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

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### 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 *Retitricolporites dubiosus* and/or the appearance of *Crassoretitriletes vanraadshooveni* and/or *Psilastephanoporites tesseroporos*; the Mar-D *Crassoretitriletes vanraadshooveni* Zone (Late Serravallian: 14.2–11.62 Ma), from the appearance of *Crassoretitriletes vanraadshooveni* and/or *Psilastephanoporites tesseroporos* to the disappearances of *Mauritiidites crassibaculatus*, *Bombacacidites nacimientoensis*, and *Cyathidites congoensis*; and the Mar-E *Psilastephanoporites tesseroporos* 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 tesseroporos* 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 tesseroporos* 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 km<sup>2</sup> (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.



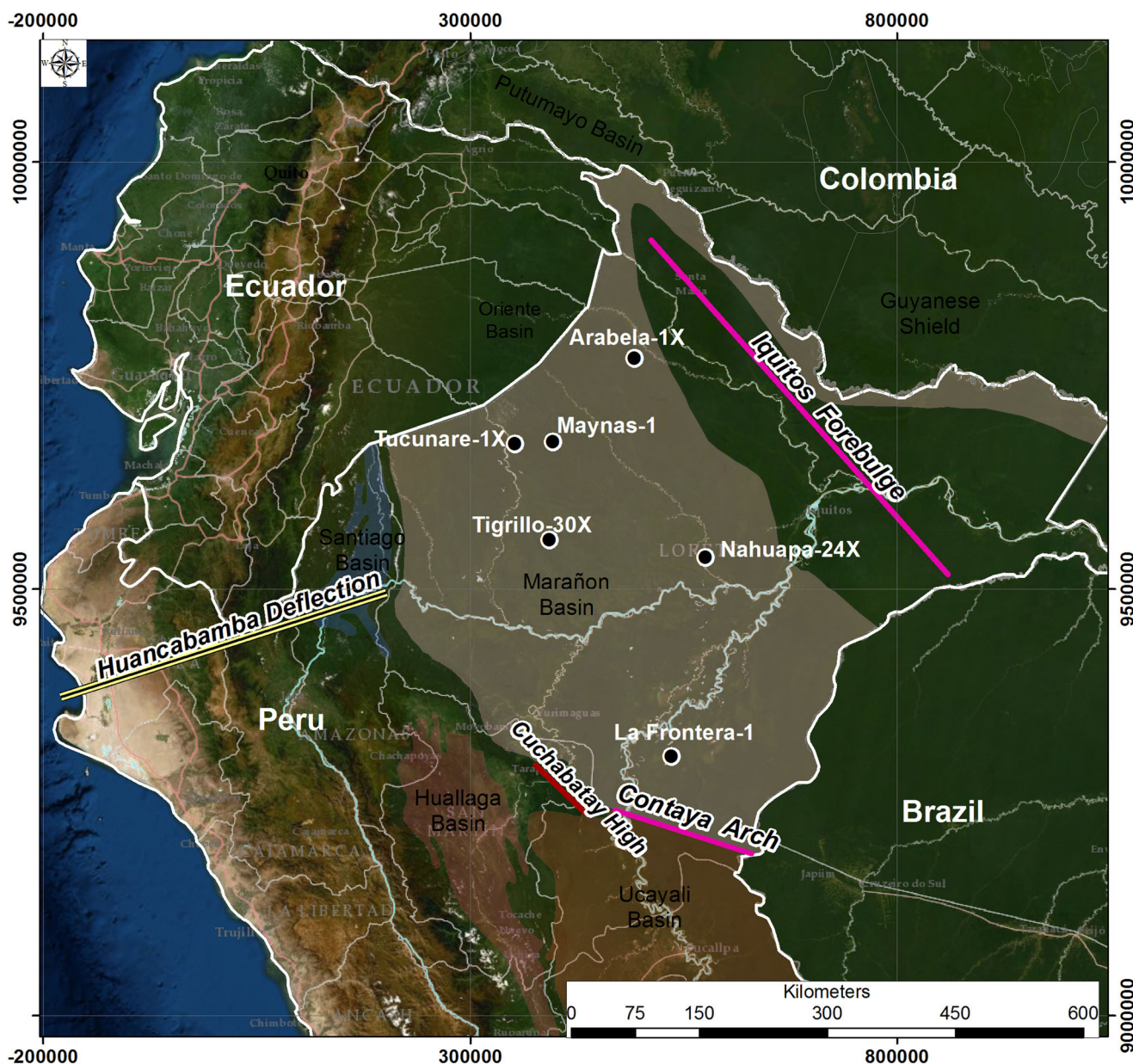


Figure 1. Location of the six studied deep exploration wells (white-black circles). Structural boundaries of the Marañón Basin (after Roddaz et al. 2005).

