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**DINAMICA DA PAISAGEM NA PORÇÃO NORTE DA ILHA
DO BANANAL-TO E ADJACENCIAS AO LONGO DO
QUATERNARIO TARDIO**

Tese apresentada por:

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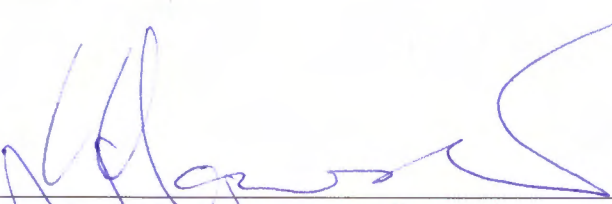
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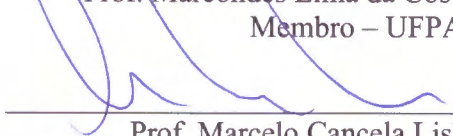
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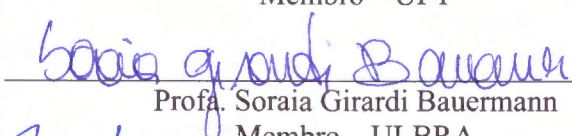
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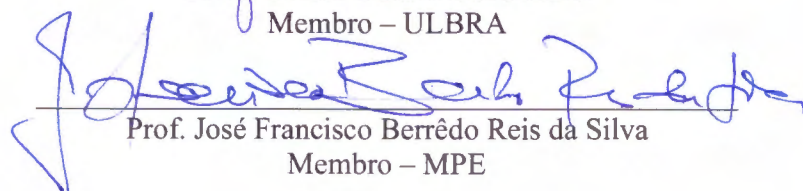
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*Aos amores Sônia e Wilton, e meus
amados irmãos, sem eles eu nada seria.*

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RESUMO

Estudos paleoclimáticos e paleoambientais visam entender os processos de evolução de paisagens globais, contribuindo para reconstituição das paisagens quaternárias e das mudanças climáticas e ambientais a que foram submetidas ao longo deste período da história geológica da Terra. Alguns estudos na Amazônia, mas, principalmente aqueles realizados em regiões mais sensíveis, como os ecótonos e *wetlands*, mostram que estas áreas sofreram várias mudanças paleoecológicas durante o Pleistoceno e Holoceno. O presente estudo foi realizado na região da Ilha do Bananal situada em uma área de transição entre os biomas amazônicos e cerrado. A Ilha do Bananal considerada por diversos autores como a maior ilha fluvial do mundo, ocupa uma área de cerca de 20.000 km² e está situada entre o curso médio do rio Araguaia e o seu afluente pela margem direita, o rio Javaés, no Estado do Tocantins. A porção norte da ilha, se destaca por um complexo mosaico de feições geomorfológicas (diques marginais, meandros abandonados, paleocanais e lagos) e geobotânicas contrastantes (florestas e savanas), que refletem a intensa atividade hidrodinâmica nesta região. Sazonalmente ela é inundada pelas águas pluviais e pela elevação do lençol freático, por isso, é considerada uma *seasonal wetland*. O objetivo deste trabalho foi entender a dinâmica dessa paisagem, com base no estudo da composição mineralógica e química dos solos e sedimentos e na composição palinológica de sedimentos lacustres dessa região. Dessa forma, foram coletadas amostras de barrancos expostos nas margens dos rios Javaés e Araguaia, de barras arenosas e sedimentos lacustres. Os solos e sedimentos foram analisados quanto à sua mineralogia por Difração de Raios- X e química por ICP-MS. Os testemunhos de sedimentos coletados em 2 lagos distintos, um localizado no interior da porção norte da Ilha do Bananal (Lago Quatro Veados) e o outro situado nos arredores do Rio Javaés (Lago da Mata Verde) foram analisados quanto ao seu conteúdo palinológico e datados por AMS ¹⁴C. Os resultados desta pesquisa estão apresentados em 3 artigos: o primeiro trata sobre a mineralogia e geoquímica dos solos e sedimentos da Ilha do Bananal, das barras e barrancos ao longo do Rio Javaés. Discorre, portanto, sobre a natureza diversificada dos minerais e elementos químicos que compõem os estratos e horizontes dessas coberturas superficiais, apontando proveniência geológica, bem como os processos geoquímicos envolvidos na dinâmica atual e pretérita dessa paisagem. O segundo artigo apresenta a dinâmica da vegetação ao longo dos últimos 2000 anos AP no interior da Ilha do Bananal e discute sua relação com as condições climáticas e edáficas locais. O terceiro artigo, por sua vez, descreve a sucessão vegetal ocorrida nos últimos 400 anos AP, com base no registro polínico de sedimentos de um lago situado nos arredores da Ilha do Bananal, bem como, analisa o espectro polínico moderno na região. Os resultados obtidos através do presente trabalho apresentam uma paisagem altamente diversificada quanto as suas geoformas, coberturas sedimentares e pedogenéticas e aspectos geobotânicos resultante dos diversos momentos de sua história geológica e que mesmo atualmente se mostra dinâmica e intrigante. Os solos e sedimentos dessa paisagem são variados quanto as suas texturas (sequencias de materiais arenosos e argilosos) e composições mineralógicas e químicas onde minerais primários e

derivados de variados graus de intemperismo químico coexistem em um mesmo perfil, evidenciando momentos de condições climáticas contrastantes. Mesmo, atualmente é possível observar *in loco* ambientes com dinâmicas variáveis (erosivas, sedimentares, pedogenéticas, etc.), bem como, processos geoquímicos diversos, tais como, aqueles de oxidação das barras e barrancos arenosos e também os processos redutivos dessas areias ferruginizadas (por vezes, confundidas equivocadamente com perfis lateríticos), devido o contato com os ácidos orgânicos produzidos pela cobertura florestada e condições hidromórficas as quais são submetidas. Com relação às mudanças na vegetação ao longo do Holoceno tardio, observou-se um controle climático, mas, sobretudo edáfico, uma vez que, essa área é sazonalmente alagada, fato este favorecido pela natureza argilosa dos horizontes superficiais dos solos, das altas taxas de pluviosidade como estação chuvosa prolongada (em média 6 meses) e da extensivamente planura do terreno. Assim, fatores como a duração das inundações e das condições de hidromorfismo decorrentes são responsáveis por controlar a instalação de florestas e/ou savanas que caracterizam a região. Dessa maneira, a regência de um clima mais seco com o encurtamento das estações chuvosas que causa a elevação do lençol freático pode representar condições favoráveis ao desenvolvimento e avanço da floresta. Por outro lado, um clima mais úmido com estações chuvosas mais prolongadas causaria inundações, abrangendo áreas maiores e os solos permaneceriam saturados por períodos mais longos, fato este que desfavorece o avanço da floresta e possibilita a manutenção ou mesmo expansão das savanas, especialmente aquelas dominadas por gramíneas sobre a região. No entanto, como já mencionado, as condições climáticas nessa região, controlam a expansão das formações florestais, porém, não são os únicos fatores protagonistas nesse processo, uma vez que, a presença da *wetland* decorrente da topografia baixa e plana, dos solos argilosos e da saturação dos solos e sedimentos se constitui um impedimento efetivo para instalação de florestas. Outro fator responsável pela substituição da floresta de galeria por savana arbórea, por exemplo, é o abandono de canais, fato observado atualmente na região, onde é possível trilhar por dentro desses antigos leitos dos rios, muitos desses locais já enriquecidos em espécies como a *Curatella americana* e *Byrsonima sp* entre outras. A Ilha do Bananal que se insere geologicamente no contexto da Bacia do Bananal e é banhada por umas das maiores bacias hidrográficas do território brasileiro (Araguaia-Tocantins), configura-se como uma paisagem extremamente importante para a compreensão da dinâmica das *wetlands* e também das áreas de ecótonos floresta-savana, durante o Quaternário, enquadrando-se nas duas situações. A parte norte da ilha onde foi desenvolvida esta pesquisa ainda carece de estudos. Entretanto, de um modo geral, esta pesquisa trouxe contribuições para entender a dinâmica funcional dessa paisagem frente as mudanças climáticas e ambientais ocorridas na região, bem como para ampliar o conhecimento sobre as paisagens de transição entre a floresta amazônica e as savanas, cujo conhecimento paleoambiental ainda é restrito.

Palavras-chave: Ecótono floresta-savana. *Wetlands*. Dinâmica da paisagem. Ilha do Bananal.

ABSTRACT

Paleoclimatic and paleoenvironmental studies aim to understand processes of global landscapes evolution, contributing to the reconstitution of the quaternary landscapes and the climatic and environmental changes to which were submitted during this period of the earth's geological history. Some studies in the Amazon, but especially those led in regions more sensitive, such as ecotones and wetlands, show that these areas underwent various paleoecological changes during the Pleistocene and Holocene. The present study was led in the Bananal Island region located in a transition area between the Amazon and Cerrado biomes. The Bananal Island, considered by many authors the largest river island in the world, occupies an area of about 20,000 km² and is located between the middle course of the Araguaia River and its tributary by the right branch, the Javaés River, in the state of Tocantins. The northern portion of the island stands out for its complex mosaic of geomorphological features (marginal dikes, abandoned meanders, paleochannels and lakes) and contrasting geobotanical features (forests and savannas), such that reflect the intense hydrodynamic activity in this region. Seasonally it is flooded by rainwater and rising water table, so it is considered a seasonal wetland. The aim of this work is to understand the dynamics of this landscape, based on the mineralogical and chemical composition of soils and sediments and the palynological composition study of lacustrine sediments of this region. Therefore, samples of ravines exposed on the banks of Javaés and Araguaia rivers, sandy bars and lake sediments were collected. Soils and sediments were analyzed for their mineralogy by X-ray diffraction and chemistry by ICP-AES and ICP-MS. The sediment cores collected in 2 distinct lakes, one located in the interior of the northern portion of Bananal Island (Quatro Veados Lake) and the other located on the surroundings of the Javaés River (Mata Verde Lake) were analyzed for their palynological content and dated by AMS ¹⁴C. The results of this research are presented in 3 articles: the first one treaties about the mineralogy and geochemistry of the soils and sediments of Bananal Island, the bars and ravines along the Javaés River. Therefore, it discusses about the diversified nature of the minerals and chemical elements that the strata and horizons of these surface covers are composed, pointing to geological provenance, as well as the geochemical processes involved in the current and past dynamics of this landscape. The second article presents the dynamics of vegetation over the last 2000 years AP in the interior of Bananal Island and discusses its relationship with local climatic and edaphic conditions. The third article, on the other hand, describes the vegetational succession occurred in the last 400 years AP, based on the pollen record of sediments from a lake located on the Bananal Island surrounds, and analyzes the modern pollen spectrum in the region. The results obtained through this work present a highly diversified landscape in terms of its geoforms, sedimentary and pedogenetic coverings and geobotanical aspects resulting from the various moments of its geological history and which even today is dynamic and intriguing. The soils and sediments of this landscape are varied as their textures (sequences of sandy and clay materials) and mineralogical and chemical compositions, where primary minerals and derivatives of varied degrees of chemical weathering coexist in the same profile,

showing moments of contrasting climatic conditions. Even, nowadays it is possible to observe in situ environments with variable dynamics (erosive, sedimentary, pedogenetic, etc.), as well as, several geochemical processes, such as those of oxidation of sandy bars and ravines and also the reductive processes of these ferruginized sands (sometimes, mistakenly confused for lateritic profiles), due to contact with organic acids produced by forest cover and hydromorphic conditions such as they are subjected. Regarding vegetation changes throughout the late Holocene, climate control was observed, but especially edaphic, since this area is seasonally flooded, a fact favored by the clayey nature of the soil surface horizons, the rainfall high rates as a prolonged rainy season (on average 6 months) and extensively flat terrain. Thus, factors such as flood duration and hydromorphism conditions stemming are responsible for controlling the installation of forests and/or savannas that characterize the region. So, the regency of a drier climate with the shortening rainy seasons that causes the water table rise, may represent favorable conditions for the development and advancement of the forest. On the other hand, a wetter climate with longer rainy seasons would cause flooding, covering larger areas and the soils would remain saturated for longer periods, a fact that undermines the advancement of the forest and allows the maintenance or even expansion of savannas, especially those dominated by grasses over the region. However, as already mentioned, the climatic conditions in this region control the expansion of forest formations, but they are not the only protagonists in this process, since the presence of wetland due to low and flat topography, clay soils, soil and sediment saturation is an effective impediment to the forest installation. Another factor responsible for replacing for gallery forest by savanna's tree, for example, is the channel abandonment, a fact that is currently observed in the region, where it is possible to tread inside these old river beds, many of these places already enriched with species such as *Curatella americana* and *Byrsonima sp* among others. The Bananal Island, which is geologically inserted in the context of the Bananal Basin and is bathed by one of the largest hydrographic basins in the Brazilian territory (Araguaia-Tocantins), sets up as an extremely important landscape for understanding the wetlands dynamics and also from the savanna-forest ecotone areas during the Quaternary, since, it fits in both situations. The northern part of the island where this research was developed still needs studies. However, in general, this research has contributed to understand the functional dynamics of this landscape in face of the region climate and environmental changes, as well as to increase the knowledge about the transition landscapes between the Amazon forest and savannas, such as the paleoenvironmental knowledge is still restricted.

Key-words: Forest-savanna Ecotone. Wetlands. Landscape dynamics. Bananal Island.

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LISTA DE SIGLAS

CNPq - Conselho Nacional de Desenvolvimento Científico e Tecnológico

CPRM - Companhia de Pesquisa de Recursos Minerais

GMGA - Grupo de Mineralogia e Geoquímica Aplicada

IBAMA-TO - Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis do Tocantins

ICB - Instituto de Ciências Biológicas

IG - Instituto de Geociências

LADIC - Laboratório de Dinâmica Costeira

LAMIGA - Laboratório de Mineralogia, Geoquímica e Aplicações

LCM - Laboratório de Caracterização Mineralógica

SISBio - Sistema de Autorização e Informação em Biodiversidade

UFPA - Universidade Federal do Pará

UFT - Universidade Federal do Tocantins

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1 INTRODUÇÃO

O interesse pela história paleoclimática e paleoambiental das paisagens globais em especial daquelas que atualmente estão sob clima tropical cresceu nas ultimas décadas. Nesse contexto, os estudos visam entender os processos de evolução dessas paisagens sob os climas que regem tais processos. Entre estes estudos estão aqueles de caráter sedimentológico (Turcq *et al.* 1993), geomorfológico (Valente *et al.* 2013), isotópico (Desjardins *et al.* 1996, Gouveia *et al.* 1997) e palinológico (Absy *et al.* 1991, Behling 2002, Behling & Costa 2004), os quais têm contribuído para a reconstituição das paleopaisagens quaternárias e das mudanças climáticas e ambientais a que foram submetidas ao longo deste período.

Na região amazônica as mudanças ocorridas no Pleistoceno, e em especial no Holoceno, são observadas tanto em regiões de **florestas** (Soubiès *et al.* 1991, Sifeddine *et al.* 1994, Van der Hammen & Absy 1994, Thompson *et al.* 1995, Colinvaux *et al.* 1996, Haberle & Maslin 1999, Behling *et al.* 2001, De Oliveira & Curtis 2001, Bush *et al.* 2004) como em regiões de **cerrados** ou **savanas** (Freitas *et al.* 2001, Pessenda *et al.* 2001, Rodríguez *et al.* 2005, Hermanowski *et al.* 2012, Meneses *et al.* 2013).

Os vários eventos paleoclimáticos e a Zona de Convergência Intertropical influenciaram nos registros paleoecológicos de modo que, apesar dos poucos estudos realizados, já é possível inferir que o clima não foi constante durante o Holoceno na região Neotropical (Irion *et al.* 2006), embora os autores não tenham notado uma mudança substancial em termo de paisagem durante esse período. Diferentemente do que Absy *et al.* (1991) perceberam na região da Serra dos Carajás, na qual houve uma expansão da savana causado por um período mais seco. Irion *et al.* (2006) concluem ainda que regiões ecotonais são sensíveis a tais mudanças paleoclimáticas e podem exibir uma mudança vegetacional exagerada. Dessa forma, alguns estudos afirmam que houve poucas mudanças na paisagem, contudo, outros, principalmente os de regiões mais sensíveis, como ecótonos e *wetlands*, mostram que estas áreas sofreram várias mudanças paleoecológicas durante o Pleistoceno e Holoceno.

Apesar dos crescentes estudos palinológicos realizados em *wetlands*, ainda existe certa dificuldade na interpretação dos resultados, devido à influência de vários fatores, principalmente porque a dinâmica dos sistemas fluviais causa, geralmente, deposição irregular de sedimentos e grãos de pólen nesse tipo de local como afirmam Berrío *et al.* (2001) em seu estudo de uma *wetland* na Colômbia. Entretanto, nesta e em outras *wetlands* no Quênia (Johnson *et al.* 2009), na China (Yang *et al.* 2008) e em Marabá-PA (Guimarães *et al.* 2013) foi possível reconhecer mudanças nos registros paleoecológicos causadas por eventos

paleoclimáticos. Neste sentido, para que haja uma melhor interpretação dos dados é necessário a união de diversas metodologias como tem sido usado por alguns autores (Berrío *et al.* 2001, Irion *et al.* 2006, Johnson *et al.* 2009, Guimarães *et al.* 2013) que têm desenvolvido estudos nesse tipo de ambiente.

A Ilha do Bananal considerada uma *seasonal wetland* (Valente 2007), é parte do Parque Nacional do Araguaia criado em 31 de dezembro de 1959, pelo decreto Nº 47.570 do governo federal, compreendendo a totalidade da ilha (Brasil 1981). Após algumas reformulações de limite, hoje o Parque Nacional do Araguaia compreende apenas o norte da Ilha do Bananal, abrangendo parte dos municípios de Pium (a norte) e Lagoa da Confusão (ao sul), ocupando uma área de 5.623,12 Km², de acordo com a última alteração no Decreto 84.844 de 1980.

Com uma área de 20.000 km², a Ilha do Bananal (Fig. 1), é considerada por diversos autores como a maior ilha fluvial do mundo (Borma *et al.* 2009, Dias *et al.* 2011, Devi 2012). A mesma está situada no território do Estado do Tocantins, na porção norte da Bacia do Bananal que por sua vez, é de idade Quaternária e está situada na região do médio rio Araguaia com aproximadamente 106.000 km². Segundo Valente (2007) a Bacia Bananal é uma das mais importantes bacias sedimentares intracratônicas do Quaternário da América do Sul e preserva registros de condições paleohidrológicas.

Apesar da importância geográfica e ecológica da Ilha do Bananal, considerada um dos últimos refúgios naturais da fauna e da flora para a região do Cerrado (Valente *et al.* 2013), poucos trabalhos de uma forma geral têm sido realizados nessa região, destacando-se neste contexto os trabalhos de cunho geomorfológico de Valente & Latrubesse (2012) e Valente *et al.* (2013). Com relação aos estudos da sua paleovegetação, cabe mencionar o trabalho de Behling (2002), que analisou o conteúdo palinológico de sedimentos coletados na lagoa da Confusão, situada no município homônimo, nos arredores da Ilha do Bananal, cujo registro permitiu reconhecer as mudanças na vegetação ocorridas durante o Pleistoceno Tardio e o Holoceno. No interior da ilha, há um único registro pontual obtido por Mendes *et al.* (2015) que através da palinologia permitiu reconstituir as mudanças na vegetação e no ambiente no último milênio.

Na verdade, ainda são raros os estudos que tratam da história paleoambiental e paleoclimática e da evolução de paisagens dessa região, apesar deste apresentar diversas paisagens com distintas formações vegetais que abrangem desde florestas tipo amazônica, cerrados até babaçuais entre outros. Portanto, pouco se conhece sobre a história paleoambiental

e paleoclimática destas formações vegetais e das paisagens desta área da Amazônia ocorrentes nesta região ao longo do Pleistoceno e Holoceno.

Diante da importância geográfica e ecológica dessa região que é de grande interesse científico, já que é uma área de transição entre o bioma Cerrado e Amazônico e pouco conhecida no que diz respeito aos processos geográficos e ecológicos ocorrentes nestas áreas (Brasil 1981), e ainda da carência de dados que contribuam para elucidar sua história paleoclimática e paleoambiental e dinâmica atuais de suas formações vegetais e coberturas pedológicas no contexto do bioma Cerrado e Amazônico, este estudo ganha importância nessa abordagem multidisciplinar que integrará dados sobre a dinâmica da vegetação e sua relação com o substrato pedológico e aspectos hidrográficos ao longo do Quaternário tardio. Dessa maneira, a presente proposta pretende ampliar espacial e temporalmente as informações obtidas por Mendes *et al.* (2015) e assim, contribuir para o entendimento da origem e evolução das paisagens do Tocantins e das mudanças ambientais e climáticas no contexto do Bioma Cerrado e Amazônico.

1.1 OBJETIVOS

1.1.1 Geral

Entender a dinâmica da paisagem norte da Ilha do Bananal e adjacências com base no estudo da composição mineralógica e química dos solos e sedimentos de barrancos e barras ao longo dos rios Javaés e Araguaia e dos registros palinológicos de sedimentos lacustres encontrados na região durante o Holoceno.

1.1.2 Específicos

- Identificar a natureza granulométrica, a composição mineralógica e química dos solos e sedimentos, a fim de entender os processos de sedimentação e sua contribuição para a evolução desses sedimentos;
- Compreender as mudanças paleoclimáticas, hidrológicas e vegetacionais locais através de estudos palinológicos de sedimentos lacustres ao longo do Holoceno;
- Avaliar aspectos da produção, dispersão e deposição de grãos de pólen e esporos atuais (chuva polínica atual) com vistas a subsidiar o entendimento dos processos de precipitação e acumulação de palinomorfos nos sedimentos;
- Identificar se houve interferência da atividade antrópica na dinâmica da vegetação ao longo do tempo a serem analisados e de que maneira ocorreu;
- Precisar a cronologia das mudanças ambientais possivelmente ocorridas na área estudada.

2 CARACTERIZAÇÃO REGIONAL DA ÁREA DE ESTUDO

2.1 LOCALIZAÇÃO GEOGRÁFICA

A área de estudo está localizada na porção norte da Bacia Bananal, entre as coordenadas 9°59' e 9°59' S e 50° 01' e 50°12' O, onde está localizada a Ilha do Bananal (Fig. 1). Esta área pertence ao município de Pium, estado do Tocantins. O acesso é pela rodovia estadual TO-080, saindo de Palmas no sentido oeste até Paraíso, onde segue-se no sentido noroeste, pela mesma rodovia, até o trevo com a rodovia estadual TO-374, próximo ao município de Marianópolis, segue-se então sentido sul até o trevo Café da Roça, e pega-se a saída sentido oeste seguindo-se a mesma rodovia (neste ponto a rodovia não é pavimentada) cerca de 54 Km, até a sede do Centro de Pesquisas Canguçu - UFT. No local, o acesso à Ilha do Bananal é realizado através de barco motorizado 2T.

2.2 ASPECTOS CLIMÁTICOS REGIONAIS

Em termos climáticos, o estado do Tocantins, apresenta ampla oscilação de leste a oeste, entre os climas Subúmido Seco, Úmido Subúmido e Úmido, conforme a classificação de Thornthwaite-Mather (Fig. 2). A precipitação média anual varia de 1.400 mm, na região sudeste do Estado, chegando a 2.200 mm na região da APA “Ilha do Bananal”, enquanto que a temperatura média do ar oscila de 26 a 28 °C (Dias *et al.* 2008). São indicados 5 tipos climáticos para o Estado, sendo eles (Embrapa 1997):

- B₂rA'a' - clima úmido, com pequena ou nula deficiência hídrica, megatérmico, evapotranspiração potencial média anual de 1.700mm e concentração da evapotranspiração potencial no verão em torno de 30% (três meses consecutivos com temperatura mais elevada).

- B₁wA'a' - clima úmido, com moderada deficiência hídrica no inverno, megatérmico, evapotranspiração potencial apresentando uma variação média anual entre 1.400 e 1.700mm e, em média 28% da evapotranspiração potencial no verão (três meses consecutivos com temperatura mais elevada).

- C₂rA'a' - clima úmido subúmido, com pequena deficiência hídrica, megatérmico, evapotranspiração potencial média anual de 1.600mm e concentração da evapotranspiração potencial no verão em torno de 26% (três meses consecutivos com temperatura mais elevada).

- C₂wA'a' - clima úmido subúmido, com moderada deficiência hídrica no inverno, megatérmico, evapotranspiração potencial média anual de 1.500mm e concentração da evapotranspiração potencial no verão em torno de 28% (três meses consecutivos com temperatura mais elevada).

- C₁dA'a' - clima subúmido seco, com moderada deficiência hídrica no inverno, megatérmico, evapotranspiração potencial média anual de 1.300mm e concentração da evapotranspiração potencial no verão em torno de 28% (três meses consecutivos com temperatura mais elevada).

Sobre a precipitação atual, Irion *et al.* (2016) encontraram médias de 1200 a 1900 mm anualmente ocorrida principalmente entre os meses de setembro a maio (Fig. 3).

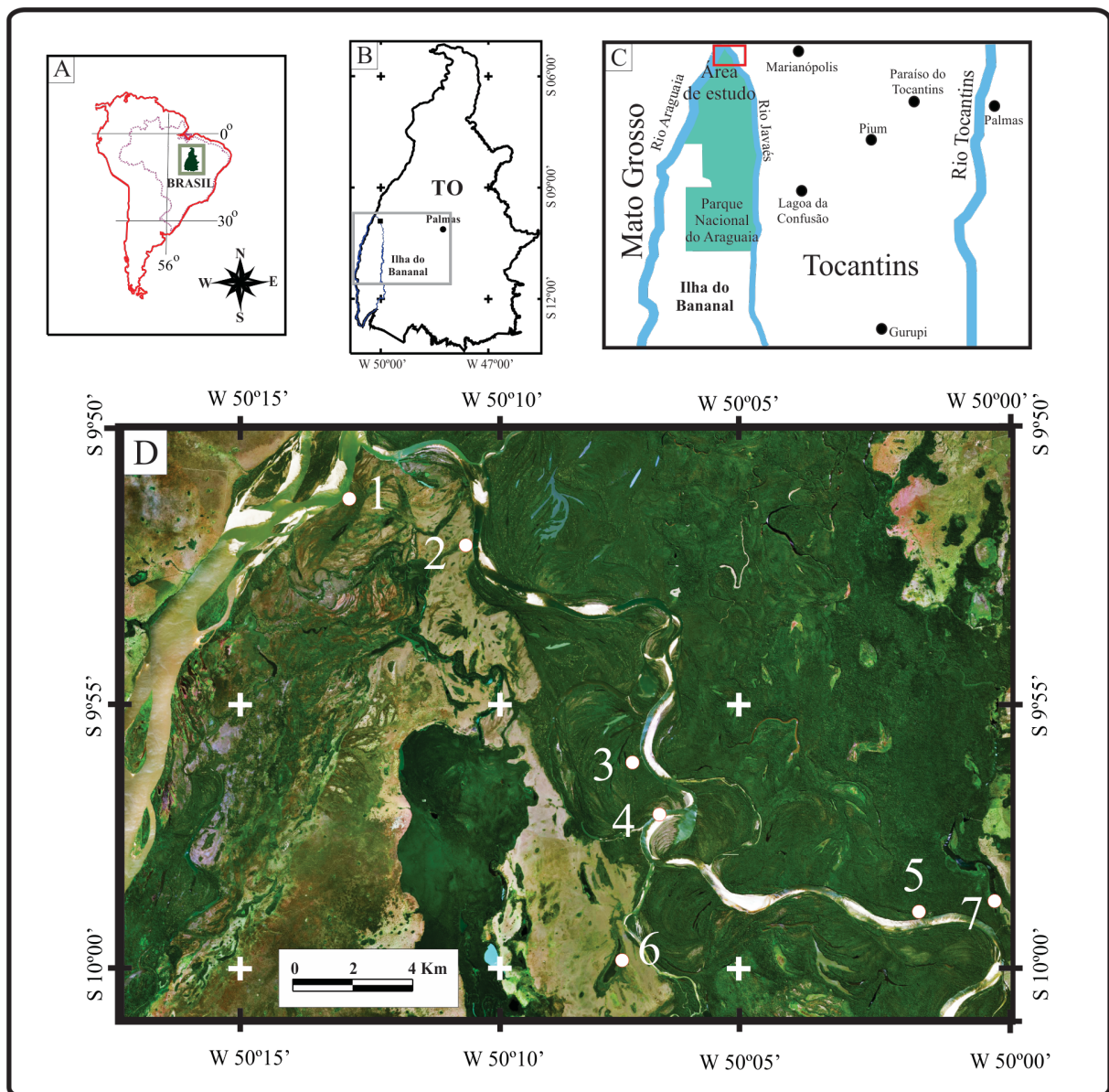


Figura 1- Mapa de localização da Bacia Bananal e da área de estudo na porção Norte da Ilha do Bananal, mostrando a localização geográfica das cinco seções e dos dois lagos estudados. A. Localização geográfica do Tocantins no contexto da América do Sul. B. Localização geográfica da Ilha do Bananal. C. Detalhe do Parque Nacional do Araguaia localizado na porção norte da Ilha do Bananal, e quadrado vermelho indicando a área de estudo. D. Localização dos pontos de coleta: 1. Barranco colapsado (Collapsed Ravine - PDZ); 2. Barreira Branca (White Barrier - BB); 3. Praia do Coco (Coco Beach - Coco); 4. Praia Comprida (Long Beach - C); 5. Porto Canguçu (Canguçu Harbor - Cang); 6. Lago Quatro Veados (L4V); 7. Lago da Mata Verde (LMV).

