been devoid of stratigraphically useful remains, suggesting an age of middle to upper Miocene, but that interpretation is not well-supported with current data (Bayona et al, 2008).

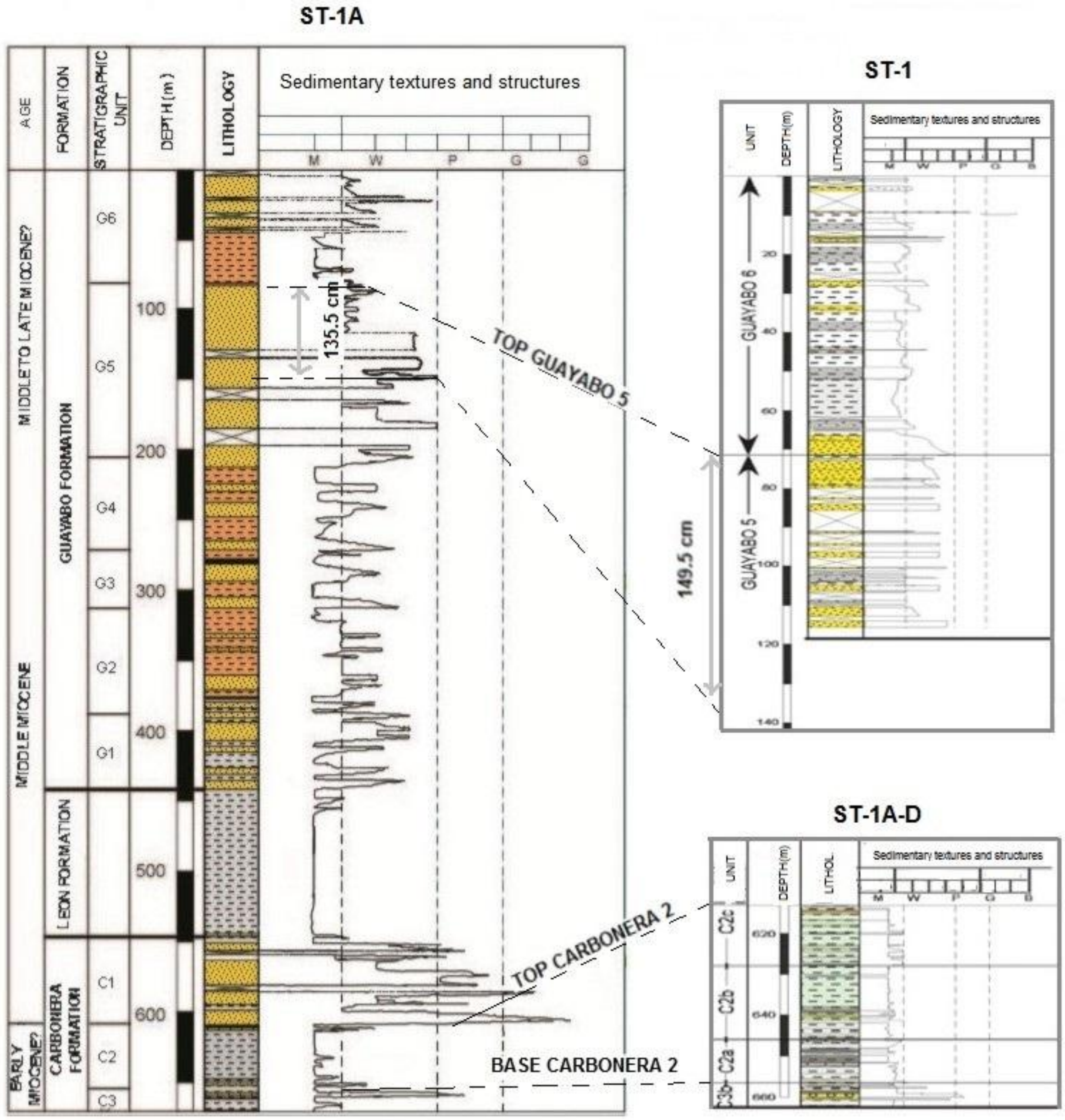

Figure 2. Lithology of Saltarin-1A and correlation with Saltarin-1 and Saltarin-1A-D (Bayona et al., 2008)

Methods

A total of 115 palynological samples (Table1) were processed by Paleoflora Ltd. laboratories (Bucaramanga, Colombia), following a standard maceration technique with HF and HCl, to digest the mineral material and separate oxidize organic matter (Funkhouser and Evitt, 1959; Faegri and Iversen, 1989; Moore et al., 1991). The specimens were examined on a Nikon Eclipse 200 microscope Scope and a Zeiss Axiophot microscope. All samples were scanned with 40X lens. At least 300 palynomorphs per slide were counted, when possible. Palynomorphs identified were pollen, spores and marine palynomorphs (foraminifera, dinoflagellates, acritarchs) and freshwater algae.

Table 3. Table of total samples analyzed to Saltarin.

Sample	Fm	Unit	Sample label	Depth(m)	Total palynomorphs	Total sp per sample
1	GUAYABO	G6	Saltarin-1	58.28	14	Sterile
2		G5	Saltarin-1A	86.3	5	Sterile
3			Saltarin-1A	90.83	337	71
4			Saltarin-1A	97.29	320	58
5			Saltarin-1A	99.53	306	55
6			Saltarin-1	101.35	17	Sterile
7			Saltarin-1A	102.93	1	Sterile
8			Saltarin-1A	105	0	Sterile
9			Saltarin-1A	107.94	1	Sterile
10			Saltarin-1A	110.83	4	Sterile
11			Saltarin-1A	112.66	209	30
12			Saltarin-1A	114.92	163	35
13			Saltarin-1A	138.5	0	Sterile
14			Saltarin-1A	143.07	331	78
15			Saltarin-1A	144.15	363	98
16			Saltarin-1A	145.35	307	55
17			Saltarin-1A	148.7	23	Sterile
18			Saltarin-1A	150.63	81	31
19			Saltarin-1A	151.7	300	75
20			Saltarin-1A	165.46	21	Sterile
21			Saltarin-1A	167.35	291	71

22		Saltarin-1A	169.77	84	45
23		Saltarin-1A	174.98	256	45
24		Saltarin-1A	179.5	1	Sterile
25		Saltarin-1A	184.33	137	46
26		Saltarin-1A	200.19	0	Sterile
27		Saltarin-1A	203.77	133	34
28		Saltarin-1A	206.29	0	Sterile
29		Saltarin-1A	212.05	9	Sterile
30		Saltarin-1A	213.91	3	Sterile
31		Saltarin-1A	216.55	2	Sterile
32		Saltarin-1A	224.45	3	Sterile
33		Saltarin-1A	230.84	0	Sterile
34	**G4**	Saltarin-1A	232.13	6	Sterile
35		Saltarin-1A	235.88	5	Sterile
36		Saltarin-1A	243.48	2	Sterile
37		Saltarin-1A	246.12	0	Sterile
38		Saltarin-1A	251.53	10	Sterile
39		Saltarin-1A	254.8	0	Sterile
40		Saltarin-1A	261.62	0	Sterile
41	**G3**	Saltarin-1A	301.78	3	Sterile
42		Saltarin-1A	309.64	1	Sterile
43		Saltarin-1A	319.58	0	Sterile
44		Saltarin-1A	331.75	1	Sterile
45		Saltarin-1A	339.13	0	Sterile
46		Saltarin-1A	345.25	0	Sterile
47	**G2**	Saltarin-1A	348.6	0	Sterile
48		Saltarin-1A	350.18	0	Sterile
49		Saltarin-1A	355.94	5	Sterile
50		Saltarin-1A	372.38	341	82
51		Saltarin-1A	376.26	346	14
52		Saltarin-1A	386.52	356	30
53		Saltarin-1A	396.22	320	53
54		Saltarin-1A	403.39	324	41
55		Saltarin-1A	406.95	309	44
56		Saltarin-1A	408.56	347	19
57	**G1**	Saltarin-1A	409.52	398	32
58		Saltarin-1A	413.49	300	35
59		Saltarin-1A	417.55	322	60
60		Saltarin-1A	422.69	308	41
61		Saltarin-1A	426.59	323	38

62			Saltarin-1A	430.82	382	64
63			Saltarin-1A	433.27	314	56
64			Saltarin-1A	440.6	397	51
65	LEON		Saltarin-1A	445.48	373	23
66			Saltarin-1A	450.28	364	48
67			Saltarin-1A	455.4	207	45
68			Saltarin-1A	458.85	358	34
69			Saltarin-1A	463.53	86	9
70			Saltarin-1A	468.84	319	20
71			Saltarin-1A	474.6	399	49
72			Saltarin-1A	479.55	287	15
73			Saltarin-1A	485.2	327	7
74			Saltarin-1A	491.73	317	26
75			Saltarin-1A	497.93	335	12
76			Saltarin-1A	503.9	314	31
77			Saltarin-1A	510.03	369	45
78			Saltarin-1A	514.37	403	18
79			Saltarin-1A	518.94	141	19
80			Saltarin-1A	523.9	399	36
81			Saltarin-1A	529.95	106	32
82			Saltarin-1A	535.08	96	21
83			Saltarin-1A	537.29	323	52
84			Saltarin-1A	539.77	303	47
85			Saltarin-1A	543.38	355	42
86			Saltarin-1A	546	370	47
87	CARBONERA	C1c	Saltarin-1A	547.18	303	49
88			Saltarin-1A	548.24	336	52
89			Saltarin-1A	550.43	307	52
90			Saltarin-1A	562.26	341	62
91		C1a	Saltarin-1A	586.7	369	125
92			Saltarin-1A	589.91	60	Sterile
93		C2c	Saltarin-1A	609.45	98	18
94			Saltarin-1A	610.2	255	24
95			Saltarin-1A	612.76	244	37
96			Saltarin-1AD	614.35	399	49
97			Saltarin-1A	615.9	262	32
98			Saltarin-1A	619.75	257	41
99			Saltarin-1A	624.77	83	13
100			Saltarin-1A	626.73	325	33
101		C2b	Saltarin-1A	627.36	391	61
102			Saltarin-1A	628.61	343	35

103		Saltarin-1AD	629.9	121	30
104		Saltarin-1A	634.12	254	18
105		Saltarin-1A	637.73	225	28
106		Saltarin-1A	638.33	302	72
107		Saltarin-1A	640.65	121	30
108		Saltarin-1A	641.88	271	50
109		Saltarin-1A	644.25	307	45
110		Saltarin-1AD	645.9	273	35
111	**C2a**	Saltarin-1A	650.29	318	61
112		Saltarin-1A	654.97	28	Sterile
113	**C3b**	Saltarin-1A	657.3	127	25
114		Saltarin-1AD	662.33	195	28
115	**C3a**	Saltarin-1A	670.98	105	21

Palynology

Identification of fossil taxa was conducted through comparison using the Palynomorph database of Jaramillo and Rueda (2013) and published photographs and descriptions (Germeraad et al., 1968; Regali et al., 1974; Lorente, 1986; Nichols et al., 1986; de Vertuil and Norris, 1992; Fensome et al., 1993; Hoorn, 1993a; b; Wrenn et al., 1998; Jaramillo and Dilcher, 2001; Head, 2003; Hoorn and Vonhof, 2006; Jaramillo et al., 2007, 2010; Matsuoka et al., 2009; Silva-caminha et al., 2010; Leal et al., 2011). The comparison with modern pollen was done using the Alan Graham Palynological Collection, located in the Smithsonian Tropical Research Institute-STRI and different atlas of pollen (Roubik and Moreno, 1991; Colinvaux et al., 1999; Leal et al., 2011; Schuler and Behling, 2011). Palynomorphs were categorized into five groups. This classification was based on previous morphological and ecological affinities with modern taxa (Table 3). The groups were: marine, spores, fungi, pollen and freshwater algae. For paleovegetation analysis, pollen group was subdivided in trees, mangrove/estuarine, herbs/grasses.

R-cran Software was used in all statistical analysis. The packages used where rioja, vegan, permute, Labdsv and ggplot2. The counting of all samples was standardized and the cutoff used was >80 grains per sample. An analysis to calculate the number of species per sample was made using the rarefaction index, i.e., the number of species is equal to the number of morphologically different entities identified. The confidence interval was 95% (Germeraad, 1968; Sanders, 1968; Rosenzweig, 1995; Jaramillo, 2008). The overall variation of floral composition was analyzed with palynograms, detrended correspondence analysis (DCA) and principal component analysis (PCA).

Chronostratigraphy

Two methods were used to establish the chronostratigraphy of Saltarin-1A. The first method was graphic correlation. Its has been the traditional method used to make chronostratigraphic inferences (Edwards, 1991; Gradstein et al., 2004; Boucot 1999; Olson and Thompson 2005; Traverse, 2007). This is based on relative abundances, first occurrences datum (FAD) and last occurrence datum (LAD) of pollen and spores presented in different stratigraphic sections to establish a palynological zonation (Germeraad, 1968; Hoorn, 1993a; b; Hoorn et al., 2010; Jaramillo and Dilcher, 2001; Jaramillo et al., 2007, 2010; Jaramillo, 2008; Silva-caminha et al., 2010). The graphic correlation to Saltarin-1A is based on the biostratigraphic and palinological zonation proposed previously for the Neogene from Northern South America (Table 2), mainly the palynological zonation proposed by Jaramillo et al. (2010) for the Llanos of Colombia. All plots were made using the R-cran software.

The second method was the maximum likelihood, proposed by Punyasena et al., (2012). The main aim of this method is to calculate an age or stratigraphic position in a sedimentary sequence of isolated samples through Biostrat Software. This method uses the microfossil abundance data of stratigraphic sections that share similar depositional environments to define confidence intervals. These data are compared with isolated samples or a single sedimentary sequences to estimate the maximum likelihood age of each sample. For Saltarin-1A the maximum likelihood was established using a dataset file downloaded from STRI Geological Database (Jaramillo et al., 2012) and the matrix of abundance of Saltarin-1A. Confidence intervals and maximum likelihood were calculated for each sample using Biostrat and the plot was made using R.

The principle used in maximum likelihood method is the same of graphic correlation. For that reason in this study, both methods were compared using a linear model, to see the tendency of the data and to propose an age correlation line to Saltarin-1A.

Table 4. Palynological zonation proposed to Miocene of Northern South America.

AGE		Germeraad et al., 1968	Lorente, 1986	Muller, 1987	Rull, 1997	Helenes and Cabrera, 2003	Hoorn, 1993	Da Silva et al., 2010	Jaramillo et al., 2010	This work
		The caribbean	**Eastern Venezuelan Basin**	**Northern South America**	**Western Venezuela**	**Eastern Venezuela**	**Northwestern Amazonia**	**Solimoes basin Brasil**	**Llanos and llanos foothills Colombia**	**Llanos Basin Colombia**
MIOCENE	Upper	*Pachydermites diederxii*	*Asteraceae: Fenestrites* *Stephanocolpites evansii*	*Echitricolporites spinosus* *Crassoretitriletes varaadshoovenii*		*Tuverculodinium vancampoe* *Kuylisporites waterbolkyi*	*Asteraceae: Fenestrites* *Grimsdalea magnaclavata*	*Grimsdalea magnaclavata*	*cyatheacidites annulatus* *Fenestrites spinosus* *Stephanocolpites evansii* *Paleosantalaceaepites cingulatus*	*Cyatheacidites annulatus* *Fenestrites spinosus* *Paleosantalaecipites cingulatus*
	middle	*Pachydermites diederixii*	*Grimsdalea magnaclavata* *Crassoretitriletes vanraadshooveni* *Psiladiporites minimus*	*Crassoretitriletes vanraadshooveni*	*Magnastriatites grandiosus* *Verrucatricolporites rotundisporis* *Jandufouria seamrogiformis*	*Psilatricolporites triangularis* *Tuverculodinium vancampoe* *Kuylisporites waterbolkyi*	*Psiladiporites minimus* *Crototricolpites* *Grimsdalea magnaclavata*	*Grimsdalea magnaclavata* *Crassoretitriletes vanraadshooveni*	*Fenestrites spinosus* *Crassoretitriletes vanraadshooveni* *Grimsdalea Magnaclavata* *Echitriletes acanthotriletoides* *Paleosantalaceaepites cingulatus* *Echitricolporites spinosus*	*Fenestrites spinosus* *Paleosantalaecipites cingulatus* *Psilastephanoporites herngreenii*
	Lower	*Grimsdalea magnaclavata* *Multimarginites vanderhammenii* *P. minutus* *Jandufouria seamrogiformis* *Cicatricosisporites dorogensis*	*Psiladiporites minimus* *Verrucatricolporites* *Cicatricosisporites*	*Echitricolporites maristellae* *Psiladiporites minimus* *Verrucatricolporites rotundisporus* *echidiporites barbeitoensis*	*Magnastriatites grandiosus* *Verrucatricolporites rotundisporis* *Jandufouria seamrogiformis* *Bombacacidites baumfalki* *Cicatricosisporites dorogensis*	*Psilatricolporites triangularis* *Tuverculodinium vancampoe* *Kuylisporites waterbolkyi*	*Verrutricolporites rotundiporus*	*Psiladiporites* *Crototricolpites* *Retitricolporites* *Verrucatricolporites*	*Echitricolporites spinosus* *Echitricolporites maristellae* *Horniella lunarensis* *cicatricosporites dorogensis* *Tuverculodinium vancampoe* *Cyclusphaera scabrata* *Clavainaperturites microclavatus* *Grimsdalea magnaclavata* *Foveotricolporites etayoi* *Bombacacidites baculatus* *Nijssenosporites fossulatus*	*Cyclusphaera scabrata* *Psilastephanoporites herngreenii*

Salinity index

Salinity index (SI) has been proposed by Rull (2000, 2002) and Santos et al. (2008) in stratigraphic sequences and paleoecolgical studies as a mathematical method to identify marine transgressions or regressions. The index proposed by Rull (2000, 2002), is based on the ratio between the relative frequencies of marine and freshwater fossil palynomorph, because the salinity tolerance is inverse in both groups. The formula proposed is $SI=\ln[(F+0.1)/(M+0.1)]/e$, where F is freshwater algae and M is marine. Santos et al. (2008) proposed an index $SI=M/T$, where M are marine palynomorph and T is the total count to each sample, that is the same proportion of marine elements in each sample.