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 *Psiladiporites*–*Crototricolporites* Concurrent Range Zone (late Early to early Middle Miocene), the *Crassoretitriletes* 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 *Crassoretitriletes* 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

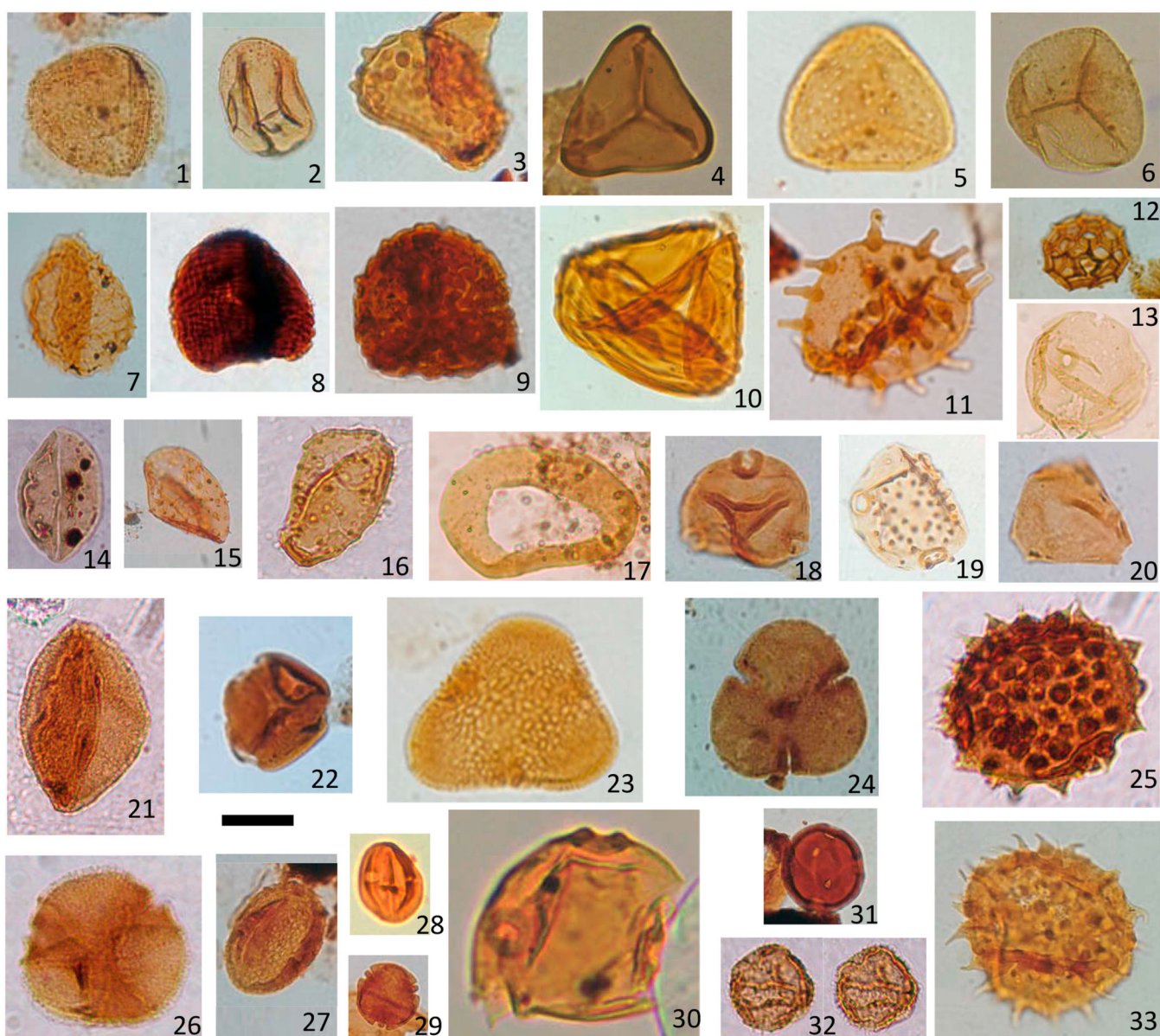
Depth: analyzed intervals of each well in meters

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. *Foveotriletes ornatus* CICYTTP-2068 Nahuapa 24X (5720–5750ft), EF N32/1-2; 6. *Osmundacidites ciliatus* CICYTTP-2074 Frontera 1 (1860–1880ft), EF R35/1; 7. *Retitriletes 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. *Crassoretitriletes vanraadshooveni* CICYTTP-2052 Nahuapa 24X (2210–2240ft), EF H43/1; 10. *Magnastriatites 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. *Monoporollenites 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 cricotriporatiformis* 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. *Crassieoapertites 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. *Malvacipolloides 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. *Psilastephanoporites 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 low focus; 33. *Echiperiporites estelae* CICYTTP-2016 Arabela 1X (2860–2890ft), EF G23/1. Scale bar is 20  $\mu\text{m}$  for all pictures except for Figures 9 and 10 where it represents 30  $\mu\text{m}$ .

## 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 Marañon 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*, *Crassoretitriletes*, *Cyathidites*, *Deltoidospora*, *Echinatisporis*, *Foveotriletes*, *Laevigatosporites*, *Magnastriatites*, *Polypodiisporites*, *Psilatritrites*, *Striatritrites*, and *Verrucosisporites*–*Verrutritrites*.

