Pleistocene and Holocene environmental changes in the Brazilian Amazon region

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Barbara Hermanowski

aus Bochum

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Betreuungsausschuss

Prof. Dr. Hermann Behling, Abteilung Palynologie und Klimadynamik, Fakultät für Biologie und Psychologie, Georg-August Universität Göttingen

PD Dr. Michael Kessler, Institut für Systematische Botanik, Universität Zürich

Mitglieder der Prüfungskommission

Referent: Prof. Dr. Hermann Behling, Abteilung Palynologie und Klimadynamik, Fakultät für Biologie und Psychologie Georg-August Universität Göttingen

Koreferent: PD Dr. Michael Kessler, Institut für Systematische Botanik, Universität Zürich

Weitere Mitglieder der Prüfungskommission

Prof. Dr. Markus Hauck, Abteilung Pflanzenökologie und Ökosystemforschung, Fakultät für Biologie und Psychologie, Georg-August Universität Göttingen

Prof. Dr. Holger Kreft, Free Floater Nachwuchsgruppe – Biodiversität, Makroökologie und Biogeographie, Fakultät für Forstwissenschaften und Waldökologie, Georg-August-Universität Göttingen

Prof. Dr. Hanns Ruppert, Abteilung Sedimentologie und Umweltgeologie, Geowissenschaftliches Zentrum, Georg-August Universität Göttingen

PD. Dr. Alexander Schmidt, Evolution der Landpflanzen & Entwicklung der terrestrischen Ökosysteme, Courant Research Center „Geobiology“, Georg-August-Universität Göttingen

Tag der mündlichen Prüfung:

Für meine Eltern

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Summary

The biodiverse Amazon rainforest biome is the world's largest rainforest ecosystem and plays an essential role for global climate, carbon budget, and the hydrological cycle. In the light of future climate change the effects of rising temperatures and changing precipitation on Amazonian biodiversity is a major point of interest. In addition to climate change forest fragmentation is one of the biggest threats the Amazonian rainforest has to suffer, besides the growing pressure of human land use. In which way future global warming would induce species extinctions and ecosystem turnovers is therefore an important issue for future conservation strategies, which are based on a profound knowledge of species responses to predicted changes. Palaeoecological studies are an essential tool at this point, as they provide insights into connections between past climatic changes and the ecological response over long time scales. As long-term data for evironmental history of Amazonia are still rare, this study contributes to a deeper knowledge of Amazonian vegetation and fire history. For this purpose it comprises a time frame of around 70,000 years which includes the late Pleistocene, the Last Glacial Maximum (LGM), and the complete Holocene. The focus of this study lies on boundary areas in the south of the Amazon basin as these regions are particularly sensitive to climate change. Two investigated records from southeast Amazonia, situated in the Serra Sul dos Carajás in the state of Pará (Brazil) show that the ecosystems mainly depend on the general amount of precipitation during the late Pleistocene and to the characteristics of rainfall seasonality since the beginning of the Holocene. In adaption to ecological and climatological changes vegetation systems in Carajás mainly reacted with a changing species composition. Hence, under drier climates a formerly humid rainforest changed into a more open forest adapted to drier conditions, and also savannas expanded in the studied area, though never replaced forest completely. The amount and timing of precipitation, and hence ecosystems in southeast Amazonia, show a tight connection with temperature fluctuations in the tropical Atlantic. Results from a lacustrine record of Lago Amapá in southwest Amazonian Rio Branco (Acre, Brazil) show that the recorded opening of forests in the past 650 years occurred under mainly humid conditions and was strongly influenced by humans of pre- and post-Columbian settlements.

Zusammenfassung

Das artenreiche Regenwaldbiom des Amazonasgebietes ist das größte zusammenhängende Regenwaldgebiet der Erde. Es spielt eine essentielle Rolle im globalen Klima, dem Kohlenstoffhaushalt und Wasserstoffkreislaufs der Erde. Angesichts des aktuellen Klimawandels sind Auswirkungen steigender Temperaturen und veränderter Niederschläge auf die Biodiversität der Regenwälder Amazoniens von besonderer Bedeutung, da sie schon heute unter zunehmender Fragmentierung leiden und verstärkt angreifbar für Dürreperioden und Waldbrände sind. Wie genau eine zukünftige Klimaerwärmung die Ökosysteme Amazoniens beeinflusst, ist daher auch von besonderem Interesse für zukünftige Schutzmaßnahmen. Paläoökologische Studien dienen hier als wichtiges Werkzeug, da sie über lange Zeitskalen hinweg Einblicke in die vielfältigen Verbindungen zwischen Klima- und Vegetationsveränderungen gewähren, doch verhältnismäßig wenige solcher Studien stehen bisher für das Amazonasgebiet zur Verfügung. Für ein tieferes Verständnis der Vegetations- und Feuergeschichte Amazoniens untersucht die vorliegende Arbeit einen Zeitrahmen von ca. 70000 Jahren, der das späte Pleistozän, das Letzte Glaziale Maximum (LGM), sowie das Holozän umfasst. Im Fokus liegen die südlichen Randgebiete des Amazonasbeckens, welche besonders empfindlich auf klimatische Veränderungen reagieren. Zwei untersuchte Sedimentarchive stammen aus Serra Sul dos Carajas (Pará, Brasilien) im Südosten Amazoniens. Die Ergebnisse zeigen, dass dortige Ökosysteme während des späten Pleistozäns hauptsächlich von der verfügbaren Niederschlagsmenge abhängig waren, während sie sich seit Beginn des Holozäns zunehmend auf eine neue Saisonalität des Niederschlags einrichteten. In Anpassung an ökologische und klimatische Schwankungen reagierten die Vegetationssysteme in Carajás vor allem mit einer veränderten Artzusammensetzung. So entwickelte sich unter trockeneren Klimabedingungen aus einem zuvor tropischen Regenwald ein an trockenere Bedingungen angepasstes offenes Waldsystem. Die bereits vorhandene Savannenvegetation breitete sich stärker aus, konnte die Waldvegetation jedoch nicht völlig verdrängen. Die Niederschläge selbst, und somit auch die Veränderungen der Ökosysteme in Südost-Amazonien, zeigen dabei eine enge Verknüpfung mit Temperaturschwankungen im tropischen Atlantik. Weitere Untersuchungen an Seesedimenten von Lago Amapá aus Rio Branco (Acre, Brasilien) zeigen, das die dokumentierte Öffnung und Störung der dortigen Waldvegetation über die letzten 650 Jahre hinweg unter haupsächlich feuchten Klimabedingungen erfolgte und primär auf das Wirken prä- und postkolumbianischer Siedlungstätigkeiten zurückgeführt werden kann.

I. Introduction

1. Palynology and palaeoecology in Amazonia – state of knowledge

In view of the vast dimensions of the Amazon basin our knowledge about its environmental history is still based on few palaeoecological studies. The hitherto existing studies from very distant regions of the basin show only an incomplete picture of the Amazonian environment in the past. The knowledge of Amazonian palaeoecology is thus affected by the variable results arising from the heterogeneous environments and climates of the basin. A comprehensive picture of past environmental and climatological conditions is therefore hard to grasp, which leads to controverse concepts of Amazonian landscapes regarding its history. The degree of forest fragmentation, e.g. its reduction to refugial areas, under drier environmental conditions and the characterization of past precipitation regimes have to be named here in particular.

1.1 Forest fragmentation or the 'refuge hypothesis'

Controverse opinions exist concerning past forest fragmentation into refugia and climate change in Amazonia. The advocates of the "refuge hypothesis" claim that the Amazon rainforest was reduced to "small fragments" during possibly dry to arid periods in the late Pleistocene (Fig. 1). Several studies (e.g. Haffer, 1969; Absy et al., 1991; Prance, 1982; van der Hammen et al., 1992; van der Hammen and Hoogiemstra, 2000) support this hypothesis, as they show an expansion of savannas suggested as the result of over-regional dry climatic conditions. And also extreme dustiness in Peruvian Huascarán ice core record is suggested to be connected to a reduced forest cover in Amazonia (Thompson et al., 2000). The opposite opinion of a closed forested Amazon basin is argued by the opponents of the refuge hypothesis. Their data show the stability of evergreen forests since the late Pleistocene which is suggested to be related to wetter climates (e.g. Bush et al, 1990; Colinvaux et al., 2000; Colinvaux and deOliveira, 2001; Mayle and Beerling, 2004; Bush and Oliveira, 2006; Urrego et al., 2005). Especially for the Last Glacial Maximum (LGM) the above mentioned studies suggest different climate regimes based on the analysed data. From studies supporting the refuge hypothesis, the LGM is suggested to be a dry period, whereas this period is presumed to be wet by studies referring to a forested Amazon basin. A wetter LGM is also suggested by marine studies in the Amazon fan (Haberle and Maslin, 1999; Kastner and Goñi, 2003). Since several years a growing agreement can be recognized for the picture of a mainly forested Amazon basin, whose southern margins were affected by expanding savannas at the expanse of forest (Mayle et al., 2000).

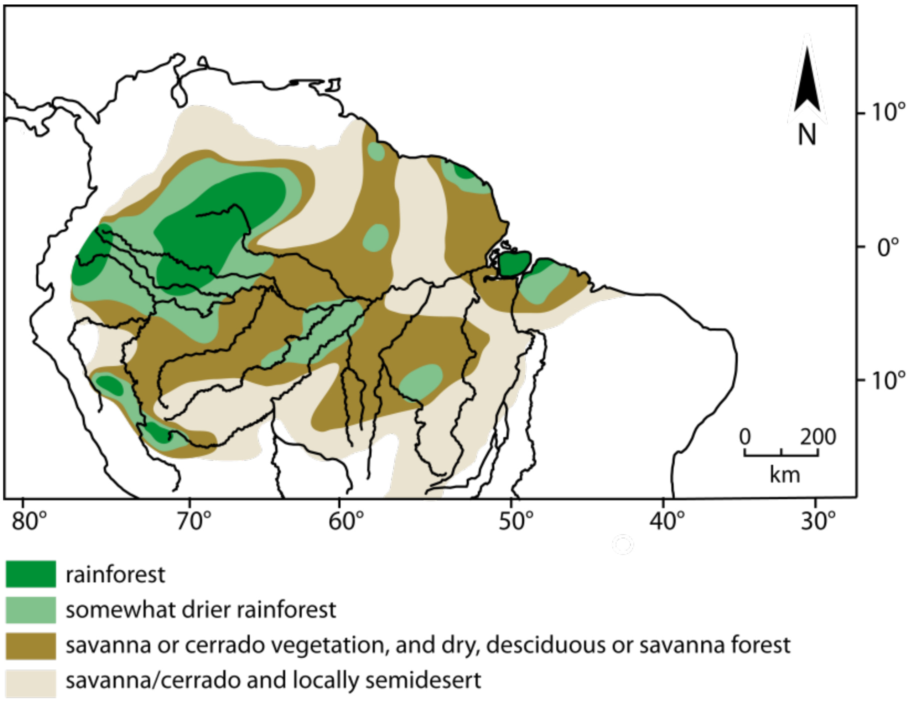

Fig. 1: The Refuge Hypothesis. Reconstructed possible vegetation in Amazonia during the Last Glacial Maximum (20 cal kyr BP); modified after Van der Hammen and Hooghiemstra (2000).

1.2 Past climates and the environment

The common ground of palaeoecological studies in Amazonia is the adjustment of Amazonian ecosystems to spatial and temporal changes in precipitation (e.g. Liu & Colinvaux, 1985, Bush et al., 1990, Absy et al., 1991; Van der Hammen et al., 1992; Colinvaux et al., 1996, Haberle, 1997, Mayle, 2000, Bush et al., 2004;

Colinvaux et al., 2000; Behling and Hooghiemstra, 2001; Sifeddine et al., 2001; Burbridge et al., 2004; Bush et al., 2004; Irion et al., 2006; Cordeiro et al., 2008). As Amazonian precipitation regimes are suggested to be tightly connected with precipitation regimes in the Andes (Baker et al.; 2001), studies from the Andean region are often consulted when climatic conditions in Amazonia have to be described.

The role of the Intertropical Convergence zone (ITCZ) and El Niño Southern Oscillation (ENSO)

Regarding precipitation a growing interest for the significance of a changing ITCZ to terrestrial ecosystems is based on the idea that the position of the ITCZ shifted significantly in the past (Haug et al., 2001). This shifting affected the regions of Amazonia differently in consideration of their latitudinal position. Between 4 and 2.4 cal yr BP a southward shift of the ITCZ is assumed (Haug et al., 2001) and the north of Amazonia would have experienced drier conditions, whereas conditions in the southern regions would have been wetter. A northward shift of the ITCZ then would produce a converse picture, which is assumed to be the case for the Holocene 'thermal maximum' from 10.4 to 5.5 cal yr BP (Haug et al., 2001). This shifting is suggested to be connected with sea surface temperatures (SST) in the northern tropical Atlantic, as a southward shift seems to be associated with colder SSTs and a northward shift with warmer SSTs. Hence, precipitation in Amazonia would have been also dependend on SST variability in the tropical North Atlantic (Chiang et al., 2001; Broccoli et al., 2006). With respect to drought events in Amazonia the influence of a mid-Holocene intensification of ENSO frequency on past ecosystems has also to be considered. The present pattern of recurrent El Niño and La Niña events established about 7000 years ago, and is thought to have repeatedly caused severe droughts at least during the past 2000 years inferred from archaeological evidence (Meggers, 1994).

LGM and late Glacial – Moisture regimes and temperature conditions

Contrasting results from Amazonian and Andean records have lead to different opinions about climatic conditions during the LGM (21,000 cal kyr BP) and late Glacial. And also the response of vegetation to past moisture availability and temperature changes differs from region to region.

Moisture regimes – For the LGM and late glacial times pollen and lake level records from north- and southwest Amazonia, as well as from the Andes and the eastern Cordillera of Colombia, suggest drier conditions (Behling and Hooghiemstra, 2000; Bush et al., 2004; Mayle et al., 2000; Hooghiemstra and Ran, 1994; Van der Hammen and Hooghiemstra, 2003). But whereas in northwest Amazonia dense forests persisted under these conditions (Bush et al., 2004), the southwest is characterized by expanding savannas (Mayle et al., 2000). In contrast, evidence for wet conditions derives from Andean lake level and ice core data of the Bolivian Altiplano (e.g. Baker et al., 2001; Fritz et al, 2004; Gosling et al., 2008; Rigsby et al., 2005; Thompson et al., 2000). A regional climate model (Vizy and Cook, 2007) indicates that the absence of convection over a dry Amazon would result in enhanced convection over the Andes, and thus a wetter Altiplano and a drier Amazon would not necessarily exclude each other. But how far and in which way Amazonian and Andean moisture regimes where coupled exactly, is still not well understood, and also the South American Summer Monsoon (SASM), the Bolivian High and moist trade winds from the Atlantic Ocean may have played an important role (Seltzer et al., 2000). Between 13 and 10 kyr BP (15.4-11.4 cal kyr BP) regional forest development and erosion events in southeast Amazonia suggested intensive rainfall events, indicative of a changing climate at the end of the late Glacial (Sifeddine et al., 2001). This is also the time when Andean Lake Titicaca overflowed (Baker et al., 2001a).

Temperature conditions – Palaeoecological records from marine and terrestrial environments suggest a clear cooling during the LGM, though estimates range between 2 and 9°C (e.g. Bush et al., 1990; Guilderson et al., 1994; Stute et al, 1995; Colinvaux et al., 1997; Klein et al., 1998; Farerra et al., 1999; Rühlemann et al., 1999; Porter, 2001; Seltzer et al., 2001; Lea et al., 2003; Paduano et al., 2003; van der Hammen and Hooghiemstra, 2003). In the Amazonian lowlands the occurrence of *Podocarpus* (Colinvaux et al., 1996; Behling, 1996, 2001; Behling et al., 1999) during glacial times is interpreted as a result of this temperature decline. This is in agreement with recorded cold conditions from western Amazonia and the eastern Andes (Bush et al., 1990; Hooghiemstra and Ran, 1994; Stute et al., 1995; Behling et al., 1998; Van't Veer and Hooghiemstra, 2000; Behling, 2001; Bush et al., 2004; Wille et al., 2001; Van der Hammen and Hooghiemstra, 2003). In line with a cooler climate is also the downward migration of Andean forest taxa to lower elevations between 19.8 and 11 cal kyr BP (Behling, 1996; Colinvaux et al., 1996; Bush et al., 1990; Haberle and Maslin, 1999). But cooler temperatures inferred from the occurence of taxa that are today known from elevated areas (e.g. *Podocarpus*) are mostly based on one or two taxa. This is often criticized, as these taxa could have also been part of lowland forest communities without an adaption to cool conditions (Van der Hammen and Hooghiemstra, 2000; Punyasena et al., 2011).

The Holocene period and a mid-Holocene dry event

The Holocene is known as a general warming period with a temperature increase of 5-6°C after the end of the Pleistocene (Seltzer et al, 2002). In lowland Amazonia numerous palaeoecological records show evidence for this warm conditions (Ledu and Mourguiart, 2001; Berrio et al., 2002; Burbridge et al, 2004; Toledo and Bush, 2007). Severeal records also document a mid-Holocene dry event widespread over the Amazon basin, but duration and timing of dry conditions are inconsistent between different parts of the Amazon basin and point to the climatic heterogeneity of this region: north- and southwest Amazonia are suggested to have experienced a dry period as forests were replaced by savannas (Behling and Hooghiemstra, 1999; Mayle et al., 2000; Burbridge et al, 2004; Toledo and Bush, 2007; Urrego, 2006). And also at the Bolivian Altiplano conditions were arid between 7.9 and 4.5 cal ka (Rigsby et al., 2005), the same time when the lake level at Lake Titicaca dropped markedly (Seltzer et al., 1998; Cross et al., 2000; Paduano et al., 2003). Other lake records also showed a drop of lake levels between 8 and 4.3 cal ka caused by drier conditions (Wirrmann and Mourguiart, 1995; Abbott et al., 2000; Baker et al., 2001a; Seltzer et al., 2002). However, records from northwest Amazonia and the Colombian Llanos Orientales let assume that conditions became wetter in the same period, more precisely after 6.4 cal ka (Behling and Hooghiemstra, 1998; Bush et al., 2004). No evidence for drier conditions comes from a marine record in the Amazon fan (Maslin and Burns, 2000) and from lowland Amazonian lakes Geral and Comprida (Bush et al., 2000).

During the late Holocene (after 4 cal kyr BP), Amazonian records consistently show generally wetter condition for the whole region. In north- and southwest Amazonia the establishment of modern rainforest communities is recorded after 3.7 cal kyr BP (Mayle et al., 2000; Bush et al., 2004), which indicates, together with rising Andean lake levels after 3.5 cal kyr BP (Abbott et al., 1997; Rowe et al., 2002), overall wetter conditions in northern South America (Baker et al., 2001a). In the Bolivian Altiplano and the Colombian Llanos Orientales the transition from dry to wet climatic conditions seems to be correlated with an increasingly anthropogenic influence (Binford et al., 1997; Berrio et al, 2002), and also in the Brazilian lowlands increasingly wetter conditions during the late Holocene are suggested to have favoured the development of human populations after long-lasting dry periods during the mid-Holocene (Araujo et al., 2005).

2. General objectives and outline

The main goals of this study are (a) to highlight environmental changes in space and time, (b) to further highlight the role of ITCZ and ENSO events for the environment in southern Amazonia, and (c) to reconstruct fire history of southern Amazonia. This includes in detail:

1. *Reconstruction of environmental dynamics and fire history* – changes of tropical forest and savanna vegetation and species composition, and their temporal classification. Analysis and determination of the driving factors behind palaeofire activity in the southern Amazon basin with respect to differences between southeast and southwest Amazonia including the role of human occupation.
2. *Climatic drivers* – investigation of the influence of temperature and varying moisture conditions on forest and savanna systems in southern Amazonia and in which way it could be connected to a shift of the ITCZ and the onset of ENSO events; of special interest is the effect of cooler temperatures during the LGM, and the timing and degree of a mid-Holocene dry event in southern Amazonia.

Three sediment archives have been studied by means of pollen, spore, charcoal, and geochemical analyses, two from southeast Amazonia and one from the southwestern Amazon region. Chapters II to IV are arranged as manuscripts for submission to peer-reviewd journals, Two are already published (chapters II and III), and one is already submitted (chapter IV). Unpublished data are added as a supplementary material after the respective chapter IV, and as an additional chapter V repectively. Chapter II and III cover the results from Pántano da Maurítia (Serra Sul dos Carajás), and focus on the reconstruction of environmental changes and their climatic drivers. A comparison with paleoecological studies from Amazonia and the Andes is given suggesting the linkage of environmental changes in Serra Sul with climatic changes and sea surface temperatures in the tropical Atlantic. Chapter IV concentrates on the local fire history at Lagoa da Cachoeira (Serra Sul dos Carajás), and results suggest that palaeofires in southern Amazonia are primarily climate driven. Here, tropical Atlantic SSTs seem to be more influencing than ENSO during the early and mid-Holocene. In chapter V first results of palynological and geochemical analyses from southwest Amazonian lake 'Lago Ampá' (Rio Branco, Acre) are given, which suggest a notable human influence on vegetation in the time when sediments accumulated.

3. Study region – an overview

The three study sites belong to the southern margins of the Amazon basin (Fig. 4). The first studied area is situated in southeastern Amazonia in the state of Pará, Brazil. The region, called Serra dos Carajás, is a mountain range hosting one of the world's largest iron deposits. The open pit mine in the Serra Norte dos Carajás (northern mountain range) is about 45 km distant northeast from the two study sites in Serra Sul (southern mountain ranges) (Fig.4). The undulated surface of Serra Sul is permeated with numerous depressions, where small lakes, lacustrine sediments and swamps can be found. The top of the plateau of Serra Sul consists of ferruginous crusts, formed during the lower Tertiary (Horbe and da Costa, 2005). The second study area is situated in western Amazonia in the state of Acre, Brazil (Fig. 4). The core derives from Lago Amapá (district of Rio Branco), an ancient branch of Rio Acre, c. 3 km long and about 75m at its broadest point.

3.1 Vegetation

The present vegetation of Serra Sul dos Carajás (Fig. 2) in southeast Amazonia comprises a mosaic of rainforest and savanna vegetation types, latter commonly known as 'campo rupestre'. According to Rayol (2006) and Nunes (2009) the 'campo rupestre' is a complex of open and dense shrub-bush savannas associated with the poor ferruginous soils of Serra Sul. It is differentiated into an 'open' and a 'dense campo rupestre'. Within the dominating Campo rupestre vegetation on top of the plateau, forest islands occur in association with rocky lake borders, depressions and small canyons. The floristic composition of these small forest patches is comparable to the forest at the slopes of the mountain range. At the slopes of Serra Sul a forest with typical taxa of upland tropical rainforests occurs. On poor soils a succession forest is present (Morellato and Rosa, 1991). The lowland of the Carajás region is covered by tropical rainforest (Amazonian terra firme forest) (Salomão et al., 1988; Morellato and Rosa, 1991).

Fig. 2: Serra Sul dos Carajás. Transition between savanna and forest vegetation (left) and the studiy sites Pántano da Maurítia (middle) and Lagoa da Cachoeira (right); photos 2005 by H. Behling.

The present vegetation at Lago Amapá (Fig. 3) is characterized by open tropical forests. As the area around the study site is intensively influenced by road construction, urban development, and agricultural use, a tremendous invasion and turnover of the natural forest vegetation is given. A detailed description of the floristic composition is carried out in chapters II-V.

Fig. 3: Lago Amapá. Vegetation at the lake shore (left and middle) and road construction at the bank of the lake (right); photos 2009 by B. Hermanowski.

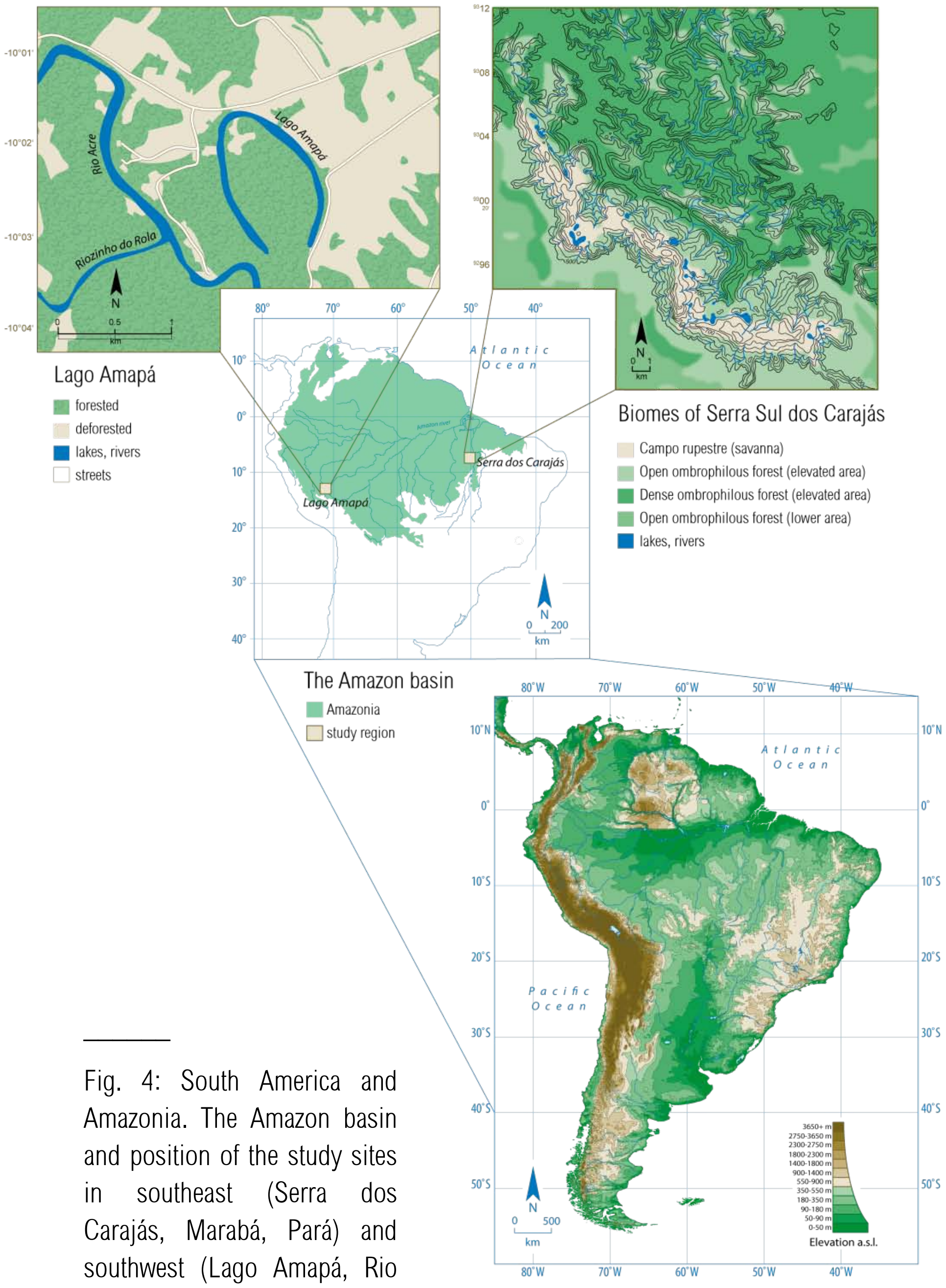

Fig. 4: South America and Amazonia. The Amazon basin and position of the study sites in southeast (Serra dos Carajás, Marabá, Pará) and southwest (Lago Amapá, Rio Branco, Acre) Amazonia. Geographical map © Map Resources (slightly modified).

3.2 Climate

The climate of southern Amazonia is characterized by a clear seasonal cycle of wet and dry seasons. With reference to the studied areas differences between seasons in southeast and southwest Amazonia are noticeable. In the southeast the pronounced dry season with hardly any rainfall from June to October is accompanied by a wet season where 90 % of rainfall in this region occurs. In southwest Amazonia seasons are defined comparibly, though less rainfall during the wet season can be recognized (Tab. 1). During the dry season, temperatures in southwest Amazonia can drop until 4°C (minimum value; more often around 10°C) when cold fronts (‘friagens’) enter the region (Duarte et al., 2002; Duarte, 2006).

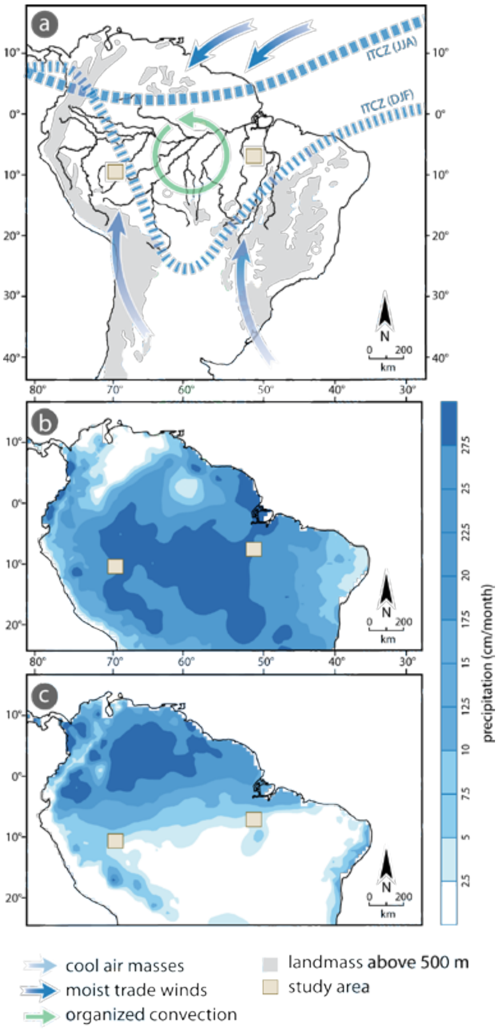

Fig. 5: Location of the study sites in relation to important climatic factors. (a) Wind directions, Amazon convection, and mean position of the ITCZ during th seasons; (b-c) Precipitation in northern South America during (b) January and (c) July, maps modified after Maslin and Burns (2000) and Webber and Willmott (1998).

The seasonal precipitation in southern Amazonia is mainly affected by four factors: (1) the migration of the Intertropical Convergence Zone (ITCZ) due to changing Atlantic sea surface temperatures, (2) the associated moisture laden trade winds from the tropical Atlantic, (3) the evapotranspiration from the Amazon rainforest itself, and (4) the coupled onset and intensity of Amazon convection (Fu et al., 2001; Liebmann and Marengo, 2001; Marengo et al., 1993, 2001; Nobre and Shukla, 1996) (Fig. 2).

The lowpressure zone of the ITCZ appears as a cloudy band near the equator, where trade winds coming from the north- and southeast converge. The position of the ITCZ varies signifcantly in the course of the year. In northern South America this movement is manifested in the seasonality of precipitation. In southeast Amazonia the moving ITCZ is responsible for the pronounced wet and dry seasons. During the wet season, the ITCZ is positioned south of the equator and the moisture laden trade winds enhance rainfall in southern Amazonia. During the dry season the ITCZ moves northward to a position north of the equator. During this time southern Amazonia experiences less precipitation between May and October. The Amazon rainforest itself is also a crucial factor for the onset of the wet season, as increased evapotranspiration at the end of the dry season increases the chance for convection (Myneni et al., 2007).

Table 1: Climate data of study areas in southeast and southwest Amazonia.

	Southeast Amazonia*	Southwest Amazonia**
Climate	Tropical humid (Aw, Köppen)	Tropical humid (Am, Köppen)
Wet season (November-April)		
Temperature	25°C	25°C
Precipitation	1250 mm/month	240 mm/month
Dry season (May-October)		
Temperature	25°C	25°C (min. 4°C possible)
Precipitation	150 mm/month	80 mm/month
Characteristics	–	'friagens' (cold spells)

*= Data from Marabá climate station (5°37'S, 49°13'W, 95 m a.s.l.) via INMET (2011).

**= Data from Rio Vranco climate station (9°95'S,68°16'W, 220 m a.s.l.) via INMET (2011).

4. Pollen and charcoal analysis – Methods and Applications

4.1 Fieldwork

Two cores used for this study, were already taken in 2005 by Hermann Behling and Marcondes Lima da Costa during fieldwork at Serra Sul dos Carajás. The third core was taken 2009 by Barbara Hermanowski, Hermann Behling, and Marcondes Lima da Costa during fieldwork at Lago Amapá, Rio Branco. Different coring techniques were used. At Serra Sul a Russian corer was applied to extract sediment core parts of 50 cm length. At Lago Amapá, a Livingstone piston corer was used to extract sediments at the deepest part of the narrow lake from an inflatable coring platform. Sediments were wrapped in film to minimize drying and stored in darkness at 4°C in plastic tubes until laboratory processing.

The planned study of modern pollen rain at the study sites could not be carried out during the PhD, as in Carajás the company (Vale do Rio Doce), which decides on the research permissions in this area, declined our application for modern pollen rain studies in Serra Sul. In Rio Branco the installed pollen traps were not traceable after one year of pollen rain sampling, presumably because they were damaged or stolen.

4.2 Laboratory techniques

Sediment cores were subsampled to allow for pollen and micro-charcoal analysis. The sediments from Pántano da Maurítia were already subsampled before the beginning of this study, and subsamples were stored in darkness at 4°C until laboratory processing. The drilled sediments from Lagoa da Cachoeira were available as a whole sediment core. Therefore, samples could have been taken separately for palynological and micro-charcoal analysis. Latter analysis needs contiguisly sampled sediments in the smallest possible intervals (here each cm) to allow for a reconstruction of fire frequency. The sediment core from Lago Amapá was sampled in larger intervals to allow for a first overview of this palynological largely unknown site.

Pollen and spores

To each subsample (0.5 cm^2) tablets of exotic marker spore *Lycopodium clavatum* was added before processing of the samples (Stockmarr, 1971), to allow for a calculation of concentration and accumulation rates. The concentration of spores per tablet used for this study is given in Table 2. Sample and marker tablet were then treated with 10% HCl and afterwards filtered through a microstrainer with a mesh width of 150 µm. Subsequently they were dehydrated with acetic acid and treated with standard methods after Fægri and Iversen (1989). These methods include the removal of silicate minerals with 70% hydrofluoric acid, and the removal of cellulose (intine) with acetolysis using a 9:1 mixture of acetic anhydride and concentrated sulfuric acid. After laboratory processing the ace-tolysed pollen was fixmounted with glycerine gelatin for light microscropy.

Table 2: Concentrations of exotic marker *Lycopodium clavatum* per tablet. Tablets produced at the Department of Quaternary Geology in Lund (Sweden).

Batch No.	Concentration of spores/tablet
177745	18584 ± 1853
1031	20848 ± 1546

Charcoal

For the Lagoa da Cachoeira sediments subsamples (1 cm²) of each cm of the core were treated with the sieving method by Stevenson and Haberle (2005). Sediments were dissolved in 4% KOH. Subsequently the organic material was bleached with 5% hydrogen peroxide over night. When needed, ethanol was added to foaming samples to reduce foam formation. For this study, a combination of sieves with a mesh width of 250 and 125 µm were used to facilitate future counting, where charcoal concentration was very high. For the Pántano da Maurítia core charcoal was not prepared separately from the pollen material, as for the sample distance of the available subsamples was not small enough to allow for a contiguous counting. Also for Lago Amapá micro-charcoal was prepared together with the pollen material, as the radiocarbon dating reveald inconsistent dates (see 'Radiocarbon dating'), which makes calculation of fire frequency impossible.

Radiocarbon dating

In total 21 sediment samples were radiocarbon dated to obtain chronologies for the cores. These ^{14}C dates (Table 3) have to be calibrated to calendar years, as radiocarbon production is not constant over long time scales. For Pántano da Maurítia radiocarbon dates are calibrated with BCal (Buck at al., 1999) using the implemented bayesien calibration method. The radiocarbon dates from Lagoa da Cachoeira were calibrated with the Clam package (Blaauw, 2010) for R 2.14.2 (R Development Core Team, 2008). From six sediment samples of Lago Amapá only three could be calibrated with Calib 6.0 (Stuiver and Reimer, 1993), as the radiocarbon dating of the other three samples produced invalid ages. Calibrated dates were used to calculate an age-depth-model for each core. In this study linear interpolation (chapter 2 and 3) and cubic spline interpolation (chapter 4) were applied for this purpose.

Table 3: Radiocarbon dates from Serra Sul dos Carajás (Pará)* and Lago Amapá (Rio Branco, Acre)**

Depth (cm)	Dated material	^{14}C yr BP	Laboratory number	Age range (cal yr BP), 2σ	Age (cal yr BP), weighted average
Pántano da Maurítia (PDM)*					
48-49	peat	2140 ± 40	Erl-12483[a]	1999-2183	2148
60-61	peat	3373 ± 26	KIA 39910[b]	3558-3692	3616
96-97	peat	8547 ± 51	Erl-12484[a]	9463-9601	9523
120-121	peat	8899 ± 39	KIA 39911[b]	9898-10189	10,034

148-149	bulk sediment	9900 ± 54	Erl-12173[a]	11207-11412	11,331
160-161	bulk sediment	10,537 ± 57	KIA 39912[b]	12220-12277	12,543
196-197	bulk sediment	19,795 ± 147	Erl-12485[a]	23230-24166	23,646
248-249	wood fragment	46,807 ± 1016	Erl-12174[a]	uncalibrated	uncalibrated
342-346	bulk sediment	39,511 ± 781	Erl-12089[a]	uncalibrated	uncalibrated
438-442	bulk sediment	47,973 ± 3976	Erl-12090[a]	uncalibrated	uncalibrated
Lagoa da Cachoeira (LDC)*					
48-49	bulk marsh sediment	2374 ± 41	Erl-12171[a]	2331 - 2498	2435
78-79	bulk marsh sediment	3619 ± 40	Erl-12481[a]	3834 - 4002	3937
133-134	bulk marsh sediment	12,414 ± 38	Erl-10586[a]	14131 - 14946	14,496
148-149	bulk marsh sediment	14,542 ± 95	Erl-12172[a]	17250 - 17986	17,675
198-199	bulk marsh sediment	21,723 ± 190	Erl-12482[a]	25373 - 26770	26,049
Lago Amapá (LARB)**					
42.5-43	bulk sediment	-1682 ± 43	Erl-13829[a]	invalid age	invalid age
87.5-88	bulk sediment	-2063 ± 43	Erl-13830[a]	invalid age	invalid age
106.5-107	bulk sediment	-2171 ± 43	Erl-13831[a]	invalid age	invalid age
181.5-182	bulk sediment	163 ± 84	Erl-13832[a]	1524- 1558	1541
210-211	bulk sediment	698 ± 90	Erl-13833[a]	1160- 1424	1292
257.5-258	bulk sediment	467 ± 85	Erl-13834[a]	1304- 1364	1334

[a] AMS-Labor Friedrich-Alexander-Universität Erlangen-Nürnberg, [b] Leibniz Labor für Altersbestimmung und Isotopenforschung, Christian-Albrechts-Universität Kiel.

X-ray fluroscence (XRF) spectrometry

An analysis of the chemical composition of the sediment core from Lago Amapá (Rio Branco, Acre) was conducted in 0.5 mm intervals with the non-destructive XRF scanner (ITRAX Core-scanner, Cox Analytical Systems) at the Geography Institute at Bremen University. The most influencing elements of the chemical composition were identified using Principal Component Analysis (PCA) of the log-transformed data, with standardized and centered vaiables.

4.3 Pollen and spore identification

The high biodiversity of the Amazon region and especially the constantly low pollen concentration in samples made pollen counting very time intensive. At Lagoa da Cachoeira and Pántano da Maurítia (Serra dos Carajás) the countable pollen concentration ranges between 10,000 and 65,000 (45,000) grains/cm^3. At Lago Amapá (Rio Branco) values was even lower with a maximum pollen concentration of 13,000 grains/cm^3. A total count of a minimum of 300 pollen grains was carried out for each sample, but where pollen concentration was too low a total of 200 grains was counted. Samples (almost) without preserved pollen grains had to be discarded. The identification of pollen types was conducted using specific pollenmorphological keys (Colin-vaux et al., 1996; Carreira and Barth, 2003; Carreira et al., 1996; Roubik and Moreno, 1991) and a reference collection of key taxa hold at the Department of Palynology and Climate Dynamics at Göttingen University. A total of 106 pollen and 15 spore types were distinguished, mostly to family and genus and rarely to species level, but a relatively high amount of recognized pollen types remained unknown.

4.4 Data presentation and interpretation

The palynological data are presented as percentage diagrams, in which the percentages of counted pollen and spores are plotted against sample depths or ages. The calculation is based on the sum of terrestrial pollen counted. The complete pollen diagrams are shown in Appendix A-B. Based on the diagrams the most significant taxa were chosen for further palaeoecological interpretation. These ‘key taxa’ are grouped into vegetation types, but it has to be taken into account, that grouping of pollen types, which are only known to family or genus level, runs the risk for certain impreciseness, as these families or genera are not restricted to only one vegetation type. The installation of pollen traps and analysis of modern pollen rain would have reduced these uncertainties to a certain degree, and therefore the cancelation of these planned analyses was a harsh loss for this study. What has also to be taken into account when interpreting percentage data is a variable pollen production of different taxa, dependent on the pollination mechanism. Taxa producing large amounts of pollen (e.g. wind-pol-linated) can cause an overrepresentation, whereas low pollen producers (e.g. animal-pollinated) are often underrepresentated. Biological factors like pollination strategies, pollen productivity and dispersal are additionally interlinked with abiotic factors like variable climatic conditions, wind and rainfall patterns, which has to be also taken into account for the interpretation of palynological data.

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II. Environmental changes in southeastern Amazonia during the last 25,000 years revealed from a paleoecological record

Barbara Hermanowski, Marcondes Lima da Costa, Hermann Behling

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Abstract

New pollen, micro-charcoal, sediment and mineral analyses of a radiocarbon dated sediment core from the Serra Sul dos Carajás (southeast Amazonia) indicate changes between drier and wetter climatic conditions during the past 25,000 years, reflected by fire events, expansion of savanna vegetation and no-analog Amazonian forest communities. A cool and dry Last Glacial Maximum (LGM) and late glacial were followed by a wet phase in the early Holocene lasting for ca. 1200 years, when tropical forest occurred under stable humid conditions. Subsequently, an increasingly warm, seasonal climate established. The onset of seasonality falls within the early Holocene warm period, with possibly longer dry seasons from 10,200-3400 cal yr BP, and an explicitly drier phase from 9000-3700 cal yr BP. Modern conditions with shorter dry seasons established after 3400 cal yr BP.

Taken together with paleoenvironmental evidence from elsewhere in the Amazon Basin, the observed changes in late Pleistocene and Holocene vegetation in the Serra Sul dos Carajás likely reflect large-scale shifts in precipitation patterns driven by the latitudinal displacement of the Inter Tropical Convergence Zone and changes in sea-surface temperatures in the tropical Atlantic.

Keywords: Amazonian rainforest; edaphic savanna; LGM; late glacial; Holocene; pollen analysis; micro-charcoal analysis; sediment analysis; climate change; precipitation

Introduction

The Amazon rainforest is one of the most species-rich regions in the world and plays a significant role in the global hydrology and climate system. About 10 % of global carbon is found in Amazonian forests and soils (Melillo et al., 1993). Given the possibility of a future constriction of the Amazon rainforest due to increased fire frequency and droughts (Nobre et al., 1991; Cox et al., 2004), it is essential to understand long-term vegetation dynamics under changing climatic conditions. Paleoecological studies in particular contribute to an improved understanding of the resilience of Amazon rainforest to large-scale environmental and climate changes.

Under the dry climatic conditions during the LGM and early to mid-Holocene the prevalence of savanna vegetation in Amazonia is suggested. But there are still questions to be addressed, including reasons for the extension of savannization during arid periods, and the complex feedbacks between climate and vegetation. Pollen records spanning the LGM have been interpreted as indicating (1) Amazonian forests were replaced by savanna (Absy et al., 1991; Van der Hammen and Absy, 1994), (2) the Amazon Basin remained forested (Haberle and Maslin, 1999; Colinvaux et al., 2000; Kastner and Goñi, 2003; Bush et al., 2004; Beerling and Mayle, 2006), and (3) Amazonia remained forested with savanna expansion at its margins (Sternberg, 2001; Mayle et al., 2009). The general consensus is that Amazonia has been forested during the late Quaternary, with the expansion of savanna at the periphery during the LGM and early Holocene. Climate was apparently drier than during the intervening periods, but ecosystems across the Amazon Basin were affected by significantly different regional precipitation patterns (Absy et al., 1991; Colinvaux et al., 2000; Behling and Hooghiemstra, 2001; Sifeddine et al., 2001; Burbridge et al., 2004; Bush et al., 2004; Irion et al., 2006; and Cordeiro et al., 2008).

The presumed climatic drivers for these different patterns are changes of the general position of the ITCZ (Mayle et al., 2000; Haug et al., 2001, Burbridge et al., 2004), moisture input from the tropical Atlantic, and the effects of El Niño/Southern Oscillation events (ENSO) (Liu et al., 2000; Marengo et al., 2001; Zheng et al., 2008). The southeastern part of Amazonia is of particular interest because it is especially sensitive to shifts of the ITCZ and to moisture input from the Atlantic Ocean, but few pollen records are available from this region, none has spanned the LGM, and the interpretation of the pollen data is still controversial (Absy et al., 1991).

Here, we describe a new paleoecological multiproxy record from the Serra Sul dos Carajás that provides (1) insights into the environmental history of this region including the LGM, (2) an extended taxa list to clarify previous uncertainties of interpretation, and (3) new proxy data to better understand fire history, soil dynamics and changes in hydrology. Of particular interest are the dynamics of edaphic savanna and forest communities and their possible connections to past climatic conditions.

Study area

Climate

The regional climate of southeast Amazonia is tropical humid (Aw, Köppen), with pronounced wet (November-May) and dry seasons (June-October) (Sifeddine et al., 2001). The average mean monthly temperature is 25°C. Mean monthly precipitation at Marabá climate station (5°37'S, 49°13'W, 95 m a.s.l.) accounts for 740 mm during the wet season, and 60 mm during the dry season (INMET, 2011). The seasonality of regional precipitation is influenced by several factors including the migration of the ITCZ due to changing Atlantic sea surface temperatures (SST), moist trade winds from the tropical Atlantic, evapotranspiration from the forest itself, and the coupled onset and intensity of Amazon convection (Fu et al., 2001; Liebmann and Marengo, 2001; Marengo et al., 1993, 2001; Nobre and Shukla, 1996) (Fig. 1b). During the dry season the ITCZ is situated north of the equator and convection in eastern Amazonia is decreased. During the wet season the ITCZ moves south of the equator and convection is enhanced.

Topography and soil

The Serra Sul dos Carajás (Serra Sul) is a series of plateaus of 600-800 m a.s.l. The top of the plateaus varies from flat to slightly wavy surface. Numerous lakes and wetlands are located in interconnected depressions with gentle to steep margins. The ferruginous lateritic crusts of the plateaus are locally porous and cavernous. These rocky substrates are covered by a thin ferruginous soil layer with a silty and sandy texture. Thicker soils with a higher availability of nutrients and water accumulate at the slopes of the plateau and at rocky lake borders, depressions, and small canyons ontop of the plateau.

Modern vegetation

The nutrient poor soils of Serra Sul are associated with a xerophytic vegetation that comprises a mosaic of dense shrubby and open shrub-bush savanna called 'Campo rupestre' (Cleef and Silva, 1994; Silva et al., 1996; Sifeddine et al., 2001; Rayol, 2007; Nunes, 2009). Evergreen tropical rainforest occurs along slopes and in the lowlands (IBAMA, 2003) (Fig. 1b).

The most common families of the 'Campo rupestre' are Poaceae, Myrtaceae, and Asteraceae. *Borreria* and *Byrsonima* are also common. Typical taxa of the 'open campo rupestre' are several *Croton* species, *Cuphea tenella*, and *Mimosa*. 'Dense campo rupestre' is characterized by Mimosa-ceae, *Byrsonima*, *Ficus nymphaeifolia, Miconia, Tibouchina,* Myrtaceae, and Rubiaceae (Rayol, 2006; Nunes, 2009). Typical taxa of the tropical rainforest are Melastomataceae, Anacardiaceae, Moraceae, Meliaceae, *Alchornea, Aparisthmium* and other Euphorbiaceae (Rayol, 2006; Nunes, 2009). The transition between forest and savanna is characterized by a successional forest dominated by *Aparisthmium* and *Erythroxylum* (Morellato and Rosa, 1991).

The dominant plant families of the tropical rainforest in the lowlands of Carajás and the surrounding region are Fabaceae, Meliaceae, Melastomataceae, Euphorbiaceae, Anacardiaceae, Bignoniaceae, Moraceae, and Combretaceae (Salomão et al., 1988; Morellato and Rosa, 1991). Islands of forest, similar in composition to the rainforest below, occur on the plateau in depressions, small canyons, and along rocky lake borders. Several *Ficus* species and two *Alchornea* species are also typical for these forest islands (Nunes, 2009).

Location of the study site

Pántano da Maurítia (6°21'6.20"S, 50°23'36.60"W, 740 m a.s.l.) is a small (surface area 100 x 200 m) wetland on a narrow plateau of Serra Sul in the southeastern Amazonian lowlands (Fig. 1). Today it is mainly covered with Cyperaceae and Junca-ceae. Previous paleoecological studies were carried out at study sites on the plateau 5 km north of this wetland (Absy et al., 1991, Sifeddine et al., 2001). Pántano da Maurítia is 600 m from the edge of the rainforest.

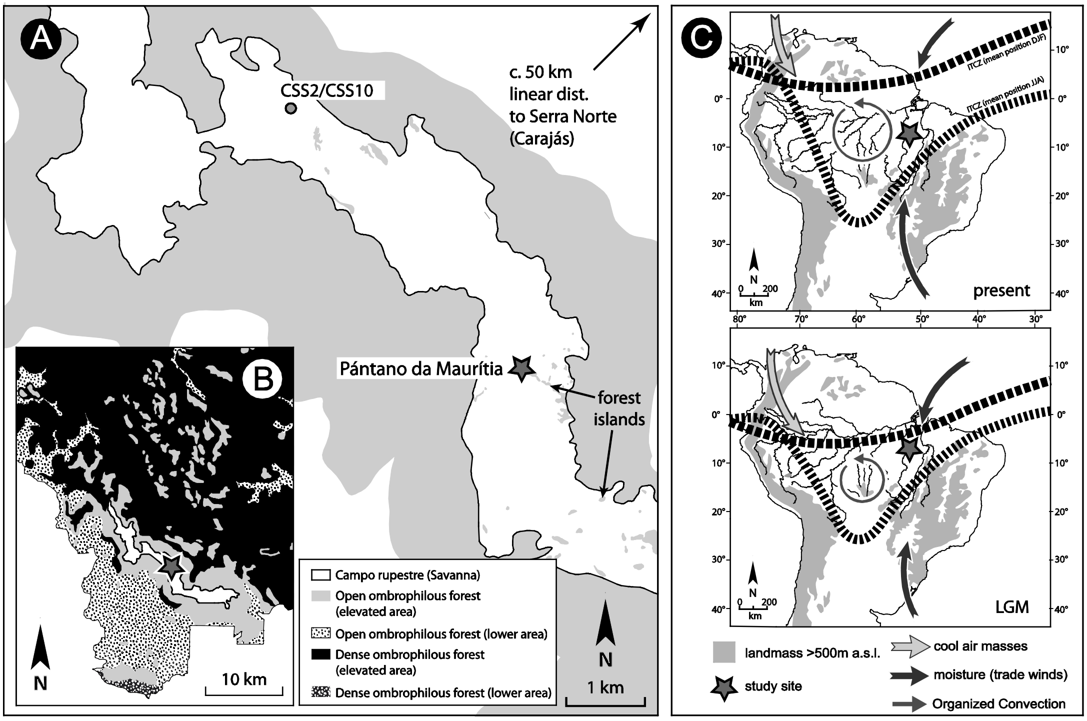

Fig. 1: Location of the study site in the Serra dos Carajás and important climatic factors. (A) Position of Pántano da Maurítia in relation to former study sites in the Serra Sul dos Carajás (CSS2/CSS10), (B) Vegetation types in the southern part of the Floresta National de Carajás (after: Plano de Manejo para uso múltiple da Floresta National de Carajás, 2003), (C) Present climatic conditions (above) and suggested conditions (below) during the LGM (DJF = austral summer, JJA = austral winter); B modified after IBAMA, 2003; C modified after Maslin and Burns 2000.

