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An environmental reconstruction of the palaeo-Amazon River system (Middle–Late Miocene, NW Amazonia)

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Abstract

New sedimentological and palynological data from the Tertiary sediments in the Upper Amazon River area suggest that these sediments are fluvio-lacustrine deposits of Middle to Late Miocene age. They were generated as a result of the uplift of the Eastern Cordillera (Andes) and constitute possibly the oldest relics of the Amazon River system. The palaeoenvironment in which these sediments were deposited is characterized by extensive wetlands environments formed by swamps, shallow lakes, crevasse splay channels and crevasse-delta lakes where the channel environment is poorly represented. The palaeovegetation was dominated by palms (e.g. Mauritia and Grimsdalea), riverine taxa (e.g. Bombacaceae, Amanoa and Alchornea), ferns and fern allies (e.g. Polypodiaceae and Selaginellaceae), floating meadows (Gramineae) and aquatic taxa (Ceratopteris, Botryococcus and Azolla). The relative abundance of Gramineae and the occurrence of Andean-type pollen taxa is related to the Andean origin of the fluvial system. The varzeas of the present Upper Amazon River flood-basin are probably the best analogue for the Middle to Late Miocene environment.

Intervals rich in marine palynomorphs, mangrove pollen, brackish tolerant molluscs and ostracods, and ichnofossils of the Thalassinoides–Teichichnus association suggest that the palaeoenvironment was characterized by brackish conditions and marine influence. These marine incursions are possibly related to the Langhian and the Serravallian global sea-level rise. Although in the Middle Miocene a global cooling is known to have occurred, no indicators of a cooler climate have been observed in the Miocene palynoflora of the Upper Amazon River area.

Finally, four new sporomorph species are described belonging to the form-genera Psilatriletes, Clavainaperturites and Psilaperiporites.

1. Introduction

The first indirect reference to the Miocene origin of the Amazon River system was made by Damuth and Kumar (1975) who estimated that the initiation of the Amazon Cone occurred between the Middle to Late Miocene. Campbell (1992) suggested that the Amazon River system fully evolved as a transcontinental drainage system from Late Miocene time onwards when clastic detritus reached the Amazon Shelf covering the pre-existing carbonate platform. A first insight into the Miocene terrestrial record of NW Amazonia was provided by data from wells drilled when the coal potential of the Solimões Formation was being explored by the Companhia de Pesquisas de Recursos Minerais (CPRM) (Maia et al., 1977). Based on a study of well IAS-4a-AM it has been showed that between the Early and Middle Miocene large geographical and environmental
changes occurred in NW Amazonia. These changes were related to the genesis of the Andean river types and were caused by tectonic activity in the Eastern Cordillera (Hoorn, 1993a).

New sedimentological and palynological data of Middle to Late Miocene fluviolacustrine sediments from the Upper Amazon River area (Fig. 1) make possible a more detailed reconstruction of the history of the Amazon River system. Miocene sediments possibly represent the oldest deposits of Andean origin that are preserved in NW Amazonia and give an insight into the history of one of the world's largest river systems. Furthermore, the palynological data allow us to reconstruct the vegetation history and to compare it with the present-day vegetation of the area.

The Middle to Late Miocene sediments extend over thousands of square kilometres (Fig. 1) and will be referred to as Solimões/Pebas Formation since both names are currently used in Brazil and Peru/Colombia, respectively. The origin of these names is further explained in the section that deals with the Solimões/Pebas Formation. This paper will focus on the Colombian Amazonas Basin and the northeastern part of Peru, and the relation with the Solimões Basin (Brazil).

Many authors have written about the Tertiary sediments of Amazonia although most of the early studies were focused exclusively on mollusc taxonomy (Orton, 1867; Boettger, 1878; Steinmann, 1930; Katzer, 1903; Ruegg and Rozenzweig, 1949; De Greve, 1938; Nuttall, 1990). The first large-scale studies on the sediments of the Amazonian Tertiary were carried out in Brazil during the seventies by CPRM (Maia et al., 1977). Other detailed information was generated during explo-

![Fig. 1. Generalized map showing the distribution of the Solimões/Pebas Formation and the study area. Basins: P = Putumayo, N = Napo, M = Marañon, CA = Colombian Amazonas, BA = Brazilian Amazonas, S = Solimões, A = Acre, U = Ucayali. MD = Madre de Dios. Arches: v = Vaupes, i = Iquitos, sm = Sierra do Moa, f = Fitzcarraldo, c = Caravari, p = Purus, ma = Monte Alegro, g = Garupa (modified after Råsänen et al., 1987).]
ration studies by Petrobras and the large-scale governmental initiative Radambrasil (1977). At the same time, a multidisciplinary exploration study took place in Colombia (Proradam, 1979). However, no conclusive data were provided about the Tertiary depositional history of NW Amazonia. The present study forms part of a multidisciplinary project that was initiated in 1988 by Tropenbos-Colombia in Colombian Amazonia.

2. Geography

The study area forms part of the Amazon River drainage basin (Fig. 1). This is a highly dynamic area where tectonic perturbation of fluvial systems has taken place during Tertiary and Quaternary time, and still determines fluvial and lake patterns today (Salo et al., 1986; Räsänen et al., 1987; Dumont, 1992, 1993). An overview of the characteristics of the Amazon River system is given by Sioli (1984). The Amazon River flows eastwards, a few degrees south of the Equator and drains 7.05 x 10^6 km² from which 5 x 10^6 km² is covered by rain forest.

At present three river types are distinguished in Amazonia: the Andean ‘white’ water rivers, and the Amazonian ‘clear’ water and ‘black’ water rivers. The Andean rivers have a high pH, high suspended load and the catchment area is the Andean region. The ‘clear’ and ‘black’ water rivers have varying pH, a high bedload and drain the shield area (Sioli, 1984). Gibbs (1967) concluded that the Andean mountain environment controls the major part of the geochemistry of the Amazon River. Lundin et al. (1983) and Frasincelli and Potter (1983) suggest that in the upper Amazon the sediments are dominated by unstable minerals, reflecting a purely Andean origin. In the lower Amazon, an increased maturity and a predominance of stable mineral content was observed due to the effects of tropical weathering and the admixing of sediments eroded from the Precambrian shields in Amazonia.

In the central part of the drainage basin, the Amazon River has an anastomosing pattern with an abundance of fluvial islands (Kalliola et al., 1992). In summer large channel bars are exposed. These bars are composed of mainly pebbles and sand, but also include locally fossils, and coal blocks (e.g. Aramaça, Fig. 2). The pebbles are reworked from Pleistocene deposits, whereas the fossils and coal blocks are reworked from the Solimões/Pebas Formation.

Two main landscape units are distinguished: terra firme, land never flooded and the varzea, land permanently or temporary flooded. Igapos are the flood-basin environments of the black and clear water rivers. The varzea covers around 5 to 6 x 10^4 km² and is characterized by numerous lakes of riverine origin. Little deltas are formed within these lakes. Sediments are distributed by secondary channels of the Amazon River during stages of high discharge. Nutrients transported by this Andean river enrich the varzea environment and hypoxic conditions can result. The varzea is characterized by floating meadows, swamps and flood-basin forest. The Amazon River estuary is funnel shaped and the tidal influence reaches about 100 km inland (Sioli, 1984). No true delta has developed at the Amazon River mouth due to the Brazilian Current which drags the sediments northwards along the Atlantic coast. All these features of the present Amazon River system are important in interpreting the Miocene sediments of Amazonia since these were largely deposited by the ancestral Amazon River.

The main geologic units that dominate the landscape are the Precambrian basement, the Miocene Solimões/Pebas Formation, and fluvial terraces produced by the the river system that dissects the aforementioned units. The terrace sediments are of Plio(?)–Pleistocene age and are partly composed of sands and gravels of Andean origin (Van der Hammen et al., 1992). The Miocene unit forms a gentle, hilly landscape. The Precambrian basement forms also gentle but larger hills, and where it crops out in the river it causes rapids (e.g. near La Pedrera, Fig. 2).

The best season for studying the outcrops of the Solimões/Pebas Formation along the Upper Amazon River (Fig. 2) is between September and November. The water level is then at its lowest which is about 20 m below the highest water level. Differences between high and low water stands tend to diminish eastwards (Sioli, 1984). Along
the Caquetá River, however, best season for studying the outcrops is between January and March. At the outcrops care has to be taken with the phenomenon of the *terras caídas*. These are slices of outcrop that fall off, especially along the outer bends of the river, due to the action of the river waters and heavy rains. The outcrops of the Solimões/Peñas Formation locally have ‘salt licks’. These are places were animals of the rain forest (e.g. monkeys, tapirs, rodents) lick the sediment to obtain mineral nutrients. It has been shown that at the ‘salt licks’ the sediment is enriched in Ca, P, Mg, Na, K and Cl (Lips and Duivenvoorden, 1991).

3. Geological background

The sediments of the Solimões/Peñas Formation are part of the infill of several sedimentary basins. In Brazil the Solimões Formation is known from the Acre (foreland) Basin and the intracratonic
Solimões and Brazilian Amazonas Basins. In the latter it only appears in the most western edge of the basin. In Peru the Pebas formation occurs in the northeast of the country and in the Marañón and Madre de Dios (foreland) Basins (Guizado, 1975; Kronberg et al., 1989; W. Morales, pers. commun., 1992). Whether it occurs also in the Ucayali (foreland) Basin remains speculative. In Colombia the Pebas formation and its equivalent the La Tagua beds (Eden et al., 1982) form part of the intracratonic Colombian Amazonas Basin and the Putumayo (foreland) Basin.

The intracratonic basins are situated in and around the graben that subdivides the Amazon Craton into the Guyana Shield and the Brazilian Shield (Fig. 1). This graben is located along the Solimões megashear. The megashear divides the continent E-W from coast to coast and is of the transcurrent fault type (De Loczy, 1966; Grabert, 1983, 1991; Caputo, 1991). The intracratonic basins are subdivided and separated from the Andean foreland basins by structural highs in the basement (Fig. 1) which are the result of flexural lithospheric uplift in response to orogenic loading of the Andean belt (e.g., Iquitos Arch, Caputo, 1991). The earliest known uplift of the Andean belt occurred in the Paleocene (Van der Hammen, 1961; Kroonenberg et al., 1990; Sarmiento, 1993) and has continued since then with a climax during the Pliocene (Van der Hammen et al., 1973).

At outcrops the beds of the Solimões/Pebas Formation present gentle dips which are due to post-Miocene tectonics in the area.

4. The Solimões/Pebas Formation

The Solimões Formation was described in Brazil by Moraes Rego (1930; validated by Caputo et al., 1971) and the type locality is situated along the Solimões River. In Peru the name Pebas beds was first introduced in the 19th century. At a later stage it was named Pebas formation although a formal description is lacking. Gabb (1869), Orton (1876), Katzer (1903), Steinmann (1930), De Grève (1938), Ruegg and Rosenzweig (1949), Sanz (1974), Pardo and Zúñiga (1976), Costa (1980, 1981) and Nuttall (1990) among others, make reference to the Pebas beds or formation. The name is derived from the village Pevas situated along the Amazon River. It has been proposed that in Colombian Amazonia the names Pebas formation (Khobzi et al., 1980; Hoorn, 1990) and Mariña sand unit (Hoorn, 1994) should be used where previously Galvis et al. (1979) suggested the name “Amazonian Tertiary”.