Angiosperm pollen grains were frequent and more diverse, including *Bombacacidites*, *Corsinipollenites*, *Crassietoapertites*, *Cyclusphaera*, *Echiperiporites*, *Echipollenites*, *Echitriporites*, *Inaperturopollenites*, *Ladakhipollenites*, *Malvacipolloides*, *Mauritiidites*, *Paleosantalaceapites*, *Perforicolpites*, *Perisyncolporites*, *Proxapertites*, *Proteacidites*, *Psilamonocolpites*, *Psilastephanocolporites*, *Psilatricolporites*, *Retimonocolpites*, *Retipollenites*, *Retistephanoporites*, *Retitrescolpites*, *Retitricolpites*, *Retitricolporites*, *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*, *Cribroperidinium*, *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) Hoor (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>Apteodinium australiense</i> (9)            | Early Eocene   | Middle 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                        |            |           |             |              |             |               |
| <i>Bombacacidites nacimientensis</i> (4)       | 56.85          | 13.05                       |            |           |             | 1618-2103    | 674-1094    | 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   | 360-366       |
| <i>Corsiniipollenites rotundiporus</i> (1)     | Neogene        | Neogene                     |            | 1859-2447 | 1798-2149   |              |             | 671-677       |
| <i>Corsiniipollenites oclusnotus</i> (1)       | Early Miocene  | Middle Miocene              |            |           |             |              |             |               |
| <i>Corsiniipollenites collaris</i> (1)         | Miocene        | Early Plioc                 | 451-460    | 1341-1356 | 1676-1692   |              | 1798-1807   |               |
| <i>Corsiniipollenites psilatus</i> (4)         |                | 17.33                       |            |           |             |              | 674-2054    |               |
| <i>Crototricolpites annemariiae</i> (4)        | 52.49          | 13                          |            |           |             |              |             | 975-981       |
| <i>Crassorettrilletes 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 cricotrifarctiformis</i> (4) | 16.8           | 3.94                        | 250-259    |           |             |              |             |               |
| <i>Echiperiporites lophatus</i> (1)            | Miocene        | Early Plioc                 |            | 1021-1356 |             |              | 701-710     | 579-585       |
| <i>Foveotricolporites lenticuloides</i> (1)    | Neogene        | Neogene                     |            |           |             |              |             |               |
| <i>Gomphrenipollis minimus</i> (1)             | Miocene        | Early Plioc                 |            |           |             |              | 1140-1149   |               |
| <i>Grimsdalea magnaclavata</i> (4)             | 16.09          | 3.4                         |            |           |             |              | 701-792     |               |
| <i>Ladakhipollenites simplex</i> (4)           | 59.92          | 12.87                       | 250-506    |           |             |              |             |               |
| <i>Ladakhipollenites? caribbiensis</i> (1)     | Late Miocene   | Pliocene                    |            |           |             |              |             | 567-573       |
| <i>Laevigatosporites catanegensis</i> (4)      | 42.53          | 4.32                        | 186-195    |           |             |              |             |               |
| <i>Lanagiopollis crassa</i> (4)                | 51.3           | 4.7                         |            |           |             |              |             | 567-573       |
| <i>Magnaperiporites spinosus</i> (4)           | 31.96          | 12.98                       | 552-561    |           |             |              |             |               |
| <i>Malvacipollidites maristellae</i> (4)       | 17.71          | 0.39                        | 186-506    |           |             |              |             | 823-981       |
| <i>Mauritiidites crassibaculatus</i> (4)       |                | 11.85                       |            | 1021-1356 | 1524-2332   | 2130-2240    | 1021-1350   |               |
| <i>Multiporopollenites apauciporatus</i> (4)   |                | 23                          |            | 823-2164  |             | 1758-2917    |             |               |
| <i>Nijssenosporites fossulatus</i> (4)         | 19.05          | 1.03                        |            | 2438-2447 |             |              |             |               |
| <i>Osmundacidites ciliatus</i> (5)             | Late Miocene   | Pliocene                    |            |           |             |              |             | 579-585       |
| <i>Palaeosantalaceapites cingulatus</i> (4)    | 12.08          | 3.72                        |            |           |             |              | 674-683     | 567-573       |
| <i>Psilastephanoporites tesseroporus</i> (4)   | 13.9           | 5.48                        | 250-259    |           |             |              |             | 567-573       |
| <i>Quadringa? 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                        |            |           |             |              |             | 469-475       |
| <i>Retistephanoporites angelicus</i> (2)       | 56             | 16                          |            |           |             |              |             |               |
| <i>Retitricolporites wijmstrae</i> (3)         | 23             | 16                          |            |           |             |              |             |               |
| <i>Retitricolporites "acerolensis"</i> (4)     |                | 16.26                       | 360-1018   | 1021-1615 | 1631-1646   | 1820-1829    |             |               |
| <i>Retitricolporites altimuratus</i> (1)       | Miocene        | Early Pliocene              |            |           |             | 1966-1975    | 674-1149    |               |
| <i>Retitricolporites dubiosus</i> (4)          | 51.47          | 14.27                       | 277-286    |           |             |              |             |               |
| <i>Selenopemphis nephroides</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       |