For this work, a correlation analysis was made between pollen, marine elements, freshwater algae and spores to determinate if both indices were useful to identify marine incursions in Saltarin-1A. Also, a salinity index was proposed, based on the relation between marine and terrestrial elements as an inverse relation. In other words, if the proportion of terrestrial palynomorph decreases, the proportion of the marine palynomorph increase (Hoffmeister, 1954; Williams, 1971; Heusser, 1983; Muller, 1984; Traverse, 2007). The index was calculated using the relative abundances for each sample as $SI = (M/(T-M))$, where M = marine (Dinoflagellates + Forams + Leiosphaeridia) and T= Total. SI values far to 0 are related indicate major marine influence, while values close to cero indicate minor marime influence. All analyses were made using R-CRAN software.

RESULTS

A total of 80 samples were included in the statistical analysis (table 1) and 657 species were identified. These consisted of 502 morphotypes of pollen, 133 types of spores, 16 marine palynomorphs, 4 morphotypes of freshwater algae, 2 types of fungi and one as indeterminate. The mean of species per sample was 41, with a highest value of 125 species/sample and a lowest value of 7 species/sample. The rarefaction index indicated that 50% of the total species appear in the first 20 samples and the other 50% appear throughout the next 60 counted samples (figure 3). The palynological description and interpretation is extended in the paleoenvironmental section (Figures 13, 14 and 15, Table 3).

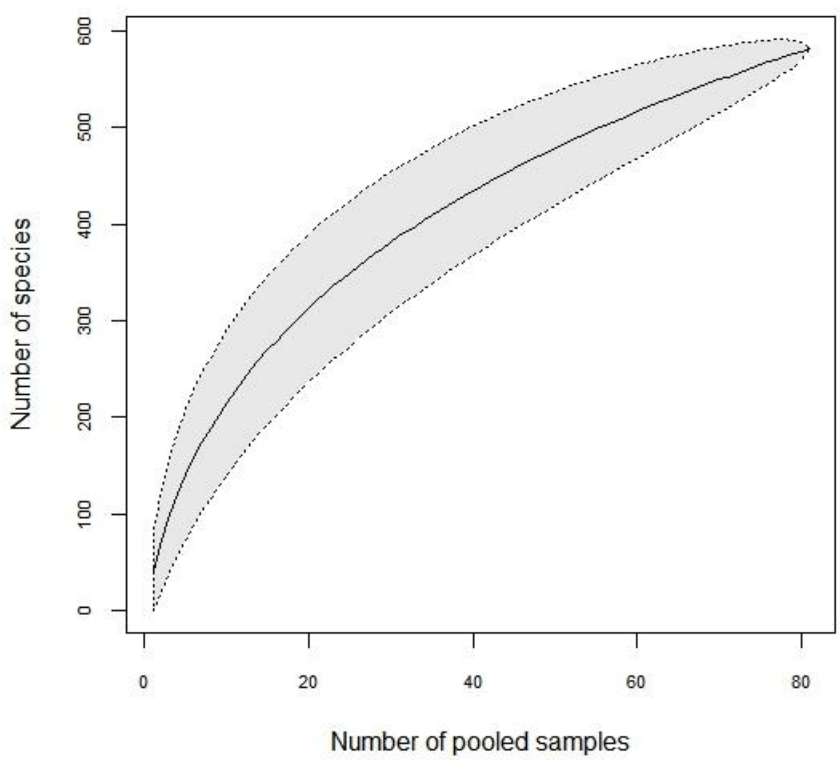

Figure 3. Bootstrap of species accumulation curve for Saltarin-1A. Shaded region shows the 95% confidence interval.

Table3. Summary of palynomorph species described for the Llanos Basin, their natural affinities and their ecology

Palynomorph	**Taxonomic Affinity**	**Literature**	**Ecology**	
Alnipollenites verus	Alnus	Germeraad et al, 1968; Lorente, 1986; Potonié, 1975	Montane	Van der Hammen, 1956
Avicennia type	Avicennia	Jaramillo and Rueda, 2013	Mangrove	Santos et al., 2008; Rull, 1997
Bombacacidites annae	Bombax ceiba type	Germeraad et al, 1968	Lowland forest, along creeks and rivers; Rain forest and mixed swamps	Hoorn, 1994; Muller et al., 1981; Lorente, 1986; Hoorn, 1993; Couper, 1958
Bombacacidites baculatus	Bombacaceae - Pachira	Lorente, 1986; Muller, 1981	Lowland forest, along creeks and rivers; Rain forest and mixed swamps	Hoorn, 1994; Muller et al., 1981; Lorente, 1986; Hoorn, 1993; Couper, 1958
Bombacacidites baumfalki	Catostemma - Bombacaceae??	Lorente, 1986	Lowland forest, along creeks and rivers; Rain forest and mixed swamps	Hoorn, 1994; Muller et al., 1981; Lorente, 1986; Hoorn, 1993; Couper, 1958
Bombacacidites bellus	Bombax	Lorente, 1986; Muller, 1981	tropical fobs/herbs	
Bombacacidites ciriloensis	Pseudobombax munguba	Lorente, 1986; Muller, 1981	Lowland forest, along creeks and rivers; Rain forest and mixed swamps	Hoorn, 1994; Muller et al., 1981; Lorente, 1986; Hoorn, 1993; Couper, 1958
Bombacacidites zuatensis	Pachira	Lorente, 1986	Lowland forest, along creeks and rivers; Rain forest and mixed swamps	Hoorn, 1994; Muller et al., 1981; Lorente, 1986; Hoorn, 1993; Couper, 1958
Chomotriletes minor	Schizaceae	Jaramillo et al., 2010	Herb; Tropical and subtropical	Jaramillo et al., 2010; Latrubesse et al., 2010; Rull

				1997
Cicatricosisporites dorogensis	Mohria type	Germeraad et al, 1968; Lorente, 1986; Regali et al., 1974; Potonié, 1975; Muller, 1981	Herb; Tropical and subtropical;	Van der Hammen, 1964
Cicatricosporites baculatus	Anemia	Lorente, 1986; Regali et al., 1974	Swampy	Van der Hammen, 1974
Clavainaperturites microclavatus	Hedyosmum	Hoorn, 1994; Martinez et al., 2013	Montane and lowland forest	Hoorn, 1994; Martinez et al., 2012; Jaramillo et al., 2013
Corsinipollenites sp.	Onagraceae?	Lorente, 1986; Regali et al., 1974	Wet tropical raingreen trees; swampy	Lorente, 1986; Regali et al., 1974; Berrio et al., 2002; Latrubesse et al., 2010
Crassoretitriletes vanraadshooveni	Lygodium microphyllum type	Germeraad et al, 1968; Lorente, 1986; Regali et al., 1974; Muller, 1981	Swampy	Latrubesse et al., 2010
Crototricolpites annemariae	Euphorbiaceae/Croton	Lorente, 1986	Lowland and Montane forest	Gonzalez-Guzman, 1967
Cyatheacidites annulatus	Lophosoria quadripinnata	Lorente, 1986; Regali et al., 1974; Muller, 1981	Tropical and subtropical;	Latrubesse et al., 2010; Rull 1997; Berrio et al., 2002
Deltoidospora adriennis	Acrostichum aureum	Lorente, 1986; Potonié, 1975	Close to mangrove vegetation; fresh-water; Tropical-subtropical	Germeraad et al, 1968; Lorente, 1986; Hoor, 1994; Rull, 1997; Latrubesse et al.,

				2010
Echiperiporites estelae	Malvaceae	Germeraad et al, 1968; Lorente, 1986; Muller, 1981	Coastal vegetation	Germeraad et al, 1968
Echitricolporites maristellae	Malvaceae	Germeraad et al, 1968; Lorente, 1989	Lowland forest	Muller, 1981
Echitricolporites mcneillyi	Ambrosia	Germeraad et al, 1968; Lorente, 1986; Muller, 1981	Mangrove; Open vegetation; aquatic	Germeraad et al, 1968; Rull 1997
Echitricolporites spinosus	Asteraceae tubuliflorae	Germeraad et al, 1968; Lorente, 1986; Regali et al., 1974; Muller, 1981	Herb	Latrubesse et al., 2010; Rull 1997
Echitriletes muelleri	Sellaginellaceae?	Lorente, 1986; Regali et al., 1974	Aquatic	Van der Hammen, 1974; Hoorn, 1994
Fenestrites longispinosus	Asteraceae-Hieracium, hypochoeris	Lorente, 1986	Herb; swampy	Latrubesse et al., 2010; Rull 1997
Fenestrites spinosus	Asteraceae liguliflorae	Germeraad et al, 1968; Lorente, 1986; Regali et al., 1974	Herb; swampy	Latrubesse et al., 2010; Rull 1997
Grimsdalea magnaclavata	extinct palm	Germeraad et al, 1968; Lorente, 1986; Muller, 1981	Swampy	Latrubesse et al., 2010; Rull 1997
ilexpollenites	Ilex	Lorente, 1986; Potonié, 1975	Montane cloud forest and lowland forest	Hoorn, 1993

Janduforia seamrogiformis	Catostemma	Germeraad et al, 1968; Lorente, 1986;Muller, 1981	Lowland forest, along creeks and rivers	Germeraad et al., 1968
Kuylisporites waterbolki	Hemitelia	Lorente, 1986; Regali et al., 1974; Potonié, 1975	Montane region	Potonie, 1975
Laevigatosporites catanejensis	Blechnaceae	Lorente, 1986	Lowland to high mountains, swamp and marshes	Germeraad et al., 1968
Longapertites vaneendenburgi	Arecaceae	Germeraad et al, 1968; Lorente, 1986; Muller, 1981	Wet tropical raingreen trees	Berrio et al., 2002
Magnastriatites howardi – M. grandis	Ceratopteris	Germeraad et al, 1968; Lorente, 1986; Muller, 1981	Coastal/ Fluvial	Latrubesse et al., 2010
Malvacipollis spinulosa	Euphorbiaceae	Lorente, 1986	Lowland forest	Lorente, 1986
Margocolporites vanwijhei	Caesalpinaceae type	Germeraad et al, 1968; Lorente, 1986; Muller, 1981	Coastal region	Germeraad et al., 1968
Matonisporites sp	Matoniaceae	Lorente, 1986	Herb; Tropical humid	Latrubesse et al., 2010; Rull, 1997
Mauritiidites franciscoi	Mauritia	Lorente, 1986	Swampy; Lowland swamps	Van der Hammen, 1956; Jaramillo et al., 2010
Monoporopollenites annulatus	Poaceae	Germeraad et al, 1968; Lorente, 1986; Regali et al., 1974; Muller, 1981	Open or aquatic vegetation; Tropical and dry temperatures	Van der Hammen, 1956; Jaramillo and Dilcher, 2001
Multimarginites	Trichanthera type	Germeraad et al, 1968;	Shurbs and herbs	Latrubesse et al., 2010; Rull,

vanderhammeni		Lorente, 1986; Muller, 1981		1997
Nijssenosporites fossulatus	Pityrogramma	Lorente, 1986	Aquatic	Silva-Caminha et al., 2010; Latrubesse et al., 2010
Pachydermites diederixi	Symphonia globulifera	Germeraad et al, 1968; Lorente, 1986; Muller, 1981	mangrove	Jaramillo and Dilcher, 2001; Hoorn, 1993
Paleosantalaceaepites cingulatus	Euphorbiaceae-	Jaramillo and Rueda, 2013		
Perfotricolpites digitatus	Merremia-Convolvulaceae	Germeraad et al, 1968; Lorente, 1986; Regali et al., 1974; Muller, 1981	Lowland forest	Gonzalez-Guzman, 1967; Jaramillo and Dilcher, 2001; Silva-Caminha et al., 2010
Perisyncolporites pokornyi	Brachypteris type - Malphigiaceae	Lorente, 1986; Muller, 1981	Coastal plain/ Forest; dominant in lower part of coastal plains	Latrubesse et al., 2010; Rull 1997; Lorente, 1986; Jaramillo et al., 2010
Podocarpidites sp.	Podocarpus	Lorente, 1986	Montane and Lowland forest	Cookson, 1947; Jaramillo et al., 2013
Polyadopollenites mariae	Mimosaceae	Lorente, 1986	Lowland forest	Duenas, 1980; Jaramillo et al., 2010
Polypodiaceoisporites pseudopsilatus	Pteris rangiferina	Lorente, 1986; Potonié, 1975	Lowland to high mountains	Lorente, 1986
Polypodiisporites usmensis	Polypodiaceae - Phlebodium aureum -	Germeraad et al, 1968; Lorente, 1986; Muller, 1981	Lowland forest	Germeraad et al, 1968; Lorente, 1986; Latrubesse et al., 2010; Rull 1997; Jaramillo

	Histiopteris incisa			et al., 2010
Proteacidites dehaani	Guavina type	Germeraad et al, 1968; Lorente, 1986; Muller, 1981	Wet tropical raingreen trees	Germeraad et al, 1968; Lorente, 1986; Berrio et al., 2002; Jaramillo et al., 2010
Proteacidites triangulatus	Proteaceae - Sapindaceae	Lorente, 1986		
Proxapertites cursus	Nypa	Germeraad et al, 1968; Lorente, 1986; Regali et al., 1974	Wet tropical raingreen trees	Germeraad et al, 1968; Lorente, 1986; Berrio et al., 2002
Proxapertites operculatus	Astrocaryum-extinct Nypa	Germeraad et al, 1968; Lorente, 1986; Regali et al., 1974; Muller, 1981		Germeraad et al, 1968; Lorente, 1986
Proxapertites tertiaria	Annonaceae	Lorente, 1986	Tree/ herbs; Tropical/dry	Lorente, 1986; Latrubesse et al., 2010; Rull 1997
Psiladiporites minimus	Artocarpus, ficus, socratea	Germeraad et al, 1968; Lorente, 1986	Lowland forest	Germeraad et al, 1968; Lorente, 1986; Jaramillo et al., 2010; Latrubesse et al., 2010
Psilamonocolpites medius	Arecaceae	Lorente, 1986	Wet tropical raingreen trees	Berrio et al., 2002; Jaramillo et al., 2010; Silva-Camhina et al., 2010
Psilaperiporites minimus	Amaranthaceae-Chenopodiaceae	Lorente, 1986; Regali et al., 1974	Lowland forest	Lorente, 1986; Van der Hammen, 1964; Jaramillo and Dilcher, 2001; Rull, 2002

Psilaperiporites robustus	Chenopodiaceae	Lorente, 1986; Regali et al., 1974	Lowland forest; Swampy	Lorente, 1986; Van der Hamman and Hooghiemstra, 2000
Psilastephanocolporites fissilis	Polygalaceae	Lorente, 1986; Regali et al., 1974	Lowland forest	Lorente, 1986; Hoorn, 1993
Psilastephanoporites stellatus	Malpighiaceae	Lorente, 1986; Regali et al., 1974	Wet tropical raingreen trees	Berrio et al., 2002
Psilatricolporites caribbiensis	Theaceae	Germeraad et al, 1968; Lorente, 1989; Regali et al., 1974	Lowland forest	Germeraad et al, 1968; Hoorn, 1993; Lorente, 1986
Psilatricolporites crassus	Euphorbiaceae	Germeraad et al, 1968	Wet tropical raingreen trees	Germeraad et al, 1968; Berrio et al., 2002
Psilatricolporites devriesi	Humiria	Lorente, 1986	Wet tropical raingreen trees	Lorente, 1986; Berrio et al., 2002; Jaramillo et al., 2010; Herrera et al., 2008
Psilatricolporites divisus	Sapotaceae - Solanaceae?	Lorente, 1986; Regali et al., 1974	Wet tropical raingreen trees; Lowland forest	Berrio et al., 2002; Regali et al., 1974
Psilatricolporites maculosus	Crysophyllum	Lorente, 1986; Regali et al., 1974	Wet tropical raingreen trees	Berrio et al., 2002
Psilatricolporites operculatus	Alchornea	Germeraad et al, 1968; Lorente, 1986; Regali et al., 1974; Muller, 1981	Lowland and montane forest; along rivers; wet tropical raingreen trees	Germeraad et al, 1968; Lorente, 1986; Regali et al., 1974; Muller, 1981; Berrio et al.,

				2002
Psilatricolporites pachydermatus	Sapotaceae - Omphalocarpum	Lorente, 1986	Wet tropical raingreen trees	Lorente, 1986; Berrio et al., 2002; Jaramillo et al., 2010
Retidiporites magdalenensis	Proteaceae	Germeraad et al, 1968	Wet tropical raingreen trees	Berrio et al., 2002
Retistephanoporites crassiannulatus	quararibea - Bombacaceae??	Lorente, 1986	Lowland forest	Lorente, 1986; Jaramillo and Dilcher, 2001; Jaramillo et al., 2010
Retitricolpites simplex	Anacardiaceae?	Lorente, 1986	Lowland forest	Lorente, 1986; Jaramillo et al., 2010; Silva-Caminha et al., 2010
Retitricolporites irregularis	Amanoa	Germeraad et al, 1968; Lorente, 1986; Regali et al., 1974; Muller, 1981	Lowland forest	Germeraad et al, 1968; Lorente, 1986; Jaramillo and Dilcher, 2001; Jaramillo et al., 2010
Rhoipites guianensis	Sterculiaceae-Tiliaceae	Germeraad et al, 1968; Lorente, 1986; Regali et al., 1974; Muller, 1981	Lowland forest	Lorente, 1986; Jaramillo and Dilcher, 2001; Jaramillo et al., 2010
Spinizonocolpites baculatus- S. echinatus	Nypa	Germeraad et al, 1968; Lorente, 1986; Regali et al., 1974; Muller, 1981	Aquatic	Lorente, 1986; Jaramillo and Dilcher, 2001; Jaramillo et al., 2010
Stephanocolpites costatus	Apocynaceae	Germeraad et al, 1968	Lowland forest	Hoorn, 1993

Striatopollis catatumbus	Crudia - Macrolobium Fabaceae	Germeraad et al, 1968; Lorente, 1986; Regali et al., 1974; Muller, 1981	Lowland forest	Germeraad et al, 1968; Lorente, 1986; Jaramillo and Dilcher, 2001; Jaramillo et al., 2010
Striatricolporites tenuissimus	Anacardiaceae, Caesalpinaceae or Campanulaceae	Lorente, 1986	Lowland forest	Lorente, 1986; Jaramillo and Dilcher, 2001; Jaramillo et al., 2010
Tetracolporopollenites transversalis/maculosus	Sapotaceae	Jaramillo and Rueda, 2013	Lowland forest	Germeraad et al, 1968; Jaramillo and Dilcher, 2001; Jaramillo et al., 2010
Verrucatisporites specious	Polypodiaceae	Lorente, 1986	swampy	Germeraad et al, 1968; Lorente, 1986; Jaramillo and Dilcher, 2001; Jaramillo et al., 2010
Verrutricolporites rotundiporus	Crenea	Germeraad et al, 1968; Lorente, 1986; Muller, 1981	Lowland forest	Jaramillo and Dilcher, 2001; Jaramillo et al., 2010
Zonocostites ramonae	Rhizophora type	Germeraad et al, 1968; Lorente, 1986; Muller, 1981	Mangrove; dominant in lower part of coastal plains	Germeraad et al, 1968; Lorente, 1986; Hoorn, 1993; Latrubesse et al., 2010; Rull 1997

Chronostratigraphy

The graphic correlation method to Saltarin-1A is based on 22 palynomorphs that were selected, because their stratigraphic range is well known and has been used to delimit palynological zones (Jaramillo et al., 2010). Based on the FAD and LAD data (figures 4 and 5), the interval between 23-17 My is delimited by the LAD of *Cyclusphaera scabrata* associated with the FAD and LAD of *Rugutricolporites* intensus, and the FADs of *Psilastephanoporites herngreenii, Grimsdalea magnaclavata, Nijssenosporites fossulatus* and *Clavainaperturites microclavatus*. The interval between 17-10 My is limited by the FADs of *Fenestrites spinosus, Paleosantalaecipites cingulatus, Echitricolporites spinosus, Retipollenites crotonicollumelatu* and, *Crassoretitriletes varaandshooveni*. The interval between 10 to 5 My is defined by the FAD of *Cyatheacidites annulatus* and the LAD of *Psilastephanoporites herngreenii*. The linear model (figure 6a), based on FADs and LADs, estimates an age between 25-0 My.