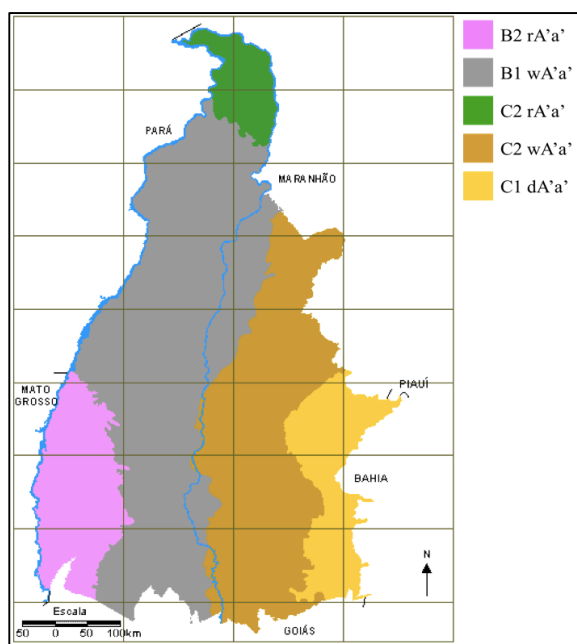


Figura 2- Distribuição dos tipos climáticos ocorrentes no estado do Tocantins segundo a classificação de Thornthwaite-Mather (Adaptado de Embrapa 1997).

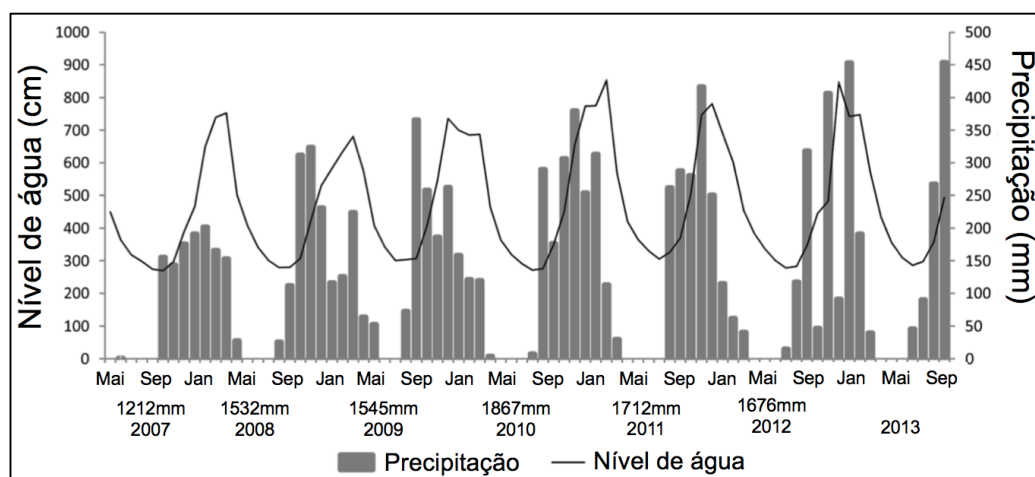


Figura 3- Precipitação mensal dos anos de 2007 a 2013, na região município de São Félix do Araguaia e flutuação do nível de água do Rio Araguaia (Adaptado de Irion *et al.* 2016, dados da Agência Nacional de Águas, ANA).

2.3 COBERTURA VEGETAL

Com relação à vegetação da Ilha do Bananal, Eiten (1985) enfatiza que há um predomínio de uma área de transição entre o Cerrado e a Floresta Amazônica considerada um ecótono (Odum 1976). Segundo Brasil (1994), ocorre na região atualmente o predomínio de campos, aparecendo fragmentos de cerrado e, ou, cerradão, matas ciliares e, em algumas partes, outras formações florestais na forma de ilhas. As formações campestres, conhecidas na região pelo nome de “varjões”, estão localizadas nas partes mais baixas e são totalmente inundadas pelas cheias dos rios durante o período das chuvas em torno de cinco meses ao ano. Nas cotas mais elevadas surgem formações vegetais típicas de mata seca, cerradão e cerrado.

De acordo com Brasil (1981) a unidade morfológica da região caracteriza-se por uma planície flúvio-lacustre, com inúmeros lagos, lagoas e canais intermitentes e que durante a estação chuvosa, por precipitação de águas locais, podendo ser classificada como uma *seasonal wetland* (Valente 2007). O relevo dessa região é em toda a sua extensão praticamente plano, com pouquíssimos morros residuais isolados (Mileski 1994).

2.4 CONTEXTO GEOLÓGICO E GEOMORFOLÓGICO

Situada no médio rio Araguaia, a Bacia Bananal consiste de uma bacia sedimentar quaternária bem desenvolvida, com aproximadamente 106.000 Km² (Fig. 4). Segundo Valente (2007) a Bacia Bananal é uma das mais importantes bacias sedimentares intracratônicas do Quaternário da América do Sul e preserva um bom registro de condições paleohidrológicas. Os depósitos do Quaternário da Formação Araguaia, de no máximo 170-320 m de espessura são compostos por compostos por sedimentos incolidados a cololidados, amarelados a amarronzados, de silte e areias ferruginizados (Araújo & Carneiro 1977).

Na porção norte desta bacia sedimentar, no território do Estado do Tocantins, ocorre a Ilha do Bananal, com uma área de 20.000 Km², considerada por diversos autores como a maior ilha fluvial do mundo (Borma *et al.* 2009, Dias *et al.* 2011, Devi 2012). A planície desta ilha é inundada temporariamente, durante a estação chuvosa, por precipitação de águas locais, que pode ser classificada como *seasonal wetland* (Valente 2007).

2.4.1 Formação Araguaia - Bacia Bananal

A Bacia do Bananal, representada pelos sedimentos aluvionares do Quaternário da Formação Araguaia, é uma superfície plana de baixa declividade com uma área próxima a 106.000 Km².

Barbosa *et al.* (1966) executou o trabalho pioneiro nos estudos da Formação Araguaia, e a definiram como sendo formada por uma sucessão de sedimentos continentais que são iniciados por um conglomerado basal (com espessura de até 3m) coberto por areias amareladas ou acastanhadas, siltosas, ferruginosas, com cores variadas e texturas, cololidadas a não cololidadas.

Já Pena *et al.* (1975), com um furo de quase 50m de profundidade na Bacia Bananal, detectaram que a Formação Araguaia possui 45,5m de espessura com intercalações métricas a decimétricas de areias, siltes e argilas. Com sedimentos arenosos predominantes entre as texturas grosseiras. Sedimentos estes que apresentam comumente uma coloração amarela a

avermelhada com uma variação de branco a cinza. No perfil há ainda um intervalo (25-29m de profundidade) com um nível de areia fina a média com intercalações de argila e de sedimento arenoso endurecido enriquecido com óxido de ferro.

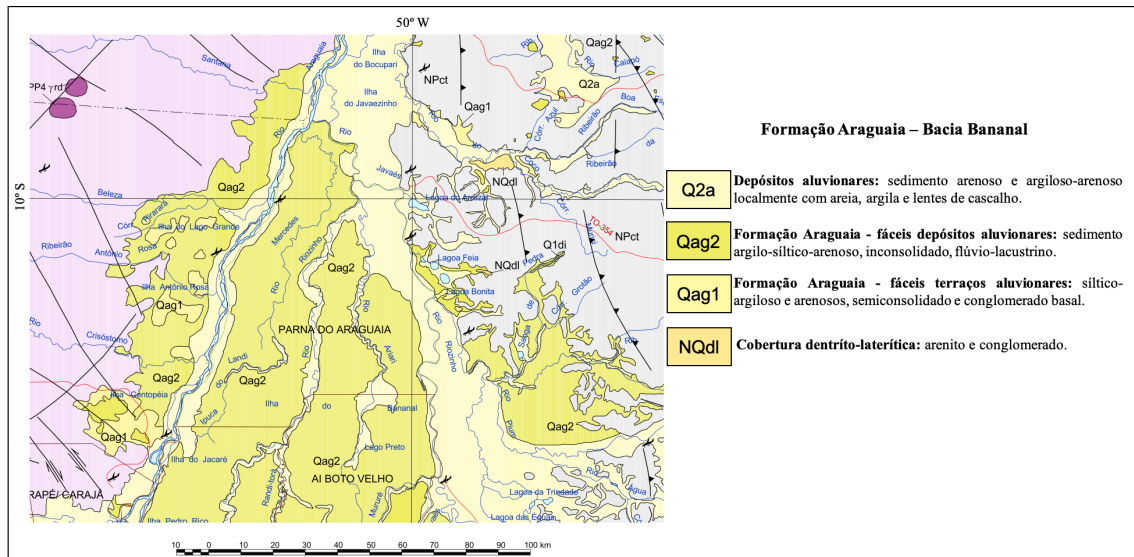


Figura 4- Mapa geológico da região norte da Ilha do Bananal (adaptado de CPRM 2004).

Valente & Latrubesse (2007) apontaram que a Formação Araguaia é constituída em sua porção norte, na margem do Rio Araguaia na Ilha do Bananal, por um estrato superior de argila cinza-claro de até 3 m que se sobrepõe a estratos sedimentares arenosos de finos a texturas médias com intercalações de argila, também visualizaram que camadas de areia endurecida enriquecida em óxido de ferro de coloração avermelhada é comum.

Valente (2007) assume a presença de crostas lateríticas Terciárias a Quaternárias na região da Ilha do Bananal, como produto de intenso intemperismo composto por assembleias minerais com ricas concreções em óxidos de Fe-Al. Essas crostas lateríticas se desenvolveram em um clima mais seco que o atual.

2.4.2 Contexto Geomorfológico

De acordo com Brasil (1981) a unidade morfológica da região caracteriza-se por uma planície fluviolacustre, com inúmeros lagos, lagoas e canais intermitentes.

Irion et al. 2016 separa três unidades de inundação tais que são: planície de inundação recentemente ativa (*active-recent floodplain*), planície de inundação paleo-ativa (*active paleo-floodplain*), planície de inundação paleo-inativa (*inactive paleo-floodplain*).

Os depósitos holocênicos formam a planície de inundação recentemente ativa (Fig. 5 e 6), e acompanham os canais do rio Araguaia e seus principais afluentes. As características hidrogeomorfológicas destes depósitos incluem morros, vales, canais abandonados, *oxbows lakes* (lagos tipo ferradura), com alta relação relevo-energia (Latrubesse *et al.* 2009).

Com relação a geomorfologia, é bem caracterizada pela ocorrência de várias feições que são referidas por nomes locais específicos, como *Ipucas*, *Esgotos*, *Murunduns* e *Monchões*. As Ipucas são pequenas depressões circulares ou alongadas que são periodicamente alagadas, geralmente com um lago permanente no centro, com cobertura vegetal arbustiva a arbórea. Esgotos são canais de drenagem sazonais que transportam água dos campos cerrado para pequenos rios vizinhos, remanescentes de antigos sistemas de drenagem. Murunduns (cupinzeiros) são morrinhos residuais de até 1,20 m de altura e com uma área de superfície de 1 a 15 m² que alcançam acima do nível médio de água, localizados nos campos cerrados sazonalmente alagados, que foram construídos por cupins para escapar da água no período de inundação. Os Monchões se estendem de 1 a 1,5 m acima do nível máximo de inundação e são remanescentes de terraços paleo-fluviais e paleo-veios. Eles se referem aos monchões como a planície paleo-inundável inativa porque eles consistem em paleo-sedimentos, mas não são inundados, proporcionando assim macro-habitats permanentemente terrestres dentro da planície de inundação. A área total dos monchões no interior da planície paleo-inundável é pequena. Remanescentes da planície inativa de paleo-inundação também ocorrem nas bordas de várzea.

De acordo com SEPLAN/TO (2008), em relação ao solo, a região está classificada como formada por depósitos aluvionares, de formação recente, holocênica, com sedimentação arenosa ativa, em formação de cotas mais baixas, apresentando solos do tipo gleissolos, nos fragmentos naturais de florestas inundáveis, e plintossolos, no restante da região. Estes são solos pouco profundos e estão sob forte influência do lençol freático.

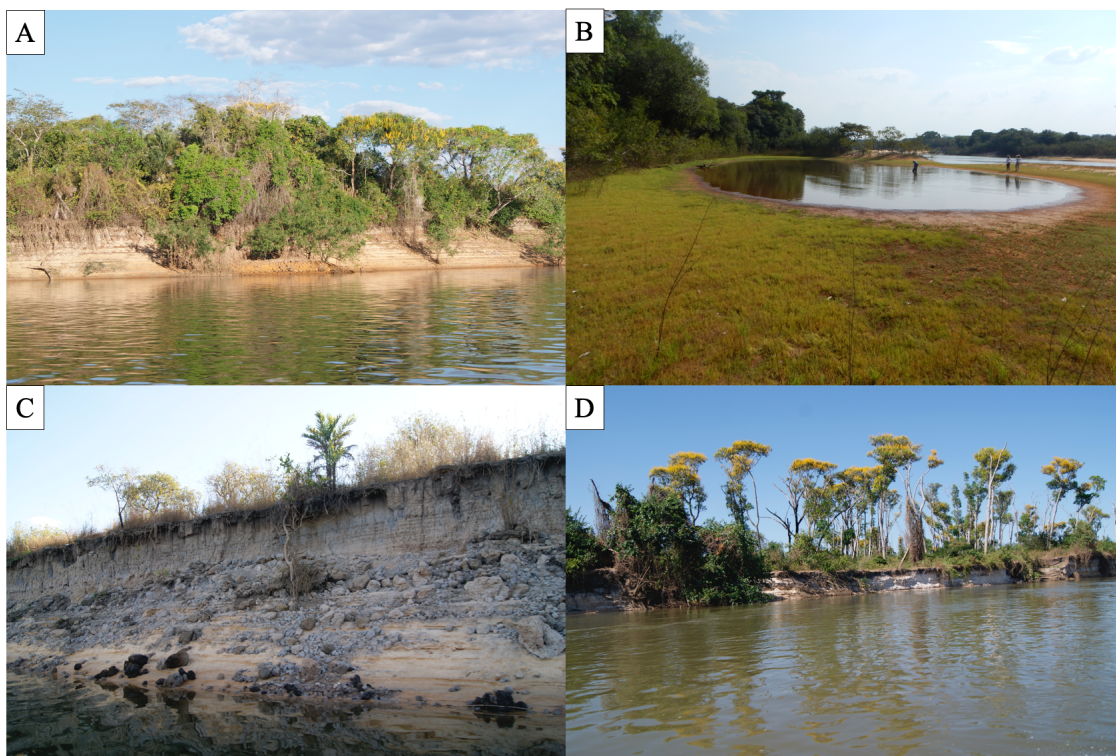


Figura 5- Aspecto das diversas paisagens da Ilha do Bananal: A. Barra arenosa vegetada por floresta; B. Corpo aquoso remanescente do período de cheias formado entre barras de canal; C. Barranco exibindo paleobarra arenosa e no topo horizonte pedológico tipo glei vegetado por savana com estrato herbáceo dominante e árvores esparsas; D. Planície arenosa inundável exibindo floração da pioneira *Vochysia divergens*.



Figura 6- Aspecto das diversas paisagens da Ilha do Bananal e arredores: A. Mosaico vegetacional da Ilha do Bananal, aos arredores do Lago Quatro Veados, mostrando a planura do terreno; C. Canal intermitente do lago da Mata Verde em período de seca; D. O mesmo canal intermitente em período de cheia.

3 MATERIAIS E MÉTODOS

A primeira etapa de campo foi realizada em agosto de 2015, com a coleta de solos e sedimentos. Uma segunda etapa foi realizada em outubro de 2016 para coleta de sedimentos lacustres, e armadilhas para coleta de grãos de pólen (*artificial pollen traps*) foram colocadas, e uma nova etapa de campo foi realizada em janeiro de 2018 para a coleta das armadilhas. Para a realização deste trabalho foi necessário a concessão de uma autorização cedida pelo órgão fiscal, Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis do Tocantins (IBAMA-TO), através do Sistema de Autorização e Informação em Biodiversidade (SISBio) online: <http://www.icmbio.gov.br/sisbio/>, sob o número 49085/1.

3.1 COLETAS

As amostras de solos e sedimentos foram coletadas com auxílio de pá e espátula, nos barrancos expostos ou nas barras de praias (Fig. 7), e acondicionados em sacos plásticos, com informações sobre o número/tipo de amostra/primeiras descrições, local (coordenadas geográficas) e data de coleta. Todas as amostras coletadas estão geograficamente indicadas na figura 8, e dispostas por perfil ou lago na tabela 1.

Para as sondagens, foi utilizado um trado manual tipo Russo, com coleta a cada 50 cm, com lâmina d'água de até 20 cm. Após a coleta, as amostras foram acondicionadas em meias-seções de PVC e devidamente identificadas. Além disso, foi utilizado o método amostragem com pistão (Colinvaux *et al.* 2005), para coleta com lâmina d'água acima de 1 m. Foram utilizados 2 botes infláveis, que acoplados formam a base flutuante de uma plataforma de madeira, posicionada no meio do lago, e estabilizada por uma âncora. Então um tubo amostrador, conectado a um sistema de hastes, e o pistão que é mantido em posição (dentro do tubo amostrador) por um cabo de aço flexível, cujo o final é preso na plataforma por uma chave de pressão modificada, foram posicionados na plataforma. Após, o tubo amostrador e o pistão foram empurrados simultaneamente até que a profundidade de amostragem foi alcançada; nesse momento a haste foi puxada para cima. O cabo do pistão foi, então, preso na plataforma, não permitindo que o pistão se aprofunde nos sedimentos. Assim, foi medido, com fita métrica, o tamanho do deslocamento do cabo (conectado ao pistão), para se conhecer o tamanho do testemunho coletado. As amostras permaneceram acondicionadas no tubo amostrador e foram devidamente identificadas.

A fim de se realizar análises de chuva polínica atual, foram colocadas armadilhas, que consistiam de tubos Falcon de 50 mL, devidamente identificados, contendo fibras de raiom e 10 mL de glicerina no fundo, recoberto por uma tela de *nylon* presa ao tubo, afim de se impedir a penetração de folhas e outros fragmentos vegetais. Tais armadilhas foram amarradas em troncos de 10 a 20 cm de diâmetro, em posição vertical à 1,8 m de altura. Após um ano, os coletores artificiais foram recuperados. Onde não foi possível a colocação de coletores artificiais, foram coletadas amostras lacustres superficiais, e amostras de solo superficial, contemplando todas as fitofisionomias.



Figura 7- Amostragem de chuva polínica, seta vermelha indicando o coletor artificial.

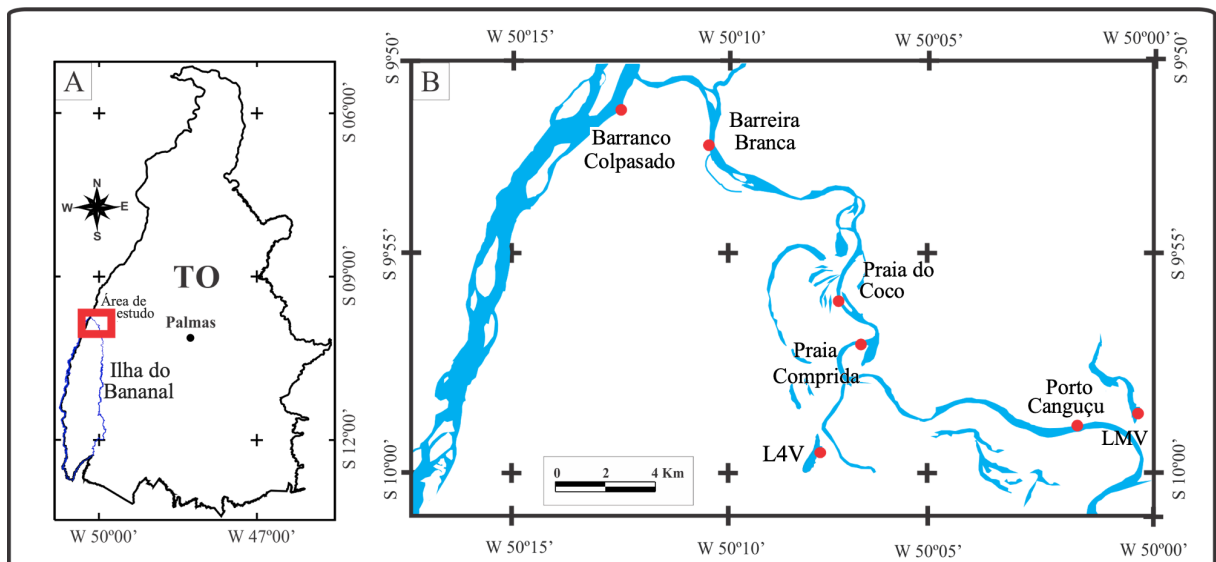


Figura 8- Mapa de localização da área de estudo. A. Mapa do Tocantins mostrando a disposição geográfica da Ilha do Bananal, quadrado vermelho indicando a área de estudo. B. Detalhe dos locais de amostragem.

Tabela 1- Perfis coletados, número do perfil, quantidade de amostras, profundidade dos perfis, análises/metodologias que foram realizadas e localização dos perfis.

Perfil	Nº	Amost.	Profund. (cm)	Análise/ Metodologia	Localização
Barranco colapsado (Collapsed Ravine - PDZ)	1	Pdz1 a Pdz6	250	Granulometria, mineralógica (DRX) e ICP-AES e ICP-MS.	9°51'28.2"S 50°12'43.9"O
Barreira Branca (White Barrier - BB)	2	BB1 a BB10	470		9°52'28.8"S 50°10'21.6"O
Praia do Coco (Coco Beach - Coco)	3	Coco1 a Coco9	513		9°55'57.7"S 50°7'20.7"O
Praia Comprida (Long Beach - C)	4	C1, C2 e C3		Infravermelho, MEV, Ferro total e amorfo por Espectrofotometria.	9°57'05.5"S 50°7'04.6"O
Porto Canguçu (Canguçu Harbor - Cang)	5	Cang1 a Cang7	590	Granulometria, mineralógica (DRX) e ICP-AES e ICP-MS.	9°58'48.2"S 50°2'13.4"O
Testemunho Lago 4 Veados	6	L4V	50	Palinológica, granulométrica	9°59'30.8"S 50°7'45.1"O
Testemunho Lago da Mata Verde	7	LMV	63		9°58'41.8"S 50°1'02.1"O

3.2 ANÁLISES GRANULOMÉTRICAS

As análises granulométricas das amostras consistiram na separação das frações areia, silte e argila, através de peneiramento em meio úmido conforme procedimentos adotados pela Embrapa (1997). A granulometria das amostras com menor índice de areia foi realizada por difração a laser com auxílio do Granulometro Fritsch modelo Analysette 22, em que 2g de amostras foram colocadas em um pote de polietileno, acrescentou-se água destilada e três gotas de um dispersante químico (pirofosfato de sódio - $\text{Na}_4\text{P}_2\text{O}_7$) para auxiliar na desfloculação e levadas a análise. O tratamento dos resultados foi realizado com auxílio do software SYSGRAN 2.4 adotando-se a classificação de Folk & Ward (1957). Nos grãos da fração areia, avaliou-se o grau de arredondamento e esfericidade, por comparação visual com as tabelas de classes de arredondamento e esfericidade apresentadas por Suguio (2003).

3.3 ANÁLISES MINERALÓGICAS

As análises para determinação dos minerais constituintes foram realizadas por difração de raios-X (DRX) em amostra total, método do pó em lamina orientada. Os registros foram realizados no intervalo de 5° a 65°, com leituras de 2θ para as amostras totais pulverizadas. As amostras pulverizadas foram colocadas em amostradores pelo método “front load” e analisadas com o Difratorômetro da Bruker modelo D2 Phaser, com anodo de Cu ($\lambda_{\text{K}\alpha 1} = 1.5406\text{\AA}$).

Para a identificação dos argilominerais foi utilizada a fração argila, cerca de 100g de cada amostra foram pesadas (balança Celtac 0,01g de precisão), foram desagregadas sem pulverização com almofariz e pistilo de porcelana, colocadas em Becker de 300 mL, adicionado 200 mL de água destilada, e desagregadas novamente por 10 minutos em cuba de ultrassom Exodo LS-SSDA-2. A solução foi passada em uma peneira de 63 μm (ou 230 mesh). O retido (fração areia), por ainda conter floculos, foi novamente desagregado e peneirado, até que de todos os grãos inferiores a 63 μm fossem incorporados ao passante (silte + argila).

A polpa é desagregada em uma cuba de ultrassom Exodo LS-SSDA-2 e, em seguida é passada em uma peneira de 63 μm (ou 230 mesh). O retido (fração areia), por ainda conter flóculos, é novamente desagregado e peneirado quantas vezes forem necessárias para que os grãos inferiores a 63 μm sejam todos incorporados ao passante (silte + argila). Após foi depositado 40 mL de passante em tubos Falcon de 50 mL (Fig. 9), levados novamente ao ultrassom para desagregação, e levados à centrífuga Heraeus Christ GMBH, onde foram aplicados 2000 rpm por 10 minutos cada. Em seguida, da suspensão obtida foram pipetados cerca de 2 mL sobre lâmina de vidro, após a secagem, a temperatura ambiente, foram submetidas à análise mineralógica difratômetro PANalytical X'PERT PRO MPD (PW 3040/60), com um goniômetro PW 3050/60 (theta-theta) equipado com um ânodo de cobre ($\lambda_{\text{Cu K}\alpha} = 1.5406 \text{ \AA}$) em condições de funcionamento de 40 kV e 35 mA, detector do tipo RTMS, X'Celerator com registros realizados no intervalo 3° a 36°. Constituindo, primeiramente em varredura orientadas e secas à temperatura ambiente, após etilenoglicoladas por 24 horas em dessecador com etilenoglicol, e a terceira aquecidas a 550 °C por 2 horas.