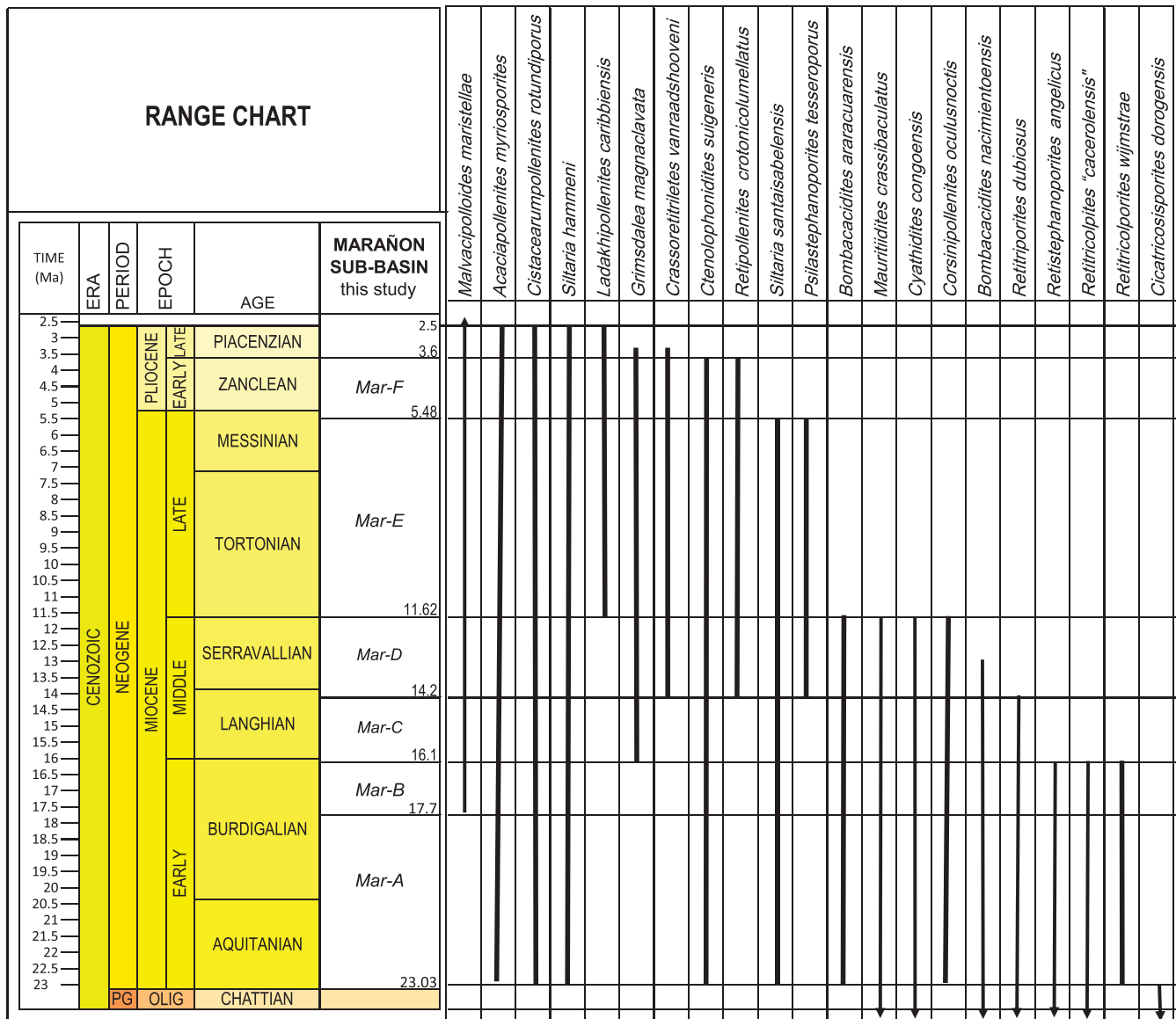


Figure 2. Range chart of taxa as used in this work, indicating the boundaries of the palynozones Mar-A to Mar-F.

(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 oculusnoctis* 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 oculusnoctis* palynozone as occurring from the LAD of *Cicatricosisporites dorogensis* to the FAD of *Malvacipolloides maristellae* or, alternatively, it is from the FAD of *Corsinipollenites oculusnoctis*, the FAD of *Retitricolporites wijmstrae*, and/or the FAD of *Acaciapollenites myriosporites* to the FAD of *Malvacipolloides maristellae* as occurring respectively in the Maynas-1, Tigrillo-30X, and La Frontera-1 wells, to the FAD of *Malvacipolloides 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 nacimientoensis*, *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>Perforicolpites</i>         | <i>digitatus</i>             | –709  | –254 |
| <i>Bombacacidites</i>                                     | <i>nacimientoensis</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>dorogensis</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>Crassiectoapertites</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>tesseroporos</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>cricotriporitiformis</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>catanegensis</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>Malvacipolloides</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 *Malvacipolloides 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 *Horniella 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 *Horniella lunarensis* is not present in the Mar-A *Corsinipollenites oculusnoctis* Zone ([Figures 2–4](#)).