In Brazil the estimated maximum thickness of the Solimões Formation is 980 m (Maia et al., 1977). At the base the Solimões Formation contacts the Ramón Formation. This contact is a gradual transition from a reddish clay- and sand-dominated lithology (Ramon Formation) into finer clastics with a variety of colours (Solimões Formation). The top of the Solimões Formation is overlaid unconformably by the Pleistocene Iqu Formation which consists mainly of sands and conglomerates (Maia et al., 1977). In the north the Solimões Formation onlaps on the basement and decreases in thickness from SW to NE.

Neither in Colombia nor Peru do precise data exist concerning the thickness and lower and upper contacts of the Pebas formation. However, a thickness of 200 and 600 m was suggested by Guizado (1975). The Pebas formation is overlaid by the Ipuruuro formation consisting mainly of sands and conglomerates and at the base it overlies the Chambira formation consisting of clay, sand and evaporites (Guizado, 1975).

The basal part of the Solimões Formation correlates with the Mariña sand unit, whereas the upper part correlates with the Pebas formation (Fig. 3). Here the notion Solimões/Pebas Formation is applied in each of the three countries since the sediments of all the studied outcrops belong to the Pebas formation or upper part of the Solimões Formation.

The most significant outcrops of the Solimões/Pebas Formation are situated along the Upper Amazon River (e.g. Santa Sofia, Figs. 4 and 7) although in general they do not exceed heights of 30 m. Other localities where the formation crops out are situated along the Putumayo River (e.g. Arica and Indostan, J.V. Galvis, pers. commun., 1989) and along the Caqueta River (Puerto Remanso and Puerto Caimán). A stratigraphic
Correlation between the field sections and well IAS-4a-AM and is presented in Fig. 3.

In the study area the formation is characterized by blue-, turquoise- and olive-coloured clay and silty/sandy clay with fine-grained sand, lignite and black-grey clay intercalations. Noticeable is the abundance of molluscs, plant and vertebrates remains, purple mottling and bioturbation in the sediments. Dark-red clay intraclasts indicate reworking of oxidized material. The prevailing dark colours together with the preservation of the organic matter of plant and animal origin suggest anaerobic conditions and a high water table during deposition. However, periods of exposure also existed, as evidenced by mottling and bioturbation in lignites and dark clays. No red colours were observed in the outcrops of the study area although reddish sediments are known from the lower parts of the formation (Maia et al., 1977; Hoorn, 1993a).

Calcium-carbonate concretions and locally septarian nodules form the only solid rocks among the otherwise unconsolidated sediments. The local population uses these rocks for building since it is the only type of “hard rock” that is available in the area.

As will be supported below, the sediments of the Solimões/Pebas Formation are the result of dynamic environment of shallow lakes and swamps fed and interconnected by a fluvial system of Andean origin with episodic marine influence.

4.1. Lithofacies and sedimentary environments (Figs. 6–8)

A detailed overview of the lithology, sedimentary structures, bedding types and the depositional environments of the Solimões/Pebas
Formation is given below, accompanied by illustrations of some selected sections (Figs. 6–8).

(a) Channel/bank deposits

Sand bar deposits and crevasse splay channel deposits: The sand fraction represents only 5 to 15% of the total sediment composition in all described sections. The sandy sequences consist of yellow–brown, well sorted, fine and very fine-grained sand beds of several decimetres up to several metres in thickness. These sands have a clayey matrix. Sedimentary structures such as small and normal scale cross-bedding (Guanabara, 0–5.6 m, Fig. 8; Sta. Sofia, 15.0–15.4 m, Fig. 7), climbing ripples (Sururua, 3.2–4.4 m, Fig. 8) and flaser bedding (Indiana, 9.0–10.5 m, Fig. 6) were observed. In the rose diagrams in Fig. 9 measurements of the cross-bedding structures of the Solimões/Pebas Formation (Middle–Late Miocene) are represented and show a predominantly eastward transport direction. This figure also shows a comparison with measurements made in the Mariñame sand unit (Early Miocene–early Middle Miocene) where transport directions were mainly northwestwards. It is clear that a drastic change in transport directions took place between the Early and Middle Miocene. The explanation for this is the incipient uplift of the Eastern Cordillera and a subsequent change in source area.

In Table 1 the heavy mineral suite of various sand samples is represented. The Middle to Late Miocene assemblage is dominated by unstable components such as garnet, chloritoid and epidote. These minerals are derived from rocks metamorphosed in the greenschist facies and considered to be of Andean origin (Hoorn, 1993a). This is in agreement with the results of Kronberg et al.
(1989) who suggested (based on a geochemical study), that at least part of the sediments of the Solimões Formation had an Andean origin.

The southernmost sections (Benjamin Constant, Guanabara, and Sururua, Fig. 8) show the highest sand content. The base of the Guanabara section represents a series of sand bar deposits which are possibly within the realm of the main fluvial channel. Sandy sequences interbedded with clays (Santa Sofia, Fig. 7) or beds showing climbing ripples (Sururua, Fig. 8) are likely to be related to a crevasse splay channel environment. These crevasses broke into the flood-basin during high water. Flaser bedding such as in the Indiana section suggest tidal influence although no other tidal features such as herring-bone structures and double mud drapes were found.

(b) Flood-basin deposits

*Shallow lake and crevasse-delta lake deposits:* Blue-, turquoise- and olive-coloured sandy clay and clay represent the dominant lithology of the Solimões/Pebas Formation in the study area. These clays often contain millimetre-sized, organic or coaly fragments. Pyrite, vivianite crystals and gypsum are locally found scattered throughout the sediments. The gypsum is probably related to pyrite oxidation and subsequent reaction with Ca from carbonates. During palynological analysis it was noticed that the sandy clay and clay samples are relatively rich in Andean-type pollen taxa.

Planar, interlayered, and lenticular bedding types are common. Sediments and structures have locally been disturbed by loading, bioturbation,
Fig. 6. Lithostratigraphy of the Peruvian sections.
rooting and mottling due to pedogenic processes. Small nodular, carbonate fragments (<0.5 cm in diameter) accompany some of the mottled beds. The interlayered bedding presents a rhythmic alternation of sand/clays and/or organic matter (e.g. Santa Teresa 2.5–4.9 m; Los Chorros II, 14.3–18.1 m; Figs. 6 and 7) suggesting a cyclic deposition of tidal origin. The beds alternate at millimetre or centimetre scale and usually have a regular, non-erosional base; however, at Pijuayal (Fig. 6) lenticular shaped sediment bodies have been observed. The occurrence of lenticular and wavy bedding types could well be related to tidal influence since periods of marine influence are known for the Miocene of Amazonia (Hoorn, 1993a,b). Moreover, mangrove pollen, brackish fauna (molluscs, ostracods, microforaminifera and dinoflagellate cysts) and trace fossils characteristic of the coastal realm occur in these sequences.

The sandy clay sequences with planar and lenticular bedding were deposited in shallow lakes in a flood-basin environment which received clastic fluvial input of Andean origin. These sediments were supplied to the lakes along crevasse splays. From time to time these lakes dried up and the sediments were exposed to pedogenesis. These pro-
cesses still occurs in the present varzea lakes of the Amazon River system, although the brackwater aspect is lacking.

**Backswamp deposits**: Lignite and black, brown and grey, organic-rich clay are common in almost all the sections and occur as single beds or as a lignite–clay alternation (Pijuayal 3.8–7.5 m; Santa Sofia, 18.8–21.0 m; Mocagua, 23.9–24.8 m; Figs. 6 and 7). The lignite varies between several centimetres to a maximum of 1 m in thickness, but most common are beds of 0.5 m whereas the dark-coloured, organic-rich clay reaches thicknesses of 3 m (Indiana, 3.3–6.3 m, Fig. 6). Most of the palynological samples were taken from these lithologies.

The lignite is usually composed of fine organic material with a high content of sulphur and ashes (Maia et al., 1977). However, large botanical remains were also found at Puerto Nariño and Paumari where large fossil tree trunks of several metres in length lay in the bedding plane. Leaves, stalks, seeds and vertebrate remains are also found in these beds. The lignite and the dark-coloured clay beds have regular, non-erosional bases and are sometimes laterally continuous for several hundreds of metres (e.g. Los Chorros and Pijuayal).

In the aforementioned lithologies thin lenticular, light-coloured clay bodies occur which were formed during fluvial floodings.

These deposits originated in swamp and drowned swamp environments of the flood-basin which are occasionally incised by shallow swamp channels. Biogenic fragments of local origin accumulated in these environments although during floodings part of these organic deposits were eroded and redeposited elsewhere.
Swamp channel and crevasse splay channel deposits: Lenticular sediment bodies composed of sandy, dark-coloured, organic-rich clay or lignite, accompanied by reddish clay intraclasts, coprolites and large fossil fragments, are a noticeable feature. These sediment bodies contain at some places large vertebrate remains (Los Chorros I E, 15.0–15.4 m, Fig. 5; Santa Sofia 14.5–14.8 m, Fig. 7) and/or molluscs, Mocagua (23.9–24.8 m). The thickness of these intervals varies but does not usually exceed 0.5 m. Aeppler and Reif (1971) refer to this kind of deposit as placer bone beds. The placer bone beds in the Solimões/Pebas Formation are thought to have been formed as lag deposits in a swamp and crevasse splay channel environment on the flood-basin during floods. In these channels all sorts of biogenic remains of the flood-basin accumulated, and were mixed with other sediment. A local origin is inferred from the good preservation of these remains.