Methods

A 466-cm-long sediment core was taken from Pántano da Maurítia in 2005 using a Russian corer (50 cm long). The core was transported to the Geoscience Institute at the Universida-de Federal do Pará (UFPA) in Belém, where it was stored in darkness at 4°C. The upper 200 cm of the core were analyzed and 7 bulk sediment samples (2-3 g) were used for radiocarbon dating by the Accelerator Mass Spectrometry (AMS) Laboratory Erlangen (Table 1).

Pollen and micro-charcoal

32 sediment subsamples (0.5 cm^3) were used for pollen and micro-charcoal analysis. Pollen samples were prepared using standard methods (Faegri and Iversen, 1989) including 70% HF treatment, addition of the exotic marker *Lycopodium clavatum* (Stockmarr, 1971), and mounting in glycerine gelatin. Almost all samples were counted to a minimum of 300 terrestrial pollen grains, but where pollen concentration was very low a minimum of 200 terrestrial pollen grains was counted. Percentages of spores and aquatic taxa are calculated relative to the terrestrial pollen sum. Micro-charcoal particles were counted on the pollen slides and were divided in two size classes. Small charcoal particles (10-125 µm) are assumed to represent regional fires, whereas large particles (>125 µm) record fires near the catchment area (Gardner and Whitlock, 2001; Sadori and Giardini, 2007). Thus, the division into size classes allows the differentiation of regional and local fire events, but given the possibility that large particles are broken into smaller pieces during laboratory processsing, the smaller size class should be interpreted with caution.

The zonation of the percentage diagram was conducted with CONISS (Grimm, 1987) using Psimpoll (Bennett, 2002). All 99 identified pollen and spore taxa were included in the CONISS analysis. The AMS radiocarbon dates were calibrated with BCal (Buck et al., 1999) using the IntCal04 calibration curve (Reimer et al., 2004). The age-depth curve was calculated in Psimpoll by linear interpolation between the weighted average of calibrated ages. Pollen and spore identification was based on appropriate literature (Colinvaux et al., 1996; Carreira and Barth, 2003; Carreira et al., 1996; Roubik and Moreno, 1991) and a pollen reference collection held at the Department of Palynology and Climate Dynamics, University of Göttingen.

Sedimentology and mineralogy

Ten samples were selected for analyses of grain size and mineralogy. Grain size distribution (0.3 to 400 µm) was characterized by laser particle analyzer Quantachrom-Cilas 920 at the Institute of Geosciences, Halle University. Approximately 0.5 g of each sample were disaggregated in distillated water and then introduced into the laser analyzer. Mineral identification was carried out by X Ray Diffraction (XRD), powder method. Scanning electron microscopy with energy dispersive system (SEM/EDS) completed the mineral characterization (both analyses carried out at the Geosciences Institute, UFPA, Belém.

Results

Chronology and zonation

The chronology for the upper 200 cm of the sediment core is based on 7 AMS ^{14}C dates spanning the last 25,000 years (Table 2). As the bedrock is not calcareous, an error by hardwater can be excluded. The age model shows uneven rates of sediment deposition, suggesting alternating phases of low and high accumulation rates (Fig. 2). No reversals in the radiocarbon data are present.

Tab. 1: Radiocarbon dates from Pántano da Maurítia

Depth (cm)	^{14}C yr BP	Laboratory number	Age range (cal yr BP), 2σ	Age (cal yr BP), weighted average
48-49	2140 ± 40	Erl-12483[a]	1999-2183	2148
60-61	3373 ± 26	KIA 39910[b]	3558-3692	3616
96-97	8547 ± 51	Erl-12484[a]	9463-9601	9523
120-121	8899 ± 39	KIA 39911[b]	9898-10189	10,034
148-149	9900 ± 54	Erl-12173[a]	11207-11412	11,331
160-161	10,537 ± 57	KIA 39912[b]	12220-12277	12,543
196-197	19,795 ± 147	Erl-12485[a]	23230-24166	23,646

[a] AMS-Labor Friedrich-Alexander-Universität Erlangen-Nürnberg, [b] Leibniz Labor für Altersbestimmung und Isotopenforschung, Christian-Albrechts-Universität Kiel.

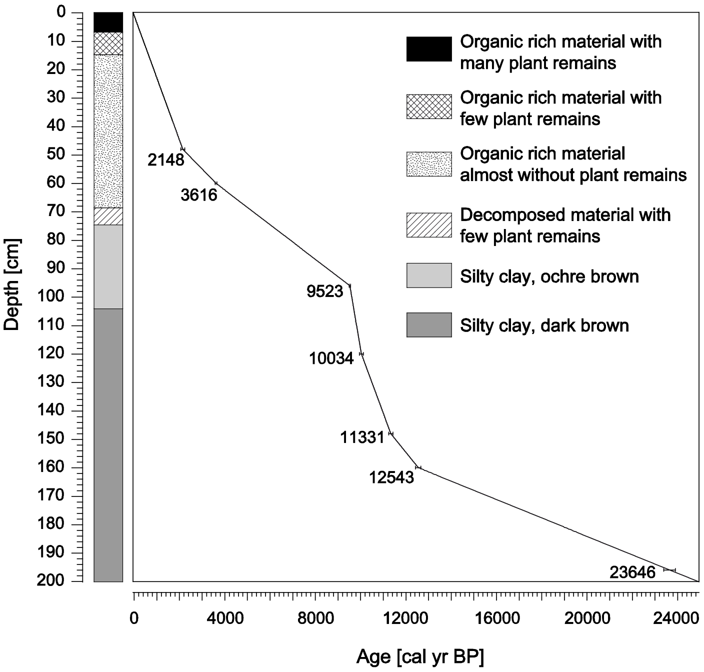

Fig. 2: Age depth curve of Pántano da Maurítia based on linear interpolation between the weighted average of calibrated ages (cal yr BP) in combination with stratigraphy of the core part from 0 to 200 cm.

Four zones (PDM = Pántano da Maurítia) were identified based on CONISS: zone PDM 1 (200-149 cm), PDM 2 (149-123 cm), PDM 3 (123-58 cm) and PDM 4 (58-0 cm) (Fig. 3). In the pollen diagram (Fig. 3) identified pollen taxa are grouped in five categories: tropical forest taxa (tropical rainforest and dry forest taxa), cold adapted taxa, palms, taxa of savanna ecosystems, and aquatic taxa (Salomão et al., 1988; Morellato and Rosa, 1991; Gentry, 1993; Cleef and Silva, 1994; Silva et al., 1996; Rayol, 2006; Marchant et al., 2007; Nunes, 2009). Only the most important or representative taxa for each category are shown. Moraceae pollen was classified as a tropical forest taxon, as today the only Moraceae species at Serra Sul associated with Campo rupestre is *Ficus nymphaeifolia*, and no *Ficus* pollen grains were encountered.

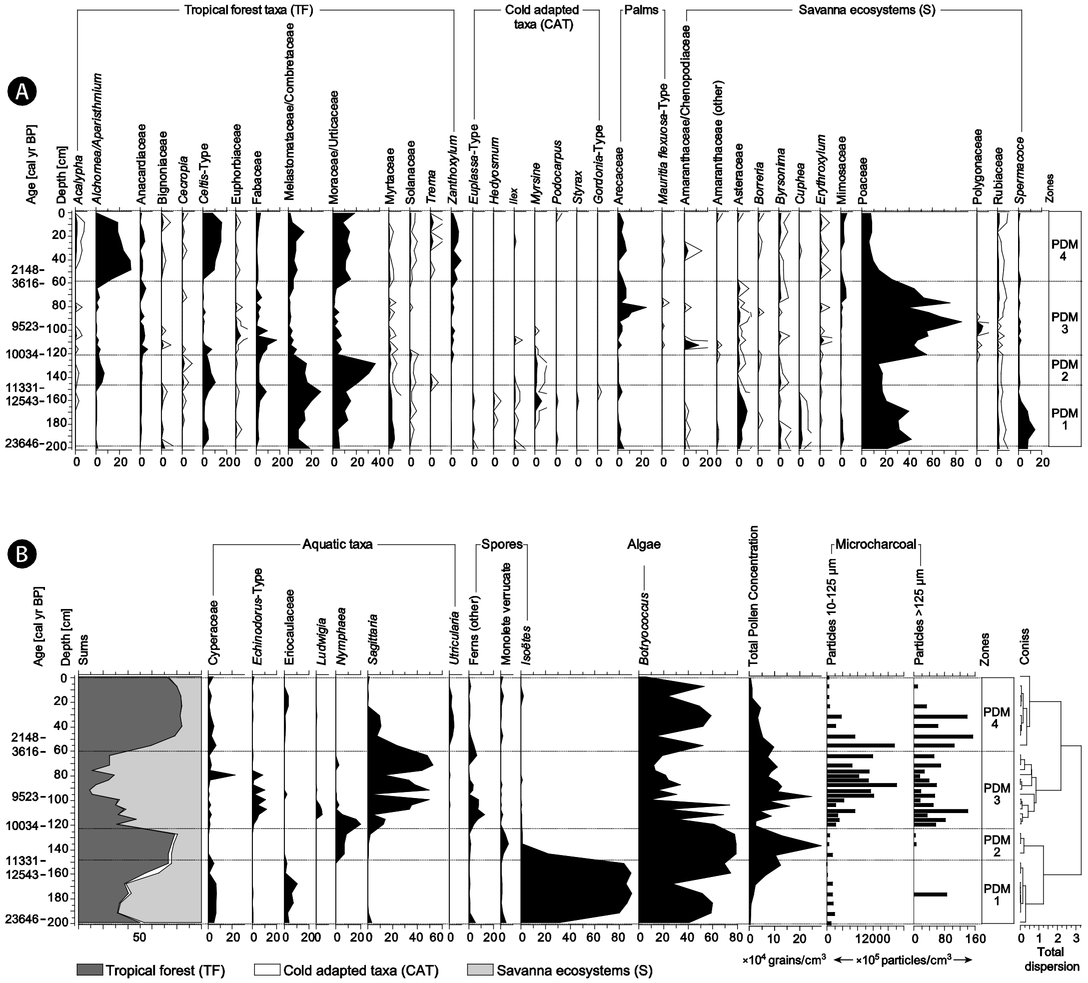

Fig. 3: Pollen percentage diagram and zonation of the Pántano da Maurítia core from 0 to 200 cm core depth. (A) Most important taxa grouped in tropical forest taxa (TR), cold-adapted taxa (CAT), palms and taxa of savanna ecosystems (S), solid lines indicate ×5 exaggeration, (B) Sums of TR, CAT and S together with aquatic taxa, spores and algae percentages, also shown are micro-charcoal concentrations.

Zone PDM 1 (200-149 cm; 7 samples; 25,000-11,400 cal yr BP)

The zone is characterized by high pollen frequencies of the savanna taxa Poaceae (40 %), *Spermacoce* (14 %), and Asteraceae (7 %). *Cuphea*, Mimosaceae, *Byrsonima*, Amaranthaceae/Chenopodiaceae, and Amaranthaceae (others) are abundant (<5 %). Tropical forest taxa (10-15 %) are mainly represented by pollen of Moraceae/Urticaceae and Melastomataceae/Combretaceae. The latter slightly increase (max. 25 %) at the end of the zone. Other tropical forest taxa include Fabaceae (max. 8 %), *Celtis*-type (7 %), and *Cecropia* (<5 %). Cold adapted forest taxa are represented by low frequencies of *Myrsine* (max. 11 %), *Ilex,* and *Hedyosmum* (both < 5 %), and single pollen grains of *Euplassa*-type, *Podocarpus*, and *Styrax*, most notably at 160-149 cm core depth. Arecaceae are abundant (<10 %), but absent at 174-160 cm (17,000-12,500 cal yr BP). The aquatic taxa Eriocaulaceae and Cyperaceae are frequent (ca. 8 %).

A high amount of spores of the aquatic *Isoëtes* (max. 90 %) is characteristic, fern spores only occur with low values (1-5 %). Colonies of the alga *Botryococcus braunii* are frequent (50 %, max. 78 %). At the beginning of the zone the total terrestrial pollen concentration is low with mean values of 5400 grains/cm^3. Between 176 and 149 cm (17,500-11,300 cal yr BP) concentrations increase to max. 124,300 grains/cm^3. The concentration of carbonized particles is low, except the high concentration of large micro-charcoal particles in one subsample (176 cm).

The zone is characterized by a brown colored clay unit with fine micro-units of dark organic matter (OM) with a cycling structure. The grain size analyses show a silt to clay domain (Fig. 4), changing from 10 to 51 µm at 50 % in frequency (35 µm in average). The sediments are composed of kaolinite, goethite, quartz, siderite, anatase, beside gibbsite, barite, talc and/or chlorite. The XRD spectrum (absence of the 20 to 22° 2Θ) shows a low structure order for kaolinite (Fig. 5). Goethite is abundant in nanocrystal scale showing an unequal distribution. Siderite is another typical mineral. It occurs with goethite, from which it has formed. Siderite forms micro- to sub-millimeter crystals, sometimes as well formed rhombohedra, which confer a friable sandy aspect to this unit. OM occurs and is strongly oxidized. A large XRD shoulder at 4.1 to 4.3 Å indicates the presence of opaline material in the sample bearing ‘Cauixi’ (fresh water sponges *Tubella reticulata* and *Parnula betesil*) and diatomaceous fragments. Opal changes gradually into quartz and kaolinite within this unit. Changing proportions of mineral and OM are responsible for the sediment bands of alternating color and texture.

Zone PDM 2 (149-123 cm; 3 samples; 11,400-10,200 cal yr BP)

High pollen frequencies of the rainforest taxa Moraceae/Urticaceae (max. 36%) characterize the whole zone. Melastomataceae/Combretaceae (max. 16%) and *Celtis*-type (11 %) are represented by moderate values. Pollen of *Alchornea/Aparisthmium* is frequent (<10 %) and the pioneer taxa *Trema* and *Cecropia* are abundant (<5 %). Percentages of the cold adapted taxon *Myrsine* decrease below 5 %. *Ilex* only occurs as a single pollen grain at 145 cm (11,200 cal yr BP). Pollen of savanna taxa show a clear decline in abundance compared to PDM 1, with lower values of Poaceae (ca. 15 %) and *Spermacoce*, Asteraceae, Myrtaceae, and *Byrsonima* (<5 %). *Cuphea* pollen is absent, and percentages of Arecaceae decrease (<5 %). Aquatic taxa are mainly represented by pollen of *Nymphaea* (3-12 %), an indicator for open water conditions.

A clear decrease in the abundance of *Isoëtes* spores is found at the beginning of this zone, together with a higher abundance of monolete verrucate fern spores (5 %). High frequencies of *Botryococcus braunii* (ca. 80 %) are characteristic. Pollen concentration is high with max. 285,000 grains/cm^3. The concentration of micro-charcoal particles is low.

The zone occurs in a thicker gray silt to clay unit rich on OM and micro-units of brown clay material, which covers PDM 1. It shows the same grain size and mineralogy of the underlying zone: kaolinite, goethite, siderite, anatase, opal, beside gibbsite, barite, talc, and/or chlorite. Opal found at 138 cm (10,800 cal yr BP) is much more frequent. OM still occurs together with the minerals, and is moderately preserved. Quartz is more abundant than in PDM 1 and is found along almost the entire zone. Most of the quartz seems to be the alteration product of organic opal mineralization (spicules and diatomaceous material) within PDM 2. Rock quartz grains are rare and primarily derive from the lateritic iron crust. Kaolinite is still frequent in the PDM 2 and shows a low structure order too. Goethite is abundant in nanocrystal scale showing an unequal distribution (PDM 1). Anatase persists as a nanocristalline mineral dispersed in the sediment and is less frequent (0.3 to 2.4 Wt. %). Together with the other minerals this confirms the persistence of lateritic source materials for the shallow lake.

Zone PDM 3 (123-58 cm; 14 samples; 10,200-3400 cal yr BP; PDM 3)

A decrease to generally low values of main tropical forest taxa (<10 %) is characteristic for this zone, though slightly higher values of Anacardiaceae, Bignoniaceae, and *Zanthoxylum*, and higher values of Fabaceae (max.18 %) between 123 and 96 cm (10,200-9400 cal yr BP) are recorded. Pollen of Arecaceae (ca. 8 %, max. 24 %) is frequent, as well as single pollen grains of *Mauritia flexuosa*-type. Only few pollen of the cold adapted taxa *Ilex* and *Myrsine* are found in the lower part of the zone, and are absent above 96 cm. Poaceae reach maximum values (max. 85 %), whereas other savanna related taxa remain below 5 %, except slightly higher values in Polygonaceae (123-92 cm, 10,200-8800 cal yr BP) and Mimosaceae (76-58 cm (6000-3300 cal yr BP). The zone is characterized by an increased abundance of seveal aquatic taxa, especially *Sagittaria* (ca. 40 %) and *Echinodorus*-type (ca. 15 %). At the base of the zone *Nymphaea* pollen increases to ca.18 %, but then decreases to low values or is even absent, while *Ludwigia* (5 %) occurs at 116-100 cm (9900-9600 cal yr BP). Cyperaceae show maximum values (22 %) at 80 cm (7000 cal yr BP).

Fern spores (ca. 8 %) slightly increase at the beginning of the zone, whereas spores of the monolete verrucate type decrease to low values or are even absent. Low mean values in *Botryococcus braunii* (20 %) are characteristic. In the lower part of the zone pollen concentration increases (max. 245,000 grains/cm^3), but decreases steadily between 92 and 58 cm (min. 72,540 grains/cm^3). High concentrations of carbonized particles occur, large particles at123-90 cm (10,200-8500 cal yr BP), and small particles at 90-58 cm (8500-3300 cal yr BP).

The zone is enclosed in a gray silt to clay sediment unit, rich on OM and micro-units of brown clay material. The organic debris reaches coarse silt. A clear enrichment of OM with an increased length of the debris up to the top of the zone can be observed. This suggests a change from a lake to a swamp environment. Quartz is frequent but kaolinite, goethite, siderite and anatase are rare or disappear in this zone. On the contrary opal becomes much more frequent as a component of 'Cauixi' (fresh water sponges *Tubella reticulata* and *Parnula betesil*) and diatomaceous fragments.

Zone PDM 4 (58-0 cm; 8 samples; 3400 cal yr BP to present)

The zone is marked by distinct increases in pollen frequencies as well as pollen accumulation rates (not shown) of the tropical forest taxa *Alchornea/Aparisthmium* (max. 30 %), *Celtis*-Type (max. 15 %), Melastomataceae/Combretaceae (max. 14 %), and Moraceae/Urticaceae (max. 19 %). A slight increase in frequencies of *Zanthoxylum* (<10 %) occurs, as well as pollen of the pioneer *Trema* (<5 %), whereas frequencies of Fabaceae (<10 %) decrease. Pollen of *Acalypha* (<5 %) occurs more continuously. Single pollen grains of *Ilex* (24 cm, 1000 cal yr BP) and *Podocarpus* (top sample) are recorded. As Mimosaceae pollen is scarcely present in the lower part of the zone, it increases to max. 10 % from 24 cm onward. Overall low pollen frequencies of savanna taxa and a clear decrease in the abundance of Poaceae pollen (ca.10 %) occur together with a decrease of the aquatic taxon *Sagittaria* (ca. 10 %),. Other aquatic taxa such as Cyperaceae, Eriocaulaceae, and

Utricularia occur with mean values around 5 %, whereas ferns spores decrease. High frequencies of *Botryococcus braunii* with strong oscillations are characteristic.

Pollen concentration decreases markedly from max. 96,800 grains/cm³ at the beginning of the zone to minimum values around 4,900 grains/cm³ at the end. High micro-charcoal concentrations are recorded up to 27 cm (1200 cal yr BP), from 27 cm onward the concentrations clearly decrease.

The zone occurs in a dark gray sediment unit primarily consisting of OM, represented by fine plant debris in the middle of the zone and coarse plant debris between 15-0 cm (7000-0 cal yr BP). Silica-rich remnants of sponges and diatoms are very frequent. Only quartz and opal can be found as minerals in this zone, where quartz is less frequent.

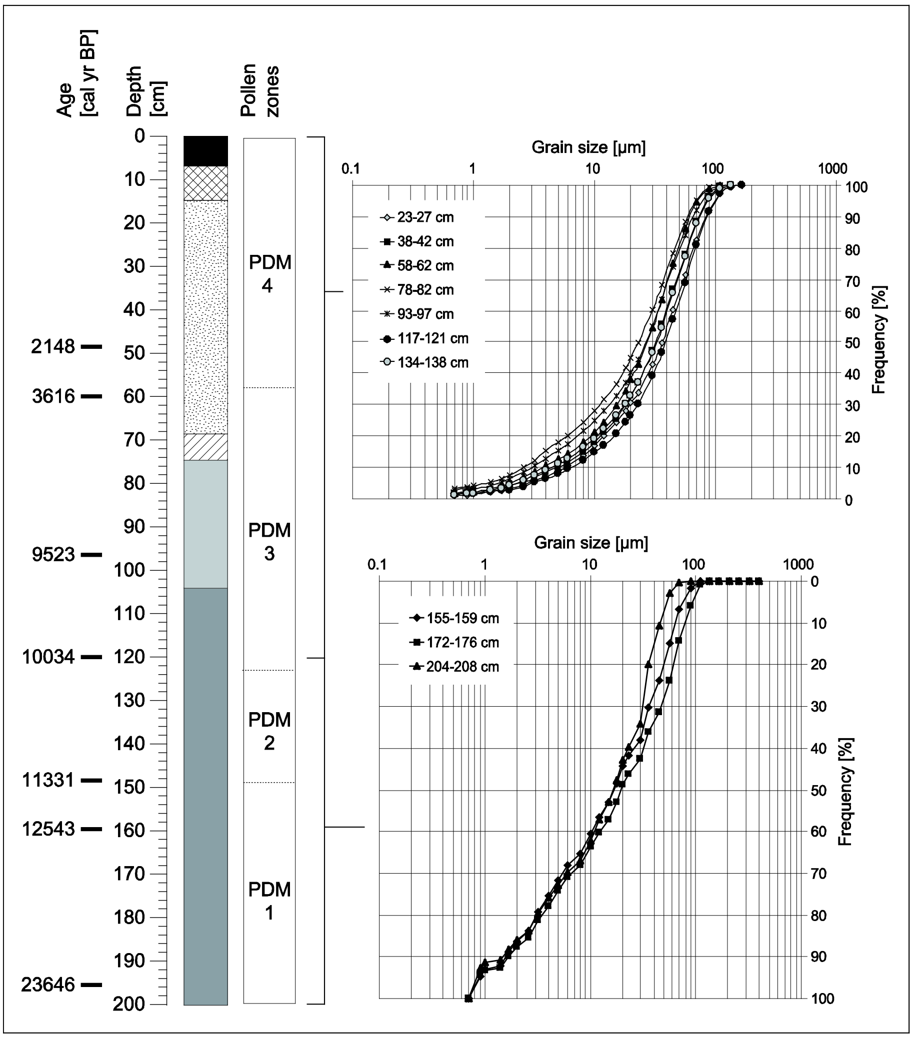

Fig. 4: Distinct grain size distribution (accumulative frequency) of sediments of Pántano da Maurítia.

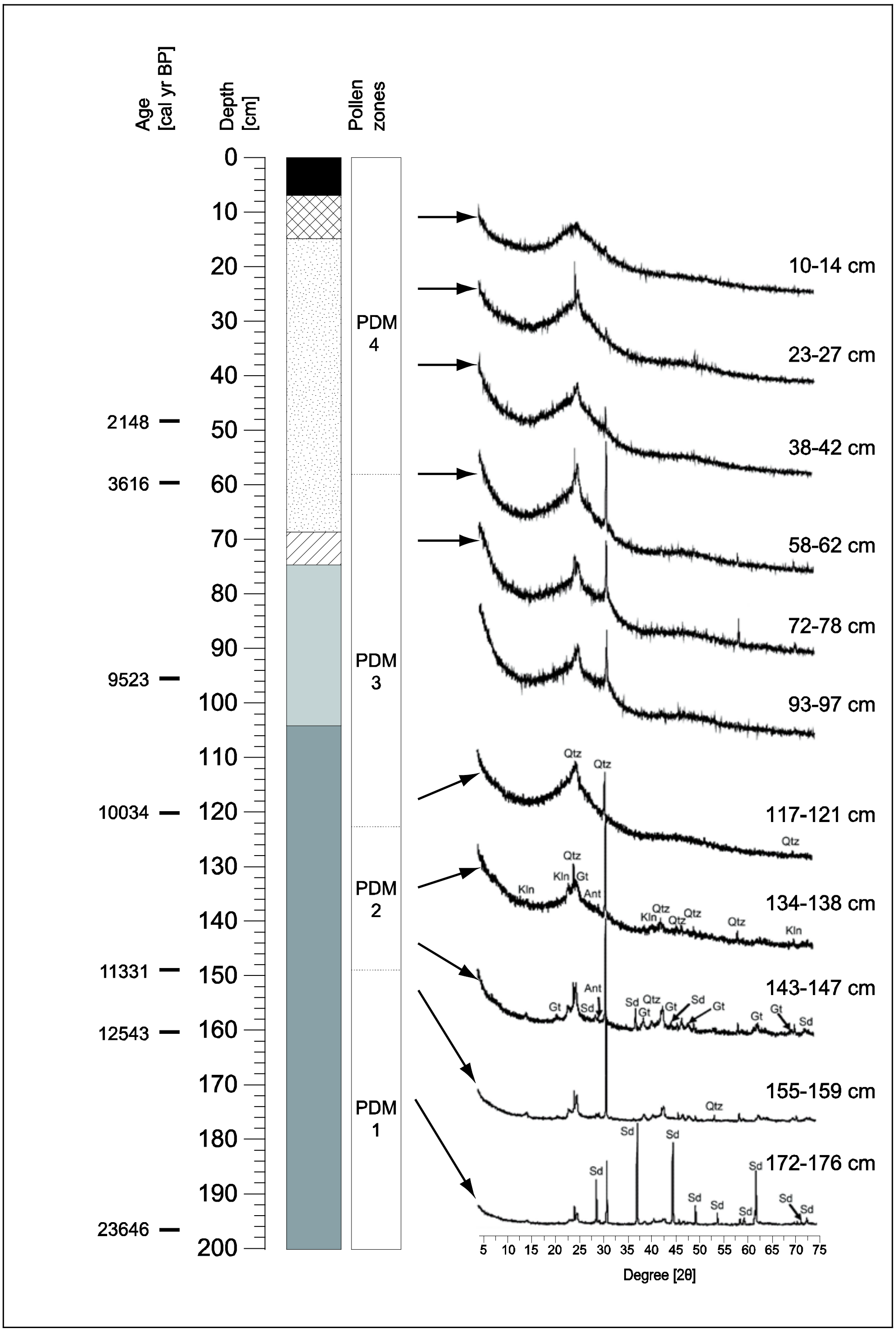

Fig. 5: The XRD main minerals at 0-200 cm core depth. Quartz (Qtz); goethite (Gt); kaolinite (Kln); anatase (Ant); siderite (Sd). The shoulder at 25° 2θ may be opal.

Paleoenvironmental reconstruction

Analyses of pollen, charcoal, organic content, mineralogy, and grain size in the Pántano da Maurítia sediment core provide insights into the local hydrology, fire, and vegetation of Serra Sul, and the regional vegetation and climate of southeastern Amazonia over the past 25,000 years. Pántano da Maurítia shows no sediment hiatus for the glacial period, in contrast to other records from Serra Sul and Serra Norte dos Carajás, which appear to have dried up during intervals of reduced precipitation (Absy et al., 1991; Sifeddine et al., 2001).

Characteristic color, grain size, and OM contents of the analysed sediment units indicate cycling environmental changes in physical sedimentary conditions from a sedimentary basin into a swamp. An inorganic domain (minerals from the neighboring lateritic crust: kaolinite, goethite, anatase, 'siderite') changed into vegetation-based organic accumulation (very small mineral contribution) under high humidity.

The late Pleistocene (25,000-11,400 cal yr BP; PDM 1)

The occurrence of semiaquatic *Isoëtes* and *Botryococcus braunii* colonies represents continuously low water depths. Poaceae, together with *Spermacoce*, Asteraceae, *Byrsonima*, and *Cuphea*, reflect larger areas of savanna vegetation than today which indicates drier climatic conditions between 25,000-11,400 cal yr BP. Rare occurrence of forest taxa suggests forested areas at the plateau's slopes, where soils with higher water and nutrient availability accumulate. These forest communities were different from today, as indicated by a suite of cold adapted taxa (Fig. 3). Even though climate was dry, the micro-charcoal data suggest low fire activity, perhaps due to cold temperatures or low biomass.

The deposition of a thick unit of inorganic, mainly lateritic material is indicative for slight weathering conditions during a long, generally dry period. The micro banding imprinted by alternation of thin gray sediment bands on the other side, may be indicative of an alternating water level of a shallow lake during short wet periods, which favored the diagenesis of laterite-bearing minerals into siderite. The deposition of lateritic detritus (hematite, goethite, and anatase) was induced by detritus flow and/or run-off during dry conditions without high vegetation.

We suggest that forests were smaller in size and the slopes were mainly covered by scrub-bush savanna until 13,000 cal yr BP. Today *Euplassa*, *Hedyosmum, Myrsine, Podocarpus*, and *Styrax* are known from montane forests (> 1000 m elevation) and *Ilex* is also associated with higher elevations (Marchant et al., 2002). These taxa, which are rare in modern lowlands, were mixed with lowland elements of tropical rainforests like Melastomataceae/Combretaceae and Moraceae/Urticaceae and are indicative for cooler climatic conditions. As these forest communities without modern analog show, forests in southeast Amazonia were not completely replaced by savannas as suggested by Absy et al. (1991). Likewise, a forest vegetation without a modern analog existed in northwest Amazonia during 22,000 - 12,000 cal yr BP (Bush et al., 2004). At the end of this period the increased occurrence of forest and decline of savanna at Pántano da Maurítia between 13,500 and 11,400 cal yr BP is in agreement with forest development in the surroundings of the plateau recorded by Sifeddine et al. (2001). The authors suggested erosion events due to intensive rainfall, indicative of wetter climatic conditions from 14,920-10,810 cal yr BP.

Both pollen data and paleovegetation simulations suggest that cold (Stute et al., 1995), dry climate and low atmospheric CO_2 may have resulted in low-density forests in Amazonia (Beerling and Mayle, 2006; Cowling et al., 2001).

Onset of the Holocene (11,400-10,200 cal yr BP; PDM 2)

A decline in abundance and diversity of cold-adapted taxa mark the transition from late glacial to early Holocene, and open water conditions (*Nymphaea*) occurred at the study site. High percentages of forest taxa and low micro-charcoal concentrations suggest the development of denser rainforest communities at sites where water and nutrient rich soil accumulated, for example at the slopes but also at lake borders and depressions ontop of the plateau.

Al-goethite, gibbsite and hematite become unstable due to strong root activity of growing trees by decomposing these minerals for nutrient extraction. The decomposition rate increases under high humidity and temperature. This caused their chemical dissolution, reduction of Fe^{3+} and simultaneously OM oxidation. Consequently HCO_3^- was formed, providing the physico-chemical conditions for new mineral formations (siderite, kaolinite). Kaolinite may be a reaction product of free Al-complexes and amorphous silica (opal OM). Forest development and restarted biochemical weathering of the exposed lateritic iron crust refer to a warming trend in the early Holocene with increasing wetter conditions.

Slowed erosion at Serra Sul from 10,810-7930 cal yr BP was interpreted as full development of humid forest (Sifeddine et al., 2001). Absy et al. (1991) interpreted the increased abundance of Melastomataceae from 11,000-8320 ^{14}C yr BP (12,600-9500 cal yr BP) as forest development. Our new detailed data suggest that forest development took only about 1200 years, with increasing abundance of various forest taxa including Moraceae/Urticaceae and Melastomataceae. Low occurrence of forest fires at Serra Norte from 11,800-7600 cal yr BP (Cordeiro et al., 2008) supports our interpretation. Furthermore, this corroborates paleovegetation simulations that show an increase in evergreen ombrophilous forests as a result of increased temperatures and atmospheric CO_2 levels (Cowling et al., 2001).

Early to mid-Holocene (10,200-3400 cal yr BP; PDM 3)

The most striking feature of this interval is the high abundance of Poaceae and *Sagittaria*, accompanied by generally low levels of arboreal savanna taxa and limited occurrence of tropical forest. The existence of aquatic and semiaquatic plants in large quantity allowed a high OM accumulation. The micro banding of brown sediments may be an indicator for conditions favoring laterite-bearing minerals coming from the swamp margins during short dry periods. The deposition of lateritic detritus (hematite, goethite, and anatase) was caused by detritus flow and/or run-off during short term rains under generally dry conditions.

Dry conditions could cause a reduction of the wetland due to a lowered water level and pollen deriving from local and aquatic vegetation (Poaceae and *Sagittaria*) would be statistically overrepresented (Fægri and Iversen, 1989) (Fig. 3a,b). Colinvaux et al. (1999) and Bush (2004) interpreted high amounts of grass (Poaceae) pollen at Serra Sul as an overrepresentation of local vegetation (wetland grasses). As it is not possible to distinguish wetland and savanna grasses palynologically, it remains uncertain if the high abundance of Poaceae is attributable to the contribution of wetland or savanna species. Thus a clear statement about the extent of the reduction of forest and expansion of savanna is almost impossible. To test if Poaceae pollen mainly derives either from wetland or savanna grasses, we excluded Poaceae from the pollen sum (not shown). As the sum of savanna taxa increases from 20 % (in the former period) to 40 % of the total pollen sum, we suggest that Poaceae pollen largely reflect the vegetation around the swamp and not only wetland grasses. Today Poaceae clearly belong to the surrounding campo rupestre vegetation (Rayol, 2006), whereas swamps are mainly covered by Cyperaceae (Cleef and Silva, 1994). Thus we think that grass dominated savanna expanded ontop of the plateau, whereas forest pollen represents forest vegetation at the slopes of the plateau only 600 m from the study site.

Our data suggest a highly variable water level over a long time period, with alternating wet and dry phases rather than an overall dry period. Frequent fires may also indicate long dry phases, as well as the overall low abundance of *Botryococcus*, which could be the result of dry seasons too long for this alga to survive. A possible scenario may be the development of a seasonal climate in southeast Amazonia with dry seasons longer than today. Longer dry seasons may have been coupled with increased precipitation during the wet season, as the presence of *Sagittaria* and a peak of Arecaceae refers to the availability of moisture sufficient to support a swamp environment. Slightly lower occurrence of forest taxa after 9000 cal yr BP could indicate even drier conditions until 3700 cal yr BP. Dry seasons longer than four months are not favorable for humid tropical rainforest (Sternberg, 2001; Maslin, 2001) and could be a possible causal factor for a more open vegetation at the slopes of the plateau. The occurrence of Anacardiaceae, Bignoniaceae, Euphorbiaceae, Fabaceae, and *Zanthoxylum* may also indicate the presence of forests similar to modern semi-deciduous dry tropical forest in southwest Amazonia that are able to handle longer dry periods (Gosling et al., 2009).

Sifeddine et al. (2001) suggested that opening of the forest at Serra Sul was caused by alternating dry and brief humid periods since 7930-9370 cal yr BP. Likewise, Martin et al. (1993) suggested that forest regression in the Carajás region was caused by a series of dry periods alternating with slightly wetter periods, in contrast to the idea of permanent dry conditions and the widespread extension of savannas (Absy et al., 1991). Fire events at Serra Sul 7000 and 5000 years ago (Elias et al., 2001), forest fires at Serra Norte between 7500-4750 cal yr BP (Cordeiro et al., 2008), and charcoal fragments in eastern Amazon soils between 6000-3000 ^{14}C yr BP (6850-3150 cal yr BP) (Soubiès, 1979) are thought to be climatically influenced. However, the recorded regional fire events from Pántano da Maurítia presumably derive from natural as well as anthropogenic ignitions, considering that early human occupation (hunter-and-gatherers) in the Carajás region occurred 9000 yr BP (Kipnis et al., 2005; Magalhães, 2009).

The late Holocene (3400 cal yr BP to present; PDM 4)

Increasing abundance of tropical forest taxa after 3400 cal yr BP suggests that modern rainforests established at this time. *Alchornea/Aparisthmium* clearly contributes to this increase as well as Moraceae/Urticaceae, *Celtis*, and *Trema*. Whereas forest trees of the genus *Alchornea* are known from mid-elevation sites, the pioneer taxon *Aparisthmium* contains small trees and shrubs growing chiefly on poor soils (Gentry, 1993; Colinveaux et al., 2000). Together with the increased abundance of the pioneers *Celtis* and *Trema* (Marchant et al., 2002) this suggests a successive expansion of tropical rainforest at the slopes, and the combined increase of *Alchornea/Aparisthmium* and *Moraceae/Urticaceae* indicates reduced water stress during this period due to increased precipitation. The occurrence of pioneers and high micro-charcoal concentrations between 3000 and 1400 cal yr BP could be indicative of human influence, but can also be explained by natural re-colonization of a more open habitat. Dark sediment units have been deposited at 1-1.5 m water level under aquatic vegetation and alga development. The domain of organic matter debris suggests the prevalence of a swamp.

Forest development with increased abundance of pioneers around 3140 cal yr BP at Serra Sul is documented also by Absy et al. (1991). The inferred changes in precipitation coincide with rising lake level at Serra Norte from 2800-1300 cal yr BP (Cordeiro et al., 2008).

Paleoclimatological context

A comparison of the record from Pántano da Maurítia with evidence from other Amazonian records is necessary to gain new insights into paleoclimatic changes in Amazonia.

Recorded dry conditions at the Carajás region from 25,000 to 11,400 cal yr BP are consistent with studies from ecotonal areas near the northern (Behling and Hooghiemstra, 2000; 2001; Behling, 2002) and southern margins (Turcq et al., 2002; Burbridge et al., 2004) of the Amazon Basin. In northeastern Amazonia aeolian activity indicates drier or seasonal conditions from 17,000 to 15,000 cal yr BP (Teeuw and Rhodes, 2004). Bush et al. (2004) interpreted drier and cooler conditions in northwest Amazonia without an increase in dry flora indicators as a reduction of precipitation in the wet season.

The mean position of the ITCZ, intensity of moist trade winds from the Atlantic Ocean, and onset and intensity of the Amazon convection are most frequently mentioned when explaining climatically induced vegetation changes in Amazonia. A reduction in annual rainfall was possibly the result of a delayed onset of Amazon convection during austral spring (Cook, 2009) and a smaller Amazon convective center (Sylvestre, 2009).

At the transition to warmer Holocene conditions, tropical South America experienced widespread environmental changes, but differences between eastern and western parts of the Amazon Basin as well as at the southern and northern margins are evident.

Contemporaneous with the wet early Holocene phase at Pántano da Maurítia, studies from northwest Amazonia suggest increasing seasonality or decreased moisture availability after 12,000 cal yr BP (Bush et al., 2004). From 11,800 to 10,000 cal yr BP a drying trend with shorter rainy seasons in northeast Brazil was possibly linked to a southern position of the ITCZ (Jacob, 2007), which could be an explanation for both the recorded increase in precipitation in southeast Amazonia and a more seasonal climate in the northwestern portions of the basin.

In southeastern Amazonia our data indicate an onset of seasonal climate at 10,200 cal yr BP with drier conditions than today. Even drier conditions from 9000-3700 cal yr BP are possibly related to an intensified seasonality in the mid-Holocene. This coincides with a regionally widespread mid-Holocene dry episode (Mayle and Power, 2008) in tropical South America, recorded in western Amazonia (Mayle et al., 2000; de Freitas et al., 2001; Burbridge et al., 2004; Bush et al., 2007) as well as in the Andes (Thompson et al., 1992; Cross et al., 2000; Baker et al., 2001; Mourguiart and Ledru, 2003; Paduano et al., 2003; Niemann and Behling, 2008; Brun-schön and Behling, 2009). Replacement of forest by savannas near the northern (Behling and Hooghiemstra, 2000) and southern (De Freitas et al., 2001; Burbridge et al.; 2004) margins of the Amazon rainforest indicates drier conditions and reduced precipitation.

Overlapping with the dry period from 9000-3700 cal yr BP, studies from northwestern Amazonia point to wetter conditions after 6060 ^{14}C yr BP (6900 cal yr BP) (Behling and Hooghiemstra, 2000) or strong seasonal conditions between 6100 and 5800 cal yr BP (Bush et al., 2000). A northward shift of the ITCZ (Haug et al., 2001; Koutavas and Lynch-Stieglitz, 2004; Silva Dias et al., 2009) could explain these drier conditions in southeast Amazonia and coevally wetter or more seasonal conditions in the northwestern Basin.

A shifting of the ITCZ is coupled with changes in Atlantic sea surface temperatures (SSTs). Early to middle Holocene dry conditions in Carajás roughly coincide with rising SSTs in the northern tropical Atlantic, which were 1-2 °C higher during the Holocene Thermal Maximum than today (Rühlemann et al., 1999). Hence, recorded vegetation changes at Serra Sul seem to be coupled with changes of Atlantic SSTs, which play a key role in modifying rainfall distribution and onset of the rainy season in central and eastern Amazonia (Fu et al., 2001; Cook, 2009). The drought in Amazonia in 2005, with delayed onset of the rainy season and occurrence of fires during the dry season, is also suggested to be linked to warming SSTs in the tropical North Atlantic (Marengo et al., 2008). Continuously increasing SSTs during the mid-Holocene possibly caused a reduced moisture transport to southern Amazonia due to reduced trade winds. It is conceivable that the influence of Atlantic conditions in southeastern Amazonia was more intense during the mid-Holocene than today due to strengthened SST rise in the Atlantic and simultaneously weaker ENSO activity (Sandweiss et al., 1996; Keefer et al., 1998; Rodbell et al., 1999; Clement et al., 2000; Sandweiss et al., 2001; Otto-Bliesner et al., 2003).

The establishment of modern humid rainforest at Serra Sul in the late Holocene, indicates increased precipitation and coincides with the expansion of modern rainforest in western Amazonia after 3000 cal yr BP in the south (Mayle et al., 2000; Burbridge et al., 2004) and around 3900 cal yr BP in the north (Behling and Hooghiemstra, 2000). Increased precipitation is also shown by records from eastern Amazonia (Bush et al., 2000; Behling and Costa, 2000), and rapid water level rise of Lake Titicaca at this time suggests generally intensified precipitation over the Amazon Basin (Cross et al., 2000). A shift of the ITCZ is suggested as a reason for precipitation changes (Haug et al., 2001), and a greater southerly migration of the ITCZ is assumed to be linked to increased annual precipitation and shorter dry seasons in southwest Amazonia (Mayle et al., 2000; Burbridge et al., 2004). Slightly reduced SSTs in the late Holocene (Rühlemann et al., 1999) probably resulted in intensified moisture transport from the tropical Atlantic and a stronger Amazon convection.

Conclusion

New results from pollen, spore, micro-charcoal, grain size and mineralogical sediment analyses from Pántano da Maurítia at the Serra Sul dos Carajás reveal a transition from a cool, dry LGM and late glacial (25,000-11,400 cal yr BP) to a warmer, wet early Holocene (11,400-10,200 cal yr BP) and the development of a strong seasonal climate in southeastern Amazonia in the course of the early-mid-Holocene (10,200-3400 cal yr BP). Humid tropical rainforest on the slopes of Serra Sul developed during an early Holocene wet period and around 3400 cal yr BP, when modern climatic conditions established. Adapted to cooler temperatures and lower atmospheric CO_2, forested areas on the slopes could have existed during the LGM together with savanna vegetation. During the mid-Holocene forested areas existed together with more extended savanna vegetation. These forests were possibly less dense forest communities that were able to handle long dry periods.

Several changes in precipitation patterns since the beginning of the Holocene affected environmental changes in southeast Amazonia. This region is tightly correlated to shifts of the ITCZ coupled with changing SSTs in the northern tropical Atlantic. In periods with lower SST and a southerly position of the ITCZ southeastern Amazonia experienced wet conditions, whereas increasing SSTs and the northward shift of the ITCZ were coupled with strong seasonal, but generally drier conditions.

Intensified fire events and the abundance of pioneer species over the past 9000 years may be partly attributable to human disturbance. However, environmental changes across the Amazon Basin coinciding with incidents in the Carajás region, strongly suggest that vegetation changes at Serra Sul are mainly forced by large scale climate fluctuations during the late Pleistocene and throughout the Holocene. Comparisons with data from other study sites in the Amazon Basin show a high accordance in timing and direction of recorded vegetation shifts, and therefore the results of this study allow for an integration into the current paleoclimatic discussion.

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III. Palaeoenvironmental dynamics and underlying climatic changes in southeast Amazonia (Serra Sul dos Carajás, Brazil) during the late Pleistocene and Holocene

Barbara Hermanowski, Marcondes Lima da Costa, Aliane Trinidade Carvalho, Hermann Behling

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Abstract

Pollen, fern spore, micro-charcoal, sediment and mineral analyses have been carried out on a 466 cm-long sediment core from the Serra Sul dos Carajás swamp in southeastern Amazonia. Ten AMS radiocarbon dates suggest that the sediment covers at least the last 73,000 years. Shifts between tropical forests and savanna, changes in species composition, as well as changes in fire frequency indicate several wet and dry periods during this time interval.

During the assumed early Pleniglacial (73-50 ka), the dominance of savanna vegetation reflects drier conditions, whereas vegetation changes in the mid-Pleniglacial (50-40 ka) suggest alternating wet and dry phases under generally cool conditions. The recorded next period before the Last Glacial Maximum (LGM) shows a transition to wetter and cooler conditions, followed by a cold and dry LGM and Lateglacial. At the beginning of the Holocene, between 11.4 and 10.2 cal ka, tropical forest expanded, reflecting stable and very humid conditions. During the early to mid-Holocene an increasingly seasonal, generally warm and dry climate established. Dry seasons were longer than at present during mid-Holocene times with a pronounced dry phase from 9 to 3.4 cal ka. Only after 3.4 cal ka did modern tropical rainforests became established under present-day climatic conditions.

Comparison with other palaeoecological studies in the Amazon basin and eastern Andean regions suggests that environmental changes in Serra Sul were strongly coupled with large scale climatic changes and sea surface temperature variability in the tropical Atlantic.

Keywords: Late Quaternary; Amazonian rainforest; edaphic savanna; pollen analysis; micro-charcoal analysis; sediment analysis

1. Introduction

The Amazon rainforest plays an important role in modulating regional precipitation patterns in northern South America, and is a major component of the global carbon and hydrological cycles as well. Changes in rainfall seasonality and rising atmospheric CO_2, accompanied by ongoing deforestation, intensified droughts and forest fires are the biggest threats Amazonia is presently experiencing (e.g. Nepstad et al., 1994; Nepstad et al., 1999; Costa and Foley, 2000; Nepstad et al., 2004). With respect to future climate change reliable long-term records revealing correlations between character and cause of climatic and vegetation changes are needed, for instance to determine areas of high and low climate-sensitivity in this region.

In Amazonia, available long-term climate and vegetation records are rare, and only few of these records date back beyond 20,000 years BP (Liu & Colinvaux, 1985, Bush et al., 1990, Absy et al., 1991; Van der Hammen et al., 1992; Colinvaux et al., 1996, Haberle, 1997, Mayle, 2000, Bush et al., 2004). These and other records (Colinvaux et al., 2000; Behling and Hooghiemstra, 2001; Sifeddine et al., 2001; Burbridge et al., 2004; Bush et al., 2004; Irion et al., 2006; Cordeiro et al., 2008) show how Amazonian ecosystems repeatedly adjusted to spatiotemporal changes in precipitation. Palaeoenvironmental records from the eastern Andean region cover considerably longer time scales than records from adjacent Amazonia (e.g. Hooghiemstra and Ran, 1994; Van't Veer and Hooghiemstra, 2000; Baker et al., 2001b; Bogotá et al., 2011; Groot et al., 2011). Given the correlation between precipitation in the Andes and Amazonia (Baker et al., 2001a) a comparison of Amazonian and Andean palaeoclimatic proxy records should result in a better understanding of the underlying causes of vegetation change in tropical South America.

In this contribution we report results from analysis of a 466 cm-long swamp sediment core from the boundary area between rainforest and savanna vegetation in southeast Amazonia, a region that today experiences a pronounced wet and dry season. The core records possibly more than 50,000 years of environmental history and includes the early and mid-Pleniglacial, LGM, Lateglacial, and Holocene periods. The upper part of the core (0 to 200 cm) from 'Pántano da Maurítia' (PDM), extending back to the LGM has been previously published (Hermanowski et al., 2012). The complete record provides new insights into the stability and dynamic of Amazonian ecosystems, including aspects of biodiversity. To support the palyno-logical analyses, we also carried out detailed grain size and mineralogical studies of the sediments. These provide very important proxies as well as help to define the nature of the geological basin and its relationship to neighbouring terrains.

Since precipitation in the eastern Andes and rainfall seasonality in southeast Amazonia is affected by the variability of Atlantic sea surface temperatures (SST) (Nobre and Shukla et al., 1996; Baker et al., 2005; Marengo et al., 1993, 2001, 2004; Fu et al., 2001; Liebmann and Marengo, 2001), we interpret our results in light of teleconnections with Atlantic SSTs (Rühlemann et al., 1999; Weldeab et al., 2006; Good et al., 2008) as well as vegetation and lake level changes in the Andes is discussed. Our results contribute to the debate on late Quaternary vegetation and climate history of the Amazon region.

2. Study area

The studied 'Pántano da Maurítia' swamp of c. 100 x 200 m size is situated in a small open valley on the narrow plateau of the Serra Sul dos Carajás (6°21'6.20"S, 50°23'36.60"W, 740 m) in southeastern Amazonia (Fig. 1). The plateau surface consists of ferruginous lateritic crusts and is characterized by numerous depressions with small lakes and swamps.

The regional climate is classified as Köppen Aw, tropical humid, with an average mean monthly temperature of 25°C. Between 2005 and 2009 the mean annual precipitation at the nearby Marabá climate station (5°37'S, 49°13'W, 95 m a.s.l.) was 1793 mm (INMET, 2010). During the peak of the wet season (December-February) mean precipitation is 1394 mm, and 61 mm during the peak of the dry season (June-August) (INMET, 2010). The pronounced wet season during austral summer is followed by a severe dry season from June to October with hardly any rainfall (Marengo, 2001; Sifeddine et al., 2001). The seasonality of regional precipitation is influenced by several factors, including the migration of the ITCZ (Intertropical Convergence Zone) due to changing Atlantic SST, moist trade winds from the tropical Atlantic blowing against the continent throughout the year, evapotranspiration from the forest itself, and the coupled onset and intensity of Amazon convection (Nobre and Shukla, 1996; Marengo et al., 1993, 2001; Fu et al., 2001; Liebmann and Marengo, 2001; Garreaud et al., 2009) (Fig. 1b). During the dry season the ITCZ is situated north of the equator and convection in eastern Amazonia is decreased. During the wet season the ITCZ moves south of the equator and convection is enhanced.