## 6.2. Mar-B *Malvacipolloides 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 (2255.5–1631 m), Tigrillo 30X interval 7350–6450 ft (2240–1966 m), Nahuapa-24X interval 4430–2600 ft (1350–792 m), and La Frontera-1 interval

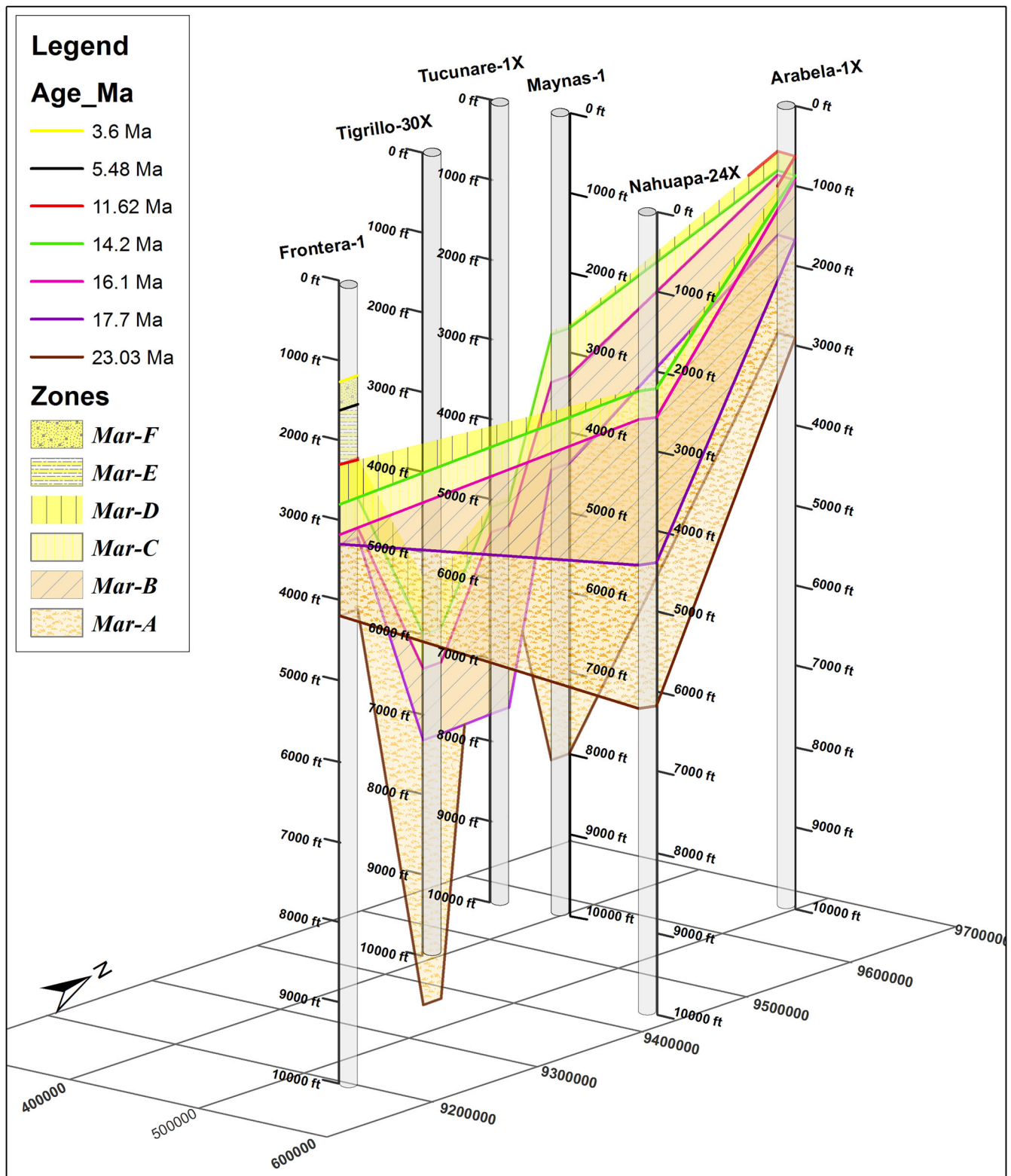




Figure 3. Maximum stratigraphic ranges of species ordered by last appearance datum (LAD) among the studied wells, constructed in a composite section from previously known appearances and disappearances of species in each well obtained by means of graphic correlation.

