



Neogene Palynostratigraphic Zonation of the Marañon Basin, Western Amazonia, Peru

Authors: Parra, F.J., Navarrete, R.E., di Pasquo, M.M., Roddaz, M., Calderón, Y., et al.

Source: Palynology, 44(4) : 675-695

Published By: AASP: The Palynological Society

URL: <https://doi.org/10.1080/01916122.2019.1674395>

BioOne Complete (complete.BioOne.org) is a full-text database of 200 subscribed and open-access titles in the biological, ecological, and environmental sciences published by nonprofit societies, associations, museums, institutions, and presses.

Your use of this PDF, the BioOne Complete website, and all posted and associated content indicates your acceptance of BioOne's Terms of Use, available at www.bioone.org/terms-of-use.

Usage of BioOne Complete content is strictly limited to personal, educational, and non - commercial use. Commercial inquiries or rights and permissions requests should be directed to the individual publisher as copyright holder.

BioOne sees sustainable scholarly publishing as an inherently collaborative enterprise connecting authors, nonprofit publishers, academic institutions, research libraries, and research funders in the common goal of maximizing access to critical research.



Neogene palynostratigraphic zonation of the Marañon Basin, Western Amazonia, Peru

F.J. Parra^{a,b,c} , R.E. Navarrete^c , M.M. di Pasquo^d , M. Roddaz^a , Y. Calderón^e and P. Baby^a

^aGéosciences-Environnement Toulouse, Université de Toulouse III-Paul Sabatier, Toulouse, France; ^bLaboratorio de Bioquímico-Estratigrafía, Facultad de Geociencias, Universidad Nacional de Colombia, Bogotá, Colombia; ^cDepartamento de Bioestratigrafía, Paleosedes EU, Bogotá, Colombia; ^dLaboratorio de Palinoestratigrafía y Paleobotánica, Centro de Investigaciones Científicas y Transferencia de Tecnología (CICYTTP-CONICET-ER-UADER), Diamante, Entre Ríos Province, Argentina; ^eDepartamento de Exploración, Perupetro, San Borja, Perú

ABSTRACT

The palynology (150 species of pollen grains, 43 species of spores, eight species of dinoflagellate cysts, five genera of algae, two genera of fungal spores, foraminiferal linings, and copepod eggs) of the Neogene succession in the Marañon Basin, north Peru, was thoroughly investigated for the first time from six industrial wells (Arabela-1X, Maynas-1, Tucunare-1X, Tigrillo-30X, Nahuapa-24X, and La Frontera-1). Six palynozones spanning the Early Miocene to the Early Pliocene were defined. The zones in stratigraphically ascending order are as follows: the Mar-A *Corsinipollenites oculusnoctis* Zone (Aquitainian to early Burdigalian: 23.03–17.71 Ma), delimited by the appearance of *Acaciapollenites myriosporites*, *Retitricolporites wijmstrae* and/or *Corsinipollenites oculusnoctis* and/or the disappearance of *Cicatricosisporites dorogensis* at the base; the Mar-B *Malvacipolloides (Echitricolporites) maristellae* Zone (Burdigalian: 17.71–16.1 Ma), from *Malvacipolloides maristellae* at the base to the disappearance of *Retitricolporites wijmstrae* at the top; the Mar-C *Mauritiidites crassibaculatus* Zone (latest Burdigalian to Late Langhian: 16.1–14.2/13.9 Ma), from the appearance of *Grimsdalea magnaclavata* at the base to the disappearance of *Retitriporites dubiosus* and/or the appearance of *Crassoretitriletes vanraadshooveni* and/or *Psilastephanoporites tesseroporus*; the Mar-D *Crassoretitriletes vanraadshooveni* Zone (Late Serravallian: 14.2–11.62 Ma), from the appearance of *Crassoretitriletes vanraadshooveni* and/or *Psilastephanoporites tesseroporus* to the disappearances of *Mauritiidites crassibaculatus*, *Bombacacidites nacimientoensis*, and *Cyathidites congoensis*; and the Mar-E *Psilastephanoporites tesseroporus* Zone (Early Tortonian to Late Messinian: 11.62–5.48 Ma) from the disappearance of *Corsinipollenites oculusnoctis* and/or *Cyathidites congoensis* to the disappearance of *Psilastephanoporites tesseroporus* and/or *Siltaria santaisabelensis*. These zones were corroborated by means of events ordination demonstrated using graphic correlation. The Mar-F *Ctenolophonidites suigeneris* Zone (latest Messinian to Zanclean) is described only in the Frontera-1 well from the disappearance of *Psilastephanoporites tesseroporus* to the last record of *Ctenolophonidites suigeneris* and/or *Siltaria hammenii*. This study suggests that Pliocene sedimentation is also recorded in the Western Amazonia of Peru, and provides new palynological information compared with the Mio–Pliocene Solimões, Acre, and eastern Amazonas basins.

KEYWORDS

South America; neotropical palynology; palynological zonation; Neogene; Western Amazonia; Marañon Basin; Peru

1. Introduction

The Marañon Basin is one of the most important basins in Peru in terms of hydrocarbon resources, but despite many decades of active exploration (Calderón et al. 2017a, 2017b; Baby et al. 2018), biostratigraphic research has not been conducted. The Marañon Basin contains Paleozoic and Mesozoic source rocks and Mesozoic reservoirs and subthrust traps. Recent studies by Calderón et al. 2017a, 2017b) have improved understanding and modeling of petroleum systems in this basin, especially regarding the formation and deformation of the subthrust traps. However, uncertainties remain concerning the timing and rate of Cenozoic burial, which forms part of the petroleum kitchen system. This is mainly because the Cenozoic deposits of the Marañon Basin are poorly dated (Roddaz et al. 2010).

The stratigraphic ages of Cenozoic units are generally based on different groups of fossils, including algae (Marocco et al. 1995) and invertebrates, such as mollusks and ostracods, from the Chambira, Pebas, and Solimões formations (Whatley et al. 1998; Muñoz-Torres et al. 2006; Ramos 2006; Wesselingh et al. 2006a; Wesselingh and Ramos 2010), and ostracods, foraminifera, and palynomorphs from the adjacent Solimões Basin (Linhares et al. 2011, 2017, 2019; Leandro et al. 2019), as well as vertebrates (Monsch 1998; Salas-Gismondi et al. 2007). The Pebas/Solimões and Nauta formations were palynologically dated from outcrops and wells in the Solimões and Acre basins (Hoorn 1993, 1994a, 1994b, 2006; Hoorn et al. 1996, 2010a, 2010b, 2017; Rebata et al. 2006a, 2006b; Leite et al. 2016; Leandro et al. 2019; Linhares et al. 2019). These units were also recognized from

Table 1. Location of the six studied wells: Arabela-1X, Maynas-1, Tucunare-1X, Tigrillo-30X, Nahuapa-24X, and La Frontera-1 in the Marañon Basin. N: number of samples analyzed; UTM (18S) coordinates in meters; depth in feet (1 ft = 0.3 meters).

WELL	N	WEST LONGITUD	SOUTH LATITUD	STUDIED INTERVAL IN FEET		STUDIED INTERVAL IN METERS			
ARABELA-1X	13	492310.37	9770151.59	610	to	3340	185.92	to	1017.98
MAYNAS-1	7	397165.18	9672338.65	2700	to	8030	822.92	to	2447.42
TUCUNARE-1X	11	352533.89	9670010.16	5000	to	7650	1523.93	to	2331.61
TIGRILLO-30X	16	393094.04	9557053.76	5310	to	10680	1648.48	to	3255.11
NAHUAPA-24X	20	575898	9536854	2210	to	6230	673.58	to	1898.81
LA FRONTERA-1	10	536014.05	9303755.13	1180	to	4420	359.65	to	1347.15

the Santa Lucia borehole drilled in the southern Marañon Basin (Hermoza 2004) and from three exploration wells (Jibaro 7/1AB-21-181, Huayuri Sur 15/1-AB-15-184D and Capahuari Norte 9/1AB-3-204) drilled in the westernmost part of the Marañon Basin (Hermoza 2004; Hermoza et al. 2005; Wesselingh et al. 2006a). These well sections were dated via mollusks by Wesselingh et al. (2006a) who also correlated them with palynozones (Hoorn 1993, 1994a).

The Neogene palynozones in South America have mainly been established in Colombian, Venezuelan, and Brazilian basins (Van der Hammen 1956; Germeraad et al. 1968; Regali et al. 1974a, 1974b; Lorente 1986; Hoorn 1993; Jaramillo et al. 2011). More specific palynostratigraphic works have been developed in the Solimões and Acre basins (Hoorn 1994a, 1994b; da Silva et al. 2010; Silveira and Souza 2015, 2016; Leite et al. 2016; Leandro et al. 2019; Linhares et al. 2019). Those paleontological studies have helped to establish correlations between Amazonian basins and to reconstruct Neogene biomass evolution (Wesselingh et al. 2006a; Hoorn and Wesselingh 2010; Jaramillo et al. 2010; Boonstra et al. 2015; Antoine et al. 2016; Jaramillo et al. 2017). However, to date, no detailed palynostratigraphic research has been carried out in the Marañon Basin, and the nature, evolution, and age range of the Neogene palynofloras of this basin remain poorly understood.

This study aims to establish a spore/pollen zonation for the Neogene sediments of the retroarc foreland (most subsiding area; Roddaz et al. 2010) of the Marañon Basin based on the identification of qualitative changes in palynomorphs (spores, pollen, and dinoflagellate cysts) through the intervals sampled in six exploration wells (Table 1 and Figure 1).

2. Geological setting

The Marañon Basin covers approximately 320,000 km² (Mathalone and Montoya 1995) and is located between 0°N and 7°30'S and 70 and 78°W in northeastern Peru (Figure 1). It is currently considered a foredeep depozone of the northern Amazonian retroarc foreland basin (Roddaz et al. 2005, 2010). The Huallaga and Santiago basins to the southwest and west, respectively, separate the Marañon Basin from the Subandean zone, and to the northeast the basin is bordered by the Iquitos forebulge (Roddaz et al. 2005, 2010). It continues as the Oriente Basin in Ecuador to the northwest and the Putumayo Basin in Colombia to the north. The Guyanese shield and Solimões Basin border the Marañon Basin to the east. To the south, the basin is bordered by the Ucayali and Acre basins, and to the southeast the Contaya arch separates it from the Ucayali Basin (Roddaz et al. 2005).

The Amazonian retroarc foreland basin system started to form between the late Maastrichtian and early Paleocene, during the first period of Amazonian Andes mountain building (Hurtado et al. 2018; Louterbach et al. 2018). This late Maastrichtian–Paleocene period of Andean tectonic loading was followed by an unloading stage during the Early–Middle Eocene (Roddaz et al. 2010). From the Middle–Late Eocene, the Amazonian retroarc foreland basin was subjected to continuous flexural subsidence driven by the continuous Andean tectonic loading, which promoted high sedimentation rates in the foredeep depozone (Roddaz et al. 2010). The formation and forward propagation of the eastern Amazonian orogenic thrust wedge began in the Oligocene (30–24 Ma) (Eude et al. 2015), causing flexural subsidence and high sedimentation rates in the Marañon foredeep (Roddaz et al. 2010).

The stratigraphy of Amazonian foreland basins has been synthesized by Roddaz et al. (2010). The Neogene sedimentary pile consists of late Oligocene–Miocene Chambira, Early–Late Miocene Pebas, Pliocene Marañon, and Quaternary Corrientes formations. These units are generally poorly dated. The Pebas Formation, with a thickness of approximately 1000 m (Wesselingh et al. 2006a), transitionally overlies the Chambira Formation (Oligocene) and is in underlying concordant contact with the Marañon Formation. The transition is characterized by blue clays, fine-grained lithic sandstones, and lignite layers rich in diverse and well-preserved invertebrate and vertebrate fossils; the base of this formation was dated around 22.5–23.9 Ma (Oligocene–Miocene boundary) (Wesselingh et al. 2006a).

3. Previous studies

Numerous studies have recorded the presence of palynomorph taxa in the Pebas and Solimões formations and other coeval units outcropping in Colombia, Brazil, and Peru (Hoorn 1993, 1994a, 1994b, 2006; Hoorn et al. 1995, 1996, 2010a, 2010b; Räsänen et al. 1995; Gingras et al. 2002a, 2002b; Hoorn and Ramos Feijó 2006; Rebata et al. 2006a, 2006b; Wesselingh 2006; Wesselingh et al. 2006a, 2006b, 2010; Hovikoski et al. 2007b; Latrubesse et al. 2007, 2010; da Silva et al. 2010; Gross et al. 2011; Leite et al. 2017; Leandro et al. 2019; Linhares et al. 2019). These formations generally date from the Early–Late Miocene (Hoorn and Wesselingh 2010; Latrubesse et al. 2010; Roddaz et al. 2010; Boonstra et al. 2015; Hoorn et al. 2017; Jaramillo et al. 2017; Leite et al. 2017). However, it is important to note that no palynological studies exist that deal with the Neogene sedimentary units of the Marañon Basin.

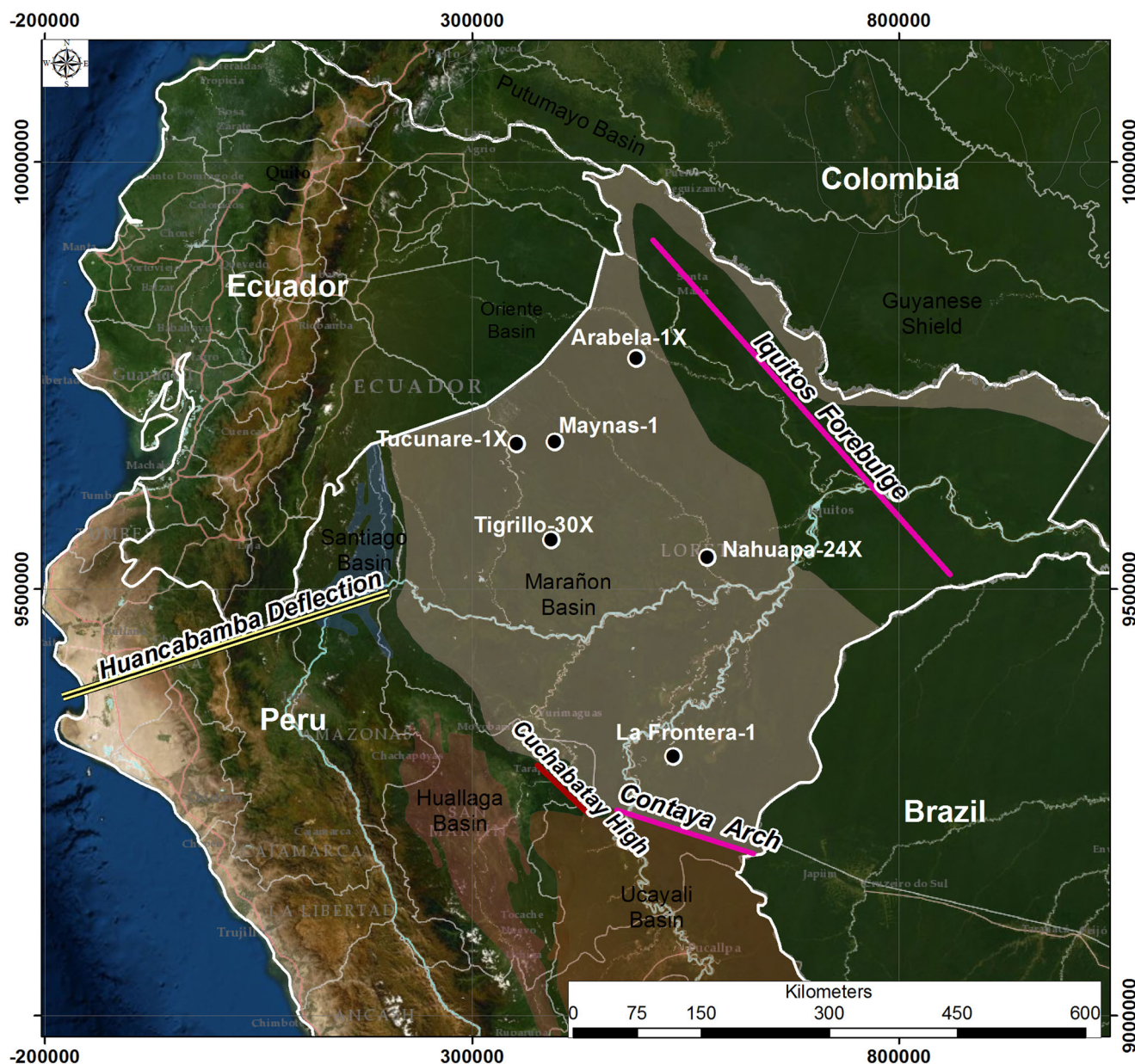


Figure 1. Location of the six studied deep exploration wells (white-black circles). Structural boundaries of the Marañón Basin (after Roddaz et al. 2005).

Neogene deposits of the Marañón Basin, to date, have been dated mainly based on palynozones defined by Hoorn (1993) for the Solimões and Acre basins, the Malacostraca zones defined by Wesselingh et al. (2006a), and the ostracod zones defined by Muñoz-Torres et al. (2006). Hoorn (1993) defined five palynozones for the Solimões Basin: the *Verrutricolporites* Acme Zone (Early Miocene), the *Retitricolporites* Acme Zone (Early Miocene), the *Psiladiopores*–*Crototricolpites* Concurrent Range Zone (late Early to early Middle Miocene), the *Crassoretitricolpites* Interval Zone (Middle Miocene), and the *Grimsdalea* Interval Zone (late Middle to early Late Miocene), which correlated with those by Germeraad et al. (1968) and Lorente (1986). In the same basin, da Silva et al. (2010) defined the *Asteraceae*–*Fenestrites* Zone and recognized the *Psilatricolporites caribbiensis* palynozone of Lorente (1986). More recently, these zones in the Solimões Basin

were recognized by (Leite et al. 2017; Linhares et al. 2017, 2019; Leandro et al. 2019), who further identified Lorente's (1986) palynozones: the *Crassoretitricolpites* Interval Zone (Middle Miocene), the *Asteraceae* Interval Zone (Late Miocene), the *Psilatricolporites caribbiensis* Interval Subzone (latest Miocene–Pliocene), and the *Echitricolporites*–*Alnipollenites* Interval Subzone (Late Pliocene).