Os difratogramas foram obtidos no software *X'Pert Data Collector*, versão 2.1a, e o tratamento dos dados com o software *X'PertHighScore* versão 2.1b, da PANalytical.

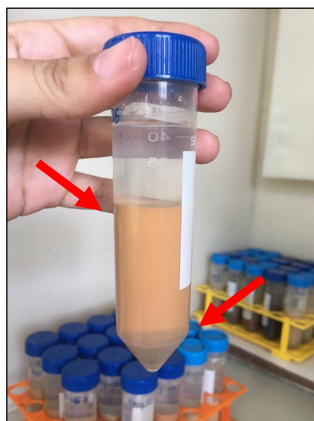


Figura 9- Tubo Falcon (50 mL), após passagem pela centrífuga, evidenciando a separação da argila-silte, evidenciado pelas setas vermelhas.

3.4 QUÍMICAS

As análises químicas para a quantificação dos elementos maiores, menores e traços, incluindo os elementos terras raras (ETR), foram efetuadas a partir de amostras pulverizadas com auxílio de grau e pistilo de Ágata, e enviados para análises de ICP-AES para elementos maiores e ICP-MS para elementos traços e ETR junto a ALS Brasil Ltda.

As análises no Espectrômetro FT-IR (Modelo Vertex 70, Bruker) com operação no software OPUS 7.0 e condições de operação na região 4000 a 400 cm^{-1} com resolução de 4 cm^{-1} , foram realizadas seguindo os padrões de preparação de amostra (0,0015 g de amostras + 0,2g de KBR) para confecção de uma pastilha prensada. Essa análise foi necessária para casos em que os sedimentos não possuíam minerais formados, ou seja, apresentaram-se amorfos, ou ainda em neoformações.

As análises de Fe total e amorfo foram realizadas no Laboratório de Hidroquímica IG/UFGA. Foi construída uma curva analítica de calibração para detecção de Fe utilizando as concentrações de Fe de 0,0 a 4,0 mg/L, preparadas a partir de uma solução padrão de Fe (10 mg/L) em que foi utilizado o mesmo procedimento de abertura utilizado nas amostras. A partir de amostras pulverizadas, utilizando-se 5 mL de hidroxilamina, 10 mL de ortofenatrolina e 10 mL de acetato de sódio foi realizada a abertura de 0,1g de cada (amostras C1, C2 e C3). As soluções foram colocadas em balões volumétricos de 100 mL e completados com água destilada até volume total. Todas as soluções foram analisadas em um espectrofotômetro-UV-Vis da marca VARIAN, modelo 50 PROBE, em comprimento de onda $\lambda=510 \text{ nm}$.

Análises complementares foram realizadas com o auxílio do Microscópio Eletrônico de Varredura (MEV) (Modelo TM3000, Hitachi Ltd., Osaka, Japan) do LaMiGA-UFGA, com operação via software TM3000, imagens foram obtidas e algumas usadas para análises químicas semi-quantitativas através da espectrometria de energia dispersiva de raios-X (EDS), com operação pelo software SwiftED3000.

3.5 ANÁLISES PALINOLÓGICAS E DE DATAÇÃO

No Laboratório de Solos e Biogeografia da UFT as amostras acondicionadas em PVC foram inicialmente descritas quanto à cor, textura e estruturas físicas e biogênicas e, em seguida, foram subtraídas as sub-amostras.

As amostras em tubos amostrados, foram enviados a Alemanha, ao Departamento de Palinologia e Dinâmica Climática da Georg-August-Universidade de Goettingen. Com auxílio

de um êmbolo e um tampão de borracha em sua extremidade, os sedimentos foram empurrados para fora do tubo, sobre filme plástico apoiado por uma meia-seção de PVC, para manter a forma cilíndrica. Em seguida, foram cortados ao meio, no sentido do comprimento, com auxílio de duas placas metálicas, medidos com régua metálica e descritos quanto à cor, textura e estruturas físicas e biogênicas e, em seguida foram subtraídas sub-amostras.

Ao longo dos testemunhos L4V e LMV, sub-amostras de cerca 0,5 cm³ foram coletadas em intervalos regulares de 2 cm. A essas amostras foram adicionados tabletes com esporos de *Lycopodium*, um marcador exótico, e posteriormente tratadas quimicamente para extração dos grãos de pólen conforme método adotado por Faegri e Iversen (1989), incluindo o método de acetólise de Erdtman (1952), no Laboratório de Tratamento Palinológico no Departamento de Palinologia e Dinâmica Climática da Georg-August-Universidade de Goettingen. A identificação e contagem dos grãos de pólen, esporos e demais palinomorfos, foram realizadas através de microscópio óptico com subsídios em chaves polínicas constantes nos livros de Salgado-Labouriau (1973), Rivas (1978), Roubik e Moreno (1991), Carreira e Barth (2003) e Colinvaux *et al.* (2005), além de artigos científicos de descrição de tipos polínicos. Para calcular e plotar o diagrama polínico foram utilizados os softwares TILIA, TILIAGRAPH (Grimm 1987).

No Brasil as análises palinológicas contaram com o auxílio da prof. Dra. Maria Ecilene N. S. Meneses, da Universidade Federal do Tocantins (UFT) no Laboratório de Paleobiologia UFT, e foram aperfeiçoadas durante período de doutorado sanduíche realizado na Georg-August-Universidade de Goettingen, sob a orientação do prof. Dr. Hermann Behling. Além da utilização de um microscópio ótico no Laboratório de Botânica do ICB-UFPA cedido pelo professor Dr. Rosildo Santos Paiva, e do Laboratório de Dinâmica Costeira (LADIC-UFPA).

As análises de datação foram realizadas a partir de sub-amostras retiradas ao longo destes testemunhos e foram analisadas utilizando a técnica “Accelerator Mass Spectrometry” (AMS) ou espectrometria de acelerador de massa, realizadas no Poznań Radiocarbon Laboratory, em Poznań-Polônia. As idades ¹⁴C obtidas foram calibradas em anos antes do presente (AP) através do software CALIB 7.10 (Stuiver *et al.* 2018).

4 RESULTADOS E DISCUSSÕES

Os resultados e discussões foram organizados em três artigos, o primeiro trata sobre a mineralogia e geoquímica dos solos e sedimentos da Ilha do Bananal, das barras e barrancos ao longo do Rio Javaés. Discorre, portanto, sobre a natureza diversificada dos minerais e elementos químicos que compõem os estratos e horizontes dessas coberturas superficiais, apontando proveniência geológica, bem como os processos geoquímicos envolvidos na dinâmica atual e pretérita dessa paisagem. O segundo artigo apresenta a dinâmica da vegetação ao longo dos últimos 2,000 anos AP no interior da Ilha do Bananal e discute sua relação com as condições climáticas e edáficas locais. O terceiro artigo, por sua vez, descreve a sucessão vegetal ocorrida nos últimos 400 anos AP, com base no registro polínico de sedimentos de um lago situado nos arredores da Ilha do Bananal, bem como, analisa o espectro polínico moderno na região.

4.1 ARTIGO 1: GEOLOGY, MINERALOGY AND GEOCHEMISTRY OF SEDIMENTS AND SOILS FROM NORTHERN BANANAL ISLAND AND THEIR CONTRIBUTION TO LANDSCAPE EVOLUTION DURING THE HOLOCENE

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Geology, mineralogy and geochemistry of sediments and soils from Northern Bananal Island and their contribution to landscape evolution during the Holocene

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Abstract

The Bananal Island is included into the extensive Araguaia floodplain, therefore, the Bananal Island is a floodplain temporarily flooded during the rainy season by local precipitation and a saturated water table, so it is a seasonal wetland. In this context, the aim of this work is to provide data and discussion using the young sediment records in the Northern Region of Bananal Island and surrounding areas in order to understand the landscape dynamic during the Late Quaternary in this classical wetland. The study area is in the northern portion Bananal Island, corresponding to a transitional area between Amazon rainforest and Brazilian Cerrado biomes. In order to investigate the sediments and soils and to understand their relationships landscape's components, three profiles located on the Javaés River bank and one profile on the Araguaia River bank were described and sampled. That were submitted to analyses such as grain size, mineralogy (XRD and FTIR) and chemistry (ICP-AES/ICP-MS). The analyses on the Coco Beach profile indicates a probable iron reduction, showing Fe²⁺ compounds (iron phosphate and/or sulphate) meanwhile a possible condition of stagnant water, just provide by the low to medium level of river water. These features of older ferruginization are common throughout the northern region of the Bananal Island. Like in the sand bars with red films complexes, that are amorphous to XRD. But, by chemical analyses the iron (amorphous) presented about 16.7% in one red film complex and 2.5% for green gel, which confirms the expressive presence of iron in red and greenish gray complexes (gley), but decreases in depth. The ferruginization in Coco Beach may be later formations related to the flow of the water table and/or the crystallizations of the iron oxyhydroxide colloids that cover the sands of the bars and also flow laterally in the body of the bar. This extensive plain in the Late Holocene seem to be resumed by a new meandering river system, with formation again of marginal dykes and broad floodplains and oxbowl lakes or lakes between point bars (closed channels). The terrain outcropping on the northern portion (White Barrier, Collapsed Ravine, Coco Beach, Canguçu Harbor) of Bananal Island represent a fluvio-lacustrine geological-geomorphological evolution during the late Pleistocene, probably mainly during the Holocene, and comprise at least four major events: A meandering fluvial phase over already fluvial land, with formation of extensive floodplain. Intensive and extensive chemical precipitation of iron hydroxides partly cemented the sandy bodies, forming crusts that make their subsequent erosive phase difficult. A phase of drying condition reached the gley soil landscape indicated by intensive formation of vertical fracturing and columnar disjunction. And finally, this landscape was resumed in the late Holocene by new meandering fluvial activity beginning with rusting indicated by the intense formation of amorphous iron hydroxide gels.

Key-words: Bananal Island Ravines, sandy bars, Javaés River, Araguaia River.

1 Introduction

The Bananal Basin is a well-developed Quaternary sedimentary basin, located in the region of the Middle Araguaia River with approximately 106,000 km². According to Valente (2007) the Bananal Basin is the most important intracratonic sedimentary basin of the Quaternary from South America and preserves a good record of paleohydrological conditions. Situated in northern portion of this sedimentary basin, in the Tocantins State, occurs the Bananal Island which with an area of 20,000 km² is regarded by some authors as the largest fluvial island in the world (Borma *et al.*, 2009; Dias *et al.*, 2011; Devi, 2012).

The Bananal Island is formed by the Araguaia River and its arm, the Javaés River. Thus, the island is included into the extensive Araguaia floodplain that covers the vast area of about 58,600 km² in the southeast of the Amazon Basin representing the fifth largest floodplain area in South America (Melack and Hess, 2010). Therefore, the Bananal Island is a floodplain temporarily flooded during the rainy season by local precipitation and a saturated water table, being classified as a seasonal wetland (Valente, 2007).

Wetlands are areas of global interest, because they are sensible to environmental changes. Mitchell (2010) elucidated the importance of the wetlands stating they are important to the process of groundwater recharge, flood control, maintenance of biodiversity, and may support some agriculture activity and fishing. Such sensible environments must be used for conservation because they support rich biodiversity, by providing habitat for large variety of animal and plant species, since they display chemical, physical and biological characteristics, which are very important for the life cycle, including rare and specific species of plants and animal, exploring the distinct, ecosystems, landscapes and processes. This way they are new frontiers for investigations, for instance, for education and tourism, since one can observe directly how the distinct natural processes to happen (Mendes *et al.*, 2015), geomorphology (Latrubesse *et al.*, 2009), geology and mineralogy (Irion *et al.*, 2016), global carbon sink (Rezende, 2000), understanding microclimates and climate changing.

Recent studies have been carried out on the Bananal basin wetlands concerning fluvial dynamics of the Araguaia River (Coe *et al.*, 2011, Latrubesse *et al.*, 1999), the geomorphological evolution (Latrubesse and Stevaux, 2002, Aquino *et al.*, 2009, Latrubesse *et al.*, 2009, Valente and Latrubesse, 2012, Valente *et al.* 2013), hydrological processes (Aquino *et al.*, 2005, Morais *et al.*, 2008). However, the geochemical and mineralogical contribution to understanding the evolution of this landscape is still scarce. In this context, the aim of this work is to provide such data and discussion using the young sediment records in the Northern Region

of Bananal Island and surrounding areas in order to understand the landscape dynamic during the Late Quaternary in this classical wetland, of the Bananal Island.

1.1 Study area

The study area is located in the northern portion of the Bananal Basin, between coordinates 9°51'28.2" S and 9°58'48.2" S, 50°2'13.4" W and 50°12'43.9" W (Fig. 1), where the Bananal Island is situated, corresponding to a transitional area between Amazon rainforest and Brazilian Cerrado biomes. The regional climate is warm and semi-humid. The average annual precipitation varies from 1,400 to 2,200 mm/year. The rainy season occurs from November to April. The dry season is marked by very low or no precipitation, and the driest months ranges from June to September. The average annual temperature is 26°C, the maximum temperatures of 38°C occurring during the months of August and September (Dias *et al.*, 2008).

According to Brasil (1981) the Bananal Island seasonal wetland consists in a morfological unit characterized by a fluvial-lacustrine plain, with numerous lakes, lagoons and intermittent channels. The hydrogeomorphologic features of this wetland includes hills, valleys, abandoned channels, oxbows lakes, related to high relief-energy relationship (Latrubesse *et al.*, 2009). The Bananal Island is drained by Araguaia and Javaés rivers and their tributary streams in the center of the Island, mainly the Jaburu and Riozinho rivers. River channels within the floodplain tend to present anabranching pattern (Valente *et al.*, 2013).

This landscape is geologically inserted in the Bananal Basin whose Quaternary sediments belongs to Araguaia Formation, 170-320m thick composed by yellowish to brownish unconsolidated sediments, silt to sand grain size and locally ferruginized (Araújo and Carneiro, 1977). Holocene alluvial deposits also occur in this region. The soils of this region are classified as being alluvial deposits of recent age (holocenic), with sandy sedimentation active in the formation of lower levels, also appearing gleysol soil type in the natural fragments of flooded forests, and plinthosols in the rest of the region. These soils are shallow and are under strong influence of groundwater (SEPLAN/TO (2008)).

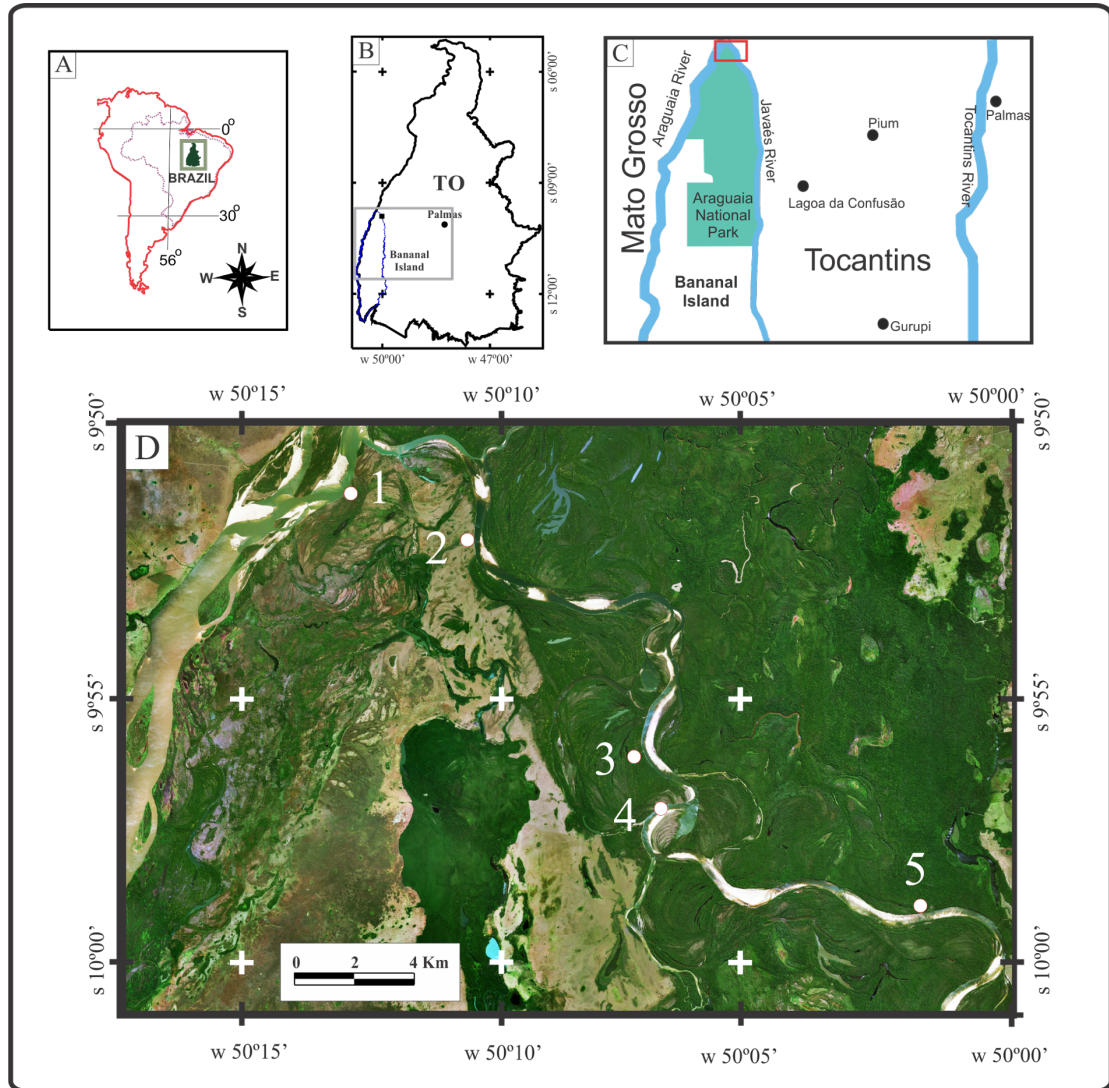


Figure 1. Location maps of the Bananal Basin and the study area in the Northern part of the Bananal Island, showing the geographical situation of the five sections studied. A. Location of Tocantins State in South America. B. Bananal Island location. C. Detail of Araguaia National Park localized in the north of Bananal Island, and in the red square the study area. D Collection sites location: 1. Collapse Ravine; 2. White Barrier; 3. Coco Beach; 4. Long Beach; 5. Canguçu Harbor.

The vegetation is composed by a mosaic of rainforest and savanna (cerrado). In this context, savanna presents variable physiognomies since grassland savanna (dominant herbaceous stratum with rare bushes and absence of trees) till shrub savanna and wooded savanna. The shrub savanna is a mixed herbaceous-shrub vegetation, with bushes and trees scattering in an extensive grassy cover, where *Byrsonima sp.*, *Curatella americana* and *Tabebuia sp.* are the shrubs and trees types dispersed along the herbaceous stratum. In the wooded savanna, the same trees occur, but form denser groups.

The forest formations appear like gallery forest that consists of the perennial forest occurs alongside of Araguaia and Javaés rivers and their tributaries, for example, Riozinho

stream that cross the Bananal Island. Forest fragments are common along the abandoned channels and floodplains associated with shrub savanna species.

2 Material and methods

In order to investigate the regoliths (soils and sediments) and to understand their relationships landscape's components (relief, vegetation cover, water bodies, etc.), three profiles located on the Javaés River bank and one profile on the Araguaia River bank (Fig. 1) were described and sampled. The selected profiles are representative of the geomorphic, pedological and botanical patterns found in the study region. The soil and sediment samples were collected using shovel and spatula in the exposed ravines. These regolith samples were submitted to analyses such as grain size, mineralogy by XRD and chemistry by ICP-AES for the major elements and ICP-MS for the trace elements at in ALS Laboratories.

The grainsize analyzes consist of the separation of the sand, silt and clay fractions through wet screening according to procedures adopted by Embrapa (1997). The samples with the lowest sand content were performed by laser diffraction with the Fritsch Granulometer *model Analysette 22*, 2 g of samples. To improve the analyzes the low sand samples were treated previously with water and pyrophosphate, $\text{Na}_4\text{P}_2\text{O}_7$, chemical dispersant (to aid in deflocculating the fine grains. The software SYSGRAN 2.4 was used for the results treatment, adopting the classification of Folk and Ward (1957). The sand grain fraction was observed the roundness and sphericity by visual comparison with the tables of rounding and sphericity classes presented by Suguio (2003).

The XRD mineral analyzes were carried out by using a powder diffraction method ("front load") with a Bruker diffractometer model *D2 Phaser*, with copper anode ($\lambda\text{K}\alpha_1 = 1.5406\text{\AA}$), operating with 40 mA currents, 40 kV voltage, with a step size of $0.02^\circ (2\theta)$, a count time of 5 s, at an angular range of $5-70^\circ (2\theta)$. To performed the clay minerals (fine fraction $< 2\text{mm}$), the samples were previous prepared using slide orientation technique, in addition, they were air-dried, solvated with ethylene glycol for 24h and heat-treated at 500°C during 2h. The diffractograms of fine fraction ($< 2\text{mm}$) were recorded with the PANalytical diffractometer model *Empyrean*, with cobalt anode ($\lambda\text{K}\alpha_1 = 1.78901\text{\AA}$), PIXCEL3D-Medpix3 1x1 detector operating with 35mA current, 40 kV voltage, with a step size of $0.02^\circ (2\theta)$, at an angular range of $5-70^\circ (2\theta)$, time of 10 s. The results were treated with the X'Pert High Score Plus software, which compares the obtained peaks with those from the International Center on Diffraction Data (ICDD) and presented with symbols according to Siivola and Schmid (2007).

Further analyzes were performed using the Scanning Electron Microscope (SEM) (Model TM3000, Hitachi Ltd., Osaka, Japan) to obtain images and the through X-ray energy dispersive spectrometry (EDS) SwiftED3000 coupled to SEM for semi-quantitative chemical analysis.

3 Results

3.1 Lithological succession of sediment

3.1.1 Coco Beach

In the Coco Beach profile (Fig. 2 and 3) the lithological succession from bottom to the top comprises: a pallid brown (10YR 8/3) medium sand, well selected, high sphericity and rounded grains (Fig. 2 C: points 9 and 8); a strong dark brown (7,5YR 5/8) medium sand, well selected, however with low sphericity and sub angular to sub-rounded grains (Fig. 2 C: point 7); the quartz grains are impregnated by iron oxy-hydroxides and become yellow brown to red in color; a brownish yellow (10YR 6/6) medium to fine sand, moderately well selected, high spherical and sub angular grains (Fig. 2 A: points 6 and 5); a brownish yellow (10YR 6/6) fine to medium sand in its largest portion, solid and compact structure (like a hardpan), with dark yellowish brown (10YR 3/6) and black (10YR 2/1) spots, moderately well selected, high sphericity and angular to sub angular grains (Fig. 2 A: point 4); an yellow (10YR 7/6) medium to fine friable sand, moderately selected, high sphericity and rounded grains, some dark grains are present; an yellow to dark brown medium to fine sand moderately selected, high spherical and sub-rounded grains (Fig. 2 A: point 3); and then a light brownish gray (10YR 6/2) to light gray (2.5Y 7/2) silty clay loam showing strong dark brown (7,5YR 5/8) spots and presence of some roots and branches (Fig. 2 B: points 1 and 2). Summarizing a domain of medium grain sand packet, of light color in the lower beds, that becomes medium to fine, showing strong dark brown and compact in the intermediary beds and then a light gray silty clay loam on the top with root records. The grain size and selection and roundness decreasing upward shows a continuous lost in the energy dynamic of the sedimentation environment.

On the other side, the thick iron oxyhydroxide impregnation in the intermediary section may support a relative long-term position above the river water high level, the basic conditions for oxygen availability for iron oxidation and complex precipitated. This becomes more expressive at interval 345 and 360 cm in depth, where a quasi of hardpan can be recognized. It presents a yellowish-brownish sandy texture in the largest portion, and dark yellowish-black and black spots. The fine light green zone between the basal sand (Fig. 2 C:

point 9) and strong dark brown (Fig. 2 C: point 8), below 493 cm depth, indicates a probable iron reduction, probably showing Fe^{2+} compounds (iron phosphate and/or sulphate) meanwhile a possible condition of stagnant water, just provide by the low to medium level of river water. The Coco beach succession may respond for quartz sand, probably a river point bar, which was strong and pervasive invaded by iron oxyhydroxides.

In the upper part of the Coco Beach profile a slight gray A soil horizon (Fig. 2 B) has already been established, followed by light grayish-brown B horizon with strong brown spots (mottling) and presence of branches and roots, those activities developed cavernous cavities, which much more common because they stay just in front of the water river impact.

The sand of the river bar probably rose above the high-water level of the earlier river, became a body of water-table that ran for drainage. These waters drained neighboring areas and perhaps crossed the sandy body with iron minerals, mainly the oxides, that in contact with the organic matter of the decayed forest with formation of humus and peat, dissolved these oxides, complexed them and the released iron, the which mediated by bacteria, oxidized mainly in the water table breaking in the paleo cliff, and precipitated around the quartz grains, originating the iron hydroxide fronts, which gradually cement the sands.

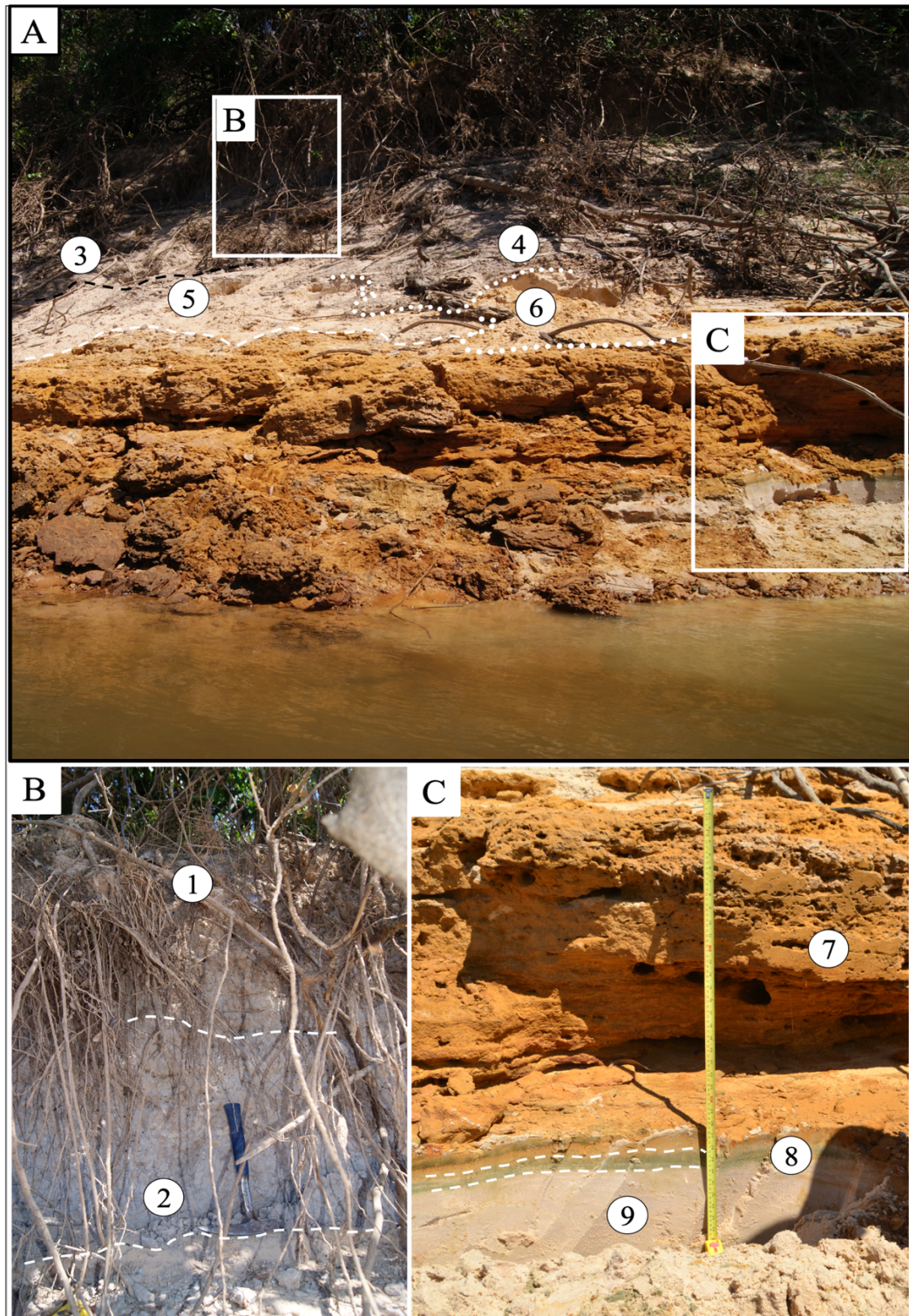


Figure 2. Lithological succession of the Coco Beach profile. A. General overview; B. Detail of soil horizon; C. Detail of reddish sand and of the thin olive zone. The samples of this material were collect in this river cliff exposition. Each number corresponds to descriptions in the fig. 3.