| TIME (Ma) | ERA      | PERIOD  | EPOCH        | AGE                                      | MARAÑÓN SUB-BASIN<br>This work             | ANALYZED WELLS OF THE MARAÑÓN BASIN     |   |                                       |                                |                               |               | FORMATIONS |  |  |  |
|-----------|----------|---------|--------------|--|--|---|---|---------------------------------------|--------------------------------|-------------------------------|---------------|------------|--|--|--|
|           |          |         |              |  |  | ARABELA-1X                              | MAYNAS-1                                  | TUCUNARE-1X                           | TIGRILLO-30X                   | NAHUAPA-24X                   | LA FRONTERA-1 |            |  |  |  |
| 2.5       | CENOZOIC | NEOGENE | PLIOCENE     | PIACENZIAN                               |  |   |   |                                       |                                |                               |               |            |  |  |  |
| 3         |          |         |              |  |  |   |   |                                       |                                |                               |               |            |  |  |  |
| 3.5       |          |         | EARLY LATE   | ZANCLEAN                                 | Mar-F                                      |   |   |                                       |                                |                               |               |            |  |  |  |
| 4         |          |         |              |  | 5.48                                       |   |   |                                       |                                |                               |               |            |  |  |  |
| 4.5       |          |         |              |  |  |   |   |                                       |                                |                               |               |            |  |  |  |
| 5         |          | MIDDLE  | LATE         | MESSINIAN                                |  |   |   |                                       |                                |                               |               |            |  |  |  |
| 5.5       |          |         |              |  |  |   |   |                                       |                                |                               |               |            |  |  |  |
| 6         |          |         |              |  |  |   |   |                                       |                                |                               |               |            |  |  |  |
| 6.5       |          |         |              |  |  |   |   |                                       |                                |                               |               |            |  |  |  |
| 7         |          |         |              |  |  |   |   |                                       |                                |                               |               |            |  |  |  |
| 7.5       | EARLY    | LATE    | TORTONIAN    | Mar-E                                    |  |   |   |                                       |                                |                               |               |            |  |  |  |
| 8         |          |         |              |  |  |   |   |                                       |                                |                               |               |            |  |  |  |
| 8.5       |          |         |              |  |  |   |   |                                       |                                |                               |               |            |  |  |  |
| 9         |          |         |              |  |  |   |   |                                       |                                |                               |               |            |  |  |  |
| 9.5       |          |         |              |  |  |   |   |                                       |                                |                               |               |            |  |  |  |
| 10        | MIOCENE  | MIDDLE  | SERRAVALLIAN | 11.62                                    | <i>Cyathidites congoensis</i> 186 m        | <i>Cyathidites congoensis</i> 823 m     | <i>Cyathidites congoensis</i> 1521 m      |                                       |                                |                               |               |            |  |  |  |
| 12        |          |         |              | Mar-D                                    |  |   |   |                                       |                                |                               |               |            |  |  |  |
| 13        |          |         |              |  | <i>Ladakhipollinites simplex</i>           |   |   |                                       |                                |                               |               |            |  |  |  |
| 13.5      |          |         |              |  | <i>Polistephanoportites tesserae</i> 259 m |   |   |                                       |                                |                               |               |            |  |  |  |
| 14        |          |         |              |  | <i>Retitriporites dubiosus</i> 277 m       |   |   |                                       |                                |                               |               |            |  |  |  |
| 14.2      |          |         | Mar-C        |  |  |   |   |                                       |                                |                               |               |            |  |  |  |
| 15        |          | EARLY   | LATE         | LANGHIAN                                 | Mar-C                                      |   |   |                                       |                                |                               |               |            |  |  |  |
| 15.5      |          |         |              |  |  |   |   |                                       |                                |                               |               |            |  |  |  |
| 16        |          |         |              |  |  |   |   |                                       |                                |                               |               |            |  |  |  |
| 16.1      |          |         |              |  |  |   |   |                                       |                                |                               |               |            |  |  |  |
| 16.5      |          |         |              |  |  |   |   |                                       |                                |                               |               |            |  |  |  |
| 17        | EARLY    | LATE    | BURDIGALIAN  | Mar-B                                    | <i>Retitricolpites urjinae</i> 360 m       | <i>R. urjinae</i> 1021 m                | <i>Retitricolpites "cucullata"</i> 1631 m | <i>R. urjinae/R. angelicus</i> 1966 m | <i>R. norimintensis</i> 1618 m | <i>R. norimintensis</i> 671 m |               |            |  |  |  |
| 17.5      |          |         | Mar-B        | <i>Multicollidites maristellae</i> 497 m | <i>M. maristellae</i> 1356 m               | <i>M. maristellae</i> 255 m             | <i>M. maristellae</i> 2210 m              | <i>M. maristellae</i> 1350 m          | <i>M. maristellae</i> 981 m    |                               |               |            |  |  |  |
| 18        |          |         |              | <i>Retitriporites maristellae</i> 513 m  | 1600 m                                     |   | <i>Retitriporites maristellae</i> 2322 m  | 1405 m                                |                                |                               |               |            |  |  |  |
| 18.5      |          |         |              |  |  |   |   |                                       |                                |                               |               |            |  |  |  |
| 19        |          |         |              |  |  |   |   |                                       |                                |                               |               |            |  |  |  |
| 19.5      | EARLY    | LATE    | AQUITANIAN   | Mar-A                                    |  |   |   |                                       |                                |                               |               |            |  |  |  |
| 20        |          |         |              |  |  |   |   |                                       |                                |                               |               |            |  |  |  |
| 20.5      |          |         |              |  |  |   |   |                                       |                                |                               |               |            |  |  |  |
| 21        |          |         |              |  |  |   |   |                                       |                                |                               |               |            |  |  |  |
| 21.5      |          |         |              |  |  |   |   |                                       |                                |                               |               |            |  |  |  |
| 22        | EARLY    | LATE    | CHATTIAN     | 23.03                                    | <i>Retitricolpites urjinae</i> 1809 m      | <i>Corsiniipollites oculatus</i> 2117 m |   | <i>Retitriporites urjinae</i> 3255 m  |                                |                               |               |            |  |  |  |
| 22.5      |          |         |              |  | <i>Retitriporites dorogensis</i> 1016      | <i>C. dorogensis</i> 2621 m             | <i>C. dorogensis</i> 2332 m               | <i>C. dorogensis</i> 3365 m           | <i>C. dorogensis</i> 1899 m    |                               |               |            |  |  |  |
| 23        |          |         |              |  |  |   |   |                                       |                                |                               |               |            |  |  |  |