The maximum likelihood calculated presents an interval of age between 24-5 My to Saltarin-1A (Figures 6). While the linear model (figure 7b) presents an interval between 27-2 My. The age range estimated with the maximum likelihood method is wide for most of the samples between 670-640m, however the estimated age for this interval is from 21 to 19.5 My. The samples from 145 to 90m, present two probabilities of age for the top of Saltarin core-- 18-13 My and 9-5 My. According to the linear model, the best age range to the top of the Saltarin core could be 9-5 My.

After comparing both methods, the age proposed to Saltarin-1A is between the Lower Miocene to the Upper Miocene (21-5 My) (Figure 8).

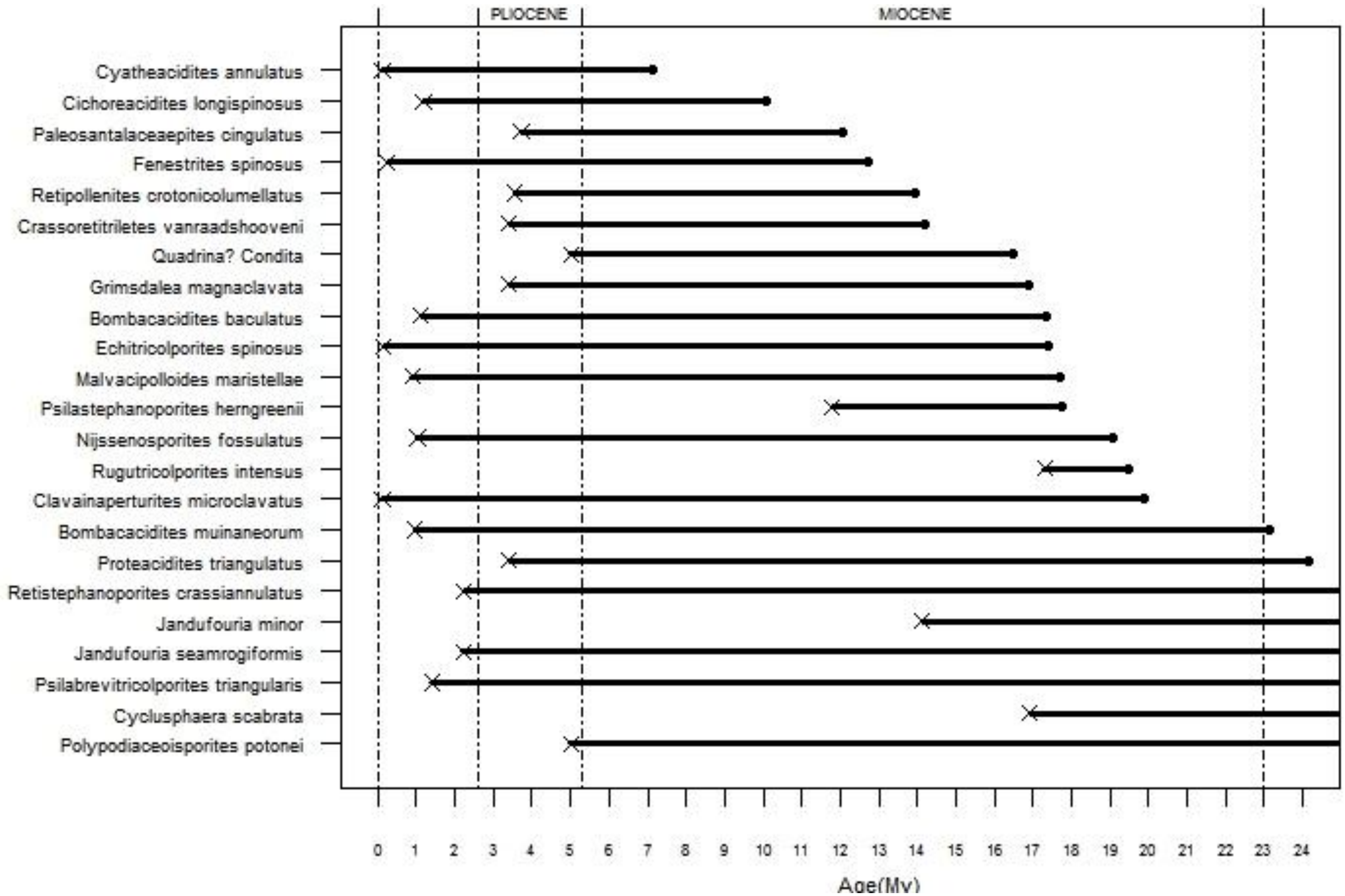

Figure 4. Age range of key species selected to Saltarin-1A

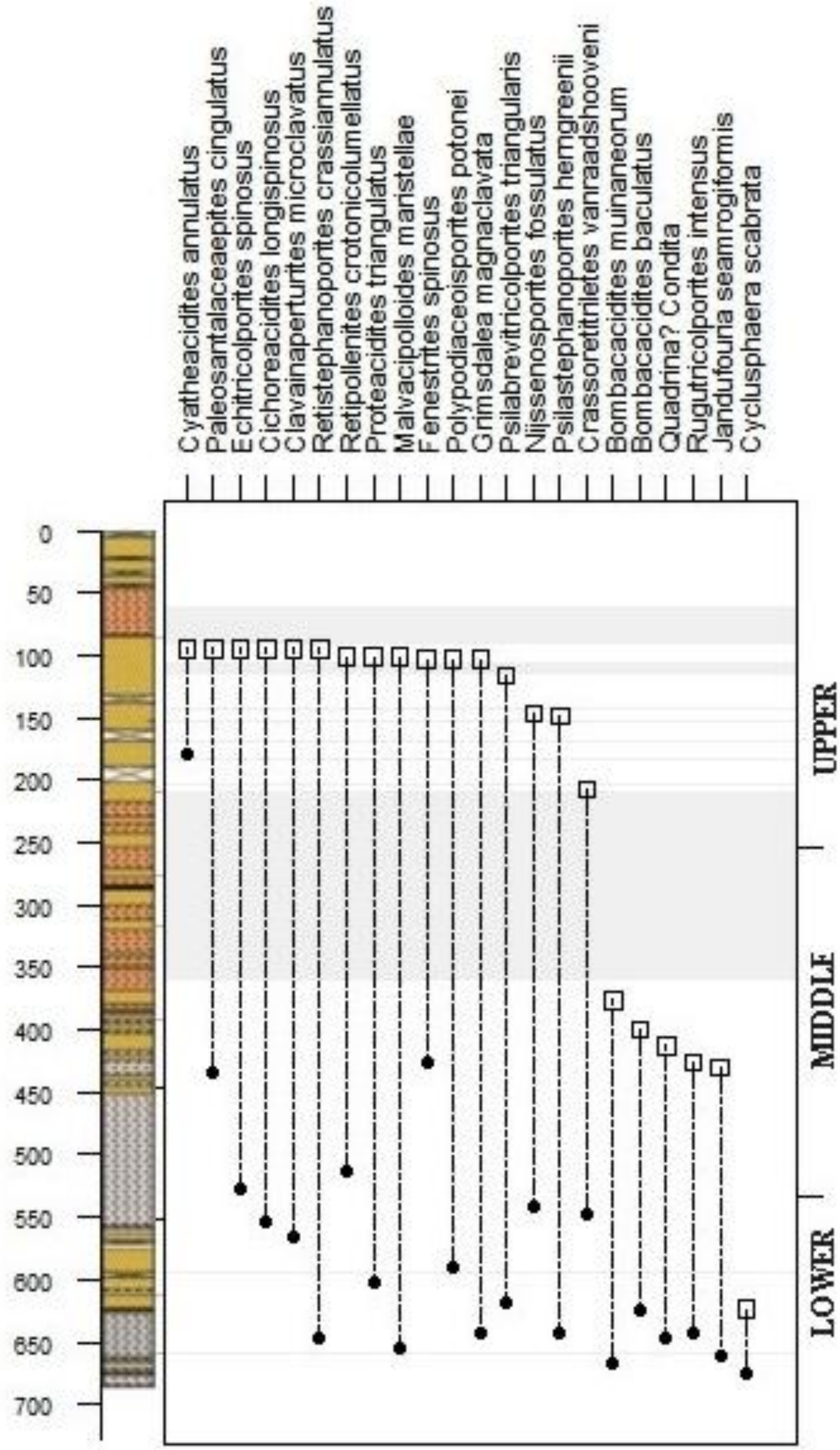

Figure 5. Graphic correlation Saltarin 1A based on palinological zonation proposed for Neogene of Northern South America. Gray areas indicate sterile levels.

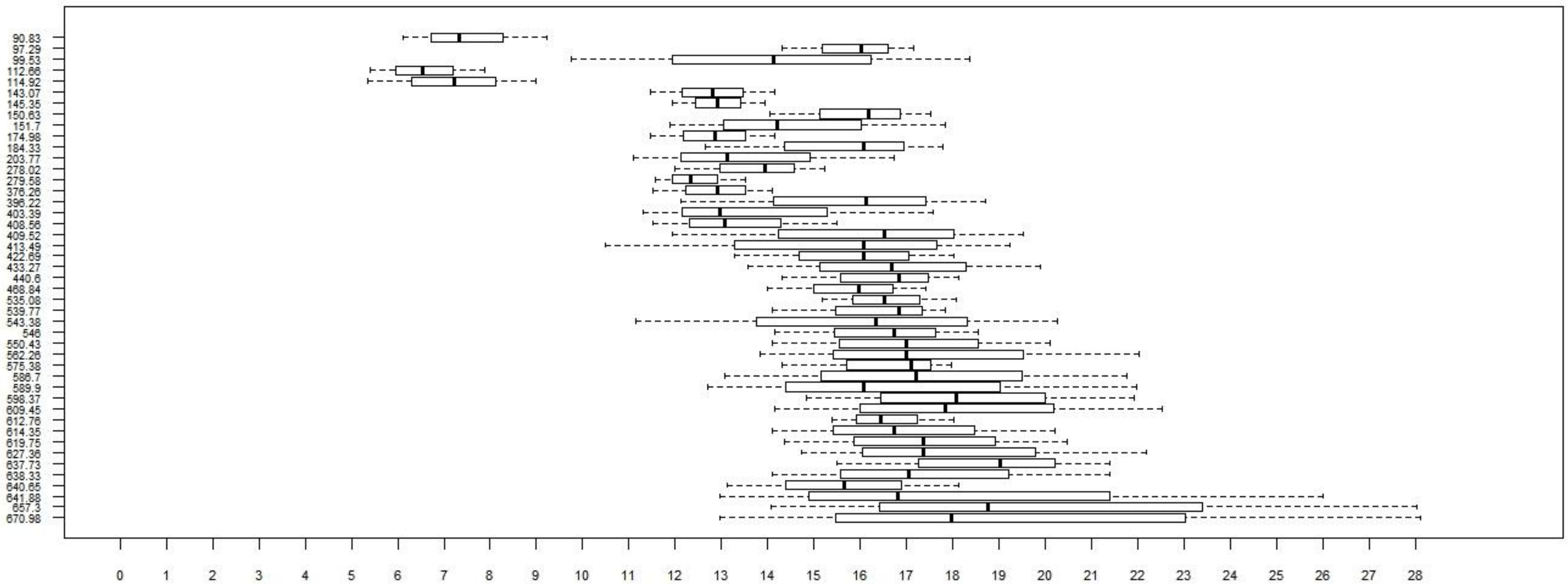

Figure 6. Boxplot of age estimate for each sample of Saltarin-1A. Maximum likelihood estimates with 95% confidence interval

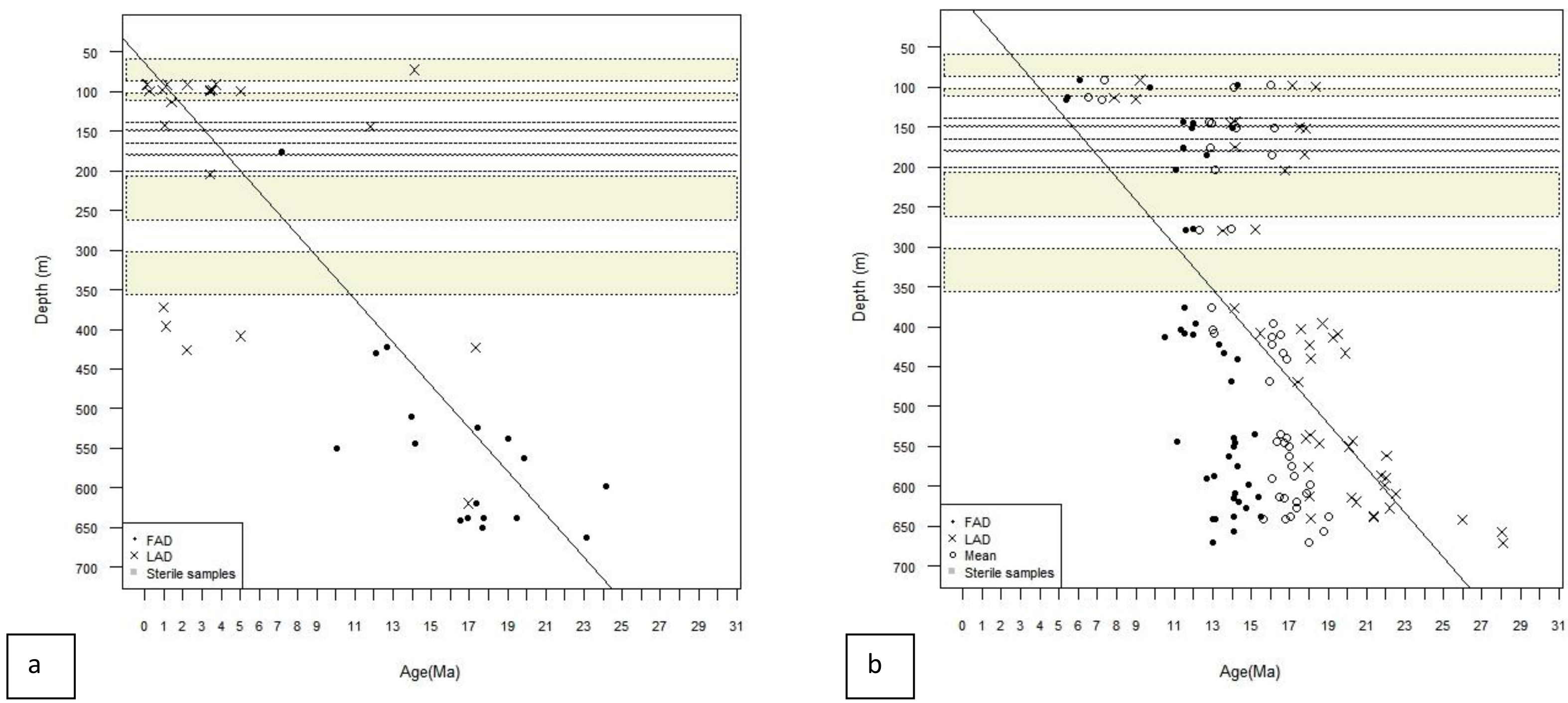

Figure 7. Linear model of the estimated age from Saltarin-1A. a. Graphic correlation. b. Maximum likelihood