4. Sample material and procedures

A total of 77 ditch-cutting samples from six exploration wells (Arabela-1X, Maynas-1, Tucunare-1X, Tigrillo-30X, Nahuapa-24X, and La Frontera-1) located in the Marañón Basin were studied for their palynological content (Table 2 and Figure 1). The samples varied from silty shale to shale, claystone, sandy clay, and clayey, very fine sandstone. The palynological samples were prepared according to the

Table 2. Analyzed intervals [depth in feet (1 ft = 0.3 meters)] from Arabela-1X, Maynas-1, Tucunare-1X, Tigrillo-30X, Nahuapa-24X, and La Frontera-1 wells in the Marañon Basin and Centro de Investigaciones Científicas y Transferencia de Tecnología a la Producción (CICYTTP-PI) collection number of each analyzed sample.

Well	CICYTTP	Depth	Well	CICYTTP	Depth	Well	CICYTTP	Depth
Arabela1X	2005	186 – 195	Tigrillo-30X	2036	1618 – 1628	Nahuapa-24X	2052	674 – 683
	2006	250 – 259		2037	1728 – 1737		2053	701 – 710
	2007	277 – 286		2038	1820 – 1829		2054	738 – 747
	2008	341 – 351		2039	1966 – 1975		2055	783 – 792
	2009	360 – 369		2040	2094 – 2103		2056	856 – 866
	2010	369 – 378		2041	2112 – 2121		2057	948 – 957
	2011	451 – 460		2042	2130 – 2140		2058	1021 – 1030
	2012	497 – 506		2043	2231 – 2240		2059	1085 – 1094
	2013	543 – 552		2044	2322 – 2332		2060	1103 – 1112
	2014	552 – 561		2045	2432 – 2441		2061	1140 – 1149
	2015	689 – 698		2046	2551 – 2560		2062	1195 – 1204
	2016	872 – 881		2047	2652 – 2661		2063	1341 – 1350
	2017	1009 – 1018		2048	2770 – 2780		2064	1405 – 1414
Maynas-1	2018	823 – 838		2049	2917 – 2926		2065	1496 – 1506
	2019	1021 – 1036		2050	3054 – 3063		2066	1588 – 1597
	2020	1341 – 1356		2051	3246 – 3255		2067	1698 – 1707
	2021	1600 – 1615					2068	1743 – 1753
	2022	1859 – 1874					2069	1753 – 1762
	2023	2164 – 2179					2070	1798 – 1807
	2024	2438 – 2447					2071	1890 – 1899
Tucunare-1X	2025	1524 – 1539					2072	360 – 366
	2026	1631 – 1646					2073	469 – 475
	2027	1676 – 1692					2074	567 – 573
	2028	1768 – 1783					2075	579 – 585
	2029	1798 – 1813					2076	671 – 677
	2030	1951 – 1966					2077	823 – 829
	2031	2057 – 2073					2078	945 – 951
	2032	2133 – 2149					2079	975 – 981
	2033	2194 – 2210					2080	1250 – 1256
	2034	2240 – 2255					2081	1341 – 1347
	2035	2316 – 2332						

CICYTTP: Centro de Investigaciones
Científicas y Transferencia de
Tecnología a la Producción

Slides collection number in CICYTTP:
CICYTTP-2005 to CICYTTP-2081

Depth: analyzed intervals of each well in meters

standard procedure (Wood et al. 1996). The preparation of palynological slides was carried out in the Paleosedes Laboratory in Bogotá, Colombia (<http://www.paleosedes.tk>). Samples were processed using hydrochloric acid, hydrofluoric acid, and zinc chloride solutions. The slides were analyzed at the Paleosedes Biostratigraphy Laboratory and the Palynostratigraphy and Paleobotany Laboratory of the institute CICYTTP-CONICET-ER-UADER (<http://www.cicyttp.org.ar>) in Argentina. Slides and residues are housed at the Palynostratigraphy and Paleobotany Laboratory of the Centro de Investigaciones Científicas y Transferencia de Tecnología a la Producción (CICYTTP) and cataloged under CICYTTP acronyms; Table 2).

Two slides per sample (oxidized and non-oxidized) were scanned for palynomorph identification using transmitted light microscopes with a digital camera (Leitz Labor Lux S and Labomed 10 in Colombia; Nikon E200 and Labomed 5 in Argentina). Well-preserved specimens were selected and illustrated in Plate 1 using England Finder™ coordinates. Palynomorph counting and logging were done by applying straight transects across each slide. Species names and abundance of taxa were recorded on data sheets. Six palynomorph distribution charts were prepared based on each palynomorph identified in the well sections, and the abundances of spores, pollen grains, fungal spores, algae, dinoflagellate cysts, acritarchs, foraminiferal linings, and copepod eggs were tabulated in the Tilia software (Grimm 2015) (Appendices 1–6). The recovered palynomorphs were gathered in seven morphogroups (Table 3) and percentages for the morphogroups in all wells were calculated (Table 4).

Approximately 100–200 specimens were counted per sample. However, some samples with abundances lower than 100 identifications were also included in the qualitative analyses due to their biostratigraphic significance (see Appendices 1–6).

The qualitative vertical arrangement of taxa identified from the wells was used to interpret first downhole occurrence or last appearance datum (LAD) and last downhole occurrence or first appearance datum (FAD) data. Palynostratigraphic studies and online catalogues of species from northern South America (Van der Hammen 1956; Germeraad et al. 1968; Regali et al. 1974a, 1974b; Lorente 1986; Muller et al. 1987; Tryon and Lugardon 1991; Hoorn 1993, 1994a; da Silva et al. 2010; Jaramillo et al. 2011; Raine et al. 2011; Silveira and Souza 2015, 2016; Leite et al. 2017; Williams et al. 2017; Jaramillo and Rueda 2019) were consulted for taxonomic determinations (see the list of species with their authors below) and stratigraphic ranges of the species suitable for biostratigraphy (Table 5). Critical palynomorph taxa were selected according to their stratigraphic value, and the most biostratigraphically significant events are indicated in Figure 2. To validate these findings, the graphic correlation technique of Shaw (1964) was applied to the dataset using GraphCor: Interactive Graphic Correlation software (Hood 1998) to obtain a composite section (Table 6) that was reordered and plotted (Figure 3) according to the stratigraphic succession, thus revealing biostratigraphic units. Details of this method can be consulted in the extensive compilation of Mann and Lane (1995).

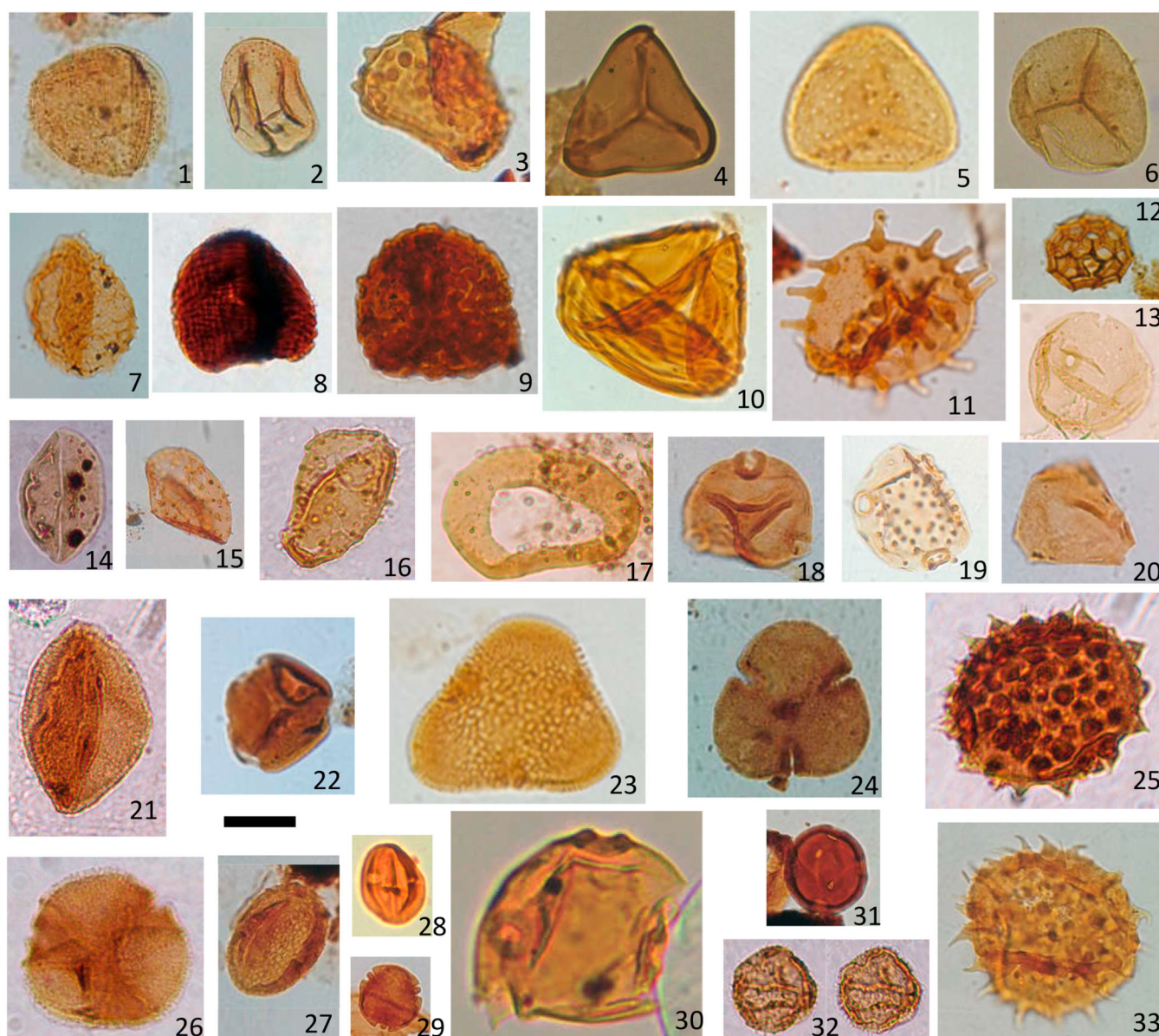


Plate 1. Photographs of the main palynomorphs from the studied wells. 1. *Laevigatosporites catanejensis* CICYTTP-2005 Arabela 1X (610–640ft), EF M12/2; 2. *Laevigatosporites granulatus* CICYTTP-2014 Arabela 1X (1810–1840ft), EF L32/2-4; 3. *Polypodiisporites usmensis* CICYTTP-2007 Arabela 1X (910–940ft), EF H25/2; 4. *Cyathidites congoensis* CICYTTP-2074 Frontera 1 (1860–1880ft), EF N35/2; 5. *Foveotrilletes ornatus* CICYTTP-2068 Nahuapa 24X (5720–5750ft), EF N32/1-2; 6. *Osmundacidites ciliatus* CICYTTP-2074 Frontera 1 (1860–1880ft), EF R35/1; 7. *Retitrilletes altimuratus* CICYTTP-2061 Nahuapa 24X (3740–3770ft), EF W21/3-4; 8. *Cicatricosisporites dorogensis* CICYTTP-2017 Arabela 1X (3310–3340ft), EF E3/3-2; 9. *Crassoretitilletes vanraadshooveni* CICYTTP-2052 Nahuapa 24X (2210–2240ft), EF H43/1; 10. *Magnastritilletes grandiosus* CICYTTP-2057 Nahuapa 24X (3110–3140ft), EF O43/2; 11. *Grimsdalea magnaclavata* CICYTTP-2053 Nahuapa 24X (2300–2330ft), EF W17/3; 12. *Gomphrenipollis minimus* CICYTTP-2061 Nahuapa 24X (3740–3770ft), EF T34/2-3; 13. *Monoporopollenites annulatus* CICYTTP-2058 Maynas 1 (3350–3400ft), EF P44/1; 14. *Psilamonocolpites medius* CICYTTP-2046 Tigrillo 30X (8370–8400ft), EF Q11/4; 15. *Mauritiidites franciscoi minutus* CICYTTP-2014 Arabela 1X (1810–1840ft), EF S38/1; 16. *Mauritiidites franciscoi franciscoi* CICYTTP-2031 Tucunare 1X (6750–6800ft), EF H42/1; 17. *Cyclusphaera scabrata* CICYTTP-2020 Maynas 1 (4400–4450ft), EF E10/3; 18. *Corsinipollenites psilatus* CICYTTP-2014 Arabela 1X (1810–1840ft), EF N12; 19. *Echitriporites crictriporatiiformis* CICYTTP-2006 Arabela 1X (820–850ft), EF F44/3; 20. *Proteacidites triangulatus* CICYTTP-2061 Nahuapa 24X (3740–3770ft), EF Z33/1; 21. *Retitricolpites simplex* CICYTTP-2035 Tucunare 1X (7600–7650ft), EF P43/2; 22. *Crassietoapertites columbianus* CICYTTP-2061 Nahuapa 24X (3740–3770ft), EF F38/1; 23. *Bombacacidites nacimientoensis* CICYTTP-2059 Nahuapa 24X (3560–3590ft), EF J35/1-3; 24. *Bombacacidites brevis* CICYTTP-2017 Arabela 1X (3310–3340ft), EF R40/3; 25. *Malvacipoloides maristellae* CICYTTP-2034 Tucunare 1X (7350–7400ft), EF N25/2; 26. *Margocolporites vanwijhei* CICYTTP-2046 Tigrillo 30X (8370–8400ft), EF M23/4; 27. *Rhoipites guianensis* CICYTTP-2014 Arabela 1X (1810–1840ft), EF H35/1; 28. *Siltaria hammenii* CICYTTP-2072 Frontera 1 (1180–1200ft), EF X48; 29. *Ranunculacidites operculatus* CICYTTP-2007 Arabela 1X (910–940ft), EF G23/3; 30. *Psilastephanopores tesseroporus* CICYTTP-2077 Frontera 1 (2700–2720 ft), EF W34/3; 31. *Perisyncolporites pokornyi* CICYTTP-2011 Arabela 1X (1480–1510ft), EF V37/3; 32. *Echiperiporites akanthos* CICYTTP-2027 Tucunare 1X (5500–5550ft), EF U27/2; left high focus and right lowfocus; 33. *Echiperiporites estelae* CICYTTP-2016 Arabela 1X (2860–2890ft), EF G23/1. Scale bar is 20 μ m for all pictures except for Figures 9 and 10 where it represents 30 μ m.

5. General characterization of the palynofloral assemblages

Seventy-seven samples from the Arabela-1X, Maynas-1, Tucunare-1X, Tigrillo-30X, Nahuapa-24X, and La Frontera-1 wells in the Mara  n Basin (Table 2; Figure 1) yielded 6262

identifiable grains, as summarized in Table 3. Quantitative distribution of palynomorphs in the wells (Table 3 and 4; Appendices 1–6) reveals a total of 226 morphotypes, including 80 genera and 150 species of pollen grains, 24 genera and 43 species of spores, nine genera and eight species of dinoflagellate cysts, five genera of algae, four morphotypes, and two

Table 3. Total grains counted per each analyzed well and percentage of each morphogroup from Arabela-1X, Maynas-1, Tucunare-1X, Tigrillo-30X, Nahuapa-24X, and La Frontera-1 wells in the Marañon Basin. NA: not applicable.

Morphogroups	Total grains	% of 6262 grains	Morphotypes	Genera	Species
Spores	3232	51.6	44	24	43
Pollen grains	1478	23.6	152	80	150
Fungal spores	167	2.7	4	2	NA
Algae	899	14.4	7	5	NA
Dinoflagellate cysts	243	3.9	13	9	8
Foram linings	110	1.8	5	NA	NA
Copepod eggs	133	2.1	1	NA	NA
Total	6262	100.00	226	120	201

Table 4. Total grains counted per morphogroup in each analyzed well and percentage of each morphogroup from Arabela-1X, Maynas-1, Tucunare-1X, Tigrillo-30X, Nahuapa-24X, and La Frontera-1 wells in the Marañon Basin.

Morphogroups	Arabela-1X	Maynas-1	Tucunare-1X	Tigrillo-30X	Nahuapa-24X	La Frontera-1
Spores	46.8	65.3	49.7	64.7	48.5	22.8
Pollen grains	28.5	16.5	28.5	24.6	19.1	25.6
Fungal spores	3.3	0.5	0.3	1.7	3.9	7.1
Algae	13.4	6.0	11.8	5.5	25.7	24.4
Dinoflagellate cysts	6.6	0.9	3.5	1.8	1.0	14.5
Foram linings	1.1	4.4	0.0	1.7	0.4	5.6
Copepod eggs	0.2	6.4	6.1	0.0	1.3	0.0
Total specimens	2120	1176	593	654	1395	324

genera of fungal spores. Foraminiferal linings and copepod eggs (indeterminate copepods) were also identified. Of the identified palynomorphs, 75.1% belonged to pollen and spore groups, 14.3% were algae, and 7.8% included dinoflagellate cysts, acritarchs, foraminiferal linings, and other palynomorph remains. Fungal palynomorphs (2.8%) and abundant organic matter were recovered in all the samples.