Due to edaphic conditions the local vegetation is highly susceptible to changes in precipitation. The modern vegetation of the Serra Sul is comprised of a mosaic of dense shrubby and open shrub-bush savanna, mostly described as 'campo rupestre' (Cleef and Silva, 1994; Silva et al., 1996; Sifeddine et al., 2001) on top of the plateau in quartzitic soils (Fig. 1a-b, 2). Within the campo rupestre vegetation occur small forest islands ("capão florestal"), mainly at lake margins and in topographic depressions (Nunes, 2009). Watercourses at the study site are bordered by 'Buritis' (Mauritia flexuosa), characteristic of swampy plains but generally rare on the plateau. Upland tropical rainforest can be found at the slopes (Nunes, 2009) and ombro-philous (evergreen) tropical forest (IBAMA, 2003) in the lower areas of the Carajás region. The characteristic components of this vegetation are described in detail as follows (Rayol 2006, Nunes 2009):

Campo rupestre, a complex of open and dense shrub-bush savannas, is associated with the nutrient poor brown to red soils composed of iron oxihydroxides, kaolinite and a small quantity of gibbsite. The most common plant families are Poaceae, Cype-raceae, Myrtaceae, and Asteraceae. Also the genera Borreria (Rubiaceae) and Byrsonima (Malpighiaceae) are characteristic. The 'open campo rupestre' vegetation is mainly characterized by several *Croton* (Euphorbiaceae) species, *Cuphea tenella*, and *Mimosa* (Mimosaceae). Characteristic of the 'dense campo rupestre' are Mimosaceae, *Byrsonima, Ficus nymphaeifolia* (Moraceae), *Miconia* and *Tibouchina* (Melastomataceae), Myrtaceae and Rubiaceae.

Forest islands within the dominating 'campo rupestre' vegetation are associated with rocky lake borders (a lateritic crust made of iron oxi-hydroxides and gibbsite), depressions and small canyons, where organic material and rain water accumulates. The floristic composition of these small forest patches is comparable to the forest at the slopes of Serra Sul. Dominant are Melastomataceae and several *Ficus* (Moraceae) species, as well as Anacardiaceae and two species of *Alchornea.*

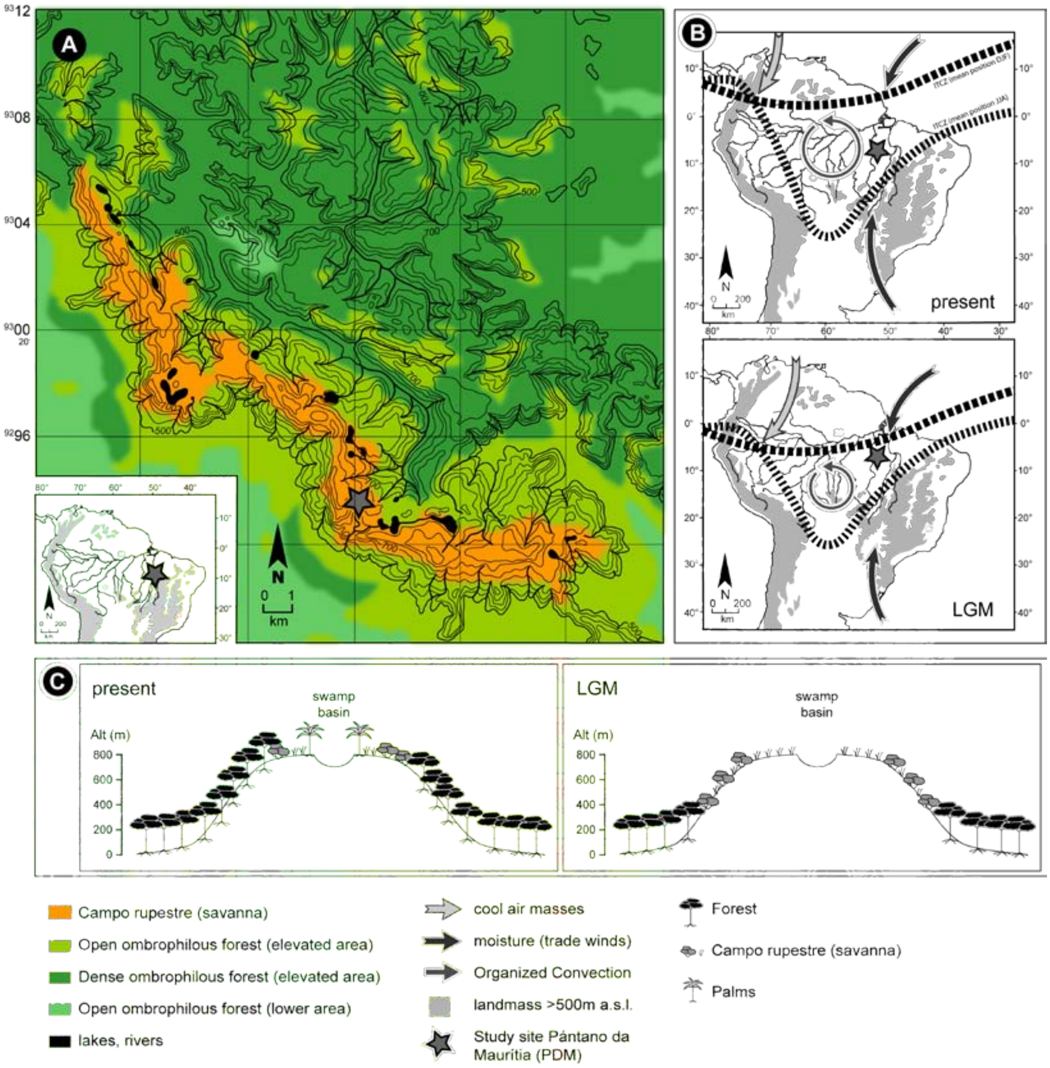


Fig. 1: Location, vegetation, and climate settings of the study site (Pántano da Maurítia; 6°21'6.20"S, 50°23'36.60"W, 740 m) in the Serra Sul dos Carajás and surrounding vegetation types. (A) Altitudinal profile and distribution of the main vegetation types (modified after: Plano de Manejo para uso múltiple da Floresta National de Carajás, 2003); (B) Comparison of the main climate circulation systems today and during the LGM; (C) Schematic cross-sections of Serra Sul today and during the LGM.

Fig. 2: Pántano da Maurítia at Serra Sul. Photographs of the study area show the transition from rainforest to savanna vegetation 'campo rupestre' (above) and the study site Pántano da Maurítia (PDM) with *Mauritia flexuosa* (below).

Along the slopes of the Serra Sul a forest with typical taxa of **upland tropical rainforests** occurs, e.g. Faba-ceae, *Alchornea* and other Euphorbia-ceae, Melastomataceae, Anacardiaceae, Moraceae and Meliaceae. On the clayey and iron oxihydroxide soils poor in nutrients a successional forest occurs represented mainly by *Aparisthmium* and *Erythroxylum* (Morellato and Rosa, 1991). The lower areas of the region are represented relatively nutrient poor and wet soils where **lowland tropical rainforest** (Amazonian terra firme forest) grows, dominated by Fabaceae, Meliaceae, Melastomataceae, Euphorbiaceae, Anacardiaceae, Bignoniaceae, Moraceae and Combretaceae (Salomão et al., 1988; Morellato and Rosa, 1991).

3. Material and methods

A 466 cm-long sediment core was recovered from the swamp using a Russian corer in 50 cm long sections in 2005. The core was transported to the Geoscience Institute at the Universi-dade Federal do Pará (UFPA) in Belém (Brazil), and stored in darkness at 4°C until sample processing. A total of 10 sediment samples (of 2-3 g each) were used for radiocarbon dating by the Accelerator Mass Spectrometry (AMS) laboratory Erlangen (Germany) and the Leibniz-Laboratory for Radiometric Dating and Isotope Research in Kiel (Germany).

3.1 Sedimentology and mineralogy

21 sediment samples were analyzed for grain size and mineralogical composition. The grain size distribution was performed by laser particle analyzer Quantachrom-Cilas 920, from 0.3 to 400 µm, at the Institute of Geosciences (University of Halle). Mineral identification was carried out by the X-Ray Diffraction (XRD) powder method with a PANalytical diffractometer X'PERT PRO. The acquisition data from 4 to 75° 2θ were carried out with X'Pert Data Collector software 2.1a, and treated with X'Pert HighScore software 2.1b. A scanning electron microscope (LEO 1450VP model) with energy dispersive system (SEM/EDS) was used to complete the mineral characterization. These analyses were carried out at the Geosciences Institute (UFPA, Belém).

3.2 Pollen and charcoal analysis

72 sediment samples (0.5 cm^3) of the core were used for pollen and charcoal analysis. Pollen samples were prepared using standard methods (Faegri and Iversen, 1989) including 70% HF treatment. The exotic marker *Lycopodium clavatum* (Stockmarr, 1971) was added for concentration and influx calculations. Pollen and spore counts were made at x400, pollen identification at x400 and x1000 magnification. Almost all samples were counted to a minimum of 300 terrestrial pollen grains, except the samples from 0 cm, 8 cm, and 200 cm, where pollen concentration was too low (Fig. 4). Spores and pollen of aquatic taxa were not included in the pollen sum, but expressed as percentages of the terrestrial pollen sum.

For charcoal analysis charred particles were counted on the same pollen slides. Two size classes were distinguished: small particles (10-125 µm) mainly representative of regional fires and large particles (>125 µm), representative of local fires near the catchment area (Gardner and Whitlock, 2001; Sadori and Giardini, 2007).

The percentage pollen diagram was plotted in Psimpoll (Bennett, 1998) and the zonation of the diagram was based on CONISS cluster analysis (Grimm, 1987). The AMS radiocarbon dates were calibrated with BCal (Buck et al., 1999) using IntCal04 calibration curve (Reimer et al., 2004). Pollen and spore identification is based on reference literature (Roubik and Moreno, 1991; Carreira et al., 1996; Colinvaux et al., 1996; Carreira and Barth, 2003) and a pollen reference collection at the Department of Palynology and Climate Dynamics (University of Göttingen, Germany) containing more than 3000 neotropical taxa.

Identified pollen taxa were grouped into five categories: tropical forest taxa, cold adapted taxa, palms, savanna vegetation and aquatics. Moraceae pollen was classified as a tropical forest taxon. Today the only Moraceae species at Serra Sul associated with the campo rupestre complex is *Ficus nymphaeifolia*; however, the counted Moraceae pollen grains never included the *Ficus* type.

4. Results

4.1 Chronology

The chronology for the core is based on 10 AMS ^{14}C dates (Tab. 1). The age depth curve is calculated in Psimpoll by linear interpolation between the weighted average of calibrated ages (Fig. 3). Radiocarbon dates at 248 cm, 342-346 cm and 438-442 cm core depth with an age of 46,807 ± 1016, 39,511 ± 781 and 47,973 ± 3976 ^{14}C yr BP, respectively, are beyond the radiocarbon dating range. The well dated upper core part suggests continuous sedimentation without any gaps. Based on the sedimentation rate of the calibrated radiocarbon dates at 196 and 160 cm core depth, the extrapolated age of the core base at 466 cm would be about 75 to 87 ka BP. Due to the limitation of the dating of the lower core part, even older ages are possible, depending on the applied method for age-depth modeling. The sedimentation rates of the core range between 0.05, 0.09, and 0.13 mm/yr.

Tab. 1: Radiocarbon dates from the Pántano de Maurítia sediment core.

Depth (cm)	Laboratory number	dated material	^{14}C yr BP	δ^{13}C (‰)‡	Age (cal yr BP)
48-49	Erl-12483[a]	peat	2140 ± 40	-28.4	2148
60-61	KIA 39910[b]	peat	3373 ± 26	-22.76 ± 0.19	3616
96-97	Erl-12484[a]	peat	8547 ± 51	-21.6	9523
120-121	KIA 39911[b]	peat	8899 ± 39	-27.42 ± 0.26	10,034
148-149	Erl-12173[a]	bulk sediment	9900 ± 54	-28.6	11,331
160-161	KIA 39912[b]	bulk sediment	10,537 ± 57	-27.69 ± 0.31	12,543
196-197	Erl-12485[a]	bulk sediment	19,795 ± 147	-21.6	23,646
248-249	Erl-12174[a]	wood fragment	46,807 ± 1016	14.3	uncalibrated
342-346	Erl-12089[a]	bulk sediment	39,511 ± 781	-27.2	uncalibrated
438-442	Erl-12090[a]	bulk sediment	47,973 ± 3976	-29.2	uncalibrated

[a] AMS-Labor Friedrich-Alexander-Universität Erlangen-Nürnberg, [b] Leibniz Labor für Altersbestimmung und Isotopenforschung, Christian-Albrechts-Universität Kiel.

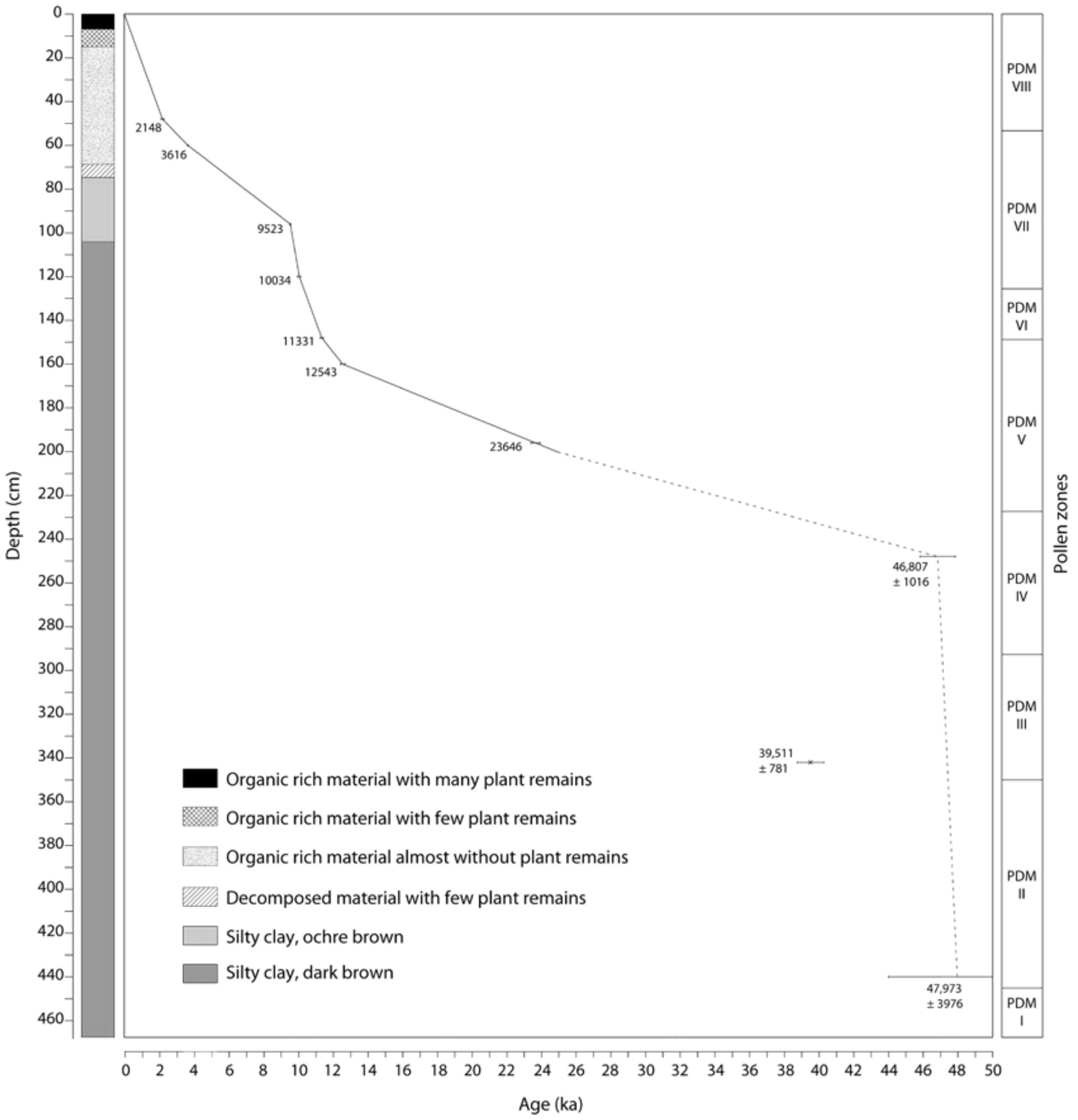


Fig. 3: Age depth curve of the Pántano da Maurítia core in combination with stratigraphy. The age depth model is based on linear interpolation between calibrated dates (cal ka).

4.2 Sedimentological and mineralogical description

The grain size changes and the identified minerals along the stratigraphical succession are shown in Figs. 5 and 6. Between the base and 442 cm core depth the sediment is composed of light brownish clayey to silty material (grain size 12 µm at 50% frequency, however it displays a wide range from 0.7 to 70 µm; Fig. 5) with saccharoidal texture, massive to somewhat finely banded by alternation of light and dark brown sediments. The dominant minerals are siderite and goethite (Fig. 6). Siderite forms large silt-size crystals giving rise to the saccharoidal texture. Siderite can be formed by diagenesis of sediments at the bottom of a lake for instance derived from goethite and organic carbon. Possibly goethite was deposited into the basin by erosion of the surrounding lateritic iron crusts composed of hematite and goethite.

From 442 to 200 cm core depth, sediments are mainly brownish, contain more silt (the grain size analyses show two modes, a light one at 15 µm and another very conspicuous at 56 µm) (Fig. 3) with alternating bands of light and dark brown. The two modes can reflect this alternating banding. They are mineralogically constituted by kaolinite and goethite, both of low order crystal structure after XRD analysis, quartz (Fig.6) and anatase is an accessory mineral. The mineral distribution along this sediment section is quite homogeneous suggesting stable environmental conditions. However, the fine banding may indicate an environment with alternating conditions during sedimentation. The brown bands dominated by kaolinite and goethite correspond to much more inorganic debris coming from the surrounding iron crust, and the dark ones beside these minerals carry fine organic matter, which may indicate climate changes that alternated in their favorability for plant development. On the other hand, the domain of kaolinite and goethite indicates a predominantly tropical soil derived from weathering alteration of the Al-bearing iron rich crust, which outcrops today on the margin of the swamp, and was derived from the banded iron formation (BIF) in Carajás. Kaolinite is the main mineral between 350 and 290 cm and the XRD diagrams display characteristics of amorphous phases (Fig.6). Goethite and quartz are less frequent than before and the dark brown sediments between 290 and 280 cm depth derive from very fine organic matter (OM) and kaolinite. At this depth interval, quartz becomes more common and goethite is rare. Possibly quartz may be a product of the mineralization of the biopal (biogenic opal) found in the spicules of the fresh water sponges *Tubella reticulata* and *Parnula betesil* ('cauixi'), which are very frequent in the sediments.

In contrast to the previous core interval from 442-200 cm, the sediments between 199 and 143 cm are characterized by a brown colored clay unit with fine micro-units of dark OM of a cyclic structure, which is clearly micro-banded. The grain size analyses show a silt to clay domain (Fig. 6), changing from 0.7 to

135µm (35 µm at 50% in frequency), becoming much more silty upwards (Fig. 6). Two grain size modes can be recognized as well, similar to the first basal sediments, from 462 to 442 cm depth. The sediments of this section are composed of kaolinite, goethite, quartz, siderite, anatase, as well as gibbsite, barite, talc and/or chlorite, which is much more distinct from the underlying sediments. Siderite is much more abundant from 208 to 172 cm depth. After the XRD spectrum (absence of the reflections though 20 to 22° 2Θ) kaolinite may be of low structure order (Fig. 6), which strongly suggests its origin is in tropical soil covering the iron crust of Pántano da Maurítia. Nanocrystalline goethite is abundant with unequal distribution and occurs together with siderite. The micro- to sub millimeter crystals of siderite confer a friable sandy aspect of this sediment unit. The presence of siderite and goethite together, besides the OM, may be an indication of intensive diagenesis inside of the sediment packet caused by strong oxidation of the OM. The diagenesis led to partial transformation of opal into kaolinite and crystallization of quartz after opal. The presence of opaline materials is indicated by the XRD shoulder at 4.1 to 4.3 Å, and they constitute the 'cauixi' and diatomaceous fragments observed under SEM. These organisms suggest a deposition of these sediments under shallow water. The color and mineral banding indicate changing proportions of minerals and OM and are responsible for the sediment bands with alternating color and texture, as a consequence of alternating changes of the water level in the environment.

The core section from 143 to 50 cm core depth is characterized by a gray silt to clay sediment unit, rich in OM and brown clay material. A clear enrichment of OM with increased length of the fragments (a typical coarse silt observed in the grain size analysis, Fig.5) from the bottom to the top of this unit is recorded, which suggests a change from a lake to a swamp environment. Quartz is frequent and becomes more abundant above 120 cm; most of it seems to be a mineralization of organic opal (spicules and diatomaceous material) as observed in the underlying unit. Quartz grains deriving primarily from the lateritic iron crust are rare. Kaolinite, goethite, siderite, and anatase are also rare or disappear completely (Fig.6). Between 120 and 50 cm, nanocrystalline goethite is abundant with an unequal distribution and nano-crystalline anatase is less frequent (0.3 to 2.4 Wt. %). The very low contribution of minerals coming from the surrounding swamp area confirms the low erosion rate. It is likely that the domain of terrestrial and swamp plants limited the erosion and transport of mineral into the basin.

From 50 cm to the core top, the sediments are of dark gray color and consist primarily of OM. In the middle of this core part, OM is represented by fine plant debris and between 15-0 cm (700-0 cal ka) it is represented by coarse plant debris. Silica-rich remnants of sponges and diatoms are frequent. The mineral component is represented by less quartz and much more opal. These mineral characteristics indicate no inorganic contribution from the lateritic rocky crust and soils surrounding the basin, which point to the general absence of erosion events in the last 3.4 cal ka.

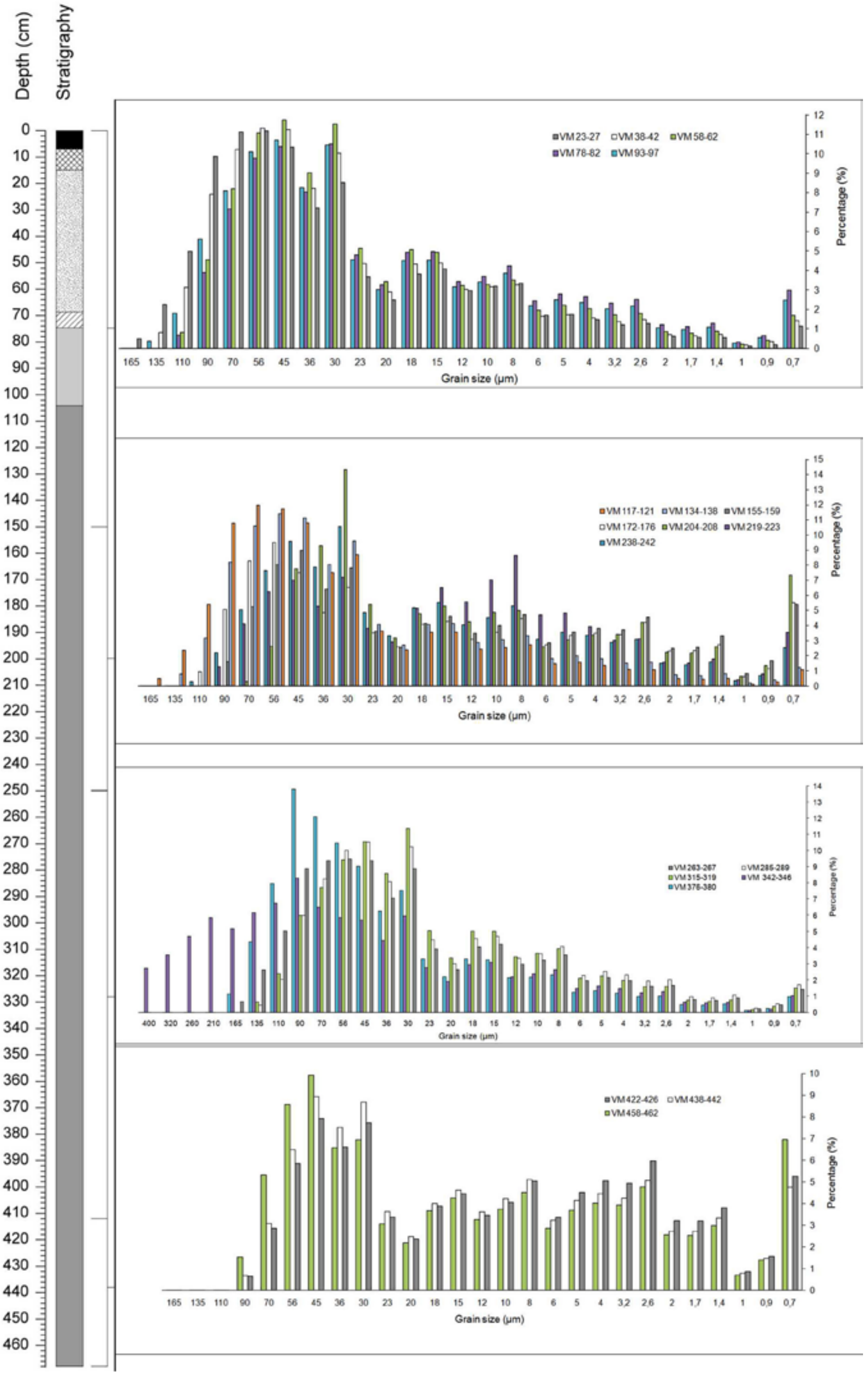


Fig. 5: Distinct grain size distribution (accumulative frequency) of sediments of Pántano da Maurítia. Sample number indicates depth in cm.

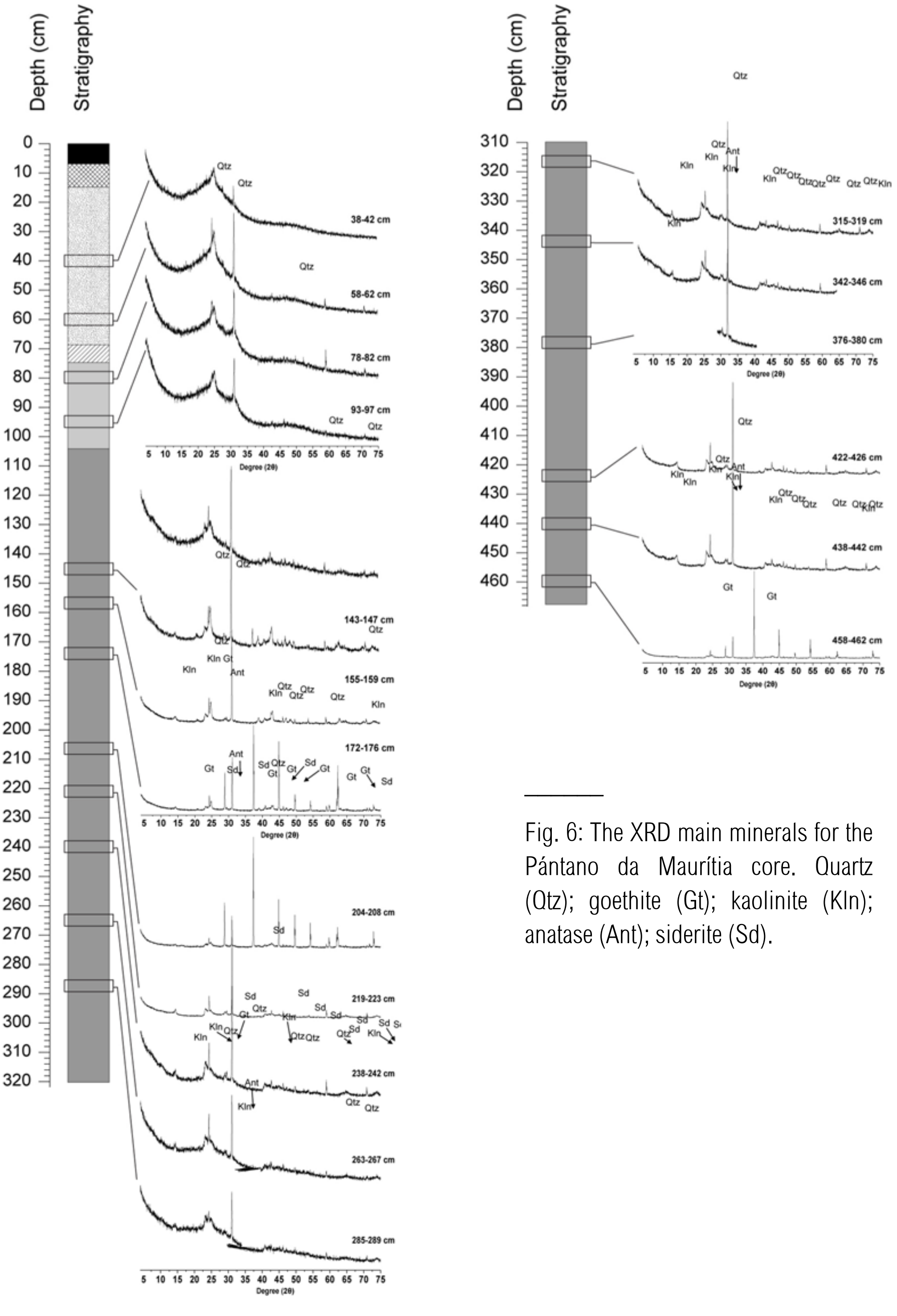


Fig. 6: The XRD main minerals for the Pántano da Maurítia core. Quartz (Qtz); goethite (Gt); kaolinite (Kln); anatase (Ant); siderite (Sd).

4.3 Description of the pollen zones

The pollen diagram shows percentages of the most important taxa, sums of the groups, as well as pollen and charcoal concentration. Pollen and spore diversity, which is based on a pollen sum of around 300, is illustrated for each category (tropical forest incl. palms, cold adapted taxa, savanna vegetation, aquatics and spores) as well as the overall palynological richness (Fig. 4). The group 'cold adapted taxa' comprises the genera *Euplassa*-type, *Ilex, Hedyosmum, Myrsine, Podocarpus, Styrax,* and *Weinmannia*-type. Those genera are mainly known from mid- and high-elevation areas in the Andes and also in the Atlantic Rainforest, though some species also occur in the lowlands of Amazonia for example *Podocarpus lambertii* (Bush, 2002) and *Ilex jenmanii*. Palynologically, mountain and lowland species are not distinguishable, but a composition of more than 3 different taxa is likely to reflect vegetation with an adaption or a tolerance to cooler conditions.

4.3.1 Zone PDM-I, 466-445cm (>50 ka ; 3 samples)

Characteristic for this zone are the low frequencies of tropical forest taxa, mainly represented by Melastomataceae/Combretaceae (max. 20%), Moraceae/Urticaceae (max. 14%), and Fabaceae (max. 10%). *Celtis, Alchornea/Aparisthmium*, and Anacardiaceae are also represented (<5%) as well as few pollen grains of Euphorbiaceae, *Acalypha*, and Bignoniaceae. The cold adapted taxon *Myrsine* (max. 10%), and *Ilex, Hedyosmum, Podocarpus,* and *Weinmannia*-type (single pollen grains only) also occur. High pollen frequencies of savanna taxa are recorded, in particular Poaceae (max. 32%) and *Spermacoce* (max. 24%). Aquatic taxa occur with low values (3-10%), mainly represented by Cyperaceae, *Echinodorus*-type, *Sagittaria*, and Utricularia. Especially prominent are very high amounts of spores of the semiaquatic *Isoëtes*. Palynological richness is relatively high at the base of the zone but then decreases based on a decline of diversity of the tropical forest (incl. cold adapted taxa) and the savanna vegetation group. Charcoal concentrations of small particles (10-125 µm) are low, accompanied by slightly higher values of large charred particles (>125 µm).

4.3.2 Zone PDM-II, 445-350 cm (>50 ka ; 15 samples)

High pollen frequencies of tropical forest taxa, in particular Melatomataceae/Combretaceae (max. 52%) dominate this zone. Moraceae/Urticaceae pollen is also frequent in the lower part of the zone (max. 24%) In the middle, Ochnaceae pollen is present (< 5%), accompanied by a few pollen grains of *Cleidion*- and *Caryo*-

dendron-type, *Protium,* and Sapinda-ceae. Cold adapted taxa are mainly represented by *Ilex* (max. 12%). Only few pollen grains of *Podocarpus* occur in the lower zone part, together with pollen of the *Gordonia*-type. In the upper part a few pollen grains of *Hedyosmum, Euplassa*-type, and *Styrax* are recorded, whereas *Myrsine* clearly decreases. The savanna taxa Poaceae (max. 30%) and *Spermacoce* (max. 2%) markedly decrease. Aquatics are mainly represented by *Eriocaulaceae* (max. 14%) between 420-350 cm and *Nymphaea* occurs with generally low values (max. 18% at 402 cm). Percentages of *Isoëtes* mainly decrease (20%) and are mostly lower at the base of the zone, but increase in the upper part. Single spores of the tree fern *Cyathea* occur in the lower zone part but remain rare throughout the record. *Botryococcus* values increase to max. 90%. The palynological richness is slightly lower than in the previous zone and remains relatively constant. In the upper part of the zone it slightly increases. The concentration of charred particles of both size classes decreases.

4.3.3 Zone PDM-III, 350-292 cm (>50-30 ka, 9 samples)

Tropical forest taxa Melastomataceae/Combretaceae and Moraceae/Urticaceae are markedly lower in this zone. Values of *Celtis*, Anacardiaceae, and Fabaceae remain relatively constant. Cold adapted taxa like *Ilex* and *Myrsine* decrease, and single pollen grains of *Hedyosmum* and *Weinmannia*-type are present. The zone is dominated by the high abundance of the savanna taxon Poaceae (max. 47%), whereas percentages of *Spermacoce* remain at low values. *Byrsonima* slightly increases in the middle of the zone (<5%). The initial increase in aquatic taxa at the base of the zone is due to Eriocaulaceae (max. 39%) which decrease to 8% in the upper part of the zone. Spores of *Isoëtes* are frequent in the lower zone part (max.58%), but then decrease to low values. In the lower half of the zone the palynological richness slightly decreases due to lower diversity of tropical forest taxa, cold adapted taxa, savanna vegetation taxa, and also aquatics. In the second half, a higher diversity of tropical forest, savanna vegetation and aquatics lead to an increase in overall palynological richness. The concentration of charred particles is higher in both size-classes than in the former zone with higher concentrations in one sample at the end of the zone.

4.3.4 Zone PDM-IV, 292-228 cm (c. 30-25 ka ; 10 samples)

This zone is dominated by the tropical rainforest taxa Melastomataceae/Combretaceae (max. 51%). The cold adapted taxon Ilex increases slightly, and at the end of the zone single pollen grains of *Hedyosmum, Podocarpus* and *Weinmannia*-type are recorded. In the savanna group, Poaceae decrease (< 30%) in the lower half of the zone, but increase in the upper half (max. 46%). In the group of aquatic taxa a decrease of *Eriocaulaceae* (max. 4%) and *Nymphaea* pollen (4-10%, max. 18%) is recorded, and Cyperaceae slightly increase (max. 4%). In the upper part of the zone, pollen of the semi-aquatic *Sagittaria* is well represented (c. 10%) and *Isoëtes* increases (max. 45%). The overall palynological richness remains relatively constant with slightly lower diversity in the middle of the zone, mainly due to lower diversity in the tropical forest and savanna vegetation group, which is accompanied by higher diversity of aquatic taxa. Concentrations of charred particles in both size classes remain constant.

4.3.5 Zone PDM-V, 228-149 cm (c. 25-11.4 cal ka ; 8 samples)

Tropical forest taxa are frequent (10-15%), mainly represented by Melastomataceae/Combretaceae, and Moraceae/Urticaceae. Other tropical forest taxa are represented by Fabaceae (max. 8%), *Celtis* (7%), and *Cecropia* (<5%). Cold adapted forest taxa are represented by low frequencies of Ilex (max. 11%), and few pollen of *Myrsine*, *Euplassa*-type, *Podocarpus*, and *Styrax*. In the upper zone part pollen of *Hedyosmum* occurs. Areca-ceae are abundant (<10%), but absent in the upper part of the zone. Relatively high pollen frequencies of savanna taxa, in particular Poaceae (40%), *Spermacoce* (14%), *Asteraceae* (7%), and *Myrtaceae* (5%) are recorded. Values of *Cuphea* and Mimosaceae slightly increase, and Amaranthaceae/Chenopodiaceae, and Amaryllidaceae are represented by only few pollen grains. *Byrsonima* shows constantly low values, or is altogether absent. The aquatic taxa Eriocaulaceae and Cyperaceae are frequent (8 %). A high number of spores of *Isoëtes* (max. 90 %) is characteristic. The overall palynological richness slightly increases in the lower half of the zone due to higher diversity in the savanna and aquatic group, and decreases in the upper half due to lower diversity of tropical forest and aquatic taxa. Concentration of carbonized particles is low in both size classes.

4.3.6 Zone PDM-VI, 149-123 cm (c. 11.4-10.2 cal ka ; 3 samples)

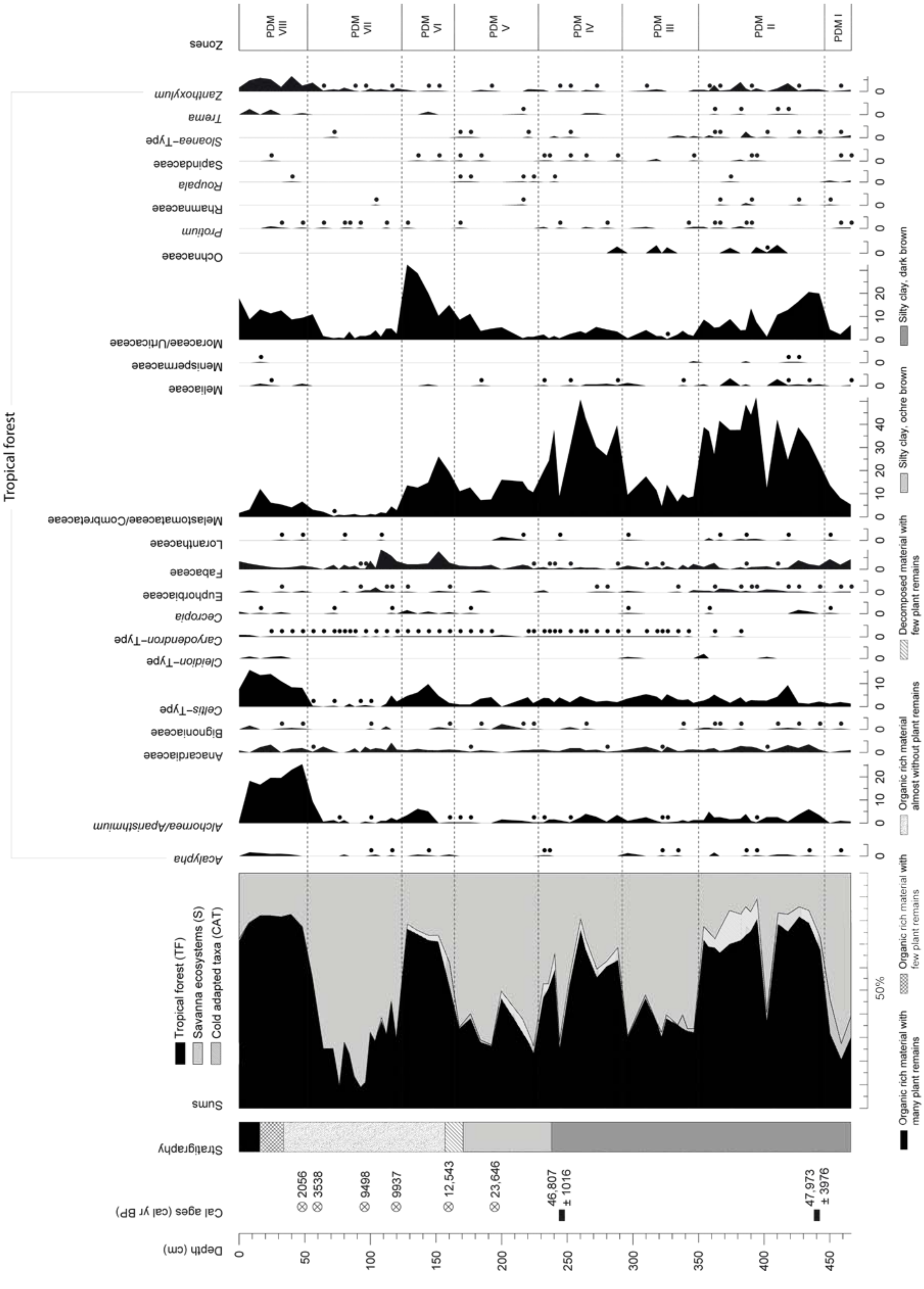
High pollen frequencies of the rainforest taxa Moraceae/Urticaceae (max. 36%) are characteristic for this zone. Melastomataceae/Combretaceae (max. 16 %) and *Celtis* (11 %) are represented by moderate values. Pollen of *Alchornea/Aparisthmium* is frequent (<10 %) and pioneer taxa *Trema* and *Cecropia* are abundant (<5 %), as well as Fabaceae (max. 7%). Cold adapted *Myrsine* decreases to values below 5 %. Pollen of *Euplassa*-type, *Podocarpus* and *Styrax* is not longer present. The percentages of savanna taxa clearly decline, with lower values of Poaceae (c. 15 %) and *Spermacoce*, Asteraceae, Myrtaceae, and *Byrsonima* (<5 %). Aquatic taxa are mainly represented by pollen of *Nymphaea* (3-12 %) in the upper half of the zone, but also by Cyperaceae and Eriocaulaceae in the lower half. *Isoëtes* spores show high values (max. 78%), and high frequencies of *Botryococcus braunii* (c. 80 %) are characteristic. The overall palynological richness remains constant and only the groups of tropical forest and cold adapted taxa show a slightly higher diversity in the lower zone part. In both size classes the concentration of charred material is low.

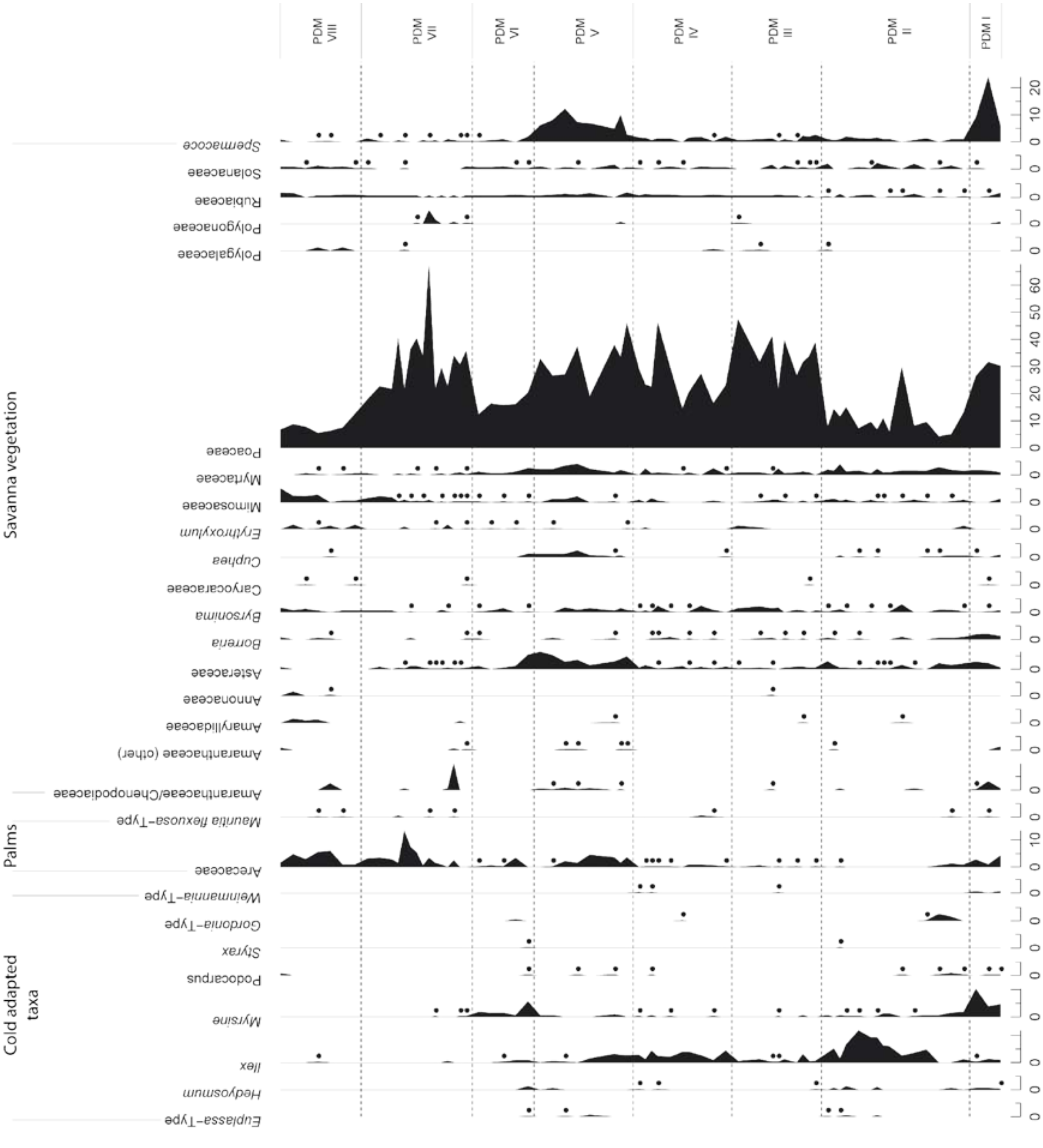
4.3.7 Zone PDM-VII, 123-53 cm (c. 10.2-3.4 cal ka ; 14 samples)

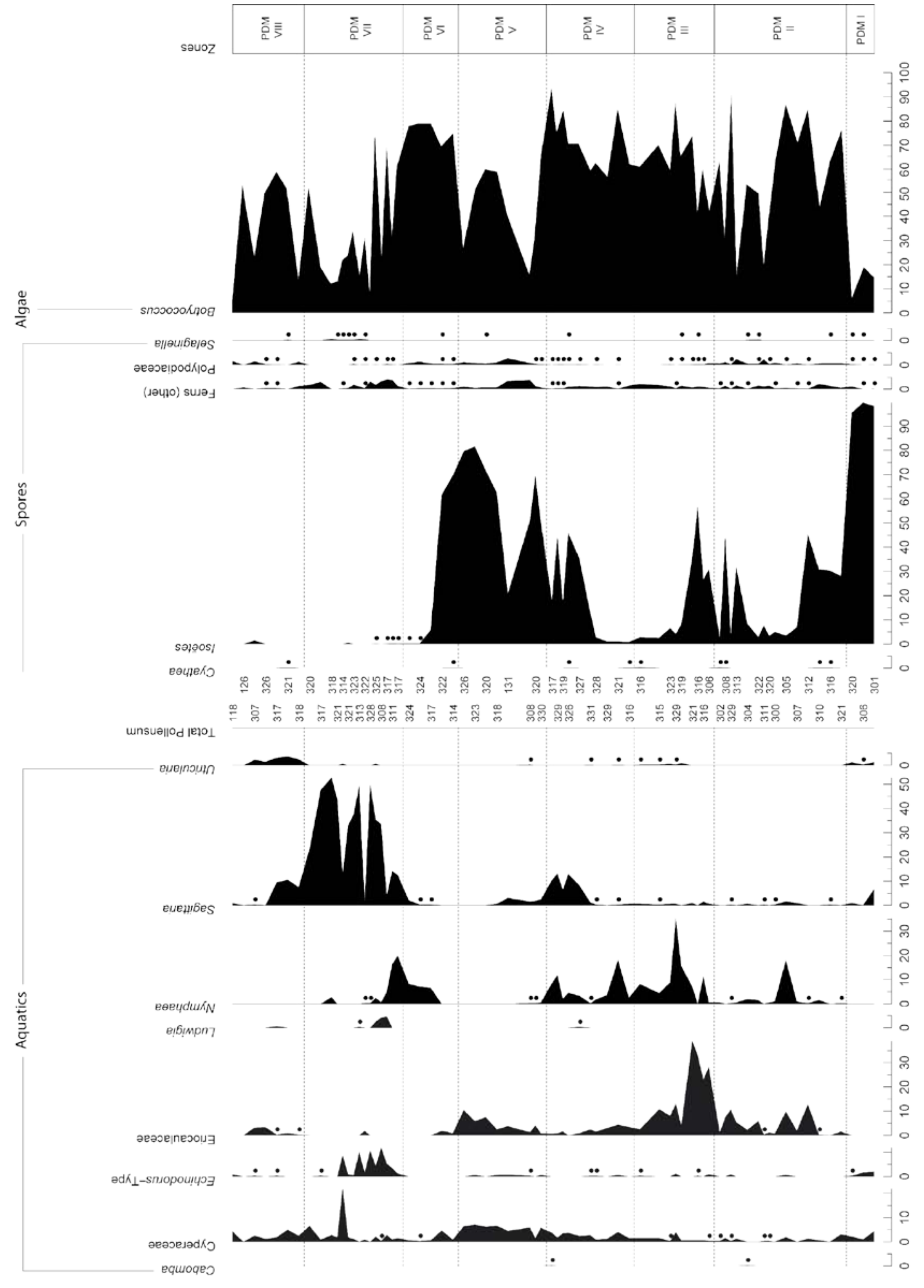
A decrease to low values of the main tropical forest taxa (<10 %) is characteristic, though slightly higher values of Anacardiaceae, Bignoniaceae, and *Zanthoxylum*, and higher values of Fabaceae (max.18 %) are recorded. Pollen of Arecaceae (8 %, max. 24 %) is frequent, as well as single pollen grains of *Mauritia flexuosa*-type. Only small amounts of pollen of *Ilex* and *Myrsine* are found in the lower zone part of the zone. Poaceae reach their highest values (max. 85 %), whereas most of the other savanna taxa remain below 5 %. The zone is also characterized by an increased abundance of aquatic taxa, especially *Sagittaria* (c. 40 %) and *Echinodorus*-type (c. 15 %). At the base of the zone *Nymphaea* pollen increases (c.18 %), but then decreases to low values or is even absent, while *Ludwigia* (5 %) occurs and Cyperaceae reach maximum values (22 %). The overall palyno-logical richness decreases, mainly due to the absence of cold adapted taxa and lower diversity of savanna and aquatic taxa. High concentrations of carbonized particles occur, large particles especially in the lower part of the zone, and small particles in the upper part.

4.3.8 Zone PDM-VIII, 53-0 cm (c. 3.4 cal ka to present; 8 samples)

This zone is marked by distinct increases in pollen frequencies of the tropical forest taxa *Alchornea/Apa-risthmium* (max. 30 %), *Celtis* (max. 15 %), Melastomataceae/Combretaceae (max. 14 %) and Moraceae/Urticaceae (max. 19 %), whereas frequencies of Fabaceae (<10 %) decrease. Mimosa-ceae pollen is scarcely present in the lower part of the zone, but it shows an increase (max. 10 %) from 24 cm onwards. Overall low pollen frequencies of savanna taxa and a clear decrease in the abundance of Poaceae (c.10 %) occur together with a decrease of the aquatic taxon *Sagittaria* (c. 10 %).High frequencies of *Botryococcus braunii* with strong oscillations are characteristic. Palynological richness markedly increases throughout the zone to values comparable to zone PDM-I due to higher diversity of tropical forest, savanna and, aquatic taxa. High charcoal concentration in both size classes is recorded up to 27 cm core depth.