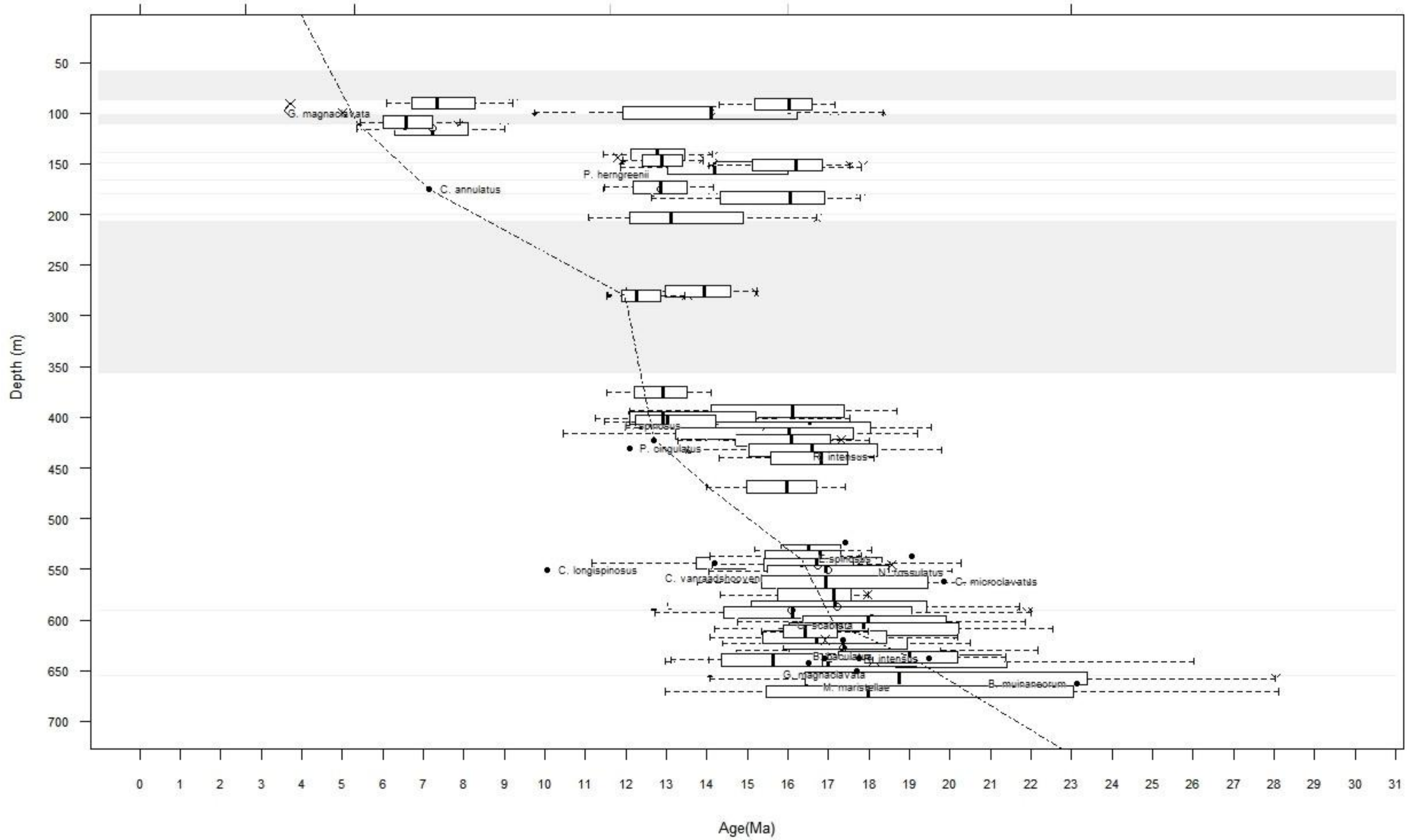

Figure 8. Line of Correlation (LOC) estimated to Saltarin-1A based in comparison of Maximum likelihood and graphic correlation.

Salinity Index

The histograms of frequency (Figures 14) of pollen and spores show a similar tendency -- when the percent of pollen is high, the percent of spores also is high. Otherwise, the histogram of marine elements shows an inverse tendency-- when the percent of pollen and spores increases, the percent of marine elements decreases. These relationships are confirmed in the figure 9 which shows a negative correlation between pollen and marine elements (r=-0.64) and also between spores and marine elements (r=-0.527). Both relationships were highly significant with P-values<0.05 and $r^2=0.3$. The relationship between freshwater algae with other groups was not clear, because the correlation values were close to zero. For this reason the SI proposed by Rull (2000, 2002) is not useful in this work because the relationship between freshwater algae and marine elements is not significant.

The PCA (Fig.10) supports a separation of the samples with a high percent of marine elements from those with a high percent of pollen and spores. The two first components explain this separation. The first component, with 63% of total variance, separates the samples in two groups: marine elements and pollen-spores-freshwater algae elements. The marine samples are grouped at one extreme where there is a major representation of marine elements, corresponding to the intervals 650-620m and 530-400m (figures 2, 11, 14). The second component, with 33.1%, presents a gradient of separation between pollen-freshwater algae and spores.

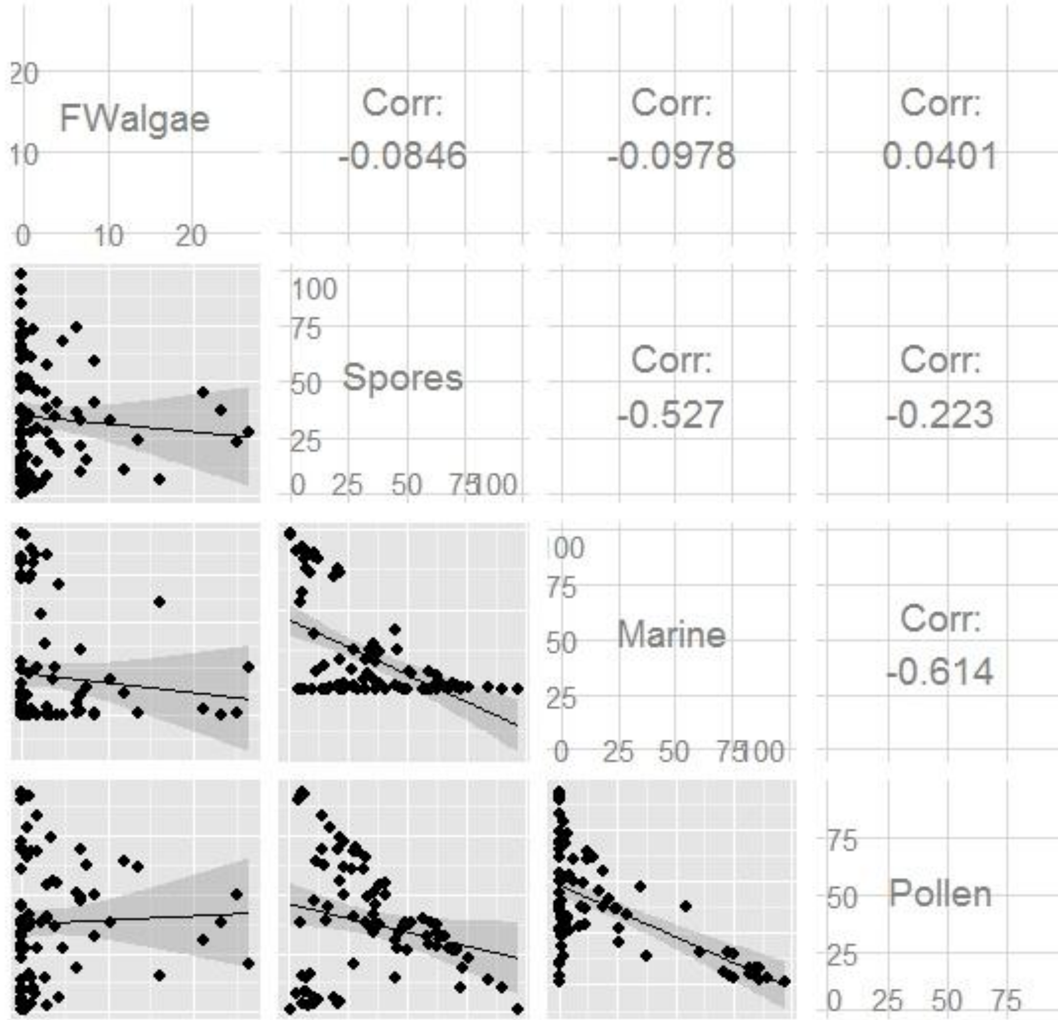

Figure 9. Pairs plot showing the correlation between the four groups analyzed. The low part is showing the relation of the four variables with the linear regression. The shadow region shows the 95% confidence interval. The upper part is showing the values of correlation.

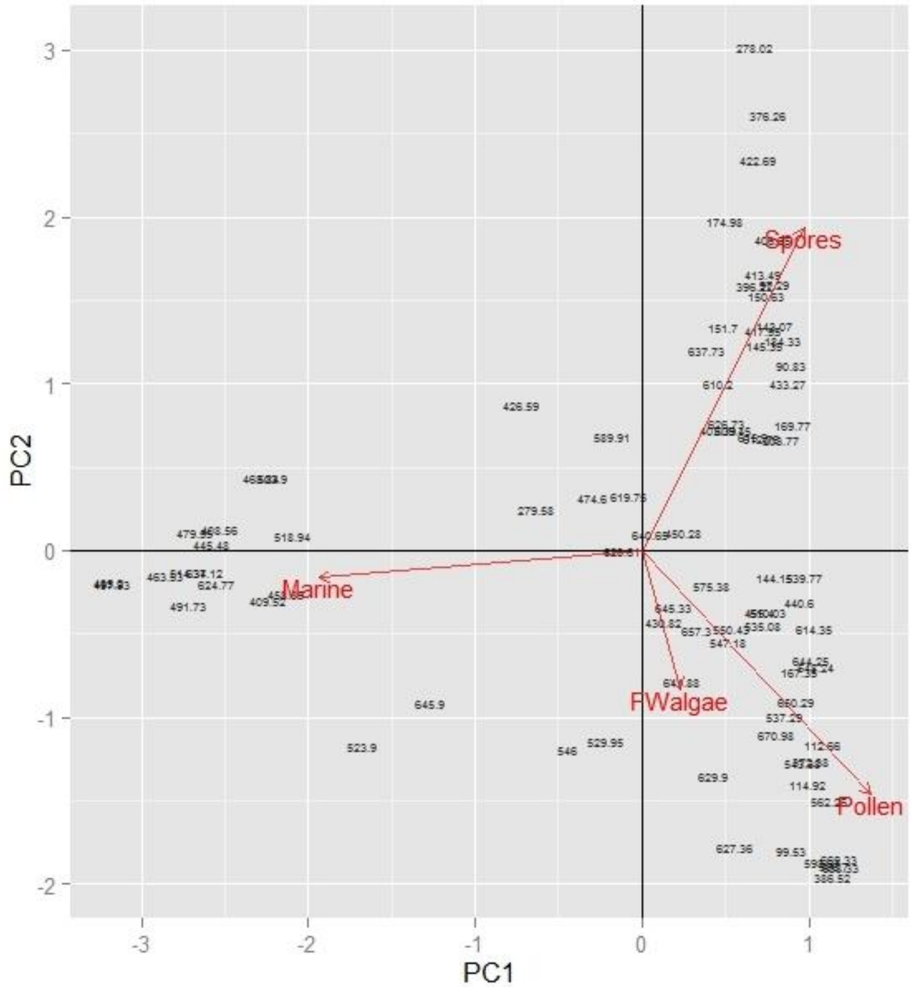

Figure 10. Principal Component Analysis of palynological data for Saltarin1-A. The eigenvalues are: 1.3088 to axis1 and 1.1177 to axis2

Both salinity indexes indicate six flooding marine events (figures11). Into these events are included the intervals separated with the PCA (10). The marine intervals shown in figures 10, 11, 13, 14 begin between 654-640m, with an age of 19.8-19.2 My, with the peack of marine elements (53%) in 645.9m, corresponding to 19.5 My. The second marine interval is found between 638-616m with an age between 19.23 to 18 My, presenting a peack of marine elements (80%) at both 634m and 624m. The levels with low marine elements representation of this interval have a percent of 10-25%. The third interval, located between 562-542m, indicates an age of 16.6-16.3 My and the high marine level with 33% is found at 546m. The fourth marine event, in the interval 537.29 to 386m and an age of 16.3-12.5 My, is the biggest marine flooding event in thickness and duration for Saltarin-1A, with values from 98 to 80% of marine elements. The last two events are located at 151.7m and 146-144m, where the marine percent is low in comparison with other marine levels, with values ranging from 10-3%.

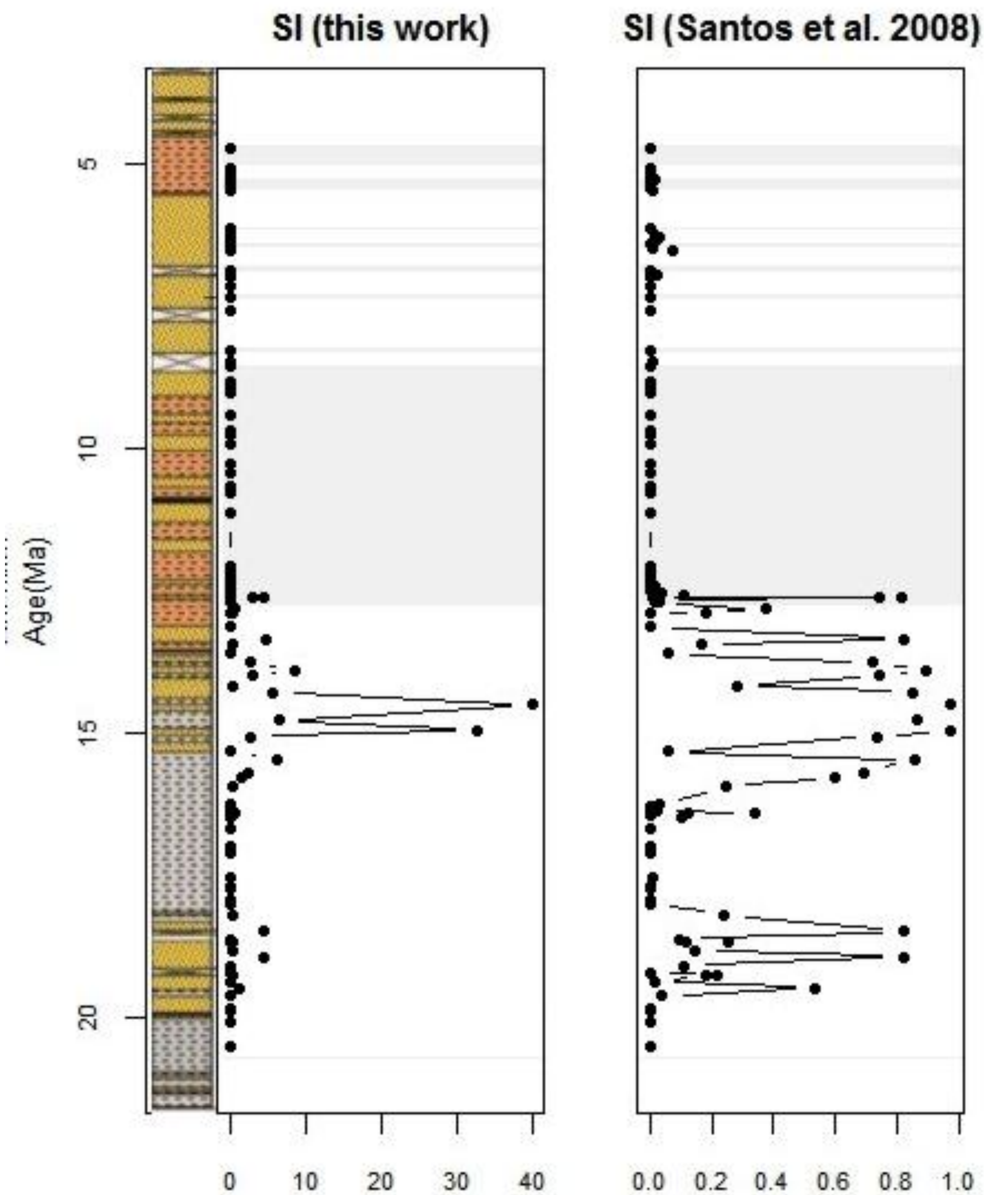

Figure 11. Comparison between Salinity indexes to Saltarin-1A. Gray areas correspond to sterile levels. High values indicate major marine influence

Paleoecology

Palynological zonation is based on the presence or absence of marine elements (figures 12, 13,14).

The interval between 670.98 and 657.3m (20.5 to 19.9 My) is characterized by gray mudstones and coal. Pollen dominate the flora ranging from 60-73%, mainly associatd with trees. At the end of this interval, the percent of pollen decreases to 26%. Dominant taxa are *Bombacacidites* group, *Retitrescolpites irregularis, Mauritidiites franciscoi, Siltaria santaisabelensis* and *Tetracolporopollenites transversalis, Tetracolporopollenites maculosus* and *Psilatricolporites pachydermatus.* Spores comprise only 6-16% of the flora. Freshwater algae and marine elements are not represented in this interval.

The level 654.97m (19.8 My) is characterized by white sandy-mudstones and was sterile.

The interval between 650.29 and 640.65 m (19.6 to 19.25 My) is comprised of gray mudstones (650.29m) and green mudstones (645.9-640.65 m). Pollen dominates the flora ranging between 3 - 50%) and is accompanied by a relatively high percentage of spores (10 - 25%). Dominant taxa are *Perisyncolporites pokornyi, Laevigatisporites* group (monolete psilate), *Polypodiisporites* group (monolete verrucate), *Retitrescolpites irregularis* and *Mauritidiites franciscoi*. There is a low percentage of marine palynomorphs at the base of the interval (3%), but the percentages increases to 18-53 % higher in the section. The marine taxa are mainly forams, *Spiniferites* and Dinocyst undiff.. Freshwater algae are present (3% of the palynoflora) and dominated by *Botryoccocus* sp.