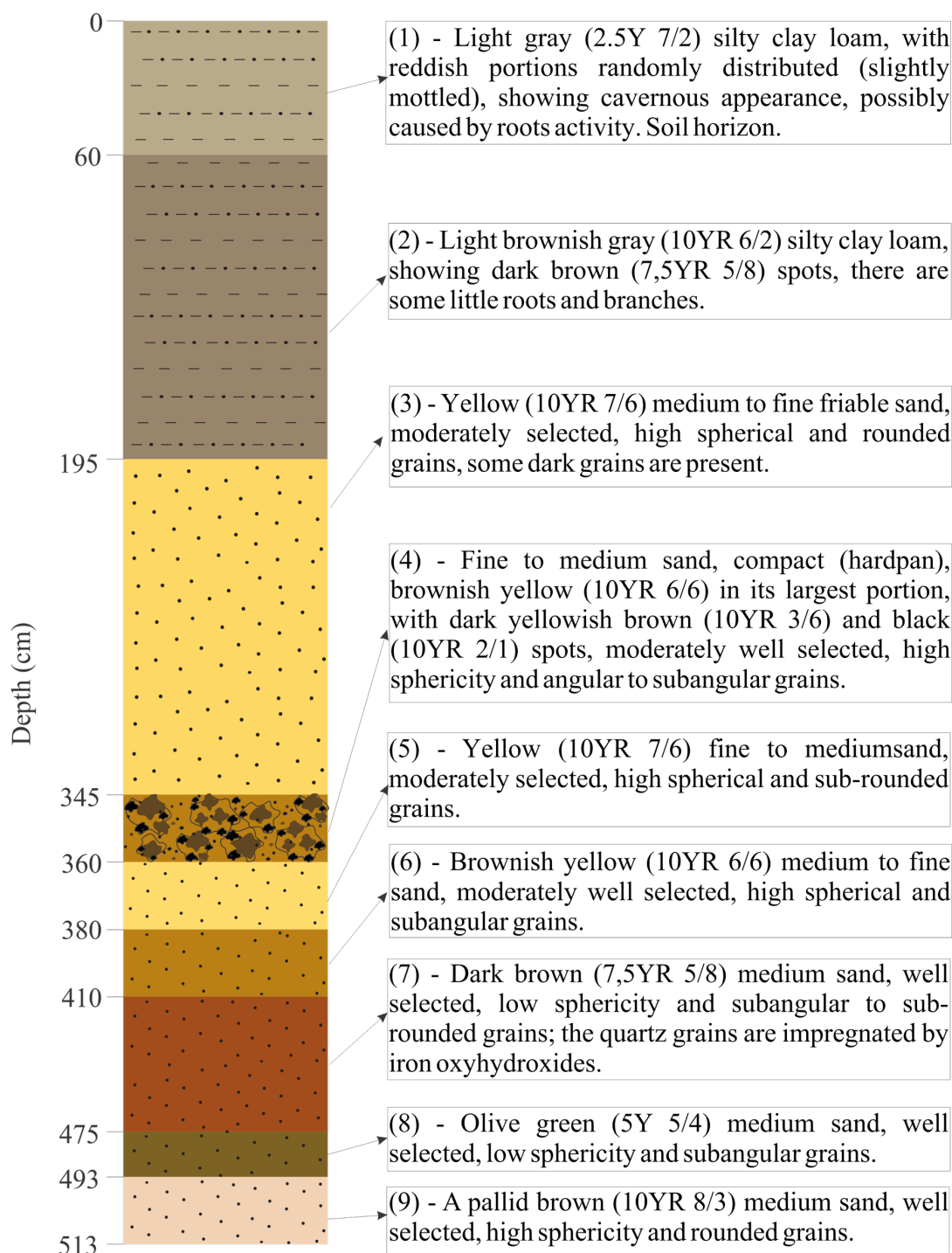


Figure 3. Schematic lithological succession of the Coco Beach profile.

These features of older ferruginization found in Coco are common throughout the northern region of the Bananal Island. They are exposed in many places, especially on the cliffs in the lower course of the Javaés river, where clayey or argillaceous silt packets usually topped by black Neosols cover old sandy bars. The ferruginization may be later formations related to the flow of the water table and/or the crystallizations of the iron oxyhydroxide colloids that

cover the sands of the bars and also flow laterally in the body of the bar. Valente *et al.* (2013) confuses them with laterites, however they are not in any way lateritic formations.



Figure 4. Typical older ferruginization (cementation of sand bar by goethite, mainly) and developing a sand-rich ironstone creating a condition to form river cliff pontoons. A: general exposition of ferruginized sands along river cliff or cliff pontoons; B: details of a thick and local ferruginized sands improving the stratification; C: details of these blocks; D: blocks showing tabular forms developed on the contact zone sand silt/clay (interface ironstone).

3.1.2 White Barrier

The lithological succession of the White Barrier (Fig. 1 and 3) comprises a light gray silty-clay to clay-silty at the bottom, up to whitish upward, showing some yellowish red spots, a slightly mottled pattern (Fig. 5: points 10 to 7; Fig. 5 A, B), dense cavernous on river wall bank (Fig. 5 C), some fish holes. It becomes slight hard (like a hardpan) (Fig. 5 point 7), very pale brown, sub horizontal stratified by color shading alternation, dominated by sandy texture, and much more fish holes (Fig. 5 B) (1 cm in diameter). A thin layer of whitish silty clay (Gley 1 8/N), with yellow (10YR 7/6) and yellowish red (5YR 4/6) random spots, cavernous structure (Fig. 5 C, point 6). This whole sequence is covered by gray silty clay (2,5Y 7/1), slightly laminated, with large horizontal fish holes, easily breakable (Fig. 5 A, B: point 5). The contact between these two sequences is undulated, locally with a lower sequence with a gray to green color marks an environment changing. Probably a paleochannel was fulfilled with floodplain sediments and reducing conditions have established on the basal contact. The gray silty clay converges upward into light gray whitish silty clay loam (5YR 8/1), with slight randomly

distributed yellowish red (5YR 4/6) spots, slightly laminated however with rare horizontal fish holes. Finally, the last 50 cm to the top of terrain surface established a typical young soil profile developed over the previous silty clay sediments. An olive brownish B horizon (2,5Y 5/4) silty clay loam from 50 to 20 cm in depth, with a massive structure with root activity and plenty of vertical fracturing (dehydration by insolation fracturing) that in part reaches the underlying layer and are partly occupied or developed by plant roots. (Fig. 5 A and B). It's followed by a grayish brown (2,5Y 4/2) thin BA horizon from 20 to 10 cm in depth, silty texture, cross-cut by roots and vertical fracturing and on the last 10 cm the A horizon, dark gray and silty, whereby the vertical fracturing is much more intensive. Grassland with some dispersed shrubs and trees covers the terrain.

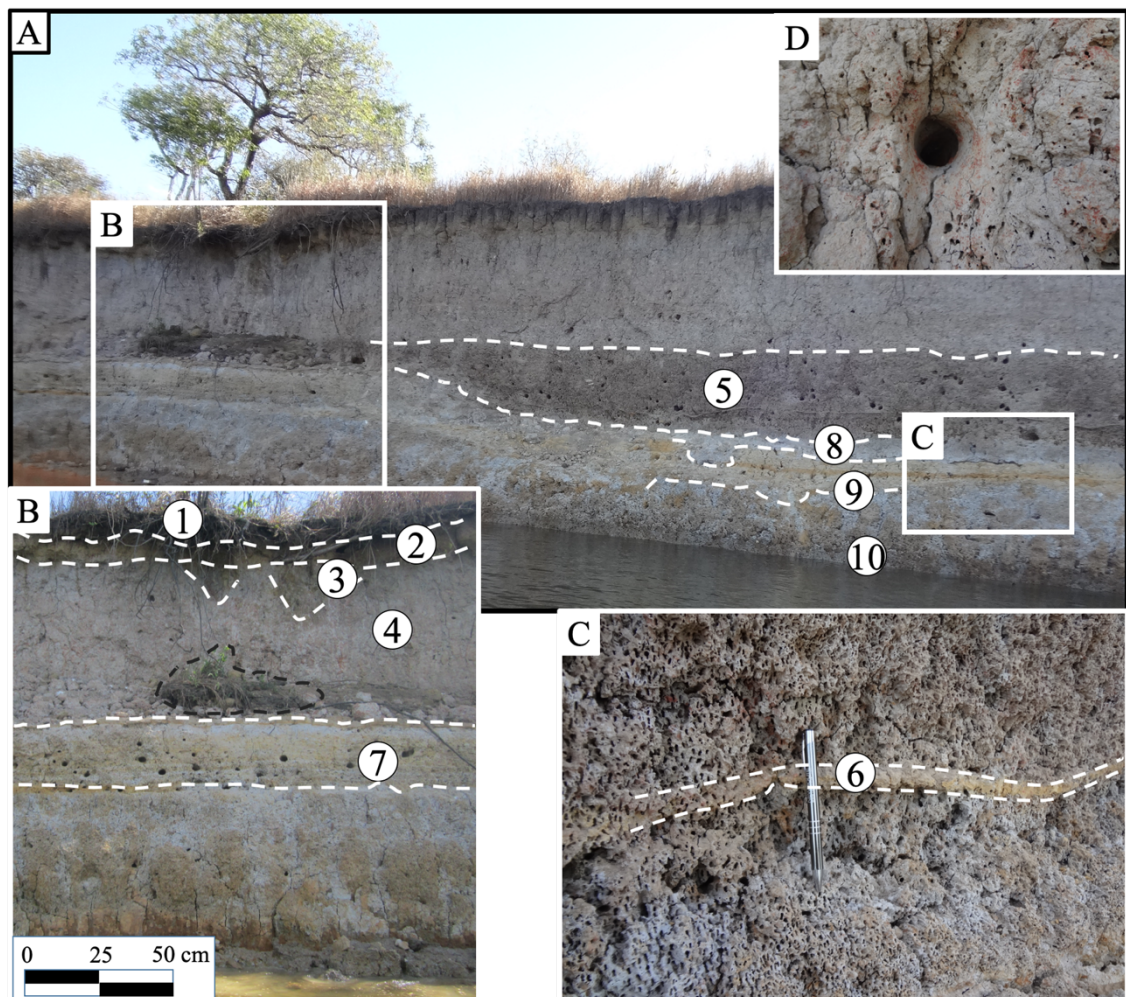


Figure 5. Lithological succession of the White Barrier profile. A. Overview. B. Detail of the White Barrier. C. A detail of the thin brownish silt layer. D. Detail of horizontal circular fish hole developed in the mottled clayey silt showing the cavernous pattern.

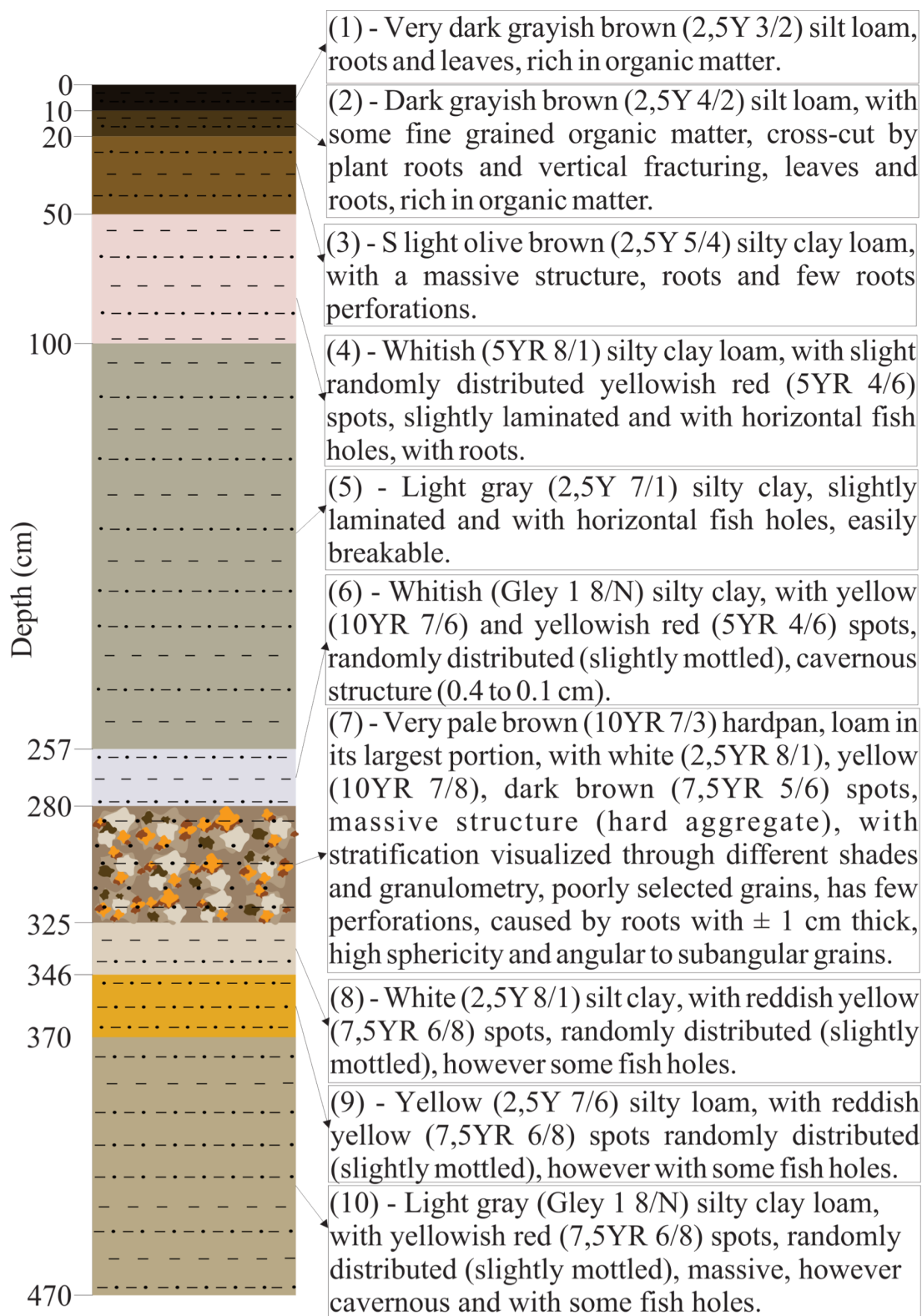


Figure 6. Schematic lithological succession of the White Barrier profile.

The described succession exposition used for chemical and mineralogical analyzes responds for southern part of a long southern-northern river cliff (Fig. 5) which converges to friable white to yellow up to brownish sand packet covered by the previous described silty clay

to clay silt (Fig. 6), which gradually get thinner and disappear. The soil profile becomes very remarkable and impressive by the development of well-formed columnar disjunctions. The mottling aspect lost identity and the yellow sub-horizontal Fe hydroxide shading fronts are common; in parallel the silty clay and clay silt assume a pallid aspect imprinted by light green or gray color, that suggests a domain of reducing conditions by a long time waterlogged from southern-northern apparently (Fig. 7 A thru P).

At the top of the sequence was established a typical dark gray soil horizon, which can be classified as Neosol or Gleysol formed from the silty clay layer, a thickness ranging from 60 to 100 cm (Fig. 8 A thru P). This A horizon generally converges to an ochre yellow color horizon given by iron hydroxides, with a variable thickness, thinner than A, and in gradual and undulated contact with the underlying silty clay layer. This contact usually has funnel-like features, associated with roots, some of them pivoting. In general, show an intense vertical fracturing through the horizons A and B, besides the columnar disjunctions, which are a great highlight too.

In Fig. 8 A a silt clay slightly mottled (reddish spots in grayish green vertical pattern) in the lower part; light brown massive silt with small green clay lens in the intermediary zone; up warding a clay silt vertical mottled in lower part, and then becomes irregular and fine subtle mottled (small reddish spots in green background), however vertical fractured and showing some plant roots; on the top (the first 50 cm depth) the B (yellowish) and A (dark gray) soil horizons massive and with columnar disjunctions. The yellowish material of B horizon penetrates the underlying layer probably following a previous fracture and takes a form of a funnel. In Figure 8B it looks similar to A image, however the intermediary zone it is much more impressive and can suggest an erosion surface and the upper layer shows locally a horizontal parallel stratification which can still be observed in the soil horizons.

To the northern (Fig. 8 C) the lower layer becomes apparently thinner, lost partly the mottling, which are vertical, and turns more gley; the intermediary zone looks much more a yellowish sub horizontal shading and upper layer is more representative and plenty of horizontal fish holes, viewed in the figure 8. In the image of Fig. 8 D it is observed that the lower layer becomes very pale, acquiring the greenish tone that will advance in the next images, losing much of its mottled. Reducing conditions increase. The intermediate zone persists but is thinner. The upper layer becomes pallid at the top, thus losing its slightly mottled appearance, close to the contact with the soil horizons B and A. Going ahead to the northern the exposition resembles the previous one, but the lower layer is thicker, irregular, with mottled and pallid portions, with the greenish gray tone striking the top, while the middle zone is very subtle and the top layer is

similar to the previous image D. The soil horizons maintain well developed columnar disjunctions. The lower layer is still more strongly pallid in its upper portion and the intermediate zone is subtle (Fig. 8 F). The upper layer maintains the anterior pattern with its pale zone at the top well delineated near the B soil horizon. A little bit to the north (Fig. 8 G) the lower layer that is pallid at its top (looks like a bed), with the intermediate zone clear but superimposed by yellow fronts of iron hydroxides, while the upper layer varies from pale to mottled and its contact with the dark soil horizon is corrugated.

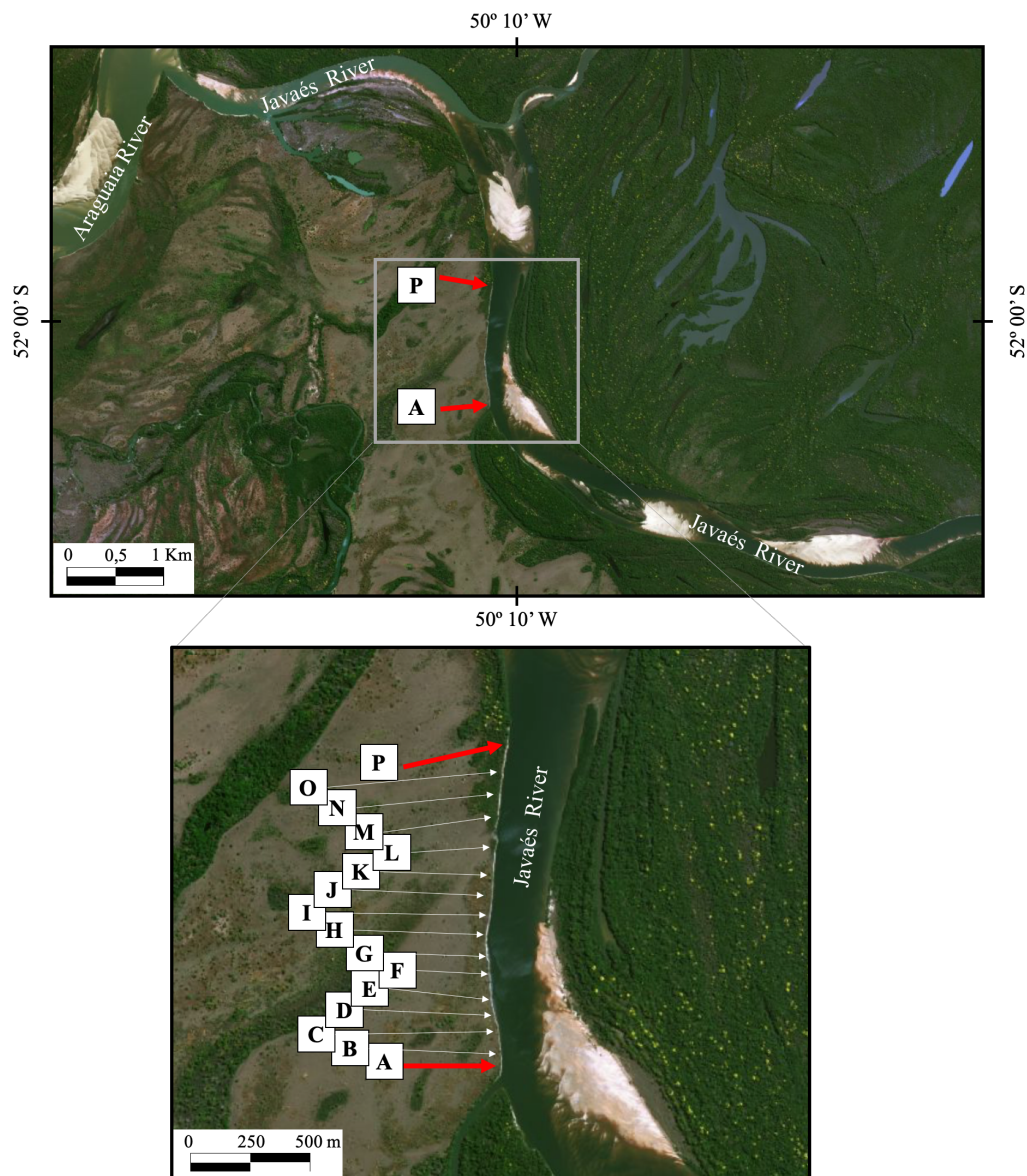


Figure 7. The southern-northern geological section along the left side bank of Javaés river in Bananal Island, illustrated images A thru P (See Fig. 1 D, point 2 for location and Fig. 8 A thru P for geological description).

Finally, much more to the north (Fig. 8 H) one can see a strong change in the sediment succession. The lower layer is practically all pale greenish with yellow parallel and horizontal

fronts of iron hydroxides, and overlaps the layer of friable sand (in the image on the right); the intermediate layer does not appear, and the upper layer is thinner, while the soils have irregular, apparently is sandier and thick, in which the yellow B horizon goes from very thick to absent, similarly the disjunctions. In next image (figure 8 I) the layer of friable white sand at the base is highlighted, followed by the lower layer of silty clay, which has become thin but still pale. The middle layer is very subtle or absent, but the iron hydroxide fronts delineate a thin, wavy body. The upper clayey silt layer is also pale, superficially mottled, with fish holes, whereas the soil does not show the yellow B horizon, but continues with disjunctions.

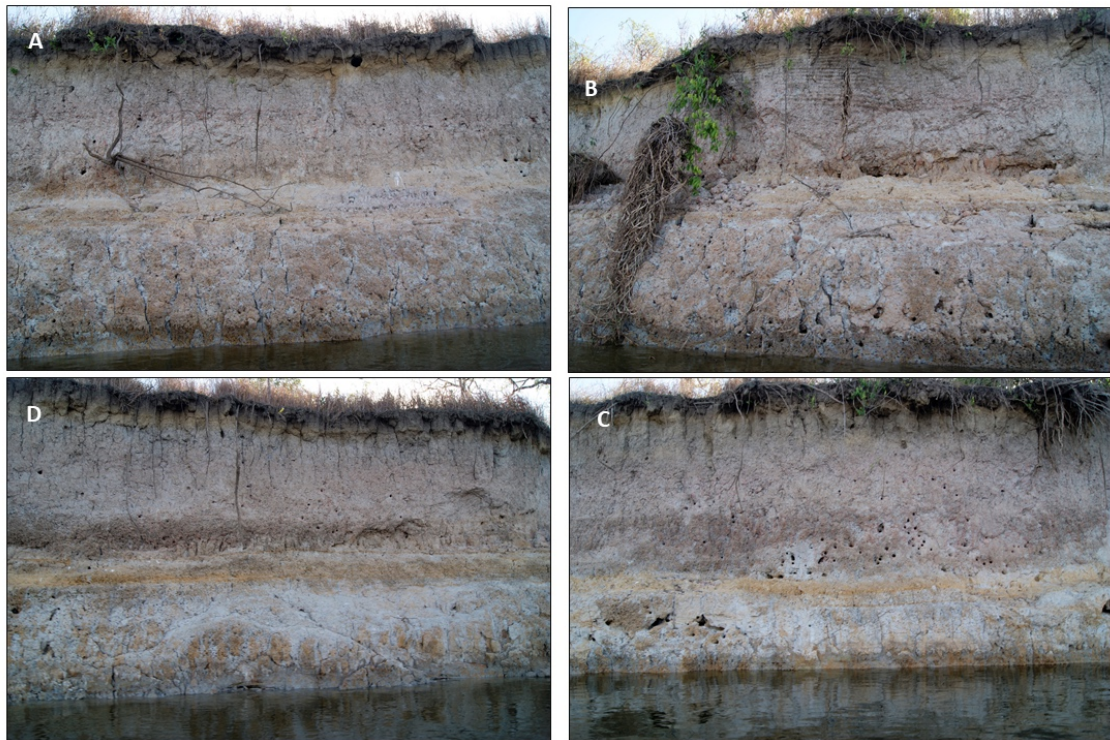
At long last, the sand packet is detachable at the base (Fig. 8 J), while the lower clay layer is discrete and confused, mottled; the intermediate zone is not clear, however the upper clayey silt remains prominent, pale green to vertically reddish mottled, also fractured in contact with the horizons B and A of soils, with vertical disjunctions. In this image (Figure 8 K) it is clear that the lower clay layer slends, remaining pale green, apparently merging with the upper clayey silt layer; instead of the middle layer, the typical iron hydroxide fronts are highlighted, in parallel and sub horizontal pulsations. The sand layer of the base is highlighted. The upper layer varies from pale to partially mottled, with the fish holes and fractured, invaded by the funnel soil coming from B horizon; the soil profile maintains its almost constant pattern.

To the northern (Fig. 8 L) the layer of sand is covered by the collapsed material of the cliff, but the layers of clay and / or silt appear to be only one unit. Thus, there is a more silt material at the base and more clayey to the top, but the pale greenish, superficially stained, remains. The parallel fronts of iron hydroxides persist. Near the contact with the soil it emphasizes the pale nature and the density of funnels and root perforations, well developed. Ahead to the north (Fig. 8 M) the yellow fronts of iron hydroxides ranges from multi-fronts to a wavy layer of varying thickness and undulated along the medial portion of the section. The clayey silt layer remains pale and wall surface mottled. The soil profile shows a B horizon from subtle to very prominent, locally with many well-developed funnels projected on the clayey silt layer as usual. Roots and vertical fractures persist. A little bit northern (Fig. 8 N) the section resembles section G, with the lower silt clay layer still showing the remnant of the mottled pattern at the base and to the left, being pale greenish gray at the top, as if they were two layers; the irregular yellow fronts of iron hydroxides are confused with the intermediate brown silt zone; then the upper clayey silt layer displays sandy lens in contact with the soil, where the B horizon may absent.