(c) Diagenetic products

Concretions, nodules and concretionary layers: Carbonate concretions are often the most obvious diagenetic feature in the mudstone and contain important information about the diagenetic evolution of the surrounding mudstone (Astin and Scotchman, 1988). In the study area concretions (regular shape), nodules (irregular shape) and concretionary layers were observed in most of the sections. The concretions and nodules are single, ellipsoidal bodies that vary from a few centimetres up to $1 \times 0.5$ m in diameter. The concretionary layers, instead, have a regular or intermittent character and follow bedding planes over several tens
Table 1
Heavy mineral composition of the Solimões/Pebas Formation (per cent of transparent heavy minerals based on counting an average of 300 grains per slide, excluding the opaques)

| Location     | Samples | opaque | Turmaline | Zircon | Garnet | Rutile | Anatase | Staurolite | Diaspore | Andalusite | Chloritoid | Epidote | Aggregates | Sp. hornbl | Pl. hornbl | Muscovite | Chlorite | Mica | Apatite | Biotite |
|--------------|---------|--------|-----------|--------|--------|--------|---------|------------|----------|------------|------------|---------|-----------|-----------|------------|------------|----------|---------|--------|---------|--------|
| Pevas        | P 1     | 47     | 1         | 9       | 6       | 3       |         |            |          |            |            | 72      | 4         | 3         |            |            |          |        |        |        |
|              | P 2     | 59     | 1         | 7       | 8       | 3       |         |            |          |            |            | 64      | 15        | 3         |            |            |          |        |        |        |
| Chorros I W  | LC 1    | 5      | 1         | 1       | 2       | 6       |         |            |          |            |            | 64      | 15        | 3         |            |            |          |        |        | 9       |
|              | LC 2    | 6      | 2         | -       | 2       | 8       |         |            |          |            |            | 62      | 9         | 3         |            |            |          |        |        | 12      |
|              | LC 3    | 13     | 2         | 3       | 5       | 3       |         |            |          |            |            | 64      | 8         | 3         |            |            |          |        |        | 12      |
| Chorros I E  | LC 4    | 9      | 2         | 3       | 3       | 4       |         |            |          |            |            | 71      | 8         | 3         |            |            |          |        |        | 7       |
|              | LC 5    | 12     | 2         | 2       | 6       |         |          |            |          |            |            | 64      | 10        | 3         |            |            |          |        |        | 10      |
|              | LC 6    | 16     | 2         | 2       | 4       | 7       |         |            |          |            |            | 58      | 12        | 3         |            |            |          |        |        | 4       |
|              | LC 7    | 12     | 1         |         | 3       | 8       |         |            |          |            |            | 65      | 12        | 3         |            |            |          |        |        | 4       |
|              | LC 8    | -      | -         | -       | 3       |         |          |            |          |            |            | -       | -         | 4         |            |            |          |        |        | -       |
|              | LC 9    | 9      | 2         | 2       | 3       | 6       |         |            |          |            |            | 60      | 11        | 3         |            |            |          |        |        | 2       |
|              | LC 10   | 18     | 1         | 1       | -       | 5       |         |            |          |            |            | 66      | 8         | 3         |            |            |          |        |        | 2       |
| Macedonia    | M 1     | 10     | 4         | -       | -       | 3       |         |            |          |            |            | 84      | 5         | 3         |            |            |          |        |        | 2       |
|              | M 2     | 23     | 4         | -       | 2       | 3       |         |            |          |            |            | 82      | 6         | 3         |            |            |          |        |        | 1       |
| Sta Sofia    | SS 1    | -      | -         | -       | -       | 3       |         |            |          |            |            | 86      | 6         | 3         |            |            |          |        |        | -       |
|              | SS 2    | 6      | 1         | 4       | -       | 6       |         |            |          |            |            | 68      | 8         | 3         |            |            |          |        |        | 6       |
| B. Constant  | BC 1    | 48     | 1         | 4       | -       | 2       |         |            |          |            |            | 61      | 4         | 1         |            |            |          |        |        | 22      |
|              | BC 2    | 57     | 7         | 5       | 2       | 3       |         |            |          |            |            | 68      | 7         | 1         |            |            |          |        |        | 3       |
| Sururua      | S 1     | 6      | 2         | 2       | 8       | 3       |         |            |          |            |            | 75      | 8         | 1         |            |            |          |        |        | 1       |
|              | S 2     | 9      | 3         | 2       | 6       | 2       |         |            |          |            |            | 72      | 9         | 1         |            |            |          |        |        | 6       |
|              | S 3     | 11     | -         | 2       | 10      | 1       | 1       | 1         | 1         |            |            | 70      | 6         | 1         |            |            |          |        |        | 1       |
|              | S 4     | 41     | 4         | 3       | 1       | 2       | 3       | 2         | 1         | 1         | 3         | 71      | 5         | 1         |            |            |          |        |        | 1       |
|              | S 5     | 18     | 3         | 2       | 8       | -       | 2       | -         |          |            |            | 62      | 9         | 2         |            |            |          |        |        | 4       |
of metres. These layers occur sometimes in rhythmic alternations (Chorros I W, 12.4–14.5 m, Fig. 7) or as lateral accretion beds such as at Benjamin Constant (a, 4–6 m, Fig. 8). At some places large-sized, septarian concretions also were found (e.g. Macedonia).

In general blue-grey colours prevail and the granulometry of the concretion or nodule ranges from clay to fine-grained sandy clay. Partially dissolved shell nuclei and sedimentary structures are occasionally preserved. The preservation of sedimentary structures in the concretions and the irregular pattern of concretionary layers suggest that these are secondary, diagenetic features. These concretions were never found in lag deposits where other intraclasts of this formation have been preserved, which suggests this is not a syn-sedimentary phenomenon.

The concretions have a calcium carbonate composition whereas the nodules of orange-brown colours are sideritic. The presence of siderite-like nodules suggests that at some stages iron reduction exceeded the sulphate reduction and the available iron could not be precipitated as FeS or pyrite (Pye et al., 1990 citing Curtis and Spears, 1968). Sandy clay can occasionally be cemented without necessarily being a concretionary layer. The abundance of calcium carbonate concretions can be explained by the abundance of carbonate available in the environment. The source of calcium is provided by dissolution of the shells in an acidic environment. The large amounts of humic acids from the surrounding swamps and forest are introduced in the aquatic environment and are responsible for the low pH that causes dissolution of the calcium.

5. Palaeontology

A special section is devoted here to the abundant occurrences of fossils other than spores and pollen in the Solimões/Pebas Formation. Although they do not form the main subject of this paper, their environmental and palaeogeographical implications are relevant to the general interpretation and are therefore reviewed.

5.1. Foraminifera

A monospecific assemblage of foraminifera was observed in a thin interval at Buenos Aires. These specimens were classified as *Protoelphidium* (S.R. Troelstra, pers. commun., 1993) and are indicative of low salinity conditions such as occur in estuarine systems. In these samples some reworked Eocene specimens were also observed. During the palynological study five different types of foraminiferal organic linings (Plate III) were observed in thin (10–15 cm) intervals of the Los Chorros and Mocagua sections. These linings show a resemblance to *Trochammina* (S.R. Troelstra, pers. commun., 1993), *Ammodiscus* and *Haplophragmoides* (H. Duque, pers. commun., 1993). However, in the inorganic fraction no trace of these genera was found. This is probably due to the fact that these genera are agglutinants which disintegrate easily leaving only the organic wall. *Trochammina* and *Haplophragmoides* are typical saltmarsh species. It is thought that the intervals of microforaminifera represent tempestites (i.e. storm deposits; Seilacher, 1982) and are related to marine incursions.

5.2. Ostracods

Ostracods are very abundant in the Solimões/Pebas Formation. Studies of these ostracods were carried out by Purper (1977), Purper and Pinto (1985), and Sheppard and Bate (1980). They suggest that the ostracod fauna indicates brackish as well as freshwater conditions. During the present study samples of ostracods were collected; D. van Harten (pers. commun., 1993) observed that the ostracod fauna indicates brackish as well as freshwater conditions. During the present study samples of ostracods were collected; D. van Harten (pers. commun., 1993) observed that the taxonomic diversity of the assemblage is low and that the abundance of specimens is high suggesting rather extreme conditions. The most common genus is *Cyprideis* which is indicative of an anomalo-haline environment. However, freshwater taxa also are present.

5.3. Molluscs

Molluscs (lamellibranchs, gastropods) are the most common type of macrofossils in the Solimões/Pebas Formation. They are very well
preserved and the bivalves often have their two valves still together indicating an in situ position. In other cases the molluscs have been transported and form part of the channel deposits. The molluscs occur in varying densities in the sediment, concentrated in beds or in lenticular bodies (0.5 m thick) with erosional bases, or as patches in clay, sandy clay and lignite. At Indiana they form cross-beded layers in a black clay interval. They also can be mixed up in the sediment due to bioturbation.

An extensive compilation of the molluscs of the Pebas formation was presented by Nuttall (1990). More recently Wesselingh (1993) completed a study on the molluscs of the Los Chorros sections. He also analyzed 13C and 18O ratios of some selected genera. Four ecological assemblages were distinguished: (1) a perimarine assemblage indicative of brackish conditions (e.g., Cymia, Nassarius, Corbula and ?Chrysallida); (2) a fluvial assemblage dominated by large species, possibly tolerant to some degree of brackishness (e.g., Dyris ortoni, Tryonia minuscula scalaroides, Aylacostoma browni and Anadontites); (3) a lacustrine assemblage dominated by small species (e.g., Dyris, Toxosoma eborea, Vitrinella, Pachydon, Pachydon trigonalis, Pebasia dispar, Ostomya papyria and ?Raetoma) where true fresh water taxa such as Sphaerium are absent; and (4) a terrestrial assemblage composed of land snails (Strophocheilus and Orthalicus) and the amphibious genus Asolene. Assemblages 2 and 3 are the most common ones.

Nuttall (1990), pointed out that the presence of the genus Pachydon is a strong indication of a N to S migration of this genus, which is known to be endemic in the Neogene of NW South America. This supports the hypothesis that a marine incursion with an entrance from the Caribbean affected the study area (Hoorn, 1993a, 1994). Wesselingh (1993) additionally proposes a migration of Andean genera into the Amazon Basin and, as a possible third migration process, dispersion due to birdtrekking.

5.4. Other macrofossils

Large macrofossils of plant and animal origin are well preserved in most of the sections. At Paumari and Puerto Nariño large tree trunks occur in the bedding plane of lignite layers. Plant remains such as seeds and leaves locally form part of swamp deposits. Most remarkable are the large vertebrate remains found in the swamp, swamp channel and crevasse splay channel deposits (Fig. 5). Among the vertebrate remains are fragments of crocodile, fish, tortoise, bird, and various others. Fish remains of the Carcharinidae (blue shark), Myliobatidae (sting ray), Callionymidae (armored catfish), Chimaeridae (chimera), Sciaenidae (drums), Anastomidae, Erythrinidae, Serrasalmidae, and Characidae were identified (H. Nijsen and K. Monsch, pers. commun., 1993).

The fragmentary but well preserved character of the macrofossils suggests a short transport distance. Reworked Miocene fossils presently are accumulating on the channel bars of the Amazon River. Various studies on the vertebrate fossils of the Solimões Formation in the Acre region were presented by Frailey (1986), Bocquentin et al. (1989), Pereira and Bocquentin (1989), Bocquentin and Rodrigues (1989), and Campbell and Frailey (1991).