Depth (cm)
0
50
100
150
200
250
300
350
400
450
Cal ages (cal yr BP)
2056
3538
9498
9937
12,543
23,646
46,807
± 1016
47,973
± 3976
Stratigraphy
Sums
Tropical forest (TF)
Savanna ecosystems (S)
Cold adapted taxa (CAT)
50%
Tropical forest
Acalypha
Alchornea/Aparisthmium
Anacardiaceae
Bignoniaceae
Celtis–Type
Cleidion–Type
Caryodendron–Type
Cecropia
Euphorbiaceae
Fabaceae
Loranthaceae
Melastomataceae/Combretaceae
Meliaceae
Menispermaceae
Moraceae/Urticaceae
Ochnaceae
Protium
Rhamnaceae
Roupala
Sapindaceae
Sloanea–Type
Trema
Zanthoxylum
Zones
PDM VIII
PDM VII
PDM VI
PDM V
PDM IV
PDM III
PDM II
PDM I
0
10
20
30
40
Organic rich material with many plant remains
Organic rich material with few plant remains
Organic rich material almost without plant remains
Decomposed material with few plant remains
Silty clay, ochre brown
Silty clay, dark brown


PDM VIII
PDM VII
PDM VI
PDM V
PDM IV
PDM III
PDM II
PDM I
Savanna vegetation
Spermacoce
Solanaceae
Rubiaceae
Polygonaceae
Polygalaceae
Poaceae
Myrtaceae
Mimosaceae
Erythroxylum
Cuphea
Caryocaraceae
Byrsonima
Borreria
Asteraceae
Annonaceae
Amaryllidaceae
Amaranthaceae (other)
Amaranthaceae/Chenopodiaceae
Palms
Mauritia flexuosa−Type
Arecaceae
Cold adapted taxa
Weinmannia−Type
Gordonia−Type
Styrax
Podocarpus
Myrsine
Ilex
Hedyosmum
Euplassa−Type
0 10 20
0 10 20 30 40 50 60
0 10


Zones
PDM VIII
PDM VII
PDM VI
PDM V
PDM IV
PDM III
PDM II
PDM I
Algae
Botryococcus
Spores
Selaginella
Polypodiaceae
Ferns (other)
Isoëtes
Cyathea
Total Pollensum
Aquatics
Utricularia
Sagittaria
Nymphaea
Ludwigia
Eriocaulaceae
Echinodorus–Type
Cyperaceae
Cabomba
0 10 20 30 40 50 60 70 80 90 100
126 326 321 320 317 318 314 323 322 325 317 317 324 322 326 320 131 320 317 319 327 328 321 316 323 319 316 306 308 313 322 320 305 312 316 320 301
118 307 317 318 317 321 321 313 328 308 311 324 317 314 323 318 308 330 329 326 331 329 316 315 329 321 316 302 329 304 311 300 307 310 321 308

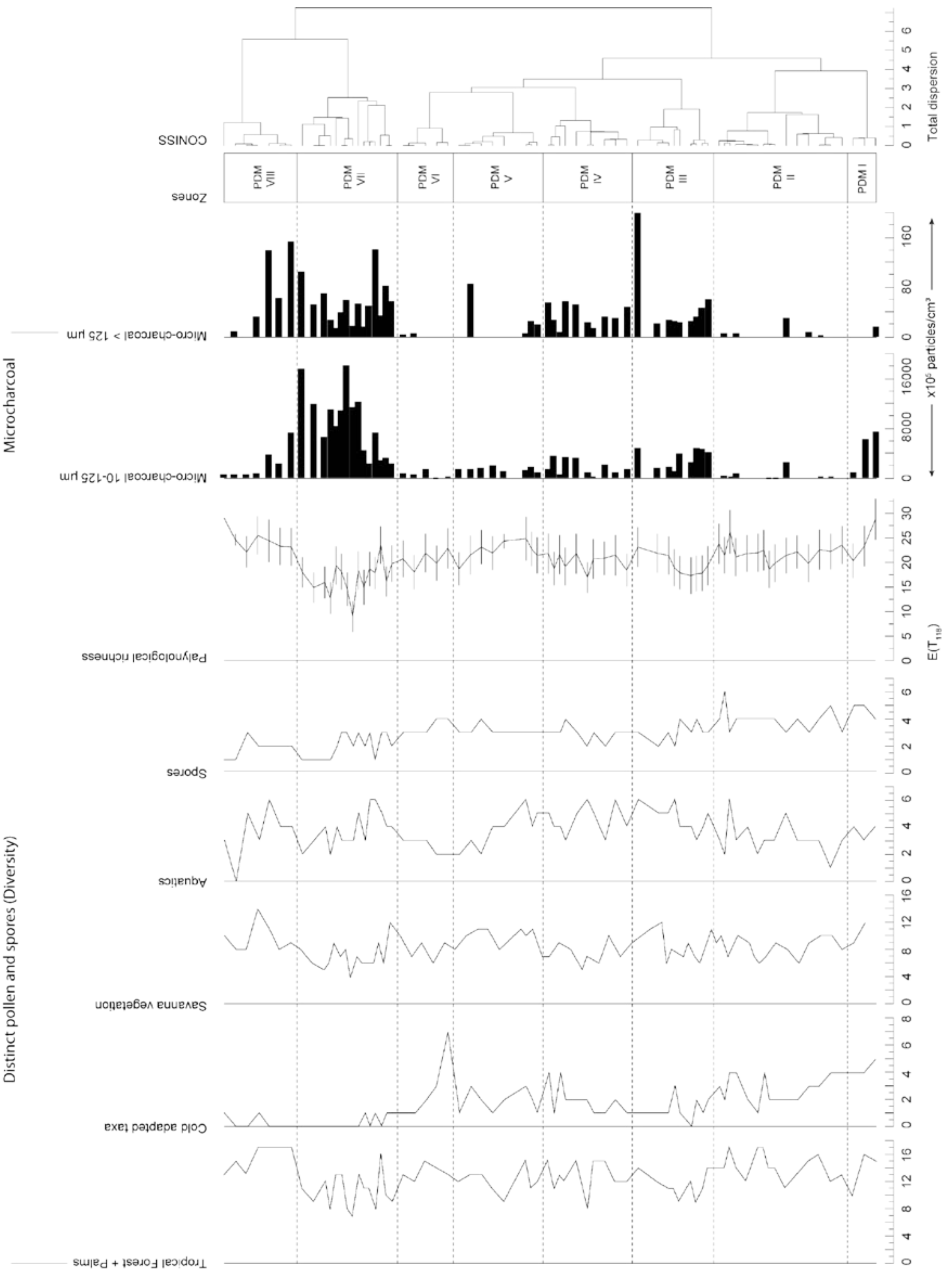


Fig. 4: Pollen diagram from Pántano da Maurítia. The diagram shows percentages of the most important taxa, sums of the groups, as well as pollen and charcoal concentration. Pollen and spore diversity, which is based on a pollen sum of around 300, is illustrated for each category (tropical forest incl. palms, cold adapted taxa, savanna vegetation, aquatics and spores) as well as the overall palynological richness.

5. Interpretation and discussion

5.1 Age estimation of the sediment core

Based on the radiocarbon dates for the upper part of the Pántano de Mauritia sediment core (above 200 cm) and the extrapolated age from the upper core part, the minimum age for the core base at 466 cm is about 73 ka. The age of 46.8 ka at 248 cm core depth, which is close to the limit of radiocarbon dating, may suggest an even older age for the core base.

However, the presence of several cold adapted taxa (*Myrsine, Podocarpus, Hedyosmum*) does not suggest warm interglacial conditions. Marked vegetation changes from an edaphic savanna (zone PDM-I) to tropical forest (zone PDM-II) and back to a savanna (PDM-III) in the lower core part suggest instead that these zones possibly represent the early to mid-Pleniglacial period from 75-40 ka. The pollen spectra of PDM-II show some analogies to the wet phase at the transition from the Lateglacial to the early Holocene (PDM-VI) and also to the late Holocene (PDM-VIII). In particular, Moraceae/Urticaceae and Melastomataceae/Combretaceae, and to a lesser extent *Alchornea/Aparisthmium*, show similar patterns, though the total abundance of the latter is not as high as in zone PDM-VI or PDM-VIII. Also, the high palynological richness in the tropical forest and savanna group at the base of the core is comparable with present-day conditions, although richness lowered at the transition from PDM-I to PDM-II. We hypothesize that wetter conditions during PDM-II could be coupled with a southward displacement of the ITCZ, possibly during a Heinrich event and the associated cooling of the northern Atlantic SSTs (Hodell et al., 2008). The duration of a Heinrich event could have been long enough for forests to develop in the Carajás region. In consideration of the dating uncertainties in the lower core part, the Heinrich events (H) in question are H5 around 45 ka or H4 around 38 ka (Bond et al., 1999), but as the chronology of the core part comprising pollen zones PDM-I to PDM-IV is yet unclear, this remains hypothetical. Significant changes in sediment character were not observed for zones PDM-II to PDM-IV.

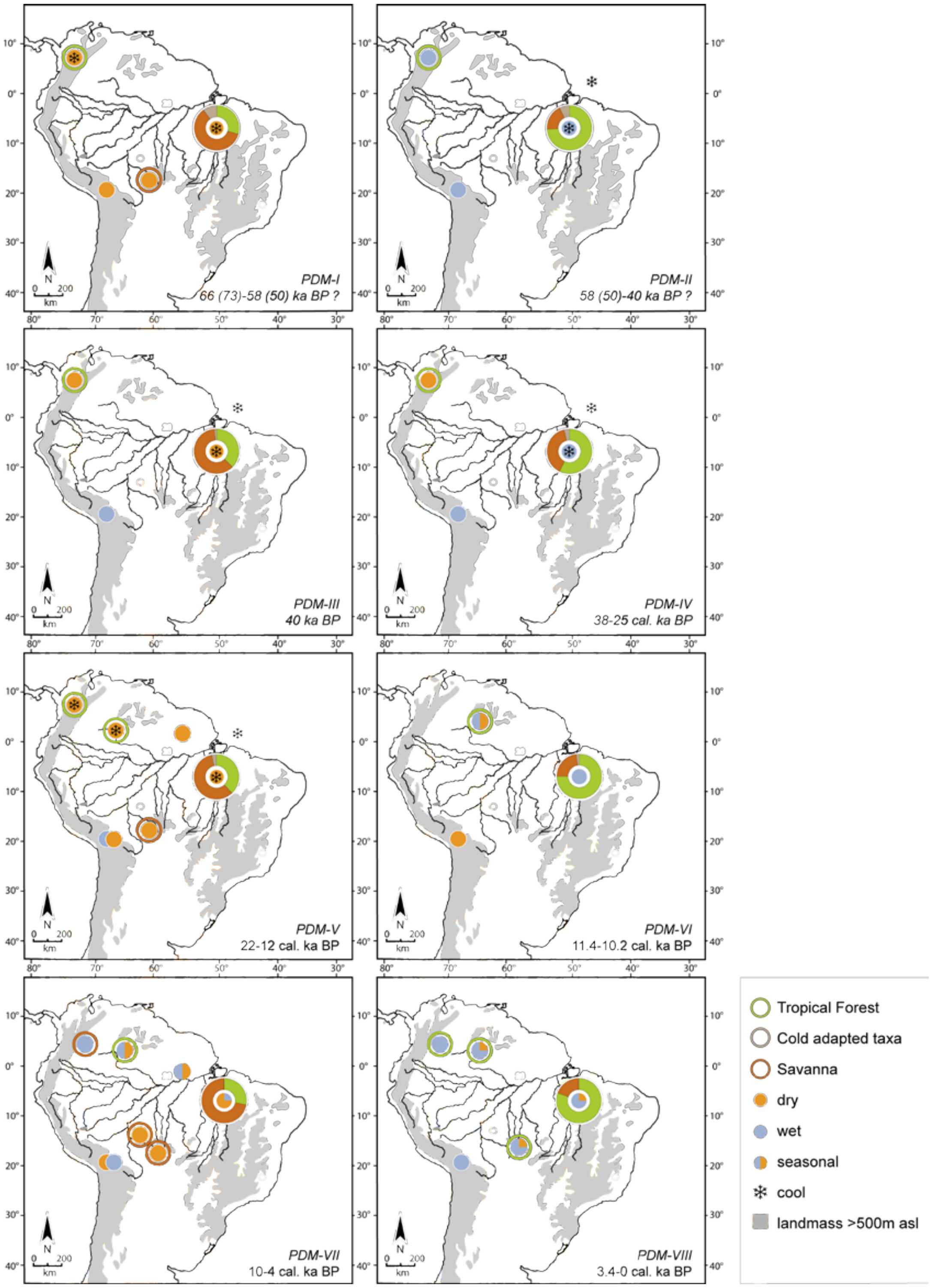


Fig. 7: Proportions of identified vegetation types at Serra Sul in southeast Amazonia (big circle) and the interpreted climatic conditions for 8 time periods in comparison with other studies in Amazonia and the Andes (small circles).

5.2 Late Pleistocene environmental reconstruction

5.2.1 Assumed early Pleniglacial (PDM-I)

The pollen record indicates that during this period, savannas rich in Poaceae, *Spermacoce*, Asteraceae, *Borreria*, Myrtaceae, and Amaranthaceae dominated the plateau of Serra Sul. Small areas of tropical forests rich in Melastomataceae/Combretaceae, Moraceae/Urticaceae, Fabaceae and *Celtis* existed, probably on the slopes of the plateau or in lower areas where soil moisture was sufficient. Cold adapted taxa like *Myrsine, Ilex, Hedyosmum* and *Podocarpus* were also present, but rare in these small forested areas. Based on this pollen assemblage, climatic conditions must have been relatively dry and cold. The high abundance of *Isoëtes* together with the presence of semi-aquatic taxa (*Sagittaria, Cyperaceae, Echinodorus*, and *Utricularia*) suggest that the water level in the studied basin was continuously low during this period. Natural fire events were rare as suggested by low charcoal concentrations, especially of particles >125 µm. The sedimentation process at the Pántano da Maurítia basin started during a dry climate interrupted by humid phases, demonstrated by the banded sediments. The widespread occurrence of siderite indicates the influence of wetter conditions with OM accumulation (Tab. 2).

5.2.2 Assumed early to mid-Pleniglacial (PDM-II)

During the assumed early to mid-Pleniglacial period a tropical forest expanded at Serra Sul, composed of a mixture of rainforest taxa common at present: Melastomataceae/Combretaceae, Moraceae/Urticaceae, and Meliaceae together with pioneer taxa (*Celtis, Zanthoxylum, Cecropia*) (Marchant et al., 2002) and taxa like Anacardiaceae representing seasonally dry forest communities. During this period *Myrsine* was rare, but the frequent occurrence of *Ilex* (middle and upper part of this period) and the rare occurrence of other cold adapted forest taxa (for example *Gordonia*, today known from upper mountain rainforests in the northern Andes according to Marchant et al., 2002, or from high altitudes in the Atlantic forest according to Oliveira-Filho and Fontes, 2000), refer to cool conditions. The occurrence of the open water plant *Nymphaea* together with Eriocaulaceae indicates a higher water level for most of this period, reflecting wetter conditions than during the previous period. High palynological richness of tropical forest taxa and the absence of fire also suggest wetter climatic conditions. The deposition of dark brown colored silt-clayey sediments rich in fine OM and partly clay mineral kaolinite together with goethite confirm the wetter climatic conditions, increased temperatures and dense vegetation. The presence of 'cauixi' and diatoms indicate that the water level in the basin reached 1-2 m depth during this period (Tab. 2).

5.2.3 Assumed mid-Pleniglacial (PDM-III)

During the mid-Pleniglacial the vegetation of Serra Sul changed to a more open savanna dominated by Poaceae with shrubs and small trees composed of *Byrsonima*, Myrtaceae, and later *Erythroxylum*. The decline of the forest taxa Melastomataceae/Combretaceae, Moraceae/Urticaceae, *Celtis*, as well as of cold adapted taxa (in particular Myrsine) and of overall tropical forest diversity, indicates drier and less cold conditions during this period. The presence of Ochnaceae suggests that sufficient soil moisture was available during this period, as members of this family request adequate moisture during the growth phase. The increased abundance of aquatic plants (Eriocaulaceae and *Nymphaea*) in the first half of this period could be indicative of a higher water level in the basin during short phases of wetter conditions. Fire became more important compared to the previous period. The fine silt banded sediments also indicate the presence of a persistent water body in the Pántano da Maurítia basin, with elevated temperatures at the beginning of the period. Later, the climate became drier, but was interrupted by short periods of wetter conditions as shown by the dominance of banded silt composed of goethite/hematite, kaolinite and partly siderite. Siderite was formed diagenetically by oxidation of organic matter and partial reduction of Fe^{3+} of oxihydroxides from the overlying zone. Apparently, a long period of reduced sedimentation took place, during which the fine detritus of the lateritic crusts was deposited, represented by dark-gray sediments (Tab. 2).

5.2.4 Pre-LGM, 30-25 cal ka (PDM-IV)

Tropical forest on the slopes expanded again and occurred together with more open grass savanna at Serra Sul, reflecting a change to wetter conditions. The occurrence of *Mauritia flexuosa*, Eriocaulaceae and *Isoëtes* indicate shallow water conditions in the basin, with a water level high enough for open water plants like *Nymphaea*. In the second half of this period, the slight decrease of dominant forest taxa accompanied by increased abundance of Poaceae and higher diversity of cold adapted taxa with *Hedyosmum, Podocarpus, Styrax,* and *Weinmannia*-type indicates the transition to cooler conditions. Also the dark brown colored silt-clayey sediments indicate wetter and cooler conditions. Natural fire events were still present during this time (Tab. 2).

5.2.5 LGM and Lateglacial, 25-11.4 cal ka (PDM-V)

During these two periods the rare occurrence of forest taxa suggests that only small forested areas existed at the slopes of the plateau. In these forests, tropical rainforest taxa (Melastomataceae/Combretaceae, Moraceae/Urticaceae) co-occurred with a suite of cold adapted taxa (*Myrsine, Ilex, Hedyosmum, Euplassa, Podocarpus*), indicating colder conditions. The plateau itself was covered by much larger areas of savanna vegetation than today, reflected by the frequent occurrence of Poaceae, *Spermacoce* and Asteraceae, indicative of markedly drier climatic conditions. The occurrence of semi-aquatic *Isoëtes* and *Botryococcus braunii* refers to continuously low water depths in the Pántano de Mauritia basin, and the typical minerals of the iron crust such as gibbsite and hematite/goethite also support dry conditions (Tab. 2).

5.3 Holocene environmental reconstruction

5.3.1 Onset of the Holocene, 11.4-10.2 cal ka (PDM-VI)

At the onset of the Holocene tropical rainforest developed and expanded. The presence of only two representatives of the cold adapted taxa group in the upper half of the zone (*Ilex, Myrsine*), together with a pronounced low fire activity reflect wetter and possibly slightly warmer conditions. Wetter conditions are corroborated by the presence of *Nymphaea* which points to predominantly open water conditions at the study site. Kaolinite is possibly formed after progressive dissolution of silica-rich sponges ('cauixi') and diatomaceous material, and simultaneous dissolution of (Fe, Al) oxyhydroxides (goethite) and Al (gibbsite) within and around the basin by weathering during a wet and warm climate. This demonstrates a strong effect of water pore diagenesis on the already deposited fine grained material deriving from the exposed lateritic crust in the directly subjacent zone. Diagenesis played an important role in the neo-formation of minerals and texture, and is a clear indication of available water at the time of sedimentation. The exposed iron crust was the source material of the Pántano de Mauritia sediments. However, dense vegetation possibly behaved as a barrier preventing erosion and deposition into the basin. The very humid and warmer climate promoted a marked development of forest and a restart of biochemical weathering of the exposed lateritic iron crust (Tab. 2).

5.3.2 Early to mid-Holocene, 10.2-3.4 cal ka (PDM-VII)

The marked reduction of tropical forest area, the expansion of savanna with abundant Poaceae with overall low occurrence of typical arboreal savanna taxa, and frequent fires all indicate a change to dry climatic conditions. The large quantity of aquatic and semi-aquatic plants was responsible for a high accumulation of OM. The brown organic sediment units may also represent a lower water level under dry environmental conditions, as suggested by the deposition of lateritic detritus (goethite and gibbsite) from the surroundings by detritus flow and/or run-off. Short cycles of darker and lighter sediments suggest variable conditions. Dry conditions for example could cause a reduction of the wetland due to a lowered water level; in that case pollen deriving from local and aquatic vegetation (Poaceae and Sagittaria) would be statistically overrepresented (Fægri and Iversen, 1989). Primarily high and subsequently decreasing sedimentation rates may refer to a highly variable water level over a long time period, with alternating wet and dry phases rather than an overall dry period. The overall low abundance of *Botryococcus* could be the result of seasonal dry seasons too long for this alga to survive. Overall, our record indicates that the Carajás region experienced generally drier climatic conditions during this time compared to modern conditions. A possible scenario for this period may be an evolving seasonal climate in southeast Amazonia, with dry seasons notably longer than today. As the presence of *Sagittaria* and Arecaceae refers to the availability of moisture sufficient to support a swamp surrounded by palms, longer dry seasons were possibly coupled with increased precipitation during the wet season. Dry seasons longer than four months are not favorable for humid tropical rainforest (Sternberg, 2001; Maslin, 2004) and could be a possible factor for open vegetation on the slopes of the plateau. Actually, the presence of Anacardiaceae, Bignoniaceae, Euphorbiaceae, Fabaceae and *Zanthoxylum* could be indicative of the presence of forest patches with a florisitc composition unknown from today in this region. As these families are not restricted to humid rainforest communities their presence suggests less dense dry forest communities capable of persisting during prolonged dry periods (Tab. 2).

5.3.3 Late Holocene, 3.4 cal. ka to present (PDM-VIII)

The marked increase of the tropical forest taxa indicates the development of humid rainforest in this region. Forest trees of the genus *Alchornea* are known from mid-elevation sites, whereas the pioneer *Aparisthmium* contains small trees and shrubs growing on poor soils (Gentry, 1993; Colinvaux et al., 2000). This suggests an expansion of tropical rainforest at the slopes of the plateau and into smaller depressions of the plateau, where sufficient water and sediment could accumulate. Likewise, the pioneers *Celtis* and *Trema* point to an extension of forest, and combined with the increase of *Alchornea/Aparisthmium* and Moraceae/Urticaceae they indicate reduced water stress due to increased precipitation. High charcoal concentrations between c. 3 and 1.4 cal are represent human activities (Tab. 2).

6. Comparison with Amazonian and Andean pollen records

The record from Pántano da Mauritia (Serra Sul dos Carajás) provides detailed results on past environmental changes. A key factor for the observed vegetation changes seems to be the overall amount of precipitation during the late Pleistocene and especially the seasonality of rainfall during the Holocene (Hermanowski et al., 2012). Today, dry season rainfall anomalies in southeast Amazonia are highly correlated with the meridional gradient of SSTs in the tropical Atlantic (Good et al., 2008), which induces a latitudinal migration of the ITCZ, affecting the intensity of Amazon convection and moist trade winds from the Atlantic Ocean (Marengo et al., 1993, 2001; Nobre and Shukla, 1996; Fu et al., 2001; Liebmann and Marengo, 2001). Moisture from the Amazon basin in turn is transported to the northern Andes via the South American Low Level Jet (Marengo et al., 2004) and is presumed to be an important factor affecting northern Andean rainfall regimes. Therefore, water levels in Andean lakes are often used as an indirect indicator for precipitation changes in the Amazon basin (Baker et al., 2001a).

Fig. 7 shows a comparison of the pollen record from Pántano da Maurítia with other records from Amazonia (Absy et al., 1991; Behling et al., 1999; Behling and Hooghiemstra, 1999; 2000; Bush et al, 2004; Mayle et al., 2000), the northeastern Andes (Hooghiemstra and Ran, 1994; Van't Veer and Hooghimestra, 2000), the Eastern Cordillera of Columbia (Van der Hammen and Hooghiemstra, 2003), the Bolivian Altiplano (Gosling et al., 2008; Wirrmann and Mourguiart, 1995) and a marine record from the Amazon Fan (Haberle and Maslin, 1999). A comparison of vegetation changes between our new Carajás record with selected Amazonian and Andean records from Bolivia/Peru (south of the equator) and Colombia (north of the equator) allows insights into different responses of vegetation to the same underlying climatic changes.

Tab. 2: Characteristics of the eight pollen zones (PDM) according to environmental conditions, lithology, mineralogy, and mineralogical changes.

POLLEN ZONE	Environmental conditions	Lithology	Mineralogy	Mineral changes
PDM-VIII, 53-0 cm, 3.4 cal. ka BP-present	Wetter/warm; rainforest dominant; high fire activity (human impact); highest OM accumulation; high water level	Dark gray packet of OM debris; frequent debris of sponges and diatoms	Minerals rare: quartz and opal, sponges and diatoms debris	Slight transformation of opal into quartz; short term existing water level and OM accumulation promoted some diagenetic siderite in the underlying zone
PDM-VII, 123-53 cm, 10.2-3.4 cal. ka BP	Dry/warm; savanna dominant, rainforest restricted; frequent fire activity; low water level	Gray silt to clay sediment, rich on OM, banded with brown clay layer; increasing OM debris towards the top	Quartz frequent; kaolinite, goethite, siderite, and anatase rare or absent; opal much more frequent as ‘cauixi’ and diatomaceous fragments	Intensive transformation of opal spicules into quartz; slightly superimposed diagenesis with formation of rare siderite in the underlying zone
PDM-VI, 149-123 cm, 11.4-10.2 cal. ka BP	Wet/warmer, rainforest taxa frequent, high water level; low fire activity; OM accumulation	Thicker gray silt to clay sediment unit rich in OM	Kaolinite, goethite, siderite, anatase, opal; gibbsite, barite, talc and/or chlorite; opal constituting ‘cauxi’ and diatomaceous	Partial superimposed latter diagenesis: formation of siderite, barite, and talc/chlorite
PDM-V, 228-149 cm 25-11.4 cal. ka BP	Dry/cold, savanna and forest; low fire activity; low water level	Brown colored clayey silt (35μm) sediments with fine micro-bands of dark color OM	Kaolinite, goethite, quartz, siderite, anatase; gibbsite, barite, talc and/or chlorite are accessory; opal constituting cauixi and diatomaceous	Partial superimposed latter diagenesis: formation of siderite, barite, and talc/chlorite
PDM-IV, 292-228 cm, 30-25 ka BP	Wet/cool, forest expands, savanna still present, fire events present; high water level; OM accumulation	Brownish to dark brown clayey silt sediments (20 a 30 μm), banded	Kaolinite and some goethite; quartz becomes frequent as constituting of ‘cauixi’ and diatomaceous; anatase	More intensive transformation of opal spicules into quartz
PDM-III, 350-292 cm, >50-30 ka BP	Dry/slightly warmer; savanna dominant; low fire activity; lowered water level, oscillating	Slightly banded brown to dark brown clayey silt sediments	Much more kaolinite, less goethite and XRD-amorphous phases; quartz constituting cauixi spicules and diatomaceous, anatase	Opal spicules transform into quartz
PDM-II, 445-350 cm, >50 ka BP	Wet/cool; forest dominant; no fire activity; high water level; OM accumulation	Slightly banded brown to dark brown clayey silt sediments	Kaolinite and goethite of low order crystalline structure and anatase	Long term staying water level and OM accumulation promoted diagenesis in the underlying zone
PDM-I, 466-445 cm, >50 ka BP	Dry/cool; savannas dominant; small forest patches; low fire activity; low water level	Massive silt brown sediments, saccharoidal; relict of lateritic iron crust	Siderite and goethite; anatase	Superimposed latter diagenesis: partial transformation of goethite into siderite

6.1 Assumed early and mid-Pleniglacial and Pre-LGM

The four oldest pollen zones are beyond radiocarbon dating, but the presence of cold adapted taxa suggests cooler conditions in Serra Sul. Presence of organic (brown) sediments, however, suggests conditions were not too cold. During the early Pleniglacial (PDM-I) widespread savanna vegetation together with more open, possibly seasonal dry forests at the slopes, indicate generally drier conditions. Earlier studies at other sites in the Carajás region recognized two dry periods around 60 ka and 40 ka (Absy et al., 1991). Prevailing savanna and dry forest communities reflect drier conditions from 51 to 10 ka also in southwestern Amazonia (Burbridge et al., 2004), and likewise dry environments were recorded north of the equator at the Colombian Caquetá river between 70 and 40 ka (Van der Hammen et al., 1992) and on the Bolivian Altiplano between 65.3 and 58 ka (Gosling et al., 2008). From the Amazon fan (Haberle and Maslin, 1999) a cold episode is recorded, based on the increased abundance of Andean taxa (*Podocarpus, Hedyosmum*). However, this record does not show pronounced variation in both savanna and rainforest taxa comparable to those in Carajás (Absy et al., 1991) and in the northeastern Andes (Hooghiemstra and Ran, 1994; Van der Hammen and Hooghiemstra, 2003). Despite dating uncertainties it is therefore possible that PDM-I dates between 66 (73) and 58 (50) ka (Fig. 7).

During mid-Pleniglacial times (PDM-II) the development of tropical rainforest substantiates wet conditions in Serra Sul. Absy et al. (1991) also recorded a wet period around 52-50 ka for the Carajás region. These wet conditions in Carajás may correspond to the altitudinal shifts of *Quercus* and *Weinmannia* forests in the Eastern Cordillera (Colombia), interpreted to reflect temperate conditions between 50 and 24 ka (Hooghiemstra and Ran, 1994). The Bolivian Altiplano experienced one of the wettest periods between 50 and 38 cal ka (Baker et al., 2001b). At this time palaeolake 'Minchin' existed at Salar de Uyuni and millennial-scale fluctuations in effective moisture under generally wet conditions were recorded (Fritz et al., 2004) (Fig. 6).

Drier conditions in Serra Sul during the mid-Pleniglacial (PDM-III), represented by the dominance of savanna vegetation, coincide with dry conditions around 40 ka recorded by Absy et al. (1991). In the Andes no corresponding drier events were recorded for this period (Fig. 7).

In the period before the LGM (PDM-IV), conditions in Carajás were slightly wetter, inferred by the increased abundance of Melastomataceae/Combretaceae. This correlates with wet conditions on the Bolivian Altiplano between 50,000 and 38,000 cal. yr BP (Rigsby et al., 2005). Palaeolake 'Minchin' still existed, and was slightly larger between 40-25 ka than the Salar is today (Wirrmann and Mourguiart, 1995; Baker et al., 2001b; Bush et al., 2010) (Fig. 7).

6.2 LGM and Lateglacial

The dominance of savanna and the rare occurrence of forest vegetation in Serra Sul during the LGM and Lateglacial indicate a dry climate in southeastern Amazonia. Probably because of dry conditions after 22.87 and before 12.52 ka (27.7 and 14.65 cal ka) the record from Carajas by Absy et al. (1991) shows a gap in sedimentation. These dry conditions are in agreement with pollen records from northwestern (Behling and Hooghiemstra, 2000; Bush et al., 2004) and southwestern Amazonia (Mayle et al., 2000) as well as from the Andes (Hooghiemstra and Ran, 1994). In the eastern Cordillera of the Colombian Andes, low lake levels and dry climatic conditions are suggested for the LGM (Van der Hammen and Hooghiemstra, 2003). And whereas north of the equator dense forests persisted in western Amazonia during that time (Bush et al., 2004), the expansion of savanna south of the equator in western Amazonia (Mayle et al., 2000) is comparable with conditions recorded in Pántano de Mauritia, although smaller forest patches were present in our study area, probably at sites on slopes where moisture was sufficient (Fig. 7).

The occurrence of several cold adapted taxa (e.g. *Podocarpus, Hedyosmum, Ilex*) in the Pántano de Mauritia record is in agreement with the documented occurence of *Podocarpus* in the lowlands of western and eastern Amazonia during glacial periods (Colinvaux et al., 1996; Behling 1996, 2001; Behling et al, 1999). Today, *Podocarpus, Hedyosmum* and *Ilex* are mainly known from cooler mid-elevation sites along the eastern Andes and are rare or absent in the Amazon lowlands (Gentry, 1993). Their occurrence at our study site indicates markedly colder temperatures in this region during glacial times than today. Cold climatic conditions in Carajás are consistent with records from western Amazonian and the eastern Andes as well (Bush et al., 1990; Hooghiemstra and Ran, 1994; Stute et al., 1995; Behling et al., 1998; Van't Veer and Hooghiemstra, 2000; Behling, 2001; Bush et al., 2001, 2004; Wille et al., 2001; Van der Hammen and Hooghiemstra, 2003). Gosling et al. (2008) suggested that the LGM (21,000 cal ka) was a relatively wet period in the Bolivian Andes, which is also supported by Rigsby et al. (2005). The regional climate model by Vizy and Cook (2007) indicates that the absence of convection over Amazonia during dry periods would result in an anomalous easterly flow from Amazonia to the Andes which would enhance convection over the Andes. Therefore, drier conditions in Amazonia and wetter conditions in the Andes are not mutually exclusive.

Between 19.8 and 11 cal ka, the pollen record from the Amazon Fan shows an increase in Andean taxa, suggesting that forest taxa from the modern Andean and uppermost subandean regions shifted to lower elevations (Haberle and Maslin, 1999). The development of rainforest in the study area, with abundant Moraceae/Ur-ticaceae, started not before 13 cal ka. This agrees with records showing regional forest development and erosion events between 13 and 10 ka (15.4-11.4 cal ka), suggesting intensive rainfall events indicative of changing climatic conditions at the end of the Lateglacial (Sifeddine et al., 2001). At this same time Lake Titicaca overflowed (Baker et al., 2001a) (Fig. 7).

6.3 Onset of the Holocene

At the transition from glacial to Holocene conditions between 11.4 and 10.2 cal ka, the climate was sufficiently warm and wet for the establishment of dense tropical forest at Pántano da Maurítia. This wet period is now better dated and corresponds to the maximum forest expansion recorded by Absy et al. (1991) between c. 9.5 and 8 ka (c. 10.7 and 8.8 cal ka. In northwestern Amazonia tropical rainforest also expanded, but based on the cyclic reduction of lake levels, Bush et al. (2004) suggested a reduction of wet season precipitation.

In contrast, at Lake Titicaca the period around 11.5 cal ka is characterized by a large and rapid drop in lake level (Wirrmann and Mourguiart, 1995; Baker et al., 2001a) and several authors (e.g. Baker et al., 2001a,b; Wille et al., 2001) suggest dry conditions in mid-elevation Andean regions from 10 to 9 ka (11.5 to 10.2 cal ka).

Baker et al. (2001a) show that these drier conditions can be attributed to higher zonal SST gradients in the North Atlantic. However, precipitation in Carajás (SE-Amazonia) depends also on changing meridional SST gradients, as these are coupled with a shift of the ITCZ. Compared with modern conditions, the meridional SST gradients were higher during this time, with a warm pool in the tropical southwest (Rühlemann et al., 1999; Weldeab et al., 2006), which could have shifted the ITCZ to a more southerly position.

6.4 Holocene

Between 10.2 and 6 cal ka, Serra Sul was dominated by savanna vegetation under generally dry conditions. In north- and southwest Amazonia the replacement of forest by savannas indicates dry conditions as well (Behling and Hooghiemstra, 1999; Mayle et al., 2000). The Bolivian Altiplano experienced the most arid conditions of the Holocene between 7.9 and 4.5 cal ka (Rigsby et al., 2005) and the lake level of Lake Titicaca dropped markedly (Seltzer et al., 1998; Cross et al., 2000) during this time (Fig. 7).

From 6 to 4 cal ka, increased fire events in the Carajás region reflect even drier conditions than before which coincide with the peak of a lake level low stand at Lake Titicaca (Paduano et al., 2003). Lowered water levels at other lakes are also recorded between 8 and 4.3 cal ka by Wirrmann and Mour-guiart (1995), Abbott et al. (2000), Baker et al. (2001a), and Seltzer et al. (2002). In contrast, the conditions in northwest Amazonia and the Colombian Llanos Orientales became wetter after 6.4 cal ka (Behling and Hooghiemstra, 1998; Bush et al., 2004) (Fig. 7). The SSTs in the northern tropical Atlantic further increased (Rühlemann et al., 1999) while the zonal temperature gradient and SSTs in the southwestern Atlantic decreased (Baker et al., 2001b; Weldeab et al., 2006). Reduced moisture transport due to weaker trade winds could have caused dry mid-Holocene conditions in Serra Sul. Also weaker ENSO activity during this period is a possible reason for a more intense influence of Atlantic conditions in southeastern Amazonia (Sandweiss et al., 1996; Keefer et al., 1998; Rodbell et al., 1999; Clement et al., 2000; Sandweiss et al., 2001; Otto-Bliesner et al., 2003).

After 3.7 cal ka, rainforest communities established in Carajás and in north- and southwestern Amazonia as well, suggesting wetter climatic conditions (Mayle et al., 2000; Bush et al., 2004). Rising Andean lake levels point to overall wetter conditions in the Andes and Amazonia (Baker et al., 2001a) (Fig. 7). The zonal temperature gradient of Atlantic SST decreased further as well as SSTs in the southwestern tropical Atlantic (Weldeab et al., 2006), whereas the SST increase in the northern tropical Atlantic slowed down (Rühlemann et al., 1999).

7. Conclusion

Pollen, micro-charcoal, sediment, and mineralogical analyses of a 466 cm-long sediment core from Pántano da Maurítia in the Serra Sul dos Carajás provide detailed insights into environmental changes in southeastern Amazonia, possibly dating back to the early Pleniglacial period. On the basis of extrapolation of the reliable AMS dates, an age of at least 75 ka can be assumed for the base of the core; as this age is still uncertain the sediments could be even older. The most striking feature of the record is the temporal instability of rainforest ecosystems in southeast Amazonia, reflected by changing pollen composition and diversity during the recorded time period. A comparison with long records from the Andes and the Amazon, and the variability of tropical Atlantic SSTs, suggests that vegetation systems in southeast Amazonia are, at least since the onset of the Holocene, especially sensitive to SST anomalies in the southwestern tropical Atlantic as well as changing meridional SST gradients, which themselves are coupled with a shift of the ITCZ. This is different than conditions in the northeastern Andes, where precipitation correlates principally with the variability of zonal SST gradients in the northern tropical Atlantic. We suggest that this was not the case during early and mid-Pleniglacial times (73-40 ka), when environmental changes in Carajás are similar to changes in southwestern Amazonia and the Andes. Beginning at around 40 ka, the differences between the compared regions (dry conditions in Serra Sul, but no dry events in the Andes) lead us to assume that other underlying climatic factors became more important for the vegetation in Serra Sul. When global climate changed markedly during the LGM, the rather abrupt turnover from tropical forest to savanna vegetation in Serra Sul corresponds to environmental changes in the entire Amazon Basin and in the Andes. But with the onset of the Holocene, Andean and Amazonian regions fell out of phase again, possibly because precipitation gained more importance for the prevailing vegetation types under rising atmospheric temperatures. Drier mid-Holocene climatic conditions in Carajás and other regions south of the equator are in contrast to wetter or more seasonal conditions north of the equator. Contemporary wet and seasonal conditions only established after 4 cal ka, both in southeastern Amazonia and the Andes. Consequently, environmental changes in southeastern Amazonia are not always in phase with environmental changes in the northern Andes, as both regions depend on different extra-regional climatic factors. Only globally extreme climatic changes are comparably reflected in records from both southeast Amazonia and the Andes.

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IV. Possible linkages of Paleofires in southeast Amazonia to a changing climate since the Last Glacial Maximum

Barbara Hermanowski, Marcondes Lima da Costa, Hermann Behling

Vegetation History and Archaeobotany (revision submitted)

Abstract

A 200 cm-long high resolution macro-charcoal and pollen record from the Lagoa da Cachoeira in Serra Sul dos Carajás (Serra Sul) in southeast Amazonia reveals insights into local palaeofire over the last 26,200 years. Local fires in Serra Sul were most frequent in transition periods from dry to wet environmental conditions between 11,000 to 10,200 years, and under seasonal climatic conditions after 5000 years ago. During pronounced dry periods fires were not a substantial component of the environment in Serra Sul. An anthropogenic influence on fire in Serra Sul may have played a role since the beginning of the Holocene, but is not likely a driver of paleofire variability. Charcoal records for southern Amazonia coupled with proxy data of precipitation and changing Atlantic seat surface temperature (SST) suggests that Holocene paleofires in southern Amazonia are driven by changes in climate.

Keywords: Amazonian forest and savanna; Late Pleistocene; Holocene; palaeofire; climate change

1. Introduction

Predictions for the next centuries highlight the growing threat for Amazonian ecosystems by climatically amplified wildfires coupled with anthropogenic influence. Increased droughts resulting from global warming and land use change may lead to increased flammability and mortality of tropical rainforests (Nepstad, 2004). Clarifying connections between past fire and vegetation under changing climatic conditions will aid in understanding long-term ecosystem dynamics of southeast Amazonia.

The analysis of charcoal fragments from lake sediments offers a tool to calculate past fire frequency in high temporal resolution. In Amazonia however, there are few high resolution records. In southeast Amazonia records mainly represent regional, low resolution fire histories of the past 8000 years (Behling, 2001; Behling & Costa, 2000, 2001; Bush et al., 2000; Bush et al., 2007a; Bush et al., 2007b; Cordeiro et al., 2008; Hermanowski et al., 2012; Irion et al., 2006; Sifeddine et al., 2001; Soubiès, 1979). In eastern Amazonia fires were recorded from 6k to 3k B.P. (calibrated: 6.7-3k cal B.P.) (Soubiès, 1979), in Serra Norte dos Carajás charcoal fragments are suggested to derive from forest fires under dry climates between 7.45k cal B.P. and 4.75k cal B.P. (Cordeiro et al., 2008). At Rio Tapajós charcoal is more frequently recorded between 5.2k and 6k cal B.P. (Irion et al., 2006). In summary these studies recognize more frequent regional fires between ca. 7.5k and 3k cal B.P.. For these periods drier climates are suggested to be the driving factor of increased fire activity.

This study presents the first high resolution macro-charcoal record for southeast Amazonia for the last 26k years. As recorded charcoal data derive from local fires (Whitlock and Larsen, 2001), pollen data is analyzed as a proxy of past vegetation and an approximation of potential fuel loads. For regional scale comparative studies, data from the Global Charcoal Database (Power et al. 2008; Tab. 1) were used for the reconstruction of regional fire histories.. These data were then compared with extra-regional proxies of past climatic conditions. Available charcoal data from southern Amazonia were chosen for this study to highlight the possible climate drivers and regional variability of fire histories in these areas over the past 26,000 years. Southeast and southwest Amazonia fire activity are compared with SST variability in the tropical (Rühlemann et al., 1999; Lea et al., 2003; Weldeab et al., 2006) and subtropical Atlantic (deMenocal et al., 2000; Lea et al., 2003) and Cariaco Basin (Haug et al., 2001) along with speleothem proxy data (Wang et al., 2007) to identify possible connections between Amazonian paleofire activity and climatic changes.

2. Study area

Lagoa da Cachoeira is a lake located on the narrow plateau of the Serra Sul dos Carajás (6°21'18"S, 50°23'35"W, 705 m a.s.l.) in southeast Amazonia (Fig. 1). The site is located in a basin with relatively steep walls, has an area of ca. 450x350 m and about 2 m water depth. The regional climate is classified as tropical humid (Aw, Köppen) with an average mean monthly temperature of 25°C. Mean annual precipitation at the nearby Marabá climate station (5°37'S,49°13'W, 95 m a.s.l.) recorded 1800 mm in 2011 (INMET, 2011).

2.1 Climate

The region experiences strong seasonal conditions with a severe dry season from June to October (Sifeddine et al., 2001) with rainfall of 150 mm/month (INMET, 2011). In the peak of the wet season from December-February, the mean precipitation is 1400mm (INMET, 2011). After Stott (2000) natural fire would be an annual event under this 'savanna-forest-climate'because the dry season is long enough to dry the fuels (i.e. dried/dead grass, litter) that are needed for the combustion of fire, whereas the amount of supplied moisture during the rainy season is high enough for the production of biomass (source of fuel load). Several factors play a role for the seasonality of precipitation throughout the year, including the migration of the Intertropical Convergence Zone (ITCZ), changing Atlantic Sea Surface Temperature (SST), moist easterly trade winds from the tropical Atlantic, and the onset and intensification of Amazon convection (Nobre and Shukla, 1996; Marengo et al., 1993, 2001; Fu et al., 2001; Liebmann and Marengo, 2001; Garreaud et al., 2009). Moist trade winds from the tropical Atlantic move across the Amazon Basin to the eastern flanks of the Andes, where the South American Low Level Jet (SALLJ) develops and transports moist air further south. It crosses the Bolivian Amazon, and subsequently reaches Southeast Brazil, where the South American Convergence Zone (SACZ) begins to form (Cook, 2009) (Fig.1). The amount of moisture from the tropical Atlantic is i.e. controlled by the zonal (NE-NW) and meridional (NW-SW) SST gradient in the Atlantic Ocean (Fig. 1). A high value of zonal SST gradient is correlated with an enhancement of northeasterly trade winds and consequently with increased advection to Amazonia (Baker et al., 2001a) Interhemispheric (meridional) SST gradients produce cross equatorial winds that influence the latitudinal position of the ITCZ (Hastenrath and Greischar, 1993; Nobre and Shukla, 1996; Chiang et al., 2001). Today higher rainfall in Amazonia south of the equator is the result of anomalously low SST in the northern tropical

Atlantic, as the ITCZ then remains south of the equator (Nobre and Shukla, 1996; Baker et al, 2001b). The latitudinal shifting of the ITCZ is responsible for the modern seasonal rainfall patterns in Amazonia. During the wet season (Nov-Apr) enhanced convection in eastern Amazonia is coupled with an ITCZ positioned south of the equator. During the dry season (May-Oct) decreased convection is coupled with a northerly position of the ITCZ. Precipitation in Amazonia is also affected by the El Niño-Southern Oscillation (ENSO) phenomenon, which is coupled with cyclic changing SST in the equatorial Pacific. During the El Niño stage (warmer SST in east Pacific) the western Amazon experiences lower rainfall than usual, whereas the La Niña (cooler SST in east Pacific) stage is associated with higher precipitation than usual (Cheng et al, 2013).

2.2 Vegetation at Serra Sul

Local vegetation in Serra Sul is susceptible to changes in precipitation due to edaphic conditions on the plateau. Modern vegetation of the area is comprised of a mosaic of edaphic dense shrubby and open shrub-bush savanna (Cleef and Silva, 1994; Silva et al., 1996; Sifeddine et al., 2001; Rayol, 2007; Nunes, 2009) on the plateau associated with a thin lateritic crust (claylike ferruginous soil), and a transition zone between dense and open ombrophilous (evergreen) tropical forest (IBAMA, 2003) in the surrounding lowlands with thicker soils and a higher availability of nutrients and accumulated water. Small forest islands within the savanna vegetation occur where organic material and water accumulates in depressions ontop of the plateau. Their floristic composition is comparable to the forest at the slopes of the plateau (Rayol, 2006; Nunes, 2009). Lagoa da Cachoeira vegetation is dominated by savanna vegetation and is situated only 50 m distance to the northwestern flank of Serra Sul covered with tropical humid rainforest.

2.3 Archaeological evidence in southeast Amazonia

For the late Glacial and early Holocene anthropogenic activity in southeast Amazonia is reported from Monte Alegre (Roosevelt et al., 1996) and Lagoa da Curuça (Behling et al., 1996, 2001) (Fig.1). In Serra Sul archaeological evidence indicates human occupation after 10k cal B.P. (Kipnis et al., 2005; Magalhães, 2009).

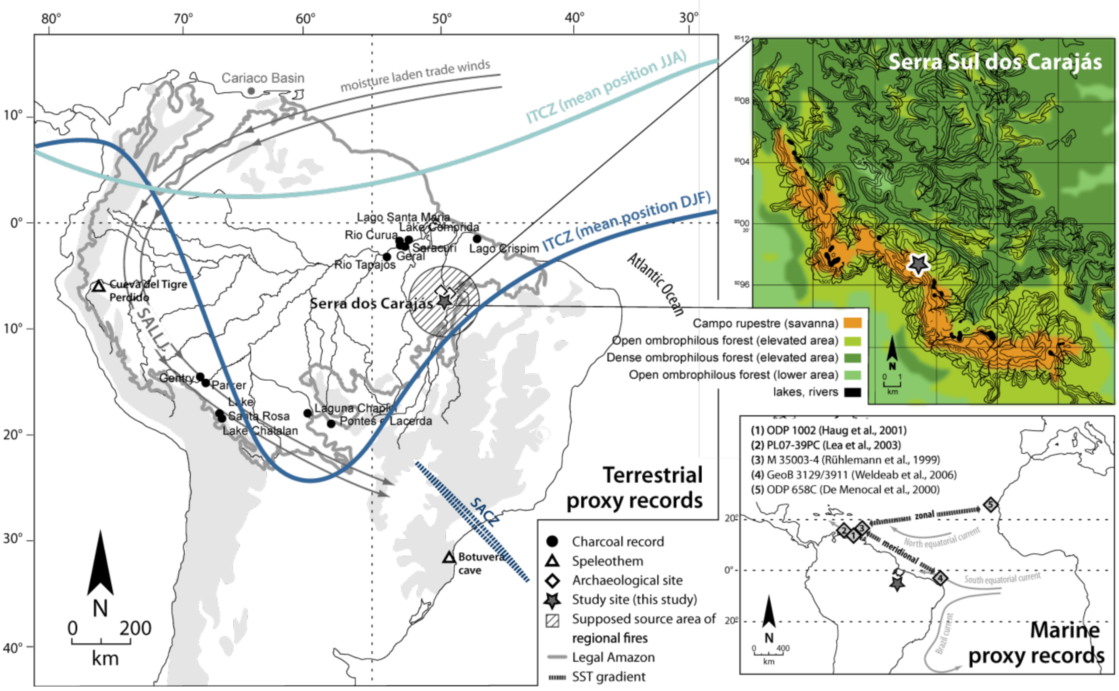


Fig. 1: Study site 'Lagoa da Cachoeira' with present vegetation types in comparison with important terrestrial and marine proxy records. Supposed source area of regional fires with 120km radius after MacDonald et al. (1989).

3. Material and methods

In 2005 a 400-cm long Livingston sediment core was taken in. The core was stored in darkness at 4°C at the Department of Palynology and Climate Dynamics (Göttingen, Germany) until analysis. The upper 200 cm of the core were analyzed for charcoal and pollen. Five bulk sediment samples (2-3 g) were used for radiocarbon dating by Accelerator Mass Spectrometry at the AMS C14-Labor Erlangen (University of Erlangen-Nürnberg). The AMS radiocarbon dates (Tab. 2) were calibrated with the Clam package (Blaauw, 2010) for R 2.14.2 (R Development Core Team, 2008) using IntCal09 calibration curve (Reimer et al., 2004).

3.1 Macro-charcoal analysis

In total 200 sediment subsamples were taken at 1cm intervals for high-resolution macro-charcoal analysis. The samples were processed following the sieving method of Stevenson & Haberle (2005). Two sieves with a mesh width of 250 µm and 125 µm were used to facilitate counting when large amounts of charred particles were present. For later calculations both fractions were summed to estimate past local fire activity (Whitlock and Larsen, 2001). Charcoal accumulation rates (CHAR) were then calculated with Psimpoll (Bennett, 1998). Subsequently, local palaeofire data are compared with the prevailing vegetation deriving from fossil pollen and fern spore analysis. For a regional comparison of palaeofire records in southern Amazonia data from 13 records from the Global Charcoal Database (Power et al., 2008) were used (Tab. 1). Charcoal data were selected based on their sample resolution. To allow for a comparison of the variable datasets, the data were standardized after Power et al. (2010) using standard Box-Cox transformation (homogenising variance) and a further rescaling to Z-scores. 250yr-time steps were chosen consistent with the temporal resolution of the Lagoa da Cachoeria core.

Tab. 1: Palaeofire records from the Global Charcoal Database[1] included in palaeofire analysis.