The geological section in next image (Fig. 8 O) can be compared to sections I, J and K, with white to yellowish, friable sands, with flat-parallel and cross-stratification at the base.

On it rests in abrupt contact the pale grayish-greenish clay that apparently forms a single unit with the upper clay silt. Two to three fronts of iron hydroxides stand out. The top layer is dominantly less pale, superficially mottled and the soil B horizon is very restricted. In the most northern image (Fig. 8 P) the sand layer at the base, thick, stratified, and yellow staining fronts with iron hydroxides, sub-parallel throughout the package, is highlighted. The layer of clayey silt rests on the sand in abrupt contact and marked by yellow iron hydroxides too. The silt layer also has a base two striking fronts of iron hydroxides, and the overall hue is pink, then turns to pale gray (thicker) and then greenish gray to the top just below the soils, whose B horizon is very discrete but with disjunctions. The same fractures, roots and a few fish holes persist.

Sometimes the yellow to ochres funnels may represent a mottling feature caused by pivoting-like plant roots which reaches the underlying clayey silt (Fig. 9). They go deep in search for water during a long-term hydric stress, where an oxidizing condition may occur and precipitation of iron hydroxides are favored. On the over side these roots most commonly pierce the substrate and when decomposing leaves a sub vertical cavity in the form of a funnel, which allows material falling from the upper zone into the same, mainly if this material is sandy, they can be compared to sandstone dykes described by Kumar and Singh (1982).







Figure

8. A sequence of field images (A to P) get from south to north showing in this direction the changing of the lithological sequence, gradual increasing of the reducing conditions indicating the by establishing of the light green to gray color of the clay silt to silt clay packet, which becomes thinner and consequent exposition of friable sand layer at the bottom. On the top the dark A and B (yellowish) soil horizons are detached by impressive vertical columnar disjunctions.



Figure 9. A typical funnel-like feature promoting by plant roots from B horizon into the underlying substrate. In the middle can still recognize the empty channel of the root drilling. On the right an image of a pivoting-like root exposed on the cliff of Javaés river. On the left side a deep pivoting root drilling creating a columnar pattern and formation of gray soil in between on the right side of Javaés river.

Similar succession to that of the White Barrier is also highlighted in the north of Javaés, where the columnar disjunctions are very evident and typical formed from silty clay layers (Fig. 10 A and B).

In conclusion the geological section as a whole clearly demonstrates that a pack of friable sand with flat-parallel and cross-stratifications representative of fluvial paleo beach (river bars) sustains a pack of clay silt at the base for clayey silt to the top, sometimes with small and thin brown sand lenses in the contact zone, which appear to correspond to large flood plains, which were locally exposed, partly eroded and then recovered. The mottling mainly in the base, allows the package located above the base level, undergo influence of the water table, receiving oxygenation (oxidizing conditions) during a small period. Then the region was dominated by a long period of marsh conditions (reducing conditions), which led to the formation of the thick soil A horizon, with gradual to intensive solubilization of the previous iron hydroxides of the layers of clay and clayey silt, and providing the migration of iron hydroxides and precipitated to levels during the temporary drying, when the water table lowered. The followed long-term drying season provided fractures, columnar disjunctions and yellow funnels.

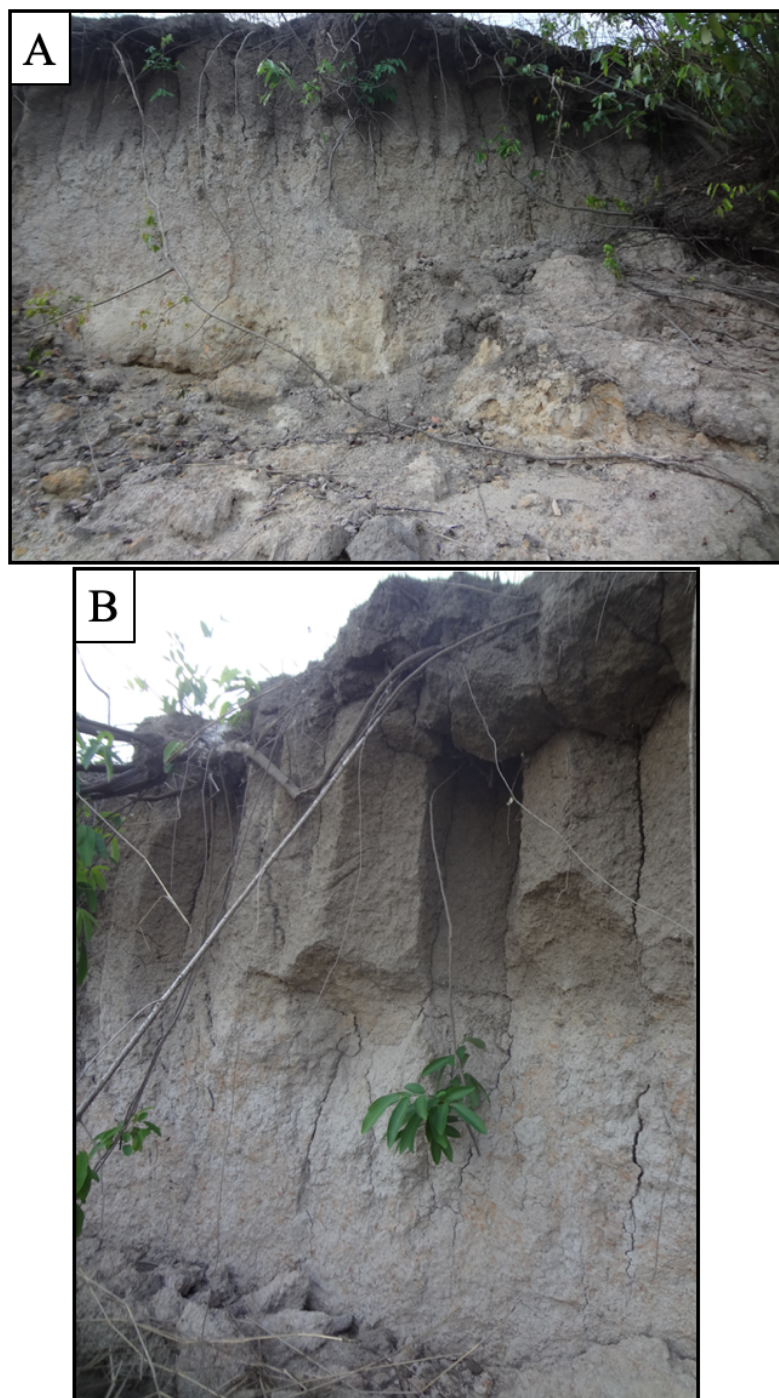


Figure 10. A possible Neosol to Gleysol A horizon on clay silt showing the typical columnar disjunctions in the northern part of the Javaés river. A: general view and B; detail of the pentagonal to hexagonal cross section of the columns.

3.1.3 Collapsed Ravine

Four units were identified in the profile of Collapsed Ravine in Araguaia River (Fig. 11 and 12): at the lower part, 300 to 150 in depth, a thick white homogeneous massive in the lower part (Fig. 11 number 5) being friable and showing locally some cross stratification (Fig. 11 number 4) to the middle and upper part, which display some aggregates of light brownish gray sandy clay. It's followed, from 150 to 100 cm in depth, by black sand rich on fine organic

complex material (Fig. 11 number 3), slightly compact, showing a light appearance of hardpan. A pallid black sandy horizon (Fig. 11 number 2), from 50 to 30 cm, established upward with irregular contact with the previous one (Fig. 11 number 3) and finally a thin dark unit (Fig. 3, number 1) carrying some humus, from 30 cm to land surface. This succession can be well correlated to a classical spodic profile, being the unit 3 the spodic horizon B and unit 2 the (Elluvial) horizon E and the unit 1 the A.

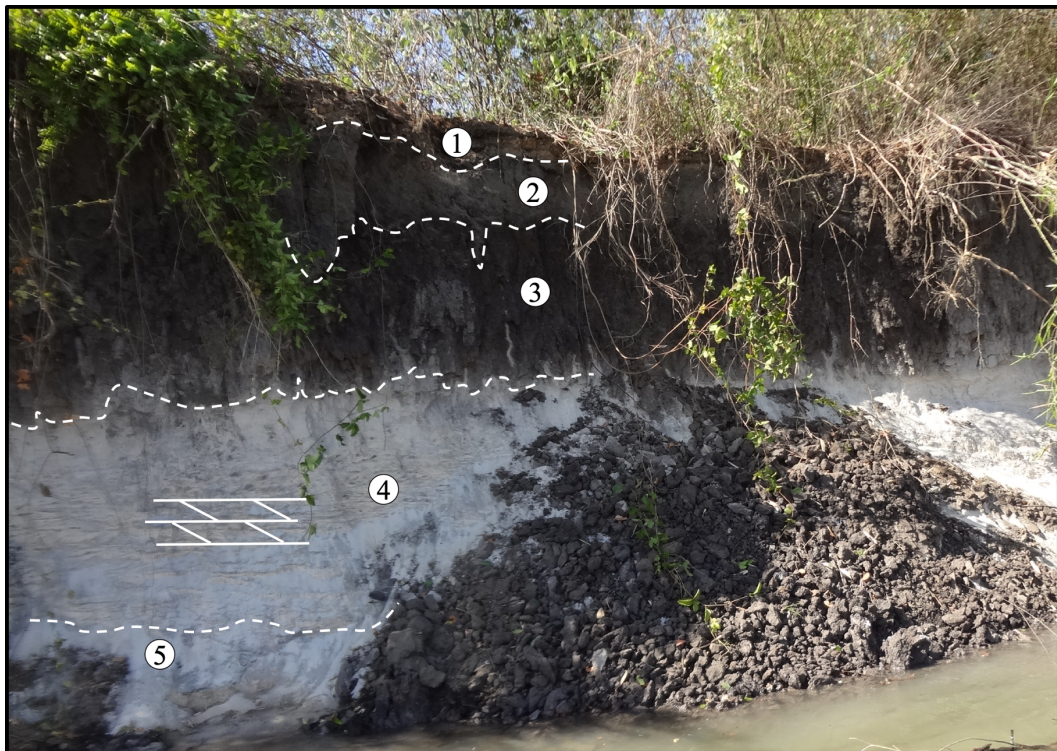


Figure 11. Lithological succession of Collapsed Ravine profile showing in general a whitish friable fine sand on the bottom (5 and 4) followed upward by a black organic-rich sand (3), correlated to a spodic horizon B, and then a pallid gray, little organic and sandy (2), the E horizon and finally at the top and thinner organic-rich with roots and plant debris, A horizon.

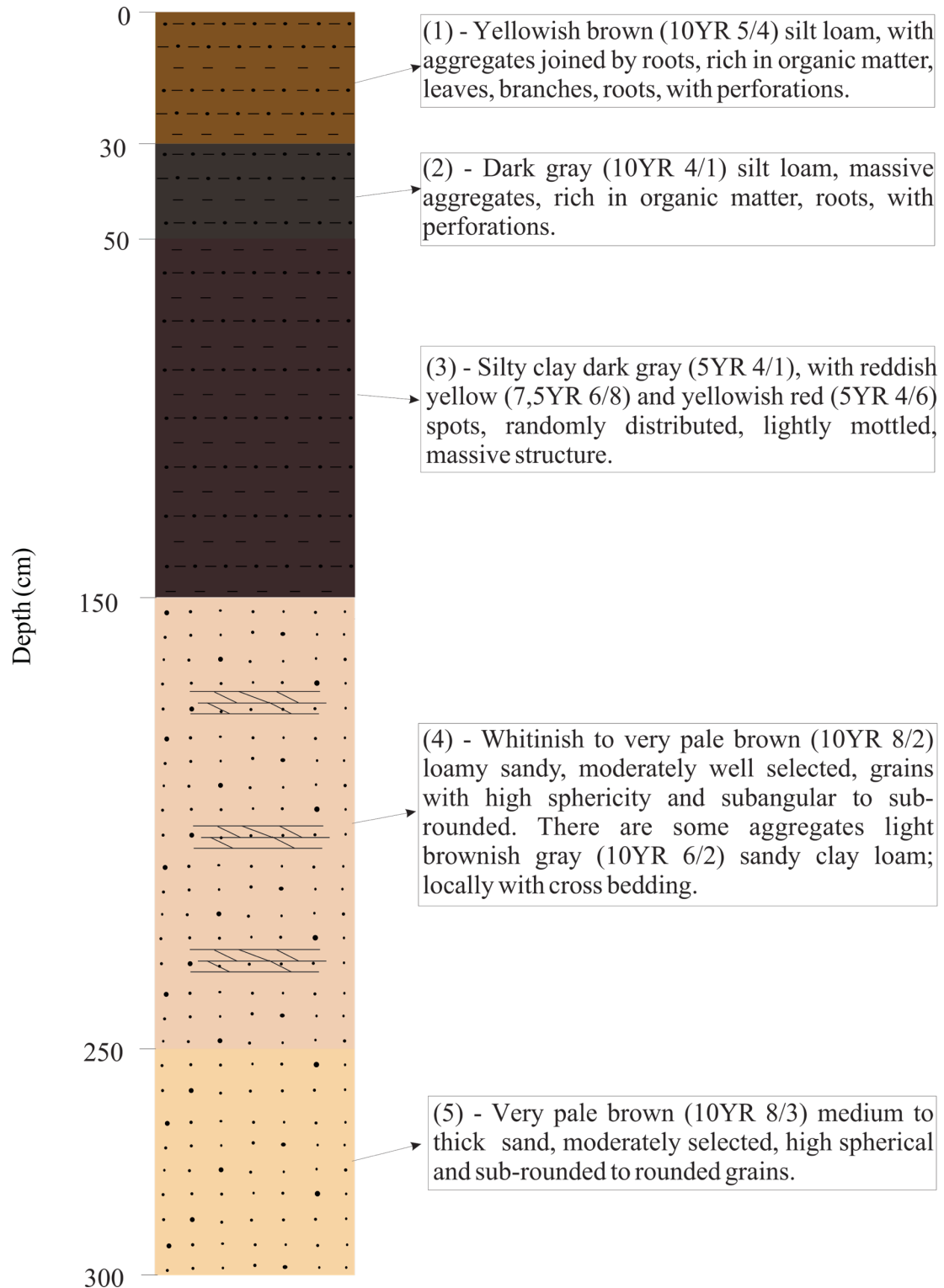


Figure 12. Schematic lithological succession of Collapsed Ravine profile.

3.1.4 Canguçu Harbor

The sediment cross section along the Canguçu Harbor (Fig. 13) shows locally a white to yellow sand unit, with cross bedding and parallel stratification, which is overlain by a thick unit (around 5 meters) composed of silt and clay, being normally silt on the lower part and

clayey silt on the upper part and then covered by a meter thick dark gray neo soil to gley soil which occupies continuously the terrain surface, and becomes very evident. The clayey silt to silty clay loam displays pale shades, sometimes presenting a yellowish red mottling, or massive structure and some fish holes, what are very frequent in this region. The upper part of this profile and the silt soil horizons are rich in roots and root perforation with a coloration ranging from very pale brown to dark grayish brown, much like the geological section of the White Barrier, which is located to the northwest of Canguçu.



Figure 13. General view of the silt to clay sediment top sequence along the Canguçu harbor with emphasis on the superficial gley soil horizon on the top.

In detail detached by the profile just on the Canguçu harbor one can observe lateral and vertical changing in the spatial distribution of silt and clay, as well as the mottling parties. Similar to what has been described in other sections in the Canguçu Harbor, sands of bars with flat-parallel stratification, also cross-bedding (Fig. 14), appear to be friable, stained yellow. On them silty clays were deposited with green clays (type lenses), which at the top assume a silty clayey nature with great lateral extension. In the contacts between silt and clay and between clay and sand is common the occurrence of yellowish areas, stains of iron hydroxides. At the top the clay silt layer gradually passes to a continuous horizon of dark gray, slightly columnar soil, gley soil (Fig. 14 and 15), as White Barrier. It stands out in the inferior and superior contact zone the yellow ocher ferruginous impregnation, that occurs nowadays in the beaches of Javaés river, that tends to be reddish. Possibly the green clay may correspond to a deposition in the common depression in the river sand bar zone. The columnar feature, with presence of roots, in gradational contact with the silty clay layer is a characteristic pattern of these soils along the northern of Bananal island.

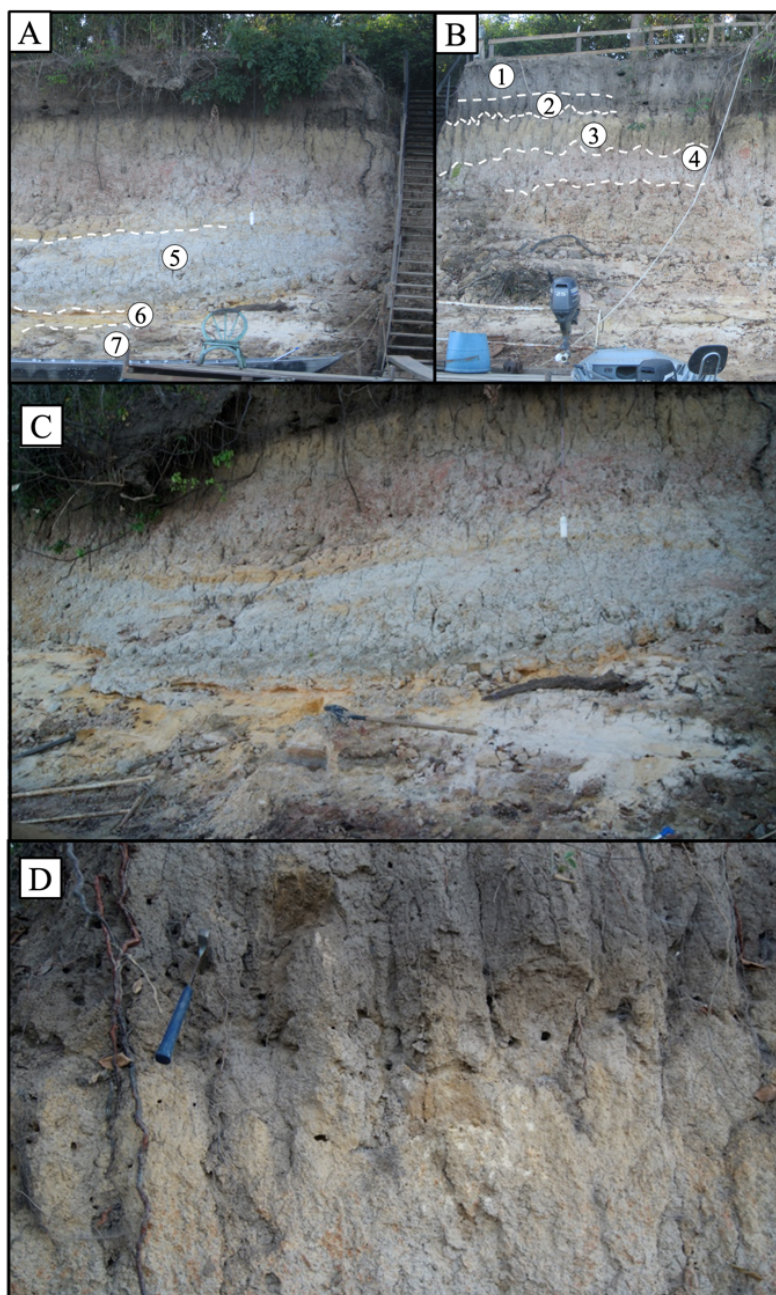


Figure 14. Lithological succession of Canguçu Harbor profile. A: Western view; B: Eastern view; C: Detail of the green massive clay loam deposited over the sand bar and involved by clay silt upward and laterally. It stands out in the inferior and superior contact zone the yellow ochre ferruginous impregnation, that occurs nowadays in the beaches of Javaés river, that tends to be reddish. Possibly a clay deposition in the common depression in the river sand bar; D: Lower zone of horizon A of the silty gley soil, light gray, showing the typical columnar feature, with presence of roots, in gradational contact with the silty clay layer. A characteristic pattern of these soils along the norther of Bananal Island.

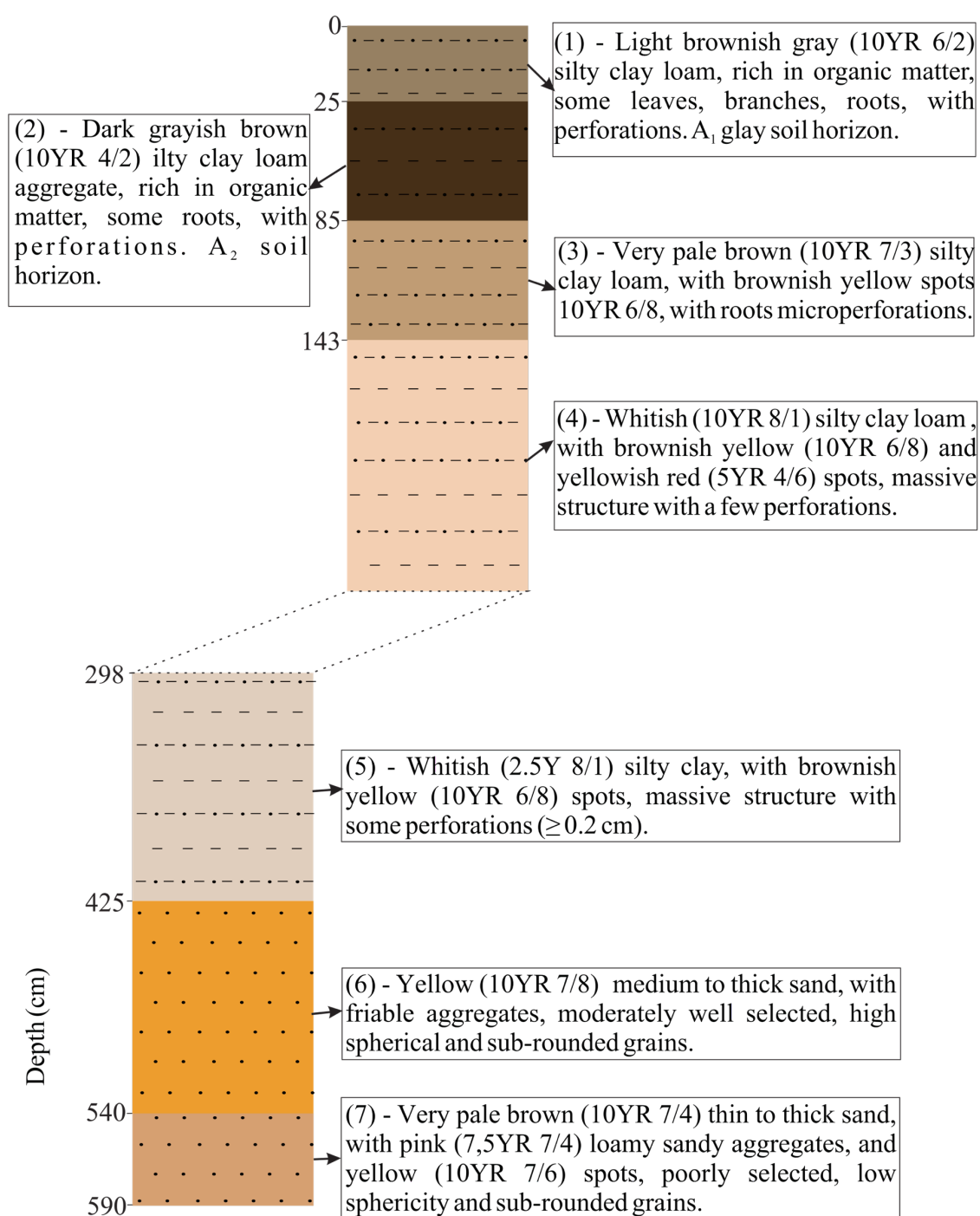


Figure 15. Schematic lithological succession of Canguçu Harbor profile.

3.2 The Neosols to Gleysols

The presence of gley to spodic soils north of Bananal Island is striking (Fig. 16), and is usually associated with a sandy substrate, either alone or deposited on a layer of silt and/or silty clay or direct on clay deposited over sand (Fig. 17). They discriminate very flat, generally still slightly low lands, in which the grasses stand out, but also form substrate of areas of shrub

or dense forest, this less frequent. Sand substrates generally represent riverbanks attached to each other and vegetated initially by grasses in this region.

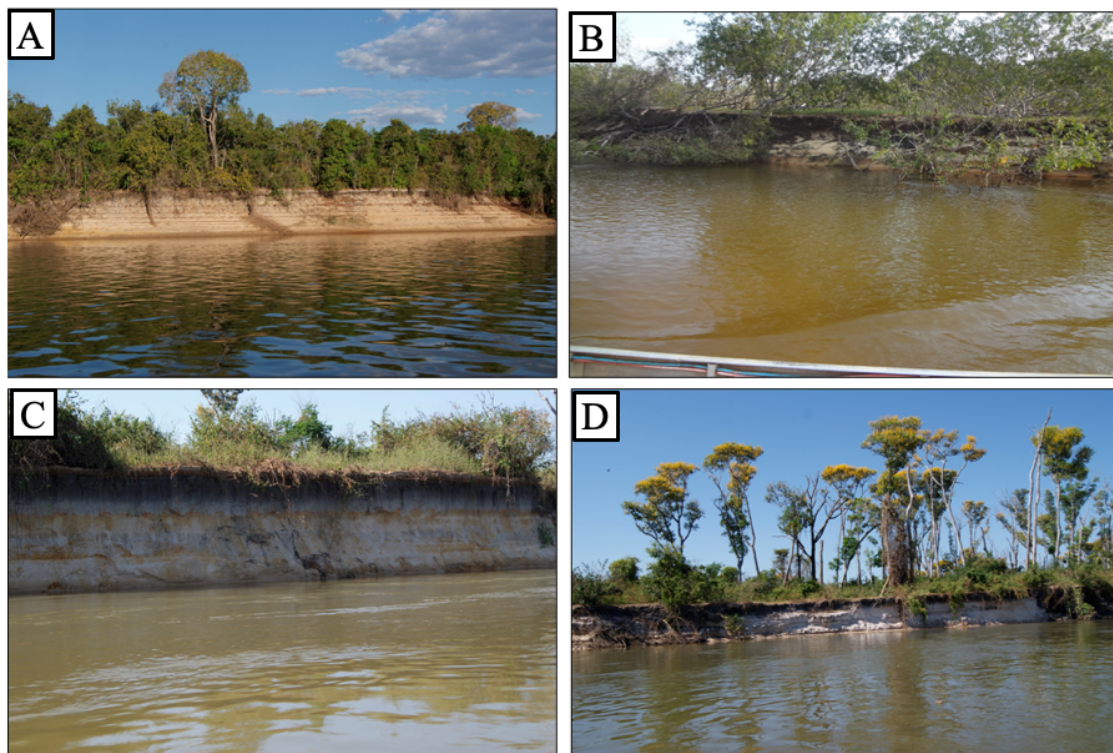


Figure 16. Distinct aspects of forests established over different stages of gley to spodic soil formation over sand river bars in the northern of Bananal island. A: An already vegetated young river bar starting the development of probable gley soil; B: partly river eroded old river bar with sandy gley soil; grassland and shrub dominate. C: Also, a typical gley soil over white sand river bar occupied by forest and grassland. D: Another typical gley soil showing a reducing condition (E horizon) and starting to form the B horizon for future spodic soil (yellowish iron hydroxides fronts).