Fairly well-preserved pteridophyte–bryophyte spores, angiosperm and gymnosperm pollen grains, phytoplankton (chlorophyceans, acritarchs, and dinoflagellate cysts) and miscellaneous groups (foraminifera, copepods, and fungal remains), characterize the palynoflora obtained from the six wells. The first group was mainly composed of spores such as *Azolla*, *Cicatricosisporites*, *Crassoretitrites*, *Cyathidites*, *Deltoidospora*, *Echinatisporis*, *Foveotritetes*, *Laevigatosporites*, *Magnastriatites*, *Polypodiisporites*, *Psilatriletes*, *Striatritetes*, and *Verrucosisporites*–*Verrutritetes*.

Angiosperm pollen grains were frequent and more diverse, including *Bombacacidites*, *Corsinipollenites*, *Crassietoapertites*, *Cyclusphaera*, *Echiperiporites*, *Echipollenites*, *Echitriporites*, *Inaperturopollenites*, *Ladakhipollenites*, *Malvacipoloides*, *Mauritiidites*, *Paleosantalaceapites*, *Perforitricolpites*, *Perisyncolporites*, *Proxapertites*, *Proteacidites*, *Psilamonocolpites*, *Psilastephanocolporites*, *Psilatricolporites*, *Retimonocolpites*, *Retipollenites*, *Retistephanoporites*, *Retitrescolpites*, *Retitricolpites*, *Scabrapollenites*, *Siltaria*, *Spinizonocolpites*, and *Striatopollis*.

Gymnosperm pollen grains were rare and less diverse: *Araucariacites*, *Cyclusphaera*, *Inaperturopollenites*, *Podocarpidites*, and *Striapollenites*. Chlorophycean algae such as *Botryococcus*, *Oedogonium*, *Pediastrum*, and *Pterospermella* were obtained. Other phytoplankton, including acritarchs and dinoflagellate cysts, such as *Apteodinium*, *Batiacasphaera*, *Bosedinia*, aff. *Ceratium*, *Cribrroperidinium*, *Leiosphaeridia*, *Quadrina*, *Selenopemphix* spp., and *Operculodinium* and *Polysphaeridium* groups, were common and always accompanied by

foraminiferal linings, copepod eggs, and fungal palynomorphs, such as *Fusiformisporites*, *Microthyraeae*, and *Tetraploa*. The distribution of the palynomorphs in the above-mentioned wells, their relative abundances (range charts), and extended Tilia diagrams are shown in [Appendices 1–6](#), and key markers are illustrated in [Plate 1](#).

6. Definition of palynozones

Fifty-two biostratigraphic marker species were recognized in the six boreholes ([Table 5](#)). Some occurred in all the wells, whereas others did not ([Appendices 1–6](#)), but all have a wide geographic distribution and well-known stratigraphic ranges given as FADs and LADs in millions of years ago for each taxon and/or based on stratigraphic ranges that have been used in biostratigraphic definitions in northern South America (Lorente 1986; Muller et al. 1987; Hoorn 1993; da Silva et al. 2010; Jaramillo et al. 2011) and elsewhere (Bujak and Williams 1985; Macphail 1999; Williams et al. 2017). Therefore, they are useful for dating the studied successions in this basin and for proposing regional correlations. Six palynozones named from the oldest to the youngest, namely Mar-A to Mar-F ('Mar' is the abbreviation for 'Marañon') are proposed considering the vertical distribution of the taxa ([Figures 2–4](#); [Appendices 1–6](#)) based on the analysis of qualitative biostratigraphic events. A quantitative deterministic method of graphic correlation (Shaw 1964) in order to test this scheme was run in GraphCor: Interactive Correlation Software Hood (1998). Maximum stratigraphic ranges of species from previously known appearances and disappearances in each well ([Table 6](#)) allowed the construction of a biostratigraphic ordination in a composite section ([Figure 3](#)) according to last appearances of species. This method corroborates the proposed zonation based on a qualitative analysis, also evidenced by stratigraphically constrained cluster analysis (CONISS) in the Tilia software (Grimm, 2015) for each well

Table 5. Marker age of palynomorphs recovered in the Arabela-1X, Maynas-1, Tucunare-1X, Tigrillo-30X, Nahuapa-24X, and La Frontera-1 boreholes in the in the Marañon Basin, in alphabetical order (occurrence levels are included; depth in meters). (1) da Silva-Caminha et al. (2010), (2) González-Guzmán (1968), (3) Hoon (1993), (4) Jaramillo et al. (2011), (5) Eisawi and Schrank (2008), (6) Cole (1992); (7) De Verteuil et al. (1992), (8) Raine et al. (2011) and (9) Williams et al. (2017).

MARKER SPECIES	FAD	LAD	ARABELA-1X	MAYNAS-1	TUCUNARE-1X	TIGRILLO-30X	NAHUAPA-24X	LA FRONTERA-1
<i>Acaciapollenites myriosporites</i> (1)(8)	Neogene	Neogene						1341-1347
<i>Aptedodium australiense</i> (9)	Early Eocene	Midle Miocene/ Serravalian						1250-1256
<i>Bombacacidites aracuarensis</i> (3)	Early Miocene	early Middle Miocene		2164-2179	1524-1539			
<i>Bombacacidites gonalezii</i> (4)	51.49	19.7				1618-2103	674-1094	
<i>Bombacacidites nacimientensis</i> (4)	56.85	13.05						579-585
<i>Bosedinia infragranulata</i> (6)	Late Oligocene	Miocene						
<i>Cicatricosisporites dorogensis</i> (4)	48.61	23.03	1009-1018	2621-2630	2316-2332	3356-3365	2054-2060	
<i>Cistacearupollenites rotundiporus</i> (1)	Neogene	Neogene		1859-2447	1798-2149			360-366
<i>Corsiniipollenites oclusnoctis</i> (1)	Early Miocene	Middle Miocene						671-677
<i>Corsiniipollenites collaris</i> (1)	Miocene	Early Plioc					1798-1807	
<i>Corsiniipollenites psilatus</i> (4)		17.33	451-460	1341-1356	1676-1692		674-2054	
<i>Crotaticolpites annemariae</i> (4)	52.49	13						975-981
<i>Crassoretiriletes vanraadshooveni</i> (4)	14.18	3.4					674-683	360-366
<i>Ctenolophinidites suigeneris</i> (1)	Miocene	Early Plioc					1140-1506	579-585
<i>Cyathidites congoensis</i> (5)	Late Miocene	Pliocene	186-1009	1021-2447	1524-2332	3255-1618	674-1753	567-573
<i>Cyclusphaera scabrata</i> (4)	55.8	16.92	360-881	1341-1356				
<i>Echitriporites crictrioratiformis</i> (4)	16.8	3.94	250-259					
<i>Echiperiporites lophatus</i> (1)	Miocene	Early Plioc					701-710	
<i>Foveatricolporites lenticuloides</i> (1)	Neogene	Neogene						579-585
<i>Gomphrenipollis minimus</i> (1)	Miocene	Early Plioc					1140-1149	
<i>Grinsdalea magnaclavata</i> (4)	16.09	3.4					701-792	
<i>Ladakhipollenites simplex</i> (4)	59.92	12.87	250-506	1021-1356				
<i>Ladakhipollenites? caribbiensis</i> (1)	Late Miocene	Pliocene						567-573
<i>Laevigatosporites catanegenis</i> (4)	42.53	4.32						
<i>Lanagipollis crassa</i> (4)	51.3	4.7						567-573
<i>Magnaperiporites spinosus</i> (4)	31.96	12.98						
<i>Malvacipollinoides maristellae</i> (4)	17.71	0.39	552-561					
<i>Mauritiidites crassibaculatus</i> (4)		11.85	186-506	1021-1356	1524-2332	2130-2240	1021-1350	823-981
<i>Multiporipollenites apauciporatus</i> (4)		23		823-2164		1758-2917		
<i>Nijssenosporites fossulatus</i> (4)	19.05	1.03		2438-2447				579-585
<i>Osmundacidites ciliatus</i> (5)	Late Miocene	Pliocene						567-573
<i>Palaeosantalaceapites cingulatus</i> (4)	12.08	3.72					674-683	567-573
<i>Psilastephanopores tesseroporus</i> (4)	13.9	5.48	250-259					
<i>Quadrina? condita</i> (7)	Middle Miocene	Late Miocene						
<i>Retimonocolpites maximus</i> (3)	Miocene	Miocene						579-585
<i>Retipollenites crotonicolumellatus</i> (4)	13.94	3.56				1820-1829		469-475
<i>Retistephanopores angelicus</i> (2)	56	16				1966-1975		
<i>Retitricolporites wilmsiae</i> (3)	23	16				1975-3255		
<i>Retitricolporites "acerolensis"</i> (4)		16.26	360-1018	1021-1615	1631-1646			
<i>Retitricolporites altimuratus</i> (1)	Miocene	Early Pliocene					674-1149	
<i>Retitricolporites dubiosus</i> (4)	51.47	14.27	277-286					
<i>Selenopemphix nephioides</i> (4)	17.83	6.89	341-351					
<i>Siltaria hammenii</i> (1)	Neogene	Neogene						360-366
<i>Siltaria santaisabelensis</i> (1)	Miocene	Miocene						469-475

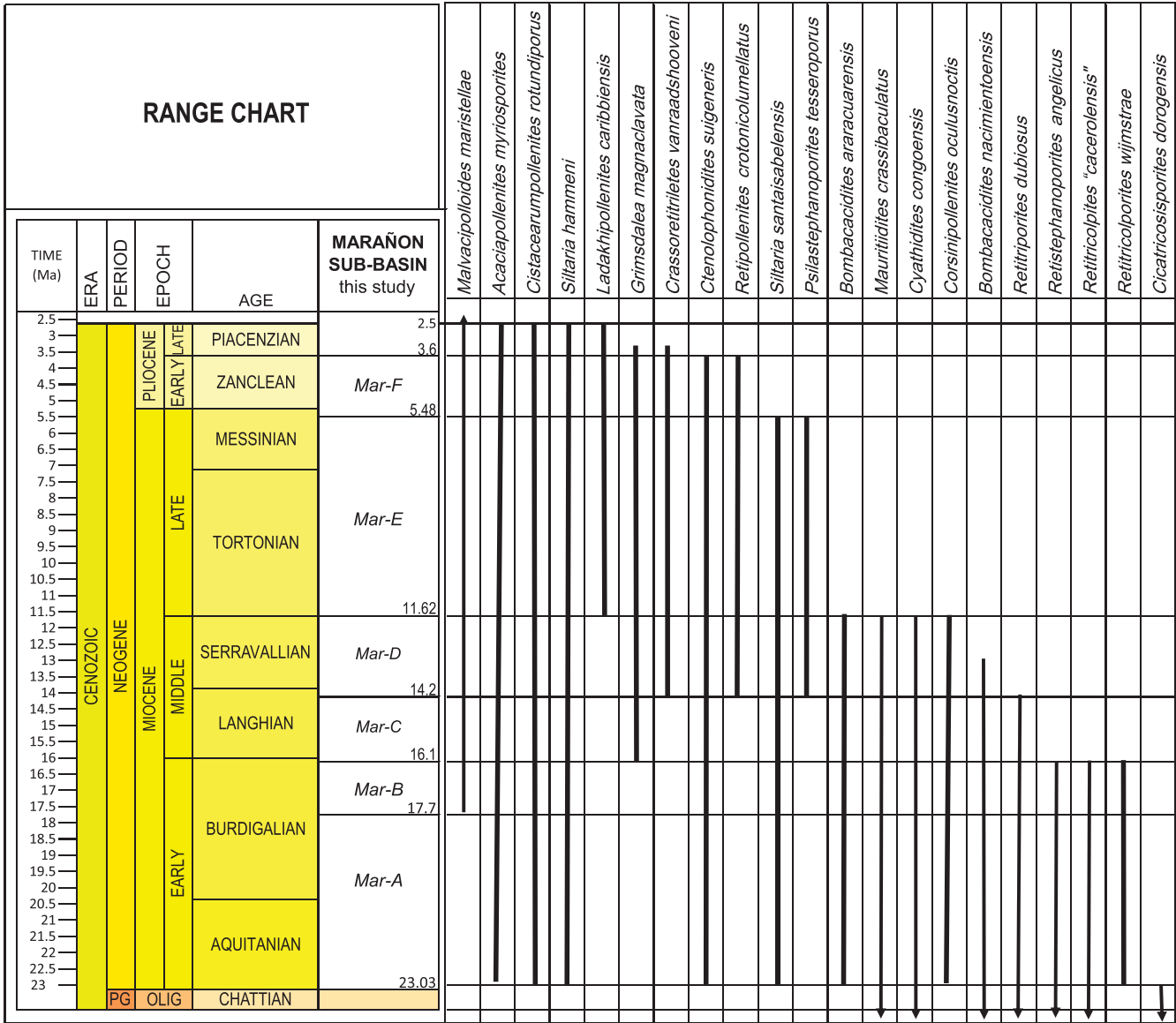


Figure 2. Range chart of taxa as used in this work, indicating the boundaries of the palynozones Mar-A to Mar-F.

(Appendices 1–6). The upper two zones are preliminarily characterized until further studies with more materials are carried out. The presence of well-known diagnostic species (FADs and LADs; Figures 2–4; Tables 5 and 6) supported the ages of the palynozones. In addition, seven timelines and a west–east and north–south correlation among the six wells were drawn (Figure 5), and a correlation of our palynozonation with other palynozones from northern South America (Figure 6) is also addressed below.

6.1. Mar-A *Corsinipollenites oculusnotis* Interval Zone

Reference section. Arabela-1X interval 2890–1660 ft (881–506 m).

Distribution. This zone was recognized in all the wells: Arabela-1X interval 2890–1660 ft (881–506 m), Tigrillo-30X interval 10,680–7620 ft (3255–2323 m), Nahuapa-24X interval 4610–3230 ft (1405–985 m), Maynas-1 interval 8030–5250 ft (2438–1600 m), Tucunare-1X interval 7650–7400 ft (2332–2255.5 m) and La

Frontera-1 interval 4420–4100 ft (1347–1250 m) (see Appendices 1–6 for details and Figures 2–6 for summary and correlation).

Description. We define the Mar-A *Corsinipollenites oculusnotis* palynozone as occurring from the LAD of *Cicatricosisporites dorogensis* to the FAD of *Malvacipoloides maristellae* or, alternatively, it is from the FAD of *Corsinipollenites oculusnotis*, the FAD of *Retitricolporites wijmstrae*, and/or the FAD of *Acaciapollenites myriosporites* to the FAD of *Malvacipoloides maristellae* as occurring respectively in the Maynas-1, Tigrillo-30X, and La Frontera-1 wells, to the FAD of *Malvacipoloides maristellae*.

Age. Aquitanian to Early Burdigalian (23.03–17.71 Ma).

Characteristics. The presence of Paleogene taxa whose extinction occurred in the Neogene, such as *Bombacacidites nacimientensis*, *Corsinipollenites psilatus*, *Magnastriatites grandiosus*, *Mauritiidites franciscoi* var. *franciscoi*, *Mauritiidites franciscoi* var. *minutus*, *Retitricolpites simplex*, and *Spirosyncolpites spiralis*, among others, is notable. This zone is characterized by the inception of other species, such as

Table 6. Maximum stratigraphic ranges of species among the studied wells, constructed in a composite section from previously known appearances and disappearances of species in each well obtained by means of graphic correlation.