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*





*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 *Crassoretitriletes 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 *Crassoretitriletes 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 *Crassoretitriletes vanraadshooveni* Zone is defined as the interval from the LADs of *Retitriporites dubiosus* (top of lower zone) and the FADs of the *Crassoretitriletes vanraadshooveni*, *Psilastephanoporites tesseroporos*, or *Retipollenites crotonicumellatus* (which should be used when *Crassoretitriletes 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 *Crassoretitriletes vanraadshooveni*, *Paleosantalaceapites cingulatus*, *Psilastephanoporites tesseroporos*, and *Retipollenites crotonicumellatus* 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 *Crassoretitriletes 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 crotonicumellatus*, which also occurs in the T-15 Zone, the FADs of both *Paleosantalaceapites cingulatus* and *Psilastephanoporites tesseroporos*, 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 tesseroporos* 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 tesseroporos* 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 tesseroporos* 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 tesseroporos*, 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 tesseroporos* 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 tesseroporos* (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 *Retitriletes* sp. *Fusiformisporites* is common among the fungal spores. The last records of *Siltaria hammenii* (Neogene), *Cistacearumpollenites rotundiporus* (LAD Pliocene), and *Crassoretitriletes 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 tesseroporos* 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 Marañon 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 *Crassoretitriletes vanraadshooveni* at the top. These markers also correlate with our Mar-B *Malvacipolloides (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 *Crassoretitriletes* Interval Zone. This zone is defined from the first records of *Crassoretitriletes 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 *Crassoretitriletes vanraadshooveni*.

We have identified in Arabela-1X, Tigrillo-30X, Nahuapa-24X, and La Frontera-1 wells an interval similar to the *Crassoretitriletes* Interval Zone, by the presence of three biostratigraphic markers, *Crassoretitriletes vanraadshooveni*, *Psilastephanoporites tesseroporos*, and *Retipollenites crotonicolumellatus* (Tables 5–6) co-occurring at the base, which belong to the bases of both the T-15 *Crassoretitriletes vanraadshooveni* palynozone (Jaramillo et al. 2011) and the *Crassoretitriletes* palynozone (Lorente 1986). GraphCor indicated the FAD of *Retipollenites crotonicolumellatus* was slightly below the FADs of *Crassoretitriletes vanraadshooveni* and *Psilastephanoporites tesseroporos*. 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 *Crassoretitriletes vanraadshooveni* Interval Zone of Muller et al. (1987). Therefore, the base of our Mar-D *Crassoretitriletes vanraadshooveni* Zone is coeval with the bases of the *Crassoretitriletes vanraadshooveni* zones of Hoorn (1993), Lorente (1986), and Jaramillo et al. (2011), whereas the top is coeval with the top of the *Crassoretitriletes vanraadshooveni* Interval Zone *sensu* Muller et al. (1987). Our Mar-D *Crassoretitriletes vanraadshooveni* Zone is also coeval with the *Crassoretitriletes* 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 Marañon Basin continued during the Pliocene, where at least 360 ft (103 m) of the Marañon 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 Marañon Basin.

## 8. Conclusions

This study of the Neogene biostratigraphic record obtained from six industrial wells in the Marañon 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 dorogensis* 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 *Crassoretitriletes vanraadshooveni* or *Psilastephanoporites tesseropus*.
- The Mar-D *Crassoretitriletes vanraadshooveni* Assemblage Zone (Late Serravallian: 14.2–11.62 Ma) is defined by the first occurrence of *Crassoretitriletes 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 Marañon 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 Marañon 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.



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## 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>

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### Spores

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*Crassoretitriletes 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  
*Foveotrilletes 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  
*Magnastriatites grandiosus* (Kedves & Sole de Porta, 1963) Dueñas, 1980  
*Nijsensporites 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  
*Striatrilletes saccolomoides* Jaramillo, Rueda & Torres, 2011  
*Verrutrilletes virueloides* Jaramillo, Pardo, Rueda, Torres, Harrington & Mora, 2007

## Pollen grains

*Acaciapollenites myriosporites* (Cookson, 1954) Mildenhall, 1972  
*Araliaceopollenites* 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  
*Crassiectoapertites 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 jutaiensis* 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  
*Malvacipolloides (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