Record/site name	Region	Coordinates	Local vegetation	Reference(s)[2]
Geral	SE-Amazonia	-1.646903, -53.5955283	rain forest and edaphic savanna	Bush et al., 2000
Lago Santa Maria	SE-Amazonia	-1.578308, -53.605371	humid rainforest	Bush et al., 2007b
Saracurí	SE-Amazonia	-1.678846, -53.570281	humid rainforest	Bush et al., 2007b
Rio Curua	SE-Amazonia	-1.734653, -51.454924	Amazon rainforest	Behling & Costa, 2000
Lago Crispim	SE-Amazonia	-0.622637, -47.643633	disturbed coastal vegetation	Behling & Costa, 2001
Lagoa da Curuçá Profile B	SE-Amazonia	-0.766667, -47.85	pasture and secondary forest, but formerly rainforest	Behling, 2001
Rio Tapajós	SE-Amazonia	-2.775833, -55.082778	savanna and cerrado patches	Bush et al., 2007; Irion et al., 2006
Gentry	SW-Amazonia	-12.177308, -69.09765	humid rainforest	Bush et al., 2007a
Lake Parker	SW-Amazonia	-12.140612, -69.021506	humid rainforest	Bush et al., 2007a
Lake Santa Rosa	SW-Amazonia	-14.476944, -67.874722	old-growth forsest, disturbed (cultivated farmland nearby)	Urrego, 2006
Lake Chalalan	SW-Amazonia	-14.427778, -67.920833	old-growth forest	Urrego, 2006
Pontes e Lacerda	SW-Amazonia	-15.266667, -59.216667	semideciduous rainforest	Gouveia et al., 2002
Laguna Chaplin	SW-Amazonia	-14.466667, -61.066667	virgin, tall humid evergreen rainforest	Mayle et al., 2000; Burbridge et al., 2004

[1] = Power, M.J., Marlon, J., et al.. 2008. Changes in fire regimes since the Last Glacial Maximum: an assessment based on a global synthesis and analysis of charcoal data. Climate Dynamics, Vol. 30, No. 7-8, pp. 887-907, June 2008. [DOI 10.1007/s00382-007-0334-x]. [2] = Complete reference list see “References”.

3.2 Pollen analysis

In total 24 sediment subsamples (0.5 cm^3) taken every 8 cm were used for pollen analysis for the radiocarbon dated core part from 200 to 0 cm. The samples were prepared using standard methods (Faegri and Iversen, 1989) including 70% HF treatment, addition of tablets with exotic marker *Lycopodium clavatum* (Stockmarr, 1971), and mounting in glycerin gelatin. Almost all samples were counted to a minimum of 300 terrestrial pollen grains. Spores and aquatic taxa are not included within the main pollen sum but expressed as percentages of the terrestrial pollen sum. The percentage pollen diagram and the zonation by CONISS (Grimm, 1987) were conducted using Psimpoll (Bennett, 1998). Pollen and spore identification is based on appropriate literature (Colinvaux et al., 1996; Carreira and Barth, 2003; Carreira et al., 1996; Roubik and Moreno, 1991) and a pollen reference collection held at the Department of Palynology and Climate Dynamics (University of Göttingen).

4. Results

4.1 Chronology and zonation

The chronology for the upper 200 cm of the lacustrine record from Lagoa da Cachoeira is based on 5 AMS ^{14}C dates comprising the last 26.2 calibrated kilo years before present (k cal B.P.) (Fig. 2). The age-depth model was calculated with the cubic spline interpolation method (R Development Core Team, 2008). The zonation was analyzed using CONISS (all 78 identified pollen and spore taxa included), and a critical visual inspection of pollen spectra and CONISS dendrogram (Fig. 3). The dating suggests a continuous sedimentation without any gaps. Sedimentation rates between 200 and 97 cm core depth are 0.045 mm a^{-1}, and from 97 cm to the core top are 0.2 mm a^{-1}.

Tab. 2: Radiocarbon dates from Lagoa da Cachoeria.

Depth (cm)	Laboratory number*	Dated material	^{14}C yr BP	δ^{13}C (‰)‡	Age (cal yr BP)
48-49	Erl-12171	bulk marsh sediment	2374 ± 41	-27.2	2435
78-79	Erl-12481	bulk marsh sediment	3619 ± 40	-30.1	3937
133-134	Erl-10586	bulk marsh sediment	12,414 ± 38	-23.8	14,496
148-149	Erl-12172	bulk marsh sediment	14,542 ± 95	-19.7	17,675
198-199	Erl-12482	bulk marsh sediment	21,723 ± 190	-18.8	26,049

*AMS-Labor Friedrich-Alexander-Universität Erlangen-Nürnberg.

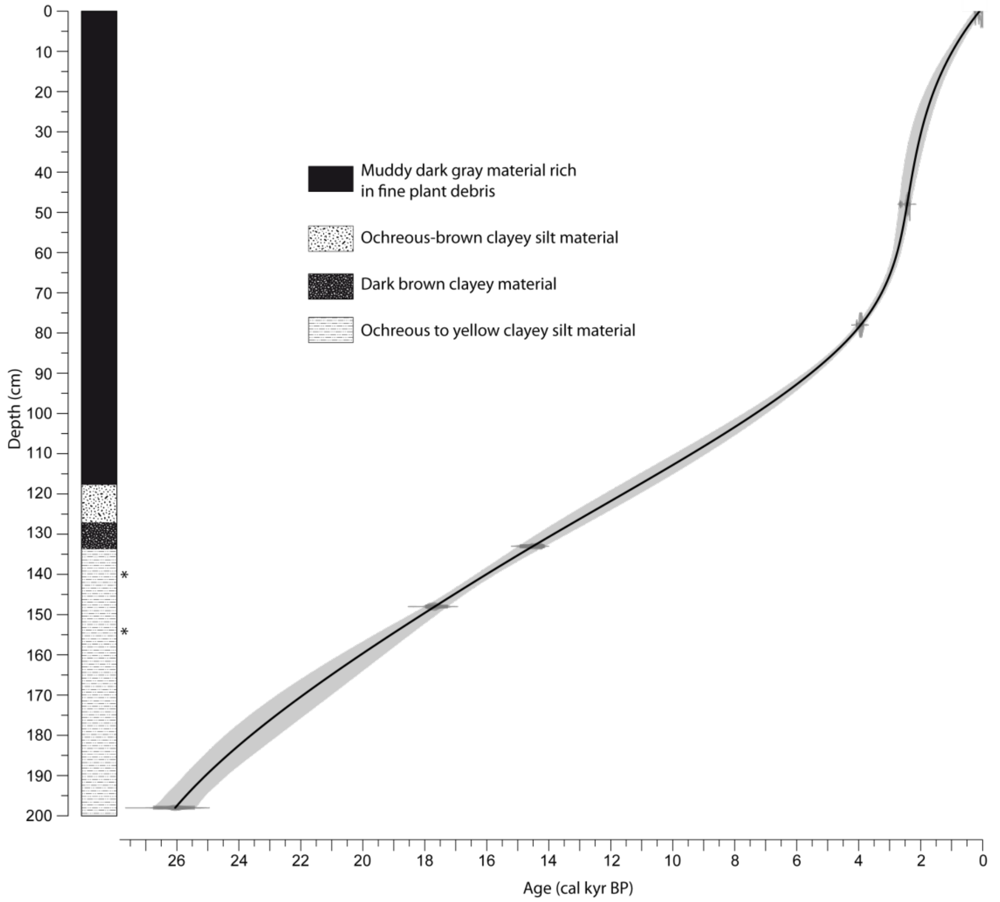


Fig. 2: Age-Depth model of 'Lagoa da Cachoeria' incl. stratigraphy; calibrated ages were calculated with the cubic spline interpolation method (R Development Core Team, 2008); stars indicate samples without preserved pollen material.

4.2 Macro-charcoal and pollen data

Lower pollen concentrations are recorded from 200-160cm core depth with with 11,000-45,000 pollen grains cm^{-3}. Between 160-0 cm concentrations range from 25,000 to 60,000 (min. 3500, max.140,000) pollen grains cm^{-3}. In three sampels (108,116, 124) very high concentrations between 270,000 and 640,000 pollen grains cm^{-3} could be recorded. Two samples (140 and 154 cm core depth) contained not enough fossil pollen for counting and were discarded for pollen analysis (Fig. 3).

Zone LDC 1 (200-158.5 cm; 26.2-19.6k cal B.P.)

During this period almost no charcoal particles were recorded. The pollen diagram is dominated by pollen of savanna vegetation systems, mainly Poaceae, *Spermacoce* (max. 40%), Amaranthaceae (incl. Chenopodiaceae ; max. 16%), and Asteraceae (max. 12%). Also *Cuphea* and Myrtaceae (both <5%) are present. Cold adapted taxa (*Podocarpus, Myrsine,* Meliaceae, *Hedyosmum, Euplassa*) are recorded in low quantities (max. 2%). Aquatic taxa are represented by Cyperaceae (max. 10%). High amounts of *Isoëtes* (95%) spores are recorded.

Zone LDC 2 (158.5-120 cm; 19.6-11.5k cal B.P.)

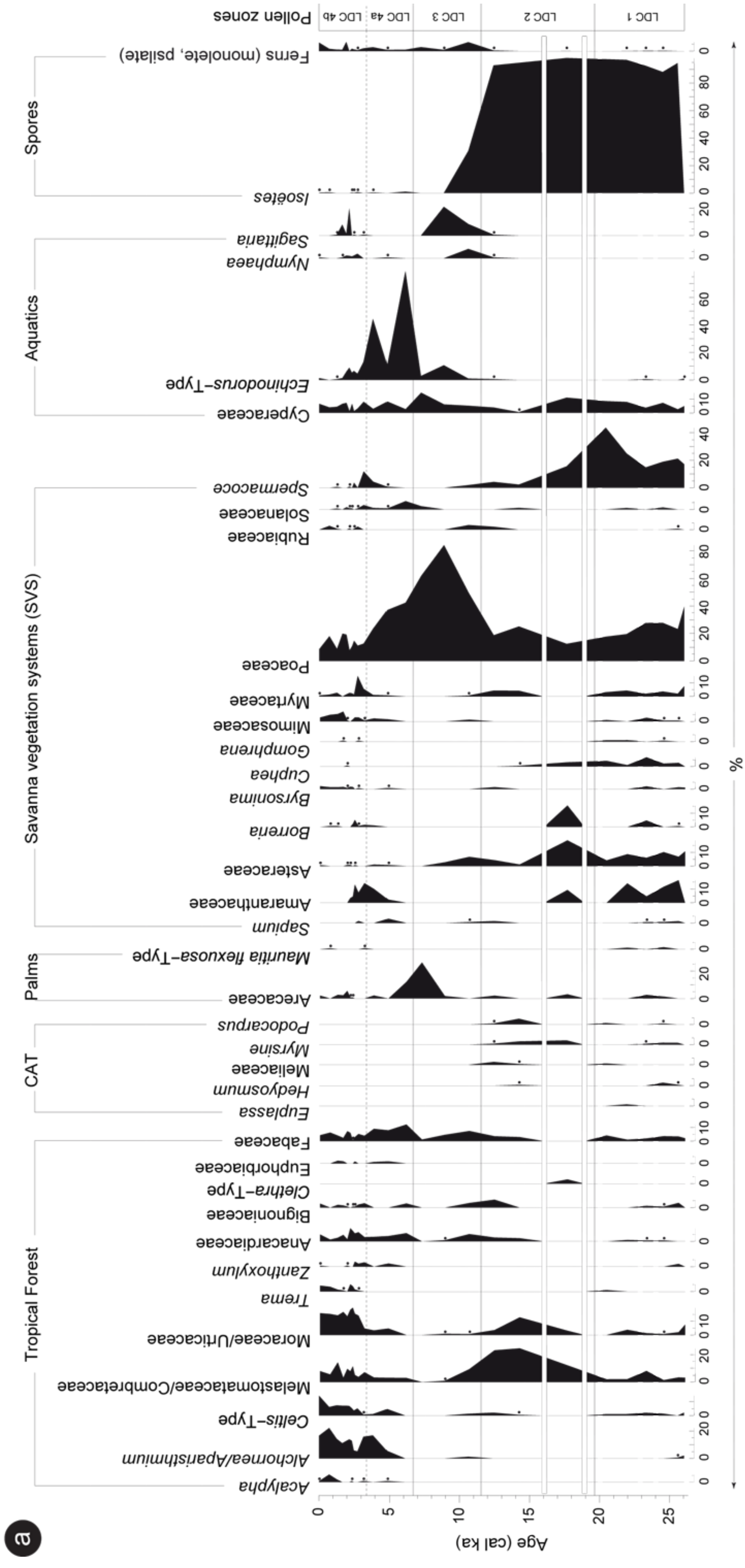
During this period almost no charcoal particles were deposited. The zone is characterized by low pollen concentrations of 3000-37,000 pollen grains cm^{-3} and contained samples with little to no pollen at about 18.5 and 16.5k cal a BP. In this period, savanna taxa are dominant, represented by Amaranthaceae (incl. Chenopodiaceae), Asteraceae, *Borreria*, and Poaceae, which latter dominate the pollen spectra (30%). Between 15.2 and 13.5k cal a BP Melastomataceae/Combretaceae (max. 22 %), Moraceae/Urticaceae (max. 12 %), and cold adapted taxa like *Podocarpus, Myrsine,* Meliaceae and *Hedyosmum* are present with low values. Cyperaceae pollen is frequently present (12 %), but decrease after 15.2k cal a BP.

Zone LDC 3 (120-97 cm; 11.5-6.7k cal B.P.)

Higher amounts of charcoal (500-1000 particles cm^{-3}) are recorded between 11 and 10.2k cal a BP. These occur together with a decreased abundance of pollen from Melastomataceae/Combretaceae. Pollen of Moraceae/Urticaceae is virtually absent. In contrast, values of Anacardiaceae (5 %), Bignoniaceae (5 %), Fabaceae (10 %), Asteraceae (10 %), Rubiaceae (4 %), and Poaceae (50 %) increased. During this time the aquatic taxon and open water indicator *Nymphaea* also increases (max. 6 %). From 10.2k to 6.7k cal a BP there is a decrease in *Nymphaea* coupled with an increase in *Sagittaria* (max. 20%). This is also the time period when Poaceae pollen (80%) dominate the pollen spectra, accompanied by Arecaceae (max. 25 %, only one sample), low amounts of Asteraceae, Fabaceae, and Cyperaceae.

Zone LDC 4a and 4b (97-37 and 37-0 cm; 6.7-3.4k and 3.4-0k cal B.P.)

A high abundance of charcoal is recorded for this zone, and is accompanied by a clear increase of tropical forest taxa. Pollen of the early secondary forest taxon *Zanthoxylum* (Marchant et al., 2002; Martins and Rodrigues, 2002) is recorded with low values. The decrease in savanna taxa is mainly attributed to the decline of Poaceae. Between 6.7k and 3.4k cal B.P. declining Poaceae pollen (40%) is still dominant together with high amounts of aquatic *Echinodorus*-type (75 %). After 3.4k cal B.P. Poaceae decrease to relatively low values (max. 20%), accompanied by increasing values of Amaranthaceae (incl. Chenopodiaceae; 15 %), Myrtaceae (12%), and *Spermacoce* (10 %), as well as Anacardiaceae (6%), Melastomataceae/Combretaceae (10%), and Moraceae/Urticaceae (12%). From 2.2k cal B.P. onwards higher percentages of *Alchornea/Aparisthmium* (20%), *Celtis*-type (max. 12%), Melastomataceae/Combretaceae (max. 10%), Moraceae/Urticaceae (15%), and Mimosaceae (6%) are recorded. Myrtaceae and *Spermacoce* pollen levels are low, as well as the aquatic *Echinodorus*-type.


a
Pollen zones
LDC 4b
LDC 4a
LDC 3
LDC 2
LDC 1
Spores
Ferns (monolete, psilate)
Isoëtes
Aquatics
Sagittaria
Nymphaea
Echinodorus–Type
Cyperaceae
Savanna vegetation systems (SVS)
Spermacoce
Solanaceae
Rubiaceae
Poaceae
Myrtaceae
Mimosaceae
Gomphrena
Cuphea
Byrsonima
Borreria
Asteraceae
Amaranthaceae
Sapium
Palms
Mauritia flexuosa–Type
Arecaceae
CAT
Podocarpus
Myrsine
Meliaceae
Hedyosmum
Euplassa
Tropical Forest
Fabaceae
Euphorbiaceae
Clethra–Type
Bignoniaceae
Anacardiaceae
Zanthoxylum
Trema
Moraceae/Urticaceae
Melastomataceae/Combretaceae
Celtis–Type
Alchornea/Aparisthmium
Acalypha
Age (cal ka)
0
5
10
15
20
25
%
0 20 40 60 80
0 20
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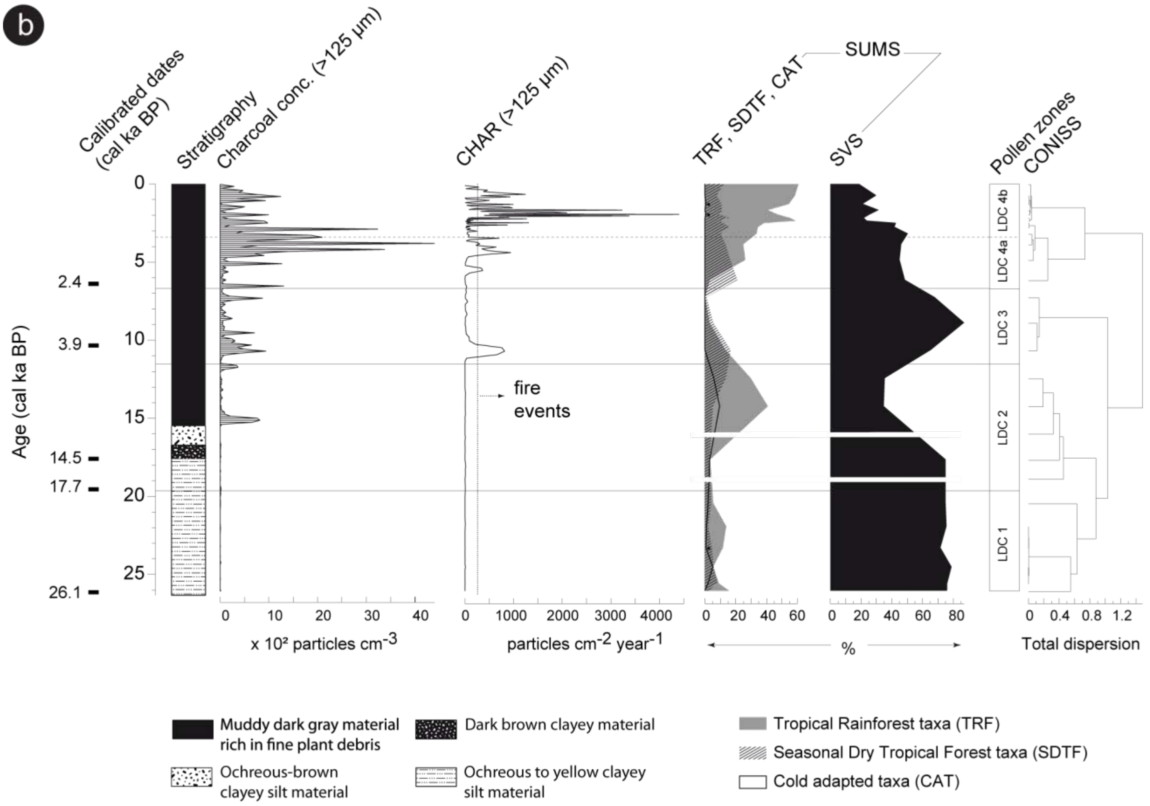

Fig. 3: Pollen and charcoal diagram; (a) pollen percentage data, (b) pollen sums, charcoal concentrations, charcoal accumulation rates (CHAR), and CONISS dendrogram; white bars indicate samples without preserved pollen.

5. Interpretation and discussion

Changes of paleovegetation at Lagoa da Cachoeira are suggested to record past conditions on the plateau and at its slopes. It is uncertain how far lowland vegetation could be also represented in the pollen record, because comparative modern pollen rain studies for this area are still lacking. The recorded paleofires are of (extra) local origin, as large charred particles of >125 and 250 µm are not transported over long distances and therefore are a reliable record for extralocal (nearby) and local fires (within the watershed) (e.g. Clark, 1988; Withlock and Millspaugh, 1996; Whitlock and Larsen, 2001; Carcaillet et al., 2001) less than 7km away (i.e. mainly restricted to the plateau).

5.1 Vegetation reconstruction

Late Pleistocene and transition to early Holocene (LDC 1 and LDC 2)

During the late Pleistocene from 26.2k to 15k cal B.P. the rare occurrence of forest taxa suggest less forested areas, possibly at the lower slopes of the plateau. A scrub-bush savanna is the dominant vegetation type, reflected by the frequent occurrence of Poaceae and *Spermacoce*, as well as Asteraceae and Amaranthaceae (incl. Chenopodiaceae). The occurrence of the semi-aquatic *Isoëtes* refers to a lower lake level until the beginning of the Holocene, indicating dry climatic conditions, which is also recorded by former studies at Serra Sul (Hermanowski et al., 2012). Between 15k and 10.2k cal B.P. the tropical forest area increased in the study area of Serra Sul, indicated by the higher occurrence of Melastomataceae/Combretaceae and Moraceae/Urticaceae. Savanna vegetation with Poaceae, Asteraceae, and Myrtaceae was still present in reduced concentrations. This overlaps with the increased occurrence of forest at Serra Sul under increasingly wetter conditions between 15.4k and 11.4k cal B.P. as suggested by Sifeddine et al. (2001) from records CSS2 and CSS10. At Pantano de Mauritia about 2.3 km distant from Lagoa da Cachoeira, the forested area increased first between 11.4k and 10.2k cal B.P. (Hermanowski et al., 2012).

Early to mid-Holocene (LDC 3)

After 10.2k cal B.P. grass became a larger component of the vegetation, and the open vegetation became more floristically similar to modern savannas found in Serra Sul today. This is indicated by a decreasing sum of tropical forest taxa and an increase in the sum of savanna and seasonal dry tropical forest taxa (Pennington et al., 2001; Mayle, 2006; Gosling et al., 2009) including Fabaceae, Bignoniaceae, and

Anacardiaceae. These taxa are able to tolerate longer dry periods than tropical forest taxa. Between 10.2k and 6.7k cal B.P. a marked reduction of tropical forest taxa and the increase of grass-dominated savanna around Lagoa da Cachoeira indicate a change to dry climatic conditions. Possibly forested areas were present at the slopes of the plateau. These mainly consisted of Arecaceae, Fabaceae, Anacardiaceae, and Bignoniaceae. The low abundance of charcoal indicates local fires were not that frequent or even absent at Lagoa da Cachoeira, whereas former studies from Pántano da Maurítia (Serra Sul) suggest regional fire activity under long phases of climatic dry conditions (Hermanowski et al., 2012).

Measurements of the molecular marker levoglucosan, which is emitted in high amounts during the burning of fuel containing cellulose, point to fire events at Serra Sul at 7k and 5k cal B.P. (Elias et al., 2001), coincident with forest fires at Serra Norte dos Carajás from 7.5k to 4.7k cal B.P. (Cordeiro et al., 2008). An opening of the forest was also suggested by Sifeddine et al. (2001) interpreted as the result of alternating dry and short humid periods between 7.9k and 9.4k cal B.P..

Mid- to late Holocene (LDC 4)

After 6k cal B.P. both tropical forests and savannas are present. Forests are more diverse, with a relatively high abundance of Fabaceae, Anacardiaceae. The presence of *Alchornea/Aparisthmium* and the pioneer *Celtis,* together with low abundance of Melastomataceae/Combretaceae and Moraceae/Urticaceae could be indicative for a first repopulation of a formerly open habitat (Hermanowski et al., 2012), but also for an increasingly influence of humans because of the presence of hunter-and-gatherers (Kipnis et al., 2005; Magalhães, 2009). After 3.4k cal B.P. the increased abundance of tropical rainforest taxa indicates the establishment of modern rainforests in Serra Sul. The pioneer trees *Celtis* and *Trema* (Marchant et al., 2002) point to an extension of the forested area, though moderate forest clearance by humans, e.g. for hunting-and-gathering purposes or forest cultivation, cannot be completely excluded. High concentrations and accumulation rates of charcoal point to frequent fires in this period of modern rainforest establishment.

The increased abundance of Moraceae/Urticaceae and *Alchornea/Aparisthmium* suggests reduced water stress due to intensified precipitation. Absy et al. (1991) recorded forest development around 3.1k cal B.P. at Serra Sul about 3.5 km distant to Lagoa da Cachoeira. Changes in precipitation are supported by rising lake levels at Serra Norte dos Carajás from 2.8k to 1.3k cal B.P. (Cordeiro et al, 2008).

5.2 Linkage between local fires, vegetation, humans, and climate

The most challenging part in the reconstruction of past fire activity is the determination of the driving factor for recorded fires. Especially when the archaeological evidence suggests that humans could have been involved it is difficult to differentiate between a climatic and/or anthropogenic origin of paleofires.

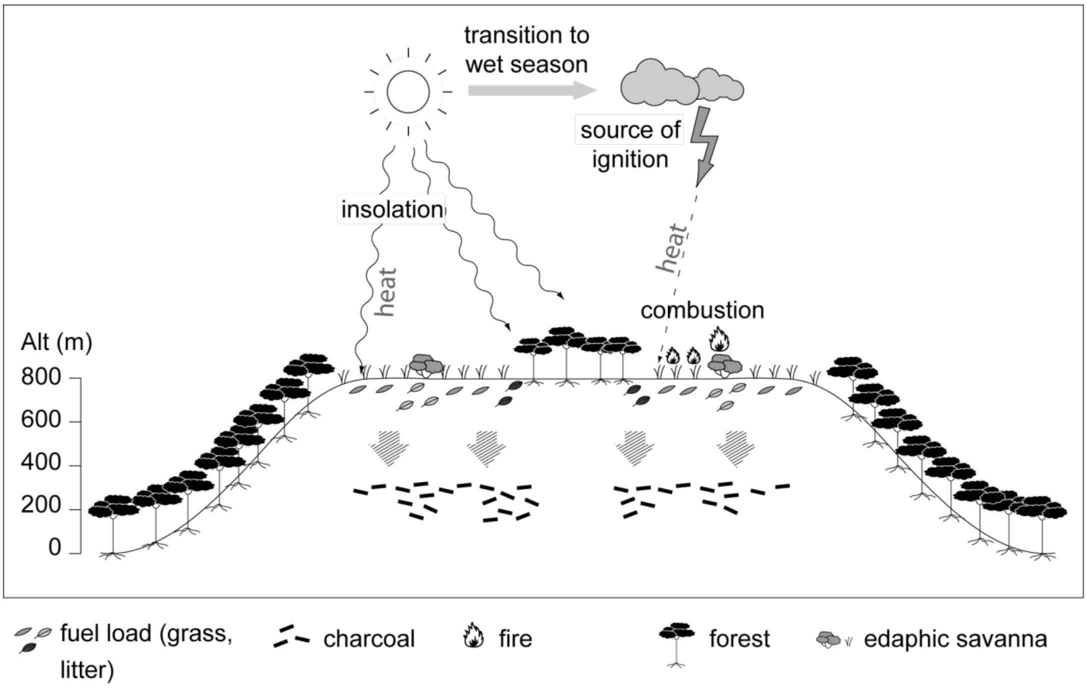

Fig. 4: Schematic diagram of the suggested establishment of natural fires at Serra Sul dos Carajás under seasonal climatic conditions (after Stott, 2000).

5.2.1 Peak fire at the glacial-interglacial transition

Strong fire activity in Serra Sul can be recognized from 11k to 10.2k cal B.P.. During this time at Pántano da Maurítia (Serra Sul) the growth of tropical rainforest at the slopes of Serra Sul suggested wetter conditions (Hermanowski et al., 2012). The frequent fires in Serra Sul occurred when forest taxa, namely Anacardiaceae, Bignoniaceae, and Fabaceae were present, that today are known from seasonal dry tropical forests in southwest Amazonia (Pennington et al., 2001; Mayle, 2006; Gosling et al., 2009). The combined presence of Anacardiaceae, Bignoniaceae, and

Fabaceae can be interpreted in three different ways.

(1) Climatic influence – The climate during this period was seasonal with a pronounced wet season. Thunderstorm lightning ignitions were frequent at the transition from dry to wet season. Taxa known from seasonal dry forests with adaption to low intensity fires (Pinard and Huffman, 1997) would then have a competitive advantage over other tropical forest taxa.

(2) Anthropogenic influence – Humans could have influenced the vegetation species composition by setting fire to clear land to potentially improve hunting grounds. Archaeological evidence indicates human occupation at Serra Sul after 10k cal B.P. (Kipnis et al., 2005; Magalhães, 2009). It is possible however, that humans arrived even earlier in Carajás, as evidence for anthropogenic activity in eastern Amazonia during the late Glacial and early Holocene is reported from activity in Monte Alegre (Roosevelt et al., 1996) and Lagoa da Curuça (Behling et al., 1996, 2001).

(3) Combination of climatic and anthropogenic influence – Seasonal climatic conditions with pronounced wet seasons were coupled with the growth of forest and the temporal presence of humans who additionally influenced local fire history in Serra Sul. The combination of favorable climate and anthropogenic influence facilitated the growth of pioneers, and plants with adaptions to low intensity fires.

Wildfires need suitable fuel load (grass, litter) and a source of ignition to expand (Stott, 2000). The most fire promoting environment would be a mosaic of forest and savanna patches. In these mosaics the ecotonal margins between forest and savanna patches are especially vulnerable during fires. After dry savanna grasses catch fire, the next would be dry woody savanna bushes and small trees. Once fire burns the lower canopy, insolation could penetrate to the surface and ground vegetation could dry further in a positive feedback loop (Fig. 4). Dried fallen litter from taxa like Anacardiaceae and Bignoniaceae at the forest margins could contribute additional ground fuel load for the spreading fire. Additionally, increased summer insolation would result in the drying of leaf fall during the dry season. The spread of fires would be inhibited by moist tropical living forests that form a natural, effective fire barrier (Stott, 2000) and the sloping hillside, as fires tend to burn uphill. Fire would then remain restricted to the top of the plateau without spreading into the forested lowlands.

Such environments could have existed in Serra Sul during transition periods between drier to wetter climates, and under a seasonal climate with distinct dry and wet seasons when available soil moisture was sufficient to provide the growth of tropical forest and shrubby savannas. The source of ignition could be provided by thunderstorms with lightning strikes, as they are common during wet seasons, and at the transition from dry to wet season, when enough climatically dried fuels would be available to set fire after lightning strikes (Stott, 2000).

We note when local palaeofires at Lagoa Cachoeira are compared with previous studies from Pántano da Maurítia (both Serra Sul), the recorded fires between 11k and 10.2k cal B.P. at Lagoa da Cachoeria are coupled with a short-term occurance of wet tropical forest. At the same time and under the same vegetational conditions no fires (local and regional) were recorded at Pántano da Maurítia (Hermanowski et al., 2012), located 2 km south of Lagoa da Cachoeira on the same plateau. Therefore a direct correlation with a higher or lower fire frequency and dry or wet climatic conditions is difficult to be draw.

5.2.2 Low local fire activity during the mid-Holocene

One striking feature in the local fire history of Serra Sul is the markedly low frequency and sometimes absence of local fires at Lagoa da Cachoeira during the mid-Holocene.

(1) Climatic influence – If we assume a natural origin of local fire activity, the reason for low or absent local fires could be a decreased frequency of thunderstorms (source of ignition) in a period with longer dry seasons (Hermanowski et al., 2012). Under drier conditions fire prone forest margins would be also situated farther downslope, out of the reach of a fireline that would be hindered by the sloping hillside (Stott, 2000). Additionally, due to the absence of ligneous savanna shrubs as a significant fuel load a natural ground fire would not produce such a large amount of charcoal particles as it would be the case in a shrubby savanna.

(2) ***Anthropogenic influence*** – If local fires are primarily coupled with human activity one reason could be the abandoning of this area because of unbearable dry conditions. Site abandonment due to dry conditions during the mid-Holocene is also suggested by Irion et al. (2006) at Rio Tapajós (eastern Amazonia; Fig. 1).

5.2.3 Frequent fires in the late Holocene

The highest fire frequency in Serra Sul is recorded after 5k cal B.P.. Comparable to the glacial-interglacial transition, the forest taxa Anacardiaceae, Bignoniaceae, and Fabaceae are present. Also the pioneer tree *Celtis* occurs at Serra Sul and is more frequent after 5k cal B.P..

(1) Climatic influence – Under a seasonal climate wet seasons were long enough for the growth of forest and shrub-bush savanna known from today in Serra Sul. During the dry season drying of this biomass would provide enough fuel load for natural fires, when thunderstorms at the transition from dry to wet season provided sufficient sources of ignitions for the combustion of dried fuel (grass, litter) load.

(2) Combination of climatic and anthropogenic influence – The above mentioned boundary conditions are also favorable for pre-Columbian societies that could have already used forest management strat-

egies comparable to the modern Kayapó Indians of the Brazilian Amazon who transform campo/cerrado into tropical forest patches also by using fire (Posey, 1985). Therefore, it is difficult to identify if paleofires in Serra Sul were primarily of natural or anthropogenic origin.

5.3. Regional fire history of southern Amazonia

To determine if local fires in Serra Sul where of natural or anthropogenic origin, we compared the fire history of southern Amazonia at a regional scale together with proxy records (Tab. 3) of past precipitation: (a) Speleothem $\delta^{18}O$ values from Peru (Van Breukelen et al., 2008) and southern Brazil (Wang et al., 2007) are conducted as a record for moisture input from Amazonia to the system of SASM, as high (low) $\delta^{18}O$ values point to weaker (strengthened) SASM due to less (more) moisture input from Amazonia (Cruz et al., 2005; Cheng et al., 2013). (b) Lower (higher) Ti values from the Cariaco Basin in northern Venezuela reflect weaker (stronger) rainfall in this region due to a southward (northward) shift of the ITCZ (Haug et al., 2001). (c) Reconstructed SST from the Cariaco Basin (Lea et al., 2003) and from the Atlantic Ocean (Rühlemann et al., 1999; deMenocal et al., 2000; Weldeab et al., 2005, 2006) are incorporated because of their influence on Amazonian rainfall regimes. The comparison is used to explain differences between the fire histories of southwest and southeast Amazonia which currently also exhibit differences in rainfall distribution (Marengo et al, 2001).

The first fire events at Lagoa da Cachoeira during the early Holocene from 11k to 10.2k cal B.P. pre-date southwest Amazonian fire activity (Fig. 5a) about 400 years, but this may be within dating uncertainties of the Lagoa da Cachoeira core (Fig. 2). From 11k to 10.2k cal B.P. speleothem data from the Botuverá cave in southern Brazil indicate generally lesser contribution by Amazon moisture to a weakened South American Summer Monsoon (SASM) (Wang et al, 2007) which indicates drier conditions in Amazonia. Also SSTs in the Cariaco Basin (Lea et al., 2003) slightly decrease after an abrupt rise, coinciding with drier conditions in northern Venezuela (Haug et al., 2001; Fig. 5c). However, during 11k and 10.2k cal B.P., at Carajas conditions were wetter (Sifeddine et al., 2001; Cordeiro et al., 2008; Hermanowski et al., 2012). We note that at the same time $\delta^{18}O$ values from Botuverá cave are somewhat lower possibly due to a slightly intensified SASM (Fig. 5b).

The reconstructed meridional (NW-SW) and zonal (NE-NW) ΔSST of the Atlantic show, that the southern Atlantic Ocean was generally warmer between 11k and 10.2k cal B.P. (Fig. 5d). When meridional ΔSTT was rather high during this time, zonal ΔSST was slightly weaker. This weaker zonal gradient would suggest weakened northeast trade winds coupled with weakened Amazon Basin convection (Baker et al., 2001b). We suggest that the described Atlantic SST conditions could be the reason for a more southerly position of the ITCZ, which would correspond to wetter conditions in southeastern Amazonia.

At Cachoeira during the mid-Holocene from 9k-6k cal BP, local fire activity was at a minimum. On a regional scale, fire activity was higher in southwest Amazonia than in the southeast (Fig. 5a), which coincides with a weakened SASM in southern Brazil (Wang et al., 2007), higher SST in the Cariaco Basin (Lea et al., 2003) , and wetter conditions in northern Venezuela (Haug et al., 2001) (Fig. 5b-c).

Between 9 and 8k cal B.P. more frequent fires in the southeast were accompanied by a lesser fire frequency in the southwest, whereas in both regions fires were generally frequent after 6.3k cal B.P.. During both periods SASM was intensified, only slightly between 9k and 8k cal B.P., but all the more after 6.3k cal B.P.. Zonal ΔSST in the tropical Atlantic around 8.25k cal B.P. show a clear cold pool in the western equatorial Atlantic, roughly coinciding with the abrupt climate change around 8.2k cal B.P. (Alley et al., 1997; Alley and Ágústóttir, 2005) and a Bond event around 8.1k cal B.P. (Bond et al., 1997), respectively. For these conditions a southward displacement of the ITCZ is suggested (Alley and Ágústóttir, 2005). Around 8k cal B.P. meridional ΔSST (Fig. 5d) shows a shift from a formerly warmer southwestern to a generally warmer northwestern tropical Atlantic. A warmer tropical north Atlantic could suggest a general northward shift of the ITCZ, and together with still cold SST in the eastern equatorial Atlantic (Weldeab et al., 2005), suggesting a delayed onset of central Amazon convection (Fu et al., 1999; Fu et al., 2001), this would result in longer dry seasons in southeast Amazonia after 8k cal B.P.. Differences between southeast and southwest Amazonian fire history may be also attributed to weaker ENSO (El Nino/Southern Oscillation) activity (Sandweiss et al., 1996; Keefer et al., 1998; Rodbell et al., 1999; Clement et al., 2000; Sandweiss et al., 2001; Otto-Bliesner et al., 2003) that influenced the southwest more than the southeast, but the temporal resolution of the present record (ca. 250 yr) is not high enough to recognize connections between fire and El Niño events in the past. Also weaker low level jets from central Amazonia to the eastern Andes and a weaker Bolivian high (Dias de Melo, 2007) may have played a role for different fire histories in SE- and SW-Amazonia.

After 6.3k cal B.P., when local fires were recorded at Lagoa da Cachoeira after a long period of markedly less local fire activity, palaeofires were frequent in both southeast and southwest Amazonia. In the southeast no distinctive pattern of palaeofire activity can be recognized. Here, climatic conditions were increasingly seasonal with severe dry seasons until 3.7k cal B.P. (Hermanowski et al., 2012). Intensified SASM (Wang et al., 2007) and wetter conditions in northern Peru (van Breukelen et al., 2008) refer to generally wetter conditions in the Amazon Basin, corresponding to slightly drier conditions in northern Venezuela (Haug et al., 2001).

After 3.7k cal B.P. enhanced fire frequency in southeastern and southwestern regions overlaps with the expansion of modern rainforest (Mayle et al., 2000; Burbridge et al., 2004; Sifeddine et al., 2002; Cordeiro et al., 2008; Hermanowski et al., 2012). In the tropical Atlantic meridional ΔSST slightly decreased around 6k cal B.P., whereas zonal ΔSST increased (~1°C). Afterwards zonal ΔSST decreased markedly about 4°C contemporaneously with a steadily increasing meridional ΔSST (Fig. 5d). Due to lower zonal ΔSST northeast trades were possibly extenuated which would weaken convection over the Amazon basin.

Differences between the composite palaeofire data from southeast Amazonia with our record from Serra Sul may be partly attributed to the latitudinal distribution of the available records (Fig. 1; Tab. 2). With the exception of Lagoa da Cachoeira (6° S), the other records used for this study are situated near the equator (0.6-2.8° S). Only two of them are older than 8,000 years (Behling, 2001; Bush et al, 2007; Irion et al., 2006), and human induced forest fires during pre-Colombian settlements could have played an important role there.

Tab. 3: Proxy records included in reconstruction of fire history in southern Amazonia.

Record/site name	Proxy data	Region	Coordinates	Reference[2]
M 35003-4	SST	Tropical north Atlantic	12° 05' N, 61° 15' W; 1,299 m water depth	Rühlemann et al, 1999
ODP 658C	SST	Tropical north Atlantic	20°44'60.00"N, 18°34'59.99"W; 2263 m water depth	De Menocal et al, 2000
GeoB 3129/3911	SST	Tropical south Atlantic	4°36'48.00"S, 36°38'12.00"W; 830 m water depth	Weldeab et al., 2006
PL07-39PC	SST	Cariaco basin, N-Venezuela	10°41'60.00"N, 65°56'30.01"W; 790 m water depth	Lea et a., 2003
ODP 1002	Ti	Cariaco basin, N-Venezuela	10°42'N, 65°10' W; 893 m water depth	Haug et al, 2001
Botuverá cave	$\delta^{18}O$	Santa Catarina, S-Brazil	27°13'S, 49°09'W; 250 m a.s.l.	Wang et al., 2007
Cueva del Tigre Perdido	$\delta^{18}O$	Nueva Cajamarca, San Martín, Peru	5°56'26"S, 77°18'29"W	Van Breukelen et al., 2008
Laguna Pallcacocha	Red color intensity	S-Ecuador	2°45'S, 79°10‘; 4060 m a.s.l.	Moy et al., 2002

[2] = Complete reference list see ‘References’.

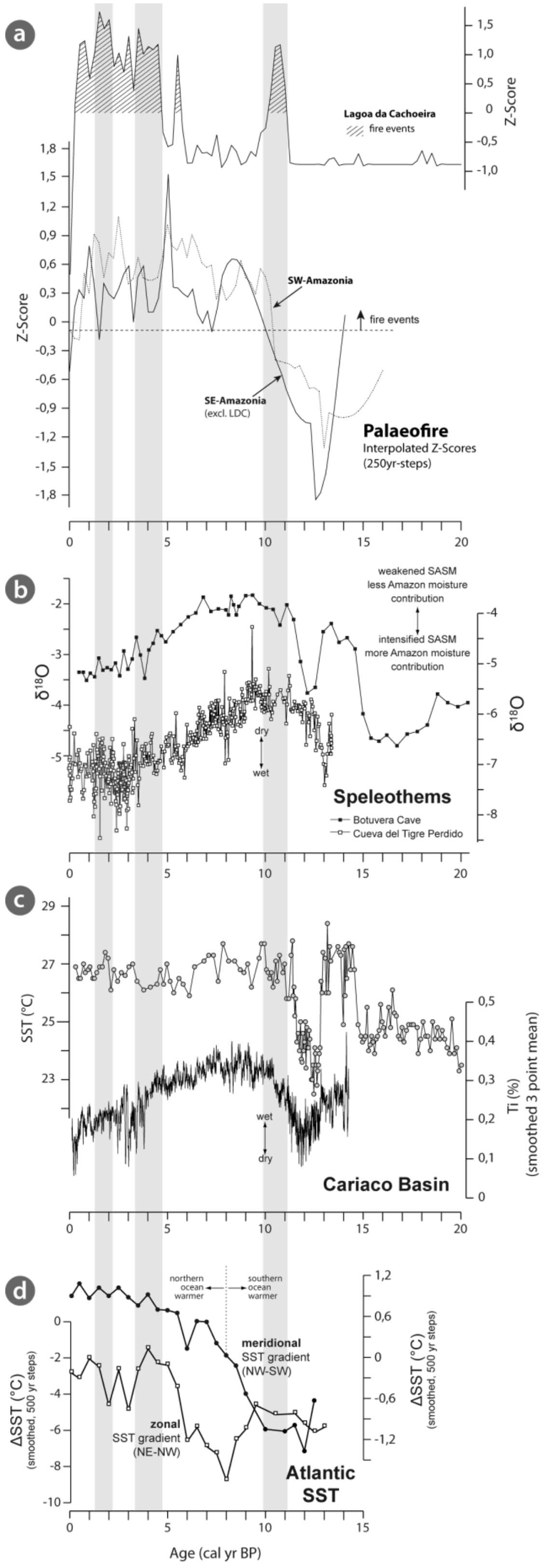

Fig. 5: Standardized charcoal data from 'Lagoa da Cachoeira' and southern Amazonia compared with data from important terrestrial and marine proxy records. (a) Interpolated Z-scores in 250 a-steps for Lagoa da Cachoeira (upper curve) , southwest and southeast Amazonia (lower curves), (b) $\delta^{18}O$ data from Botuverá cave (Wang et al., 2007) and Cueva del Tigre Perdido (van Breukelen et al., 2008), (c) SST and Ti (%) from the Cariaco basin (Haug et al., 2001; Lea et a., 2003), (d) zonal and meridional ΔSST in the tropical Atlantic obtained from marine records (Rühlemann et al., 1999; de Menocal eta l., 2000; Weldeab et al., 2005, 2006).

6. Conclusions

For the reconstruction of long-term fire history in southern Amazonia the various interactions between fire, prevailing vegetation, regional climate, and anthropogenic influence need be addressed. The new study from Serra Sul dos Carajás in southeast Amazonia shows, that a clear correlation between wetter (drier) climates and lower (higher) frequency of paleofires cannot be easily drawn. Most frequent fires recorded at Lagoa da Cachoeira occurred during seasonal and generally wetter periods from 11 to 10.2k cal B.P. and after 5k cal B.P., when moist tropical forest and savanna vegetation coexisted at Serra Sul. The crucial factor for local fires seems to be the amount of time, during that sufficient moisture is available to foster the growth of woody vegetation. This vegetation then serves as fuel for fire, naturally and/or anthropogenically induced. We suggest that these conditions are both favorable for natural fires but as well as for the presence of human societies in Serra Sul. Also the archaeological evidence suggests that humans could have influenced vegetation by using fire, as presence of hunter-and-gatherers in Serra Sul is recorded after 10k cal. B.P. (Kipnis et al., 2005; Magalhães, 2009). Markedly less frequent fires at Lagoa da Cachoeira under dry early-mid-Holocene conditions between 10.2k and 6.7k cal B.P. could be attributed to less fuel load in a more grass dominated savanna and less sources of ignition (lack of thunderstorms). On the other hand it could be also explained with site abandonment by humans due to unbearable dry conditions.

In both cases changing precipitaion patterns would be the driving factor for the presence/absence of humans and both natural and/or anthropogenic fire. The comparison of the present study with fire records from Amazonia (southeast and southwest) and proxy records of past precipitation suggests connections between fire history in southern Amazonia and the seasonality of precipitation. Composite fire records from southeast and southwest Amazonia also suggest a sensitivity of these regions to changing conditions in the Atlantic Ocean at least since 11.5k cal B.P., due to its strong influence on precipitation regimes. We note that paleofire activity is antiphased in southeast Amazonia in the time window around 8.2k cal B.P., when for a short time (ca. 200 years) climate was cooler due to freshwater input to the North Atlantic (Bond et al., 1997; Urrego et al., 2009).

The different fire histories of southeast versus southwest Amazonia show that in the southwest palaeofire activity is generally higher throughout the Holocene, which may be also partly attributed to an increased frequency of ENSO warm events (Moy et al., 2002). But the underlying factor for Holocene fire frequency seems to be the influence of zonal and meridional SST gradients on Amazonian precipitation regimes, which could have not only influenced past vegetation composition, but also Pre-Colombian human societies entering Serra Sul. For a comprehensive reconstruction of fire history further high-resolution palaeofire studies south of 5° S in eastern Amazonia are needed. To clarify the role of Pre-Colombian societies in the Carajás region archaeological sites in Serra Sul need to be studied intensively.

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Supplementary pollen data of an undated core segment from Lagoa da Cachoeira

(unpublished)

Material and Method

The core part from 200 to 400 cm depth was analyzed by means of fossil pollen and charcoal (cp. chapter IV). This core part is still undated. Multivariate data analysis was performed using C2 software (Juggins, 2007), using a Principal Component Analysis with a square root transformation of count data (Fig. 4). The zonation of the percentage diagram was conducted with CONISS implemented in the Psimpoll software by Bennett (1998).

Results

Multivariate analysis (PCA)

The ordination diagram (Fig. 4) shows the course of pollen compositional changes (43 taxa chosen, Tab. 4) according to sample depth (Fig. 4). The first two axes explain 34% of the total variance in the data (Fig. 4). A significant directional change can be recognized between 336 and 328 cm core depth separating pollen assemblages of 400-336 cm from pollen assemblages of 336-200 cm. This directional change corresponds to the pollen zones obtained by CONISS (Appendix A). At the positive end of axis 1 the pollen assembladge from 400 and 336 cm is found, mainly characterized by Anacardiaceae, *Alchornea/Aparisthmium*, *Celtis*-type, Melastomataceae/Combretaceae, Moraceae/Urticaceae and Mimosaceae, and also the cold adapted taxa *Myrsine* and *Hedyosmum*. The negative end of axis 1 is mainly driven by Asteraceae, Amaranthaceae/Chenopodiaceae, Poaceae, and *Spermacoce*, which occur together with the cold adapted taxa *Ilex* and *Podocarpus.*

Tab. 4: Alphabetical list of the abbreviations of pollen taxa in the ordination diagram (Fig. 4).

Abbreviation	Taxon	Vegetation group[1]	Abbreviation	Taxon	Vegetation group[1]
Acal	*Acalypha*	TF	Hedy	*Hedyosmum*	CAT
Alch/Ap	*Alchornea/Aparisthmium*	TF	Ilex	*Ilex*	CAT

Am/Chen	Amaranthaceae/Chenopodiaceae	SVS	Lora	Loranthaceae	TF
Ama	Amaryllidaceae	SVS	MaurT	*Mauritia flexuosa*-type	Palms
Ana	Anacardiaceae	TF	Mel/Combr	Melastomataceae/Combretaceae	TF
Api	Apiaceae	SVS	Mel	Meliaceae	TF
Apo	Apocynaceae	TF	Mim	Mimosaceae	SVS
Ara	Araceae	TF	Mor/Urt	Moraceae/Urticaceae	TF
Aral	Araliaceae	TF	Myrs	*Myrsine*	CAT
Arec	Arecaceae	Palms	Myrt	Myrtaceae	SVS
Aster	Asteraceae	SVS	Plant	Plantago	SVS
Bign	Bignoniaceae	TF	Poa	Poaceae	SVS
Borr	*Borreria*	SVS	Podo	*Podocarpus*	CAT
Brass	Brassicaceae	SVS	Poly	Polygonaceae	SVS
Byrs	*Byrsonima*	SVS	PouT	*Pouroumea*-type	TF
Cary	Caryocaraceae	SVS	Rub	Rubiaceae	SVS
CelT	*Celtis*-Type	TF	Sap	*Sapium*	
CleiT	*Cleidion*-Type	TF	Sola	Solanaceae	SVS
Cuphea	*Cuphea*	SVS	Sperm	*Spermacoce*	SVS
Euph	Euphorbiaceae	TF	Trema	*Trema*	TF
Fab	Fabaceae	TF	Zanth	*Zanthoxylum*	TF
Gomph	*Gomphrena*				

[1] = CAT (Cold adapted taxa), SVS (Savanna vegetation systems), TF (Tropical Forest)

Pollen diagram

Pollen zone LDC-I (400-331 cm) – The pollen spectra are dominated by taxa of tropical rainforest, specifically *Alchronea*/*Aparisthmium* and *Zanthoxylum*. Fabaceae, *Clethra*-type, Proteaceae, *Pouroumea*-type, and *Cecropia* also occur (max. 5%). Furthermore, a relatively high amount of cold adapted taxa is recorded, namely *Myrsine*. But also *Ilex*, Meliaceae, and sporadical pollen of *Weinmannia*-type were found. Besides, a high amount of Arecaceae pollen occurs with values ranging from 10-34%. Savanna vegetation is mainly represented by low amounts of Asteraceae, *Spermacoce*, and Poaceae. Aquatic taxa *Echinodorus*-type and *Ludwigia* are also present with values around 10%. At the end of the zone, percentages of *Isoëtes* spores clearly increase from 12 to 60%, accompanied by increased values of the colonial algae *Botryococcus*. Pollen concentration is high in the lower half of the zone (100,000 grains/cm^3), but decreases markedly between 350 and 331 cm core depth. Palynological richness is relatively high. Almost no charred particles were deposited (Appendix A).