5.5. Ichnofossils

Two kinds of ichnofossils were observed: bioturbation by burrowing fauna and coprolites of various sizes. Most common is bioturbation of the Thalassinoidei–Teichichnus association (?? Mangano and G. Buatois, pers. commun., 1993), indicating a brackish environment with marine influence. Thalassinoidei is characterized by large, interconnected burrows (ca. 1 cm wide–15 cm long) of irregular shape which occur in organic-rich, black clay or lignite beds up to 1 m thick and are visible because of the turquoise blue clay that fills the burrows (Fig. 10). Crab fragments are present in some burrows. Mollusc beds and sedimentary structures have often been disturbed by bioturbation characterized by single, non-connected burrows. Coprolites with sizes of approximately 1 x 5 cm were found in the placer bone-beds. Less common are the clusters of small pellets of approximately 1 mm in diameter found
6. Palynology

The abundance of organic-rich lithologies in the Solimões/Pebas Formation permitted a thorough palynological analysis, allowing the age of the sediments to be established, and providing an insight into the palaeovegetation of Miocene Amazonia. The palynological results are presented in 7 pollen percentage diagrams (Figs. 11 and 12a,b) which are subdivided into 8 ecological zones (A–H) based on the occurrence of ecologically significant taxa. A total 149 taxa were determined; full names, taxonomic affinities and the ecological significance of these taxa are presented in the systematic part. Each diagram is accompanied by a cumulative diagram representing the total sporo-morph content counted per sample. These cumulative diagrams show the relation of the pollen sum with *Psilamonoles tibui* and *Verrucatosporites usensis* (rather common spores) and the indetermined Pteridophyta and Angiosperms. The sections presented here are dated using the biostratigraphical markers and zones presented in Hoorn (1993a). These pollen zones relate to the earlier defined Miocene zones in the Venezuelan basins (Lorente, 1986) with ages based on the Caribbean foraminifera zonations (Germeraad et al., 1968).

6.1. Materials and methods

In total 118 samples were processed following the standard procedure of the Hugo de Vries-Laboratory. From each sample 1 cm$^3$ of material is sieved through a 250 $\mu$m mesh. The organic-rich clays are treated with sodium pyrophosphate
Fig. 11. Pollen percentage diagrams of the Peruvian sections.
v = no samples  + = < 0.5%  * = known taxonomic affinity

Included in pollen sum (Σ 100)
Key

- V. usmensis
- P. tibui
- Indet. Pteridophyta
- Pollen sum
- Indet. Angiosperms
Fig. 12. (a) Pollen percentage diagrams of the Colombian sections.
COLOMBIA
Los Chorros I E

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Fig. 12. (b) Continued.
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$v = \text{no samples} \quad + = < 0.5\% \quad * = \text{known taxonomic affinity}$
\( v = \text{no samples} \quad + = < 0.5 \% \quad * = \text{known taxonomic affinity} \)
Key

- V. usmensis
- P. tibui
- Indet. Pteridophyta
- Pollen sum
- Indet. Angiosperms

Excluded from pollen sum
(Na₄P₂O₇·10H₂O) in a 10% solution with H₂O and lignites are oxidized with Schulze mixture (2HNO₃, 60%:KClO₃, 7%). Finally, bromoform with density 2.0 g/cm³ was used to separate the inorganic fraction. The resulting organic residue was mounted in glycerine and sealed with paraffin.

Sporomorphs were counted taking a pollen sum ranging in general between 100 and 400 specimens. Twenty four samples were barren or gave a sum lower than 100 specimens. The data were stored and processed in a spreadsheet programme (Excel 3.0™) and classified with TWINSPAN (Two-way indicator species analysis; Hill, 1979). The pollen percentage diagrams were constructed with 'Pollen diagram', created by J.J. Duivenvoorden at the Hugo de Vries-Laboratory, in combination with the drawing programme Macdraw II™. The classification program TWINSPAN was used to group ecologically similar species together. A particular ordering was chosen for each of the two main biostratigraphic zones (the Psiladiporites/Crototricolpites Zones considered as one zone). TWINSPAN classifies species as well as samples in a tabular matrix. This program is widely used in vegetation studies and can also be applied with good results to a palynological data set (Sarmiento, 1993; Hoorn, 1994). Before applying TWINSPAN, eight cut levels (0.25, 0.50, 1, 2.5, 5, 10, 20 and 30%) were introduced. In the resulting matrix, samples were grouped on similarity of composition. This matrix was used to arrange the individual curves in the diagrams, and as a base for ecological zonation.

6.2. Age (Fig. 3)

The Santa Teresa section belongs to the Psiladiporites/Crototricolpites Zone (Early Miocene early Middle Miocene) based on the presence of Proxapertites tertiaria, Crototricolpites annemariae and Retimonocolpites absyae. Species indicative of a younger age such as Crassoretirritiletes vanraadshoovenii, Grimsdalea magnaclavata and an acme of Compositae (Echitricolporites spinosus) are absent. Neither are there indications for an older age such as a Retricolporites guianensis Acme or the presence of Verrutricolporites rotundiporus and Cicatricosisporites dorongensis. However, in the biostratigraphical zonation of the Solimões Basin (Hoorn, 1993) it was shown that in the Crassoretirritiletes Zone (Middle Miocene) there is an interval where Crassoretirritiletes vanraadshoovenii is absent. It is possible that Santa Teresa belongs to this interval of the Middle Miocene zone. Additionally, the presence of biostratigraphical markers was checked in samples from La Tagua, San Vicente del Caguán (Putumayo Basin) and Indiana. Only one marker species of the Psiladiporites–Crototricolpites Assemblage Zone was found. This indicates that an age of Early Miocene to early Middle Miocene is most likely for these samples.

The Iquitos and Pevas sections belong to the Crassoretirritiletes Zone (Middle Miocene). This age is based on the presence of Crassoretirritiletes vanraadshoovenii and the absence of Grimsdalea magnaclavata and other younger pollen marker species.

The Los Chorros, Mocagua and Santa Sofia sections belong to the Grimsdalea Zone (Middle–Late Miocene) because of the presence of Grimsdalea magnaclavata and Crassoretirritiletes vanraadshoovenii. The absence of an Echitricolporites spinosus Acme and other marker species such as Anhipollenites verus and Fenestrites spinosus excludes a younger age. For samples of the Puerto Caimán section a similar age is suggested.

6.3. Description of the pollen percentage diagrams (Figs. 11 and 12a,b)

Eight ecological zones (A–H) were differentiated, and their main characteristics will be described briefly before considering the details of each individual section. Zones A–C are exclusive to the Peruvian sections and defined on the basis of the high percentages of Mauritiidites franciscoci (zone B). Monoporites annulatus, Deltoidospora adriennis and riverine taxa such as Retritricolporites irregularis and Psilatricolporites operculatus (zone A). Zone C is similar to the A and B but has large amounts of Cyperaceaepollis sp. Zones D–H are exclusive to the Colombian sections. In Zone D large percentages of Grimsdalea magnaclavata are the main characteristic. Zone E includes large percentages of Deltoidospora adriennis and
Psilatricolporites silvaticus whereas zone F is characterized by the abundance of Monoporites annulatus. Zone G was differentiated because of the abundance of marine palynomorphs and zone H because of the high percentages of Heterocolpites rotundus.

Santa Teresa section (Peru); Psiladiporites– Crototricolpites Zone (early Miocene to early Middle Miocene)

The lower part of the diagram, zone A (1.4–3.8 m), is characterized by abundances of Psilamonocolpites nanus (Palmae), Perisyncolporites pokornyi (Malpigiaceae), Psilatricolporites cf. varius, Deltoidospora adriennis (Acrostichum), Zonocostites ramonae (Rhizophora) (5%), Echiperiporites akanthos, Echitricolporites maristellae, Scabra- triportites redundans and Echitreites cf. muelleri–Bacutriletes sp. (Selaginellaceae). In the upper part of the diagram, zone B (9.7–10.4 m), there is a large peak of Mauritiidites franciscoi (Mauritia) (65%). In both zones Monoporites annulatus (Gramineae) is common, oscillating from 5 to 20%. Furthermore, low abundances were observed of Heterocolpites incomptus (Miconia?), Magnastriatites grandiosus (Ceratopteris), Retimonocolpites maximus (Palmae), Psilatricolpites operculatus (Alchornea), Psilatricolpites costatus and Echitreites cf. muelleri–Bacutriletes sp. (Selaginellaceae). In the Iquitos and Pevas sections (Peru); Crassoretitriletes Zone (Middle Miocene)

The Iquitos section belongs to zone A (1.6–3.1 m), and is characterized by peaks of Psilatricolporites operculatus (Alchornea) (50%), Deltoidospora adriennis (Acrostichum) (65%), and Monoporites annulatus (Gramineae) (25%). There are moderate peaks in the Retitricolporites porconspactus and Psilatricolporites costatus curves. More constant throughout the diagram are Mauritiidites franciscoi (Mauritia) and Retimonocolpites maximus (Palmae). Zonocostites ramonae (Rhizophora) occurs in low percentages. Andean taxa such as mentioned before are present with additionally Kayilsporites waterbolkit (Hemithela).

The Pevas section is subdivided into three ecological zones. Zone A (2.2–3.3 m) is dominated by Deltoidospora adriennis (Acrostichum) (25%), Crassoretitriletes vanraadhsovenii (Lygodium) (20%), Monoporites annulatus (Gramineae) (20%). Peaks occur in the curves of Mauritiidites franciscoi (Mauritia), Proxapertites tertiairia (Crematosperma), Retitricolporites lalongatus, Magnastriatites grandiosus (Ceratopteris), and Botryococcus sp. (70%). Zone B (3.3–7.5 m) is dominated by Mauritiidites franciscoi (Mauritia) (35%), Psilamonocolpites amazonicus (Euterpe) (10%), Retitricolporites irregularis (Amanoa) (15%), R. solimoensis (30%), R. milnei, Psilatricolporites cras- soexinatus and P. devriesii. At the top of this interval there is a little peak of Zonocostites ramonae (Rhizophora) (7%). Noticeable is the absence of Gramineae and the aquatic indicators. Zone C (11.6–19.5 m) is characterized by the presence of Mauritiidites franciscoi (Mauritia) (15–20%) and peaks in the curves of Monoporites annulatus (Gramineae) (15%), Retimonocolpites maximus (Palmae), Perisyncolporites pokornyi (Malpigiaceae), Bombacacidites bellus (Bombacaceae) and Psilatricolporites costatus. At 12.7 m there is a noticeable peak in the curve of Cyperaceaepollis sp. (Cyperaceae) (80%) followed at 13.7 m by a peak of Botryococcus sp. Other relevant species to the diagram are Heterocolpites incomptus (Miconia?), Psilatricolporites operculatus (Alchornea) and P. cf. varius. Taxa of probable Andean origin are present although not abundant.

Santa Sofia, Mocagua and Los Chorros sections (Colombia); Grimsdalea Zone (Middle–Late Miocene)

The Santa Sofia section is subdivided into three ecological zones. Zone D (3.1–10.8 m) is characterized by abundances of Grimsdalea magnaclavata (Palmae) (35%), Monoporites annulatus (Gramineae) (20%), Cyatheacidites sp. (Cyatheaeeae) (20%) and Azolla sp. (20%). Zone E (14.1–14.5 m) is a lignite layer dominated by Deltoidospora adriennis (Acrostichum) (25%), Polypodiaceisporites cf. potoniei (15%), Retimonocolpites maximus (Palmae) (12%), Heterocolpites incomptus

Iquitos and Pevas sections (Peru); Crassoretitriletes Zone (Middle Miocene)

The Iquitos section belongs to zone A (1.6–3.1 m), and is characterized by peaks of Psilatricolporites operculatus (Alchornea) (50%), Deltoidospora adriennis (Acrostichum) (65%), and Monoporites annulatus (Gramineae) (25%). There are moderate peaks in the Retitricolporites porconspactus and Psilatricolporites costatus curves. More constant throughout the diagram are Mauritiidites franciscoi (Mauritia) and Retimonocolpites maximus (Palmae). Zonocostites ramonae (Rhizophora) occurs in low percentages. Andean taxa such as mentioned before are present with additionally Kayilsporites waterbolkit (Hemithela).