Composite section for taxa from sections in studied wells							
<i>Acaciapollenites</i>	<i>myriosporites</i>	–1018	–194	<i>Mauritiidites</i>	<i>franciscoi franciscoi</i>	–693	–282
<i>Apteodinium</i>	<i>australiense</i>	–888	–888	<i>Mauritiidites</i>	<i>franciscoi minutus</i>	–795	–165
<i>Araliaceae</i>	<i>pollenitis</i>	–364	–364	<i>Monoporopollenites</i>	<i>annulatus</i>	–603	–191
<i>Arecipites</i>	<i>perfectus</i>	–194	–165	<i>Monocolpopollenites</i>	<i>ovatus</i>	–451	–451
<i>Bombacacidites</i>	<i>araracuarensis</i>	–190	–190	<i>Osmundacidites</i>	<i>ciliatus</i>	–191	–191
<i>Bombacacidites</i>	<i>brevis</i>	–1013	–1013	<i>Paleosantalaceae</i>	<i>cingulatus</i>	–191	–191
<i>Bombacacidites</i>	<i>gonzalezi</i>	–1013	–834	<i>Perforicarpites</i>	<i>digitatus</i>	–709	–254
<i>Bombacacidites</i>	<i>nacimientensis</i>	–1013	–186	<i>Perisyncolpites</i>	<i>pokorny</i>	–834	–194
<i>Bombacacidites</i>	<i>psilatus</i>	–1013	–1013	<i>Polyadapollenites</i>	<i>mariae</i>	–644	–245
<i>Bosedinia</i>	<i>infragranulata</i>	–194	–194	<i>Polypodiisporites</i>	<i>speciosus</i>	–693	–282
<i>Retitricolpites</i>	<i>"cacerolensis"</i>	–308	–236	<i>Polypodiisporites</i>	<i>usmensis</i>	–834	–217
<i>Cicatricosisporites</i>	<i>doroensis</i>	–1018	–1018	<i>Polypodiisporites</i>	<i>verrucatus</i>	–442	–364
<i>Colombipollis</i>	<i>tropicalis</i>	–547	–547	<i>Proteacidites</i>	<i>triangulatus</i>	–442	–442
<i>Corsinipollenites</i>	<i>collaris</i>	–835	–835	<i>Proxapertites</i>	<i>minutus</i>	–364	–364
<i>Corsinipollenites</i>	<i>oculusnoctis</i>	–945	–219	<i>Proxapertites</i>	<i>operculatus</i>	–547	–547
<i>Corsinipollenites</i>	<i>psilatus</i>	–556	–254	<i>Proxapertites</i>	<i>psilatus</i>	–364	–364
<i>Crassietoapertites</i>	<i>columbianus</i>	–442	–442	<i>Proxapertites</i>	<i>verrucatus</i>	–364	–364
<i>Crassoretitricolpites</i>	<i>vanraadshooveni</i>	–268	–195	<i>Psilamonocolpites</i>	<i>medius</i>	–644	–191
<i>Ctenolophonidites</i>	<i>suigeneris</i>	–612	–194	<i>Psilastephanocolporites</i>	<i>fissilis</i>	–834	–834
<i>Cyathidites</i>	<i>congoensis</i>	–795	–190	<i>Psilastephanocolporites</i>	<i>tesseraporus</i>	–259	–165
<i>Cyathidites</i>	<i>minor</i>	–194	–191	<i>Psilatricolpites</i>	<i>papilioniformis</i>	–364	–364
<i>Cyclusphaera</i>	<i>scabrata</i>	–876	–364	<i>Psilatricolporites</i>	<i>crassoexinatus</i>	–364	–364
<i>Deltoidospora</i>	<i>adriennis</i>	–364	–191	<i>Psilatricolporites</i>	<i>operculatus minutus</i>	–364	–364
<i>Echinatisporis</i>	<i>muelleri</i>	–219	–219	<i>Quadrina?</i>	<i>condita</i>	–194	–194
<i>Echiperiporites</i>	<i>akanthos</i>	–945	–254	<i>Ranunculacidites</i>	<i>operculatus</i>	–282	–282
<i>Echiperiporites</i>	<i>estelae</i>	–876	–165	<i>Retimonocolpites</i>	<i>maximus</i>	–165	–165
<i>Echiperiporites</i>	<i>lophatus</i>	–217	–217	<i>Retimonocolpites</i>	<i>retifossulatus</i>	–945	–945
<i>Echistephanoporites</i>	<i>"annulatus"</i>	–193	–193	<i>Retipollenites</i>	<i>crotonicolumellatus</i>	–293	–288
<i>Echitriporites</i>	<i>cricotriporatiformis</i>	–254	–254	<i>Retistephanoporites</i>	<i>angelicus</i>	–363	–363
<i>Foveotricolporites</i>	<i>lenticuloides</i>	–194	–191	<i>Retistephanoporites</i>	<i>crassiannulatus</i>	–834	–256
<i>Foveotrilletes</i>	<i>"ornatus"</i>	–795	–190	<i>Retitrescolpites</i>	<i>irregularis</i>	–680	–294
<i>Foveotrilletes</i>	<i>proximopsilatus</i>	–245	–245	<i>Retitrescolpites</i>	<i>magnus</i>	–547	–364
<i>Gomphrenipollis</i>	<i>minimus</i>	–442	–442	<i>Retitrescolpites</i>	<i>saturum</i>	–963	–963
<i>Grimsdalea</i>	<i>magnaclavata</i>	–356	–217	<i>Retitrescolpites?</i>	<i>Irregularis</i>	–259	–194
<i>Inaperturopollenites</i>	<i>psilatus</i>	–364	–364	<i>Retitricolpites</i>	<i>colpiconstrictus</i>	–364	–364
<i>Inaperturopollenites</i>	<i>solimoensis</i>	–364	–364	<i>Retitricolpites</i>	<i>simplex</i>	–680	–193
<i>Ladakhipollenites</i>	<i>simplex</i>	–506	–250	<i>Retitricolporites</i>	<i>wijmstrae</i>	–1009	–363
<i>Ladakhipollenites?</i>	<i>caribbiensis</i>	–254	–191	<i>Retitricolporites</i>	<i>altimuratus</i>	–442	–442
<i>Laevigatosporites</i>	<i>"annulatus"</i>	–497	–497	<i>Retitricolporites</i>	<i>dubiosus</i>	–501	–282
<i>Laevigatosporites</i>	<i>catanagensis</i>	–190	–190	<i>Rhoipites</i>	<i>guianensis</i>	–556	–256
<i>Laevigatosporites</i>	<i>"gemmatus"</i>	–603	–603	<i>Rhoipites</i>	<i>hispidus</i>	–547	–191
<i>Laevigatosporites</i>	<i>granulatus</i>	–963	–236	<i>Selenopemphix</i>	<i>nephroides</i>	–346	–346
<i>Laevigatosporites</i>	<i>ovatus</i>	–194	–194	<i>Selenopemphix</i>	<i>quanta</i>	–194	–194
<i>Magnaperiporites</i>	<i>spinosus</i>	–556	–556	<i>Siltaria</i>	<i>santaisabelensis</i>	–165	–165
<i>Magnastriatites</i>	<i>grandiosus</i>	–835	–245	<i>Spirosyncolpites</i>	<i>spiralis</i>	–709	–364
<i>Malvacipollobes</i>	<i>maristellae</i>	–497	–409	<i>Striatilletes</i>	<i>saccolomoides</i>	–875	–447
<i>Margocolporites</i>	<i>vanwijhei</i>	–644	–556	<i>Tetracolporopollenites</i>	<i>maculosus</i>	–501	–346
<i>Mauritiidites</i>	<i>crassibaculatus</i>	–834	–245				

Apteodinium australiense, *Leiosphaeridia*, and *Polysphaeridium* groups (dinoflagellate cysts); the end of the acme of dinoflagellate cysts (Late Oligocene/Burdigalian); underlying *Malvacipollobes maristellae* (FAD); the first appearance of *Acaciapollenites myriosporites*, *Corsinipollenites collaris*, *Corsinipollenites oculusnoctis*, *Corsinipollenites psilatus*, *Ctenolophonidites suigeneris*, *Multiporopollenites* aff. *pauciporatus*/M. *pauciporatus*, *Cyathidites congoensis*, *Retitricolporites wijmstrae*, and *Selenopemphix nephroides* (dinoflagellate cysts); and the LAD of *Bombacacidites gonzalezi*. They frequently occur along with *Clavinaaperturites* aff. *clavatus*, *Laevigatosporites* spp., *Polypodiisporites speciosus*, *Polypodiisporites* spp., and *Psilamonocolpites* spp., and seldom with *Magnaperiporites spinosus* (see Appendices 1–6 for details and Figures 2–6 for summary and correlations).

Comparison. The co-occurrence of several taxa (see Tables 5–6 and Figures 2–4) supports the correlation (summarized in Figure 6) of this zone with the palynostratigraphy of

Venezuela (Lorente 1986), northern South America (Muller et al. 1987), and the Solimões Basin in Western Amazonia (Hoorn 1993). It is coeval with the T-12 *Hornella lunarensis* Zone from Llanos in Colombia (Jaramillo et al. 2011), the zonal boundaries of which are coeval with the Mar-A Zone. However, the T-12 taxon *Hornella lunarensis* is not present in the Mar-A *Corsinipollenites oculusnoctis* Zone (Figures 2–4)

6.2. Mar-B *Malvacipollobes maristellae* Interval Zone

Reference section. Arabela-1X 1660–1210 ft (506–369 m).

Distribution. This zone was recognized in the intermediate section of the six wells analyzed: Arabela-1X interval 1660–1180 ft (506–360 m), Maynas-1 interval 4450–3350 ft (1356–1021 m), Tucunare-1X interval 7400–5350 ft (2255–1631 m), Tigrillo 30X interval 7350–6450 ft (2240–1966 m), Nahuapa-24X interval 4430–2600 ft (1350–792 m), and La Frontera-1 interval

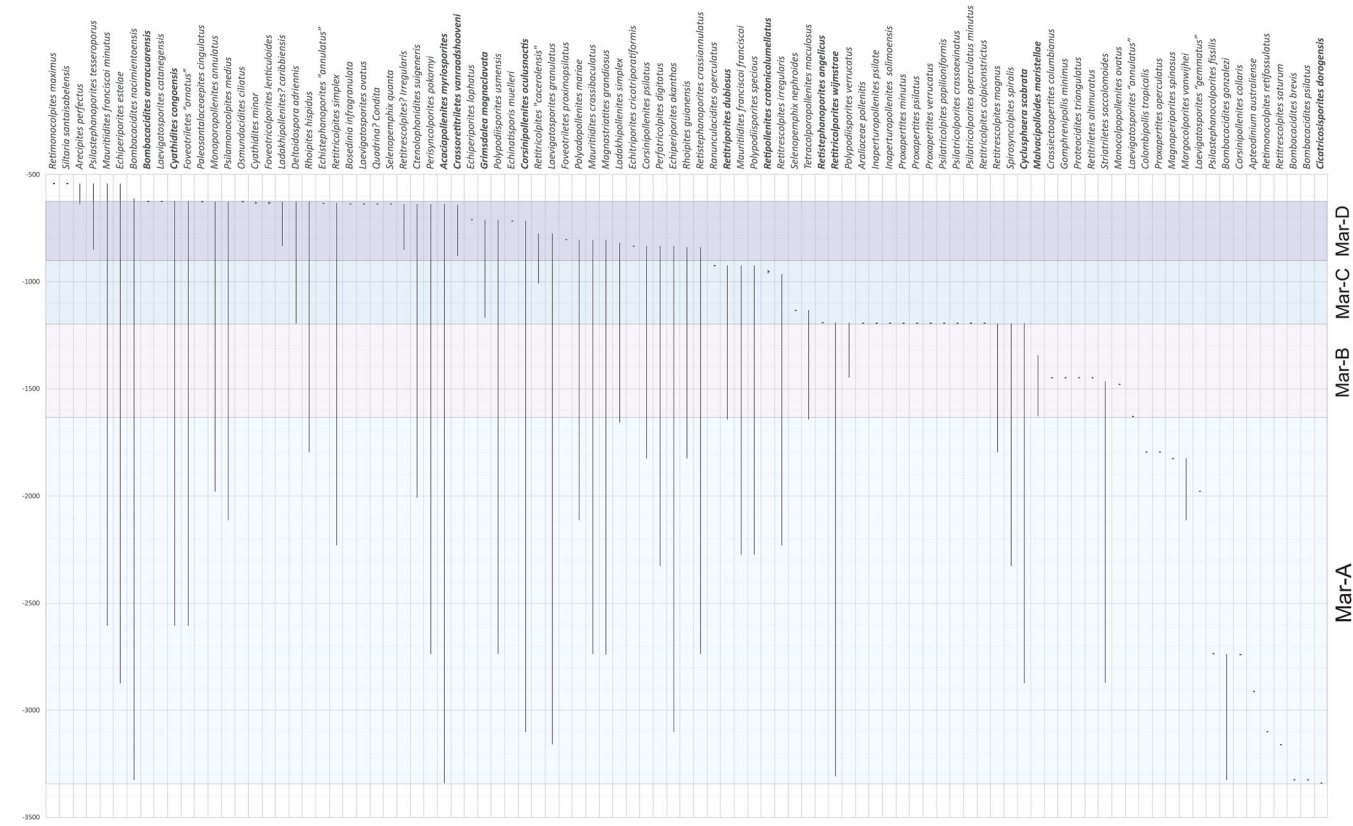


Figure 3. Maximum stratigraphic ranges of species ordered by last appearance datum (LAD) among the studied wells, constructed in a composite section from previously known appearances and disappearances of species in each well obtained by means of graphic correlation.

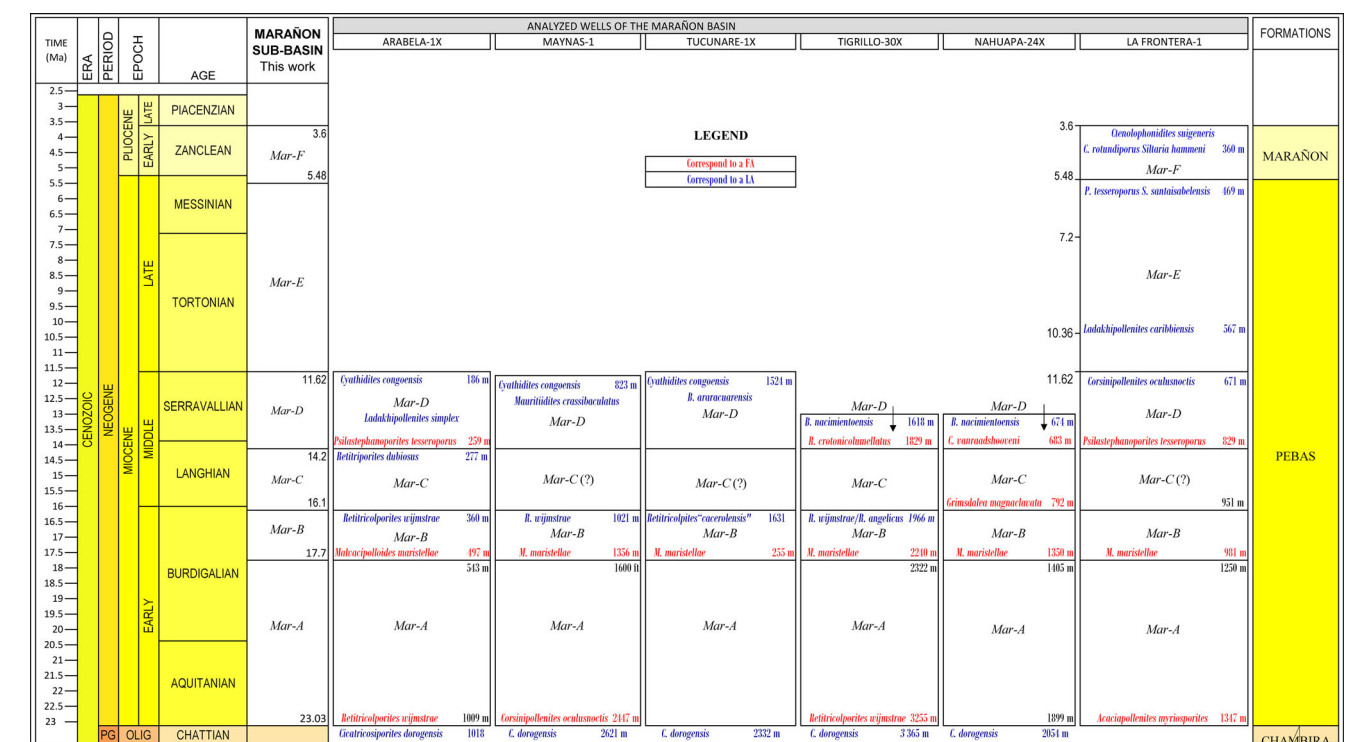


Figure 4. First palynological zonation for the Marañón Basin (this work) and correlation (time-lines). See Appendices 1–6 and Table 5 for details, and see Figures 2–3 and 5–6 for timeline correlation and correlation with other South American palynozones.

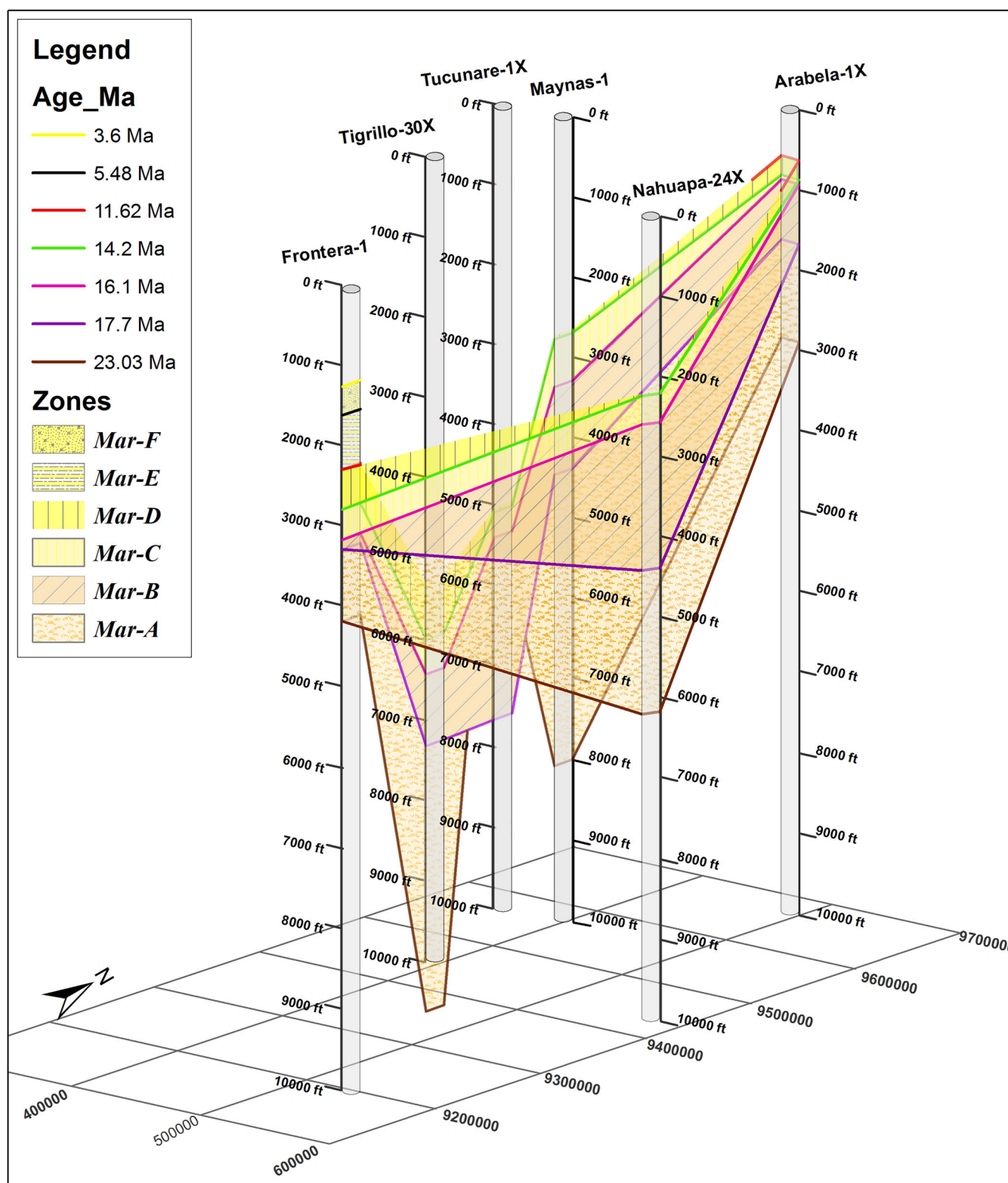


Figure 5. First palynological zonation for the Marañon Basin (this work), and south-west and north-east correlation and timelines between boreholes of the six exploration wells Arabela-1X, Maynas-1, Tucunare-1X, Tigrillo-30X, Nahuapa-24X, and La Frontera-1 in the Marañon Basin.