Pollen zone LDC-II (331-211 cm) – The zone is characterized by a clear increase of savanna taxa, accompanied by a marked decrease of tropical forest taxa.

Tropical forests are mainly represented by pollen of *Acalypha* (<5%), *Zanthoxylum*, and also *Sapium* (10%). Increased percentages of the cold adapted taxon *Myrsine* (max. 35%) are obvious. Other cold adapted taxa (*Euplassa, Ilex,* Meliaceae) occur with low values. Pollen of Convolvulaceae (max. 14%), Solanaceae (max. 9%), Burseraceae (max. 9%), and Brassicaceae (4%) clearly contribute to the increase of savanna taxa. Poaceae are scarcely present, but increase from 5 to 25% between 240 and 211 cm core depth. This increase is accompanied by higher percentages of the aquatic taxa *Echinodorus*-type and *Ludwigia* as well as by decreasing values of *Isoëtes* spores and *Botryococcus* colonies. Pollen concentration and palynological richness are clearly lower. Furthermore, the zone is characterized by a high amount ofsamples containing (almost) no fossil pollen material, indicated by white bars in the pollen diagram (Appendix B). Almost no charred particles were deposited (Appendix A).

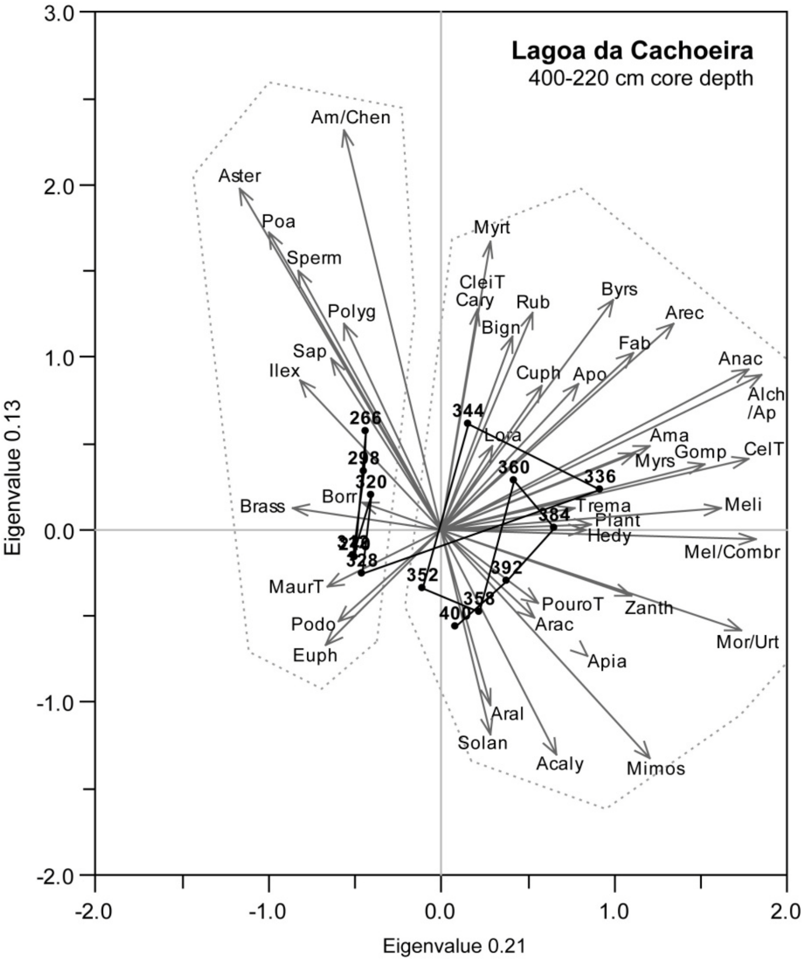

Fig. 4: Ordination diagram (PCA) showing taxa composition and the respective core depth of the undated core part. Axis 1 explains 21%, axis 2 13% of variance of the dataset.

Interpretation

Pollen zone LDC-I (400-331 cm)

Dominating forest vegetation with a clear amount of taxa from seasonal dry forest types point to a period when sufficient soil moisture was available for the prevalence of forests. This is corroborated by the presence of *Acalypha*, Moraceae/Urticaceae, and *Pouroumea* (Moraceae) between 400 and 392 (Fig. 4), mainly known from humid evergreen forests. A compositionl change of species between 392 and 336 cm core depth indicate a further opening of the forests possibly due to slightly drier conditions, suggested by the presence of pioneer taxa (*Trema, Zanthoxylum*) and taxa which can handle a lower daily precipitation amount (Anacardiaceae, Bignoniaceae, Fabaceae, Myrtaceae). As *Cuphea* usually occurs at lake margins and wetter sites, conditions were possibly wet enough to support the prevalence of small lakes at Serra Sul. Inferred from the presence of cold adapted taxa, with special reference to *Weinmannia*, cold conditions are suggested for this period. Fire did not play a role during this time.

Pollen zone LDC-II (331- 220 cm)

During this period Lagoa da Cachoeira is suggested to be surrounded mainly by shrubby savanna vegetation, dominated by herbaceaous (Poaceae, Amaranthaceae/Chenopodiace, Polygonaceae) and ligneous (*Spermacoce, Borreria*) taxa also known today from the 'campo rupestre' vegetation of Serra Sul. This shift from a formerly open forest to a shrubby savanna is corrobated by the directional change suggested by the ordination diagram between 336 and 328 cm core depth (Fig. 4). The increased abundance of *Echinodorus* and *Ludwigia* (Appendix B), and the high amount of sediment samples without countable pollen material further suggests that the water table of Lagoa da Cachoeira was lowered and the investigated lake area possibly fell temporarily dry. A lowering is also corroborated by lower amounts of *Botryococcus* algae and decreasing *Isoëtes*, which needs relatively deep water conditions to be permanyntly submerged. The occurrence of *Myrsine* and *Ilex* points to still cold conditions. No significant local fires were active in the time, when sediments accumulated.

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V. First results of pollen, charcoal, and geochemical analyses of lacustrine sediments from Lago Amapá (Rio Branco, Acre) in southwest Amazonia

1. Introduction

From a palynological point of view, Rio Branco (Acre, Brazil) is a virtually unknown region. So far no palaeoecological studies are published for this area, though the history of this region is indeed highly relevant for biogeographical and archaeological questions. For example, the region is suggested to be the origin of today widely distributed Amazonian crops like manihot, pineapple or peach palm (Clement et al., 2010). Also pre-Columbian 'geoglyphs' of yet unknown function exist first spotted in the 1970ies after forest clearance. These anthropogenic earth structures are suggested to be the remnants of highly developed ancient societies and date back to 1191-912 cal BC (Saunaluoma and Schaan, 2012), contemporaneous with recorded presence of complex human societies from other parts of Amazonia (Pärssinen et al., 2009). Palynological and palaeoecological studies from neighbouring regions however already exist. Approximatly 800 km south of Acre, studies from a forest-savanna environment in the Bolivian Noël Kempff National Park (NKMNP) shows a long-term trend of climatically driven southward expansion of tropical rainforest at the expanse of dry forests and savannas (Mayle et al., 2000; Burbridge et al., 2004; Mayle, 2007). The spread of rainforests is mainly attributed to an increasing precipation over the past 2000 years. In the Bení region, 700 km west from NKMNP, mesic rainforest systems were continuously present in the Holocene, but increasing human disturbance towards the present was recorded by the presence of *Cecropia* (pioneer tree) and abundant amounts of deposited charcoal (Urrego, 2006). Also in the Peruvian Amazon palaeorecords reveal consistent human occupation, though the manipulation of the surrounding rainforest vegetation was restricted to relatively small areas (Bush et al., 2007). Despite this anthropogenic influence, and though the region also experienced dry conditions during the mid-Holocene (Paduano et al., 2003), forests were continuously present in this region over the last 7000 years (Bush et al., 2007).

In Acre, palaeoecological studies could espacially contribute to the current debate of how complex and widespreaded pre-Columbian societies in Amazonia actually were and to what extent these societies affected the surrounding natural vegetation (e.g. Heckenberger et al., 2003, 2007; Denevan, 2005; Bush et al., 2007; Bush and Silman, 2007; Lombardo and Prümers, 2010; McKey et al., 2010; McMichael et al., 2012a, 2012b; Meggers, 2012).

2. Study area

The studied lake ‘Lago Amapa’ (9°57’37.10°S, 67°45’31.88°W) is an ancient branch (oxbow lake) of the Rio Acre, situated in southwest Amazonian Rio Branco in the state of Acre (Brazil), where it is part of the protected “Área de Proteção (APA) Lago do Amapá (Fig.1). During highwater (approx. every 9 to 11 years) the whitewater-lake is connected to the Rio Acre river system (Costa, pers. comm.).

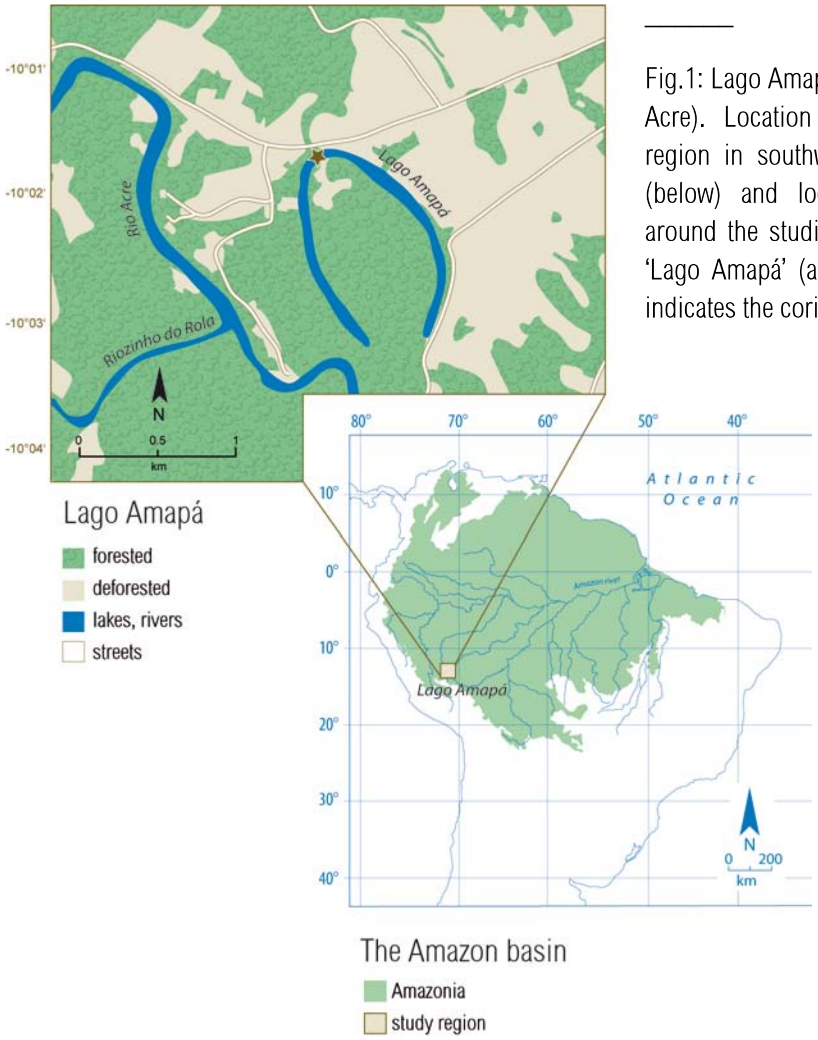

Fig.1: Lago Amapá (Rio Branco, Acre). Location of the study region in southwest Amazonia (below) and local conditions around the studied oxbow lake ‘Lago Amapá’ (above); the star indicates the coring site.

Climate and vegetation

The climate of Rio Branco is tropical humid (Am, Köppen) with mean monthly temperatures of 25°C. Rainfall in Rio Branco is clearly seasonal over the year, with a wet season from November to April and a dry season from May to October. Between May and August cold air masses from the Atlantic (*'friagems'*) can enter the region inducing a temporary decline of temperature to about 5°C (Duarte, 2006).

Today the vegetation of this region is mainly characterized by open semi-evergreen tropical rainforests with palms and bamboo (Lani et al., 2008), but large areas in Rio Branco and at Lago Amapá are cleared for pastures and cropped fields (Fujisaka et al., 1998). Forests are dominated by tree species of e.g. Meliaceae, Anacardiaceae, Bignoniaceae, Moraceae, Apocynaceae, Bombacaceae, Euphorbiaceae, Fabaceae (e.g. *Dipteryx* sp.), and Lecythidaceae (*Eschweilera* sp.), besides several palm and bamboo species (Lani et al., 2008).

Tab. 1: Climate at Rio Branco, Acre in southwest Amazonia.

	Southwest Amazonia*
Climate	Tropical humid (Am, Köppen)
Wet season	
Temperature	25°C
Precipitation	240 mm
Duration	November to April
Dry season	
Temperature	25°C (<10°C possible)
Precipitation	80 mm
Duration	May to October
Characteristics	'friagens' (cold spells)

*= Data from Rio Branco climate station (9°95'S, 68°16'W, 220 m a.s.l.) via INMET (2011).

3. Material and methods

Pollen and charcoal analysis

A sediment core of 240 cm length was taken in 2009 from the middle of the oxbow-lake Lago Amapá (Fig. 1). Until sample processing sediments were stored in darkness at 4°C at the Department of Palynology and Climate Dynamics (Göttingen, Germany). Six samples (bulk sediment and leaf fragments) were used for radiocarbon dating by Accelerator Mass Spectrometry at the AMS C14-Labor Erlangen (University of Erlangen-Nürnberg). The AMS radiocarbon dates (Table 2) were calibrated with Calib 6.0 (Stuiver and Reimer, 1993) using the Shcal04 calibration curve (McCormac et al., 2004). For this study 16 subsamples (0.5 cm^3) were used for pollen and charcoal analysis. Pollen samples were prepared following the standard methods of Fægri and Iversen (1989) including 70% HF treatment, addition of the exotic marker *Lycopodium clavatum* (Stockmarr, 1971), and mounting in glycerine gelatin. Samples were counted to a minimum of 300 terrestrial pollen grains, where pollen concentration was low a minimum of 200 terrestrial pollen grains was counted. Samples (almost) lacking preserved pollen material, where discarded. Percentages of spores and aquatic taxa are calculated relative to the terrestrial pollen sum. The zonation of the pollen diagram was conducted with CONISS and critical visual inspection of pollen spectra and the CONISS dendrogram. Pollen and spore identification was based on apropriate literature (Colinvaux et al., 1996; Carreira and Barth, 2003; Carreira et al., 1996; Roubik and Moreno, 1991) and a pollen reference collection held at the Department of Palynology and Climate Dynamics, University of Göttingen. Charcoal (10-250 µm) was counted on the same pollen slides for analysis of regional fire history.

XRF (X-ray fluroscence) spectrometry

Analysis of chemical composition of the sediments was conducted in 0.5 mm intervals with the non-destructive XRF scanner (ITRAX Corescanner, Cox Analytical Systems) at the Geography Institute at Bremen University. The most influencing elements of the chemical composition were identified using Principal Component Analysis (PCA) of the log-transformed data, variables were standardized and centred.

4. Results

4.1 Chronology

Three of the six dated samples revealed invalid ages that could not be calibrated. The remaining three calibrated dates are not consistent which makes age-depth calculation impossible. However, the oldest date from Lago Amapá is around 1331 AD (c. 658 cal yr BP), which is younger than the youngest dated construction of geoglyphs by pre-columbian societies at Rio Branco between 1244 and 1378 AD (Pärssinen et al., 2009), but still predates the Europeans' arrival. The low pollen concentrations and the relatively young ages argue for high sedimentation rates.

Tab. 2: AMS radio carbon dates for Lago Amapá sediments.

Depth (cm)	Dated material	^{14}C yr BP	Laboratory number	Age range (cal yr AD), 2σ	Age (cal yr AD), median probability
42.5-43	leaf fragment	-1682 ± 43	Erl-13829 [a]	invalid age	invalid age
87.5-88	leaf fragment	-2063 ± 43	Erl-13830 [a]	invalid age	invalid age
106.5-107	bulk sediment	-2171 ± 43	Erl-13831 [a]	invalid age	invalid age
181.5-182	bulk sediment	163 ± 84	Erl-13832 [a]	1646- 1954	1803
210-211	bulk sediment	698 ± 90	Erl-13833 [a]	1215- 1436	1331
257.5-258	bulk sediment	467 ± 85	Erl-13834 [a]	1390- 1646	1489

[a] AMS-Labor Friedrich-Alexander-Universität Erlangen-Nürnberg

4.3 Description of the pollen diagram

The investigated sediments of Lago Amapá are characterized by low concentrations of fossil pollen (6000-13,000 grains/cm³). Sample depths between 240 and 192 cm, and also at 160 and 144 cm yielded (almost) no pollen material. Therefore only 10 of 16 samples were counted for a first pollen analysis. In consideration of the low number of counted samples, recorded pollen diversity is unusually low for tropical regions with only 38 identified pollen types.

Tab. 3: Stratigraphy of the upper core part from Lago Amapá from 0-170 cm core depth.

Core depth (cm)	Description of the sediment
0-97	Ochreous to yellow clayey material (oxidized)
97-115	Gray material with fine dark gray bands
115.5-136.5	Gray material with thick dark gray bands
136.5-176	Bands of clayey ochreous (oxidized) and gray material

Pollen zone LARB-1 (176-104 cm)

The zone is characterized by moderate abundance of pollen from *Cecropia* (30%), Moraceae/Urticaceae (20 %), and Poaceae (10 %). Also Fabaceae, Solanaceae, and Asteraceae occur, latter two with values below 10 %. Between 120 and 108 cm core depth *Cecropia* values slightly decrease (20 %), accompanied by a slight increase in Fabaceae and Moraceae/Urticaceae. Also low values of *Zanthoxylum, Trema, Ilex,* and *Hedyosmum* are recorded, as well as *Alchornea/Aparisthmium* and Bignoniaceae. Monolete fern spores also occur within this zone but decrease between 112 and 104 cm. Pollen concentration is low and ranges between 7000 and 8000 grains/cm³. Charcoal concentration is higher between 176 and 140 cm core depth and slightly lower between 140 and 104 cm.

Pollen zone LARB-2 (104-72 cm)

Between 104 and 72 cm *Cecropia* pollen is represented with highest values (>75%). This is accompanied by a clear decrease of Moraceae/Urticaceae (max. 12%) and Fabaceae (max. 5%). Pollen concentration is even lower than in the former zone with minimum values about 6000 grains/cm^3. No change in charcoal concentration is recorded.

Pollen zone LARB-3 (72-0 cm)

Values of *Cecropia* decrease slightly but still dominate the pollen spectra. Slightly lower values of this pollen type fall together with higher values of Moraceae/Urticaceae (<20%) and *Celtis* (<5%). At 32 cm depth *Zanthoxylum* values are slightly higher (8%), as well as values of *Alchornea/Aparisthmium* and Anacardiaceae (5%). Poaceae (max. 11%) are still present, accompanied by Solanaceae, Arecaceae, and Cyperaceae (<5%). Also recorded are tetrads of *Mimosa scabrella* (<5%). Pollen concentration increases markedly between 48 and 0 cm to 13,500 grains/cm^3. Changes in charcoal concentration are not recorded.

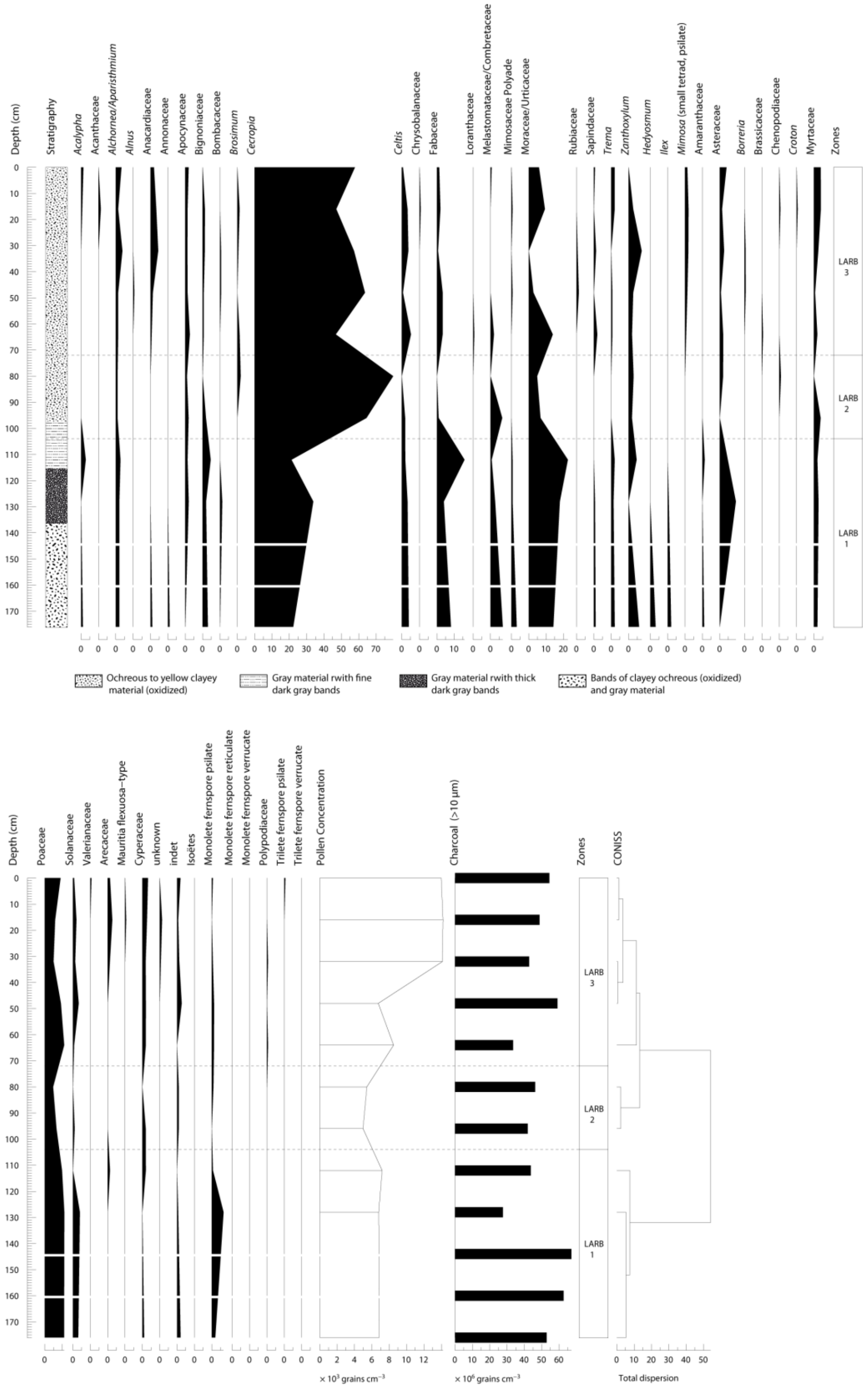

Fig. 2: Percentage diagram and charcoal concentrations of Lago Amapá, Rio Branco, Acre.

4.4 XRF analysis

The most influencing elements identified by PCA are shown in Fig. 3 and 4. The first principle component (PC1) represents 42% of the variation in the data set. While Zn, K, Ca, Rb, and Fe are more correlated with PC1, Sr, Al, Cu, and Br show a correlation with PC2. Mn and Ti are correlated equally with both PCs. All elements are negatively correlated with PC1, and whereas Sr, Ti, Zn, K, Ca, and Rb are positively correlated to PC2, Fe, Mn, Pb, inc, and coh show a negative correlation to PC2.

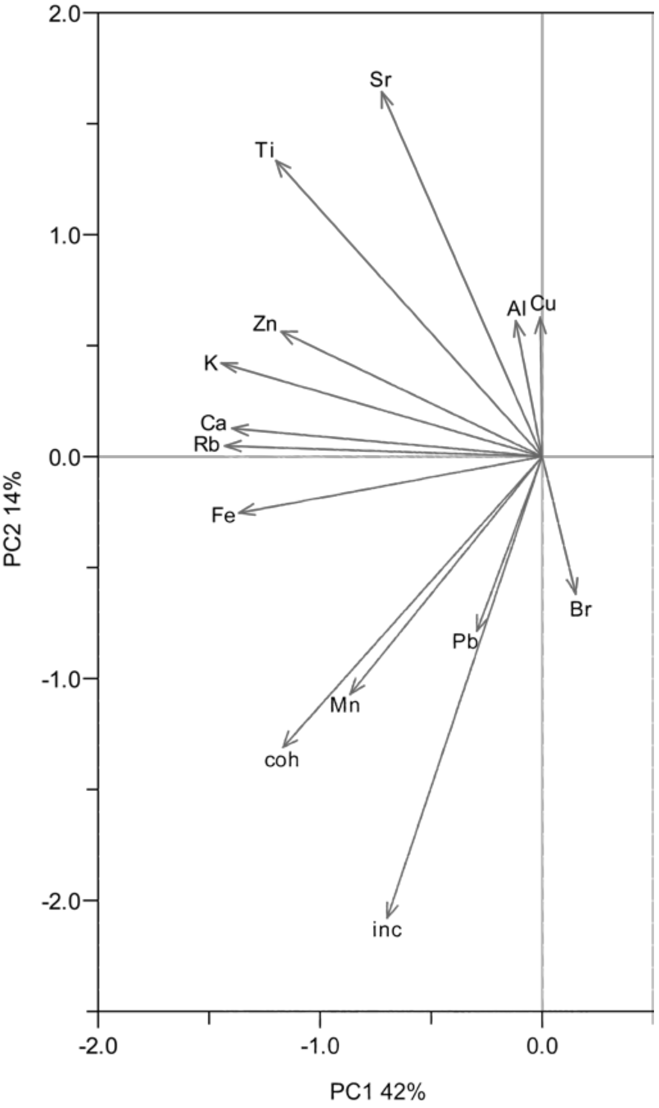

Fig. 3: Principle component analysis (PCA) of the most important elements from Lago Amapá. The first principle component (PC1) represents 42% of the total variability of the chemical assemblage, the second principle component (PC2) 14%.

Profiles of the most important elements show only slight oscillations throughout the core (Fig. 4a). On the whole sequence Ti and Fe show a trend of a slight decrease from the bottom to the top of the sediment core. From 90 to 78 cm core depth even lower values of Ti and Fe can be recognized. The Mn content remains mainly constant, but from 160 to 0 cm core depth (corresponding to pollen zones LARB-1 to LARB-3) the Mn profile stronger oscillates. Ca slightly increases from 400 cps (270-170 cm core depth) to 600 cps (80-0 cm).

Fe and Mn, represented in sediments as anthigenic oxyhydroxides or carbonates, are related to the redox-cycling (Dean, 1993) and the ratio between Fe and Mn (Fig. 4b) can be used as a paleo-redox-indicator in lacustrine sediments (Wersin et al., 1991). An increase of the Fe/Mn ratio would be indicative for reducing conditions (Brüchmann and Negendank, 2004; Cohen, 2003), a decrease for a lower lake level as the oxygen supply to the sediment-water-interphase would be enhanced (Haberzettl et al., 2007). At Lago Amapá the Fe/Mn (Fig. 4b) ratio shows a higher variability between 273 and 138 cm core depth. A slight decrease of Fe/Mn from 73 to 19 cm, mainly corresponding to pollen zone LARB-3, may indicate a lowering of the lake level, but could also point to an opening of the catchment vegetation wich allows wind shears to mix oxygen to the sediment/water-interphase (Stevens et al., 2000). Also higher Fe/Ti ratios (Fig. 4b), referring to a relative increase in Fe, would indicate anoxic conditions and higher lake level due to wetter climate. But the Fe/Ti ratio at Lago Amapá remains constantly high throughout the sequence, and even slightly higher between 138 and 0 cm core depth (corresponding to LARB-1, upper half), indicative for remaining wet conditions during the recorded period.

The Ti content in depositional environments is also representative for the input of allochtoneous material due to runoff and rainfall (Haug et al., 2003), and higher Ti could therefore indicate more humid conditions. As a runoff is also assumed to influence lake level, Ti can be also used as an indicator for lake level changes (Haberzettl et al., 2007). The Ca/Ti ratio hence reflects the hydrological variability of a lake, with high values reflecting dry phases and low values representing humid conditions. At Lago Amapá the Ca/Ti ratio remains rather constant throughout the sequence assuming a mainly constant lake level under humid conditions (Fig. 4b).

Changes of lake productivity can be inferred by calculation of the ratio between incoherent (inc) and coherent (coh) scatter (Fig. 4b), which represents the variation of the relative proportion of light to heavy elements and is therefore useful as an indicator of organic matter content (Jenkins, 1999). In Lago Amapá the inc/coh ratio slightly increases from the bottom to the top of the core, indicating a slight increase in lake productivity.

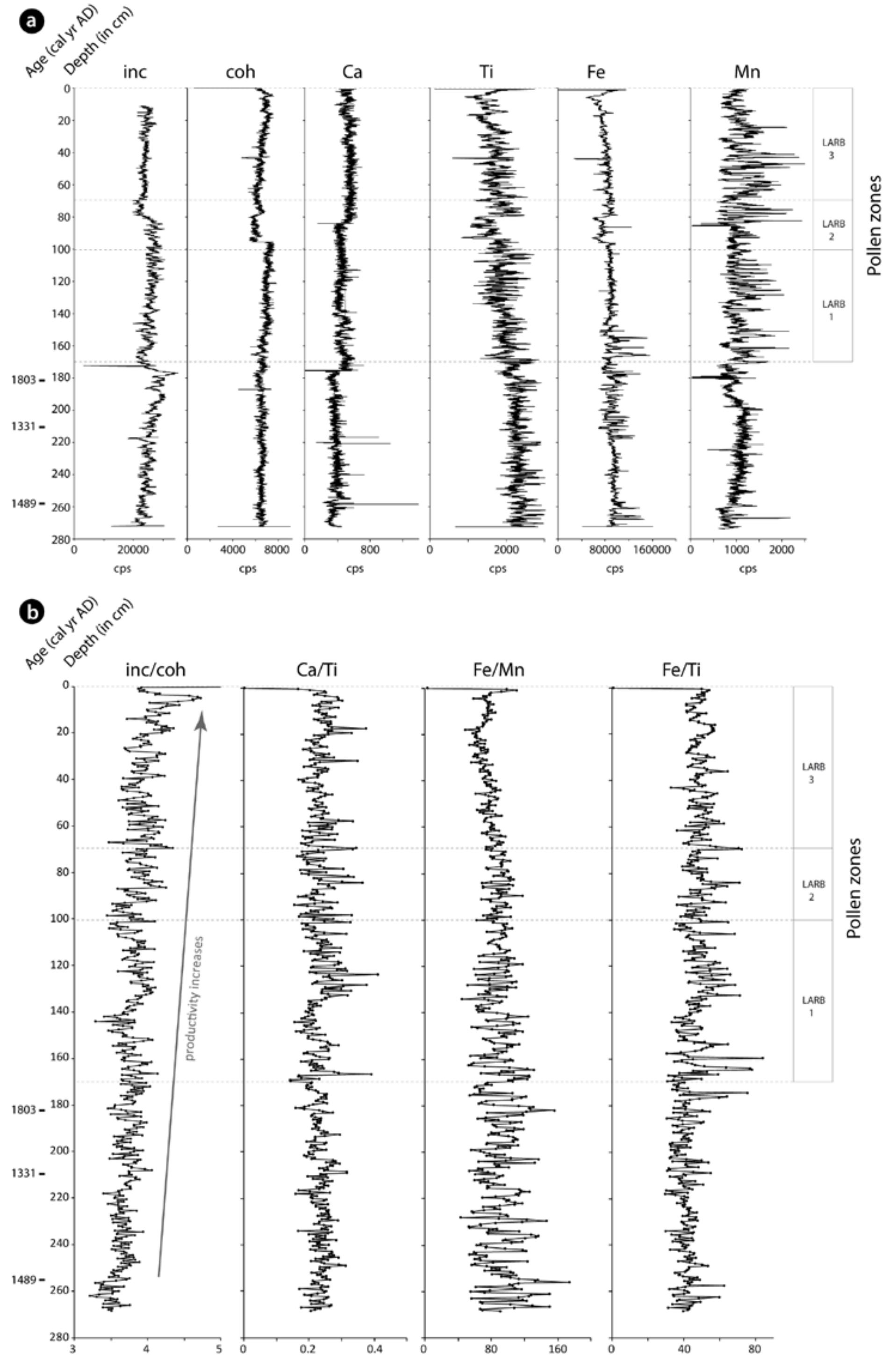

Fig. 4: Profiles of the XRF-scanning elemental analyses of the sediment core from Lago Amapá. Data are plotted in (a) counts per second (cps) and (b) ratios (without dimensions). The corresponding pollen zones are indicated by dashed lines.

5. Interpretation and discussion

What has to keep in mind when examining the pollen record from Lago Amapá, is the oxbow nature of the lake. Pollen spectra obtained from an oxbow-lake typically reflect vegetation on a local scale (<1km^2). Recorded vegetation changes are therefore possibly a very local event without corresponding changes on a larger scale.

The most striking feature of the recorded pollen spectra from Lago Amapá is the overall dominance of *Cecropia*, a pioneer tree that today primarily occurs on fallow land (Fujisaka et al., 1998). Over-represented pollen of *Cecropia* could derive from a gallery forest at Lago Amapá, as for oxbow-lakes like Lago Amapá high concentrations of this pollen type are even possible without disturbance by humans (Listopad, 2001). However, together with forest taxa like Moraceae/Urticaceae, Fabaceae, *Alchornea/Aparisthmium*, and Bignoniaceae in pollen zone LARB-1 it could also refer to the beginning of forest clearing by humans at this site. Where forests were cleared, more open sites with pioneers (*Cecropia, Celtis, Trema, Zanthoxylum*), grasses (Poaceae), Asteraceae, Solanaceae, and Myrtaceae occurred. As the XRF data (Fe/Ti, Ca/Ti) point to constantly humid conditions for the recorded period, an anthropogenic source of forest opening is even more likely. The marked increase of *Cecropia* in the following zone LARB-2, accompanied by fewer Fabaceae and Moraceae/Urticaceae, could refer to a preceeding forest clearance and an increasingly open environment around Lago Amapá. In zone LARB-3 typical taxa of underused fields (*Zanthoxylum, Trema, Acalypha*) together with *Cecropia* and *Asteraceae* provide the picture of an highly disturbed area.

Pollen spectra from Lago Amapá are untypically species poor for tropical regions. Though species poorness may be partly attributable to the low number of counted samples, the low variety of pollen types per sample compared to other already counted material from Amazonia is noticeable and suggests an intense transformation of the surrounding vegetation of LAgo Amapá. A constraint for pollen analysis of sediments from Lago Amapá may be the input of formerly deposited material from nearby Rio Acre during periods of extensive rainfall (flash floods). This is particularly problematic for the temporal delimitation of recorded vegetation changes as an exact dating of the sediments is hampered.

Despite the uncertainties regarding the chronology of the studied sediments, the pollen spectra suggest an anthropogenic influence for the period when sediments accumulated. If the oldest date of 1331 AD is correct, the recorded vegetation changes would be set right after an intense period of human occupation in the Rio Branco area, which was characterized by the construction of geometric anthropogenic earthworks. However, the youngest dated material (1229-1386 AD) of geometric earthworks ('geoglyphs') at the archaeological site 'Fazenda Colorada' in the Rio Branco area (Pärssinen et al., 2009;

Saunaluoma and Schaan, 2012) could be roughly coinciding with the radiocarbon date from Lago Amapá in consideration of dating uncertainties. The dated core part which could possibly contain sediments from the period of earthwork construction unfortunately contained not enough pre-severed pollen material for palynolo-gical analyses. The construction of such earthworks but also the maintenance of an open area around these earthworks (over centuries) would have required a substantial clearing and transformation of the natural vegetation (Erickson, 2010) as recorded in the undated upper core part from Lago Amapá. As increasingly wet conditions in southwest Amazonia during the late Holocene (Mayle et al., 2000) would have promoted tropical forests like they are recorded today, a transformation of vegetation by humans is even more likely.

6. First conclusions

The first results of this palynological yet unknown region show that the deposited sediments of Lago Amapá could be useable for the reconstruction of anthropogenic influence on local vegetation in this area. In combination with phytolith, charcoal, and archaeological analyses they could provide insights into timing of human occupation and the dynamics of ancient societies with respect to their surrounding vegetation. This is also of special interest regarding the numerous gaps in our knowledge about the apparently complex ancient societies in Amazonian *terra firme* areas. Here, the question is still open, if human impact was restricted to a relatively local scale or if humans converted vegetation on a regional scale resulting in a ‘cultural parkland’ (Heckenberger et al., 2003, Mayle and Iriarte, 2012). Suitable records from several small lakes together could be helpful to reconstruct the impact of human societies on a regional scale. Regarding the reconstruction of vegetation history over longer time scales, older undisturbed sediment archives still have to be discovered for this area.

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VI. Synthesis

Research outcomes

Palaeoenvironmental changes in southern Amazonia were interpreted for the late Quaternary from three pollen, spore, and charcoal records. The environmental changes recorded in southeast Amazonia coincide with vegetation changes across the Amazon Basin as summarized in chapters II to IV. This suggests that environmental changes in southeast Amazonia are mainly forced by large scale climate fluctuations during the late Pleistocene and throughout the Holocene. First results from a lacustrine record in southwest Amazonia documents the influence of human populations on vegetation at least during the past 680 years as shown in chapter V. According to the general objectives of this study, the results can be summarized as follows:

1. *Reconstruction of environmental dynamics and fire history*

Vegetation – In southeast Amazonia (Serra Sul dos Carajás) rainforest ecosystems were temporal unstable, reflected by a change in pollen composition and diversity during the late Pleistocene and throughout the Holocene. The oldest recorded period, assumed as belonging to the early Pleniglacial (73-50 kyr BP), is suggested to be a cold and dry period when savannas dominated the plateau and fires were rare. Small areas of tropical forests containing taxa with adaptions to cooler temperatures existed, probably on the slopes of the plateau or in nearby lowland areas. The mid-Pleniglacial (50-40 kyr BP) is characterized by the occurrence of more open savannas under drier, but less cold conditions. Fires became more important during this period. In the following Pre-LGM (30-25 cal yr BP) forests expanded at the slopes of the plateau and existed together with an open grass savanna during a transition to wetter and cooler conditions, reflected by continuously higher water levels and the presence of cold adapted taxa. Fires were still active during this period. The LGM and late glacial period (25 to 11.4 cal kyr BP) are characterized by larger areas of scrub-bush savanna accompanied by smaller areas of open forests under dry and cold conditions. These forests, without a modern analog, showed an adaption to cooler temperatures and drier climates. From 13 to 11.4 cal yr BP forests developed at the slopes of the studied mountain range, at lake borders and in depressions on top of the plateau. At the same time savannas slightly retreated. Denser forest communities developed between 11.4 and 10.2 cal kyr BP showing adaptions to an increasingly warmer (clearly less cold adapted taxa) and wetter climate at the onset of the Holocene. After this relatively short period of wetter conditions (1200 years) savannas expanded again until 3.4 cal kyr BP. During this period the ecosystems contained less arboreal taxa than during the LGM and Late Glacial. Yet forested areas (extension unknown) harbored forests of a species composition today known from semi-deciduous dry forests in southwest Amazonia, as comparisons with other studies suggest. During this early to mid-Holocene period the presence of these forests in Serra Sul could be the result of an evolving seasonal climate with longer dry periods than today. As a swamp surrounded by palms was still present, reflected by semi-aquatics and Arecaceae, longer dry seasons were possibly followed by wet seasons with increased precipitation. Tropical rainforests comparable to present forests in Serra Sul occurred only after 3.4 cal yr BP. They contained a recognizable amount of pioneer and early secondary growth taxa, whose presence could be explained by the natural re-colonization of habitats that were formerly covered by savannas. But also an anthropogenic influence cannot be excluded (chapter II-III). At the southwestern Amazonian study site, an open and increasingly disturbed forest, indicated by the occurrence of pioneers and grasses, is more likely anthropogenic in origin. The prevailing humid conditions indicated by XRF-data assumingly would not have lead to a natural opening of the forest (chapter V).

Fire history – The reconstruction of long-term fire history in southeast Amazonia shows that between 11 to 10.2 cal kyr BP and after 5 cal kyr BP palaeofires predominantly occurred during transition periods from drier to wetter conditions, and are dependent on the seasonality of precipitation. An important factor for natural fire activity seems to be the amount of time, during that sufficient moisture is available. This would foster the growth of woody vegetation that would serve as fuel load for fires. Such conditions would be favorable for natural fires as well as for the presence of human who could have influenced past fire activity as well. In both cases changing precipitaion patterns would be the driving factor for the presence/absence of humans and therefore natural and/or anthropogenic fire.

The comparison with available proxy records of past precipitation in northern South America suggests a connection between the local fire history in southeast Amazonia and regional climate change (chapter IV). Despite of a possible human influence the main driver of the instability of rainforests and changing fire frequency are changes in the climatic conditions during the late Pleistocene and throughout the Holocene. This is corroborated by comparisons of records across the Amazon basin and between southeast- and southwest Amazonia, respectively (chapter II-IV).

2. *Climatic drivers*

The general amount of precipitation in the late Pleistocene and the characteristics of seasonality since the beginning of the Holocene are suggested to be the key factors for environmental changes in southern Amazonia. This is supported by regional comparisons with suitable records from the Amazon basin and the northeastern Andean region. Regarding precipitation, adjustments of the ITCZ and SST anomalies in the tropical Atlantic show a tight connection to changing plant communities in southeast Amazonia. When a cold pool in the western tropical North Atlantic and a suggested southward displacement of the ITCZ took place, rainforests established at Serra Sul dos Carajás, reflecting wet conditions. In contrast, a mixture of semi-deciduous forests and savanna systems, reflecting drier or strongly seasonal conditions, occurred when a warm pool in the tropical North Atlantic is recorded suggesting a northward displacement of the ITCZ (chapter III-IV).

The palaeofire record from Lagoa da Cachoeira in Serra Sul dos Carajás shows that fires in the past where more active during periods of seasonal and generally wetter conditions from 11 to 10.2k cal B.P. and after 5k cal B.P., when moist tropical forest and savanna vegetation coexisted at Serra Sul. Though an anthropogenic influence on past fire activity could not be excluded completely, the comparison with available palaeofire reconstructions from Amazonia and with other terrestrial and marine proxy data (lake level reconstructions, SST reconstructions, speleothem records) suggests, that the primary cause for fires during the recorded periods is the change towards seasonal rainfall conditions. These are strongly connected to variabilities of the zonal and meridional SST gradients in the Atlantic Ocean, and could have not only influenced past vegetation composition, but also Pre-Colombian human societies entering Serra Sul. Though an increased frequency of ENSO events after 7 cal kyr may have affected fire frequency in Amazonia, it seems not to be the crucial component of fire history in the southeast Amazonian Carajás region (chapter IV).

Concluding remarks

Southeast Amazonia – This study provides detailed insights into environmental changes in the Carajás region over a period of more than 70 000 years. The results confirm the assumption of Colinvaux (2000) that the varying vegetation types of Carajás react with an adaptation of species composition to ecological and climatic changes. A large-scale expansion of savannas at the expense of lowland rainforest as postulated by Absy et al. (1991) remains still open. Regarding past climatic conditions and species composition, the results of the present study suggest that drier climates in the past turned tropical rainforest ecosystems into an open forest with species adapted to less moisture input. Savannas expanded, but did not displaced forests completely (chapter II-IV). This could be also a thinkable scenario for this area under future global warming. If the remnants of forests in this region will be able to adapt to climatic changes in the future, like they did in the past, remains yet open in consideration of the tremendous and unsustainable land use this region has to suffer at present.

Southwest Amazonia – The first results from this palynological largely unknown region of Rio Branco (Acre) suggest a massive anthropogenic influence in this area for at least the past 650 years (chapter V). Therefore, palynological studies from Lago Amapá and neighbouring lakes, together with phytolith and charcoal analyses, and in combination with landscape archaeology, would be a valuable tool to investigate the processes of human occupation and its impact on past ecosystems in this part of southwest Amazonia.

Thoughts for the future – The number of palynological studies in the Amazon basin is continuously growing, but still cannot cope with the vast dimensions of this diverse region. The focus of most of these studies lies on areas in the periphery of the basin as these are especially sensitive to climate change – in the past and in the future. Whereas in southern Amazonia most of these studies are concentrated in the western part, available data from the southeast only derive from a relatively small outlined area. Here, future palynological studies could attach. Beside more long-time records spanning back at least to the beginning of the Holocene (or even further), intensive studies of modern pollen rain and corresponding vegetation surveys are strongly needed. The discovery of other suitable sites for palaeoecological investigations gains even more importance, as plans (for the near future) to recover the iron ore covered in the mountains of Serra Sul will further hamper research (ecological and archaeological) in this area. The irretrievable loss of the study sites in Serra Sul is even more dramatic, as for a comprehensive palynological analysis in this mountain range a study of modern pollen rain is still lacking. Also for a comprehensive reconstruction of southern Amazonian fire history more high-resolution sediment archives south of 5° S in Amazonia are needed, which especially applies to the southeast. Though some excellent pollen keys already exist for Amazonia (see Appendix A), future work regarding pollen morphology would be helpful for a more comprehensive identification of fossil pollen material, as a high amount of recognized pollen types remains still unknown.

Appendix

A. Identified pollen, spores, and NPPs
B. Complete pollen and charcoal records

Appendix A.
Identified pollen, spores, and NPPs

Pollenmorphology after Burn and Mayle (2008), Carreira et al. (1996), Carreira and Barth (2003), Colinvaux et al. (1996), Gosling et al. (2009), Roubik and Moreno (1991), and own observation.

Burn, M.J., Mayle, F.E., 2008. Palynological differentiation between genera of the Moraceae family and implications for Amazonian palaeoecology. Review of Palaeobotany and Palynology 149, 187-201.

Carreira, L.M.M., Barth, O.M., 2003. Atlas de Pólen da vegetação de canga da Serra de Carajás (Pará, Brasil). Belém: Museu Paraense Emílio Goeldi.

Carreira, L.M.M., da Silva, M.F., Lopes, J.R.C, Nascimento, L.A.S., 1996. Catálogo de Pólen das Leguminosas da Amazônia Brasileira. Belém: Museu Paraense Emílio Goeldi.

Colinvaux, P.A., Liu, K.-B., DeOliveira, P., M.B., Bush, Miller, M.C., Steinitz-Kannan, M., 1996. Temperature depression in the lowlands tropics in glacial times. Climatic Change 32, 19-33.

Gosling, W.D., Mayle, F., 2009. Differentiation between Neotropical rainforest, dry forest, and savannah ecosystems by their modern pollen spectra and implications for the fossil pollen record. Review of Palaeobotany and Palynology 153, 70–85.

Roubik, D.W., Moreno, E., 1991. Pollen and Spores of Barro Colorado Island. Monographs in Systematic Botany, v. 36, Missouri Botanical Garden.

Table A.1: List of identified pollen types in alphabetical order.