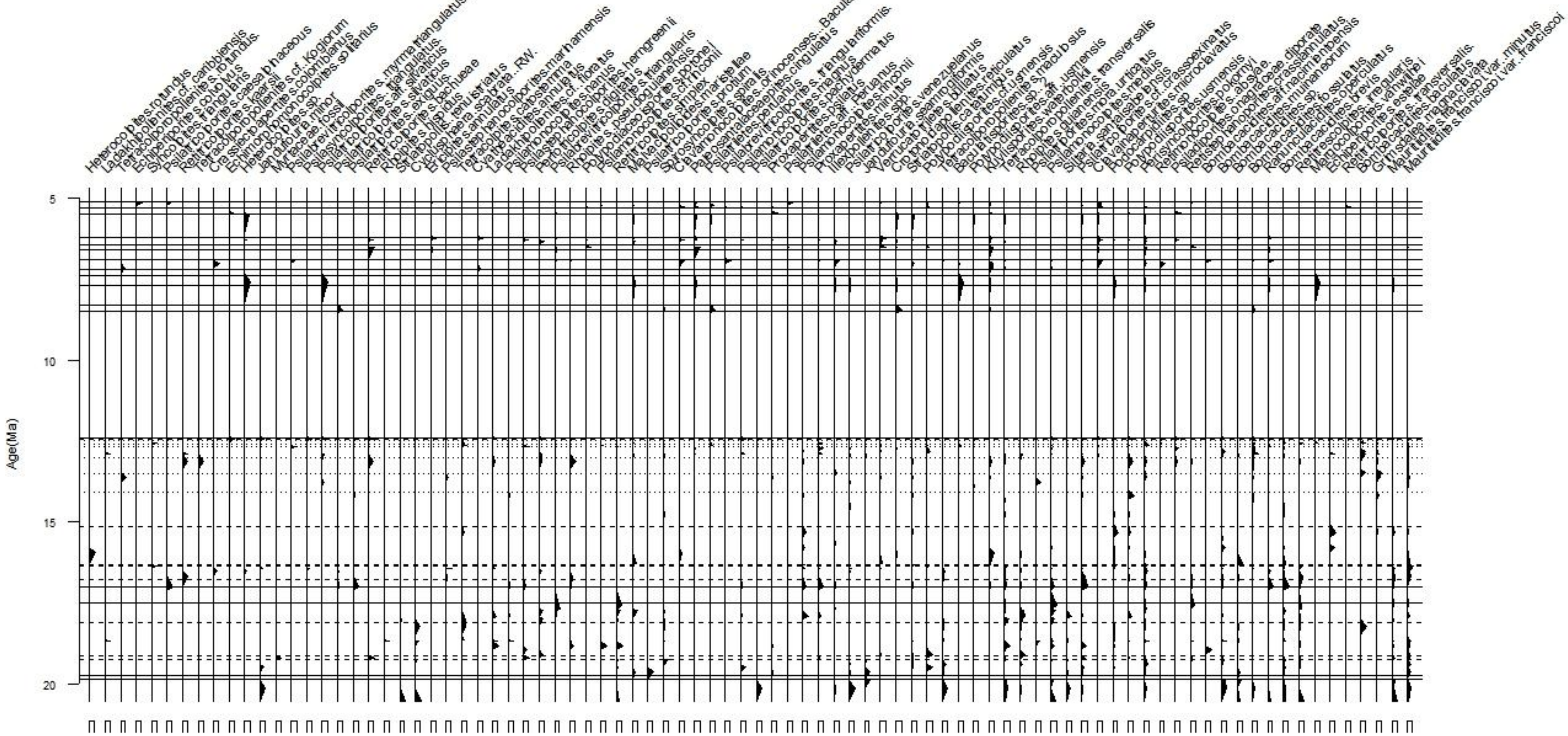

Figure 12. Variation of relative abundances of pollen associate to trees elements from Saltarin during Miocene.

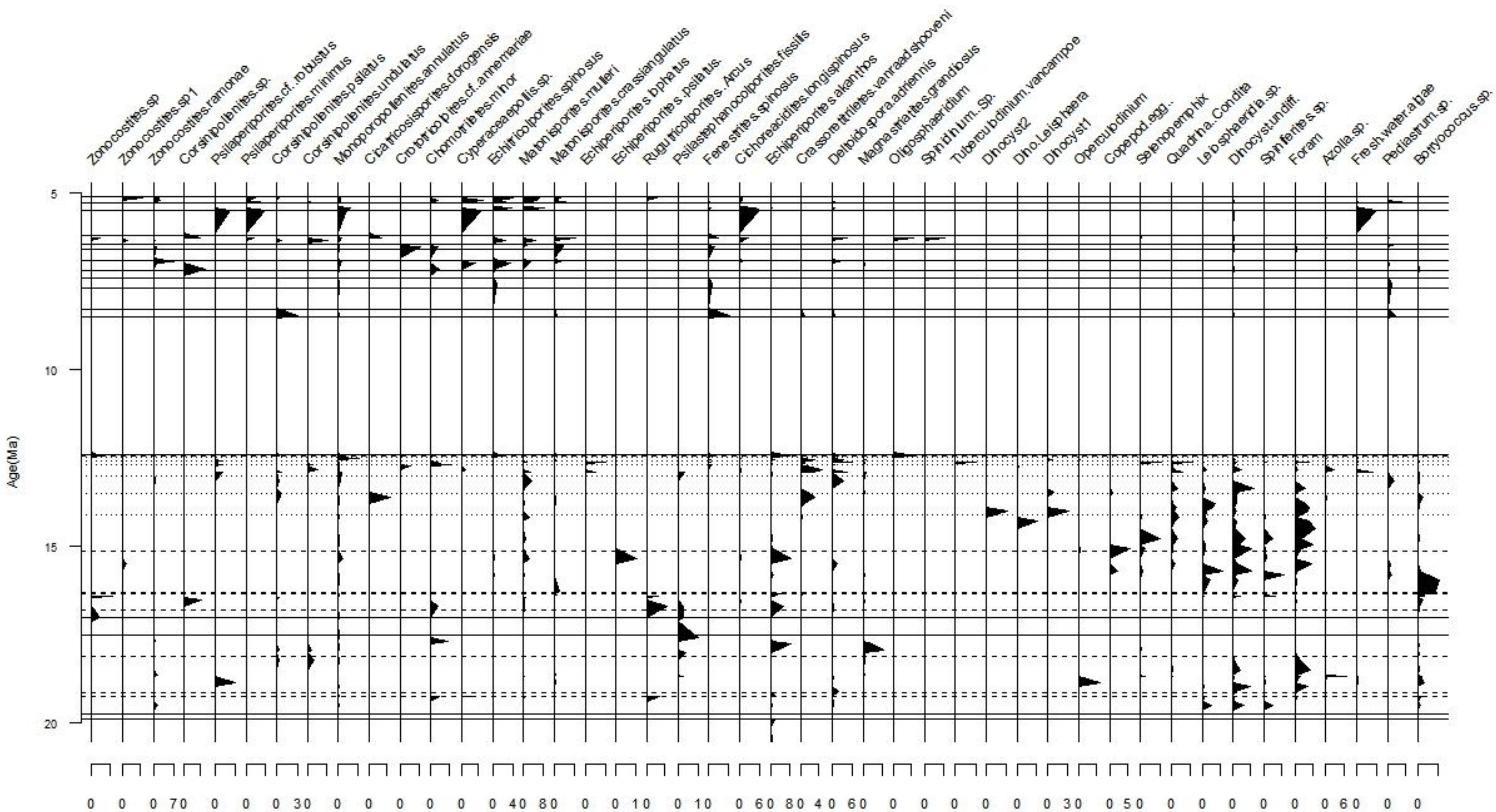

Figure 13. Variation of relative abundances of palynomorphs associate with mangrove, grasses and herbs, marine and freshwater eenvironments from Saltarin during Miocene.

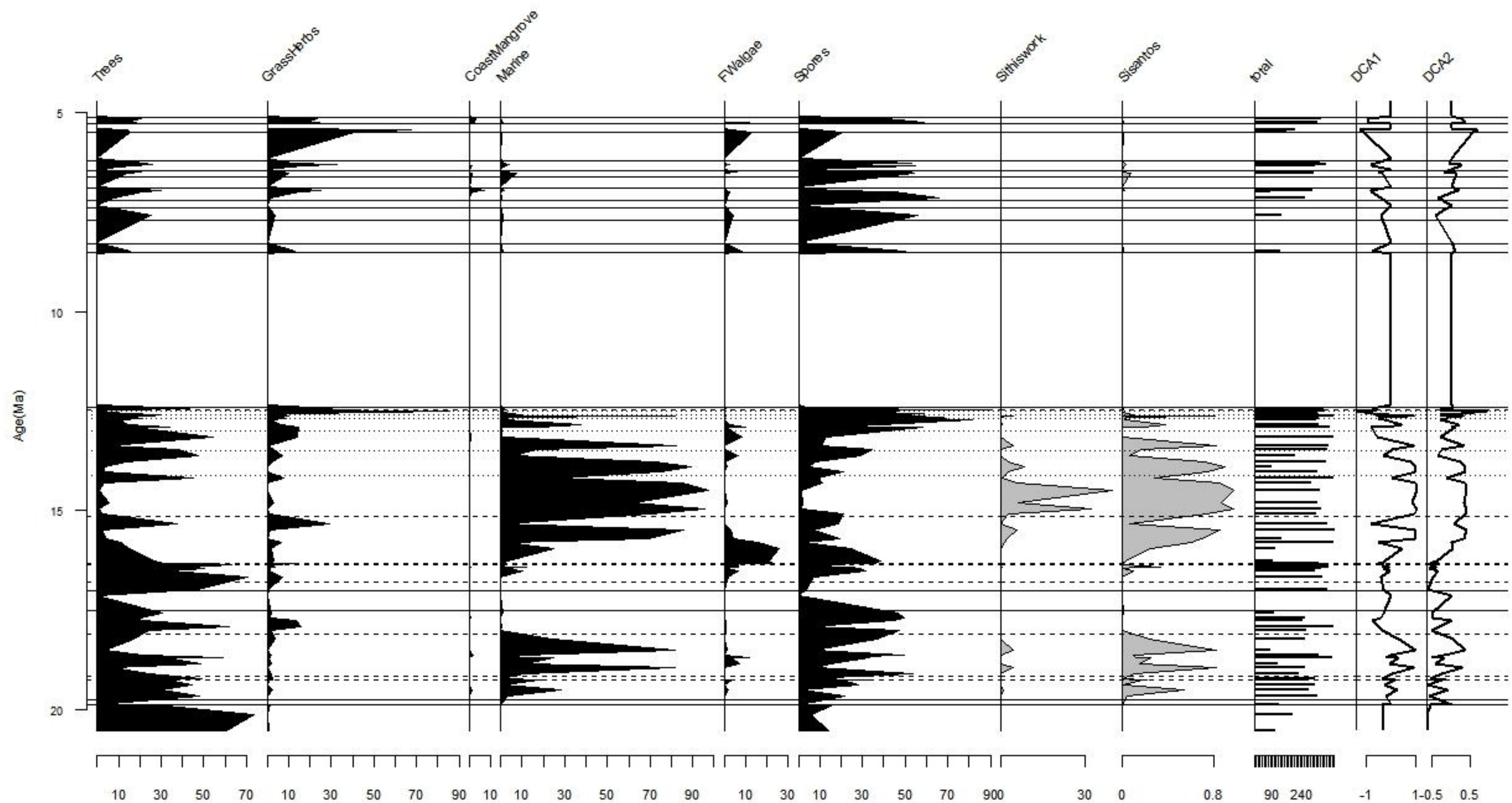

Figure 14. Diagram with relative abundances of ecological groups, salinity index and DCA analysis for Saltarin.

The 638.33 m (19.23 My) level is characterized by gray mudstones. Tree pollen occurs in high frequency (49%) with the presence of *Mauritidiites franciscoi, Retitricolpites “zigzaguensis”, Scabratricolporites planetensis, Retitrecolpites irregularis, Bombacacidites* group and *Psilatricolporites cf. crassiexinatus*. Only 1% percent of the flora are spores. Marine and freshwater algae are absent.

The interval between 637.73 and 619.75 m (19.1 to 18.2 My) is characterized by green mudstones. Spores dominate the flora the 637.73 m (53%) level. Dominant taxa are *Laevigatosporites tibuensi* and *Polypodiisporites usmensis*. Tree pollen comprises 20% of the flora and is dominated by *Mauritidiites franciscoi*. Marine elements are present and comprise 11% of the palynoflora with forams and Dinocyst undiff.. At the 634.12 m level, there is an increase in the percentage of forams and Dinocyst undiff. (80% of total). Subsequently, at the 629.9 to 626.73 m interval, marine elements decrease (9-25%) concomitant with the increase in the representation of spores, including *Laevigatosporites tibuensis*, *Polypodiisporites* group. There is also pollen mainly associated trees, e.g., *Perisyncolporites pokornyi, Retitrescolpites irregularis, Bombacacidites* group, *Mauritidiites franciscoi* and *Psilamonocolpites rinconii*. Freshwater algae range from 3-11%, dominated by *Botryoccocus* sp. and *Azolla* sp. At the 624.77 m interval (18.5 My) marine elements dominate once again (81%). Tree pollen comprises about 8 % and freshwater algae 1%. At the top of this interval, the level 619.75m shows a decrease of marine elements (54%) and an increase of pollen and spores, 20% and 36% respectively. Freshwater algae are absent.

The interval 615 to 609.45 m (18 to 17.56 My) is characterized by green mudstones. Spores and pollen of angiosperms are dominant and are represented by *Rhoipites guianensis, Psilamonocolpites* group, *Polypodiisporites usmensis, Mauritidiites franciscoi, Retitrescolpites* *irregularis, Tricolpites* cf. *clarensis, Polypodiisporites usmensis, Laevigatosporites tibuensis, Perysincolporites pokornyi* and *Magnastriatites grandiosus.*

Above the 609.45 m level, sterile sands are punctuated by a depositional hiatus. After this, the interval 586.7 to 562.26m (16.9 to16.6 My) is characterized by gray mudstones. Tree pollen dominates characterized by *Bombacacidites group, Ranunculacidites operculatus*, *Striatopollis catatumbus*, *Retitrescolpites irregularis*, *Rhoipites guianensis*, *Tetracolporopollenites transversalis* and *Mauritidiites franciscoi.*

The interval 550.43 to 543.38m (16.5-16.37 My) is characterized by green mudstones. Tree pollen dominates the flora with values ranging between 30-50%. The dominant taxa associated with trees are *Mauritidiites franciscoi, Perisyncolporites pokornyi, Psilatricolporites medius, Rugutricolporites felix, Retitrescolpites irregularis*, and species of *Bombacacidites* and *Tetracolporopollenites.* Marine elements are represented by forams, dynocysts and other dinoflagellates such as *Spiniferites* in low percentages, except at the 546 m level where the marine elements increase to 33%. Freshwater algae comprise about 7% of the palynoflora (*Botryoccocus* sp.).

The 539.77 m (16.33 My) level is characterized by green mudstones. Tree pollen is dominant (50%). The common taxa are *Striatopollis catatumbus, Podicarpidiites* sp., *Mauritidiites franciscoi, monoporopollenites annulatus, Retitrescolpites irregularis* and *Echiperiporites akanthos*. Fresh water algae occur in low percentage (*Botryoccocus* sp.).

The interval from 537.29 to 386.52 m (16.32 to 12.5 My) is green mudstones. This interval presents the major sequence of marine elements and will be described in seven events:

Subinterval 537.29 to 510.03 m (16.32-15.3 My): the lowest part of this interval is dominated by spores (40%), primarily *Polypodiisporites* group and *Laevigatosporites tibuensis*.

Tree pollen is well represented (30%) and is dominated by *Mauritidiites franciscoi and Perisyncolporites pokornyi*. Freshwater algae range between 15-22% (primarily *Botryococcus* sp.). Marine palynomorphs are present but in low percentages. In the middle part of this interval, marine elements increase and are dominated (60-85%), and are comprised of forams, Dinocyst undiff., *Quadrina condita*, *Spiniferites* sp, *Selenopemhix* sp. Freshwater algae comprise 15 to 25% percent of the palynoflora dominated by *Botryoccocus* sp and *Pediastrum* sp. At the top of this interval marine elements decrease to 5%. The palynoflora is dominated by spores increases until almost 40%. Freshwater algae are absent at the top of this interval.

Subinterval 503.9 to 474.6 m (15.07-14.18 My) is dominated by marine elements with values from70% to almost 100% and is comprised of forams, Dinocyst undiff. and *Quadrina condita*. Marine elements decrease to about 28% at the top of this interval (474.6m).

The Subinterval between 468.84 and 455.4 m (14-13.6 My) is dominated by marine elements (70-90%), except at the top of the interval where the percentage of marine elements decreases to only 6%. The major marine elements are forams, Dinocyst undiff. and *Quadrina condita*. The pollen at the top of the interval is primarily tree pollen (50%). The dominant taxa are *Mauritidiites franciscoi, Perisyncolporites pokornyi, Retitrescolpites irregularis* and *Grimsdalea magnaclavata*. In addition, freshwater algae increase at the top of the interval dominated by *Azolla* sp, *Pediastrum* sp., and *Botryoccocus* sp.

The subinterval between 450.28 and 440.6 m (13.5-13.1 My) is dominated by tree pollen, G*rimsdalea magnaclavata* and *Mauritidiites franciscoi*. Spores are high at the base of the interval (34%). Marine elements dominate the middle of this interval (82%), comprised of *Quadrina condita,* Dinocyst undiff. and forams. At the top of the interval the freshwater algae comprise 10 % of the palynoflora, primarily *Pediastrum* sp.

The subinterval between 433.27 and 422.69 m (12.8-12.7 My) is dominated at the base and the top of the interval by spores, 57% and 82% respectively. The dominant taxa are *Laevigatosporites tibuensis*, *Polypodiisporites* group and *Deltoidospora* sp. Pollen percentages are generally low, except at the 430.82 m level, with a percent of almost 40% dominated by *Bombacacidites* group, *Striatopollis catatumbus*, *Clavainaperturites microclavatus* and *Podocarpidiites* sp. Freshwater algae comprise 10% of the palynoflora. Marine elements are present in low frequency at the base and the top of the interval (1% and 2% respectively), but increase to 18-37% in the middle portion. The marine elements are comprised of *forams, Dinocyst undiff.* and *Quadrina condita*.