3220–3120 ft (981–951 m) (see [Appendices 1–6](#) for details and [Figures 2–6](#) for summary and correlation).

Description. We propose the Mar-B *Malvacipoloides maristellae* Zone as corresponding to the interval from the FAD of *Malvacipoloides maristellae* to the LAD of *Retitricolporites wijmstrae* and/or from the LADs of *Retistephanoporites*

angelicus or *Cyclusphaera scabrata* to the FAD of *Grimsdalea magnaclavata* in the upper zone.

Age. Burdigalian (17.71–16.1 Ma).

Characteristics. This zone is characterized by the first appearance and continuous presence upward of *Malvacipoloides*

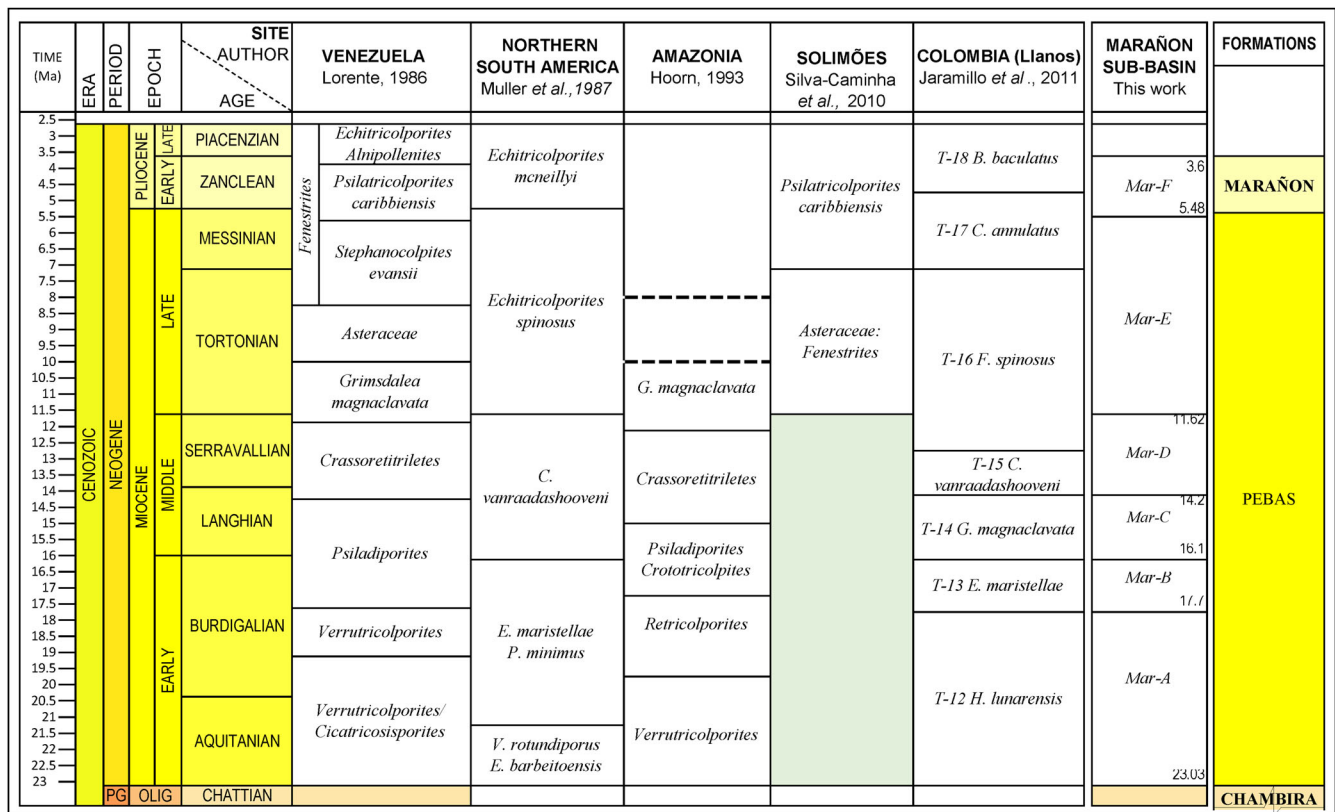


Figure 6. First palynological zonation for the Marañon Basin (this work) and its suggested correlation with other South American palynozones and the geological column.

maristellae, often accompanied by *Retistephanoporites angelicus*, *Corsinipollenites psilatus*, and *Retitricolporites wijmstrae*; the rare occurrence of *Bombacacidites nacimientoensis*, *Crototricolpites* cf. *annemariae*, *Ctenolophonidites suigeneris*, *Gomphrenipollis minima*, and *Retitricolpites altimuratus*; and the continued presence of *Cyathidites congoensis*. Furthermore, *Clavainaperturites* aff. *clavatus*, *Laevigatosporites* spp., *Magnastriatites grandiosus*, *Mauritiidites franciscoi* var. *franciscoi*, *Mauritiidites franciscoi* var. *minutus*, *Perisyncolporites pokornyii*, *Polypodiisporites speciosus*, *Polypodiisporites* spp., *Polypodiisporites usmensis*, *Psilamonocolpites* spp., *Retipollenites* spp., and *Retitricolporites* sp. are commonly present in moderate abundances. Acritarchs and dinoflagellate cysts, such as *Batiacasphaera* sp., *Leiosphaeridia*, *Selenopemphix* spp., and *Operculodinium* group, also occur. A peak abundance of *Pterospermella* spp. (prasynophycean algae) is noticeable (see Appendices 1–6 for details and Figures 2–6 for summary and correlations).

Comparison. The co-occurrence of taxa (see Tables 5–6 and Figures 2–4 for details) supports the correlation of this zone with others in South America (summarized in Figure 5; Lorente 1986; Muller et al. 1987; Hoorn 1993; Jaramillo et al. 2011). The record of the Early Miocene *Malvacipoloides maristellae* (Muller et al. 1987) in the six wells (Figures 3 and 5) reinforces the age assigned to this zone. The zonal limits of the T-13 *Malvacipoloides maristellae* Zone from Llanos in Colombia (Jaramillo et al. 2011) were identified in one of the six wells, the Nahuapa-24X (Figure 3), supporting their correlation (Figures 4 and 5).

6.3. Mar-C *Mauritiidites crassibaculatus* Assemblage Zone

Reference sections. Arabela-1 interval 1180–910 ft (360–277 m) and Nahuapa-24X interval 2600–2240 ft (792–683 m).

Distribution. This zone was recognized in three wells, namely Arabela-1 interval 1180–910 (360–277 m), Tigrillo-30X interval 6450–6000 ft (1966–1829 m), and Nahuapa-24X interval 2600–2240 (792–683 m). Only the lower limit of this zone was recognized in the Maynas-1 and Tucunare-1X wells, and only the upper limit was recognized in the La Frontera-1 well (see Appendices 1–6 for details and Figures 2–6 for summary and correlations).

Description. The Mar-C *Mauritiidites crassibaculatus* Zone is defined as the interval with *Mauritiidites crassibaculatus* from the LAD of *Retitricolporites wijmstrae* (top of the lower zone) and/or the FADs of *Grimsdalea magnaclavata* to the LADs of *Retitricolporites dubiosus* or FAD of *Crassoretitricolporites vanraadshooveni* in the upper zone. Alternatively, the upper boundary may be defined by the FAD of *Psilastephanoporites tesseropus* and/or that of *Retipollenites crotonicolumellatus* (in the upper zone), which should be used when *Retitricolporites dubiosus* and *Crassoretitricolporites vanraadshooveni* are absent.

Age. Latest Burdigalian to Late Langhian (16.1–14.2/13.9 Ma).

Characteristics. This zone is characterized by the continuous presence of *Ladakhpollenites simplex*, *Mauritiidites crassibaculatus*, *Bombacacidites nacimientoensis*, *Retitricolpites simplex* and *Cyathidites congoensis* along with the frequent occurrence of *Laevigatosporites* spp., *Magnastriatites grandiosus*,

Mauritiidites franciscoi var. *franciscoi*, *Polypodiisporites* spp., *Polypodiisporites usmensis*, *Psilamonocolpites* spp., and *Retistephanoporites crassiannulatus*. It also contains *Leiosphaeridia* spp., *Selenopemphix* spp., *Selenopemphix nephroides*, and other indeterminate dinoflagellate cysts (see [Appendices 1–6](#) for details and [Figures 2–6](#) for summary and correlations).

Comparison. The co-occurrence of taxa (see [Tables 5–6](#) and [Figures 2–4](#) for details) supports the correlation of this zone with others in South America (summarized in [Figure 5](#); Lorente 1986; Muller et al. 1987; Hoorn 1993; Jaramillo et al. 2011). This zone, in the six wells, is coeval with the T-14 *Grimsdalea magnaclavata* Zone ([Figure 5](#)) from Llanos in Colombia (Jaramillo et al. 2011). The T-14 Zone was defined as extending from the FAD of *G. magnaclavata* to the FAD of *Crassoretitrites vanraadshooveni*. These zonal boundaries identified in Nahuapa-24X ([Figure 4](#)) reinforce the age given to our zone and their correlation ([Figures 4–6](#)).

6.4. Mar-D *Crassoretitrites vanraadshooveni* Assemblage Zone

Reference section. Arabela-1 interval 850–610 ft (259–186 m) and La Frontera-1 interval 2720–2220 ft (829–677 m).

Distribution. This zone was recognized in the six wells analyzed: Arabela-1 interval 850–610 ft (259–186 m), Maynas-1 interval 2750–2700 (838–823 m), Tucunare-1X interval 5000–5050 (1524–1539 m), Tigrillo-30X interval 6000–5310 (1829–1618 m), Nahuapa-24X interval 2240–2210 ft (683–674 m), and La Frontera-1 interval 2720–2220 (829–677 m) (see [Appendices 1–6](#) for details and [Figures 2–6](#) for summary and correlations).

Description. The Mar-D *Crassoretitrites vanraadshooveni* Zone is defined as the interval from the LADs of *Retitriporites dubiosus* (top of lower zone) and the FADs of the *Crassoretitrites vanraadshooveni*, *Psilastephanoporites tesseropus*, or *Retipollenites crotonicolumellatus* (which should be used when *Crassoretitrites vanraadshooveni* and *Retitriporites dubiosus* are absent) to the LAD of *Corsinipollenites oculusnoctis* and/or the LAD of *Cyathidites congoensis*, and/or that of *Bombacacidites araracuensis*.

Age. Late Serravallian (14.2–11.62 Ma).

Characteristics. This zone comprises the FADs of *Crassoretitrites vanraadshooveni*, *Paleosantalaceapites cingulatus*, *Psilastephanoporites tesseropus*, and *Retipollenites crotonicolumellatus* and the last records of *Bombacacidites araracuensis*, *Bombacacidites nacimientoensis*, *Corsinipollenites oculusnoctis*, *Crototricolpites* cf. *annemariae*, *Ladakhpollenites simplex*, *Mauritiidites crassibaculatus*, and *Cyathidites congoensis*. Also occurring in this zone are *Ctenolophonidites suigeneris*, *Deltoidospora adriennis*, *Echitriporites cricotriporatiformis*, *Laevigatosporites* spp., *Laevigatosporites catanejensis*, *Magnastriatites grandiosus*, *Mauritiidites franciscoi* var. *franciscoi*, *Polypodiisporites* spp., *Polypodiisporites usmensis*, *Psilamonocolpites* spp., and *Retitricolpites simplex*. *Leiosphaeridia* sp., prasinophytes (algae), and

indeterminate dinoflagellate cysts occur frequently (see [Appendices 1–6](#) for details and [Figures 2–6](#) for summary and correlations).

Comparison. The characteristic co-occurrence of taxa (see [Tables 5–6](#) and [Figures 2–4](#) for details) supports the correlation of this zone with other zones in South America (summarized in [Figure 5](#); Lorente 1986; Muller et al. 1987; Hoorn 1993; Jaramillo et al. 2011). This zone is coeval with the T-15 *Crassoretitrites vanraadshooveni* Zone and the lower part of the T-16 Zone from Llanos in Colombia (Jaramillo et al. 2011), where the LAD of *Mauritiidites crassibaculatus* (as in the Maynas-1 well) occurs. The upper boundary of our zone occurs in La Frontera-1 before the first record of *Ladakhpollenites caribbiensis* that is known from the Late Miocene (da Silva et al. 2010). The lower limit of the Mar-D Zone in the Nahuapa-24X well coincides with that of the T-15 Zone ([Figure 6](#)) of Jaramillo et al. (2011). Our zone comprises the FAD of *Retipollenites crotonicolumellatus*, which also occurs in the T-15 Zone, the FADs of both *Paleosantalaceapites cingulatus* and *Psilastephanoporites tesseropus*, and the LAD of *Mauritiidites crassibaculatus*, which also occurs in the T-16 Zone of Jaramillo et al. (2011). Therefore, these presences also emphasize the age given to our zone and their correlation ([Figures 2–6](#)).

6.5. Mar-E *Psilastephanoporites tesseropus* Interval Zone

Reference section. La Frontera-1 interval 2220–1540 (677–469 m).

Distribution. This zone was present only in the La Frontera-1 well, interval 2220–1540 ft (677–469 m). Note that in the other wells, samples were not analyzed above the top of the Mar-D zone (see [Appendices 1–6](#) for details and [Figures 2–6](#) for summary and correlations). Nevertheless, GraphCor confirmed this zone as defined here.

Description. We propose the Mar-E *Psilastephanoporites tesseropus* Interval Zone as occurring from the LAD of *Corsinipollenites oculusnoctis* and/or that of *Cyathidites congoensis* (top of the lower zone) to the LAD of *Psilastephanoporites tesseropus* and/or the LAD of *Siltaria santaisabelensis*.

Age. Early Tortonian to Late Messinian (11.62–5.48 Ma).

Characteristics. This zone includes the inception and presence of pollen grains of *Ctenolophonidites suigeneris*, *Foveotricolpites lenticuloides*, *Lanagiopollis crassa*, *Paleosantalaceapites cingulatus*, *Nijssenosporites fossulatus*, and *Retimonocolpites maximus* and the LADs of *Acaciapollenites myriosporites*, *Deltoidospora adriennis*, *Ladakhpollenites caribbiensis*, *Psilastephanoporites tesseropus*, and *Siltaria santaisabelensis*. Other taxa such as *Osmundacidites ciliatus* and dinoflagellate cysts *Bosedinia infragranulata*, *Quadrina? condita* and *Selenopemphix quanta* along with *Echiperiporites estelae*, *Magnastriatites grandiosus*, and *Rhoipites hispidus* are common.

Comparison. This zone is coeval with the *Echitricolporites spinosus* Zone from northern South America (Muller et al. 1987) and can be compared with the upper part of the T-16 *Fenestrites spinosus* Zone of Jaramillo et al. (2011), where the LAD of *Ladakhipollenites? caribbiensis* occurs, and to the lower part of the T-17 *Cyatheacidites annulatus* Zone of Jaramillo et al. (2011), where the LAD of *Psilastephanoporites tesseroporus* occurs (upper boundary of our Mar-E zone) (Figures 2–6).

6.6. Mar-F *Ctenolophonidites suigeneris* Zone

Reference section. La Frontera-1 interval 1560–1180 ft (475–360 m).

Distribution. This local zone was only identified in the La Frontera-1 well, interval 1540–1180 ft (469–360 m). Note that in the other wells, samples were not analyzed above the top of the Mar-D zone (see Appendices 1–6 for details and Figures 2–6 for summary and correlations).

Description. We propose the Mar-F *Ctenolophonidites suigeneris* Zone for the interval from the LAD of *Psilastephanoporites tesseroporus* (5.48 Ma) to the LADs of *Ctenolophonidites suigeneris* (3.6 Ma) and/or *Cistacearumpollenites rotundiporus* (LAD Pliocene). Note that samples above 1180 ft (360 m) were not analyzed.

Age. Latest Messinian to Zanclean (5.48–3.6 Ma).

Characteristics. This zone comprises the inception or frequent presence of *Deltoidospora* spp., *Echiperiporites akanthos*, *Echiperiporites estelae*, *Laevigatosporites ovatus*, *Lanagiopollis* cf. *crassa*, *Magnastriatites grandiosus*, *Mauritiidites franciscoi* var. *minutus*, *Monoporopollenites annulatus*, *Polypodiisporites usmensis*, *Retimonocolpites maximus*, and *Retitritiletes* sp. *Fusiformisporites* is common among the fungal spores. The last records of *Siltaria hammenii* (Neogene), *Cistacearumpollenites rotundiporus* (LAD Pliocene), and *Crassoretitritiletes vanraadshooveni* (3.4 Ma) occur in this zone. Noticeable is the absence of *Echitricolporites mcneillyi*.