The Pevas section is subdivided into three ecological zones. Zone A (2.2–3.3 m) is dominated by Deltoidospora adriennis (Acrostichum) (25%), Crassoretitriletes vanraadhsovenii (Lygodium) (20%), Monoporites annulatus (Gramineae) (20%). Peaks occur in the curves of Mauritiidites franciscoi (Mauritia), Proxapertites tertiairia (Crematosperma), Retitricolporites lalongatus, Magnastriatites grandiosus (Ceratopteris), and Botryococcus sp. (70%). Zone B (3.3–7.5 m) is dominated by Mauritiidites franciscoi (Mauritia) (35%), Psilamonocolpites amazonicus (Euterpe) (10%), Retitricolporites irregularis (Amanoa) (15%), R. solimoensis (30%), R. milnei, Psilatricolporites cras- soexinatus and P. devriesii. At the top of this interval there is a little peak of Zonocostites ramonae (Rhizophora) (7%). Noticeable is the absence of Gramineae and the aquatic indicators. Zone C (11.6–19.5 m) is characterized by the presence of Mauritiidites franciscoi (Mauritia) (15–20%) and peaks in the curves of Monoporites annulatus (Gramineae) (15%), Retimonocolpites maximus (Palmae), Perisyncolporites pokornyi (Malpigiaceae), Bombacacidites bellus (Bombacaceae) and Psilatricolporites costatus. At 12.7 m there is a noticeable peak in the curve of Cyperaceaepollis sp. (Cyperaceae) (80%) followed at 13.7 m by a peak of Botryococcus sp. Other relevant species to the diagram are Heterocolpites incomptus (Miconia?), Psilatricolporites operculatus (Alchornea) and P. cf. varius. Taxa of probable Andean origin are present although not abundant.
(Miconia) (17%) and taxa of the Sapotaceae type such as Psilatricolporites spp., Psilatricolporites transversalis and P. silvaticus (15%). This interval is followed by sandy clay (14.5–17.4 m) representing again zone D with Grimsdalea magnaclavata (Palmae) (30%) as the main species. Zone F (17.4–20.2 m) is dominated by Monoporites annulatus (Gramineae) (35%) including an interval with high percentages of Azolla sp. (15%) and peaks of Psilamonocolpites amazonicus (Euterpe) (20%). Psilatricolporites cf. varius, P. operculatus (Alchornea), Retitricolpites lorentaeae (Bombacaceae) (20%), Echitriletes rotundus, Verrucatosporites sp.-Verrutriletes varius. An interval with abundant Andean taxa (each curve around 8%) overlaps zone D and E, coinciding with a lithology of sandy clay. From the entire diagram the following taxa were observed: Magnas triattites grandiosus (Ceratopteris), Psilamonocolpites amaz onicus (Euterpe, Mauritidites francis coi (Mauritia), Psilamonocolpites spp. (Palmae) and Echitriletes cf. muel ler–Bacutril etes sp. (Selaginellaceae).

The Mocagua section is subdivided into three ecological zones. Zone F (2.3–6.1 m) shows abundant Monoporites annulatus (Gramineae) (12%), Psilatricolporites cf. varius (12%), Heterocolpites rotundus, Verrucatosporites sp.–Verrutriletes sp., Echitriletes cf. muel ler–Bacutril etes sp. (Selaginellaceae), Psilatricolporites perumus, Perinomonoletes sp.–Echinosporis sp., Pediastrum sp. and an assemblage of taxa of probable Andean origin. Zone G (6.1–7.1 m) is dominated by Grimsdalea magnaclavata (Palmae) (45%) accompanied by Mauritidites francis coi (Mauritia) (15%), Echidiporites barbiertoensis (Korthalsia). There are peaks in the marine palynomorphs (20%) curve and a minor peak in the Zonocostites ramonae (Rhizophora) (1.5%) curve. Zone D (15.1–21.1 m) is characterized by abundant Grimsdalea magnaclavata (Palmae) (10–50%) and peaks in the curves of Magnas triattites grandiosus (Ceratopteris) (20%), Psilamonocolpites amazonicus (Euterpe), P. nutus (Palmae), Psilatricolporites operculatus, (Alchornea), Retitricolpites lorentaeae (Bombacaceae) and Bombacacidites baumfalkii (Bombacaceae). In the upper part of this interval taxa of probable Andean origin prevail. The top of the section belongs to zone F (23.9–24.8 m) which is defined by abundant Monoporites annulatus (Gramineae) (25%) and Psilatricolporites cf. varius (25%). In general, all zones present prominent curves of Deltilo dospora adriennis (Acrostichum), Monoporites annulatus (Gramineae) and Azolla sp.

The two Los Chorros I sections are about 300 m apart. The symbol (≈) indicates the correlation level. The western section is subdivided into two ecological zones. Zone D (2.9–8.5 m) is characterized by fluctuating amounts of Grimsdalea magnaclavata (Palmae) (5–32%), Monoporites annulatus (Gramineae) (0–15%), Deltoidospora adriennis (Acrostichum) (2.5–30%), Mauritidites francis coi (Mauritia) (2.5–30%), Echidiporites barbiertoensis (Korthalsia) (0–30%), Retimonocolpites maximus (Palmae), Heterocolpites incomptus (Miconia?) and Retitricolporites irregularis (Amanoa). Zone F-G (8.5–15 m) is dominated by Monoporites annulatus (Gramineae) (30%), and peaks in the curves of Grimsdalea magnaclavata (Palmae), Retitricolpites cf. maledictus and Botryococcus sp. At the top of this interval there is a peak of marine palynomorphs (60%) accompanied by a small peak in the Zonocostites ramonae (Rhizophora) curve.

The eastern section is subdivided into three ecological zones. Zone G (9.7–15.4 m) overlaps with zone F–G of the western section. This zone is dominated by Grimsdalea magnaclavata (Palmae) (5–30%) and variable amounts of Monoporites annulatus (Gramineae) (2.5–60%), Deltoidospora adriennis (Acrostichum) (2.5–30%), Mauritidites francis coi (Mauritia) (15%), Echidiporites barb iertoensis (Korthalsia) and marine palynomorphs (30%). Zone E (19.4–20 m) is dominated by Deltoidospora adriennis (Acrostichum) (80%), and taxa of the Sapotaceae type such as Psilatricolporites transversalis and P. silvaticus. Zone H (20–26.6 m) is characterized by Psilamonocolpites amazonicus (Euterpe) (10%), Grimsdalea magnaclavata (Palmae) (5–15%), and fluctuating amounts of Retimonocolpites maximus (Palmae) (15%), Polyspodiaceispores cf. potonie i (Pteris), Heterocolpites rotundus (35%) and H.
verrucosus (Melastomataceae). At the base of the zone there is a moderate peak of marine palynomorphs accompanied by Zonocostites ramonae (Rhizophora). Andean taxa, and Botryococcus sp. and Azolla sp. show fluctuating values in the both diagrams.

6.4. Interpretation of the diagrams

The Miocene sections of the Upper Amazon River represent a highly dynamic flood-basin environment where swamps, drowned swamps, shallow lakes and swamp and crevasse splay channel deposits alternate with each other. The pollen percentage diagrams present an erratic pattern where a sustained succession can rarely be detected.

In general the palaeovegetation is dominated by palms. The most common palm types are Mauritia, Grimsdalea, Euterpe, Psilamonocolpites nanus, Korthalsia and Retimonocolpites maximus. However, there is an important difference between the palm composition of the Peruvian and the Colombian sections. In the Peruvian sections Mauritia is the dominant species whereas in the Colombian sections Grimsdalea (an extinct palm type) dominates. This suggests that the palm vegetation changed in character during the Middle to Late Miocene and that Grimsdalea took over the dominant role from Mauritia. Mauritia is a palm type that grows on poorly drained soils. For Grimsdalea no ecological affinity is known although it is thought to form part of the coastal backswamps (Germeraad et al., 1968). The Grimsdalea peaks are common in the lacustrine deposits. They probably formed the dominant vegetation that surrounded the shallow flood-basin lakes.

An important characteristic of all diagrams is the fluctuating percentage of Gramineae which represent floating meadows in the fluvial environment. The Gramineae can occur together with other aquatic taxa such as Ceratopteris, Azolla sp., Botryococcus sp. and Pediastrum sp. which are prolific during periods of high water stands. In the Santa Sofia section (17.4–21 m, Fig. 12a) there is an apparent succession of Acrostichum/Sapotaceae – Grimsdalea-Gramineae – Azolla-Gramineae. Peaks of the planktonic algae Botryococcus sp. represent episodic lacustrine phases.

Spores such as Verrucatosporites usmensis and Psilamonoletes tibui form a very important part of the total sporomorph content of all samples. The ecological implications of these spores remain speculative. They are possibly related to a semi-aquatic environment.

Taxa common in the mountainous Andean region such as Podocarpus, Hedyosmum, Cyatheaceae, Hemitelia and Alsophila were observed mainly in the sandy clay intervals (e.g. Santa Sofia, 14.5–18.5 m, Fig. 12a). These taxa reached Amazonia by river transport and were deposited together with the sediments in shallow lakes of the flood-basin. The Andean assemblage is occasionally accompanied by reworked Cretaceous palynomorphs.

Taxa related to riparian vegetation such as Bombacaceae, Amanoa, Alchornea and Crematosperma are abundant only in certain intervals. In the Pevas section Crematosperma and Retitricolpites lalongatus seem to be the main components of a swamp deposit (Pevas, 2.4 m; Fig. 11) which at a later stage was inundated by clastic sediments where ferns (Acrostichum and Lygodium) dominated followed by the riverine taxa Mauritia, Amanoa and Retitricolporites solimoensis (Pevas, 2.4–7.5 m; Fig. 11). In the upper part of this section there is a thin swamp interval which is dominated by local stands of Cyperaceae (Pevas, 14.8 m; Fig. 11).

Occasional low abundances of Rhizophora suggest an influence of coastal waters on the depositional environment. In the Colombian Mocagua and Los Chorros sections (Fig. 12b), marine incursions are reflected by abundant marine palynomorphs in the organic matter (microforaminifera and dinoflagellate cysts). The large amounts of Acrostichum, an indicator of coastal conditions, in combination with Rhizophora, confirm this view.

7. Miocene, Holocene and Present palynological and vegetational data compared

At present, the composition of swamp vegetation in Amazonia differs according to the water type that invades the site (Junk, 1983). Floating meadows are restricted to the Amazon River (and
other white water affluents) and do not occur along the rivers of Amazonian origin (black water). The genesis of Middle Miocene wetland deposits is related to a white, Andean river type and therefore the recent and subrecent wetland systems of the present Amazon River system might be the best analogues.