Subinterval 417 to 406.95 m (12.65-12.63 My) is dominated by high spore percentages at the base of the interval (about 60%). Tree pollen ranges between 15-20%. Marine elements are present but occur in low percentages (3%). However, in the middle of this interval, marine elements dominanted the palynoflora ranging between 74-82% (forams, Dinocyst undiff., *Quadrina condita* and *Selenopemphix* sp.) The top of the interval is also dominated by spores (60%). The dominant taxa are *Deltoidospora* sp, *Polypodiisporites* group and *Matonisporites* sp.The pollen increases to 30% dominated by *Perysincolporites pokornyi*, *Mauritidiites franciscoi*, *Monoporopollenites annulatus*. Marine elements decrease to 1%.

Subinterval 403.39 to 385.52 m (12.57 to 12.50 My) is dominated by spores at the base and in the middle of the interval ranging between 47-58%. Pollen ranges between 15% - 85% and is mostly associated with grasses and herbs, dominated by *Monoporopollenites annulatus*. Marine elements are present in low frequency but decrease to 0%.

Level 376.26 m (12.47 My) is characterized by the presence of coal. Spores dominate this flora (88%), comprised mainly of *Laevigatosporites tibuensis*. The remaining pollen is associated with trees.

Level 372.38 m (12.44 My) is characterized by orange mudstones. The palynoflora is dominated by tree pollen (40%) and 30% of the palynoflora is comprised of pollen associated with grasses and herbs, dominated by *Monoporopollenites annulatus*.

The Guayabo Fm is comprised of sandstones and orange mudstones. There are also known depositional hiatus. Samples between 355.94-206.29 m (12.34 to 8.5My), 110.83-101.35 m (5.4 to 5.2My) and 86.3- 58.28 m (5 to 4.7 My) were sterile. Only the levels with palynomorphs between 203.77 to 58.28, will be described.

Levels 203.77 m (8.4 My) and 184.33 m (7.5 My) are characterized by sandy sediments. Samples are comprised of 50% spores, 6% are freshwater algae, mainly *Pediastrum* sp., and 30% are pollen associated with trees, dominated by *Crotonoidapollenites reticulatus*, *Podocarpidiites sp*, *Corsinipollenites psilatus* and *Mauritidiites franciscoi.*

The interval 174.98-167.35m (7.1 to 6.9 My) has two lithologies, sands and gray mudstones. Spores range between 16-65%. Herbaceous pollen ranges from 15 to 25%; the dominant taxa are *Echitricolporites spinosus*, *Monoporopollenites annulatus* and *Zonocostites ramonae*. Pollen associated with mangroves comprises 7% of the palynoflora at the top of the interval which also includes pollen associated with trees, i.e., *Clavainaperturites microclavatus* and *Psilabrevitricolporites triangulariformis.*

The interval between 151.7m-150.63 m (6.5 to 6.4 My) is characterized by sandstones. Spores comprise 53% of the palynoflora. Marine elements decrease in this interval from 8 to 1%.

Pollen associated with mangrove, herbs and grasses is almost 6% and freshwater algae appear in the top of this interval and comprise 6% of the palynoflora.

The interval between 145.35-143.07 m (6.3-6.2 My) is dominated by spores at the base and the top of the interval. Pollen associated with mangroves is present at the top and middle of the interval and is accompanied by approximately 3.5 % marine elements. Grass and herbaceous pollen increases to 25% of the palynoflora. The dominant taxa are mainly *Monoporopollenites annulatus*, *Echitricolporites spinosus*, *Fenestrites spinosus* and *Cichoreacidites longispinosus*. In the middle of the interval freswater algae comprise 2% of the palynoflora.

The last two intervals 114.92-112.66 m and 99.53-90.83 m (5.4 - 5 My) exhibit an increase of pollen associated with grasses and herbs (50-25%), dominated by*Monoporopollenites annulatus*, *Echitricolporites spinosus*, *Fenestrites spinosus* and *Cichoreacidites longispinosus*. Pollen associated with mangroves is also present (3%) at the top of the core. Freshwater algae range between 12-24%.

Interpretacion of depositional environments

The integration of lithological and palynological data in Saltarin suggests that during the Miocene the distal portion of the Llanos Basin was environmentally dynamic. During the lower Miocene, the lower portion of the stratigraphic section which includes the Carbonera Fm and the base of the Leon Fm are characterized by lacustrine and fluvial systems. In the middle of the section marine to estuarine systems dominate and in the upper part of this section deltaic environments are represented. The sediments deposited during the middle Miocene that correspond to the Leon and Guayabo Fms (G1, G2, G3) are dominated by marine and lacustrine environments. The upper part of Saltarin-1A core, corresponding to the upper-middle Miocene and upper Miocene, with G4 and G5 are interpreted as a deltaic and fluvial system with a low rate of deposition and is interrupted by erosional events.

The first interval corresponds to the base of Saltarin (C3) and has an age of 20.5 to 19.8 My. Palynological and lithological data suggest that the sediments were deposited in a lacustrine environment that allowed the establishment of a canopy forest and floodplains with few ferns and herbs. There is also development of paleosol through the section.

The next intervals correspond to C2a, C2b and part of C2c with two marine events. Palynology and lithological data suggest that this portion of the section was deposited in deltaic and estuarine environments. The low percent of palynomorphs at the base of C2 and the occurrence of sandstones indicate a delta shore. This is followed by a marine transgression. This transgressive marine event reaches its maximum at 19.5 My. This is further supported by the occurrence of estuarine taxa in the palynoflora, e.g. mangrove and freshwater algae. This is followed by a minor regressive event at 19.3 My. Another transgression occurs from 19.27 to

19.23 My. The regression of the marine incursion is indicated by the decreasing of the marine elements, an absence of mangrove elements, and the establishment of a lacustrine environment up to 19.2 My.

A second major marine interval characterized by the high frequency of forams and Dinocyst undiff. suggest a marine incursion punctuated by a minor regression from 19 to 18.1 My. The regression is characterized by the increase in taxa that suggest the occurrence of floodplains that were occupied by estuarine and grasses/herbs species of pollen. The occurrence of freshwater algae indicate lacustrine environments as a result of fluvial canals.

The palynological record and lithology, in the upper part of C2c and C1 (18-16.6 My), is characterized by the deposition of sandstones indicating deltaic and fluvial systems intercalated by erosional events. The mudstones deposited in the floodplains preserve a good record of terrestrial palynomorphs, e.g., fungi, pteridophytic spores and pollen associated with Bombacaceae, Arecaceae (*Mauritia)* and Apocynaceae as well as other herbaceous.

The depositional environments of the upper-lower Miocene and the middle Miocene in Saltarin are indicative of marine influence. The first phase, the C1c and the base of the Leon Fms, corresponding to the upper-lower Miocene (16.5-16.3 My), has a high representation of terrestrial palynomorphs and a low presences of marine, coastal and freshwater algae elements. This palynoflora composition associated with the accumulation of sands, gray and green mudstones indicates either marine or near shore environments. This marine incursion was less significant than the previous incursions.

The second phase corresponding to the middle Miocene (16.2 to 12.4 My), with the Leon and Guayabo Fms (units G1 and G2), is the longest marine incursion in the Llanos Basin. This incursion has seven identifiable intervals. The first interval, with a duration of 0.98 My, is a marine transgression, characterized by marine and terrestrial palynomorphs, a major concentration of freshwater algae suggesting a transition between a lacustrine/deltaic and marine environment. The second and third interval, with a duration of 0.89 and 0.39 My respectively, suggest two major marine transgressions with adjacent open vegetation and forest near to the shore. The fourth interval is a marine transgression of 0.31My where the palynoflora suggests the establishment of an estuarine environment close to the shore. The fifth interval with 0.19My suggests a minor marine transgression with a deltaic environment, characterized by terrestrial palynomorphs and freshwater elements. The sixth interval, with a duration of 0.02 My is a marine transgression with adjacent near-shore estuarine environments, open vegetation and forest. The seventh interval, the shorest at the point at 0.07 My is also is the least marine transgression. During the last marine regression, after the last interval, many sandstones were deposited at the same time that floodplains were expose, forming paleosoils or allowing the establishment of grasses and herbs.

After the last marine regression, 12.5 to 12.4 My, the area was covered with open savanna-like vegetation. The expansion and dominance of this type of vegetation indicates a change in the drainage of the basin and probably a dry period. After the expansion of grasses and herbs a sterile section at 3.8My begins to be associated with the development of paleosoils and sandstones. This period corresponds to the upper part of the middle Miocene and the upper Miocene.

At the top of Saltarin core (8.5 to 5 My) there is a change in the rate of sedimentation in the Llanos Basin. The palynological composition suggests an increase in open vegetation with floodplains and estuarine areas. The occurrence of sandstones and erosional events can be associated with a shoreline or the border of meandric rivers.

DISCUSSION

Chronology

The Saltarin-1A core has a high probability of having been deposited between 21- 5 My (Figure 6).

The Carbonera and the bottom of the Leon Fms suggest an age of 21-16 My, corresponding to the lower Miocene. This section of the core belongs to the zones T-12 (*Horniella lunarensis*) and T-13 (*Echitricolporites maristellae*), according to the palynological zonation from the Llanos Basin of Colombia, proposed by Jaramillo et al (2010). The palynomorphs that indicate this concordance are the FAD of *Malvacipolloides maristellae, Horniella lunarensis* and *Nijssenosporites fossulatus* and the LAD of *Cyclusphaera scabrata*. The FAD of *Malvacipolloides maristellae* as indicator of the lower Miocene was registered previously in a palynological zonation from Venezuela, proposed by Lorente (1968).

Sedimentological, tectonic, geomorphological, thermochronological and structural studies from the eastern Cordillera and the Llanos Basin (eastern foothills and foreland basin) indicated that the top of the Carbonera Fm (units C1, C2, C3) was deposited during the lower Miocene (Parra et al., 2010; Bayona et al., 2007, 2008; Mora et al. 2010; Ochoa et al, 2012). These studies also indicate that the Leon Fm was deposited in the Llanos Basin during the middle Miocene. However, both the graphic correlation and the maximum likelihood methods of this study suggest that the base of the Leon Fm (the first 10m) was deposited at the end of the lower Miocene. The estimated age for this interval is based on the FADs of *Echitricolporites spinosus* (523.9m) and *Nijssenosporites fossulatus* (537.29m) and the FAD of *Crassoretitriletes vanraadshooveni* (543.38m).

These three palynomorphs presented in the base of Leon Fm have been indicated in previous studies in the interval from the upper part of the lower Miocene to the lower part of the middle Miocene. Firstly, the FAD of *Echitricolporites spinosus* suggested in Saltarin-1A was 15.99 My. This result is supported by Regali (1975), Germeraad et al. (1968) and Hoorn (1993) which indicated this palynomorph as an indicator of the middle Miocene. However this finding is not supported by Jaramillo et al. (2010), who indicated the FAD of this palynomorph from 17.41My (lower Miocene). Secondly, the FAD of *Nijssenosporites fossulatus* was indicated in the Leon Fm with an age of 16.32 My, according to the age model proposed for Saltarin-1A. Jaramillo et al (2010) also indicated this palynomorph during the lower Miocene, but the FAD proposed was 19.05My, while Lorente (1968) registered this palynomorph in the middle Miocene. Thirdly, *Crassoretitriletes vanraadshooveni* was registered previously by Lorente (1968), Regali (1975) and Germeraad et al. (1968) in the upper part of the lower Miocene, supporting the FAD suggested in Saltarin-1A (16.37 My). However, Muller et al. (1975), Hoorn (1993) and Jaramillo et al. (2010) registered this in the middle Miocene with a FAD of 14.18My. These results suggest that the base of the Leon Fm was deposited in the Llanos Basin in the transitional period between the lower to the middle Miocene.

The Leon and Guayabo Fms (units G1, G2, G3) indicate an age between 16-12My (middle Miocene), between 530 to 300m(Figure 6). This section of the core belongs to the zones T-14 (*Grimsdalea magnaclavata*), T-15 (*Crassoretitriletes vanraadshooveni*) and part of T-16 (*Fenestrites spinosus*), according to the palynological zonation from the Llanos Basin of Colombia as proposed by Jaramillo et al. (2010). The palynomorphs that indicate this concordance are the FAD of *Fenestrites spinosus*, *Paleosantalaceaecipites cingulatus* and *Retitripollenites crotonicolumellatus* and the presence of *Quadrina condita.*

Paleosantalaceaecipites cingulatus and *Retipollenites crotonicolumellatus* were registered by Jaramillo et al. (2010) with FADs of 15.33My and 12.89My respectively. In the case of *Fenestrites spinosus*, this palynomorph has been proposed as an indicator of the middle Miocene by Germeraad et al. (1968), Jaramillo et al. (2010), Regali et al. (1974) and Potonie (1975), and the upper Miocene by Graham (1993) and Muller (1987). Also, *Quadrina condita* has been considered as an indicator of the middle Miocene (de Verteuil and Norris, 1992; Edwards et al, 1998; Kurita and Obuse, 2003; Head and Norris, 2003). However, this palynomorph has not been included in previous palynological zonations proposed for Northern South America. In this study *Q. condita* has been considered as a possible indicator of the middle Miocene, because of its high representation in the marine levels of the Leon Fm and the Guayabo, unit G1, (Figure 13) section dated from the middle Miocene.

The upper part of the Guayabo Fm (units G4, G5 and G6), which belongs to the upper 260m of the Saltarin-1A core, has been dated from the upper Miocene (11-7 My). This section of the core belongs to part of the zone T-16 (*Fenestrites spinosus*) and the zone T-17 (*Cyatheacidites annulatus*), according to the palynological zonation from the Llanos Basin of Colombia (Jaramillo et al., 2010). The palynomorphs which indicate this concordance are the FAD of *Cyatheacidites annulatus* and the LAD of *Psilastephanocolporites herngreenii*.

The FAD of *Cyatheacidites annulatus* from the Saltarin-1A core was 174.98 m, which corresponds to 11.74 My according to the graphic correlation and the maximum likelihood. The FAD proposed by Jaramillo et al (2010) was 7.15 My supporting this datum. Previous studies indicate that the fossil record *of Cyatheacidites annulatus* is from the upper Miocene to the upper Pliocene (Muller et al., 1987; Lima and Angulo, 1990; Regali et al., 1974). In the case of *Psilastephanocolporites herngreenii*, the LAD registered in Saltarin-1A core was 144.15m and suggests an age of 6.2My. This datum is supported by previous studies which indicate this palynomorph in the interval from the middle to the upper Miocene.

Sedimentological, tectonic, geomorphological and thermochronological studies from Northern South America indicate that the sediments of the Leon Fm were deposited during the middle Miocene (Hoorn, 1993; Martinez et al., 2006; Wesseling and Macsotay, 2006; Bayona et al., 2007; 2008a; 2008b; Mora et al. 2010; Parra et al., 2010; Ramirez et al., 2012), supporting the palynological data. Otherwise, the time of deposition of the sediments from the Guayabo Fm is still debated. Part of these studies indicate that this Formation was deposited from the upper-middle Miocene to Pliocene-Pleistocene (Gomez et al. 2005; Bayona et al., 2008a; Parra et al., 2010; Branquet et al., 2010, Bande et al. 2012). The other part of these studies suggests that this Formation was deposited from the upper Miocene to the Plio-Pleistocene (Cooper et al., 1995; Martinez et al., 2006, Bayona et al., 2008b; Horton et al., 2010; Mora et al., 2010; Ramirez et al., 2012).

The sediments deposited on the Guayabo Fm have been described as sandstones and yellow-red mudstones with thin intervals of black mudstones layers (Bayona et al., 2008; Mora et al., 2010; Parra et al., 2009; 2010; Ramirez et al., 2012), obscuring the dating age. In fact the Saltarin-1A core has a hiatus of 144m (between 355m to 206m), that corresponds to the units G2-G4, and sterile intervals mixed with black mudstones at the units G5and G6. The palynomorphs found in the sections before (the FAD of *P. cingulatus* in 430.82m and *F spinosus* at 422.69m) and after (the FAD of *C. annulatus* in 174.98m and the LAD of *P. herngreenii* in 144.15) the 144m hiatus, suggest it is the level of the transition between middle and late Miocene. According to the age model (Figure 8) this transition is indicated in an interval of 7m, between 261 and 254m, supporting the studies that proposed the deposition of the Guayabo Fm from the middle Miocene.

Paleoecology

The palynomorphs from the Saltarin-1A core indicate five habitats occurred in the Llanos Basin during the Miocene (Fig 12, 13, 14). These ecological associations of the fossil palynomorph assemblages are considered to be similar to their extant relatives (Nearest Living Relative Method, Mosbrugger, 2009). These habitats are, 1) a lowland forest inferred by the presence of pollen taxa associated with trees such as *P. pokornyi, S. Catatumbus, C. microclavatus, Mauritiidites, Bombacacidites, Illexpollenites* and *Podocarpidites*, 2) a marine habitat indicated by the presence of foraminifera and dinoflagellates , 3) mangroves indicated by the presence of *Zonocostites*; 4) a freshwater habitat inferred by the presence of *Botryoccocus* and *Pediastrum*, and 5) a open habitat (e.g. example a svanna or wooland savanna) that is characterized by palynomorphs with affinities in the Poaceae (*M. annulatus*), Cyperaceae (*Cyperaceaepollis spp)*, and Asteraceae, (*F. spinosus, C. longispinosus*). The classification of these five habitats is based on ecological affinities proposed in previous works primarily from Northern South America (Table 3) (Germeraad et al., 1968; Lorente, 1968; Regali, 1975; Hoorn, 1993; 1994; Rull, 1997; 2002; Behling and Hooghiemstra, 1999; Jaramillo and Dilcher, 2001; Berrio et al., 2002; Jaramillo et al., 2007; 2009; Latrubesse et al 2007; Hoorn, et al., 2010; Silva et al., 2010; Ochoa et al., 2012).