Comparison. This zone is coeval with the *Psilatricolporites caribbiensis* Subzone from Venezuela (Lorente 1986), due to the absence of *Echitricolporites mcneillyi*, and can be compared with the lower part of the *Echitricolporites mcneillyi* Zone of northern South America (Muller et al. 1987), where the LAD of *Psilastephanoporites tesseroporus* occurs (upper boundary of our Mar-E zone). The upper part of T-17 and the lower part of T-18 (Jaramillo et al. 2011) are also correlated (Figures 2–6).

7. Correlation with other Western Amazonian basins and discussion

The vertical succession of species in the six wells investigated from the Mara on Basin (see Appendices 1–6 for details) allowed us to propose the first palynozonation in a chronostratigraphic context (Figure 5). The presence of selected species in some or all of the boreholes and their stratigraphic

ranges (FAD and LAD ages; Figures 2–3 and Tables 5–6) were used to date our zones and establish correlations with relatively coeval palynozones in South America (Figure 6). Some diachronisms exist between the ages of published palynozones from northern South America and ours. For instance, the Early Miocene to earliest Middle Miocene in Venezuela was characterized by the successive *Verrutricolporites* and *Psiladiporites*–*Echitricolporites* pollen zones (Lorente 1986). These zones are equivalent to the *Verrutricolporites rotundiporus*–*Echidiporites barbeitoensis* and *Echitricolporites maristellae*–*Psiladiporites minimus* zones defined by Muller et al. (1987). The *Verrutricolporites* Interval Zone and the *Verrutricolporites rotundiporus*–*Echidiporites barbeitoensis* Zone are defined as extending from the first records of *Verrutricolporites rotundiporus* to the first occurrence of *Psiladiporites minimus* or *Echitricolporites maristellae*.

Hence, the *Verrutricolporites* (Lorente 1986) and the *Verrutricolporites rotundiporus*–*Echidiporites barbeitoensis* (Muller et al. 1987) zones can be correlated with our Mar-A *Corsinipollenites oculusnoctis* Interval Zone. In addition, the *Psiladiporites*–*Echitricolporites* Interval Zone (Lorente 1986) and the *Echitricolporites maristellae*–*Psiladiporites minimus* Zone (Muller et al. 1987) are defined by the first occurrence of *Psiladiporites minimus* or *Echitricolporites maristellae* at the base, and the first occurrence of *Crassoretitritiletes vanraadshooveni* at the top. These markers also correlate with our Mar-B *Malvacipoloides* (*Echitricolporites*) *maristellae* and Mar-C *Mauritiidites crassibaculatus* zones. Hence, our Mar-A, Mar-B, and Mar-C zones are within the Early Miocene to earliest Middle Miocene pollen zones of Lorente (1986) and Muller et al. (1987). Our Mar-A, Mar-B, and Mar-C zones are also coeval with the T-12 *Horniella lunarensis*, T-13 *Echitricolporites maristellae*, and T-14 *Grimsdalea magnaclavata* zones, respectively, of Jaramillo et al. (2011).

The late Early Miocene in Venezuela and in Western Amazonia was characterized by Lorente (1986) and Hoorn (1993), respectively, by the *Crassoretitritiletes* Interval Zone. This zone is defined from the first records of *Crassoretitritiletes vanraadshooveni* and *Trichotomocolpites* sp. to the first occurrence of *Grimsdalea magnaclavata* in the latest Middle Miocene (Lorente 1986; Hoorn 1993). The top of this zone was defined by Muller et al. (1987) based on the first record of *Echitricolporites spinosus* in the earliest Tortonian. The FAD of *Grimsdalea magnaclavata sensu* Jaramillo et al. (2011) is the oldest at ca. 16.1 Ma, meaning that this FAD would occur before that of *Crassoretitritiletes vanraadshooveni*.

We have identified in Arabela-1X, Tigrillo-30X, Nahuapa-24X, and La Frontera-1 wells an interval similar to the *Crassoretitritiletes* Interval Zone, by the presence of three biostratigraphic markers, *Crassoretitritiletes vanraadshooveni*, *Psilastephanoporites tesseroporus*, and *Retipollenites crotonicolumellatus* (Tables 5–6) co-occurring at the base, which belong to the bases of both the T-15 *Crassoretitritiletes vanraadshooveni* palynozone (Jaramillo et al. 2011) and the *Crassoretitritiletes* palynozone (Lorente 1986). GraphCor indicated the FAD of *Retipollenites crotonicolumellatus* was slightly below the FADs of *Crassoretitritiletes vanraadshooveni* and *Psilastephanoporites tesseroporus*. However, this might be

explained by the quality of sampling. The top is identified by *Corsinipollenites oculusnoctis*, *Cyathidites congoensis* and *Mauritiidites crassibaculatus* at ca. 11.62 Ma (Serravallian/Tortonian limit), as shown in the *Crassoretitritiles vanraadshooveni* Interval Zone of Muller et al. (1987). Therefore, the base of our Mar-D *Crassoretitritiles vanraadshooveni* Zone is coeval with the bases of the *Crassoretitritiles vanraadshooveni* zones of Hoorn (1993), Lorente (1986), and Jaramillo et al. (2011), whereas the top is coeval with the top of the *Crassoretitritiles vanraadshooveni* Interval Zone *sensu* Muller et al. (1987). Our Mar-D *Crassoretitritiles vanraadshooveni* Zone is also coeval with the *Crassoretitritiles* Interval Zone of Lorente (1986), recognized by Leite et al. (2017) in the Solimões Basin (Brazil).

The late Miocene from northern South America is characterized by the *Echitricolporites spinosus* Zone (Muller et al. 1987), so our Mar-E zone is coeval and can be also compared with the upper part of the T-16 *Fenestrites spinosus* Zone of Jaramillo et al. (2011), where the LAD of *Ladakhipollenites? caribbiensis* occurs. It is also correlated to the lower part of the T-17 *Cyatheacidites annulatus* Zone of Jaramillo et al. (2011), in which the LAD of *Psilastephanoporites tesseropus* occurs (upper boundary of our Mar-E zone: 5.48 Ma). Although sediments referable to Mar-E and Mar-F zones were studied only in the Frontera-1 well, GraphCor displays the events limiting these zones. Furthermore, due to the abovementioned correlations this interval has a preliminary zonal character which can be improved with additional biostratigraphic studies above the upper section of the studied wells.

Some authors have suggested that there is no record of Pliocene deposits in the Solimões Basin (Latrubesse et al. 2007, 2010). However, recent palynostratigraphic studies (da Silva et al. 2010; Silveira and Souza 2015, 2016; Leite et al. 2017) have documented Pliocene sedimentation in some areas of the Solimões Basin. These palynological studies are based on the presence of the *Psilatricolporites caribbiensis* Interval Subzone (Late Miocene to Early Pliocene: 5.6–3.7 Ma; Lorente 1986) and the *Alnipollenites verus* Interval Subzone (Late Pliocene to Holocene: 3.7 to present; Lorente 1986) found in the studied Solimões wells. Similarly, our study showed that Neogene sedimentation in the Marañón Basin continued during the Pliocene, where at least 360 ft (103 m) of the Marañón formation sediments were deposited (see La Frontera-1 well, Appendix 6 and Figures 4–6). We propose that the Mar-F *Ctenolophonidites suigeneris* Zone (Late Miocene to Early Pliocene, 5.48–3.6 Ma) comprises the youngest deposits dated here. However, since we did not analyze sediments above 1180 ft (356 m), we cannot exclude the possibility of the younger sediments belonging to the *Alnipollenites verus* Interval Subzone *sensu* Lorente (1986) or any coeval zone at depths over 1180 ft (356 m), and/or any coeval zone at depths over those of the last intervals from the other wells studied herein for the Marañón Basin.

8. Conclusions

This study of the Neogene biostratigraphic record obtained from six industrial wells in the Marañón Basin allowed us to

define six palynozones (Mar-A to Mar-F); five of them (Mar-A to Mar-E) were validated by GraphCor. They range from the Aquitanian (Early Miocene) to the Messinian–Zanclean (latest Miocene to earliest Pliocene):

- The Mar-A *Corsinipollenites oculusnoctis* Interval Zone (Aquitanian to early Burdigalian: 23.03–17.71 Ma) is defined as extending from the first occurrence of *Retitricolporites wijmstrae*, occurring immediately over the *Cicatricosisporites dorensis* marker species (latest Oligocene), to the first appearance of *Malvacipolloides maristellae*.
- The Mar-B *Malvacipolloides maristellae* Interval Zone (Burdigalian: 17.71–16.1 Ma) is recognized from the first appearance of *Malvacipolloides maristellae* to the last record of *Retitricolporites wijmstrae*.
- The Mar-C *Mauritiidites crassibaculatus* Assemblage Zone (latest Burdigalian to Late Langhian: 16.1–14.2/13.9 Ma) is defined as occurring from the last record of *Retitricolporites wijmstrae* (top of the lower zone) or the first appearance of *Grimsdalea magnaclavata* (e.g. the Nahuapa-24X well) to the first occurrence of *Crassoretitritiles vanraadshooveni* or *Psilastephanoporites tesseropus*.
- The Mar-D *Crassoretitritiles vanraadshooveni* Assemblage Zone (Late Serravallian: 14.2–11.62 Ma) is defined by the first occurrence of *Crassoretitritiles vanraadshooveni* and or that of *Psilastephanoporites tesseropus* at its base and by the last record of *Cyathidites congoensis* and *Mauritiidites crassibaculatus* or *Corsinipollenites oculusnoctis* at its top (e.g. La Frontera-1 well).
- The Mar-E *Psilastephanoporites tesseropus* local Interval Zone (Early Tortonian to Late Messinian: 11.62–5.48 Ma) represents the time interval with *Psilastephanoporites tesseropus* from the last occurrence of *Corsinipollenites oculusnoctis* and/or *Cyathidites congoensis* to the last occurrence of *Psilastephanoporites tesseropus*. It is dominated by *Psilastephanoporites tesseropus* and *Siltaria santaisabelensis*.
- The Mar-F *Ctenolophonidites suigeneris* local Zone (latest Messinian to Zanclean: 5.48–3.6 Ma) is defined at its base by the last appearance of *Psilastephanoporites tesseropus* and at its top by the last occurrence of *Ctenolophonidites suigeneris*. *Cistacearumpollenites rotundiporus* and *Siltaria hammenii* dominate this zone.

The biostratigraphic scheme proposed for the Marañón Basin is based on the presence of species in common with Miocene palynozones of northern South America (Colombia, Venezuela, and western Brazil), and a correlation between them is also established. Our study corroborates recent studies regarding the palynostratigraphy of the Miocene Solimões and Acre basins, and documents that Pliocene sedimentation occurred in Peru (western Amazonia). Future study of the interval above the analyzed wells may provide information to characterize the Pliocene palynofloras of the Marañón Basin. A comparison with Amazonia and elsewhere in northern South American basins will achieve new insights for the less well-known evolution of floras during the Pliocene.

Acknowledgements

This work was supported by the French Research Institute for Development (IRD) under Grant BTDR and by PALEOSEDES E.U. (Colombia) under Grant STU04-2016, as well as by collaboration and partnership with the Toulouse III Paul Sabatier University (France), National University (Colombia), and CICYTTP-CONICET (Argentina) under CONICET PIP 0812. The first author is a PhD candidate and IRD scholarship holder and received Graphic Correlation software training from Dr Jaramillo at STRI, Panama. We thank Perupetro for allowing us to study the ditch-cutting samples and their permission to publish this article. Special thanks are given to Dr C. Jaramillo and another, anonymous reviewer, for their suggestions that allowed us to substantially improve the manuscript.

Disclosure statement

In accordance with Taylor & Francis policy and our ethical obligation as researchers, all the authors state that there is no conflict of interest.

Data availability statement

The data that support the findings of this study are openly available in NeotomaDB at:

Maynas-1 <https://apps.neotomadb.org/Explorer/?datasetid=40652>
 Tucunare-1X <https://apps.neotomadb.org/Explorer/?datasetid=40785>
 Arabela-1X <https://apps.neotomadb.org/Explorer/?datasetid=40947>
 Frontera-1 <https://apps.neotomadb.org/Explorer/?datasetid=40956>
 Nahuapa-24X <https://apps.neotomadb.org/Explorer/?datasetid=40965>
 Tigrillo-30X <https://apps.neotomadb.org/Explorer/?datasetid=40995>

Notes on contributors



Francisco Parra has obtained a MSc Degree in Geology of Natural Resources at the University of Toulouse, France. He is currently a PhD student in co-tutorship at the University of Toulouse and the National University of Colombia, funded by the IRD. His experience mainly spans sedimentology and stratigraphy combining laboratory and field work with a focus in post-Paleozoic micropaleontology (foraminifers, ostracods, spores, pollen, dinoflagellates, and charophytes), biostratigraphy, paleogeography, paleoenvironmental analysis in Colombian and Peruvian Amazonia.



Rosa E. Navarrete is a PhD geologist, micropaleontologist and biostratigrapher, mainly focused on marine and terrestrial environments, tectonic – erosion, paleogeography and paleoclimate. She is much experienced in multidisciplinary biogeochronology (foraminifers, ostracods, calcareous nannofossils, mollusks, and palynostratigraphy) of the post-Paleozoic interval in Americas, with emphasis on South American sedimentary basins. She is Chairwoman and research senior of biostratigraphy consulting Colombian company Paleosedes E.U. assessing Oil & Gas industry over 25 years.



Mercedes di Pasquo Ph.D. 1999. Univ. Buenos Aires, Argentina. 2002: CONICET permanent researcher. 2010: Senior researcher, responsible Paly-Lab, CICYTTP. 2009-2020: President ALPP. 2009: Fulbright Research Fellow - Univ. Idaho. 2013-14: Researcher of "Ciencias sem Fronteiras" -CNPq in Brazil. Researches on palynofloras of Silurian/ Permian Arg/ Bolivia/Peru/Brazil, Dev-Carb Montana, Cret. Antarctica, Holoc. Entre Rios. Supervisor PhD students from America. Phanerozoic Oil industry consultant.



Martin Roddaz is an Associate Professor of geology in the University of Toulouse, France. His main scientific interests include the understanding on controls on sediment production, transport and deposition in the Andes-Amazon system at both short and geological timescales. He has participated in or led several field expeditions in the Amazon basin (Peru, Bolivia) since 2001. He is WP2 Leader of CLIMAMAZON project (Joint Brazilian–European facility for climate and geodynamic research on the Amazon River Basin sediments, <http://www.clim-amazon.eu/>).



Ysabel Calderón is a geologist working at PERUPETRO, Private Law State Company of the Energy and Mines Peruvian Sector. Since joining PERUPETRO in 2000, she evaluated new plays and promoted areas in different basins of Peru (Offshore and Onshore basins). Also, she is a PhD student at Géosciences-Environnement Toulouse in Paul Sabatier University, France, funded by the Institut de Recherche pour le Développement. She obtained a Master degree in Geology from the same university. Her research has been focused on structural architecture, sedimentary evolution and hydrocarbon potential in a wedge-top foredeep zone in the northern Peruvian subandean basins.



Patrice Baby is a geologist. He is Research Director at the Institute for Research and Development. He has a PhD in Earth sciences from the University of Toulouse, France. His works focus mainly on Andean, Subandean, and Amazonian geodynamics. In the last 20 years, he has cooperated with academic and industrial institutions in Bolivia, Peru, and Ecuador. In the last decade, he has also been working with biologists and paleontologists on the tectonic control of the diversification of biota in Western Amazonia. In particular, he has launched the multidisciplinary research group primarily coinciding with the coauthors of this review, and led several geological-paleontological expeditions in Amazonia.

ORCID

F.J. Parra <http://orcid.org/0000-0003-0801-9446>
 R.E. Navarrete <http://orcid.org/0000-0003-0131-352X>
 M.M. di Pasquo <http://orcid.org/0000-0003-3068-0089>
 M. Roddaz <http://orcid.org/0000-0001-8562-8582>
 Y. Calderón <http://orcid.org/0000-0003-1060-4425>
 P. Baby <http://orcid.org/0000-0001-6142-5174>

References

- Antoine P-O, Abello MA, Adnet S, Altamirano Sierra AJ, Baby P, Billet G, Boivin M, Calderón Y, Candela A, Chabain J. 2016. A 60-Million-year Cenozoic history of western Amazonian ecosystems in Contamana, eastern Peru. *Gondwana Research*. 31:30–59.
- Baby P, Calderón Y, Louterbach M, Espurt N, Brusset S, Roddaz M, Brichau S, Eude A, Calves G, Quispe A, Ramirez L, Bandach A, Bolanos R. 2018. The peruvian sub-Andean Foreland Basin System: Structural overview, geochronologic constraints, and unexplored plays. In: Zamora G, McClay KR, Ramos VA, editors. *Petroleum Basins and Hydrocarbon Potential of the Andes of Peru and Bolivia*, v. Memoir 117, AAPG, p. 91–120.
- Boonstra M, Ramos MI, Lammertsma EI, Antoine P-O, Hoorn C. 2015. Marine connections of Amazonia: evidence from foraminifera and dinoflagellate cysts (early to middle Miocene, Colombia/Peru). *Palaeogeography, Palaeoclimatology, Palaeoecology*. 417:176–194.
- Bujak JP, Williams GL. 1985. *Mesozoic and Cenozoic dinoflagellates. Plankton stratigraphy*. Cambridge: Cambridge University Press; p. 847–965.