Absy (1979) presents a detailed palynological study of the Holocene Terra Nova section (Brazilian Amazonia). She concludes that the most common taxa in the Holocene section are *Alchornea*, *Symmeria*, *Myrtaceae*, *Miconia*, *Cecropia* and Graminaceae and that vegetation fluctuations are largely determined by the changes in water level. The water level also forms the basis of the swamp classification by Kalliola et al. (1992). Kalliola et al. (1992) distinguish four present-day swamp vegetation types in Peruvian Amazonia. These are (1) herbaceous swamps with permanent lakes, characterized by free floating aquatic taxa with grass mats followed by a shallow water association of *Azolla*-Graminaceae-*Ludwigia*/Cyperus, (2) shrub swamps, characterized by *Alchornea*-Annona-Palmae which surround the herbaceous vegetation, (3) palm swamps, dominated by *Mauritia*-Ficus-Virola, and (4) a combined forest swamp. They conclude that the Marañon wetlands are highly unstable and transitional in nature.

The Miocene diagrams do not show a very close resemblance to the Holocene Terra Nova section (Absy, 1979). For instance, there is no characteristic riverbank genus such as *Cecropia* in the Miocene sections. Also *Cyperaceae* and *Compositae* are relatively rare in the Miocene sediments. However, indications of a riverine environment with flood plain lakes which are eventually invaded by floating meadows exist in both Holocene and Miocene sections. Also Andean taxa such as *Podocarpus* and montane ferns are present in both sections. The ecological zones that were distinguished in the Middle to Late Miocene sections seem to relate best to the present swamp types described by Kalliola et al. (1992).

8. **Amazonia and the Miocene global climate**

Kennett (1982) presented a review of the Neogene palaeoclimatic history as inferred from palaeoceanographic studies. These studies show that the evolution of Miocene climate was strongly dependant on changes in the deepwater circulation patterns caused by plate tectonic readjustments. A global cooling in the Middle Miocene (from ca. 14 Ma onwards) resulted in a significant expansion of the East Antarctic ice sheets. The growth of these ice sheets is related to the thermal isolation of Antarctica due to the creation of the Circum-Antarctic Current in the Oligocene. Since the expansion of the East Antarctic ice sheet, global climates have not returned to the temperatures of the Early Miocene and the early part of the Middle Miocene. This cooling episode initiated a major change in the terrestrial plant assemblage over wide areas. More recently it has been suggested that the Miocene cooling trend was a relatively gradual process (Woodruff and Savin, 1991) and occurred through 2–3 glacial-interglacial cycles (Wright et al. 1992).

In Amazonia the Pleistocene climatic changes have been recorded palynologically in the form of vegetation changes from forest or woodland into open savannah (Absy and Van der Hammen, 1976; Van der Hammen, 1972; Van der Hammen et al., 1992; Van der Hammen and Absy, 1994). The change to the savannah vegetation was recognized by these authors in the form of increasing percentages of Graminaceae accompanied by taxa such as *Byrsonima*, *Didymopanax* and *Curatella*.

The Miocene sediments of NW Amazonia present no evidence for a vegetational change related to the Middle Miocene (14.8–12.6 Ma) cooling event. However, the Middle to Late Miocene polynoflora of the palaeo-Amazon River environments differs considerably from that found in the Early Miocene fluvial sediments (Hoorn, 1993a, 1994). The Early Miocene fluvial sediments have an Amazonian origin and are characterized by a rather diverse assemblage of palm and forest taxa. The Middle Miocene to Late Miocene fluvio-lacustrine sediments are dominated by palms, Graminaceae, ferns, fern allies, aquatic taxa and an assemblage of transported Andean taxa. However, no taxa of the savannah vegetation were observed. It is thought that large-scale environmental changes triggered by uplift of the Eastern Cordillera and the marine incursions played a
decisive role in the change in composition of the palaeovegetation during the Miocene. The increase of Gramineae in the Crassoreitreliates Zone represents the appearance of floating meadows in a lake and swamp environment of a white water river system and not a feature of grasslands in a drier climate.

9. Discussion

The fluvio-lacustrine deposits of the Miocene Amazon River system present a strong brackish component. This was concluded on the basis of sedimentological, palaeontological and palynological evidence. It is thought that the Miocene marine incursions that affected Amazonia were due to a transgression from the north via the present Maracaibo Lake area in Venezuela. This is supported by the occurrence of marine intervals in the Llanos Basin (NELL, 1992) and by the absence of marine sediments of Miocene age between the Purus High (Fig. 1) and the River Xingu, to the east, in Brazil (Caputo, 1984). In addition, marine deposits such as the Early Miocene Pirabas Formation (Garrafelo and de Araujo, 1990) and the partially marine Middle Miocene Barreiras Formation (Arai et al., 1988) extend no more than ±300 km inland from the Atlantic coast (?? Machado, pers. commun., 1991). It seems unlikely, therefore, that a direct connection existed between the Atlantic and NW Amazonia before the Late Miocene. Moreover, terrigenous elastic sediments of the Amazon River cover the carbonate sequences of the Atlantic shelf from Late Miocene onwards (Campbell, 1992).

Nuttall (1990) suggested that the presence of the bivalve Pachydona in NW Amazonia is an indication for this northern connection since this genus is known only in the Neogene from the Caribbean region. Additionally, the presence of the fossil fish Colossoma and Arapaima in the Miocene Honda Group (Magdalena Valley) gives further indication of a connection between Amazonia and the north (Lundberg et al., 1986; Lundberg and Chernoff, 1992). At present, Colossoma and Arapaima are exclusively known from the Amazon and Orinoco Rivers. Nuttall (1990) and Lundberg et al. (1986) suggest that this northern connection went through the Magdalena Valley prior to completion of the uplift of the Eastern Cordillera.

Sedimentological evidence in the Honda Group (Magdalena Valley) indicates a strong affect of an uplift phase of the Eastern Cordillera at the beginning of the Middle Miocene (Van der Wiel, 1991; Guerrero, 1993). Sedimentological and palaeomagnetical data from the Villavieja Formation suggest that a significant uplift pulse of the Andes occurred between 12.9 and 11.5 Ma (Guerrero, 1992). At 11.8 Ma a continuous mountain range is thought to have existed, isolating the Magdalena Valley, and a new river system originated in the Magdalena Valley (Magdalena River—Neiva Formation) at 10.13±0.18 Ma with an E to W transport direction (Guerrero, 1993). The genesis of the Amazon River system seems related to the same tectonic event. This is supported by the sediment composition and palaeocurrent directions of Middle to Late Miocene sediments in Amazonia described above, which suggest an Andean origin and an eastward transport direction.

10. Conclusions

The Middle to Late Miocene sediments of NW Amazonia are the first deposits of the incipient Amazon River system. This river system originated as a result of uplift of the Eastern Cordillera and bears a strong resemblance to the present Upper Amazon River system. Initially, during Middle Miocene time, no connection existed between the palaeo-Amazon and the Atlantic. However, from the beginning of the Late Miocene, elastic deposits from the Amazon River in the Atlantic proves the existence of such a connection.

In NW Amazonia the Middle to Late Miocene environment was dominated by a fluvio-lacustrine, moderately anastomosing system with eastward transport directions. Sedimentological, palynological and palaeontological characteristics suggests brackish conditions that point towards an estuarine character for the system.

Transport directions, heavy mineral composition and pollen taxa of probable Andean origin are the most important evidence for the Andean provenance of this fluvio-lacustrine system which
is dominated by suspended load transport. Sedimentary environments of the wetlands such as shallow lakes, crevasse splay channels, crevasse-delta lakes and backswamps were common, but there is no evidence of a true fluvial channel. The paleo-vegetation was characterized by floating meadows in shallow lakes which were fringed by palm swamps, ferns, fern allies and riverine forest. The Miocene lake/swamp environment is comparable to the present varzeas of the Amazon River flood-basin.

There is a pronounced difference in pollen composition between the Early Miocene and the Middle Miocene sediments. In the Early Miocene the vegetation was dominated by palm swamps and riverine forest (Hoorn, 1994). In the Middle to Late Miocene deposits Gramineae, ferns, fern allies, and Andean taxa (Podocarpus, Hedyosmum, Hemitelia, Alsophila, and Cyatheaceae) occur frequently. It is thought that this change in pollen composition reflects a major environmental change related to the genesis of the Amazon River and subsequent invasion of this river into Amazonia.

Although a global climatic cooling began in the Middle Miocene (Kennett, 1982), no evidence of savannah development was detected in the Middle to Late Miocene of Amazonia as is known from the cooler periods in the Quaternary (Absy, 1979; Van der Hammen, 1972; Van der Hammen and Absy, 1994). Throughout the Miocene, marine influxes occurred in NW Amazonia (Hoorn, 1993a,b, 1994). The Solimões/Pebas Formation contains molluscs (lamellibranchs, gastropods), ostracods, trace fossils (Thalassinoides–Teichichnus association), marine palynomorphs, mangrove pollen, and sedimentological indications of tidal influence (e.g., flaser bedding, interlayered bedding) which all point to a brackish environment and marine influence. However, the overall continental character of the deposits and the lack of unambiguous tidal and coastal features exclude a shallow marine environment and suggest solely episodic marine influence. The episodes of marine influence are possibly linked with the Langhian and Serravallian global sea-level rise and are thought to have a Caribbean origin (Hoorn, 1993a, 1994).

Relatively rapid subsidence and possibly also an increasing base level due to global sea-level rise were the main parameters that determined sediment aggradation in NW Amazonia. In general the sediment input did not hold pace with the subsidence rates and therefore drowning and the formation of extensive wetlands occurred.

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Appendix: Species list

All species and genera from the pollen diagram are listed, and accompanied by references. Additionally, taxonomic
affinity and ecology are presented. Suprageneric categories are after Iversen and Troels-Smith (1950), Potonié (1956) and Germeraad et al. (1968). When possible, taxonomic affinities are suggested based on Germeraad et al. (1968), Lorente (1986), Dueñas (1980) and Hoorn (1993a). The ecological significance of some of the present related species is based on the previously mentioned authors and, on Lindeman (1953), Van der Hammen (1963), Van Roosmalen (1985) and Graham (1988). The list includes 4 new sporomorphs formally described in the Systematics section. Three plates illustrate the holotypes of the new species and other specimens.

### Pollenites

**Clavainaperturites microclavatus nov. sp., Plate I, 9**


**Cyperaceaepollis** sp. Krutzsch 1970


**Grimsdalea magnaclavata** Germeraad et al. 1968, Plate I, 3

Taxonomic affinity: unknown, possibly an extinct palm type of the coastal vegetation.

**Ephedripites** sp. Bolkhovitina 1953

**Ephedripites renzonii** Dueñas 1986

Taxonomic affinity: Araceae, *Spathiphyllum*.

**Monocolpatae**

**Clavamonocolpites** sp. González Guzmán 1967?, Plate I, 11


**Mauritiidites franciscoi** (Van der Hammen 1956a) Van Hoeken-Klinkenberg 1964


**Proxapertites tertiaria** Van der Hammen et Garcia de Muits 1965

Taxonomic affinity: Annonaceae, *Crematosperma*. Ecology: the Annonaceae are known from the floodplains of the present day Caqueta River.