Pollen type name	Taxonomic family	Vegetation group[1]	Pollen morphological description	Record[2]	Photo No.
Acacia	Fabaceae	TF	Polyade (16 cells), inaperturate, tectate, psilate to slightly scabrate	PDM	1
Acalypha	Euphorbiaceae	TF	5-porate, suboblate, tectate, psilate, pores sxtruded	PDM, LDC	2
Acantahceae	Acantahceae	TF	tricolpate, subprolate, scabrate, tectate	PDM	-
Alchornea/Aparisthmium	Euphorbiaceae	TF	tricolporate, spheroidal, operculate, scabrate, tectate, oblate	PDM, LDC	3
Amaranthaceae/Chenopodiaceae	Amaranthaceae, Chenopodiaceae	SVS	periporate, spheroidal, tectate, scabrate to baculate	PDM, LDC	4
Amaryllidaceae	Amaryllidaceae	SVS	sulcate, oblate, reticulate, semitectate	PDM	5
Anacardiaceae	Anacardiaceae	TF	tricolporate, subprolate, semitectate, striato-reticulate	PDM, LDC	6
Annonaceae	Annonaceae	TF	inaperturate, spheroidal, semitectate	PDM	-
Apiaceae	Apiaceae	SVS	tricolporate, perprolate, tectate, psilate to slightly scabrate	PDM	-
Apocynaceae	Apocynaceae	TF	diporate, spheroidal, tectate, psilate to slightly scabrate	PDM, LDC	7
Araceae	Araceae	TF	sulcate, speroidal, semitectate, reticulate	PDM	-
Araliaceae	Araliaceae	TF	tricolporate, subprolate to prolate, semitectate, reticulate	PDM	-
Arecaceae	Arecaceae	PALMS	sulcate, suboblate to spheroidal, tectatte, scabrate	PDM, LDC	8
Asteraceae	Asteraceae (Asteroideae)	SVS	tricolporate, spheroidal, tectate, echinate	PDM	9
Asteraceae	Asteraceae (Liguliflorae)	SVS	tricolporate, spheroidal, fenestrate	PDM	10
Banara-type	Flacourtiaceae	TF	tricolporate, subprolate, tectate, microreticulate, pores circular	PDM	-
Bignoniaceae	Bignoniaceae	TF	tricolporate, subprolate to prolate, tectate, psilate	PDM, LDC	11
Blepharandra-type	Malpighiaceae	SVS	tricolporate, spheroidal, semitectatte, microreticulate	PDM	-
Bocconia-type	Papaveraceae	SVS	periporate, spheroidal, semitectate, reticulate	PDM	-
Bombacaceae 1	Bombacaceae	TF	tricolpate, oblate, reticulate, tectate	PDM, LARB	12
Bombacaceae 2	Bombacaceae	TF	tricolpate, oblate, reticulate, tectate	LARB	13
Boraginaceae	Boraginaceae	TF	tricolporate, zonorate, prolate, tectate, psilate	PDM	-
Borreria	Rubiaceae	SVS	Stephanocolpate, spheroidal, intectate, baculate	PDM, LDC	14
Bromeliaceae	Bromeliaceae	TF	inaperturate, semitectate, reticulate	PDM	-
Byrsonima	Malpighiaceae	SVS	tricolporate, spheroidal to subprolate, tectatte, scabrate	PDM, LDC	15
Cabomba	Cabombaceae	AQUA	sulcate, prolate, oblate, tectate, rugulate	PDM	16
Caryodendron-type	Euphorbiaceae	TF	tricolporate, suboblate, semitectatte, reticulate	PDM	-
Caryocaraceae	Caryocaraceae	SVS	tricolporate, subprolate, semitectate, rugulate	PDM	-
Casearia-type	Flacourtiaceae	SVS	tricolporate, spheroidal, tectate, psilate to slightly scabrate	PDM	-
Cecropia	Urticaceae	TF	diporate, subprolate, tectatte, psilate	PDM, LDC	17
Celtis	Cannabaceae	TF	triporate, suboblate, tectate, psilate	PDM, LDC	18
Cleidion-Type	Euphorbiaceae	TF	tricolporate, operculate, spheroidal, semitectate, scabrate	PDM	-
Clusiaceae (Guttiferae)	Clusiaceae	TF	tricolporate, suboblate, semitectate, reticulate	PDM	-
Convolvulaceae	Convolvulaceae	SVS	tricolpate, suboblate, semitectate, reticulate	PDM	-
Croton-type	Euphorbiaceae	SVS	inaperturate, spheroidal, intectate, clavate (‘croton pattern’)	PDM	-

Cucurbitaceae	Cucurbitaceae	SVS	triporate, spheroidal, baculate, intectate	PDM	-
Cuphea	Lythraceae	SVS	syncolporate, suboblate, tectatte, psilate	PDM, LDC	19
Curatella	Dilleniaceae	SVS	tricolporate, subprolate, semitectate, reticulate	PDM	-
Cyperaceae	Cyperaceae	AQUA	>3 poroids (indistinct margins), obovoid, tectate, scabrate	PDM, LDC	-
Echinodorus	Alismataceae	AQUA	periporate, spheroidal, tectatte, scabrate	PDM	20
Eriocaulaceae	Eriocaulaceae	AQUA	spiraperturate, microechinate, tectate, spheroidal	PDM, LDC	21
Erythroxylum	Erythroxylaceae	SVS	tricolporate, subprolate, tectate, reticulate	PDM, LDC	-
Euphorbiaceae	Euphorbiaceae	TF	tricolporate, prolate, semitectate, reticulate	PDM, LDC	22
Euplassa	Proteaceae	CAT	triporate, triangular (concave) semitectate, reticulate	PDM	23
Fabaceae	Fabaceae	TF	tricolporate, subprolate, tectate, psilate	PDM, LDC	24
Flacourtiaceae	Flacourtiaceae	TF	4-colporate, spheroidal to subprolate, tectate, psilate	PDM	25
Gallesia-type	Phytolaccaceae	TF	tricolporate, spheroidal to subprolate, tectate, coarsely scabrate	PDM	-
Gordonia-type	Theaceae	CAT	tricolporate, suboblate, tectate, granulate/clavate	PDM	26
Hedyosmum	Chloranthaceae	CAT	inaperturate, spheroidal, intectatte, clavate	PDM	-
Hippocratea-type	Hippocrateaceae	SVS	Polyad (4 tetrahedral tetrads), reticulate (heterobrochate)	PDM	-
Ilex	Aquifoliaceae	CAT	tricolporate, spheroidal to subprolate, intectate, clavate	PDM	27
Lamiaceae	Lamiaceae	SVS	tricolpate, spheroidal to subprolate, tectate, psilate	PDM	-
Loranthaceae	Loranthaceae	TF	syncolpate, oblate, tectate, psilate	PDM, LDC	28
Ludwigia	Onagraceae	AQUA	triporate, oblate, tectate, verrucate	PDM	29
Magnoliopsidae 1-type	-	TF	triporate, scabrate	PDM	-
Malpighiceae	Malphigiceae	SVS	stephanoporate, spherodal, tectatte, psilate	PDM	-
Mauritia flexuosa	Arecaceae	PALMS	monosulcate, spheroidal, tectate, echinate	PDM	-
Melastomataceae/Combretaceae	Melastomataceae/Combretaceae	TF	heterocolpate, spheroidal to subprolate, tectate, psilate	PDM, LDC	30,31
Meliaceae	Meliaceae	TF	4-colporate, subprolate, tectate, psilate	PDM	32
Menispermaceae	Menispermaceae	TF	inaperturate, spheroidal, semitectate, reticulate (heterobrochate)	PDM	33
Mimosa	Mimosaceae	SVS	Tetrads, psilate	LARB, PDM	34,35
Moraceae/Urticaceae	Moraceae/Urticaceae	TF	diporate, subprolate, tectate, scabrate (*Pourouma*-type)	PDM, LDC, LARB	36
Moraceae/Urticaceae	Moraceae/Urticaceae	TF	diporate, oblate, tectate, scabrate (*Helicostylis*-type)	PDM	-
Myrsine	Myrsinaceae	CAT	4-colporate, subprolate to rectangular, tectate, slightly scabrate	PDM	37
Myrtaceae	Myrtaceae	SVS	syncolporate, oblate, tectate, psilate	PDM, LDC	38
Nymphaea	Nymphaeaceae	AQUA	monosulcate, oblate, tectate, psilate	PDM, LDC	39
Nymphoides	Menyanthaceae	AQUA	parasyncolporate, suboblate-spheroidal, rugulate	PDM	40
Ochnaceae	Ochnaceae	TF	tricolporate, spheroidal, tectate, scabrate	PDM	-
Pinzona-type	Dilleniaceae	TF	tricolporate, subprolate, tectatte, microreticulate	PDM	-
Poaceae	Poaceae	SVS	ulcerate, heteropolar, tectate, scabrate	PDM, LDC	41
Podocarpus	Podocarpaceae	CAT	bisaccate, heteropolar, tectate, scabrate	PDM	42
Polygalaceae	Polygalaceae	SVS	stephanocolporate, subprolate, (semi)tectate, scabrate	PDM	43
Protium	Burseraceae	TF	tricolporate, subprolate, tectate, psilate	PDM	-

Rhamnaceae	Rhamnaceae	TF	tricolporate, suboblate/triangular (convex), tectate, psilate	PDM	-
Rosaceae	Rosaceae	SVS	tricolporate, subprolate, tctate, scabrate	PDM	-
Roupala	Proteaceae	TF	triporate, oblate (triangular (straight), scabrate	PDM	44
Rubiaceae	Rubiaceae	SVS	tricolporate, semitectate, reticulate	PDM, LDC	45
Sagittaria	Alismataceae	AQUA	5-porate, spheroidal, tectate, echinate	PDM, LDC	46
Sapindaceae	Sapindaceae	TF	syncolporate, suboblate/triangular (straight), tectate, psilate to slightly scabrate	PDM, LDC	-
Sapotaceae	Sapotaceae	TF	tricolporate, subprolate, tectatte, psilate	PDM	-
Scrophulariaceae	Scrophulariaceae		tricolporate, oblate, semitectate, microreticulate	PDM	-
Sloanea-type	Elaeocarpaceae	TF	tricolporate, subprolate/trilobate, tectate, psilate	PDM	-
Solanaceae	Solanaceae	SVS	tricolporate, subprolate, semitectate, microreticulate	PDM, LDC	47
Spermacoce	Rubiaceae	SVS	periporate, spheroidal, tectate	PDM, LDC	48
Styrax	Styracaceae	CAT	tricolporate, subprolate, tectate, rugulate	PDM	49
Trema	Cannabaceae	TF	diporate, suboblate, tectate, scabrate	PDM, LDC	-
Utricularia	Lentibulariaceae	AQUA	stephanocolporate, oblate, tectate, psilate	PDM	50
Verbenaceae	Verbenaceae	CAT	tricolpate, spheroidal, tectatte, echinate	PDM	-
Weinmannia-type	Cunoniaceae	CAT	tricolporate, subprolate, tectate, microreticulate	PDM	51
Zanthoxylum	Rutaceae	TF	tricolporate, subprolate, semitectate, reticulate	PDM, LDC	52

Table A.2: List of identified spore types in alphabetical order.

Spore type	Family	Spores, morphological description	Record	Photo No.
Cyathea	Cytheaceae	trilete, heteropolar, triangular (concave), verrucate	PDM, LDC	53
Isoëtes	Isoëtaceae	monolete, heteropolar, extended perine, scabrate to rugulate	PDM, LDC	54
Ferns (other)	-	monolete. heteropolar, psilate; trilete, psilate	PDM, LDC	-
Hemitelia	Cyatheaceae	trilete, heteropolar, triangular (straight), apices sharply rounded	PDM	55
Polypodiaceae	Polypodiaceae	monolete, heteropolar, verrucate	PDM, LDC	56,57
Schizaea-type	Schizaeaceae	monolete, heteropolar, sclerine foveolate	PDM	-
Selaginella	Selaginellaceae	trilete, hereopolar, subtriangular (convex), spinulose pattern	PDM	-
Sphagnum	Sphagnaceae	trilete, heteropolar, triangular (convex), psilate to scabrate/fine verrucate; greenish	PDM	-

Table A.3: Charred particles, Algae and reoccurring (unidentified) NPPs.

Particle	Description	Record	Photo No.
Botryococcus braunii (Dictyosphaeriaceae)	colonial algae, irregular shape	PDM, LDC	58
Charcoal	charred wood fragment with sharp edges	PDM, LDC, , LARB	59,60
Fungal spore 1	4 cells, with frill-like outer layer	PDM, LDC	61
Fungal spore 2	4 cells	PDM	62
Fungal spore 3	1 cell, oval	PDM	63
Fungal spore 4	6 cells	PDM	64
Fungal spore 5	'striped', with 'bar-like' dense area	PDM	65

[1]=Abbreviations for vegetation groups; AQUA (Aquatic taxa), CAT (Cold Adapted Taxa), SDTF (Seasonal Dry Tropical Forest), SVS (Savanna Vegetation Systems), TF (Tropical forest); [2]=Abbreviations for pollen records; LARB (Lagoa Amapá); LDC (Lagoa da Cachoeira), PDM (Pántano da Maurítia)

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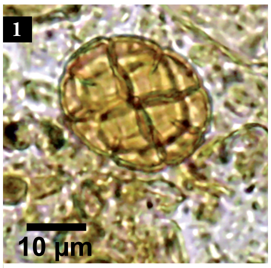

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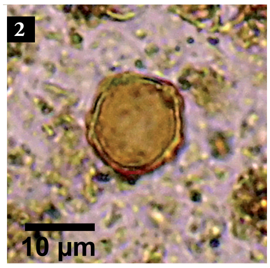

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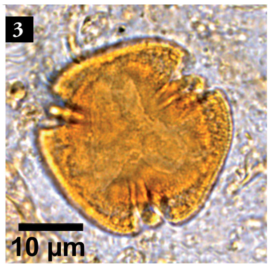

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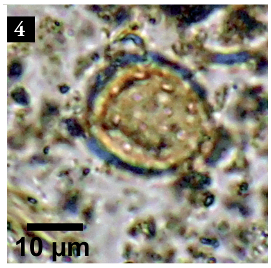

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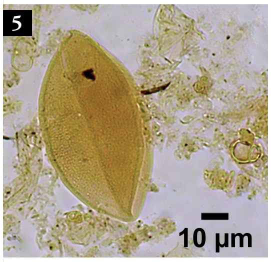

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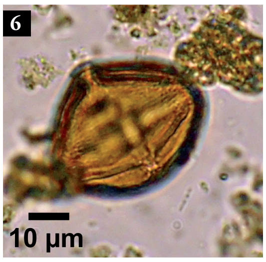

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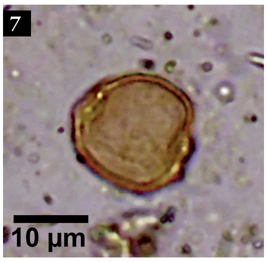

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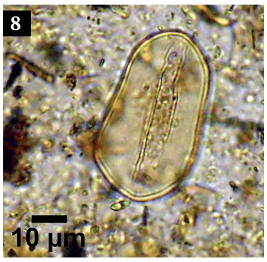

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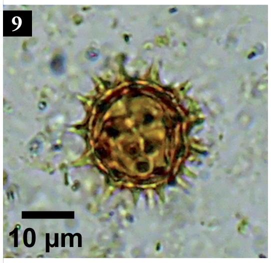

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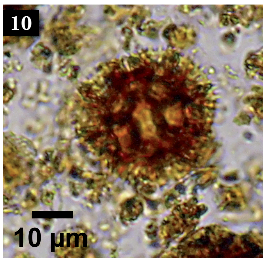

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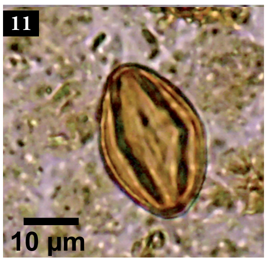

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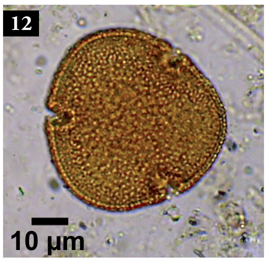

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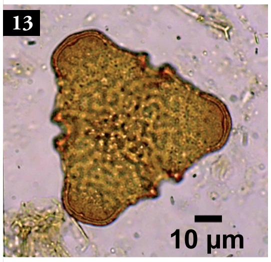

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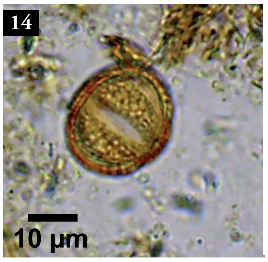

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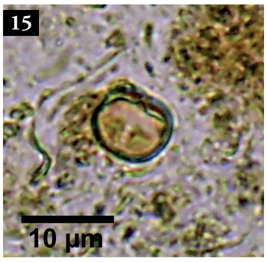

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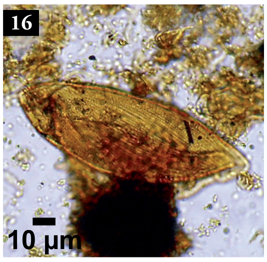

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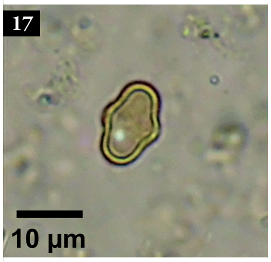

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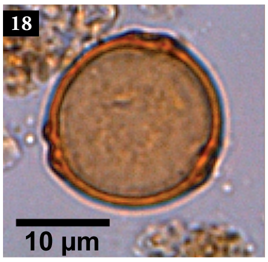

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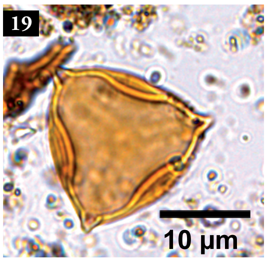

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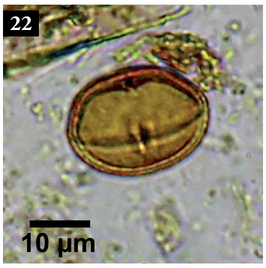

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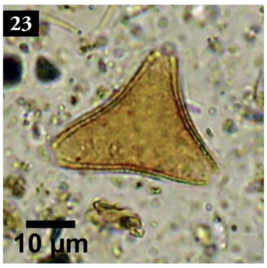

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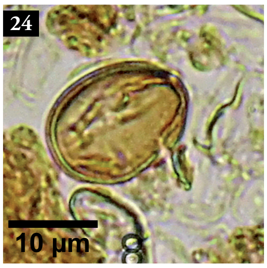

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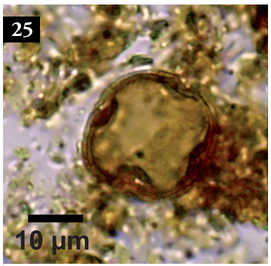

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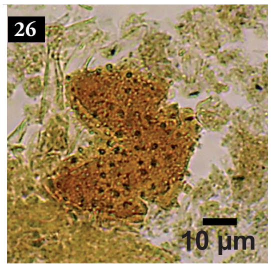

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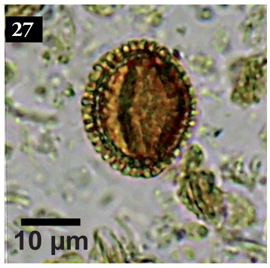

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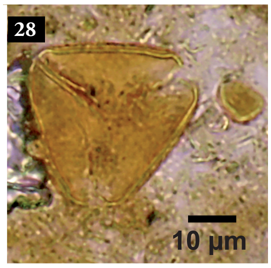

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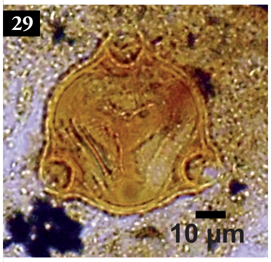

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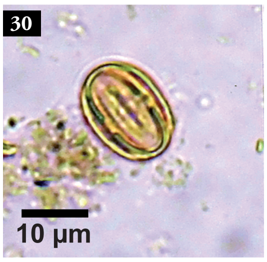

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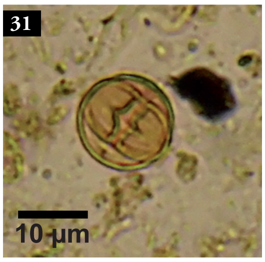

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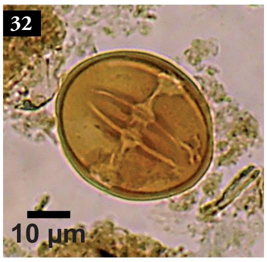

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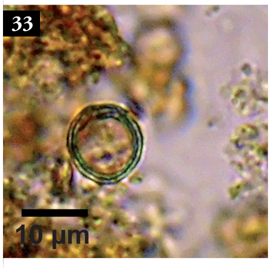

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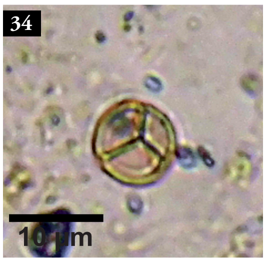

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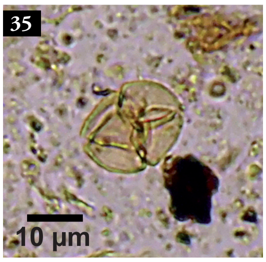

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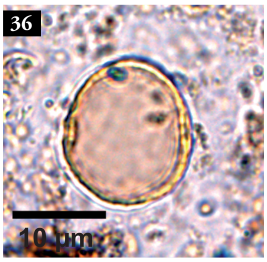

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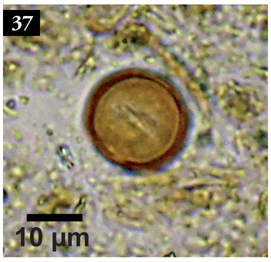

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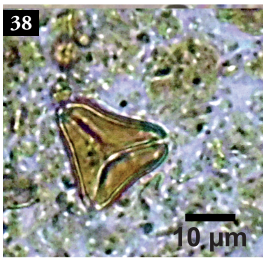

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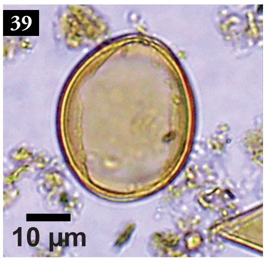

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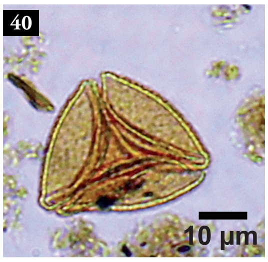

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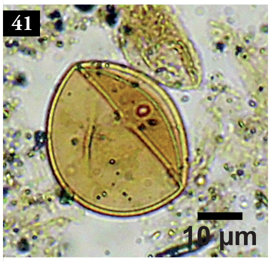

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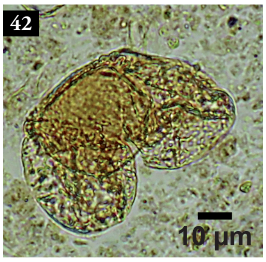

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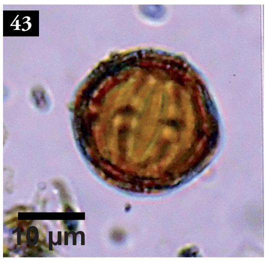

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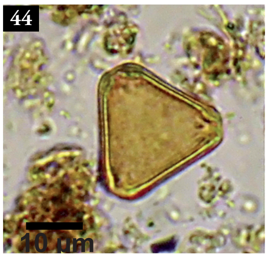

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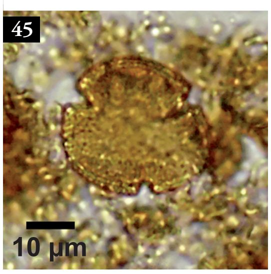

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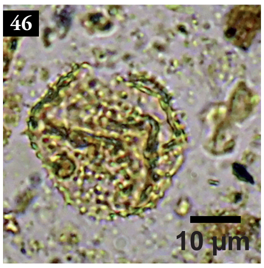

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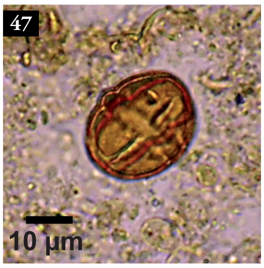

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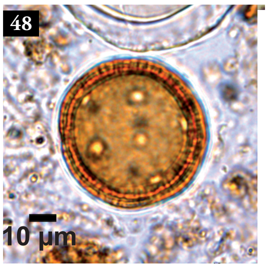

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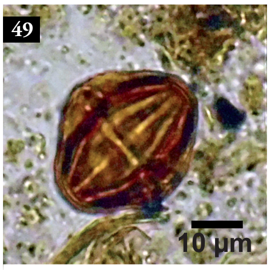

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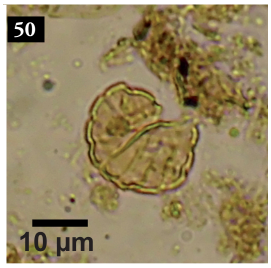

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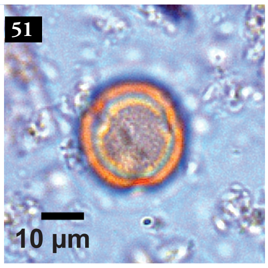

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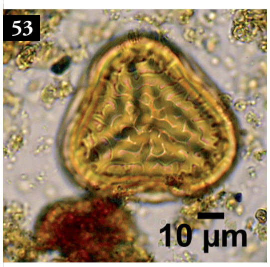

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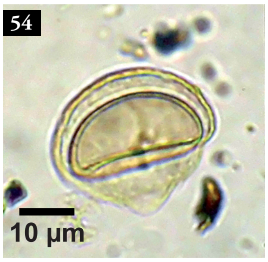

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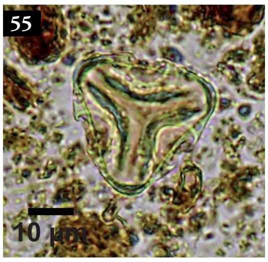

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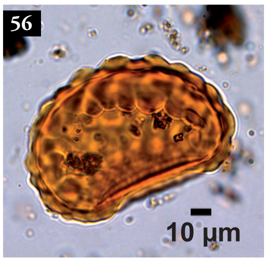

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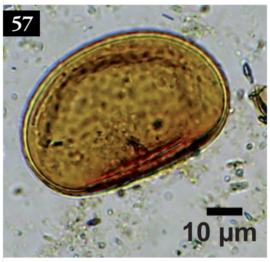

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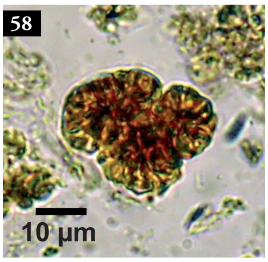

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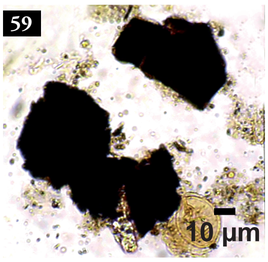

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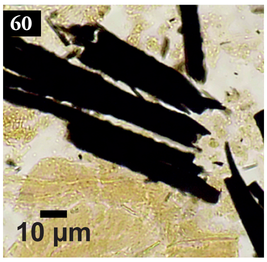

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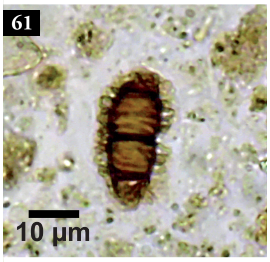

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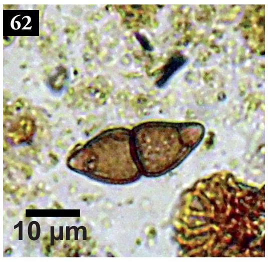

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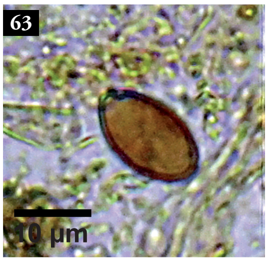

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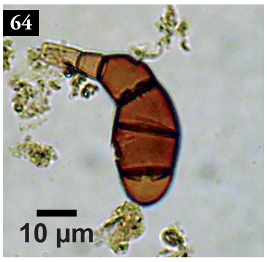

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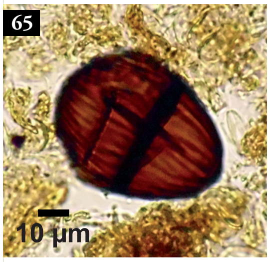


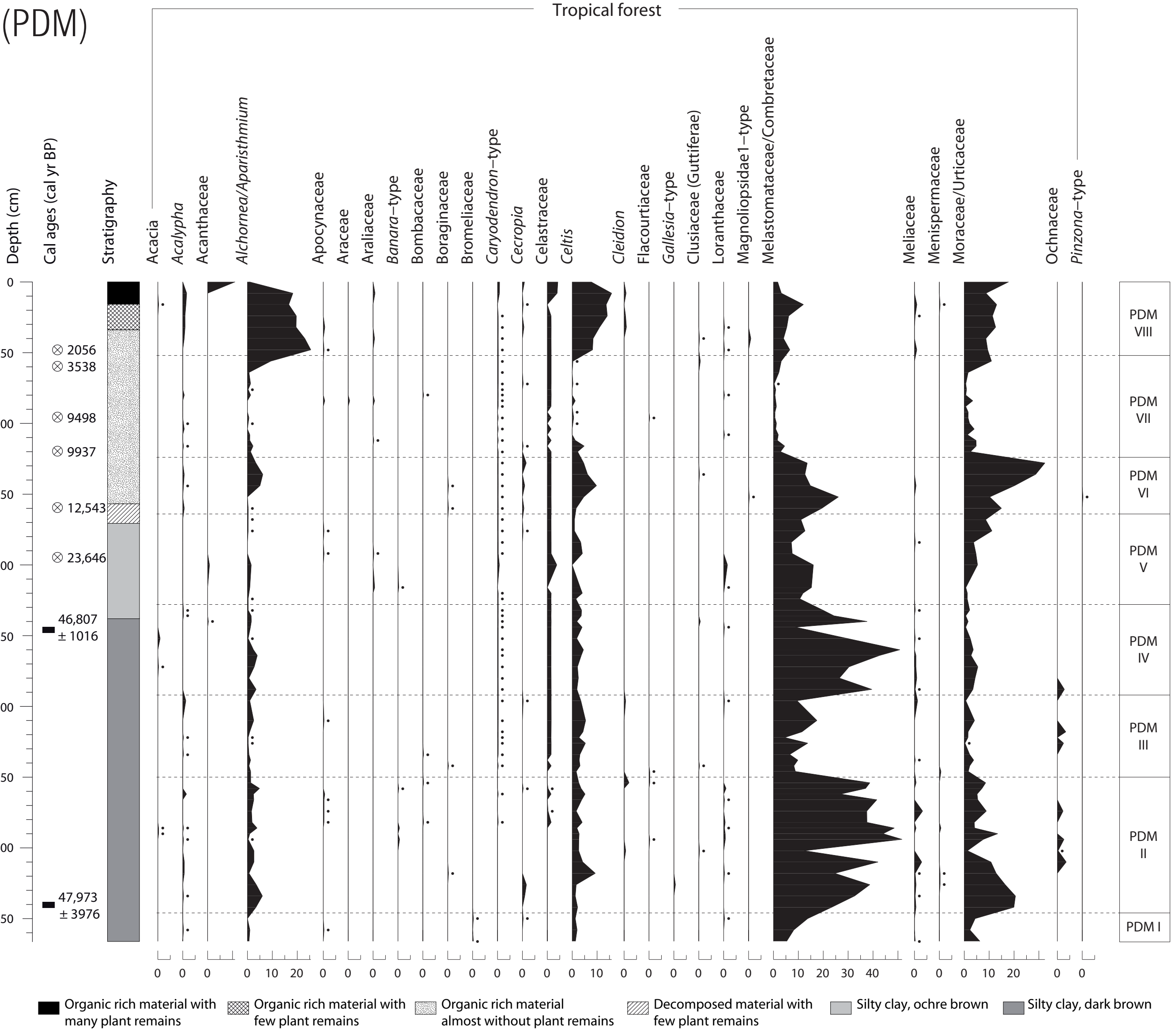
Appendix B.

Complete pollen and charcoal records

- Pántano da Maurítia (PDM), Serra Sul dos Carajás, Pará, Brazil
- Lagoa da Cachoeira (LDC), Serra Sul dos Carajás, Pará, Brazil

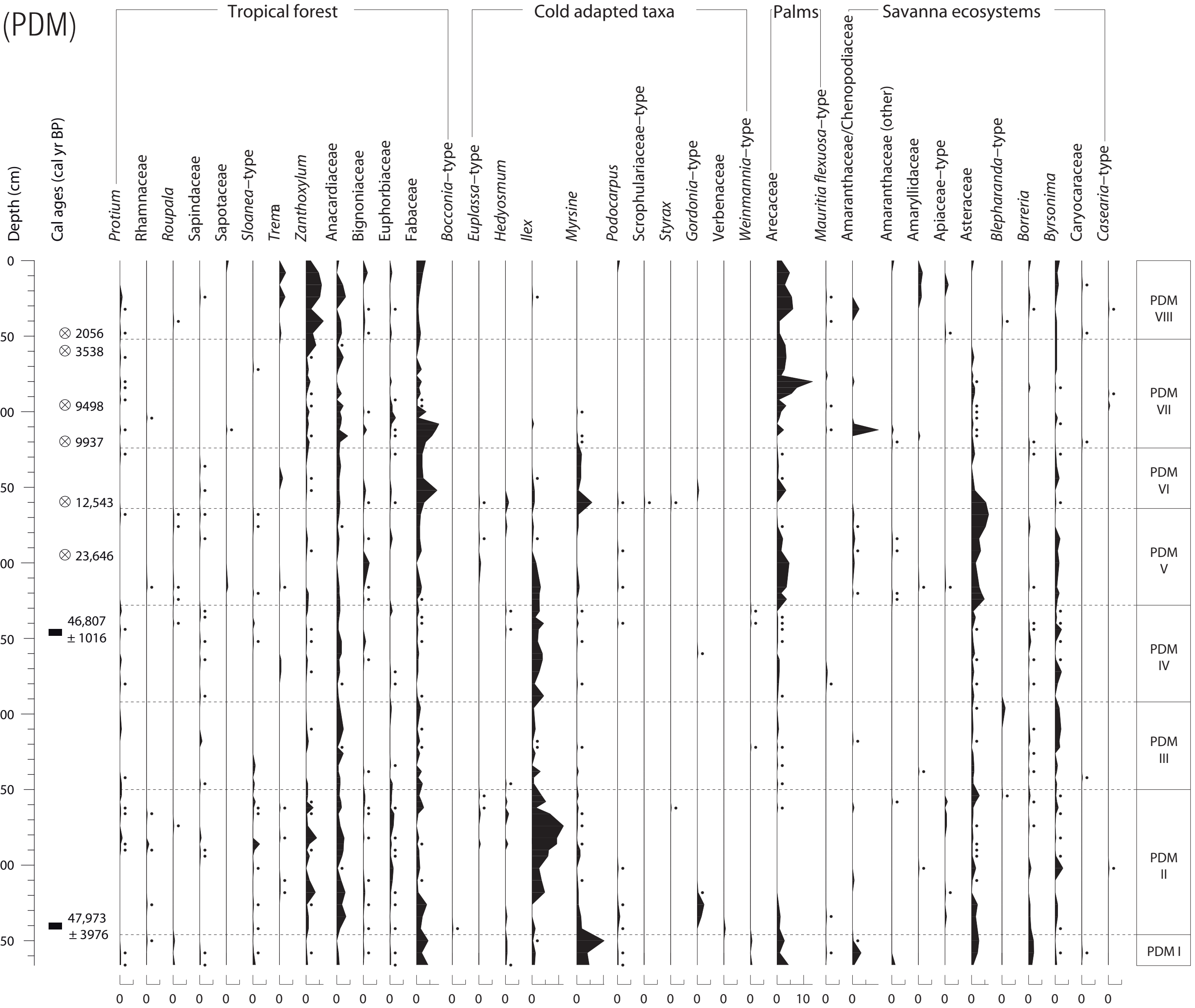
Pántano da Maurítia (PDM)

Complete record
(Percentage diagram)

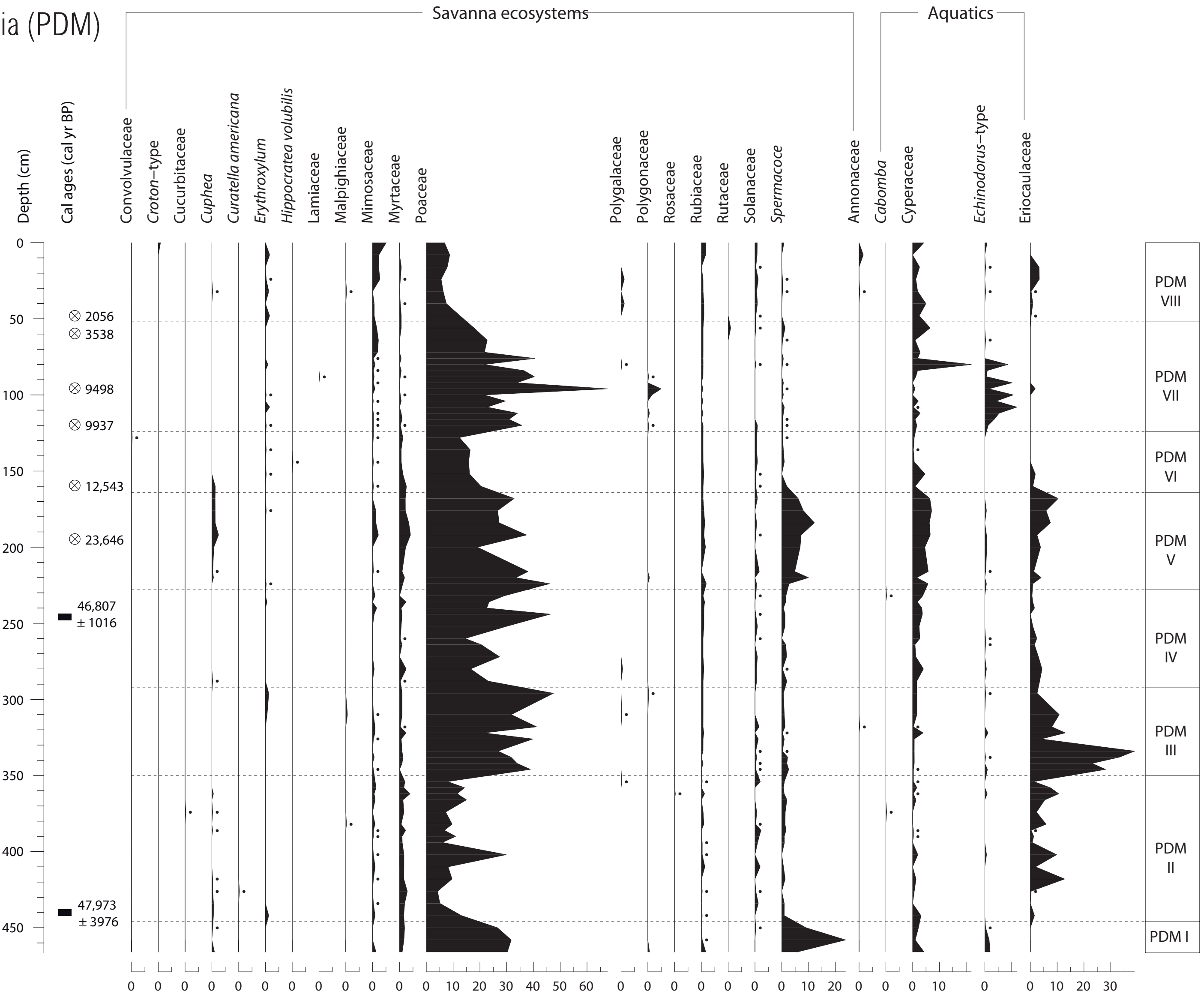


Pántano da Maurítia (PDM)

Complete record (continued)

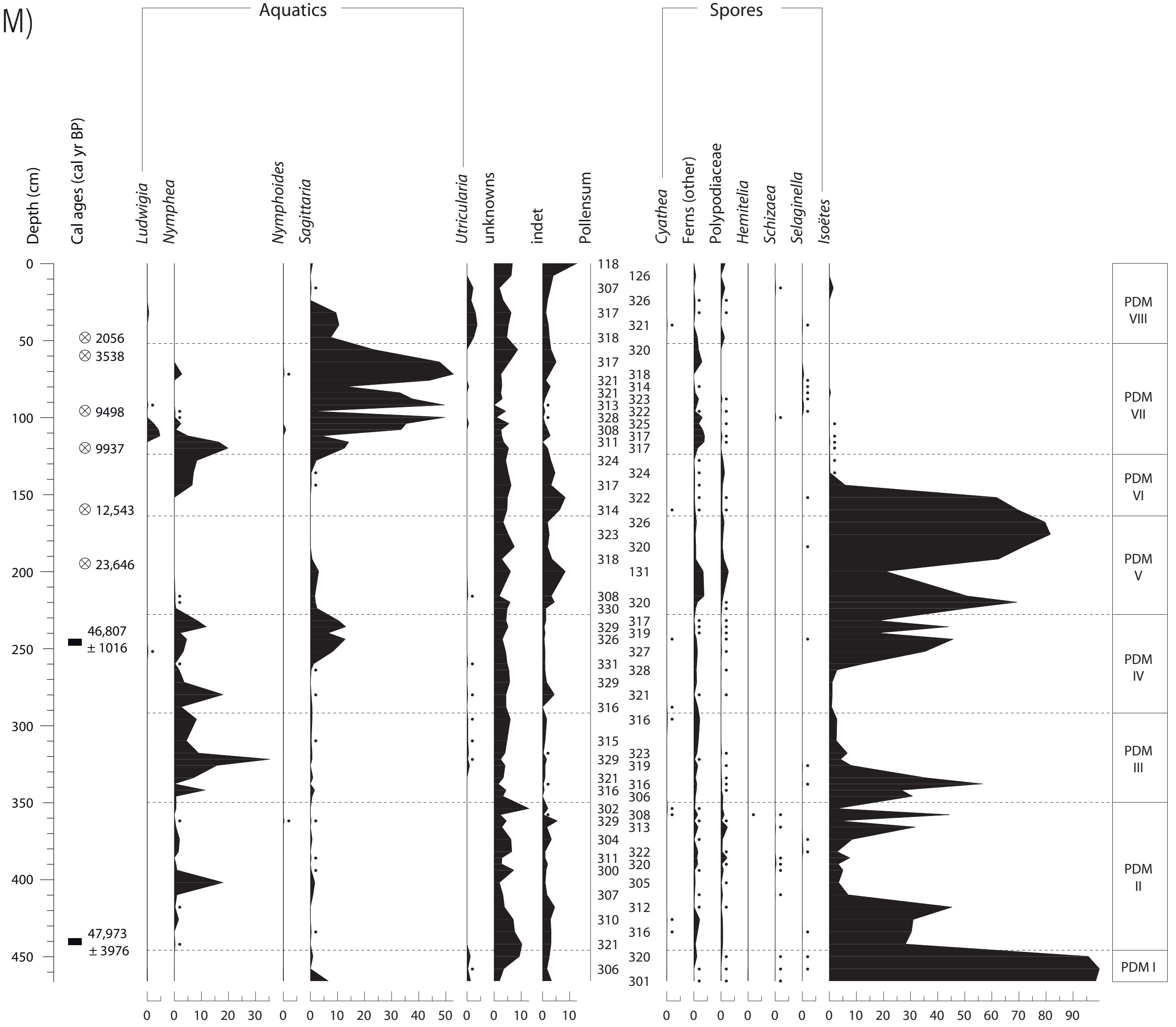


Pántano da Maurítia (PDM)
Complete record
(continued)



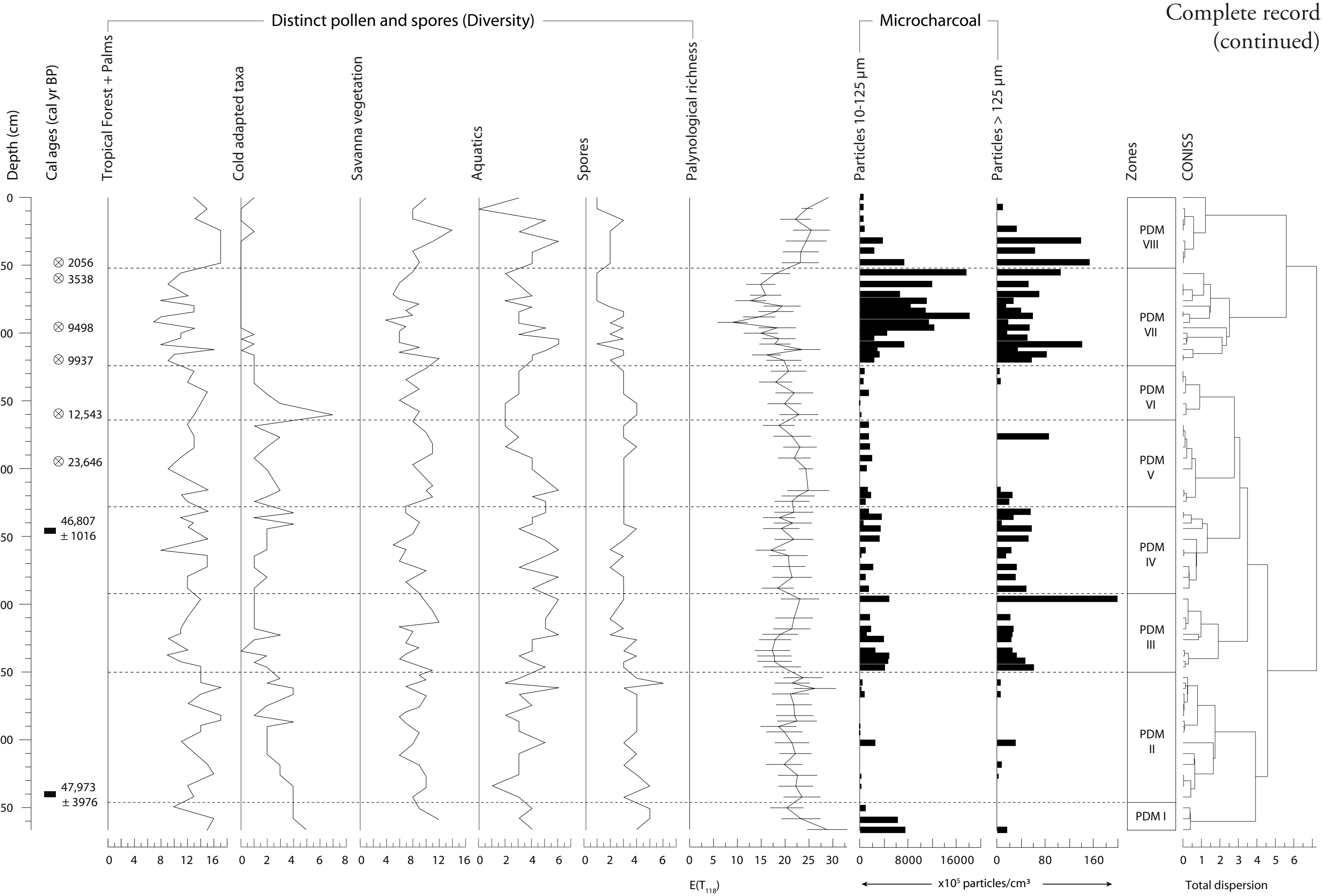
Pántano da Maurítia (PDM)

Complete record
(continued)



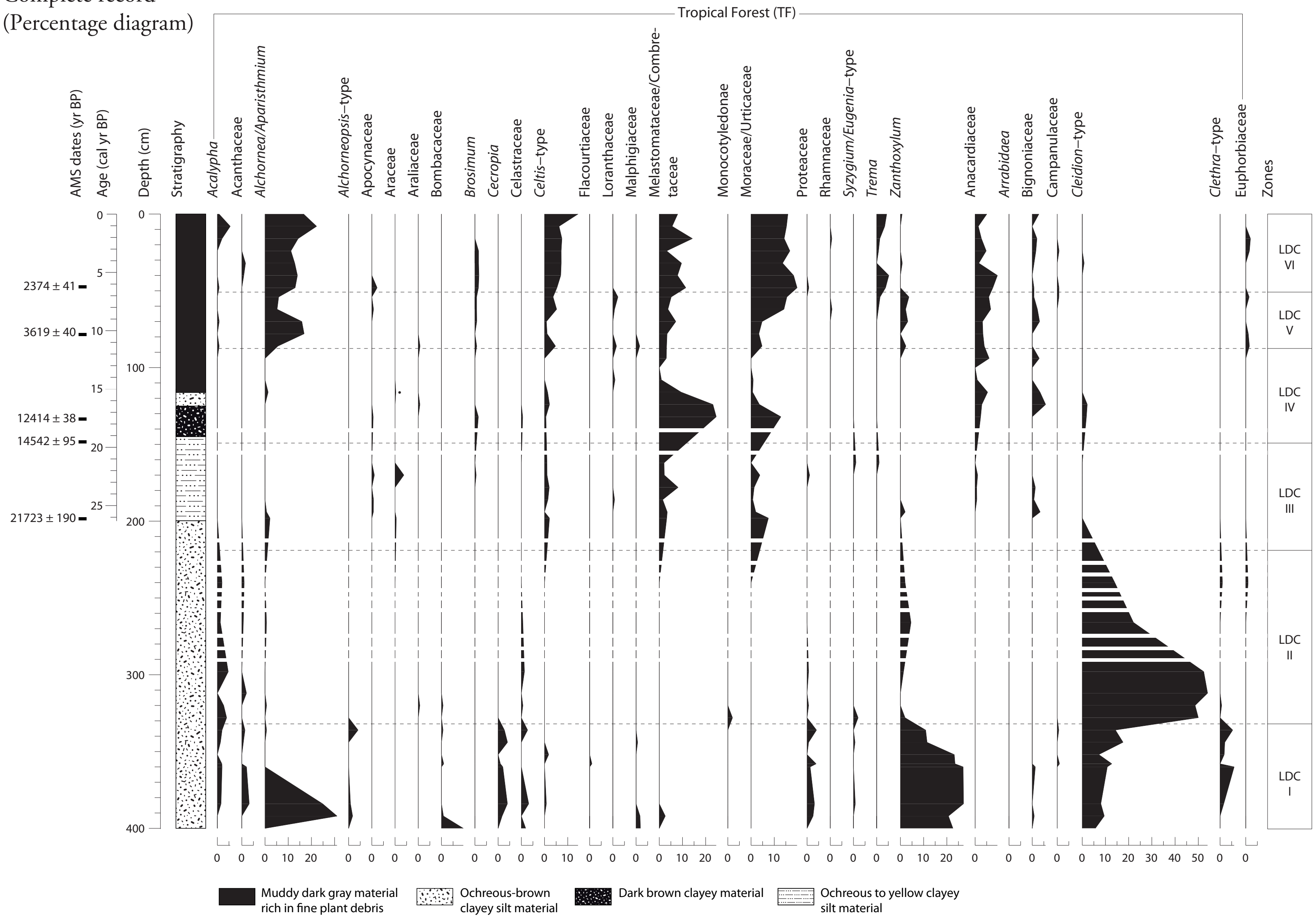
Pántano da Maurítia (PDM)

Complete record
(continued)



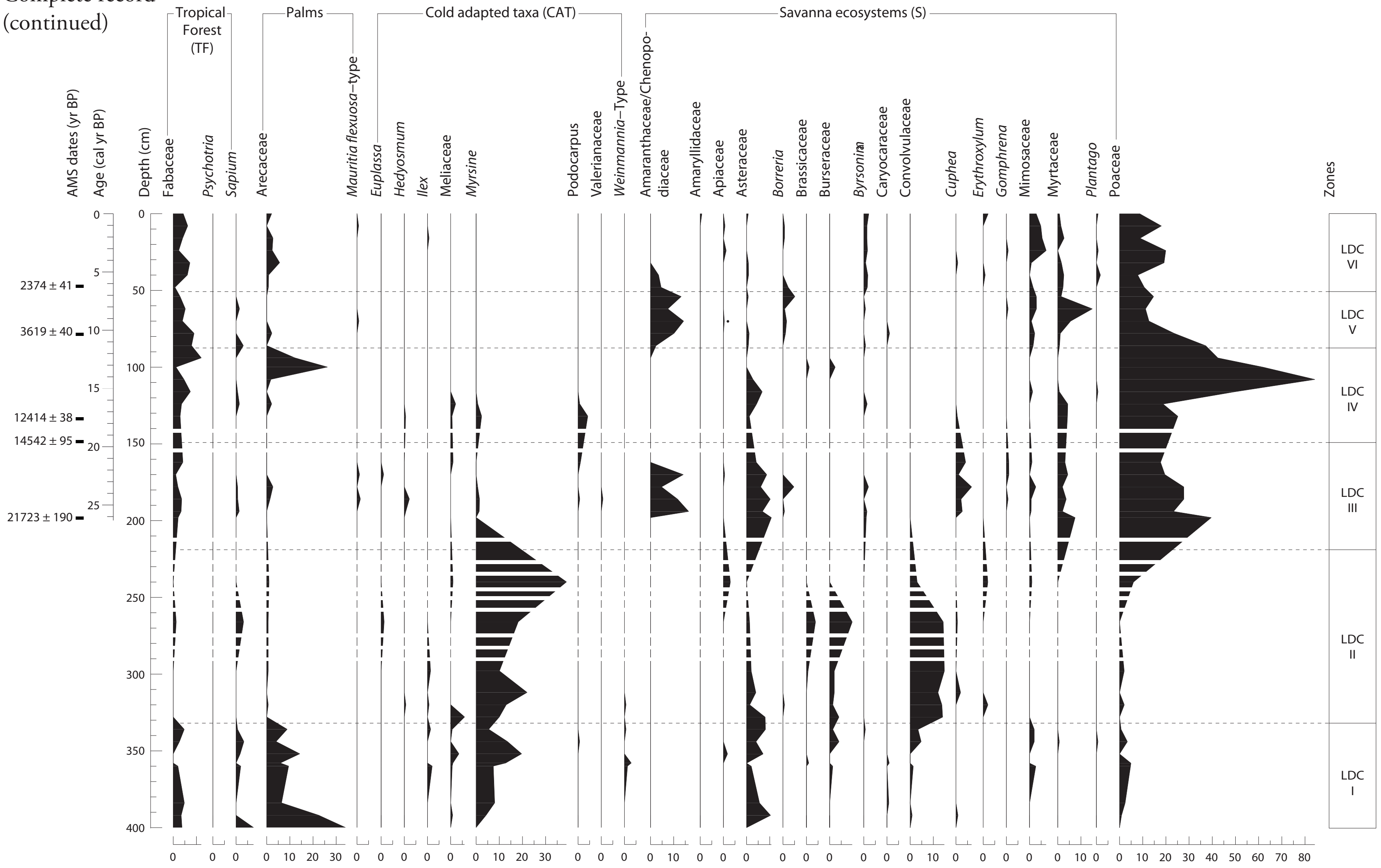
Lagoa da Cachoeira (LDC)

Complete record
(Percentage diagram)