The palynomorphs recovered from the base of the Saltarin-1A core (Carbonera Fm), corresponding to the lower Miocene (21-19 My), suggest a change in the depositional environment from a lowland forest to a mangrove / marine environment. In the lower 20 meters of the core there is a dominance of terrestrial elements, mainly trees (*Bombacacidites muinaneorum, Retitrescolpites irregularis, Mauritidiites franciscoi, Tetracolporopollenites maculosus*), and there are no freshwater or marine elements present. The next 10m indicate a sterile sandstone interval, followed by the first appearance of marine elements (dinoflagellates, foraminifera and *Leiosphaeridia*). Freshwater algae are also present (*Botryococcus*). This shift in habitat type (lowland forest to mangrove/marine) corresponds to a shift in the rate of sedimentation in the Carbonera Fm (Bayona et al. 2008). The shift in habitats suggests a change in sea level, possibly attributable to a change in the rate of subsidence. In addition, the sedimentological, structural and geological studies made in Cenozoic rocks from the distal part of the Llanos Basin and from the Llanos foothills registered changes in the sediments deposited from the late Oligocene to the lower-middle Miocene (Cooper, 1995; Bande et al., 2002; Sarmiento et al., 2002; Gomez et al., 2005; Martinez, 2005; Bayona et al., 2008; Jaramillo et al., 2009; Parra et al., 2010; Ramirez et al., 2010). The change in the drainage of the Llanos basin and the establishment of floodplains as a consequence of subsidence event(s), has been indicated in other studies in foreland basins (Rogers, 1994; Uba et al., 2005).

The first occurrence of the mangrove /marine habitats of the Carbonera Fm, is the first of three relatively minor mangrove / marine fluctuations that take place in the Llanos Basin during the lower Miocene (19.8-19.2My). The other two marine incursions are identified in the middle-upper part of the Carbonera and the base of the Leon Fms, from 19.1 to 18.2 My and from 16.6 to 16.3 My respectively. The presence of the pollen of mangrove and freshwater algae in these intervals also suggests the formation of deltaic and estuarine floodplains in the basin associated with the mangrove/marine habitats. This mangrove These results are supported by previous studies which indicate that the accumulation of the Carbonera and the Leon Fms took place in fluvial-deltaic plains with coastal influence (Cazier et al., 1995; Cooper, 1995; Bande et al., 2012; Gomez et al., 2005; 2009).

The palynological assemblages of the sediments deposited in the Leon Fm and in the lower part of the Guayabo Fm (units G1 and G2), between 16 and 12.5 My (middle Miocene), suggest two major marine incursions accompanied by relatively minor fluctuations in the coastal mangrove / marine habitats similar to those described in the Carbonera Fm.

Bayona et al. (2008) indicated that the sediments from Saltarin-1A deposited in the Leon Fm suggested surfaces of maximum inundation, supporting the interpretation based in the palynological record. However, Bayona et al. (2008) suggested that these sediments were deposited in a fluvial system without marine influence. Parra et al. (2010) and Bande et al. (2012), in geological and structural studies made in the eastern Llanos and Llanos foothills, also indicated that the Leon Fm was deposited in a fluvial system, but they also indicated estuarine deposits, suggesting a marine influence. Other studies made in this area support this interpretation as does the palynological record, which indicates that the sediments from the Leon Fm were deposited during the major marine transgression from the Miocene in the basin (Cazier et al., 1995; Cooper et al., 1995; Rochat et al., 2003; Gomez et al., 2005; 2009; Bayona et al, 2006; Mora et al., 2010; Ramirez et al 2012).

The palynomorphs deposited in the lower part of the Guayabo Fm (unit G1 and the base of the unit G2) exhibit a decrease of marine elements and the increasing of the pollen of grasses and herbs. Previous studies (Bayona et al., 2008; Mora et al., 2010; Parra et al., 2009; 2010; Ramirez et al., 201) in this region indicated a transitional period in this section of the Guayabo Fm, but the interpretations of the depositional environments differ among the investigators. After the decline of the marine elements, there is a dramatic increase in Poaceae, indicating the establishment of a savanna-like habitat. Units G2, G3 and G4 of the Guayabo Fm are palynologically sterile. A lithological analysis made by Bayona et al. (2008) of the Saltairn-1A core indicated the deposition of sands and paleosols in this section. They suggested three possible explanations for this change in the sedimentation: tectonic variation as an increase of the uplift rate; decreasing sea level, exposing areas of the basin; and/or a climatic change. Geological, structural and tectonic studies indicated a change in the rate of sedimentation of the basin between the Leon and the Guayabo Fms (Hoorn et al., 1987; Duque-Caro, 1990; Helmens and Van der Hammen, 1994; Hooghiemstra and Van der Hammen, 1998; Taboada et al., 2000; Branquet et al., 2002; Martinez et al., 2005; Mora et al., 2010; Parra et al., 2009; 2010; Shephard et al., 2010; Bande et al., 2012; Ramirez et al., 2012). These studies also suggested a deformation of the basin caused by the increase of the tectonic activity, mainly the eastern Andean Cordillera, during this period of time. Haq et al. (1987) indicated a decrease of the global sea level after the middle Miocene, supporting one of the explanations of Bayona et al. (2008). All of these explanations account for the low concentration or absence of organic material in this part of the core.

After the preceding sterile section, the palynomorphs deposited in the upper 145m of Saltarin-1A core, corresponding to the Guayabo Fm (unit G5) and are dated as the upper Miocene (8.4-5 My). This interval is characterized by the transition from lowland forest with mangrove elements to a more open woodland / woodland savanna in the upper part of the section (latest Miocene). There is also a presence of freshwater taxa throughout the 145 m section. Bayona et al. (2008) indicates that the lithology of this section is characterized by the deposition of sandstones, paleosoils and intervals with mudstones. They suggested that the upper part of Guayabo Fm was deposited in a fluvial system with anastomosing channels. This interpretation was supported by other studies made in the Llanos Basin and the Llanos foothills (Cooper et al., 2005; Branquet 2002; Martinez, 2005; Bayona et al., 2007; Parra et al., 2009; 2010; Mora et al. 2008; 2010; Ochoa et al, 2012; Ramirez et al., 2012). Additionally other studies suggest that this change in the rates of sedimentation of the upper part of the Guayabo Fm indicates a change in the direction of the paleocurrents and the formation of the Orinoco River (Parra et al., 2009; Mora et al., 2010; Bande et al. 2012; Ramirez et al., 2012).

CONCLUSIONS

- The Saltarin-1A core ranges in age from 21 (Lower Miocene) to 5 My (Upper Miocene). The sediments of the Carbonera and the base of the Leon Fms were deposited during the lower Miocene. The sediments of the Leon and the lower part of the Guayabo (units 1, 2, 3) Fms were deposited during the middle Miocene. The sediments of the upper part of the Guayabo Fm (units 4, 5) were deposited during the upper Miocene.
- During the lower and the middle Miocene the the dominant vegetation in the Llanos Basin was more like a forest than a savanna. In the upper Miocene the forest vegetation decrease of savanna-like
- The vegetation was punctuated with minor and major marine incursions, mainly during the middle Miocene, between 16-12.5My.

Future considerations

The palynological analysis of Saltarin-1A allowed to make a review of the chronology proposed to this core, a reinterpretation of the depositional environments of the distal part of the Llanos Basin during the Miocene and the review and identification of the changes of the vegetation during the Miocene in the Llanos Basin.

This work also allowed to infer that one of the factors that played and important role in the dynamic of the vegetation and depositional environments of the basin were the subsidence events as a consequence of the Andean uplift. Other possible factor was the climatic variation indicated from the Miocene to regional or global level, but more analyses and the use of other proxies are necessary to support this inference as isotopes.

This work as part of a large scale project which has as a future goal to compare the results of this work with other palynological studies, that are in development, in two areas of Northern South America: Urumaco (Venezuela) and Manaos (Brasil), to corroborate and correlate the marine events suggested in this work. Another goal is to analyze and compare two sections located in the Llanos foothill and the eastern Cordillera to understand how change the vegetation and climate of Northern South America, from the Miocene to Pleistocene, as a consequence of the Andean uplift.

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ANNEX 1

PLATES OF PALYNOMORPHS FOUND IN THE SALTARIN CORE, LLANOS BASIN

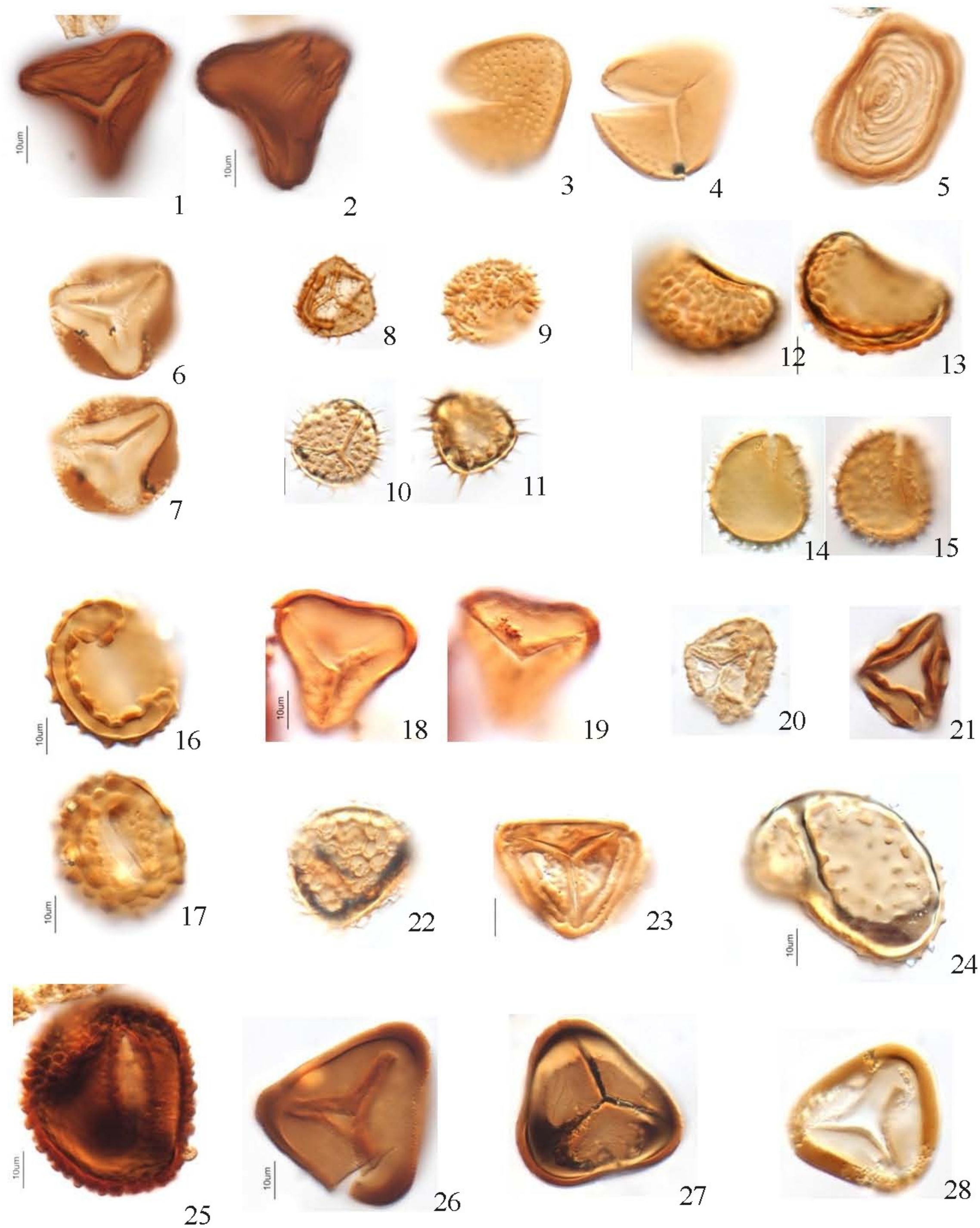

PLATE 1 1,2 Psilatriletes “venosus”. 3, 4 Psilatriletes “adiantus”. 5 Chomotriletes sp. 6, 7 Psilatriletes lobatus. 8, 9 Echinatisporis circularis. 10, 11 Echinatisporis muelleri. 12, 13 Polypodiisporites scabratus. 14, 15 Echimonoletes sp. 16, 17 Polypodiisporites sp1. 18, 19 Polypodiaceoisporites verrucosus. 20 Echitriletes” acanthotriletoides”. 21 Kuylisporites waterbolkii. 22 Retitriletes sp. 23. Nijssenosporites fossulatus. 24 Polypodiisporites usmensis 25. Polypodiisporites densus. 26. Matonisporites crassiangulatus 27. Matonisporites mulleri. 28 Psilatriletes sp1.

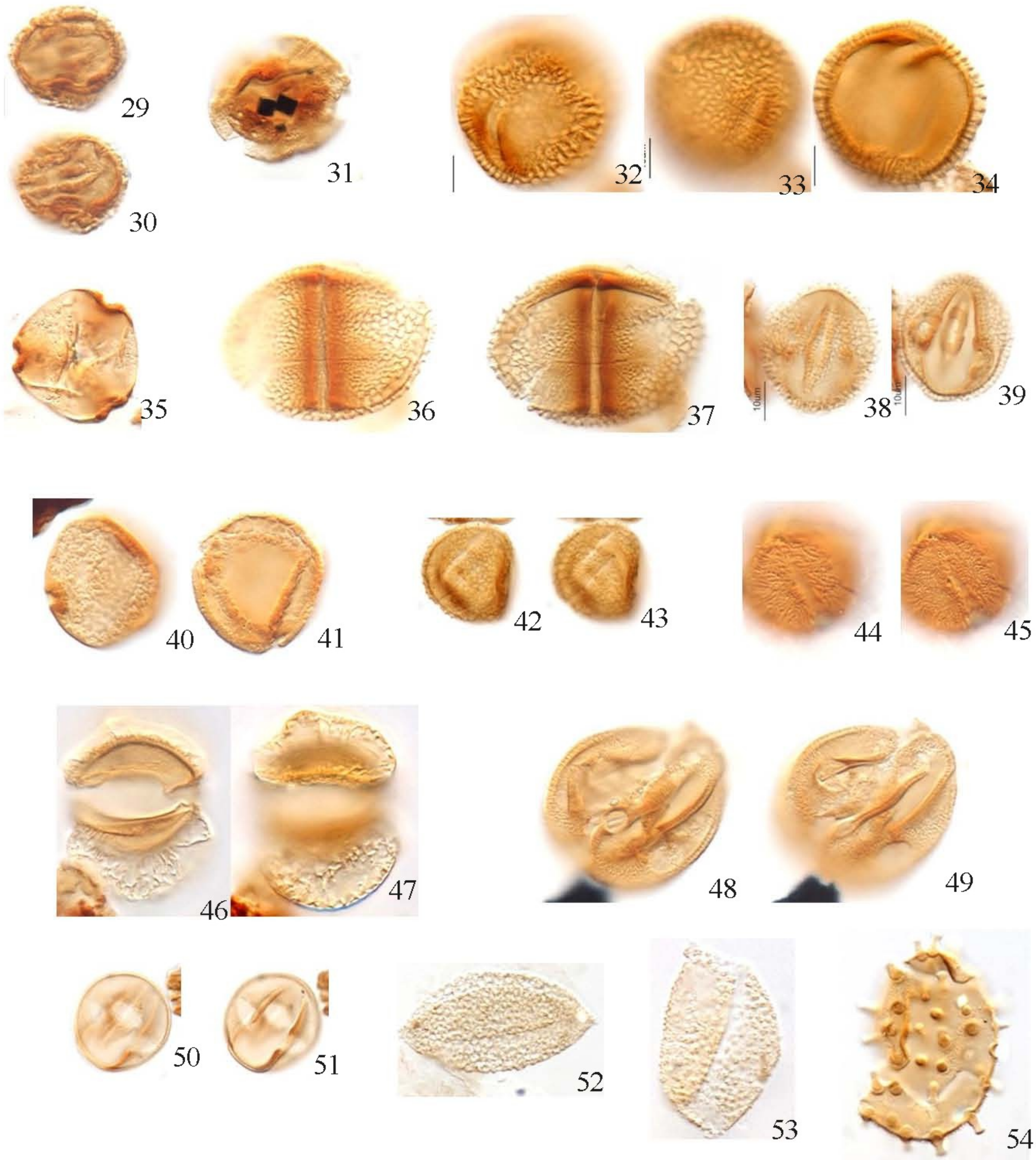

PLATE 2 29, 30 Rugutricolporites minor. 31 Rugitricolporites intensus. 32, 33, 34 Retitricolporites bachueae. 35 Cricotriporites sp. 36, 37 Retitricolporites karsii. 38, 39 Retitricolporites " porusannulis". 40, 41 Rugutricolporites "breviaperturatus" 42, 43 Rhoipites guianensis. 44, 45 Rugutricolporites felix. 46, 47 Podicarpidiites sp. 48, 49 Retitricolporites "maximus" 50, 51 Triporites sp. 52 Retitricolpites " heteroreticulatus". 53 Mauritidiites franciscoi minor. 54 Grimsdalea magnaclavata