The north of the Bananal Island stands out for the almost continuous occurrence of a horizon of gray soil, dark gray to black on its surface, with thickness ranging from 30 to almost 200 cm thick as already presented in Coco Beach (Fig. 2 and 3), White Barrier (Fig. 5 and 6), Collapsed Ravine (Fig. 11 and 12) and Canguçu Harbor (Fig. 14 and 15). The tonality is, as in most soils, given by the abundance of humus organic matter, as well as woody fragments and leaves mineralized. Normally is it silt-sandy to clay-silty. Its contact with the sediments below varies from gradual to abrupt, which may be mottled or not. A strong aspect of these soils is the tendency to present vertical columnar disjunctions, from pentagonal to hexagonal cross-section, which extends weakly to the sediments below. These columns however occur only when the nature of the silt-clayey soil. Vertical fractures accompany columnar disjunctions, just as pivoting roots are frequent and reach the lower layers just below. They suggest a long time of drought, leading to dehydration, which occurs in slightly clayey soils, where the clay mineral is at least in part 2:1.

These soils, however, formed on different substrates or derived from them (Fig. 17). Of particular note are those formed directly from clayey silt sediments, corresponding to old floodplain deposits (Fig. 17 A); or else on silt sediments deposited erosive over older mottled clayey silt sediments (Fig. 17 B and C) or on sands of young to old bars. The sandy black soils do not develop the columnar aspect, while, as already mentioned, the clay silt ones do.

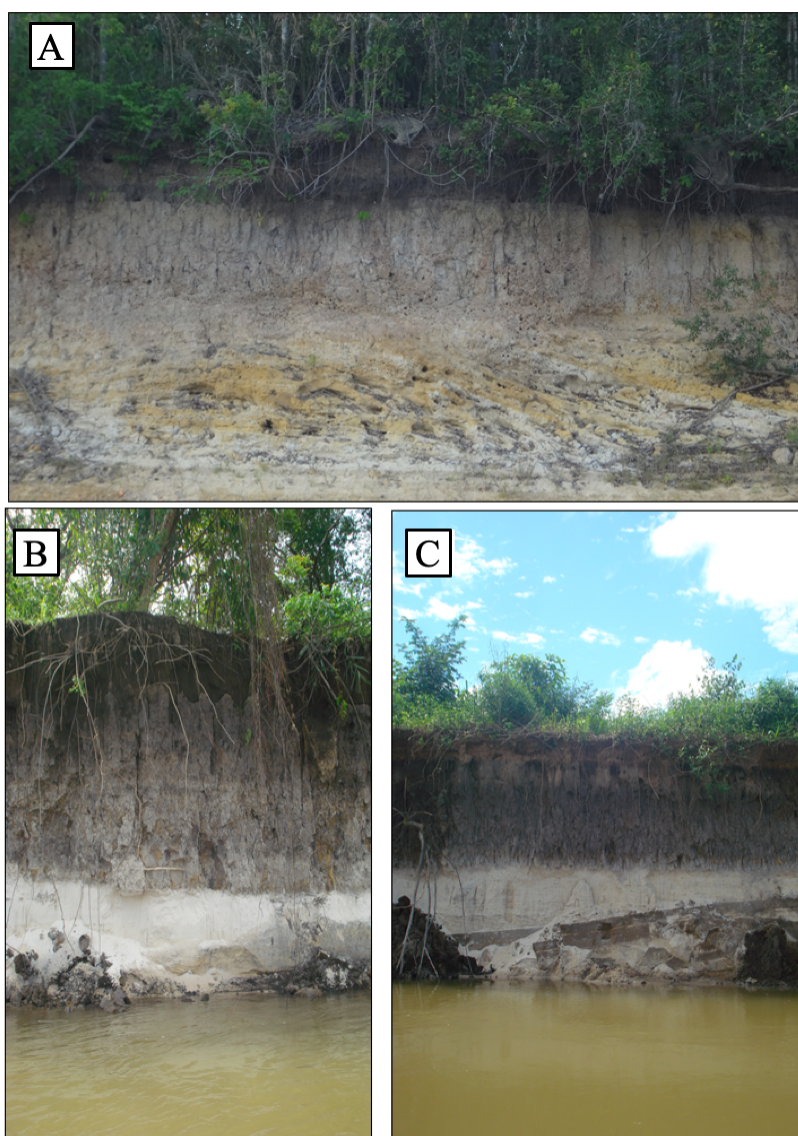


Figure 17. Three distinct occurrences of the dark soils (Gleysols) in the land surface in the Northern of Bananal Island. A. Dark soil A horizon formed direct over the clay silt layer, vertical fractured, columnar. B. Dark gray soil A horizon formed from new sediment deposited over white sand. C. Another gray A horizon, compact, vertical fractured, columnar, already obliterated by young flooding sediments, formed directly from clay deposited on sand.

3.3 The Reddish Film (muddy lamina) at Long Beach (Praia Comprida)

A very striking feature during the recent drought period of the Javaés river are the long, sometimes undulating, yellow to brown sand bars (river beaches), with of sub circular to

the ellipsoidal depressions, contoured by red rather than reddish films (Fig. 18), which extend to the water level of the river. They also cover the bottom and margin of the depressions, giving them a very special coloring. At the depressions tend to be thicker, taking on the appearance of iridescent muds, full of small-to-large bird-footprints, as well as feathers and much excrement. All in all, they describe an image of rare beauty. Locally this fine reddish iron hydroxide complexes in mm thick can be found centimeter deeper in sandy bar cementing the quartz grains in different parallel levels. In depressions it is common to find a grayish green zone just below the red muddy film, which has a strong, sulfurous odor corresponding to a possible reduction action of iron hydroxides and accumulation of organic matter and its mineralization. The red film and sand bar interface, the substrate of depressions, is an oxygen-poor environment, due to the non-renewed water and the activity of birds, fish, which are consumed by the birds, excrements, bones of these animals, and at the end lead to the formation of a reducing microenvironment, something like a eutrophication.

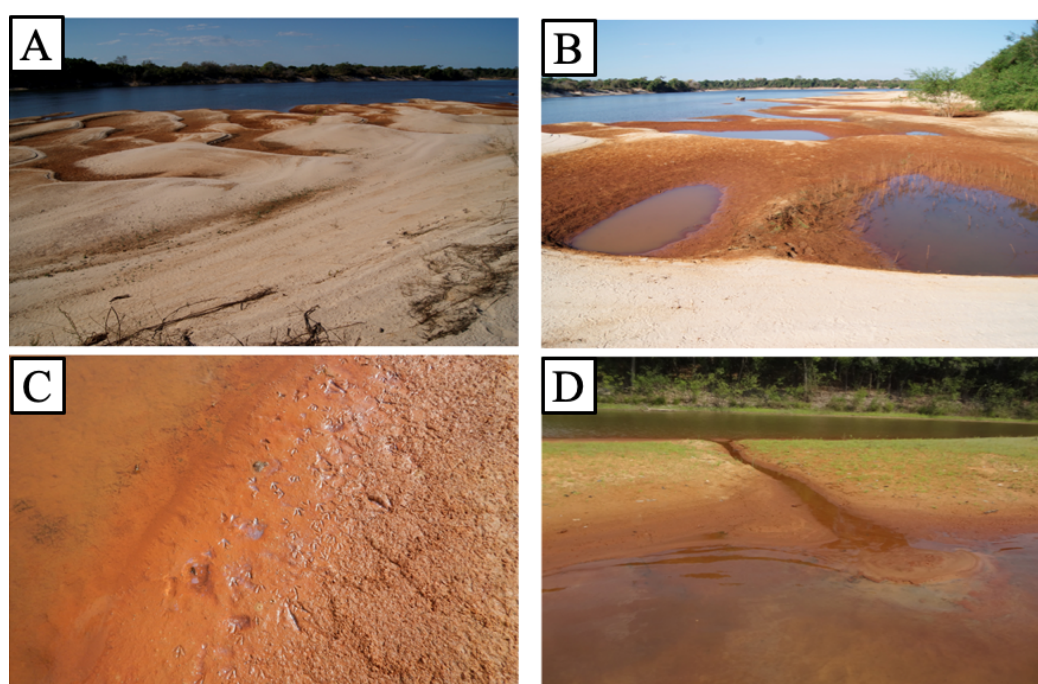


Figure 18. The reddish films or reddish thin muddy lamina on the sandy bars of the Javaés river. A. corrugated bars contoured by red films, in the same way their depressions covered by these films and muddy lamina; B. Well-developed depressions bordered by surficial red films and red muds in their interior. C. It shows the red mud on the contact zone between sand bar and the lagoon water and prints of bird movements are engraved in the mud. D. Canal interconnecting a small circular lagoon with the Javaés River, transferring red mud from this to the river. The sand of the boundary bar is impregnated with the same red complexes of the films.

The superficial red film converges to a thin red zone within which the quartz grains are surrounded by red films which converge to a grayish green (glei) zone below, and gradually

to the bar sand. The two zones together generally vary from 4 to 8 cm thick (Fig. 19 A thru C). This pattern can be observed in the most sand bars along the Javaés river.

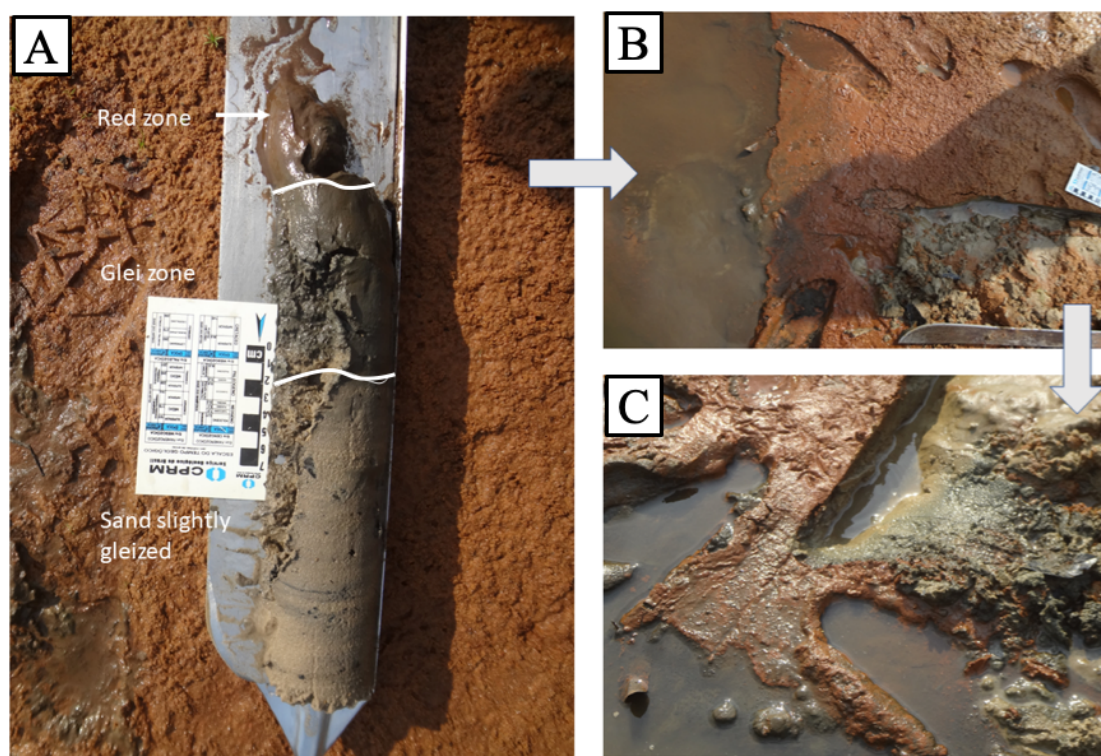


Figure 19. Transition of the oxidizing red film or reddish sand zone to the underlying reducing zone developed on the sand bar (river beach) on Javaés river. A. A 20 cm long sediment drill hole getting through the sand bar showing the reddish sand zone (film on the surface) converging downward to gley reducing zone, and then gradually to sand. B. A cross section along the red film and thinner reddish zone (4 cm depth) inside of the sand bar. C. Detail of the previous cross section showing on the right the gley reducing material and then the original sand bar.

The red color of the films and red zones is given by colloidal complexes consisting of iron oxyhydroxides whose formation was mediated by bacterial actions on the surface of the sands and also in the first cm of depth, as the water level of the river goes down. The resumption of water level rise may partially or completely destroy the products of this process. But on the other hand, the deposition of a new layer of sand may favor partial preservation.

The red film complexes are amorphous to XRD, with the exception, of course, of the quartz grains present. However, by FTIR it was possible to identify bands related to clay minerals equivalent to kaolinite, goethite and possibly illite (Fig. 20). The sample (3) of greenish-like gel shows a slightly different pattern, which was to be expected, the other is reddish-like gel, with the much stronger 3697 and 3621 bands, likewise at 914, 696, 537 cm^{-1} bands. Iron is not present as a ferric hydroxide, but possibly as an amorphous ferrous complex, responsible for the green color. The content of iron (amorphous) (Fig. 20) is 16.7% for C1, 12.5% for C2, both represented by red gel and 2.5% for green gel (Tab. 1), which confirms the expressive presence of iron in red and greenish gray complexes (gley), but decreases in depth.

SAMPLES	Fe_2O_3		
	Total (Wt. %)	Crystalline (Wt. %)	Amorphous (Wt. %)
C1 (reddish gel)	17.41	0.68	16.72
C2 (reddish gel)	14.77	2.30	12.47
C3 (greenish gel)	4.45	1.94	2.51

Table 1. Iron concentration in the reddish (C1 and C2) and greenish gels or colloids (C3) distributed on the sand bar surface along the Javaés river.

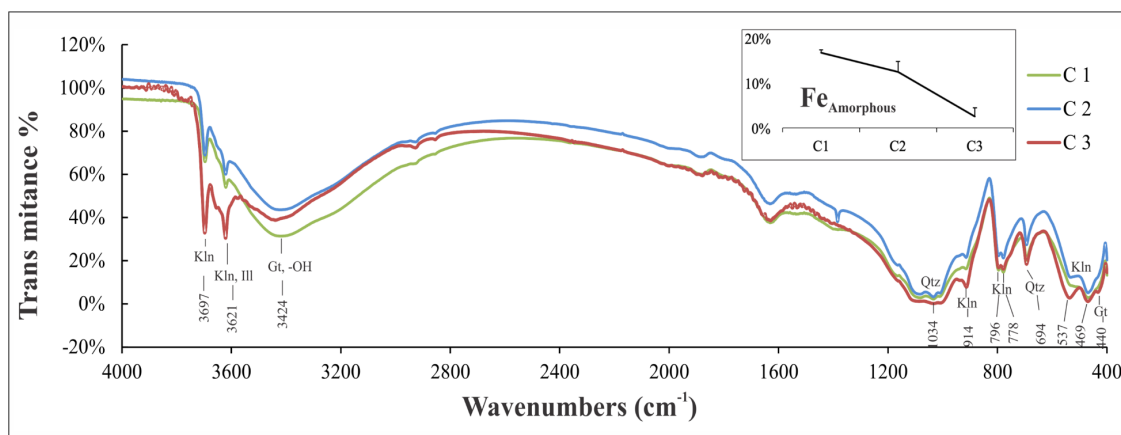


Figure 20. FTIR analyzes of red films (red gel) and green zone (green gel) from Long Beach, showing the possible sample mineral composition, as well the content of amorphous iron ($\text{Fe}_{\text{amorphous}}$).

The thermal analyzes show that the samples of red films C1 and C2 have a similar thermal behavior in TG, DTG and DSC (Fig. 21), so they resemble each other, as demonstrated by the FTIR analysis. The DTG curves allow to identify three important thermal events, around 112° C, 250°C and 460°C, perhaps at 950°C in C2. The events at 250°C and 460°C are represented by slightly greater mass loss (TG curve), although in general the mass loss gradient is accentuated and almost continuous until about 500°C, when it then becomes smooth and continuous until near 900°C. Loss of water of amorphous material (Fe hydroxides and amorphous opal in diatoms) is allowed, non-structural, compatible with the physical state of gel (colloid). Changes in physical states appear to have occurred at 250°C (very subtle), 573°C and 725°C (C1 only), representing the possible structural ordering of the ferric colloid in goethite/lepidocrocite, the displacive polymorphic transformation of quartz α (low temperature quartz) to quartz β (high temperature quartz) or opal to quartz, and metakaolinite, respectively. The endothermic peak between 975 and 1000°C in C2 seems to indicate the melting of metakaolinite on the way to mullite formation.

The DTG curve for C3, colloid or gray green gel shows endothermic events at 90°C, 265°C (irregular and subtle, unlike C1 and C2), 480°C, 573°C and 950°C, respectively representing changes in mass loss gradients, the strongest at 480°C. The DSC curve shows transformations at 90°C, subtle at 265° and clear at 480°, 573°C and 925°C, the same

transformations of C1 and C2, but with clear formation of mullite at 925°C. At 265°C it seems to indicate the oxidation of Fe^{2+} to Fe^{3+} , which diverges from C1 and C2.

In the red gel C2, similar to C1, the chemical analyzes obtained by SEM/EDS demonstrate the domain of O and Fe, while Al and Si are in less quantity, as red film involving the quartz grains and also as whole gel material, besides the presence of P (Fig. 22 A). The domain of O and Fe characterize the presence of iron oxides (hydroxides), as indicated by FTIR, however amorphous after XRD. The parallel pattern of Al and Si, side by side, in the EDS spectrum suggests the presence of kaolinite structure, but the more elongated asymmetry of the Si peak also recommends the presence of amorphous quartz or silica, such as diatoms (Fig. 22 B) very frequent. The presence of diatoms indicates a high relative concentration of soluble silica in the river waters. Phosphorus occurs locally, to a lesser extent, then by the presence of Fe and O, it can consider as possible amorphous iron phosphate, type vivianite, or a precursor of this mineral, as was established in Coco Beach.

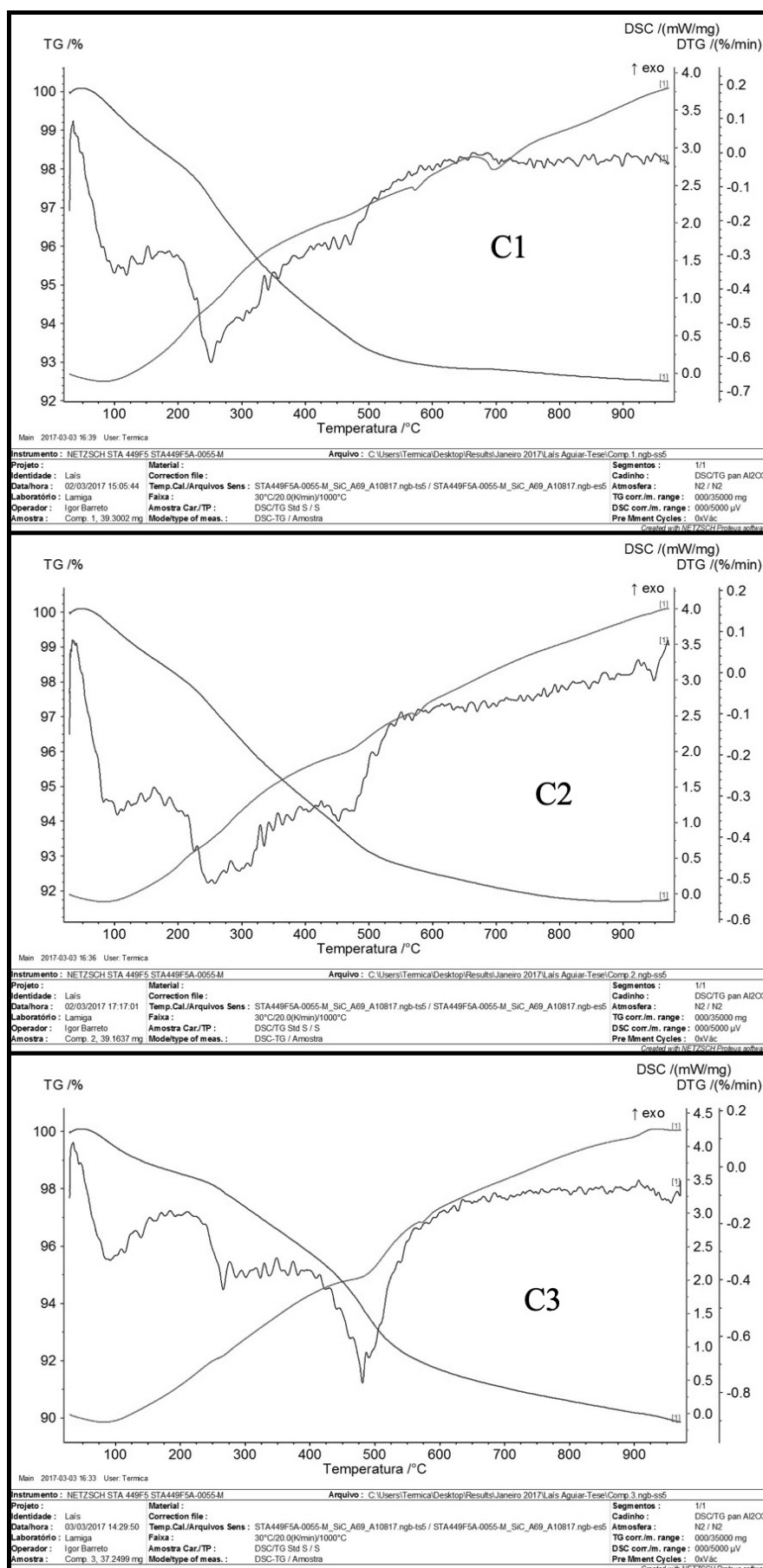


Figure 21. Thermal analyses of the reddish and green gel from red films and red and green zones.

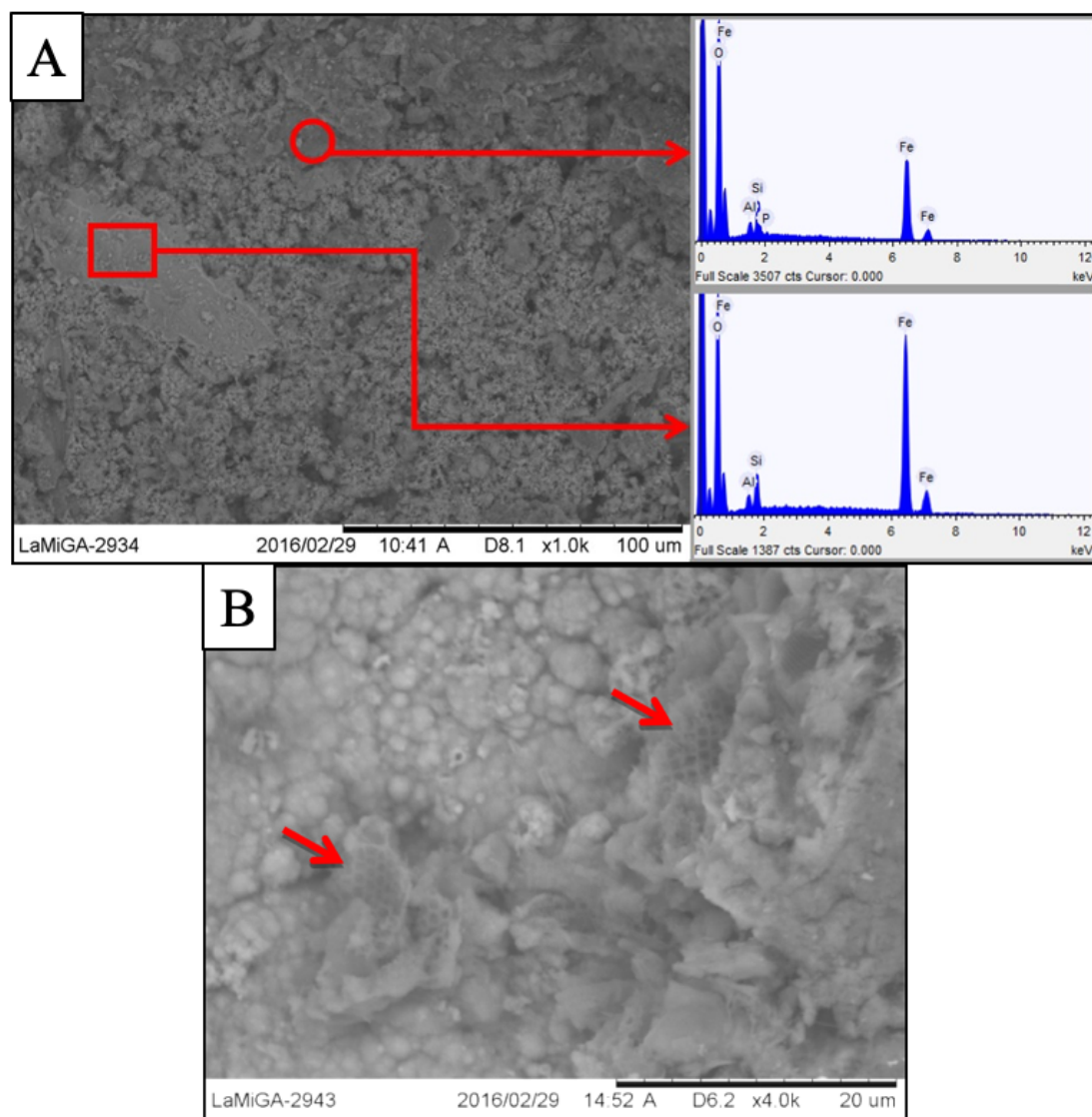


Figure 22. A: SEM/EDS analyzes of the red film or gel around the grain materials (minerals and organic) and of the cement showing the domain of O and Fe. B: Several diatom fragments in the red gel (red arrows).

3.4 XRD Mineralogical Composition

The XRD results of Coco Beach sediments (Fig. 23) showed mainly the domain of quartz, being kaolinite and illite/muscovite as accessory minerals in the clayey sediments and soil, rutile may be also present.

Quartz is also the main minerals of White Barrier being kaolinite and illite/muscovite however much more abundant than Coco Beach and probably rutile (Fig. 24). Kaolinite occurs in all the samples, being more frequent of course in the clay silt and illite is restrict to samples 10, 6, 5 and 4.

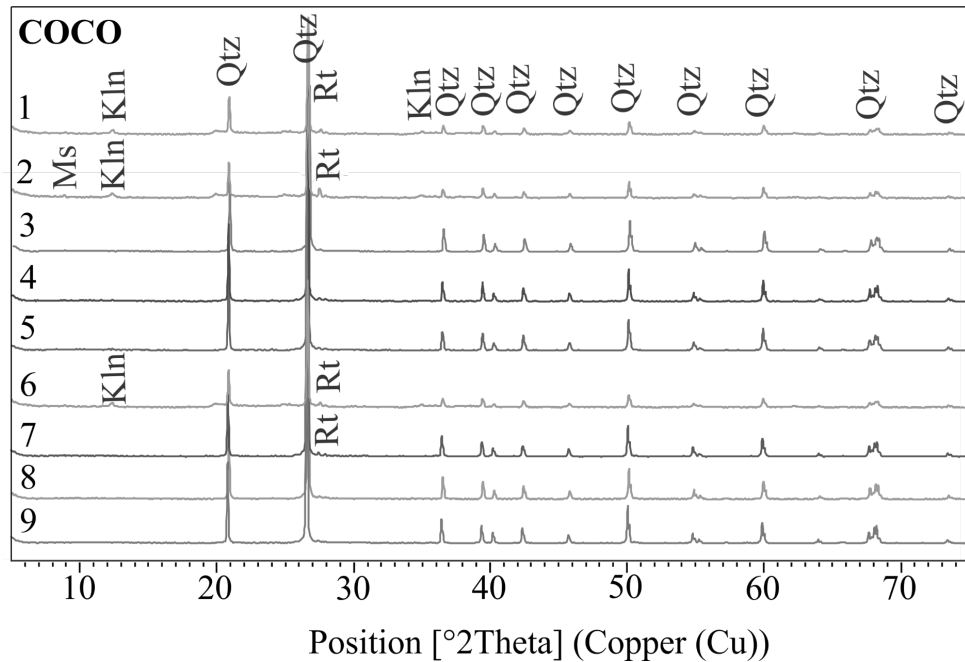


Figure 23. X-ray diffraction pattern from Coco Beach Profile (Coco). Kln: Kaolinite, Ms: Muscovite, Qtz: Quartz, Rt: Rutile.