**Psilamonocolpites** spp. Van der Hammen et Garcia de Muits 1965, Plate I, 1

Remark: pollen grains of this form-genus that were not identified at species level form part of this group. Taxonomic affinity: Palmae

**Psilamonocolpites amazonicus** Hoorn 1993a

Taxonomic affinity: Palmae, *Euterpe*

**Psilamonocolpites namus** Hoorn 1993a

Taxonomic affinity: Palmae

**Psilamonocolpites rinconii** Dueñas 1986

Taxonomic affinity: Palmae

**Reitimonalpites absyae** Hoorn 1993a

Taxonomic affinity: Myristicaceae, *Virola*. Ecology: very common in marsh forests but also known from the rain forests.

**Retimonocolpites longicolpatus** Lorente 1986

Taxonomic affinity: Palmae

**Retimonocolpites maximus** Hoorn 1993a

Taxonomic affinity: Palmae

**Retimonocolpites retifossulatus** Lorente 1986

Taxonomic affinity: Palmae

**Trichotomosulcites** sp. Couper 1953

Remark: pollen grains of this form-genus with a taxonomic affinity to *Bactris* (Palmae) are here included. Ecology: *Bactris* is common in the lowlands.

### Monoporatae

**Monoporites unnulatus** Van der Hammen 1954

Taxonomic affinity: Gramineae. Ecology: forms part of open vegetation in a range of environments from humid to dry.
Some members of this family act as pioneer vegetation in open water habitats (floating meadows) and on mud and sand flats.

**Diporatae**

*Psiladiporites minus* Van der Hammen et Wijmstra 1964

Taxonomic affinity: Moraceae, Ficus–Artocarpus–Xorocarpus

Remarks: although the form-genus was formally named *Psiladiporites* (Varma et Rawat, 1963), at a later stage it was also referred to as *Psilodiporites* (Van der Hammen et Wijmstra 1964; González Guzmán 1967). Since also a pollen zone was designated as *Psilodiporites* (Germeraad et al. 1968; Muller et al. 1987; Lorente, 1986), for discussion purposes, preference was given here to the latter in order to avoid confusion.

**Psiladiporites**

Taxonomic affinity: Moraceae

Echidiporites *barbeitoensis* Muller et al. 1987, Plate I, 2

Taxonomic affinity: Patmae, *Korthalsia jerox*.

**Dicolporatae**

*Multimarginites* vanderhammenii Germeraad et al. 1968, Plate I, 8

Remark: an orthographical correction has been introduced. In the original publication the species name was written as *M. vanderhammeni*. Taxonomic affinity: Anacardiaceae, *Trichantera gigantea* or *Bravaisia integerrima*. Ecology: *Bravaisia* grows in tropical forests.

**Tricolpatae**

*Bacutricolpites* spp. Van der Hammen 1956a

Remarks: pollen grains corresponding to *Bacutricolpites* were not identified at species level. The name is in invalid and is used here in an informal way since no well preserved pollen grains were available for validation.

*Crototricolpites* annemariae Leidelmeyer 1966

Taxonomic affinity: Euphorbiaceae, *Croton*

*Perforoticolpites digitatus* González Guzmán 1967

Taxonomic affinity: Convolvulaceae, *Merremia*

*Psilatricolpites acerbus* González Guzmán 1967

*Psilatricolpites mcnicoides* Hoorn 1994

*Psilatricolpites minutus* González Guzmán 1967

*Psilatricolpites simplex* González Guzmán 1967

*Retitricolpites antonii* González Guzmán 1967

*Retitricolpites caquetanus* Hoorn 1994

Taxonomic affinity: Bombacaceae–Tiliaceae?

*Retitricolpites depressus* Wijmstra 1971

*Retitricolpites lalongatus* Wijmstra 1971

*Retitricolpites lewistii* Wijmstra 1971

*Retitricolpites lorenteae* Hoorn 1993a

Taxonomic affinity: Bombacaceae

*Retitricolpites cf. maledictus* González Guzmán 1967

*Retitricolpites cf. maturus* González Guzmán 1967

*Retitricolpites simplex* González Guzmán 1967

Remarks: this species was originally described as tricolpate.

Lorente 1986, observed that this species also can appear as tricolporate. Taxonomic affinity: Anacardiaceae?

*Retibrevitricolpites catatumbus* González Guzmán 1967

*Retibrevitricolpites yavarenensis* Hoorn 1993a

*Striatricolpites catatumbus* González Guzmán 1967

Remarks: in the species are included some specimens which present oval pori. Dueñas 1980 distinguished these pollen grains as *Striatricolporites melena*. However, following the example of Lorente (1986) and Germeraad et al. (1968), here these specimens are included in *Striatricolpites catatumbus*. Taxonomic affinity: Leguminosae, Caesalpinioideae, *Crudiante–Macrolobium–Isoberlinia*. Ecology: Caesalpinioideae are common in the lowlands. *Macrolobium* occurs on the riverbanks at poorly drained sites.

**Triporatae**

*Cricotriporites guianensis* Leidelmeyer 1966

*Corsinipollenites oculusnooticiti* (Thiergart 1940) Nakoman 1965


*Proteacidites* spp. Cookson 1950 ex Couper 1953

Remark: pollen grains of this form-genus that were not identified at species level form part of this group.

*Proteacidites* cf. *triangulatus* Lorente 1986

Taxonomic affinity: Sapindaceae–Proteaceae

*Psilatricolpites sarmientoi* Hoorn 1993a

*Retitriporites* sp. 1 (Van der Hammen 1956a) Ramanujam 1966

Remark: pollen grains with a taxonomic affinity to *Duroia* (Rubiacae) are here included.

*Retitriporites dubiosus* González Guzmán 1967

Remark: this pollen type varies from having 3 to 4 pores.

*Scabratriporites redundans* González Guzmán 1967

**Tricolpatae**

*Bombaccidites* spp. Couper 1960

Remark: pollen grains of this form-genus that were not identified at species level form part of this group. Taxonomic affinity: Bombacaceae. Ecology: trees and large shrubs of the tropical lowlands which grow on the river banks.

*Bombaccidites baccatus* Muller et al. 1987


*Bombaccidites baculatus* Muller et al. 1987


*Bombaccidites baumfalki* Lorente 1986 O.C.

Remark: an orthographical correction has been introduced. Originally the name was published as *B. baumfalki*. Taxonomic affinity: Bombacaceae.

*Bombaccidites bellus* Frederiksen 1983

Taxonomic affinity: Bombacaceae, *Bombax*.

*Bombaccidites muinaneorum* Hoorn 1993a


*Crassecoapertites columbiaenas* Dueñas 1980

Remarks: this pollen grain presents sometimes 4 apertures
instead of l. Taxonomic affinity: Leguminosae, Papilionoideae.
Carnavalia europaea—Dioecia virgata
Echitricolporites maritellae Muller et al. 1987
Taxonomic affinity: Bombacaceae—Malvaceae
Echitricolporites spinosus Van der Hammen 1956a ex Germeraad et al. 1968, Plate I, 5
Taxonomic affinity: Compositae.
Echitricolporites sp. Thiergart 1937 ex Potonié 1960
Margarocolporites vanwijheii Germeraad et al. 1968
Taxonomic affinity: Leguminosae, Caesalpinioideae.
Carnavalia europaea—Dioecia virgata
Psilatricolporites triangularis Van der Hammen et Wijmstra 1964
Remark: species which show a taxonomic affinity with Sapotaceae, are included in this form-genus.
Psilatricolporites atalayensis Hoorn 1993a
Psilatricolporites costatus Dueñas 1980
Psilatricolporites crussoexinatus Hoorn 1993a
Psilatricolporites cyamus Van der Hammen et Wijmstra 1964
Psilatricolporites devriesii Lorentz 1986 O.C.
Remark: an orthographic correction has been introduced. The name was originally published as P. devriesii. Taxonomic affinity: Humiriaceae, Humrta.
Psilatricolporites divisus Regali et al. 1974
Taxonomic affinity: Sapotaceae
Psilatricolporites exiguus Hoorn 1993a
Psilatricolporites garzonii Hoorn 1993a
Psilatricolporites labiatus Hoorn 1993a
Taxonomic affinity: Sapotaceae, Pouteria. Ecology: rain forest and along creeks and rivers.
Psilatricolporites magniporatus Hoorn 1993a
Taxonomic affinity: Leguminosae?
Psilatricolporites normalis González Guzmán 1967
Psilatricolporites obesus Hoorn 1993a
Taxonomic affinity: Sapotaceae
Psilatricolporites operculatus Van der Hammen et Wijmstra 1964
Taxonomic affinity: Euphorbiaceae, Alchornea. Ecology: rain forests, premontane and montane forests. In the Cagüe River area this genus is known to be tolerant to inundation and to grow on the river banks
Psilatricolporites cf. operculatus Van der Hammen et Wijmstra 1964
Psilatricolporites silvaticus Hoorn 1993a
Taxonomic affinity: Burseraceae—Sapotaceae
Psilatricolporites transversalis Dueñas 1980
Taxonomic affinity: Sapotaceae
Psilatricolporites triangularis Dueñas 1980
Psilatricolporites cf. varius Dueñas 1981
Psilatricolporites venezuelanus Lorentz 1986
Retitricolporites sp. 1 Van der Hammen 1956a ex Van der Hammen 1964
Remark: pollen grains of this form-genus with a taxonomic affinity to Avicennia (Verbenaceae) are here included. Ecology: this species is tolerant to brackish water and common along the coast in the mangrove forest.
Retitricolporites sp. 2 Van der Hammen 1956a ex Van der Hammen et Wijmstra 1964
Remark: Pollen grains of this form-genus with a taxonomic affinity to Rubiaceae are here included.
Retitricolporites caputoi Hoorn 1993a
Retitricolporites crassicostatus Van der Hammen et Wijmstra 1964
Taxonomic affinity: Rubiaceae
Retitricolporites crassopolaris Hoorn 1994
Retitricolporites ellipticus Van Hoeken-Klinkenberg 1966
Retitricolporites guianensis Van der Hammen et Wijmstra 1964
Taxonomic affinity: Stereuliaceae—Tiliaceae. Ecology: dry and moist forest, premontane and lower montane forests
Retitricolporites hispidus Van der Hammen et Wijmstra 1964
Retitricolporites irregularis Van der Hammen et Wijmstra 1964
Retitricolporites kaarsii Hoorn 1993a
Taxonomic affinity: Euphorbiaceae, Dalechampia
Retitricolporites leticianus Hoorn 1993a
Retitricolporites medius González Guzmán 1967
Retitricolporites milnei Hoorn 1993a
Retitricolporites obtusus Hoorn 1994
Retitricolporites poriconspicuus Hoorn 1994
Taxonomic affinity: Leguminosae
Retitricolporites pygmaeus Hoorn 1994
Retitricolporites solimoensis Hoorn 1993a
Retitricolporites tunicorum Hoorn 1993a
Ruguricolporites arcus Hoorn 1993a
Taxonomic affinity: Chrysobalanaceae, Licania
Syncolporites cf. incomitus Van Hoeken-Klinkenberg 1964
Taxonomic affinity: Loranthaceae?
Syncolporites sp. Van der Hammen 1954
Syncolporites poriconspicuus Van Hoeken-Klinkenberg 1966
Taxonomic affinity: Myrtaceae
Zonocostites ramonae Germeraad et al. 1968
Taxonomic affinity: Rhizophoraceae, Rhizophora. Ecology: grows on muddy soils forming part of the coastal tropical vegetation because of its tolerance to marine and brackish water
Zonocostites duquei Dueñas 1980 O.C.
Remarks: this species was first published with the name Z. duquei (1981). Taxonomic affinity: Rhizophoraceae, Rhizophora. Ecology: grows on muddy soils forming part of the coastal tropical vegetation because of its tolerance to marine and brackish water
Syncolpatae
Spirosyncolpites spiralis González Guzmán 1967
Stephanocolpatae
Psilastephanocolpites marginatus Wijmstra 1971
Stephanocolpites sp. Van der Hammen 1954 ex Potonie 1960, Plate I, 4
Taxonomic affinity: Passifloraceae?
 Stephanoceplolites evansii Muller et al. 1987