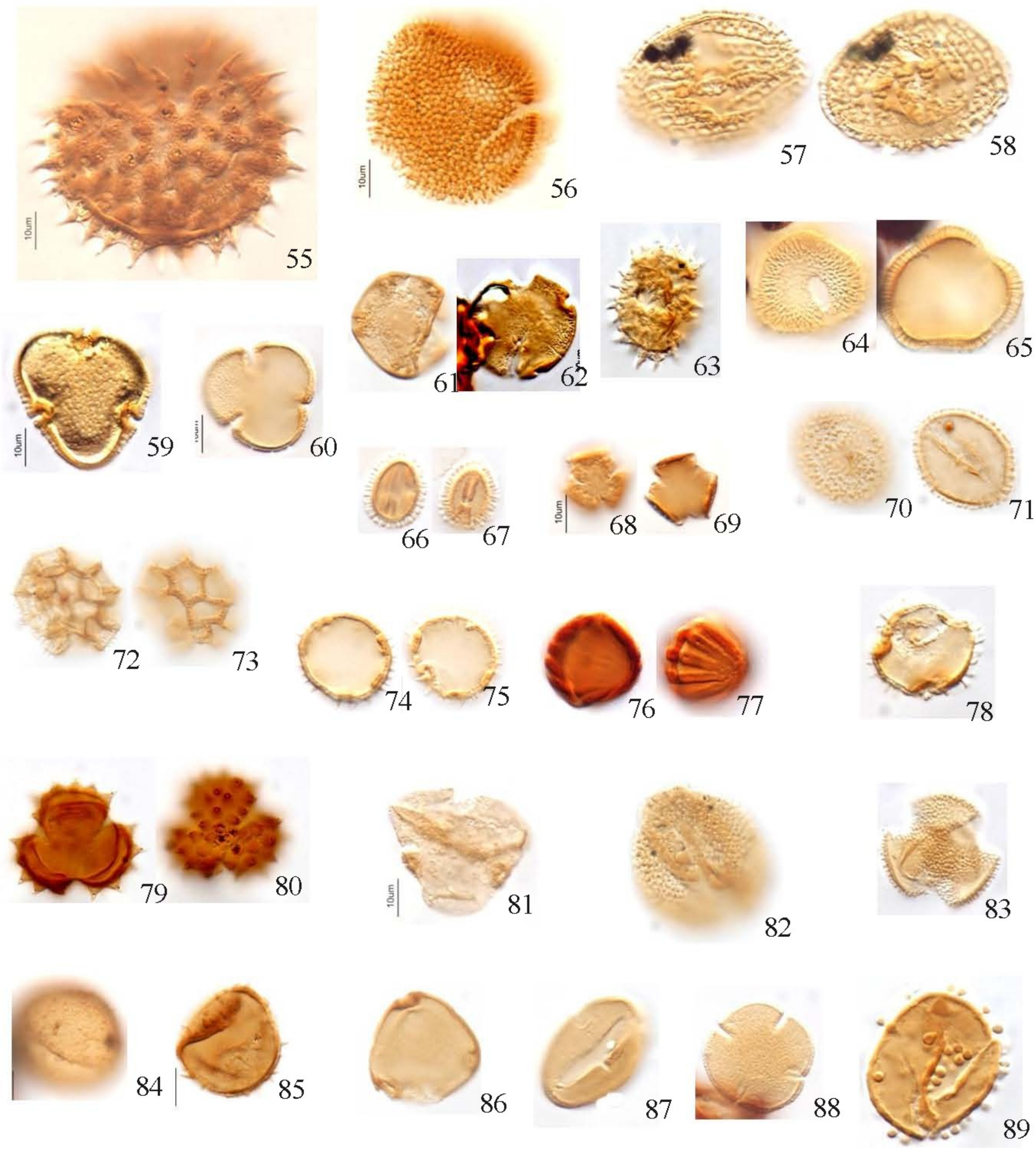

PLATE 3 55 Echiperiporites lophatus. 56 Crotonoidaepollenites reticulatus. 57, 58 Multimarginites vanderhammeni. 59 Bombacacidites sp. 60. Bombacacidites brevis. 61, 62 Cricotriporites pentagonalis. 63. Cichoreacidites longispinosus 64, 65 Psilastephanocolpites "digitatus". 66, 67 Illexpollenites sp. 68, 69 Scabratrcolporites " simple". 70, 71 Baculamonoletes sp 72, 73 Fenestrites spinosus 74, 75 Echiperiporites akanthos. 76, 77 Psilastephanocolpites fissilis 78. Baculatricolporites "ralus" 79, 80 Echitricolporites spinosus. 81 Bombacacidites sp1. 82 Echitricolpites "Reticulatus" 83 Crototricolpites "finitus" 84 Echitricolpites "microechinatus". 85 Echiporites sp. 86 Cricotriporites sp. 87 Psilamonocolpites medius 88 Catostemma type 89 Baculapollenites sp.

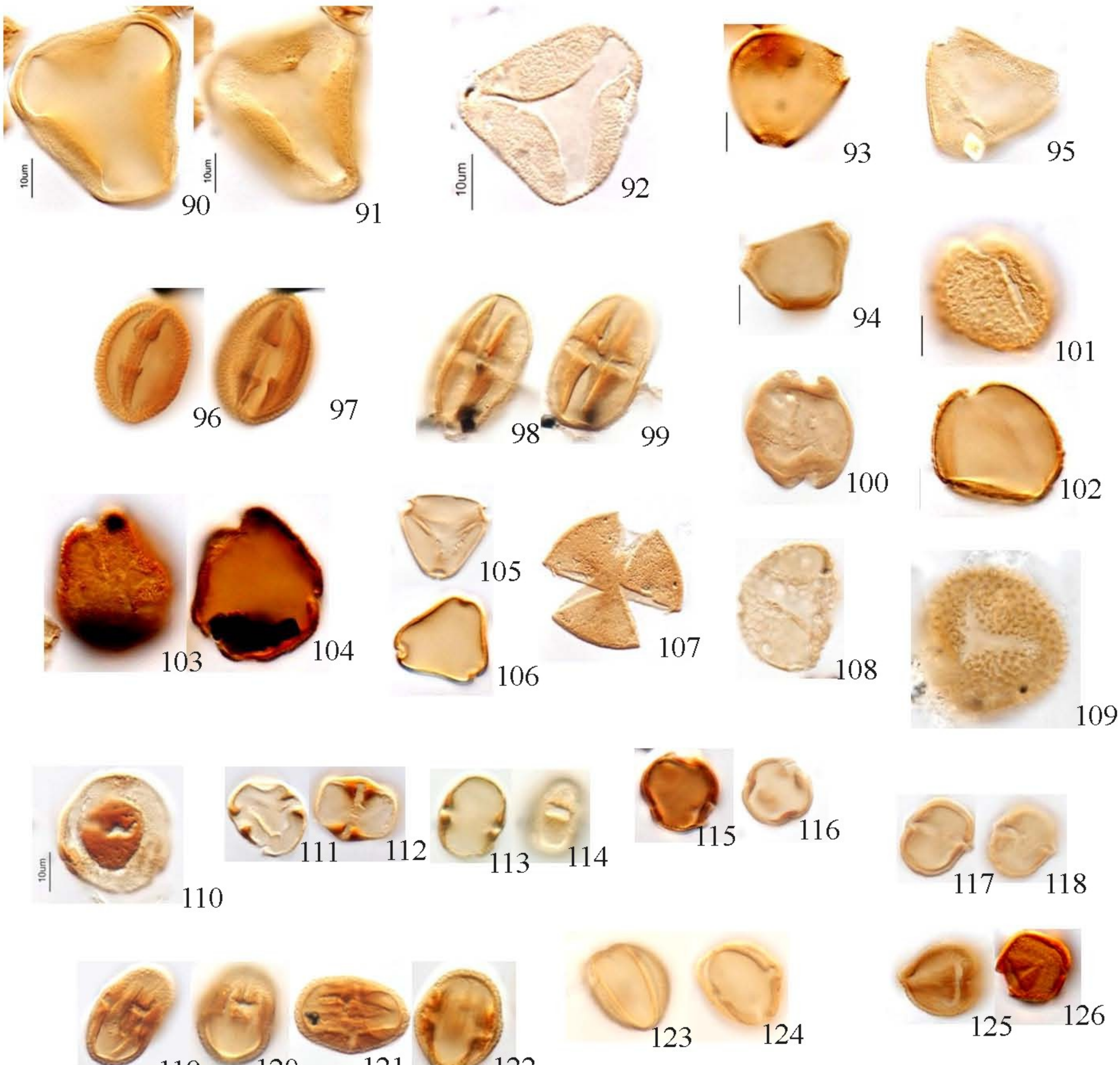

PLATE 6 90, 91 Luminidites sp. 92 Luminidites colombianensis 93, 94 Propylipollis pseudocostatus. 95 Proteacidites triangulatus 96, 97 Retitricolporites ” densus” 98, 99 Psilatricolporites “protium” 100 Psiladiporites “magniporus” 101, 102 Verrutricolporites sp1 103, 104 Retitricolporites “verrucosus” 105, 106 Psilatricolporites “”triangulariformis” 107 Psilatricolpites sp. 108 Retiperiporites sp. 109 Echitrichotomosulcites sp. 110 Cricotriporites sp. 111, 112 Tetracolporopollenites transversalis. 113, 114 Psilatricolporites “labiats”. 115, 116 Ranunculacidites operculatus. 117, 118 Psilatricolporites ”. transversalis”. 119-122 Retitricolporites caputoi. 123, 124. Heterocolpites sp. 125, 126. Psilatricolporites lalongiporatus

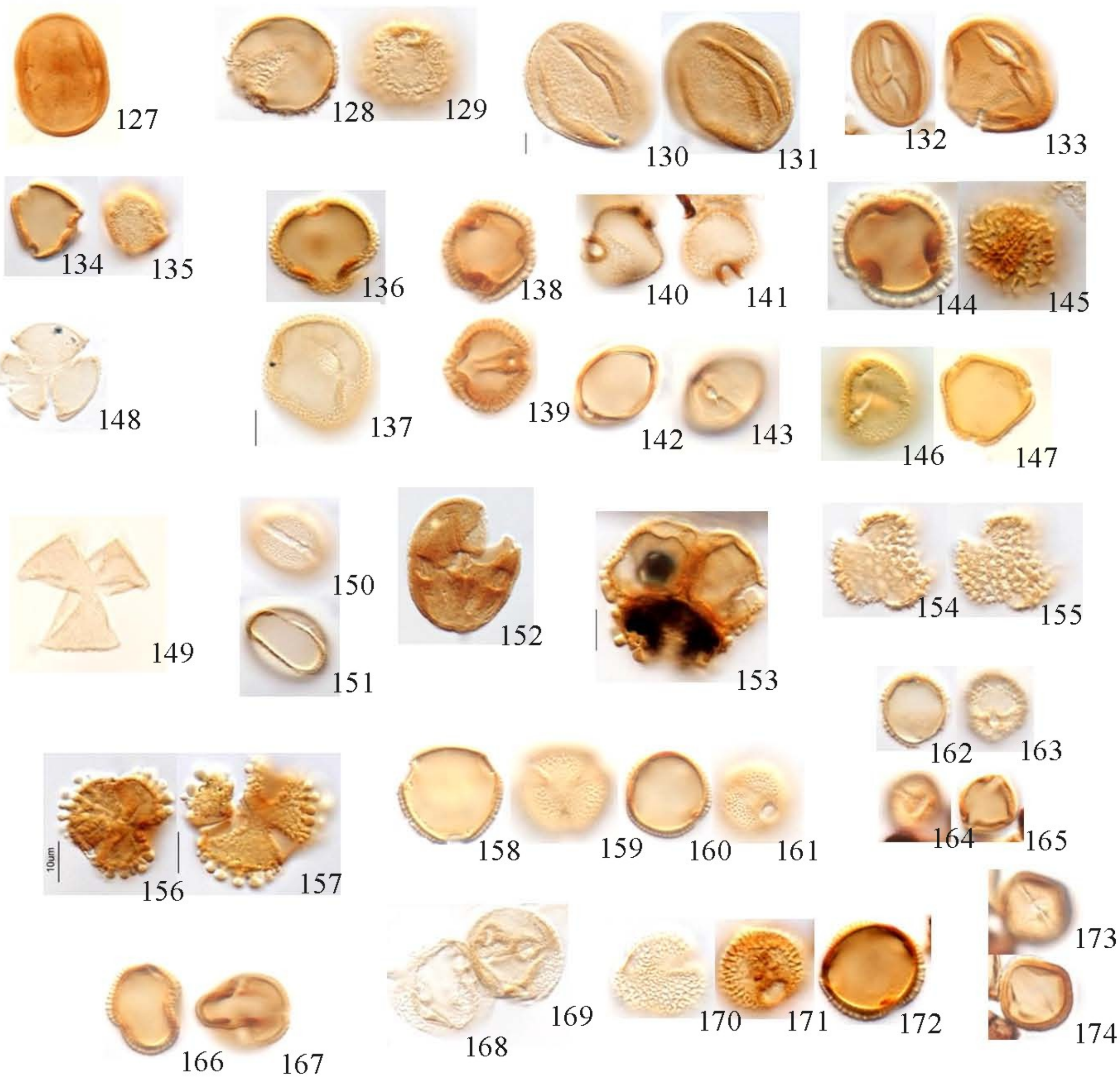

PLATE 7 127 Psilatricolporites pachydermatus. 128, 129 Rugutricolporites “orinocenses”. 130, 131 Retitricolporites “delicatus” 132, 133 Retitricolpites colpiconstrictus. 134, 135 Psilatricolporites ” verrucosus” 136, 137 Retitrcolporites “zigzagensis” 138, 139 Retitricolporites “annulus” 140, 141 Retitricolporites “vestibularis” 142, 143 Retitricolporites ovlatus minor 144, 145 Retitrescolpites irregularis 146, 147 Retitricolporites “triangulatus” 148 Retitricolpites “poratus” 149 Striatricolpites sp. 150, 151 Psilatricolpites minor 152 Retitricolporites “scabratus” 153 Clavalapollenites “triada” 154, 155 Echitricolpotes “densus” 156, 157 Clavatricolporites “marginalis” 158-161 Margocolporites “finitus”. 162, 163 Retitricolporites solimoensis 164, 165 Psilatricolporites minor 166, 167 Retitricolporites “collumelatus” 168, 169 Retitricolporites “scabrosus” 170, 172 Margocolporites “gigantipori” 173, 174 Psilatricolporites “tectum”

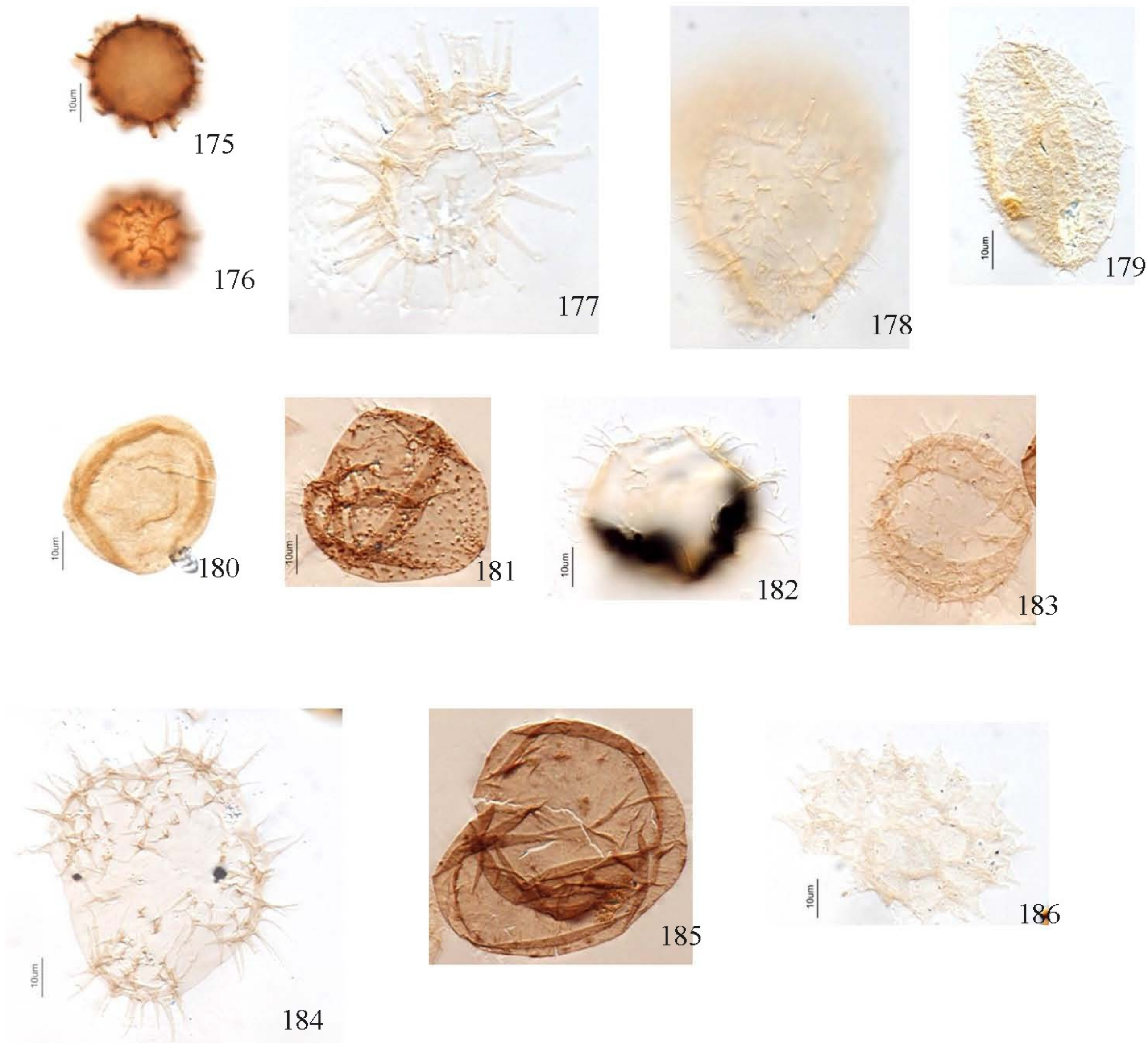

PLATE 8 175, 176 Acritarcha. 177 Polysphaeridium 178 Operculodinium sp.179 Dinocyst sp. 180 Leiosphaera 181. Trinovantedinium 182, 183 Spiniferites sp. 184 Quadrina? condita 185 Selenopemhpix sp, 186. Pediastrum