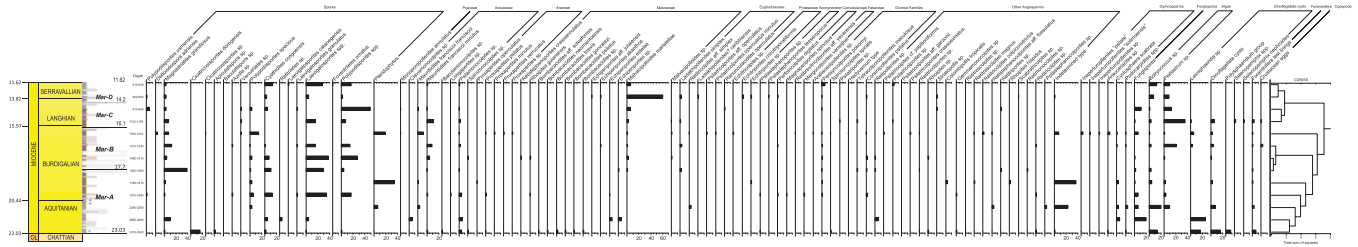
*Monocolpopollenites ovatus* Jaramillo & Dilcher, 2001  
*Monoporopollenites annulatus* (Van der Hammer, 1954) Jaramillo & Dilcher, 2001  
*Multiporopollenites pauciporatus* Jaramillo & Dilcher, 2001  
*Paleosantalaceaeapites cingulatus* Jaramillo, Rueda & Torres, 2011  
*Perfotricolpites digitatus* González-Guzmán, 1967  
*Perisyndolporites pokornyii* 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

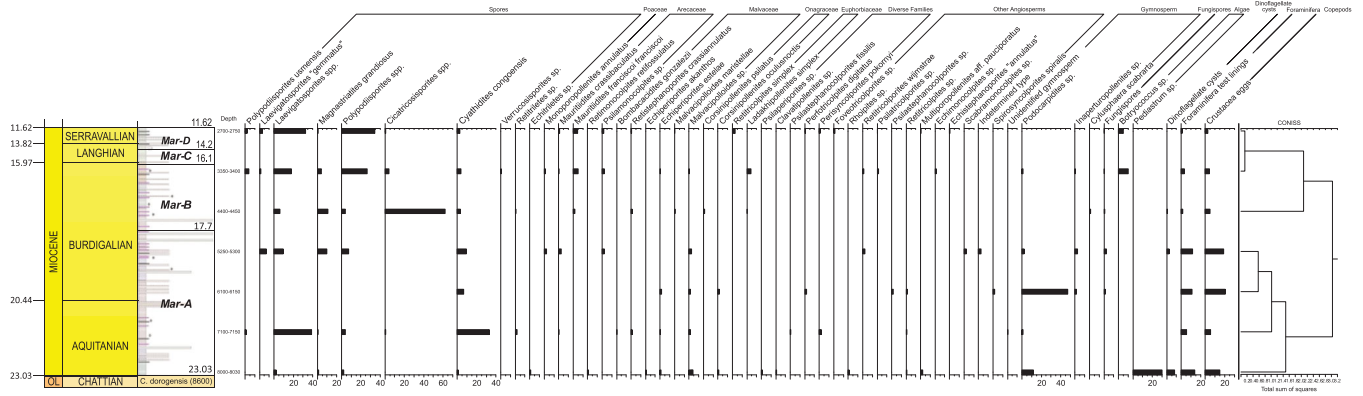
*Chomotrilletes minor* Pocock, 1970  
*Apteodinium australiense* Williams, 1978  
*Selenopemphix quanta* (Bradford, 1975) Matsuoka, 1985  
*Bosedinia infragranulata* He, 1984  
*Operculodinium* group Wall, 1967  
*Polysphaeridium* group Davey & Williams, 1966b  
*Selenopemphix nephroides* Benedek, 1972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



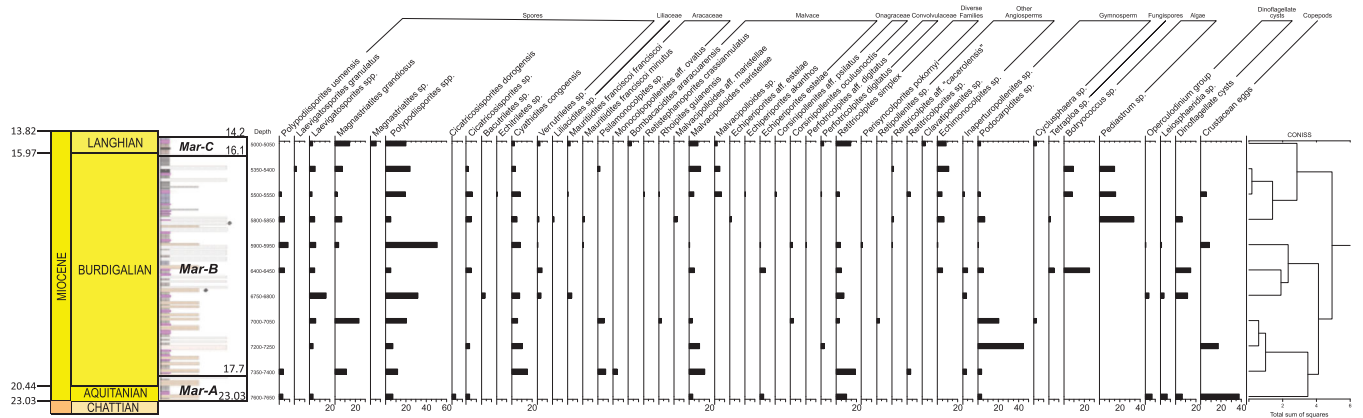
### Appendix 1. Arabela



### Appendix 2. Maynas



### Appendix 3. Tacunare



### Appendix 4. Tigrillio