- Calderón Y, Baby P, Hurtado C, Brusset S. 2017a. Thrust tectonics in the Andean retro-foreland basin of northern Peru: Permian inheritances and petroleum implications. *Marine and Petroleum Geology*. 82: 238–250. doi:10.1016/j.marpetgeo.2017.02.009
- Calderón Y, Vela Y, Hurtado C, Bolaños R, Baby P, Eude A, Roddaz M, Brusset S, Calvès G. 2017b. Petroleum systems restoration of the Huallaga—Marañon Andean retroforeland basin, Peru. In: AbuAli MA, Moretti I, Nordgård Bolås HM, editors. *Petroleum systems analysis—case studies*. AAPG; p. 95–116. Elsevier. doi:10.1016/j.marpetgeo.2017.02.009
- Cole JM. 1992. Freshwater dinoflagellate cysts and acritarchs from Neogene and Oligocene sediments of the South China Sea and adjacent areas, in: Head, M.J., Wrenn, J.H. (Eds.), *Neogene and Quaternary dinoflagellate cysts and Acritarchs*. American Association of Stratigraphic Palynologists Foundation, Dallas, Texas, pp. 181–196.
- da Silva-Caminha SAF, Jaramillo CA, Absy ML. 2010. Neogene palynology of the Solimões basin, Brazilian Amazonia. *Palaeontographica Abteilung B*. 284(1–3):13–79.
- de Verteuil L, Norris G, Head MJ, Wrenn JH. 1992. Miocene protoperidiniacean dinoflagellate cysts from the Maryland and Virginia coastal plain. In: Head MJ, Wrenn JH, editors. *Neogene and Quaternary dinoflagellate cysts and acritarchs*. Dallas: American Association of Stratigraphic Palynologists Foundation; p. 391–430.
- Eisawi A, Schrank E. 2008. Upper Cretaceous to Neogene Palynology of the Melut Basin, Southeast Sudan. *Palynology*. 32(1):101–129.
- Eude A, Roddaz M, Brichau S, Brusset S, Calderón Y, Baby P, Soula JC. 2015. Controls on timing of exhumation and deformation in the northern Peruvian eastern Andean wedge as inferred from low-temperature thermochronology and balanced cross section. *Tectonics*. 34(4):715–730.
- Germeraad JH, Hopping CA, Muller J. 1968. Palynology of Tertiary sediments from tropical areas. *Review of Palaeobotany and Palynology*. 6(3–4):189–348.
- Gingras MK, Rasanen ME, Pemberton SG, Romero LP. 2002a. Ichnology and sedimentology reveal depositional characteristics of bay-margin parasequences in the Miocene Amazonian foreland basin. *Journal of Sedimentary Research*. 72(6):871–883.
- Gingras MK, Räsänen ME, Ranzi A. 2002b. The significance of bioturbated inclined heterolithic stratification in the southern part of the Miocene Solimões Formation, Rio Acre, Amazonia Brazil. *Palaios*. 17(6):591–601.
- González-Guzmán, AE. 1968. A palynological study on the upper los cuervos and mirador formations (Lower and Middle Eocene; Tibú area, Colombia), ed. E. J. Brill. Leiden: Hugo de Vries Laboratory. 68.
- Grimm EC. 2005. TILIA and TILIAGRAPH software. Springfield (IL): Illinois State Museum. <https://www.tiliat.com/download/>
- Gross M, Piller WE, Ramos MI, Douglas da Silva Paz J. 2011. Late Miocene sedimentary environments in south-western Amazonia (Solimões Formation, Brazil). *Journal of South American Earth Sciences*. 32(2):169–181.
- Hermoza W. 2004. *Dynamique tectono-sédimentaire et restauration séquentielle du retro-bassin d'avant-pays des Andes Centrales* [Unpublished Ph.D. thesis]. Toulouse: Université Paul Sabatier; p. 296.
- Hermoza W, Baby P, Brusset S, Roddaz M, Bolaños R. 2005. Eocene to present-day latitudinal variations in the retroforeland basin system of the Peruvian Andes.: 6th International Symposium on Andean Geodynamics (ISAG 2005). Extended Abstracts, p. 368–371
- Hermoza W, Brusset S, Baby P, Gil W, Roddaz M, Guerrero N, Bolaños R. 2005. The Huallaga foreland basin evolution: thrust propagation in deltaic environment, in the northern Peruvian Andes. *Journal of South American Earth Sciences*. 19(1):21–34.
- Hood KC. 1998. GraphCor Interactive Graphic Correlation Software. Version 3.0. Houston.
- Hoorn C. 1993. Marine incursions and the influence of Andean tectonics on the Miocene depositional history of northwestern Amazonia: results of a palynostratigraphic study. *Palaeogeography, Palaeoclimatology, Palaeoecology*. 105(3–4):267–309.
- Hoorn C. 1994a. An environmental reconstruction of the palaeo-Amazon river system (middle–late Miocene Amazonia). *Palaeogeography, Palaeoclimatology, Palaeoecology*. 112(3–4):187–238.
- Hoorn C. 1994b. Fluvial palaeoenvironments in the intracratonic Amazonas basin (early Miocene–early middle Miocene, Colombia). *Palaeogeography, Palaeoclimatology, Palaeoecology*. 109(1):1–54.
- Hoorn C. 2006. Mangrove forests and marine incursions in Neogene Amazonia (lower Apaporis river, Colombia). *Palaios*. 21(2):197–209.
- Hoorn C, Bogotá-A GR, Romero-Baez M, Lammertsma EI, Flantua SGA, Dantas EL, Dino R, do Carmo DA, Chemale FJ. 2017. The Amazon at sea: Onset and stages of the Amazon river from a marine record, with special reference to Neogene plant turnover in the drainage basin. *Global and Planetary Change*. 153:51–65.
- Hoorn C, Guerrero J, Sarmiento GA, Lorente MA. 1995. Andean tectonics as a cause for changing drainage patterns in Miocene northern South America. *Geology*. 23(3):237.
- Hoorn C, Paxton CGM, Crampton WGR, Burgess P, Marshall LG, Lundberg JG, Räsänen ME, Linna AM. 1996. Miocene deposits in the Amazonian foreland basin. *Science*. 273(5271):122–120.
- Hoorn C, Wesselingh FP. 2010. Amazonia, landscape and species evolution: a look into the past. Chichester: Wiley-Blackwell Publishing Ltd.
- Hoorn C, Wesselingh FP, Hovikoski J, Guerrero J. 2010a. The development of the Amazonian mega-wetland (Miocene; Brazil, Colombia, Peru, Bolivia). In: Amazonia, landscape and species evolution: a look into the past. Chichester: Wiley-Blackwell Publishing Ltd; p. 123–142.
- Hoorn C, Wesselingh FP, ter Steege H, Bermudez MA, Mora A, Sevink J, Sanmartin I, Sanchez-Meseguer A, Anderson CL, Figueiredo JP, et al. 2010b. Amazonia through time: Andean uplift, climate change, landscape evolution, and biodiversity. *Science*. 330(6006):927–931.
- Hovikoski J, Gingras M, Rasanen M, Rebata LA, Guerrero J, Ranzi A, Melo J, Romero L, del Prado HN, Jaimes F. 2007. The nature of Miocene Amazonian epicontinental embayment: high-frequency shifts of the low-gradient coastline. *Geological Society of America Bulletin*. 119(11–12):1506–1520.
- Hovikoski J, Räsänen M, Gingras M, Lopéz S, Romero L, Ranzi A, Melo J. 2007. Palaeogeographical implications of the Miocene Quendeque Formation (Bolivia) and tidally-influenced strata in southwestern Amazonia. *Palaeogeography, Palaeoclimatology, Palaeoecology*. 243(1–2):23–41.
- Hurtado C, Roddaz M, Santos RV, Baby P, Antoine P-O, Dantas EL. 2018. Cretaceous–early Paleocene drainage shift of Amazonian rivers driven by equatorial Atlantic ocean opening and Andean uplift as deduced from the provenance of northern Peruvian sedimentary rocks (Huallaga basin). *Gondwana Research*. 63:152–168.
- Jaramillo CA, Rueda M. 2019. A morphological electronic database of Cretaceous–Tertiary and extant pollen and spores from northern South America. <http://biogeodb.stri.si.edu/jaramillosdb/web/morphological/>.
- Jaramillo CA, Hoorn C, da Silva SAF, Leite F, Herrera F, Quiroz L, Dino R, Antonioli L. 2010. The origin of the modern Amazon rainforest: implications of the palynological and palaeobotanical record. In: Hoorn C, Wesselingh FP, editors. *Amazonia, landscape and species evolution: a look into the past*. Chichester: Wiley-Blackwell Publishing Ltd; p. 317–334.
- Jaramillo C, Romero I, D'Apolito C, Bayona G, Duarte E, Louwye S, Escobar J, Luque J, Carrillo-Briceño JD, Zapata V, et al. 2017. Miocene flooding events of western Amazonia. *Science Advances*. 3(5):e1601693.
- Jaramillo CA, Rueda M, Torres V. 2011. A palynological zonation for the Cenozoic of the Llanos and Llanos foothills of Colombia. *Palynology*. 35(1):46–84.
- Latrubesse EM, Cozzuol M, da Silva SAF, Rigsby CA, Absy ML, Jaramillo CA. 2010. The late Miocene paleogeography of the Amazon basin and the evolution of the Amazon river system. *Earth-Science Reviews*. 99(3–4):99–124.
- Latrubesse EM, da Silva SAF, Cozzuol M, Absy ML. 2007. Late Miocene continental sedimentation in southwestern Amazonia and its regional significance: biotic and geological evidence. *Journal of South American Earth Sciences*. 23(1):61–80.
- Leandro LM, Vieira CEL, Santos A, Fauth G. 2019. Palynostratigraphy of two Neogene boreholes from the northwestern portion of the Solimões basin, Brazil. *Journal of South American Earth Sciences*. 89:211–218.
- Leite FPR, Paz J, do Carmo DA, Silva-Caminha SA. 2017. The effects of the inception of Amazonian transcontinental drainage during the Neogene on the landscape and vegetation of the Solimões basin, Brazil. *Palynology*. 41(3):412–422.
- Linhares AP, Ramos Feijó MI. 2011. Evidence for marine influx during the Miocene in southwestern Amazonia, Brazil. *Geología Colombiana*. 36(1):91–103

- Linhares AP, Ramos MIF, Gaia VCS, Friaes YS. 2019. Integrated biozonation based on palynology and ostracods from the Neogene of Solimões Basin, Brazil. *Journal of South American Earth Sciences*. 91: 57. doi:10.1016/j.jsames.2019.01.015.
- Linhares AP, de Souza Gaia VC, Ramos MI. 2017. The significance of marine microfossils for paleoenvironmental reconstruction of the Solimões Formation (Miocene), western Amazonia, Brazil. *Journal of South American Earth Sciences*. 79:57–66.
- Lorente MA. 1986. Palynology and palynofacies of the Upper Tertiary in Venezuela. Berlin and Stuttgart: Lubrecht & Cramer Ltd
- Louterbach M, Roddaz M, Antoine P-O, Marivaux L, Adnet S, Bailleul J, Dantas E, Santos RV, Chemale F, Baby P, et al. 2018. Provenance record of late Maastrichtian–late Paleocene Andean mountain building in the Amazonian retroarc foreland basin (Madre de Dios basin, Peru). *Terra Nova*. 30(1):17–23.
- Macphail MK. 1999. Palynostratigraphy of the Murray basin, inland southeastern Australia. *Palynology*. 23(1):197–240.
- Mann KO, Lane HR. 1995. Graphic correlation: a powerful stratigraphic technique comes of age. SEPM Special Publication 53, Tulsa, p. 262.
- Marocco R, Bolanos R, Paz M, Tarazona A. 1995. Informe preliminar sobre el estudio de la sedimentación neógena del nororiente del Perú en base al análisis de los pozos Tangarana 18-4x, Jibaro 1, Valencia 25x, Chapuli 20-1x, Maranon 10-1x, Cuinico norte 6-46x, Nahuaca 3x, Tapiche 36-2x, la Frontera 46-3x. [preliminary report about the study of Neogene sedimentation, northeast Peru on the basis of the analysis of wells Tangarana 18-4x, Jibaro 1, Valencia 25x, Chapuli 20-1x, Maranon 10-1x, Cuinico norte 6-46x, Nahuaca 3x, Tapiche 36-2x, la Frontera 46-3x]. Lima: ORSTOM, PETROPERU.
- Mathalone JMP, Montoya MR. 1995. Petroleum geology of the sub-Andean basins of Peru. In: Tankard AJ, Suárez-Soruco R, Welsink HJ, editors. *Petroleum basins of South America*. Houston (MA): AAPG; p. 423–444.
- Monsch KA. 1998. Miocene fish faunas from the northwestern Amazonia basin (Colombia, Peru, Brazil) with evidence of marine incursions. *Palaeogeography, Palaeoclimatology, Palaeoecology*. 143(1–3):31–50.
- Muller J, Di Giacomo E, Van Erve AW. 1987. A palynological zonation for the Cretaceous, Tertiary Quaternary of northern South America. Dallas (TX): American Association of Stratigraphic Palynologists. Contribution Series 19; p. 1–77.
- Muñoz-Torres FA, Whatley RC, Van Harten D. 2006. Miocene ostracod (crustacea) biostratigraphy of the upper Amazon basin and evolution of the genus *Cyprideis*. *Journal of South American Earth Sciences*. 21(1–2):75–86.
- Raine JI, Mildenhall DC, Kennedy EM. 2011. New Zealand fossil spores and pollen: an illustrated online catalogue. 4th ed. Lower Hutt: GNS Science. <http://data.gns.cri.nz/sporepollen/index.htm>.
- Ramos MI. 2006. Ostracods from the Neogene Solimões Formation (Amazonas, Brazil). *Journal of South American Earth Sciences*. 21(1–2): 87–95.
- Räsänen ME, Linna AM, Santos JCR, Negri FR. 1995. Late Miocene tidal deposits in the Amazonian foreland basin. *Science (New York, N.Y.)*. 269(5222):386–390.
- Rebata LA, Gingras MK, Räsänen ME, Barberi M. 2006a. Tidal-channel deposits on a delta plain from the upper Miocene Nauta Formation, Marañón foreland sub-basin, Peru. *Sedimentology*. 53:971–1013.
- Rebata LA, Räsänen ME, Gingras MK, Vieira V, Barberi M, Irion G. 2006b. Sedimentology and ichnology of tide-influenced late Miocene successions in western Amazonia: the gradational transition between the Pebas and Nauta Formations. *Journal of South American Earth Sciences*. 21(1–2):96–119.
- Regali MSP, Uesugui N, Santos AS. 1974a. Palinologia dos sedimentos Meso-Cenozóicos do Brasil (i). [Palynology of Meso-Cenozoic sediments of Brazil (i)]. *Boletim Técnico da Petrobras*. 17(3):177–191.
- Regali MSP, Uesugui N, Santos AS. 1974b. Palinologia dos sedimentos Meso-Cenozóicos do Brasil (ii). [Palynology of Meso-Cenozoic sediments of Brazil (ii)]. *Boletim Técnico da Petrobras*. 17(4):263–301.
- Roddaz M, Baby P, Brusset S, Hermoza W, Darrozes JM. 2005. Forebulge dynamics and environmental control in western Amazonia: the case study of the arch of Iquitos (Peru). *Tectonophysics*. 399(1–4):87–108.
- Roddaz M, Hermoza W, Mora A, Baby P, Parra M, Christophoul F, Brusset S, Espurt N. 2010. Cenozoic sedimentary evolution of the Amazonian foreland basin system. In: Hoorn H, Wesselingh FP, editors. *Amazonia, landscape and species evolution: a look into the past*. Chichester: Wiley-Blackwell Publishing Ltd; p. 61–88.
- Salas-Gismondi R, Antoine P-O, Baby P, Brusset S, Benammi M, Espurt N, De Franceschi D, Pujos F, Tejada-Lara JV, Urbina M. 2007. Middle Miocene crocodiles from the Fitzcarrald arch. Amazonian Peru. *Cuadernos Del Museo Geominero*. 8:355–360.
- Shaw AB. 1964. *Time in stratigraphy*. New York (NY): McGraw Hill; p. 365.
- Silveira R, Souza P. 2015. Palinologia (grãos de pólen de angiospermas) das formações Solimões e Içá (bacia do Solimões), nas regiões de Coari e Alto Solimões, Amazonas. [Palynology (pollen grains of angiosperms) of the Solimões and Içá formations (Solimões basin), in the regions of Coari and Alto Solimões, Amazonas]. *Revista Brasileira de Paleontologia*. 18(3):455–474.
- Silveira R, Souza P. 2016. Palinologia (esporos de fungos e pteridófitas, grãos de pólen de gimnospermas, cistos de algas e escolecodonte) das formações Solimões e Içá (Neogeno e Pleistoceno, bacia do Solimões), Amazonas, Brasil. [Palynology (spores of fungi and ferns, grains gymnosperms pollen, algal cysts and scolecodonts) of the Solimões and Içá formations (Neogene and Pleistocene, the Solimões basin), Amazonas, Brazil.]. *Pesquisas em Geociências*. 43(1):17–39.
- Tryon AF, Lugardon B. 1991. Spores of the pteridophyta: surface, wall structure, and diversity based on electron microscope studies. New York (NY): Springer Science & Business Media.
- Van der Hammen T. 1956. Description of some genera and species of fossil pollen and spores. *Boletín Geológico. Servicio Geológico Colombiano, Bogotá*. 4(2–3):111–117.
- Wesselingh FP. 2006. Miocene long-lived lake Pebas as a stage of mollusc radiations, with implications for landscape evolution in western Amazonia. *Scripta Geologica*. 133:1–17.
- Wesselingh FP, Guerrero J, Räsänen ME, Romero Pittman L, Vonhof HB. 2006a. Landscape evolution and depositional processes in the Miocene Amazonian Pebas lake/wetland system: evidence from exploratory boreholes in northeastern Peru. *Scripta Geologica*. 133:323–361.
- Wesselingh FP, Hoorn C, Guerrero J, Räsänen ME, Romero Pittman L, Salo JS. 2006b. The stratigraphy and regional structure of Miocene deposits in western Amazonia (Peru, Colombia and Brazil), with implications for late Neogene landscape evolution. *Scripta Geologica*. 133: 291–322.
- Wesselingh FP, Hoorn C, Kroonenberg SB, Antonelli A, Lundberg JG, Vonhof HB, Hooghiemstra H. 2010. On the origin of Amazonian landscapes and biodiversity: a synthesis. In: Hoorn C, Wesselingh FP, editors. *Amazonia, landscape and species evolution: a look into the past*. Chichester: Wiley-Blackwell Publishing Ltd; p. 419–431.
- Wesselingh FP, Ramos MI. 2010. Amazonian aquatic invertebrate faunas (mollusca, ostracoda) and their development over the past 30 million years. In: Hoorn C, Wesselingh FP, editors. *Amazonia, landscape and species evolution: a look into the past*. Oxford (UK): Wiley-Blackwell Publishing Ltd; p. 302–316.
- Whatley RC, Muñoz-Torres FA, Van Harten D. 1998. The ostracoda of an isolated Neogene saline lake in the western Amazon basin. What about Ostracoda. 20:231–245.
- Williams GL, Fensome RA, MacRae RA. 2017. Dinoflag3. American Association of Stratigraphic Palynologists, data series no. 2. http://dinoflag3.smu.ca/dinoflag3/index.php/Main_Page.
- Wood GD, Gabriel AM, Lawson JC. 1996. Palynological techniques – processing and microscopy. In: Jansonius J, McGregor DC, editors. *Palynology: Principles and applications*. Dallas (TX): American Association of Stratigraphic Palynologists Foundation; Volume 1, p. 29–50.