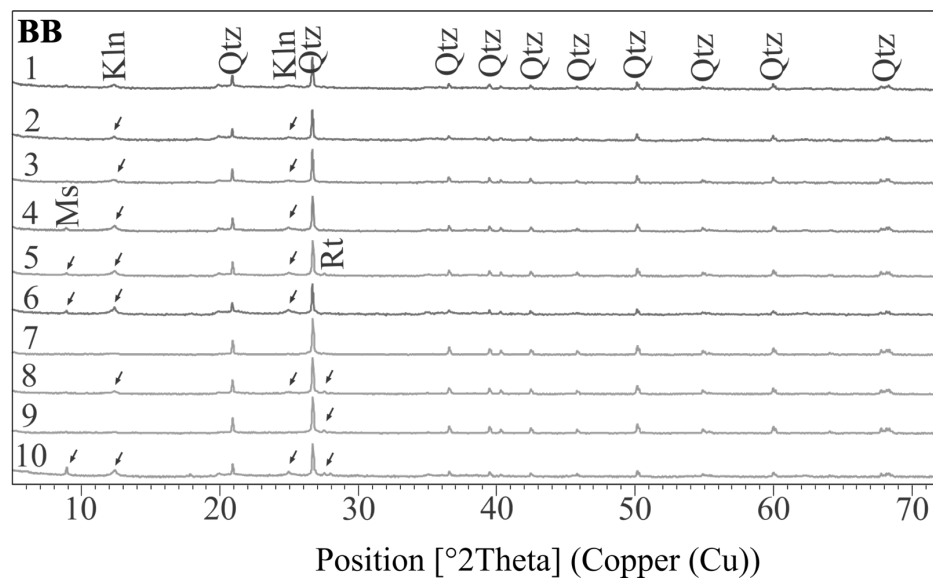


Figure 24. X-ray diffraction pattern from White Barrier profile (BB). Kln: Kaolinite, Ms: Muscovite, Qtz: Quartz, Rt: Rutile.

The main minerals which constitute the sediments of Collapsed Ravine are besides quartz, kaolinite (units 4, 3, 2 and 1), smectite (units 4, 3 and 2) and illite/muscovite (unit 1), and probably rutile (Fig. 25). These clay minerals become components of the probable B spodic horizon.

Again the main mineral constituent of the sediments of Canguçu Harbor (Fig26) is quartz; illite/muscovite (units 5, 4, 2 and 1) and kaolinite (units 5 to 1), which is much more frequent, and probably rutile, similarly to Coco Beach and White Barrier. The sand layer is only constituted by quartz after the XRD data.

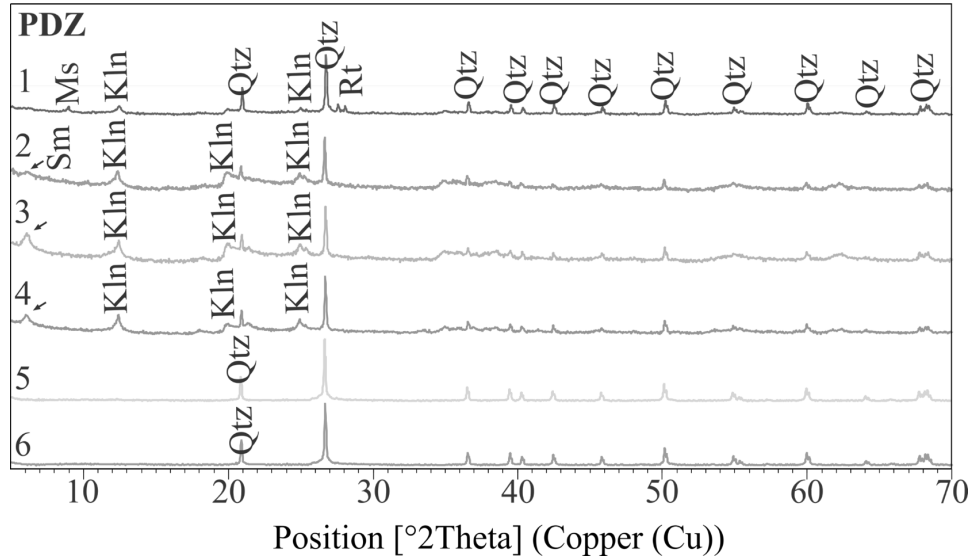


Figure 25. X-ray diffraction pattern from Collapsed Ravine profile (PDZ). Sm: Smectite, Ms: Muscovite, Kln: Kaolinite, Qtz: Quartz, Rt: Rutile.

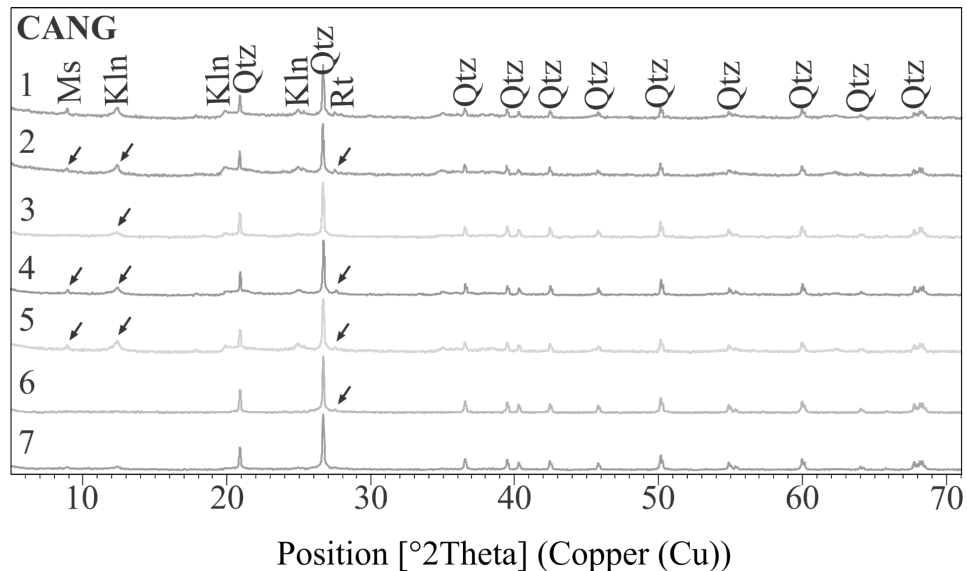


Figure 26. X-ray diffraction pattern from Canguçu Harbor profile (Cang). Kln: Kaolinite, Ms: Muscovite, Qtz: Quartz, Rt: Rutile.

The mineralogical analyzes of the clay fraction of each sample investigated by X-ray diffraction, on a glass sheet, under natural conditions, glycolated and heated to 550°C, allowed to better characterize the clay minerals (Fig. 27). These analyzes confirmed the presence of the minerals already demonstrated, and allowed to show the presence of smectite and seldom chlorite. The abundance of kaolinite, present in the vast majority of non-sandy samples, was similarly clear, as did the illite/muscovite as the second most abundant clay mineral. Smectite has been identified in clay fraction of most samples in all geological sections investigated, even in the fine sand spodic soil profile. This mineral contributes to develop the columnar

disjunctions, very common in the dark gray soil A horizon. Chloride was identified only in the fine sand spodic soil profile, which is very surprising.

The mineralogical constitution of all the geological sections investigated, sediments and soils is simple, dominated by quartz, in which kaolinite, illite/muscovite and smectite, rarely chlorite, make up the clay fraction of silty sediments and fine sand.

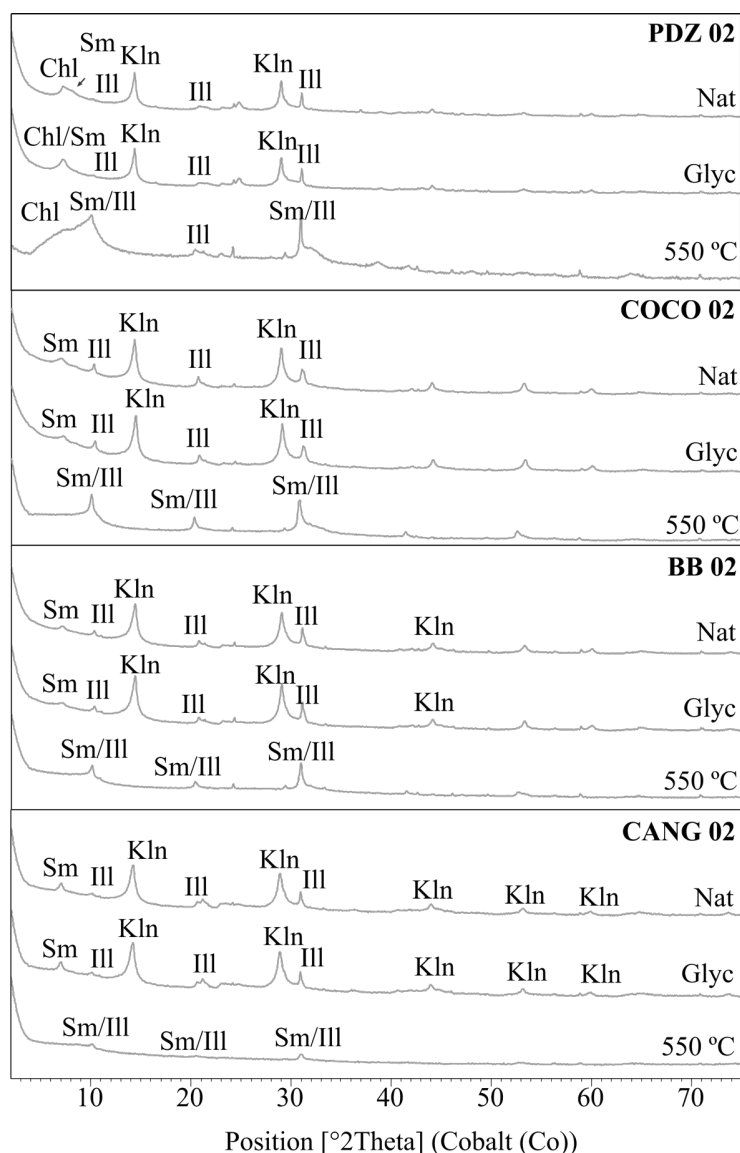


Figure 27. X-ray diffraction pattern of clay minerals from Coco Beach Profile (Coco), White Barrier (BB), Collapsed Ravine (PDZ) and Canguçu Harbor (Cang). Chl: Chlorite, Sm: Smectite, Ill: Illite, Kln: Kaolinite. Nat: natural, Glyc: glycollated, 550 °C: heated to 550°C.

3.5 Chemical Composition

The sediments and soils of the Bananal Island show a strong variation in the contents of chemical components (Tab. 2), which are basically represented by few ones: SiO₂ (37.5 to 99.5%), Al₂O₃ (0.35 to 19.4%), Fe₂O₃ (0.67 to 5.88%), K₂O (0.08 to 6.6%) and TiO₂ (0.05 to

1.5%). The contents of MgO (< 0.68 %) and P₂O₅ (<0.33 %) are low, however not negligible and of CaO, Na₂O and MnO very low, below 0.19 % (mostly < 0.11%), 0.27% (mostly < 0.13), 0.05%, respectively.

This large variation in the oxides content of the major and minor elements, which was expected after the grain sizes (sand and clayey silt), very well depicts the variation of quartz sands, which normally constitute the riverbanks, as substrate of the silt or clayey silt sediments of flood plains, besides the dark soil horizon rich in organic matter. These latter carriers of clay minerals, such as kaolinite, illite/muscovite and smectite, that constitute the silt-clay fraction. The high levels of LOI determined in the soil samples depict the high content of organic matter (humus) of these materials. The relatively higher contents of Al₂O₃ and SiO₂ are clearly responsible for kaolinite, and also for illite/muscovite, highlighted by K₂O, and also smectite, which is strengthened by the determined Fe₂O₃ (in part), MgO and CaO. Some relatively high contents of K₂O indicate that illite/muscovite can be abundant as well those ones of Al₂O₃ for high contents of kaolinite and/or smectite, when K₂O is low level. These chemical aspects are very important because X-ray diffraction analyzes tend to give an idea that these clay minerals are in small concentrations, which is not true, they can reach high concentrations in silt sediments. The relatively high iron contents do not respond to crystalline iron minerals (not identified by x-ray diffraction; however, by FTIR), but are correlated with the spots and with the ferruginizing fronts, therefore considered to be iron hydroxides amorphous.

The distribution of the contents of the major and minor elements throughout the investigated sections (Fig. 28) show in general terms similar patterns, especially in those of Coco Beach, White Barrier and Canguçu Harbor. The decreasing levels of SiO₂ and increasing Al₂O₃, Fe₂O₃, K₂O, among others, faithfully depict the quartz sand substrate and the silt and silty clayey sediments overlapping, and LOI at the top the domain of dark soil rich in organic matter. This behavior is also presented in the sand profile with gley or spodic type soil. It is practically possible to conclude that the SiO₂ contents are in opposition to the other major and minor chemical elements, in a negative linear or linear tendency correlation, that is, quartz against the clay minerals as shown in fig. 28 (and appendix I, tab. 3). And two groups of samples according to the chemical composition are also recognized: high silica/low aluminum + alkalis and low silica/high aluminum + alkalis, respectively, sands and clay silt, river bars and floodplains.

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	LOI	V	Cr	Ga	Rb	Sr	Y	Zr	Nb	Sn	Cs	Ba	Hf	Ta	W	Th	U
PDZ01	62	0.8	15	3.5	0.02	0.5	0.1	0.1	1.1	0.12	15.2	92	80	22.6	51.4	48.4	36.8	393	19.1	3	5	361	10.5	1.4	4.0	12.25	3.0
PDZ04	67	1.1	19	2.2	0.01	0.5	0.1	0.1	0.8	0.06	10.0	110	100	28.1	47	58.1	42.9	256	31.1	3	7.8	369	6.9	2.1	5.0	14.25	3.16
PDZ06	100	0.1	0.35	0.7	0.01	0.01	0.02	0.04	0.1	0.01	0.2	5	10	3.3	2.1	5.7	2.2	109	1.2	<1	0.12	32.2	2.8	0.1	1.0	0.91	0.31
BB01	38	1.5	16	5.9	0.05	0.7	0.2	-	0.9	0.1	23.6	190	200	-	60	-	130	820	-	-	2.2	-	-	-	-	-	-
BB05	74	0.9	14	2.9	0.02	0.3	0.1	0.1	0.7	0.04	7.4	68	100	21.2	29.8	32.2	20.6	566	17.8	2	3.11	240	14.1	1.4	4.0	11.1	2.81
BB10	66	1.1	16	4.3	0.01	0.5	0.2	0.3	1.4	0.06	9.0	102	110	24.1	55.2	70.1	43.2	529	23	2	4.21	502	14	1.6	4.0	13.45	3.13
COCO02	74	1.0	14	2.9	0.01	0.5	0.1	0.2	1.5	0.05	7.9	73	70	20.3	58.5	54	34.9	526	20	3	4.1	402	13.8	1.4	3.0	12.45	3.03
COCO07	93	0.2	2	2.1	0.01	0.1	0.1	0.1	0.4	0.13	1.5	15	20	5.4	10.5	20.6	5.8	168	2.9	<1	0.71	137	4	0.2	4.0	2.2	0.56
COCO08	95	0.1	2	1.3	0.01	0.0	0.1	0.1	0.3	0.33	0.9	9	10	4.1	9.1	18.5	3.7	81	2.9	1	0.32	126	2	0.2	3.0	2.1	0.36
CANG02	56	1.5	19	2.0	0.03	-	0.04	-	1.0	-	15.0	320	300	-	70	50	50	302	-	-	-	-	-	-	-	-	-
CANG05	66	1.2	18	2.9	0.01	0.4	0.1	0.1	1.2	0.03	9.2	95	110	27.6	44.8	51	41.3	575	30.4	3	4.37	462	15.1	2.6	4.0	13.85	3.33
CANG07	89	0.4	4	0.7	0.01	0.1	0.01	0.1	0.3	0.01	2.4	22	40	7.7	10	10.5	15.6	284	7	1	0.92	102	7.2	0.7	1.0	4.09	1.15
Average	73	0.8	12	2.6	0.02	0.3	0.1	0.1	0.8	0.09	8.5	91.8	96	14	37	35	36	384	13	2	3	228	8	1	3	7	2
UCC	67	0.6	15	5.0	0.1	2.5	3.6	3.3	2.8	0.15	-	97	92	17.5	84	320	21	193	12	2.1	4.9	624	5.3	0.9	1.9	10.5	2.7
PAAS	66	0.5	15	4.5	0.1	2.2	4.2	3.9	3.9	0.2	-	107	85	17	112	350	22	190	12	5.5	4.6	550	5.8	1	2	10.7	2.8

Table 2. Chemical composition for major and minor elements (%), as well as trace elements including the rare earth elements (REE) (ppm) of sediments and soils from Northern Bananal Island: Collapsed Ravine (PDZ), White Barrier (BB), Coco Beach (COCO) and Canguçu Harbor (CANG).

Sample	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	$\Sigma \text{ REE+Y}$	$\Sigma \text{ HREE}$	$\Sigma \text{ LREE+Y}$
PDZ 01	46.2	91.6	10.6	38.1	7.41	1.73	8.02	1.13	6.95	1.32	4.02	0.6	3.99	0.57	259	187	51.8
PDZ 04	73.9	128.5	14.75	51.6	9.25	1.82	9.17	1.18	6.9	1.42	4.41	0.65	4.07	0.53	351	269	58.3
PDZ 06	3.9	7.2	0.78	2.7	0.34	0.11	0.47	0.05	0.42	0.09	0.28	0.06	0.28	0.05	18.9	14.6	3.18
BB 01	-	67	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
BB 05	26.1	240	5.44	17.9	3.65	0.81	3.81	0.56	3.67	0.77	2.36	0.37	3.09	0.4	330	99.4	29.7
BB 10	56.4	502	12.45	41.8	8.8	1.65	9.08	1.24	7.03	1.37	4.02	0.62	4.15	0.63	694	223	58.4
COCO 02	41.5	79.3	9.14	32.3	6.42	1.32	6.86	0.98	6.04	1.22	3.58	0.54	3.61	0.51	228	48.13	162
COCO 07	8.4	14.2	1.79	5.8	0.93	0.26	0.96	0.15	1.03	0.2	0.64	0.09	0.58	0.08	40.9	8.05	30.2
COCO 08	5.6	10.6	1.17	4.1	0.76	0.13	0.79	0.08	0.61	0.13	0.36	0.09	0.36	0.1	28.6	5.03	21.5
CANG 02	-	119	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CANG 05	61.9	116	11.65	40.5	7.97	1.66	8.39	1.3	6.8	1.41	4.25	0.57	4.34	0.58	309	230	505
CANG 07	15.4	31.8	3.74	12.9	2.97	0.6	2.87	0.41	2.59	0.54	1.62	0.27	1.87	0.23	93.4	63.8	757
Average	34	117	7.15	24.8	4.85	1.0	5.0	0.7	4.2	0.85	2.6	0.39	2.6	0.4	235	115	168
UCC	31	63	7.1	27	4.7	1	4	0.7	3.9	0.83	2.3	0.3	2	0.31	169	128	31.3
Chondrites	1	2.608	0.394	1.937	0.629	0.237	0.835	0.153	1.04	0.231	0.68	0.104	0.674	0.103	36.6	5.94	29

Table 2. (continued)

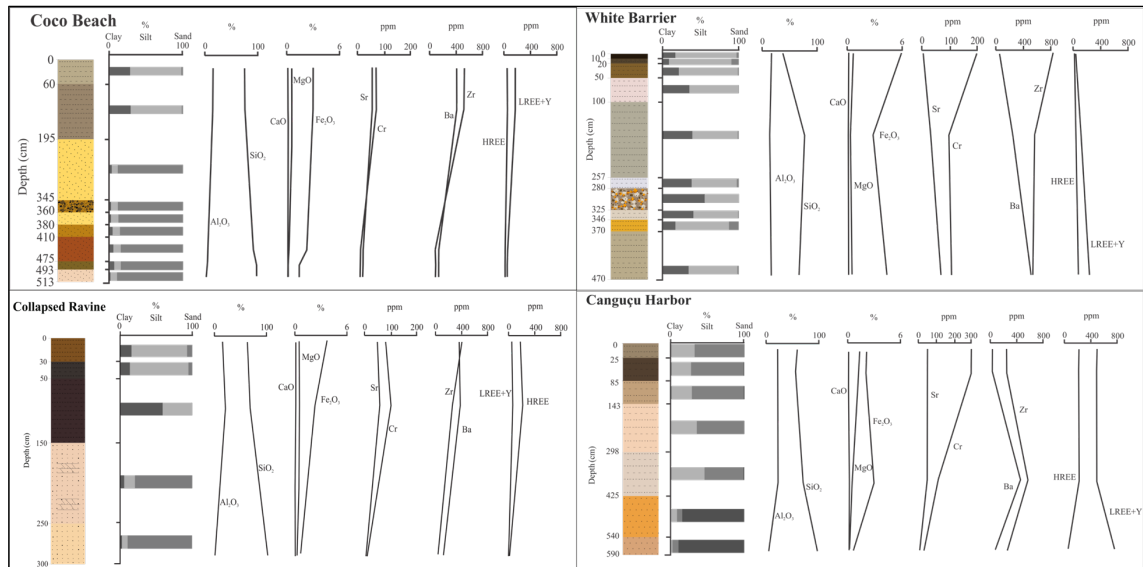


Figure 28. Distribution of the concentrations of SiO₂, Al₂O₃, Fe₂O₃, MgO, CaO, Sr, Cr, Zr, Ba, LREE+Y, HREE and grain size along the sediment and soil profiles of Coco Beach (COCO), White Barrier (BB), Collapsed Ravine (PDZ) and Canguçu Harbor (CANG).

The chemical contents of the analyzed samples when normalized both the chemical composition of the Earth's Superior Crust and the PAAS (Fig. 29) sediments show that the sediments and soils of Northern Bananal Island are impoverished in almost all elements. This becomes much more evident in Fig. 30, in which SiO₂, Al₂O₃ do not change and Zr, V, Cr, TiO₂ and Y are enriched clayey silts.

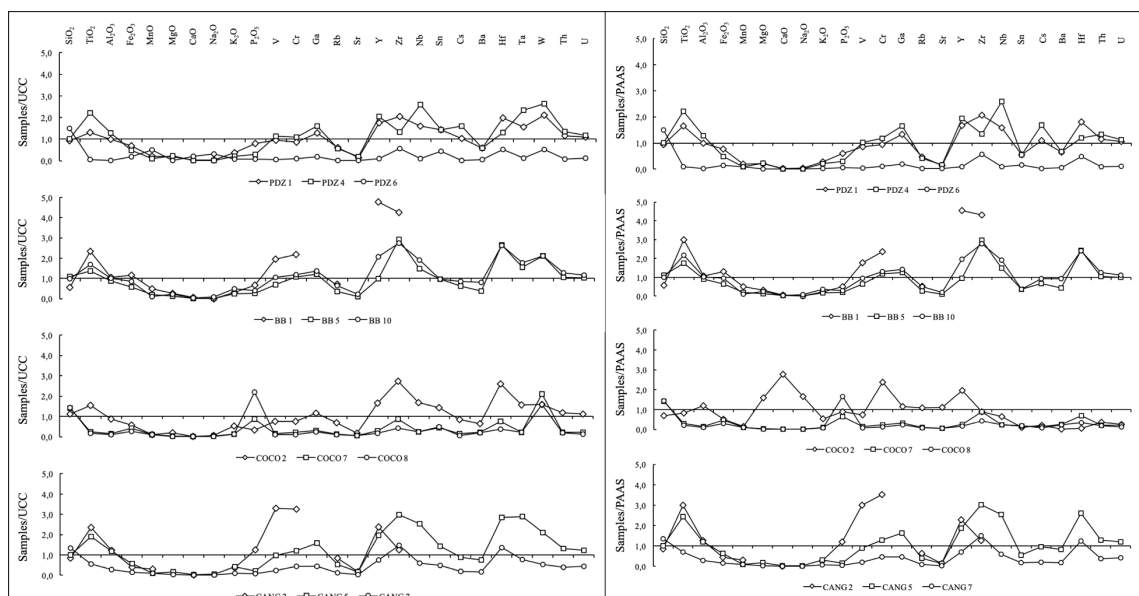


Figure 29. Chemical concentrations of investigated samples (Collapse Ravine, Coco Beach, White Barrier and Canguçu Harbor) normalized to UCC and PAAS (According to Taylor and McLennan (1985)).

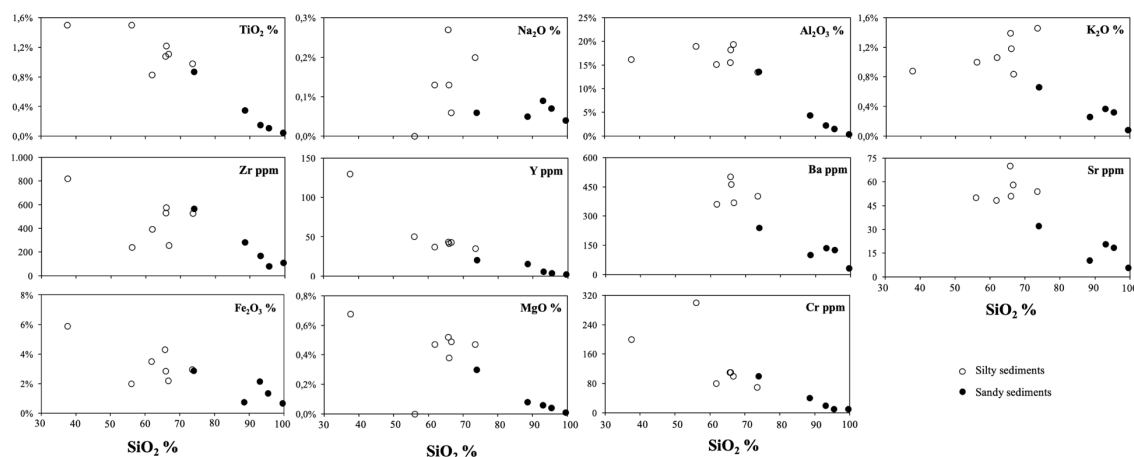


Figure 30. Hacker diagrams illustrating the negative correlations between SiO₂ and other major, minor and trace elements. Legend: open circles: silty sediments, close circles: sandy sediments.

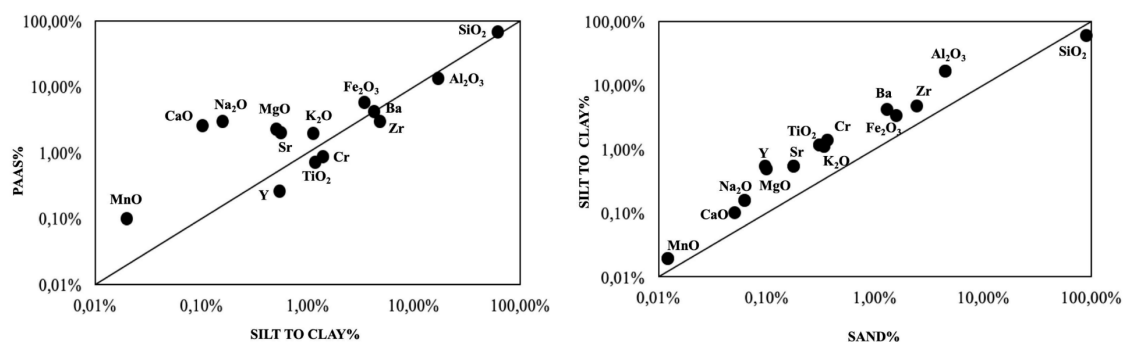


Figure 31. Correlation between the chemical composition of the silt to clay sediments against the PAAS and between silt to clay and sand sediments from Bananal Island.