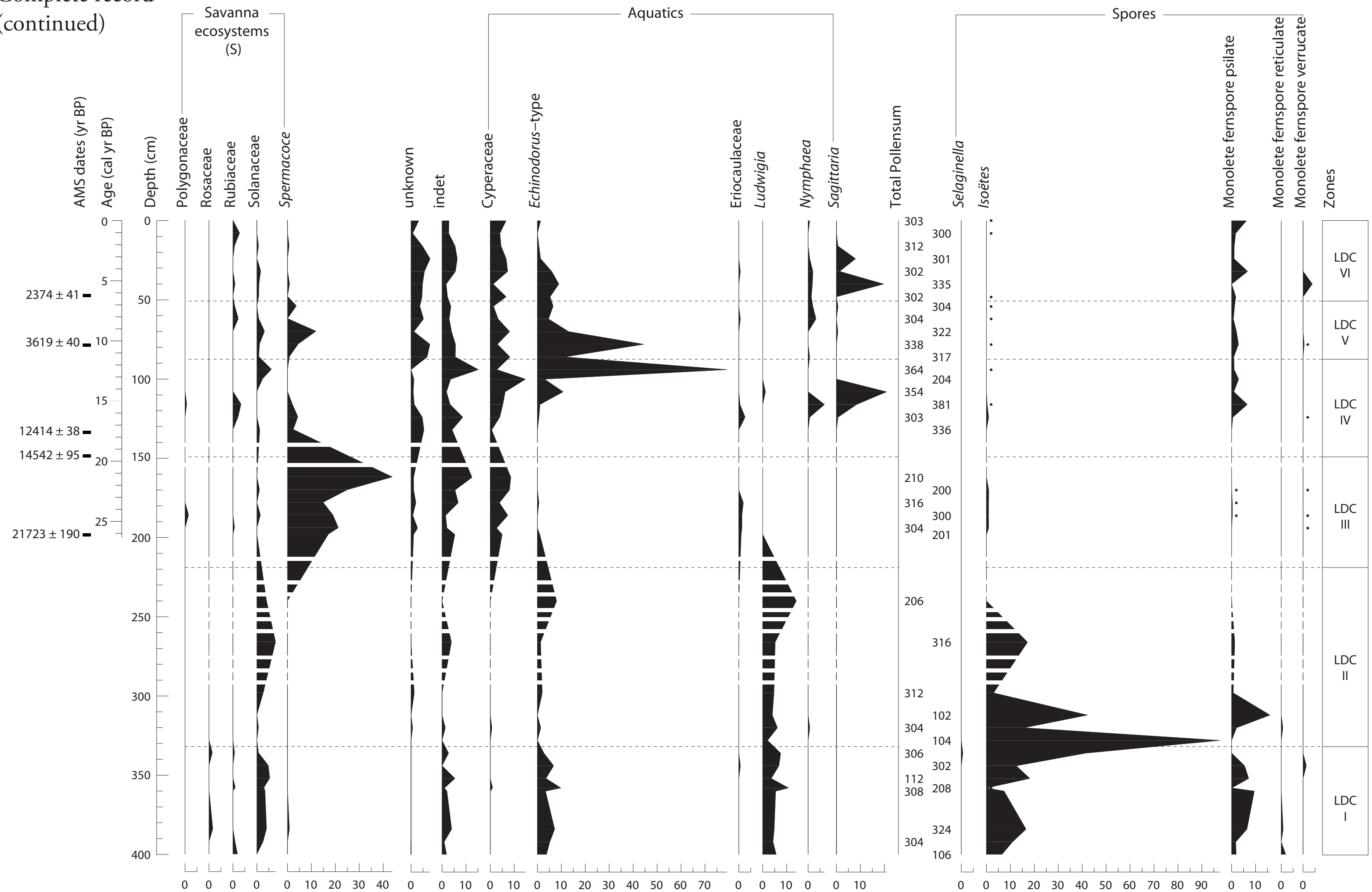
Lagoa da Cachoeira (LDC)

Complete record (continued)



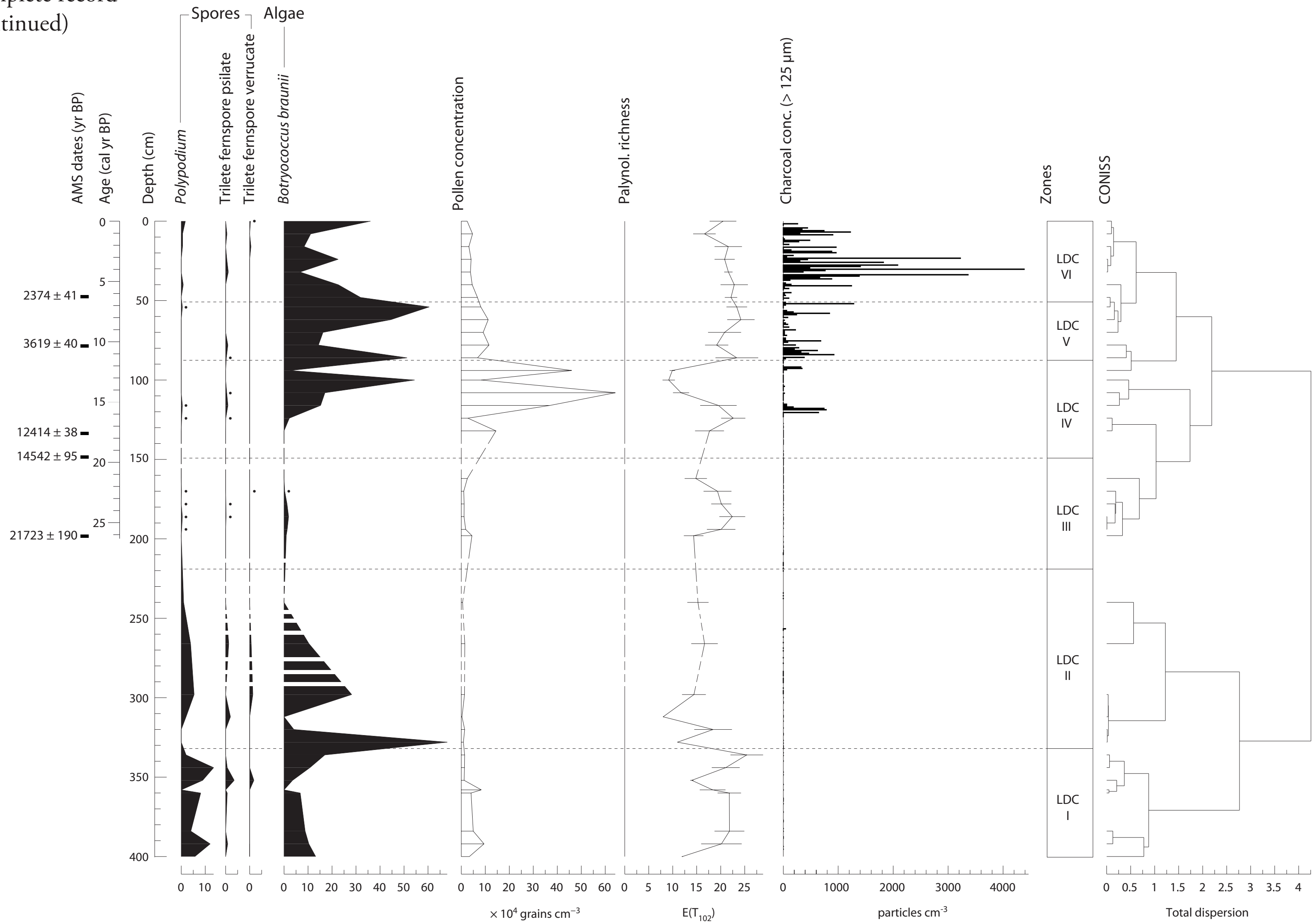
Lagoa da Cachoeira (LDC)

Complete record (continued)



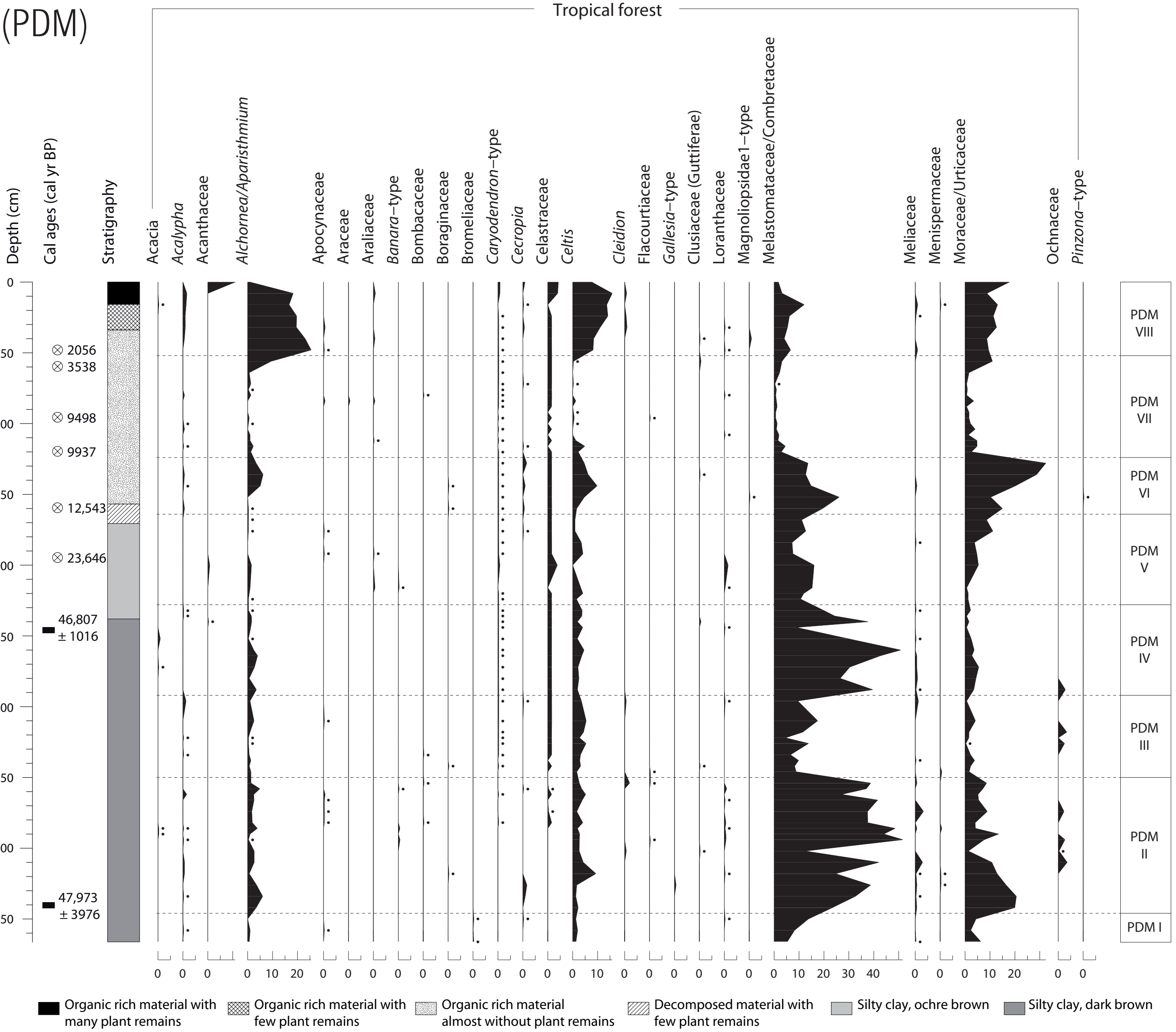
Lagoa da Cachoeira (LDC)

Complete record (continued)



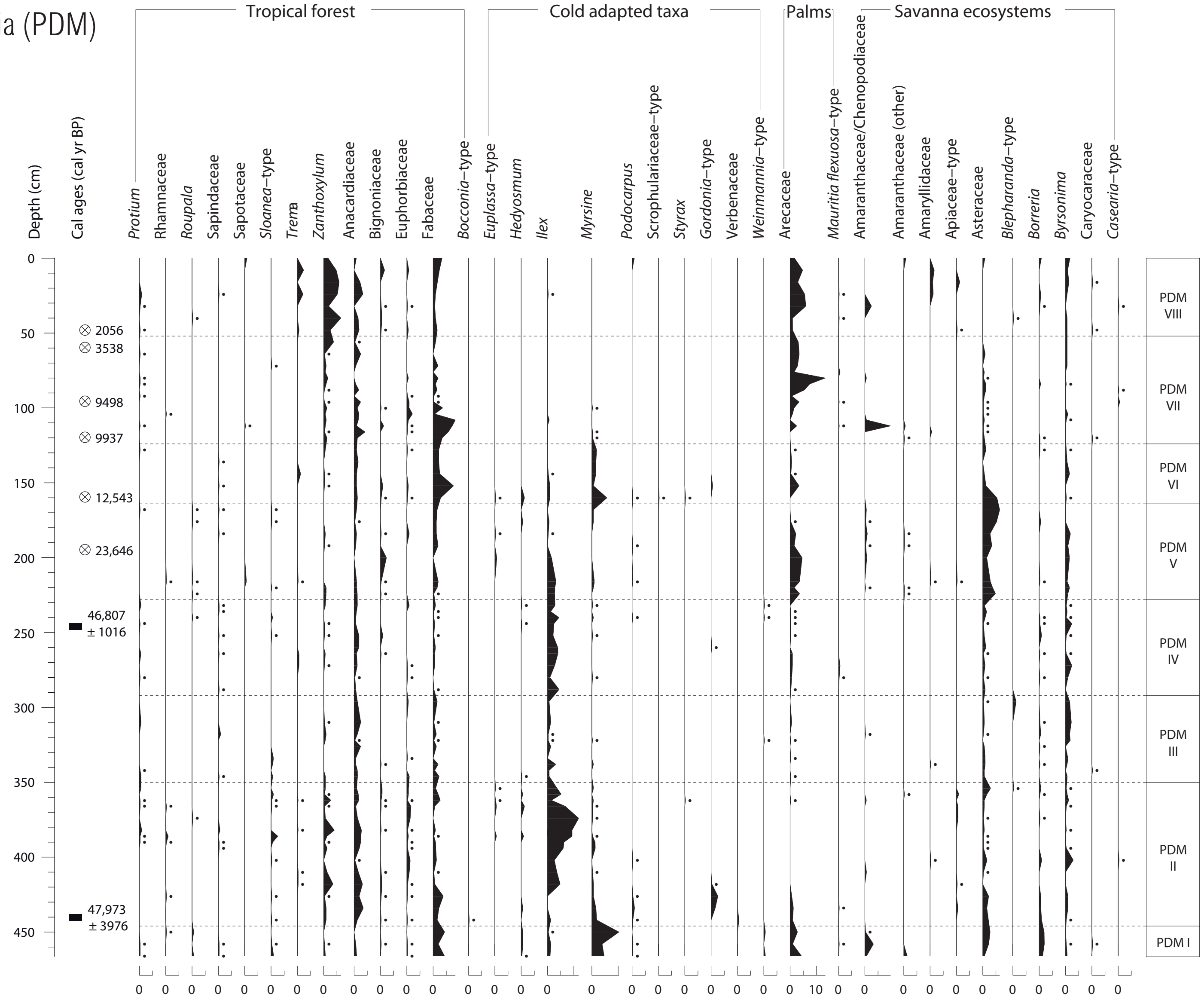
Pántano da Maurítia (PDM)

Complete record
(Percentage diagram)



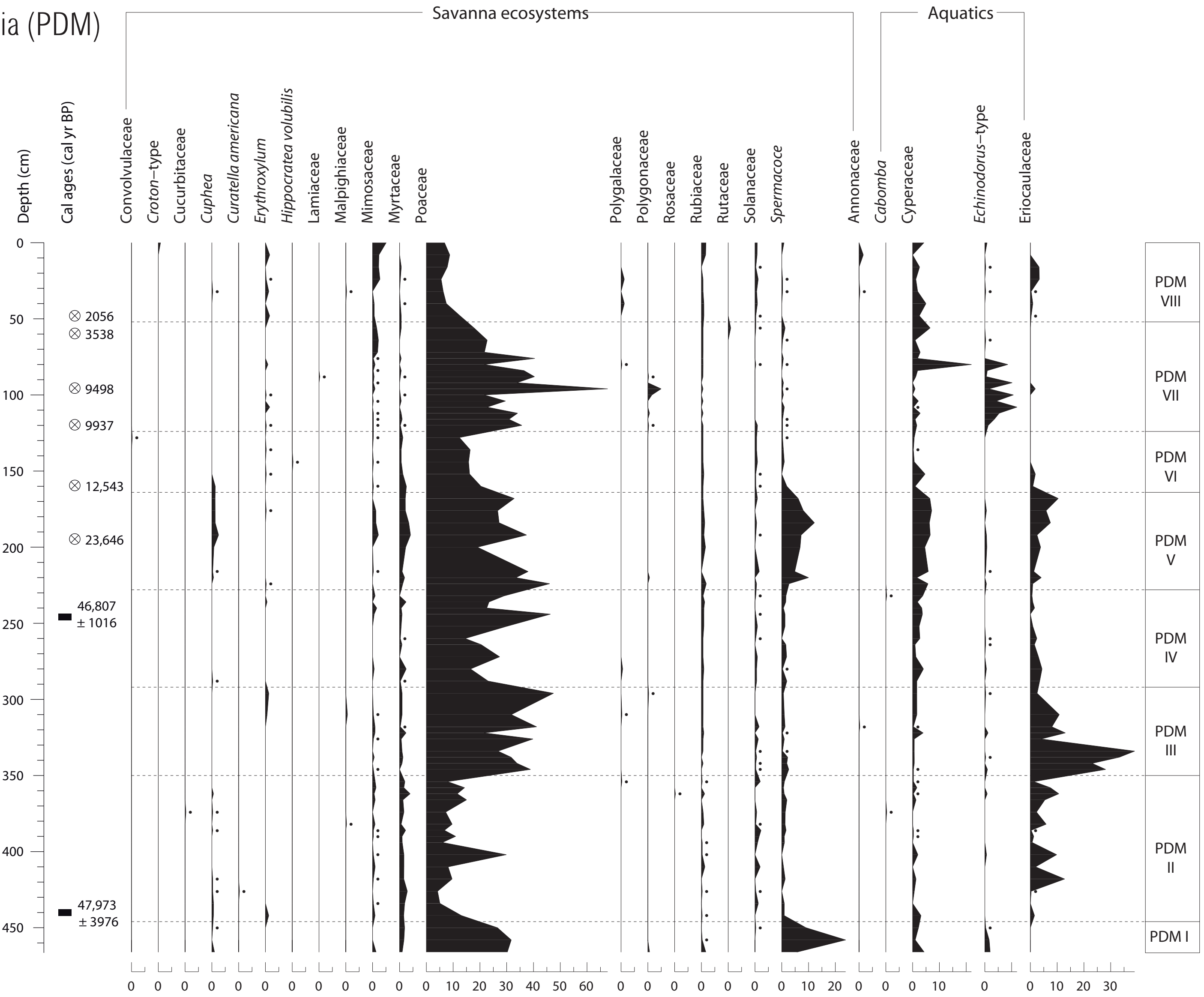
Pántano da Maurítia (PDM)

Complete record (continued)

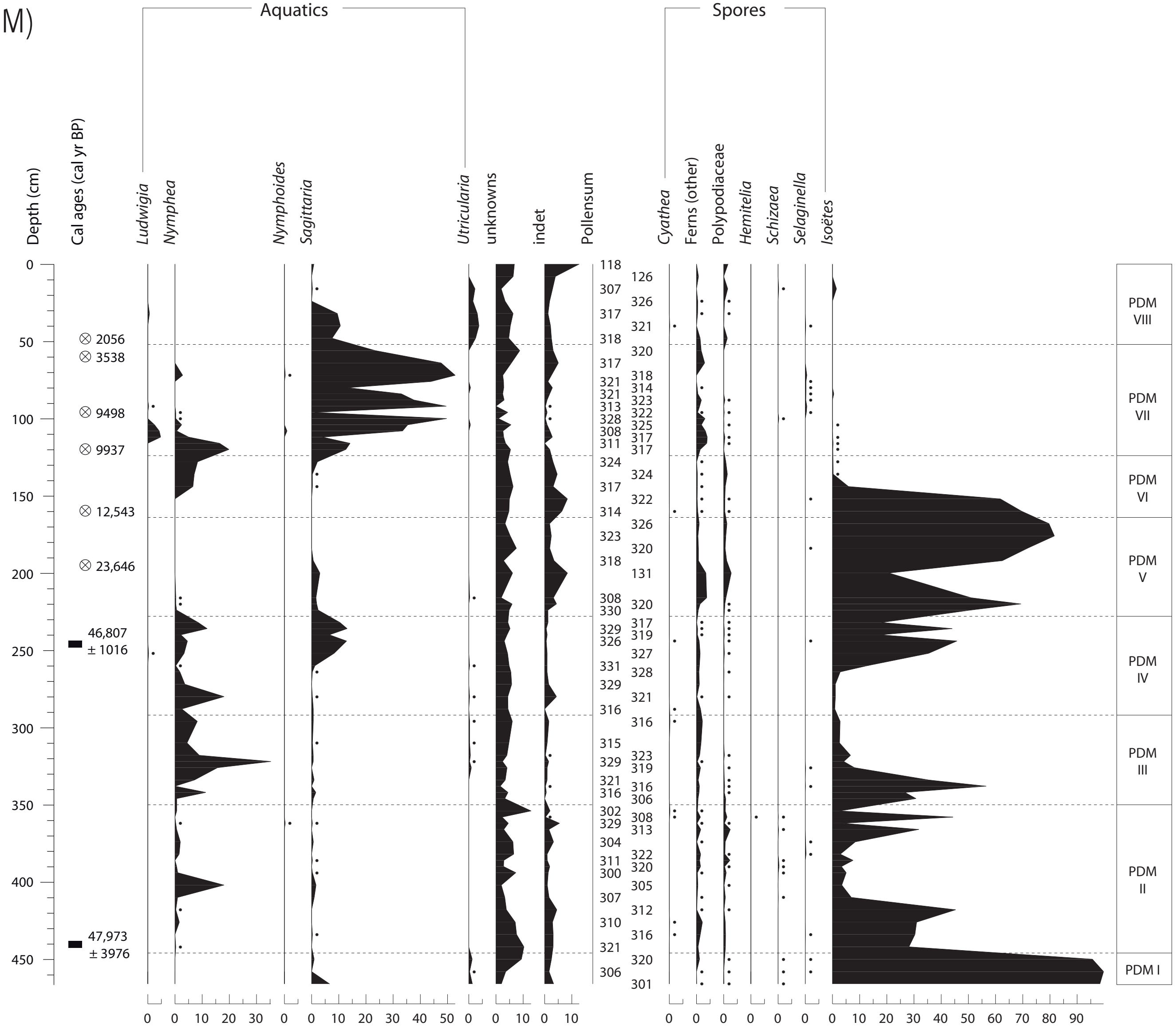


Pántano da Maurítia (PDM)

Complete record (continued)

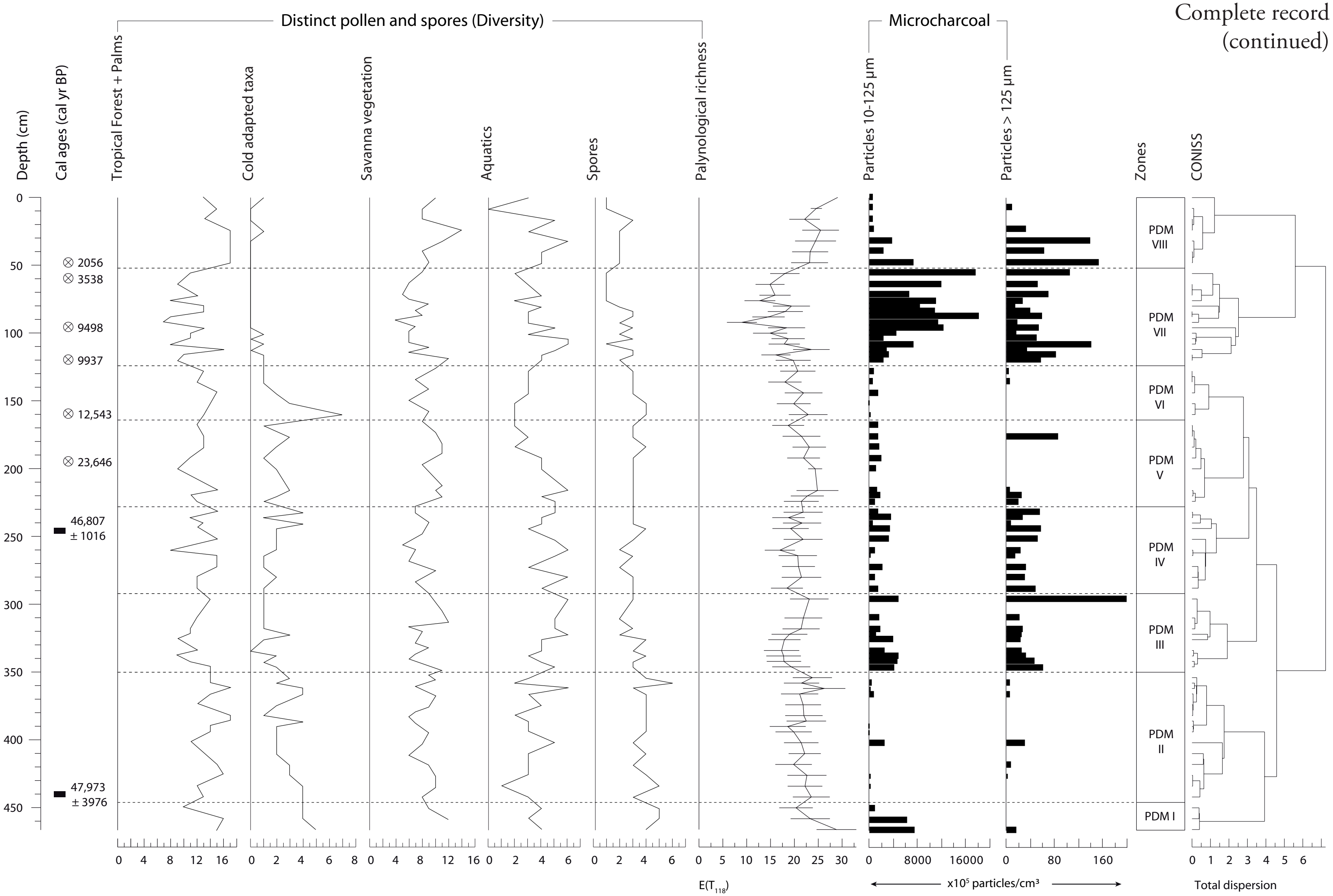


Pántano da Maurítia (PDM)
Complete record
(continued)



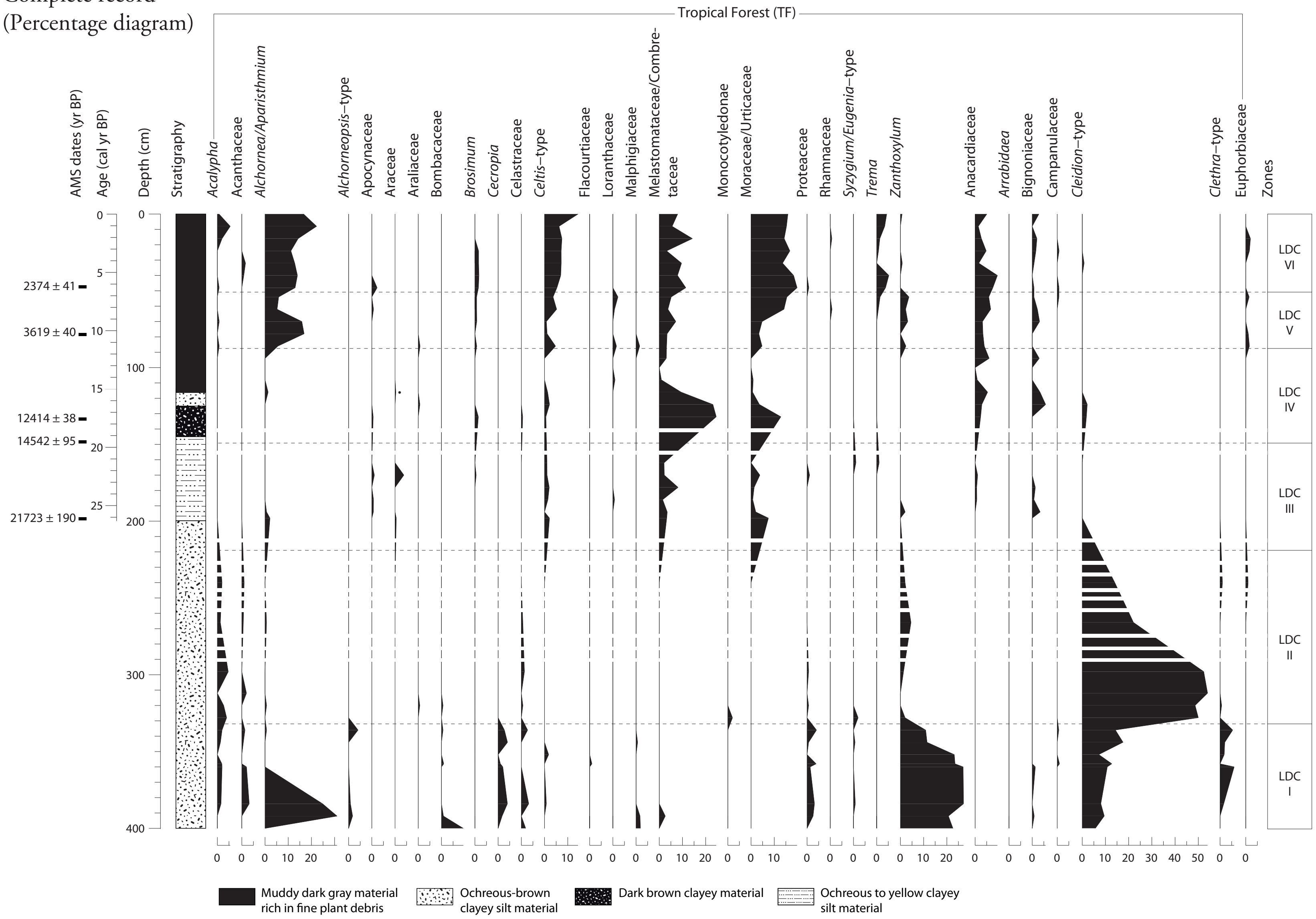
Pántano da Maurítia (PDM)

Complete record (continued)



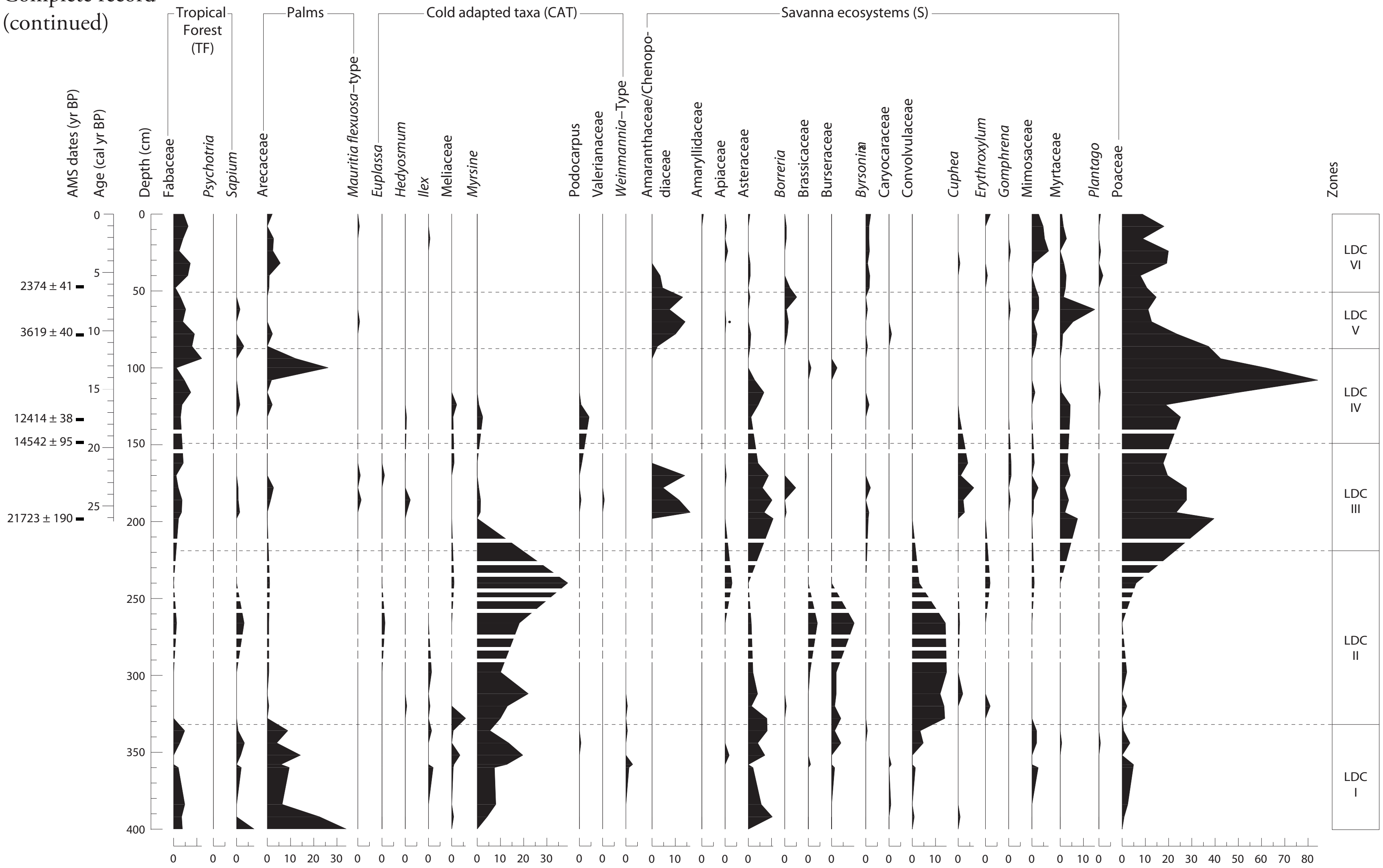
Lagoa da Cachoeira (LDC)

Complete record
(Percentage diagram)



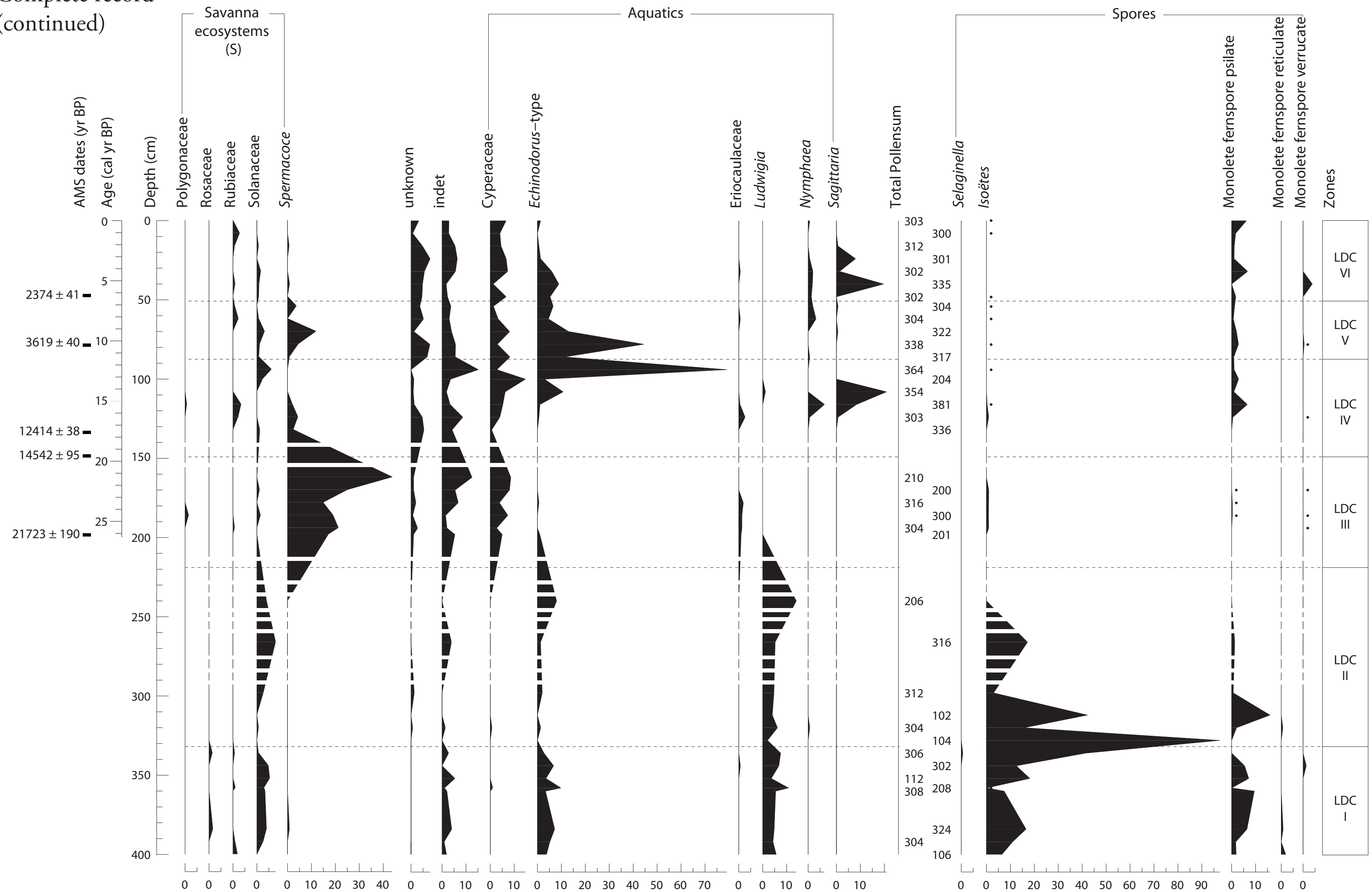
Lagoa da Cachoeira (LDC)

Complete record (continued)



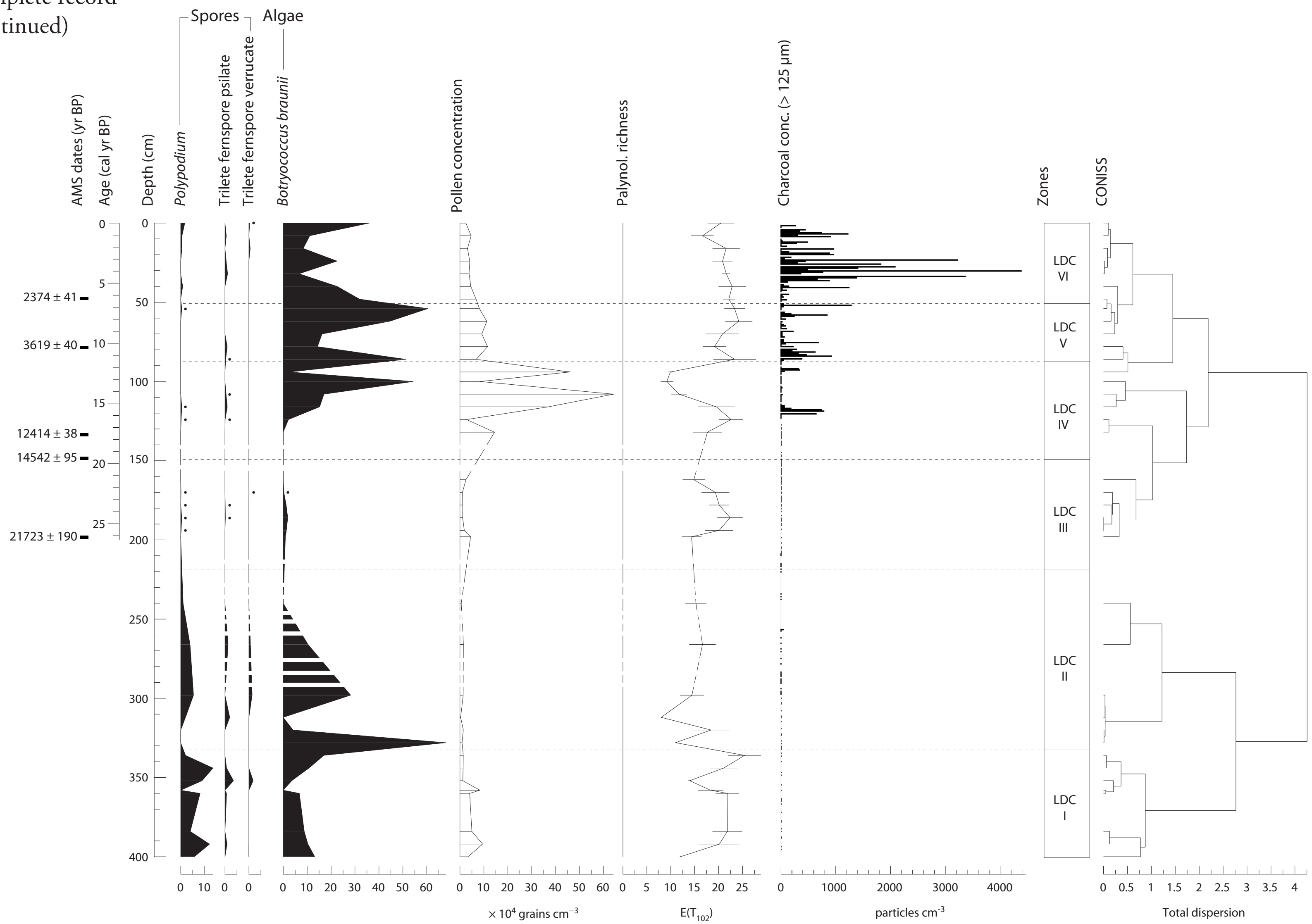
Lagoa da Cachoeira (LDC)

Complete record (continued)



Lagoa da Cachoeira (LDC)

Complete record
(continued)



Lebenslauf

Vor- und Nachname: Barbara Hermanowski
Geboren am: 29.09.1976
Geboren in: Bochum, Deutschland
Nationalität: deutsch

Ausbildung

1983-1987	Besuch der Grundschule; Natorp-Schule in Bochum
1987-1996	Besuch des Gymnasiums; Graf-Engelbert-Schule in Bochum
1996-2002	Studium der Biologie an der Ruhr-Universität Bochum
2002	Diplom (Dipl.-Biol.) an der Ruhr-Universität Bochum
	Hauptfächer: Botanik, Evolution; Diplomarbeit: Studien am Pollen der Gymnospermen
2008-2013	Promotionsstudium (Biologie) an der Georg-August-Universität Göttingen, Albrecht-von-Haller Institut für Pflanzenwissenschaften, Abteilung für Palynologie und Klimadynamik

Praktische Erfahrung

1998-1999	Leitendes Mitglied des Tutorienprogramms der Fakultät für Biologie, Ruhr-Universität Bochum
2002	Technische Mitarbeit im FWF-Projekt P15346 „Evolution in *Gentianella* MOENCH Sect. *Gentianella* (Gentianaceae)“
	Technische Mitarbeit im FWF-Projekt P14352-Bio „Phylogeny and evolution of holoparasitic plants: *Orobanche*“
2002-2004	Technische Mitarbeit an der palynologischen Online Datenbank PalDat, Abteilung Ultrastrukturforschung und Palynologie, Institut für Botanik, Universität Wien
2003-2004	Technische Mitarbeit am FWF-Projekt P15225 „Phylogeny, Speciation and Biogeography in South America“
2004-2007	Kuratorin des Herbariums am Institut für Botanik an der Universität für Bodenkultur, Wien
2007-2008	Technische Mitarbeit im Sonderforschungsbereich 552 (STORMA), Unterprogramm C7 „Stability of rainforest margins in space and time: Holocene rainforest, climate, fire, human impact and land use dynamics in Sulawesi, Indonesia”
2008-2011	Wissenschaftliche Mitarbeiterin an der Abteilung Palynologie und Klimadynamik, Georg-August-Universität Göttingen

Publikationen

2004	Greimler, J., Hermanowski, B., Jang, C.-G., 2004. A re-evaluation of morphological characters in European *Gentianella* section *Gentianella* (Gentianaceae). Plant Systematics and Evolution 248, pp. 143 – 169
2005	Botanische Texte in: R. Kurdiovsky, Die Gärten von Schönbrunn. Ein Spaziergang durch einen der bedeutendsten Barockgärten Europas; Residenz Verlag 2005, ISBN 3-7017-1411-8.

2006	Samuel, R., Gutermann, W., Stuessy, T. F., Ruas, C. F., Lack, H.-W., Tremetsberger, K., Talavera, S., Hermanowski, B., Ehrendorfer, F., 2006. Molecular Phylogenetics reveals *Leontodon* (Asteraceae, Lactucaceae) to be diphyletic. American Journal of Botany 93, 1193-1205.
2012	Hermanowski, B., Costa, M.L., Behling, H., 2012. Environmental changes in southeastern Amazonia during the last 25,000 yr revealed from a paleoecological record. Quaternary Research 77, 138-148.
	Hermanowski, B., Costa, M.L., Trinidade Carvalho, A., Behling, H., 2012. Palaeoenvironmental dynamics and underlying climatic changes in southeast Amazonia (Serra Sul dos Carajás, Brazil) during the late Pleistocene and Holocene.Palaeogeography, Palaeoclimatology, Palaeoecology 366, 227-246.

Tagungen und Kongresse

2010	8. European Palaeobotany – Palynology Conference (EPPC); Hermanowski, B., Costa, M.L., Behling, H., Southeast Amazonia – 25,000 years of vegetation and fire dynamics. [Vortrag]
	International meeting of the Association for Tropical Biology and Conservation (ATBC),; Hermanowski, B., Costa, M.L., Behling, H., Southeast Amazonia - 25,000 years of environmental dynamics in relation to Global Climate Change. [Vortrag]
2009	Joint Annual Meeting ATBC-GTÖ „Impacts of Global Change on Tropical Ecosystems“; Hermanowski, B., Costa, M.L., Behling, H., Late Quaternary environmental dynamics of Amazonian rainforest in northern Brazil – New palynological insights. [Poster]
2008	International Conference of the Society for Tropical Ecology (GTÖ); Jeske-Pieruschka, V., Hermanowski, B., Behling, H., Late Holocene forest-grassland dynamics inferred from the São José dos Ausentes record in the southern Brazilian highlands. [Poster]
	12th International Palynological Congress IPC-XII 2008; Hermanowski, B., Behling, H., Late Quaternary environmental dynamics of Amazonian rainforest in northern Brazil – New palynological insights. [Poster]
	XII Simpósio Brasileiro de Paleobotânica e Palinologia, Florianópolis: Hermanowski, B., Behling, H., Late Quaternary environmental dynamics of Amazonian rainforest in northern Brazil – New palynological insights. [Poster]
2007	Mitglied des Organisationskomitees zum 17. Jahrestreffen des Arbeitskreises Vegetationsgeschichte, Reinhold-Tüxen-Gesellschaft
2002	5. Annual Meeting of the Society for Biological Systematics (GFBS); Hermanowski, B., Seven at one stroke - new and old characters (LM, SEM) of pollen from Pinaceae, Podocarpaceae and Phyllocladaceae (Coniferales, Gymnospermae). [Poster]

Göttingen, 22.01.2013

Curriculum vitae

Full name: Barbara Hermanowski
Born on: 29.09.1976
Born in: Bochum, Germany
Nationality: German

Practical experience

2008-2011	Scientific Co-Worker at the Department of Palynology an Climate Dynamics, Georg-August-Universiyt Göttingen
2007-2008	Technical Assistance; Research program 552 (STORMA), Subprogram C7 „Stability of rainforest margins in space and time: Holocene rainforest, climate, fire, human impact and land use dynamics in Sulawesi, Indonesia”
2004-2007	Curator at the Institute of Botany, University of Natural Resources and Life Sciences, Vienna
2003-2004	Technical Assistance; am FWF-Project P15225 „Phylogeny, Speciation and Biogeography in South America“
2002	Technical Assistance; FWF-Project P15346 „Evolution in *Gentianella* MOENCH Sect. *Gentianella* (Gentianaceae)“
	Technical Assistance; FWF-Project P14352-Bio „Phylogeny and evolution of holoparasitic plants: *Orobanche*“
2002-2004	Technical Assistance; Palynological Online Database PalDat, Department of Ultrastructure and Palynology, Institute for Botany, University Vienna
1998-1999	Executive member of the tutorial program at the Faculty of Biology, Ruhr-University Bochum

Publications

2012	Hermanowski, B., Costa, M.L., Trinidade Carvalho, A., Behling, H., 2012. Palaeoenvironmental dynamics and underlying climatic changes in southeast Amazonia (Serra Sul dos Carajás, Brazil) during the late Pleistocene and Holocene. Palaeogeography, Palaeoclimatology, Palaeoecology 366, 227-246.
	Hermanowski, B., Costa, M.L., Behling, H., 2012. Environmental changes in southeastern Amazonia during the last 25,000 yr revealed from a paleoecological record. Quaternary Research 77, 138-148.
2006	Samuel, R., Gutermann, W., Stuessy, T. F., Ruas, C. F., Lack, H.-W., Tremetsberger, K., Talavera, S., Hermanowski, B., Ehrendorfer, F., 2006. Molecular Phylogenetics reveals *Leontodon* (Asteraceae, Lactucaceae) to be diphyletic. *American Journal of Botany 93, 1193-1205.*
2005	Botanic texts in: R. Kurdiovsky, Die Gärten von Schönbrunn. Ein Spaziergang durch einen der bedeutendsten Barockgärten Europas; Residenz Verlag 2005, ISBN 3-7017-1411-8.
2004	Greimler, J., Hermanowski, B., Jang, C.-G., 2004. A re-evaluation of morphological characters in European *Gentianella* section *Gentianella* (Gentianaceae). Plant Systematics and Evolution 248, pp. 143 – 169

Symposia and Congresses

2010	8. European Palaeobotany - Palynology Conference (EPPC), Budapest: Hermanowski, B., Costa, M.L., Behling, H., Southeast Amazonia – 25,000 years of vegetation and fire dynamics. [Presentation]
	International meeting of the Association for Tropical Biology and Conservation (ATBC), Bali: Hermanowski, B., Costa, M.L., Behling, H., Southeast Amazonia - 25,000 years of environmental dynamics in relation to Global Climate Change. [Presentation]
2009	Joint Annual Meeting ATBC-GTÖ „Impacts of Global Change on Tropical Ecosystems“, Marburg: Hermanowski, B., Costa, M.L., Behling, H., Late Quaternary environmental dynamics of Amazonian rainforest in northern Brazil – New palynological insights. [Poster]
2008	International Conference of the Society for Tropical Ecology (GTÖ), Stuttgart: Jeske-Pieruschka, V., Hermanowski, B., Behling, H., Late Holocene forest-grassland dynamics inferred from the São José dos Ausentes record in the southern Brazilian highlands. [Poster]
	12th International Palynological Congress IPC-XII 2008, Bonn: Hermanowski, B., Behling, H., Late Quaternary environmental dynamics of Amazonian rainforest in northern Brazil – New palynological insights. [Poster]
	XII Simpósio Brasileiro de Paleobotânica e Palinologia, Florianópolis: Hermanowski, B., Behling, H., Late Quaternary environmental dynamics of Amazonian rainforest in northern Brazil – New palynological insights. [Poster]
2007	Member of the organizing committee of the 17. Meeting of the „Arbeitskreis Vegetationsgeschichte, Reinhold-Tüxen-Gesellschaft“
2002	5. Annual Meeting of the Society for Biological Systematics (Gesellschaft für Biologische Systematik): Hermanowski, B., Seven at one stroke - new and old characters (LM, SEM) of pollen from Pinaceae, Podocarpaceae and Phyllocladaceae (Coniferales, Gymnospermae). [Poster]

Education

2008-2013	PhD-Program (Biology) at the Georg-August-University of Göttingen, Albrecht-von-Haller Institute of Plant Sciences, Department of Palynology and Climate Dynamics
2002	Graduation in Biology (Dipl.-Biol.) at the Ruhr-University of Bochum
	Major subject: Botany, Evolution; Thesis title: Studien am Pollen der Gymnospermen
1996-2002	Studies of Biology at the Ruhr-University of Bochum
1987-1996	Secondary school (Gymnasium); Graf-Engelbert-Schule, Bochum
1983-1987	Elementary school; Natorp-Schule, Bochum

Göttingen, 22.01.2013