List of species with author citations

Spores

Cicatricosisporites doregensis Potonié & Gelletich, 1933
Crassoretitrites vanraadshooveni Germeraad, Hopping & Müller, 1968
Cyathidites congoensis Sah, 1967
Cyathidites minor Couper, 1953

Deltoidospora adriennis (Potonié & Gelletich, 1933) Frederiksen, 1983
Echinatisporis muelleri (Regali, Uesugui & Santos, 1974) Silva-Caminha, Jaramillo & Absy, 2010
Foveotrilites ornatus Regali, Uesugui & Santos, 1974
Laevigatosporites catanagensis Muller, Di Giacomo & Van Erve, 1987
Laevigatosporites granulatus Jaramillo, Pardo, Rueda, Torres, Harrington, & Mora, 2007
Laevigatosporites ovatus Wilson & Webster, 1946
Magnatriatites grandiosus (Kedves & Sole de Porta, 1963) Dueñas, 1980
Nijseniosporites fossulatus Lorente, 1986
Osmundacidites ciliatus Sah, 1967
Polypodiisporites speciosus Sah, 1967
Polypodiisporites usmensis (Van der Hammen, 1956) Khan & Martin, 1972
Retitriletes altimuratus Silva-Caminha, Jaramillo & Absy, 2010
Striatrilites saccolomoides Jaramillo, Rueda & Torres, 2011
Verrutrilites virueloides Jaramillo, Pardo, Rueda, Torres, Harrington & Mora, 2007

Pollen grains

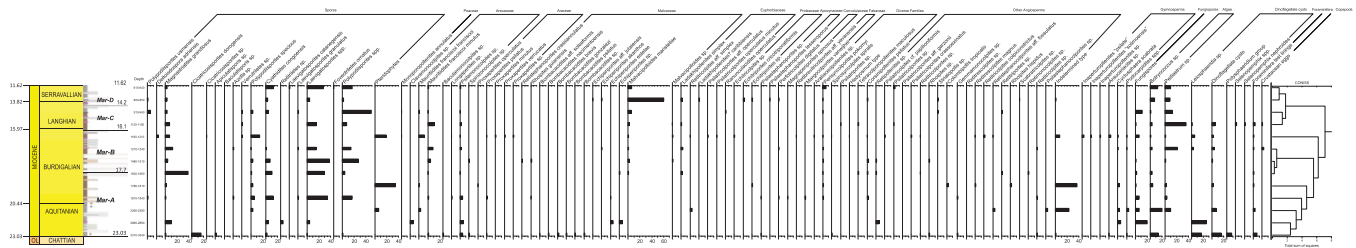
Acaciapollenites myriosporites (Cookson, 1954) Mildenhall, 1972
Araliaceipollenites Jussieu, 1789
Arecipites perfectus Silva-Caminha, Jaramillo & Absy, 2010
Bombacacidites soleaformis Muller, Di Giacomo & Van Erve, 1987
Bombacacidites annae (Van der Hammen, 1954) Leidelmeyer, 1966
Bombacacidites araracuarensis Hoorn, 1994
Bombacacidites brevis (Dueñas, 1980) Muller, Di Giacomo & Van Erve, 1987
Bombacacidites gonzalezi Jaramillo & Dilcher, 2001
Bombacacidites nacimientoensis (Anderson, 1960) Elsik, 1968
Bombacacidites psilatus Jaramillo & Dilcher, 2001
Catostemma type Bentham, 1843
Cistacearumpollenites rotundiporus Silva-Caminha, Jaramillo & Absy, 2010
Clavainaperturites clavatus Van der Hammen & Wymstra, 1964
Colombipollis tropicalis Sarmiento, 1992
Corsinipollenites psilatus Jaramillo & Dilcher, 2001
Corsinipollenites collaris Silva-Caminha, Jaramillo & Absy, 2010
Corsinipollenites oculusnoctis (Thiergart, 1940) Nakoman, 1965
Corsinipollenites psilatus Jaramillo & Dilcher, 2001
Crassietoapertites columbianus (Dueñas, 1980) emend. Lorente, 1986
Crototricolpites annemariae Leidelmeyer, 1966
Ctenolophonidites suigeneris Silva-Caminha, Jaramillo & Absy, 2010
Cyclusphaera scabrata Jaramillo & Dilcher, 2001
Echiperiporites estelae Germeraad, Hopping & Müller, 1968
Echiperiporites jataiensis Silva-Caminha, Jaramillo & Absy, 2010
Echiperiporites akanthos Van der Hammen & Wymstra, 1964
Echiperiporites estelae Germeraad, Hopping & Müller, 1968
Echiperiporites lophatus Silva-Caminha, Jaramillo & Absy, 2010
Echitriporites trianguliformis van Hoeken-Klinkenberg, 1964
Echitriporites cricotriporatiformis Jaramillo, Rueda & Torres, 2011
Foveotricolporites lenticuloides Silva-Caminha, Jaramillo & Absy, 2010
Gomphrenipollis minimus Silva-Caminha, Jaramillo & Absy, 2010
Grimsdalea magnaclavata Germeraad, Hopping & Müller, 1968
Hedyosmum type Swartz, 1788
Ladakhipollenites simplex (González-Guzmán, 1967) Jaramillo & Dilcher, 2001
Ladakhipollenites? caribbiensis (Muller, Di Giacomo & Van Erve, 1987) Silva-Caminha, Jaramillo & Absy, 2010
Lanagiopollis crassa (Van der Hammen & Wymstra, 1964) Frederiksen, 1988
Magnaperiporites spinosus González-Guzmán, 1967
Malvacipollis (*Echitricolporites*) *maristellae* (Muller, Di Giacomo & Van Erve, 1987) Silva-Caminha, Jaramillo & Absy, 2010
Margocolporites vanwijhei Germeraad, Hopping & Muller 1968
Mauritiidites crassibaculatus Van Hoeken-Klinkenberg, 1964
Mauritiidites franciscoi franciscoi (Van der Hammen, 1956) van Hoeken-Klinkenberg, 1964
Mauritiidites franciscoi minutus Van der Hammen & Garcia, 1966

Monocolpopollenites ovatus Jaramillo & Dilcher, 2001
Monoporopollenites annulatus (Van der Hammer, 1954) Jaramillo & Dilcher, 2001
Multiporopollenites pauciporatus Jaramillo & Dilcher, 2001
Paleosantalaceapites cingulatus Jaramillo, Rueda & Torres, 2011
Perforicolpites digitatus González-Guzmán, 1967
Perisyncolporites pokorny Germeraad, Hooping & Müller, 1968
Polyadopollenites mariae Dueñas, 1980
Proteacidites triangulatus Lorente, 1986
Proxapertites tertiaria Van der Hammen & Garcia, 1966
Proxapertites minutus Dueñas, 1980
Proxapertites operculatus (Van der Hammen, 1954) Van der Hammen, 1956
Proxapertites psilatus Sarmiento, 1992
Proxapertites verrucatus Sarmiento, 1992
Psilamonocolpites medius (Van der Hammen, 1954) Van der Hammen & Garcia, 1966
Psilastephanocolporites fissilis Leidelmeyer, 1966
Psilastephanoporites tesseroporus Regali, Uesugui & Santos, 1974
Psilatricolpites papilioniformis Regali, Uesugui & Santos, 1974
Psilatricolporites garzoni Hoorn, 1993
Psilatricolporites operculatus Van der Hammen & Wymstra, 1964
Psilatricolporites crassoexinatus Hoorn, 1993
Psilatricolporites operculatus minutus González-Guzmán, 1967
Ranunculacidites operculatus (van der Hammen & Wymstra, 1964) Jaramillo & Dilcher, 2001
Retibrevitricolporites yavarensis (Hoorn, 1993) Silva-Caminha, Jaramillo & Absy, 2010
Retimonocolpites maximus Hoorn, 1993
Retimonocolpites retifossulatus Lorente, 1986
Retipollenites crotonicolumellatus Jaramillo, Rueda & Torres, 2011
Retistephanocolporites fossulatus Jaramillo & Dilcher, 2001
Retistephanoporites angelicus González-Guzmán, 1967
Retistephanoporites crassiannulatus Lorente, 1986
Retitrescolpites irregularis (Van der Hammen & Wymstra, 1964) Jaramillo & Dilcher, 2001
Retitrescolpites magnus (González-Guzmán, 1967) Jaramillo & Dilcher, 2001
Retitrescolpites saturum (González-Guzmán, 1967) Jaramillo & Dilcher, 2001
Retitricolpites simplex González-Guzmán, 1967
Retitricolpites colpiconstrictus Hoorn, 1994
Retitricolpites simplex González-Guzmán, 1967
Retitricolporites wilmstrae Hoorn, 1994
Retitriporites dubiosus González-Guzmán, 1967
Rhoipites guianensis (Van der Hammen & Wymstra, 1964) Jaramillo & Dilcher, 2001
Rhoipites hispidus (Van der Hammen & Wymstra, 1964) Jaramillo & Dilcher, 2001
Siltaria hammenii Silva-Caminha, Jaramillo & Absy, 2010
Siltaria santaisabelensis (Hoorn, 1994) Silva-Caminha, Jaramillo & Absy, 2010
Spirosyncolpites spiralis González-Guzmán, 1967
Tetracolporopollenites maculosus (Regali, Uesugui & Santos, 1974) Jaramillo & Dilcher, 2001

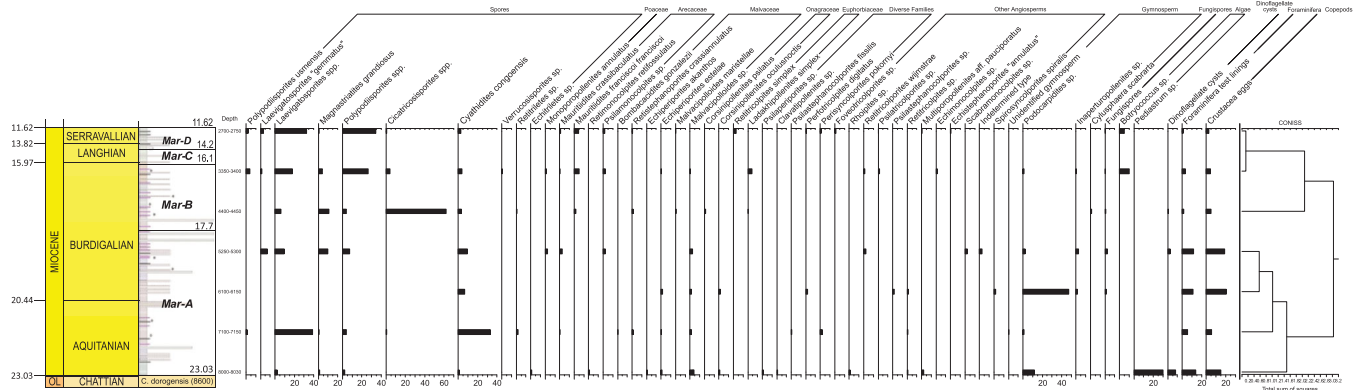
Microplankton

Chomotrilites minor Pocock, 1970
Apteodinium australiense Williams, 1978
Selenopemphix quanta (Bradford, 1975) Matsuoka, 1985
Bosedinia infragranulata He, 1984
Operculodinium group Wall, 1967
Polysphaeridium group Davey & Williams, 1966b
Selenopemphix nephroides Benedek, 1972
Retitrescolpites? irregularis (Van der Hammen & Wymstra, 1964) Jaramillo & Dilcher, 2001
Quadrina? condita de Verteuil & Norris, 1992

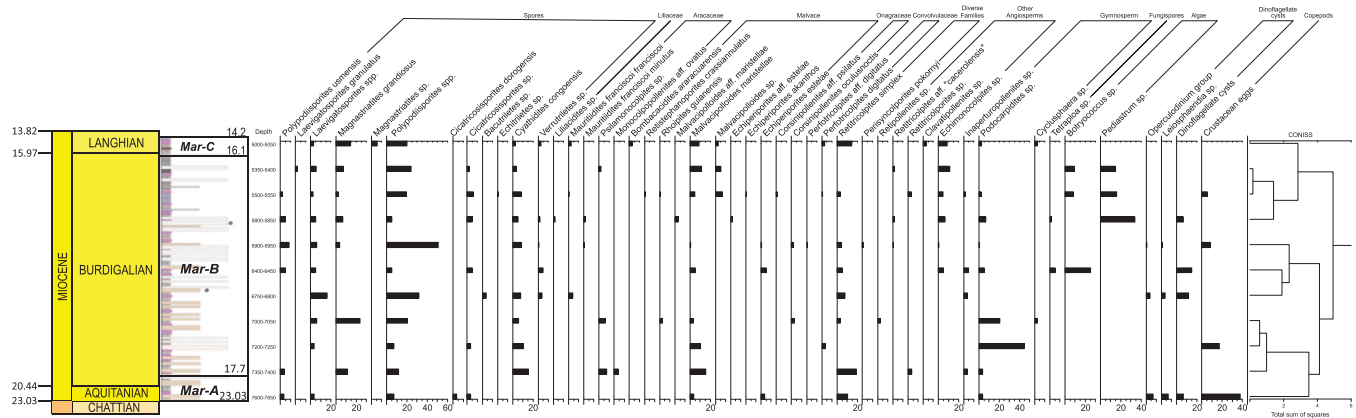
Appendix 1. Arabela



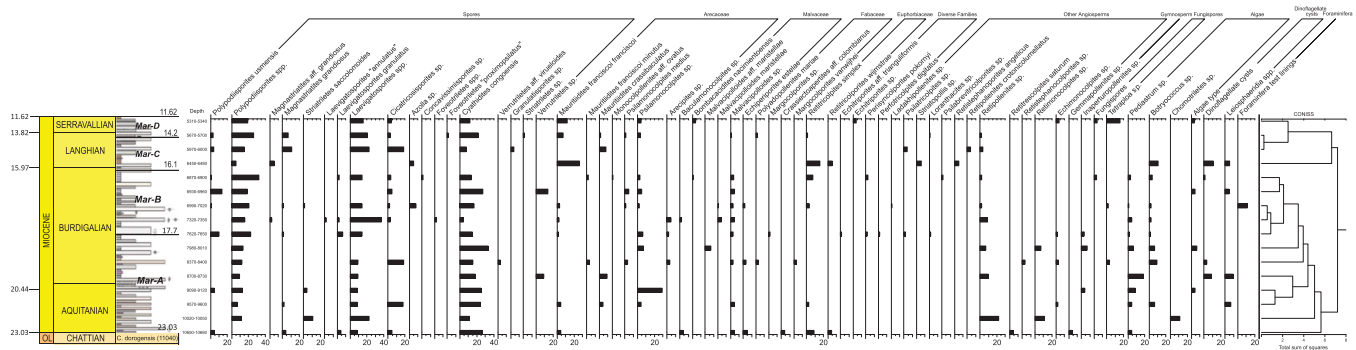
Appendix 2. Maynas



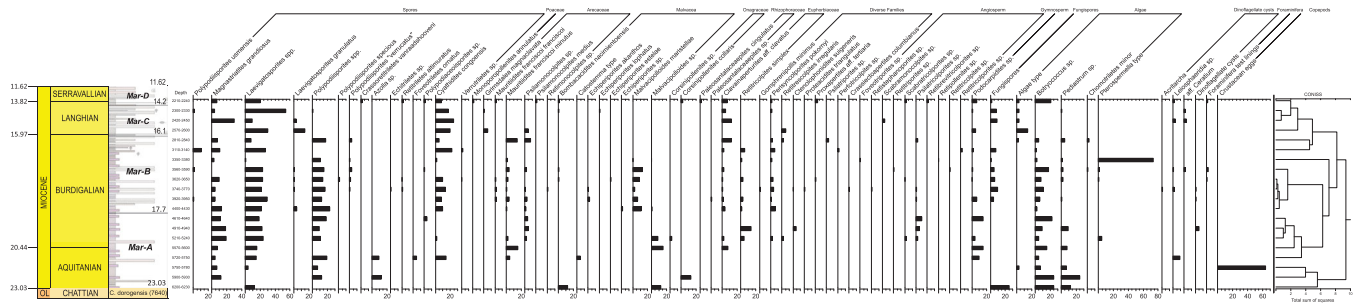
Appendix 3. Tacunare



Appendix 4. Tigrillio



Appendix 5. Nahuapa



Appendix 6. Frontera