Stephanoporatae

Retistephanoporites crassiannulatus Lorente 1986
Taxonomic affinity: Boubacacaeae, Quararileae. Ecology: rain and marsh forests, along rivers and creeks.
Psilastephanoporites henchreui Hoorn 1993a
Taxonomic affinity: Apocynaceae

Stephanocolporatae

Jandufouria saemrogiformis Germeraad et al. 1968
Psilastephanocolporites fissions Leidelmeyer 1966
Taxonomic affinity: Polygalaecae
Psilastephanocolporites marinensis Hoorn 1994
Taxonomic affinity: Sapotaceae
Psilastephanocolporites schneideri Hoorn 1993a
Taxonomic affinity: Rhizophoraceae?

Pericolporatae

Echiperiporites spp. Van der Hammen et Wijmstra 1964 Plate I, 10 and 12
Remarks: two species which show a taxonomic affinity with Malvaceae are grouped in this form-genus. One of these species probably represents Hibiscus (Plate I, 12), the other one is a unknown Malvaceae.
Echiperiporites akanthos Van der Hammen et Wijmstra 1964
Echiperiporites estelae Germeraad et al. 1968
Psilaperiporites minimus Regali et al. 1974
Taxonomic affinity: Amaranthaceae–Chenopodiaceae
Psilaperiporites multiporatus nov sp. Plate I, ?

Heterocolpatae

Heterocolpites incomptus Van der Hammen 1956a ex Hoorn 1993a
Taxonomic affinity: Melastomataceae, Miconia. Ecology: grows in a large range of environments. In Amazonas Miconia is an important element of the understory in the Mauritia swamps.
Heterocolpites rotundus Hoorn 1993a
Taxonomic affinity: Combretaceae–Melastomataceae
Heterocolpites verrucosus Hoorn 1993a
Taxonomic affinity: Melastomataceae

Polyadeae

Polyadopollenites spp. Pflug et Thomson 1953, Plate I, 6
Taxonomic affinity: Leguminosae, Mimosoideae (Inga?). Ecology: in dry lands from sea level up to 1500 m. Inga is common today along fresh water creeks in the Lower Magdalena Valley.

Vesiculatae

Podocarpidites sp. Cookson 1947 ex Couper 1953
Remark: pollen grains of this form-genus that were not identified at species level form part of this group. Taxonomic affinity: Podocarpaceae, Podocarpus. Ecology: common of the montane forest. Locally Podocarpus is also found in lowland tropical vegetation (e.g., Iquitos and Araracuara).
Sporites

Triletes

*Bacutritites* sp. Van der Hammen 1956a ex Potonie 1956, Plate II, 4

Taxonomic affinity: Selaginellaceae

*Crasoretitritites vanraadshooveni* Germeraad et al. 1968, Plate II, 11

Remarks: this species was first published with the name *Crasoretitritites vanraadshooveni*. An orthographical correction has been introduced. Taxonomic affinity: Schizaceae, *Lygodium microphyllum*. Ecology: a climbing fern, common of the humid marshes and swamps forests of West Africa and Indo-Malaysia. This species is also related to the coastal swamps (Germeraad et al. 1968). At present absent from South America.

*Cyatheacidites* sp. Cookson 1947 ex Potonie 1956


*Deltoidospora adriennis* (Potonie et Gelletich 1933) Frederiksen 1983

Taxonomic affinity: *Polypodiaceae*, *Acrostichum aureum*. Ecology: halophytic fern associated with the mangrove vegetation. This species is here used as environmental indicator in association with *Zonocostites*.

*Echitriletes* cf. *muelleri* Regali et al. 1974

Taxonomic affinity: *Selaginellaceae*?

*Eveotriletes ornatus* Regali et al. 1974, Plate II, 8

Taxonomic affinity: *Lycopodiaceae*.

*Kuylisporites waterbolkii* Ponio 1956 O.C., Plate II, 6

Remark: this species was first published with the name *Kuylisporites waterbolki*. An orthographical correction has been introduced. Taxonomic affinity: *Cyatheaceae*, *Cyathea horrida* type. Ecology: montane forest.

*Magnastriatites grandiosus* (Kedves et Sole de Porta 1963) Dueñas 1980


*Matonisporites mulleri* Playford 1982, Plate II, 2

Taxonomic affinity: *Polypodiaceae* or *Dicksoniaceae*, also resemblance to *Cyatheaceae*, *Hemitelia*.

*Psilamonoletes tibui* Van der Hammen 1956a

Taxonomic affinity: *Polypodiaceae*.

Other palynomorphs

Marine palynomorphs

Dinoflagellate cysts (Plate III, 7) and 5 types of foraminiferal organic linings (Plate III, 1–5).

Aquatic taxa

*Botryococcus* sp. (Chlorophyta). Ecology: a lacustrine planktonic alga tolerant to salt.

*Pediastrum* sp. (Chlorophyta) (Plate III, 8). Ecology: a planktonic alga of fresh, stagnant water and tolerant to a degree of brackishness.

*Azolla* sp. (Salviniaceae, Pteridophyta), a fern common in stagnant, eutrophic or oligohaline water.

Fungi

*Tetraploa* cf. *aristata* (Plate III, 4), a saprophytic fungus very common on grasses and usually found on leaf bases and stems just above the soil.

Systematic part

The new species recognized in the studied samples are placed within the form-genera *Clavainaperturites*, *Psilaperiporites* and *Psilatriletes* and described according to the norms of the International Code of Botanical Nomenclature (ICBN). For each species, structure, sculpture, shape, size, variability of size (measured on 5 different grains) was described. The accompanying plates illustrate all holotypes and others characteristic pollen grains. The holotypes are stored at the Hugo de Vries-Laboratory of the University of Amsterdam. The following information is given for each holotype: sample location (Mocagua etc.) followed by the sample number; the residue
1000 ×
1. 2, 3 and 5. Microforaminifera (500 ×).
7. Dinoflagellate cyst.
8. *Pediastrum* sp. (500 ×).
number at the Hugo de Vries-Laboratory and the location of the pollen grains on the slides. Coordinates were measured with Leitz microscope PO 6 in the Hugo de Vries-Laboratory. The following abbreviations have been used in the descriptions: Lg, + longitude; Lt, + transverse longitude; ex-M, + thickness of the exine.

*Clavainaperturites* Van der Hammen et Wijmstra 1964

*Clavainaperturites microclavatus* nov. sp., Plate I, 9
Derivatio nominis: the name is derived from the very small size of the clava.
Holotype: Mocagua-7 HdV18210, Colombia. Location in slide: 104.9/57.8. Plate I, 9
Diagnosis: Inaperturate, microclavate pollen grain. Medium sized with subspheroideal shape. Apolar, asymmetric. Tectum perforate. Clavae thin and very small (1–1.5 µm).
Dimensions: Lt, + = 23 µm; ex-M, + = 1 µm
Variability in size: Lt, + = 22–26 µm; ex-M, + = 1–1.5 µm
Remark: this species differs from the type-species, *Clavainaperturites clavatus* Van der Hammen et Wijmstra 1964, because of its subspheroideal shape and the smaller size of the clavae.

Form-genus *Psilaperiporites* Regali et al. 1974

*Psilaperiporites multiporatus* nov sp. Plate I, 7
Derivatio nominis: the name is derived from the large amount of pores.
Holotype: Santa Sofia-23HdV 18183, Colombia. Location in slide: 96.3/51. Plate I, 7
Diagnosis: Periporate, psilate pollen grain. Apolar, asymmetric. Medium sized with subspheroideal shape. The diameter of the pores ranges between 2 and 4 µm. An annulus of 2–3 µm thick surrounds these pores. The amount of pores ranges from 9 to 16.
Dimensions: Lt, + = 33 µm; ex-M, + = 1 µm
Variability in size: Lt, + = 32–36 µm; ex-M, + = 1–1.5 µm
Taxonomic affinity: unknown.
Remarks: this species differs from the type-species, *Psilaperiporites robustus* Regali et al. 1974, because of the smaller size and amount of pores.

Form-genus *Psilatriletes* Van der Hammen 1956a

*Psilatriletes lobatus* nov. sp. Plate II, 5
Derivatio nominis: the name is derived from lobed sclerine.
Holotype: Mocagua-58 HdV18222, Colombia. Location in slide: 60.7/105.1. Plate II, 5
Diagnosis: Trilete, psilate spore. Radially symmetrical. The sclerine forms at the equator, interradial, lobe-shaped thickenings. The laesura is thin lined and almost reaches the equator.
Dimensions: Lt, + = 33 µm; scl-M, + = 5.5 µm
Variability in size: Lt, + = 27–35 µm; scl-M, + = 4.5–7.5 µm
Taxonomic affinity: unknown.

Remark: this species differs from the type-species, *Psilatriletes guaduensis* Van der Hammen 1956b, because of the thickness of the sclerine and lobe-shaped thickenings at the equator. This species is named as type 290 by Hooghiemstra (1984).

*Psilatriletes peruanus* nov. sp. Plate II, 10
Derivatio nominis: name after the country Peru.
Holotype: Santa Sofia 26-HdV18184, Colombia. Location in slide: 101.5/62. Plate II, 10
Diagnosis: Trilete, psilate spore. Radially symmetrical. Sclerine thickened at the equator. The laesura is bordered by thick ridges (2 µm) and reaches the equator forming there little protrusions.
Dimensions: Lt, + = 45 µm; scl-M, + = 5.5 µm
Variability in size: Lt, + = 39–45 µm; scl-M, + = 4.5–7.5 µm
Taxonomic affinity: *Jamesonia* or *Pteris rangiferina*?
Remarks: this species differs from the type-species, *Psilatriletes guaduensis* Van der Hammen 1956b, because of the thickness of the sclerine and the protrusions at the laesura.

References