If, on the other hand, we confront the silt to clay with the sandy sediments, it is clear that the clayey ones are enriched in all analyzed elements, except SiO₂. Therefore, clay minerals and amorphous iron hydroxides are the main mineral carriers of the chemistry of these materials, but the levels are below the PAAS values and the crustal average.

Concentrations of rare earth elements in the average are equivalent to crustal and PAAS average (Tab. 2), however in silty-clay sediments it is higher, while in sandy ones it is much lower. This behavior, which is similar to all investigated sections, demonstrates the importance of clay minerals (smectite and illite/muscovite) as possible single REE carriers, as already presented by Prudêncio *et al.* (1989), for sedimentary rocks mostly composed by smectite, illite and kaolinite. The respective normalized chondrite curves show enrichment in light rare earths, with slight negative europium anomaly (Fig. 32), compatible with those minerals, indirectly to feldspars from which they must have originated by weathering.

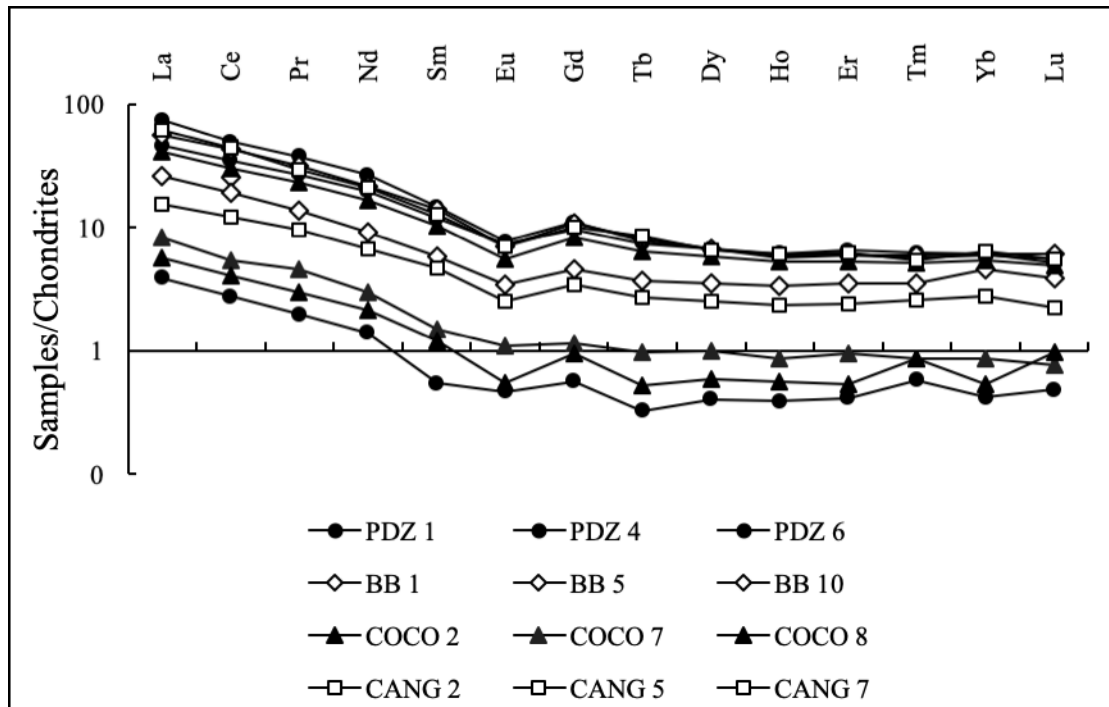


Figure 32. Rare earth element concentrations of investigated samples (Collapse Ravine, White Barrier, Coco Beach and Canguçu Harbor normalized to chondrites.

4 Discussion

4.1 River point bar formation and floodplains: from Medium Holocene to Actual

The geological and sedimentological data in the sections investigated in the northern region of Bananal Island (Fig. 33) allow us to recognize that it was the scene of meandering river channels with its marginal dykes and extensive and broad floodplains already in the Holocene. This extensive plain in the Late Holocene seem to be resumed by a new meandering river system, with formation again of marginal dykes and broad floodplains and ox bowl lakes or lakes between point bars (closed channels). Irion *et al.* (2016) on the other side already identified three flooding units: active floodplain, active paleo-floodplain and inactive paleo-floodplain. As shown, these three units are not so evident in north of Bananal Island.

The sediments are dominated by sand deposited in bars and channels, silts on the river dykes and silt clay to clay in floodplains and also in small depressions formed in the lateral evolutions of the bars. This development can now be observed in this region. The present rivers, especially the Javaés, are sculpting the previous river sediments and its floodplain sediments and from their constituents forming new bars, in general, colored horizontally and superficially by gels of iron hydroxides, which presents itself as a very characteristic and beautiful feature. These activities occupy the entire area and are responsible for the immense seasonal wet to dry lowland, which characterizes the northern portion of the Bananal Island. This land formed from

riverbanks extends inland, not yet vegetated, or only along the low sutures between them, while in the lands on the right bank of the Javaés river, similar bars, perhaps a little older, with lakes and “paranás” (river channels between sand bars) transformed into lakes, are already fully occupied by dense young forest. The morphology of these bars may be related to mid-channels to point-bars, typical for river of low discharge and meandering. The same can be concluded for the left side of this river in front of Canguçu and stations 3 and 4. In the right bank of the Araguaia River, where station 1 was described, dominated by sandy bars and silt deposits probably overlapping like marginal dikes, the vegetation is in the phase of installation. To the west, central zone, the bars are bare of vegetation and also of sediments type flood plain and / or marginal dikes. These described features can be clearly seen in recent images made available by Google Earth (Fig. 1). The actual channels of Javaés and Araguaia rivers are reworking these already deposit and not completely vegetated young fluvial sediments.

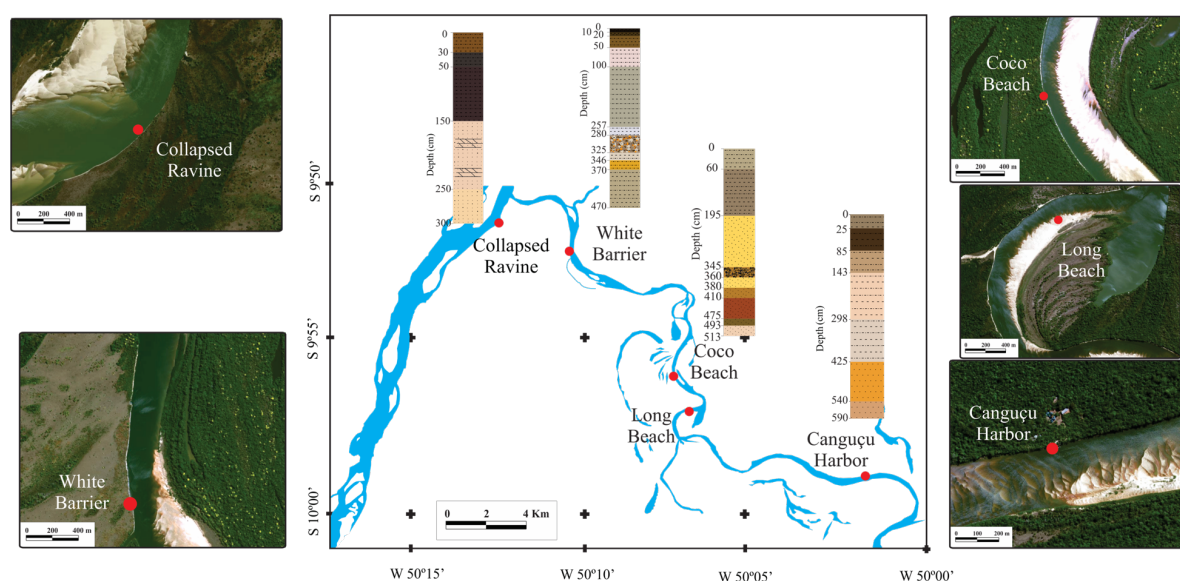


Figure 33. Geographical distribution of the main geological section on the northern of Bananal Island.

4.2 Older ferruginization of sandy point bars

The sandy sediment bodies or in the contact between these sediments and the silty in the recent past was reached by intense ferruginization (formation of red iron oxyhydroxides), which partially cemented the quartz grains of the sands, giving a crust appearance, and still stained the sandy body in the zone of contact with the silty ones. These fragile crusts partially support the cliffs. This ferruginization goes back to the oscillation of the fluvial waters during the drought and of the water table and does not represent lateritization processes. Similar

process will be observed in the young and actual river point bars. This another quite distinct aspect of the investigated region.

4.3 Gleysol and Neosol

The old sandy deposits of point bars and the older overlapping clayey silt sediments were partially covered by thin layer, less than 1 meter thick, dark in color, contains a lot of organic matter (plant detritus), grass roots and humus, and is fully correlated with gley or neosol soil profiles, and together they become a striking feature of the lowland plain in the north of the island. In general, presents vertical fractured and exhibiting typical columnar disjunctions. A luxuriant, medium-sized vegetation is developed over it. This material is a typical feature of the low plain on the north of Bananal Island.

4.4 Erosion and Sedimentation (Fluvial and Lacustrine)

According to the data obtained, the low flat plain of the northern portion of Bananal Island represents an active system of lateral erosion and sedimentation river to fluvio-lacustrine, as already identified by Latrubesse *et al.* (2009) and Valente and Latrubesse (2012) on the island as a whole, although apparently older. The Javaés River apparently settled on ancient river sediments deposited also on long plains. The Javaés River apparently settled on ancient river sediments deposited also on a long plain. Different types of bars, from small to large extensions are established along the riverbed, which in their lateral evolution give rise to lakes between bars and at the time of flooding partially cover the previous gley soils, in a new phase of floodplain lowland sedimentation.

4.5 Actual Ferruginization

The red-stained sands of the bars at the current points, markedly in the Javaés river, besides constituting a beautiful visual scenery, represent a new event of ferruginization of these bodies during the low-level season of the waters of that river. The gel aspect, rich in amorphous iron oxyhydroxide complexes, show the very young nature of the same, and contrary to the previous condition, they still do not cement, but only stain the grains and create a moist mass around them. Some depressions within the bars accumulate more of these gels and create an underlying reducing environment. Indicative of the reducing conditions is the presence of ferrous minerals such as vivianite, which readily forms in the depressions, which are the scene of animal life (fish and birds), which add to these waters P and C coming from the dissolution of their excrements and bones. Therefore, a resumption in a short period of time, without

involving rock alteration, as with laterite weathering. These iron gels demonstrate the high concentration of iron in the fluvial waters of the region, which drain the oldest rich bodies in that element, and at the same time a new phase of iron enrichment in the sand body. Iron rich rocks (laterites) are common in the neighboring region (Valente, 2007) and may be iron source for these ferruginization. The formation of iron oxyhydroxides and gley soils and of slightly mottling demonstrates that the northern part of the island cannot be characterized as a typical wetland, but with low, flat terrain, with great contrast in water availability, droughts and floods.

4.6 Vegetation

The vegetation diversity north of the island is clearly controlled by the mineralogical, particle size nature and age of the substrate, and the time of contact with river waters (seasonality and flood zones). Grasses occupy the quartz sandy banks, the margins of lakes and channels, and semi-evergreen and evergreen marshes. Its persistence contributes to the accumulation of organic matter and formation of organic soil, and below this the gley soil and same times a little bit spodic soil. In areas occupied by floodplain sediment, clay silt and silt clay, with the presence of clay minerals (smectite and illite, sometimes chlorite, which may release Mg, Ca, K, Si and P for the soils), and therefore higher fertility, medium-sized forest is rapidly developing since unaffected by long flood season. Valente *et al.* (2012) associated the floodplain with gallery forest, that occurs along of the inner rivers of the Bananal Island, which contributes significantly to the maintenance of the region's biodiversity. Availability of water and high concentration of nutrients associated with the portion of internal relief of the floodplain, allow the development of gallery forest. This unit develops from sandbanks, where they are colonized by Myrtaceae and continue to increase in size according to seasonal floods, consequently the gallery forest is expanded.

4.7 Weathering and Sediment Provenances

The mineral and chemical composition of the sand and clay sediments on the north of the Bananal island, dominated by quartz, or quartz and kaolinite, besides illite and smectite, rutile as accessory, however, minerals of Si, Al, Mg, Ca, K, and Fe, show a provenance from acid rock composition submitted to deep tropical weathering. Similarly, trace element concentrations including REE confirm the affiliation with acid rocks and their distribution controlled primarily by the clay minerals typical of the tropical zone. The comparison between various chemical alteration indexes (Fig. 34), calculated for these sediments and soils and for

some reference standards, such as those of the upper continental crust (UCC) and PAAS, they confirm the high degree of weathering that materials underwent in relation to these same standards. However, with average values of CIA (Chemical Index of Alteration) around 97 and CIW (Chemical Index of Weathering) around 89. The STI (Silica-Titania Index), developed specially to measure the degree of weathering of metamorphic rocks, presents an average value of 78, that is corroborating to the chemical alteration of the studied sediments.

The great variation in the chemical composition in the sediments and soils in itself reflects the grain size (sand for quartz domain; silt and clay for quartz plus clay minerals), and therefore the energy of the water drainage. Normally the sand domain at the base of the profiles and of silt and clay with organic matter at the top. The chemical stratigraphy observed in the sediments of the trails is mirrored by the decrease in SiO_2 values and increase of Al_2O_3 , MgO , CaO , K_2O and LOI (mainly organic matter) towards the top (Fig. 34).

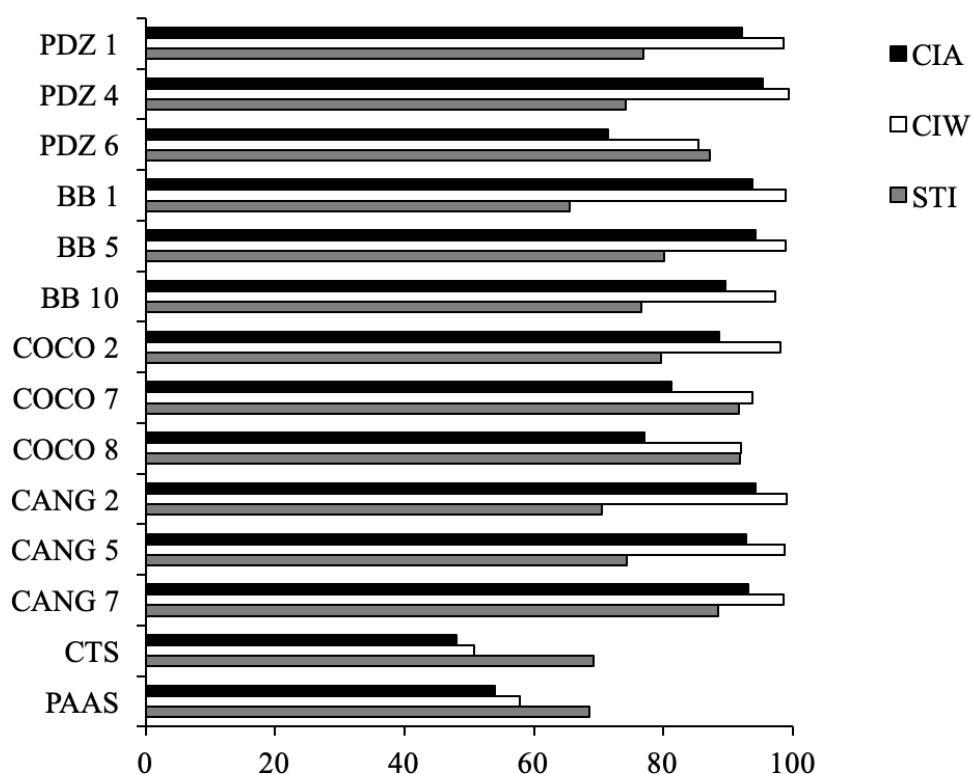


Figure 34. Distinct weathering indexes (CIA, CIW and STI) applicated to analyzed sediments and soils at Northern Bananal Island.

4.8 Landscape evolution

The data obtained in the geological sections investigated north of Bananal Island show that this region probably in the Middle Holocene was a meandering river scenario, with intense

erosive and sedimentary lateral activity over a vast plain, and apparently with poor vegetation cover.

Probably this dense drainage network already reworked sandy, silty and clayey sediments, which in addition to quartz contained clay minerals such as kaolinite, illite/muscovite and smectite, perhaps iron oxyhydroxides. The presence of silica and soluble iron complexes is indicated by the systematic presence of diatoms and ferruginous armoring. It is very likely that part of the smectites and chlorite are newly formed in situ due to the presence of these components and Mg and Ca in river water.

In turn, it is very likely that almost the entire fluvial region has become a marshy grass forest-occupied environment by indicated by the almost continuous gley soil cover of dark, sometimes spodic nature, organic soil that reaches up to 1 m in thickness, a typical wetland. This material is tempted to contain chlorite and smectite and to be enriched in trace elements as well. This landscape promoted very likely neoformation of smectite and chlorite and dissolution of iron oxyhydroxides and consequently the yellow iron front and spodic soils.

Finally, in the Late Holocene the gley soils experienced a relative long term of drying represented by vertical fracturing and columnar disjunction formation.

In the last centuries the landscape of gley soils has been taken over by a new meandering river event, eroding it and forming new bars, in a similar lateral process to the previous one, including the development of iron amorphous oxyhydroxide gel rusting, staining red the point bars, giving them rare beauty.

5 Conclusion

The terrain outcropping on the northern portion of Bananal Island represent a fluvio-lacustrine geological-geomorphological evolution during the late Pleistocene, probably mainly during the Holocene, and comprise at least four major events: A meandering fluvial phase over probably already fluvial land, with formation of extensive floodplain. Intensive and extensive chemical precipitation of iron hydroxides partly cemented the sandy bodies, forming crusts that make their subsequent erosive phase difficult. This landscape was the scene of extensive cover formed by gley soils, which represent a typical marshy environment or wetland, that led to the partial remobilization of iron hydroxides leading to the ochreous fronts of iron hydroxides. It was a moment of dense vegetation formation. A phase of drying condition reached the gley soil landscape indicated by intensive formation of vertical fracturing and columnar disjunction. And finally, this landscape was resumed in the late Holocene by new meandering fluvial activity

beginning with rusting indicated by the intense formation of amorphous iron hydroxide gels. The river water bear in solution Fe complex and silica, allowing the formation of Fe hydroxides and diatomaceous, respectively, and probably Ca, Mg and K, giving rise to some smectite and chlorite neoformation.

The generally similar chemical (major and trace elements) and mineralogical composition, varying only according to the size of the grains, sand and/or silt/clay, show that the investigated sediments had a common source, probably acidic, aluminosilicate rocks, submitted to tropical weathering, that in the Bananal island experienced locally reducing conditions promoted by the gley soils and paralytic waters in the marshes and depressions on the beach.

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Appendix

	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Cr	Ba	Sr	Zr	Y	CIA
SiO ₂	1															
TiO ₂	-0,94	1														
Al ₂ O ₃	-0,87	0,95	1													
Fe ₂ O ₃	-0,82	0,69	0,61	1												
MnO	-0,76	0,59	0,40	0,64	1											
MgO	-0,73	0,65	0,68	0,85	0,35	1										
CaO	-0,69	0,56	0,49	0,95	0,54	0,77	1									
Na ₂ O	0,03	0,04	0,16	0,27	-0,50	0,40	0,30	1								
K ₂ O	-0,69	0,78	0,81	0,65	0,15	0,70	0,54	0,62	1							
P ₂ O ₅	0,24	-0,39	-0,38	0,01	-0,05	-0,08	0,12	0,01	-0,23	1						
Cr	-0,82	0,87	0,75	0,46	0,72	0,24	0,35	-0,27	0,49	-0,37	1					
Ba	-0,14	0,25	0,46	0,27	-0,49	0,56	0,30	0,84	0,69	-0,08	-0,17	1				
Sr	-0,32	0,50	0,68	0,20	-0,31	0,37	0,15	0,66	0,79	-0,21	0,28	0,81	1			
Zr	-0,76	0,71	0,63	0,86	0,55	0,82	0,81	0,23	0,63	-0,27	0,43	0,32	0,15	1		
Y	-0,91	0,79	0,64	0,83	0,84	0,71	0,72	-0,16	0,48	-0,14	0,69	-0,08	-0,01	0,76	1	
CIA	-0,76	0,80	0,83	0,47	0,40	0,54	0,34	0,00	0,58	-0,41	0,64	0,30	0,44	0,61	0,56	1

Table 3. Correlation matrix for sediments and soils in the Northern part of Bananal Island.

4.2 ARTIGO 2: VEGETATION DYNAMICS FROM A FOREST-SAVANNA SEASONAL WETLAND AREA IN THE BANANAL ISLAND, BRAZIL DURING THE LATE HOLOCENE



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VEGETATION DYNAMICS FROM A FOREST-SAVANNA SEASONAL WETLAND AREA IN THE BANANAL ISLAND, BRAZIL DURING THE LATE HOLOCENE

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ABSTRACT

A sediment core from Lake Quatro Veados in a seasonal wetland from the Bananal island, located in the Tocantins State, Brazil, was studied by pollen and charcoal analysis. Two sediment subsamples were dated by AMS-radiocarbon dates indicating that the sediments were deposited during the last about 2200 years. The Late Holocene environmental changes were inferred by predominant forest, savanna and marsh/lacustrine vegetation identified from 72 pollen types and other palynomorphs. From 2.190 to 1.470 cal yr BP were found the marked presence of forest taxa including *Bambusa*, *Cecropia*, Moraceae/Urticaceae, *Sebastiania*, Rubiaceae, *Sloanea* and Melastomataceae/Combretaceae. Savanna vegetation was dominated by Poaceae and marsh/lacustrine vegetation was less important, dominated by Cyperaceae, *Eichhornia* e *Sagittaria*. Since 1.470 to 590 cal yr BP the vegetation was similar to the previous phase except for a maximum of *Cecropia* at the end of the period indicating vegetation regeneration. The final phase began after 590 cal yr BP and extended until the present-day being marked by the increase of marsh/lacustrine vegetation while the forest maintained stable until reduces in the present day. Savanna decreased slightly in the end of this phase. In a general way, this palynological record revealed a vegetation stability and the few changes in the vegetational composition noticed during the last two millennia were induced by higher or lower water level of lake. Our results are supposed to be useful to improve the understanding of the articulate spatial-temporal patterns of environmental changes in Amazon forest –savanna ecotone and wetlands areas.

Keywords: Forest – Savanna – Wetland Dynamics, Pollen Analysis, Bananal Island, Brazil, Late Holocene.

1 INTRODUCTION

The interest about the paleoclimatic and paleoenvironmental history of global landscapes, especially those that are currently under tropical climate, has grown in recent decades. In this perspective, the studies purpose to understand the processes of evolution of these landscapes under the climates that govern such processes. Among these studies are those of sedimentological character (Turcq *et al.*, 1993), geomorphological (Valente *et al.*, 2013), isotopic (Desjardins *et al.*, 1996, Gouveia *et al.*, 1997) and palynological (Absy *et al.*, 1991, Behling 2002, Behling and Costa 2004), which have contributed to the reconstitution of the Quaternary landscapes and climatic changes, that were submitted during this period.

In the Amazon region, changes occurred in the Pleistocene, and especially in the Holocene, are observed both in forest regions (Behling *et al.*, 2001; De Oliveira and Curtis, 2001; Bush *et al.*, 2004), and savanna regions (Freitas *et al.*, 2001; Pessenda *et al.*, 2001; Rodríguez *et al.*, 2005; Hermanowski *et al.*, 2012; Meneses *et al.*, 2013 and 2015, Rodríguez-Zorro *et al.*, 2017).

Various paleoclimatic events and the Intertropical Convergence Zone influenced the paleoecological records so that, despite the few studies, it is possible to infer that the climate was not constant during the Holocene in the Neotropical region (Irion *et al.*, 2006), although the authors did not notice a substantial change in the landscape during that period. Differently, Absy *et al.* (1991) perceived in the region of the Carajás Plateau, in which there was an expansion of the savanna caused by a drier period. Irion *et al.* (2006) further conclude that ecotonal regions are sensitive to such paleoclimatic changes and may exhibit an exaggerated vegetation change. In fact, a review of pollen records from tropical South American savanna and forest-savanna ecotone areas show that sites situated in zones of transition between forest and savanna were most sensitive to past environmental changes (Behling and Hooghiemstra, 2001).

Thus, some studies affirm that there were few changes in the landscape, however, others, especially those of more sensitive regions, such as ecotones and wetlands, show that these areas underwent several paleoecological changes during the Pleistocene and Holocene.

Despite the growing palynological studies conducted in wetlands, there is still some difficulty in interpreting the results, due to the influence of several factors, mainly because the dynamics of fluvial systems generally causes irregular deposition of sediments and pollen grains in this type of place as claim Berrio *et al.* (2001) in their study of a wetland in Colombia. In this sense, for a better interpretation of the data is necessary the union of several

methodologies as it has been used by some authors (Berrio *et al.*, 2001; Irion *et al.*, 2006; Johnson *et al.*, 2009; Guimarães *et al.*, 2013) that have developed studies in this type of environment.

The aim of this work is to study a sediment core from a lake named Lake Quatro Veados (L4V), by pollen and charcoal analysis to reconstruct vegetation, climate and other environmental changes on the north region of Bananal Island during the Late Holocene.

2 ENVIRONMENTAL SETTING

This study has been carried in the north part of the Bananal Island located in the Tocantins state (Fig. 1). The Bananal Island with an area of 20,000 km² is considered the largest fluvial island in the World (Borma *et al.*, 2009). The island is a floodplain temporarily flooded during the rainy season by precipitation of local waters, being classified as a seasonal wetland characterized by a fluvial-lacustrine plain, with numerous lakes, lagoons and intermittent channels (Valente, 2007).

The climate is tropical with two well defined seasons: a dry season and a wet season, which corresponds to the Aw in Köppen's Climatic Classification. The mean annual rainfall varies from 1400 to 2200mm/year with more than 70% rainfall during November and March. The annual mean temperature varies from 22 to 38 °C.

The modern vegetation from this region is composed by a mosaic of rainforest and savanna vegetation arranging an ecotone zone. In this context, grassland savanna, shrub savanna, wooded savanna, woodland savanna and gallery forest physiognomies occur in the studied region. Grassland savanna presents a dominant herbaceous stratum with rare bushes and absence of trees. This kind of vegetation is rich in species of the Poaceae family and found covering plain and lower areas subjected to flooding with saturated water soils. The shrub savanna is a mixed herbaceous-shrub vegetation, with bushes and trees scattering in an extensive grassy cover. *Byrsonima sp.*, *Curatella americana* and *Tabebuia sp.* are the shrubs and trees types dispersed along the herbaceous stratum. In the wooded savanna, the same trees occur in a denser group occupying the relatively more elevated areas where the surface remains distant from the flooding or are affected by short flooding period only.

The gallery forest vegetation that consists of the perennial forest occurs alongside of Araguaia and Javaés rivers and their tributaries, for example, Riozinho stream that cross the Bananal Island. Forest fragments are common along the abandoned channels and floodplains

associated with shrub savanna species. The gallery forest main representative vegetation with Fabaceae, Myrtaceae, Euphorbiaceae and Rubiaceae families.

3 MATERIAL AND METHODS

The coring site is a lake about 3.613 m in circumference, located about 3.27 Km from the right edge of Bananal Island (09°59'30.8" S and 50°07'45.1" W) (Fig. 1). A 50 cm long sediment core (L4V) was recovered from Lake Quatro Veados using a Russian corer. The section of 50 cm in length were wrapped in plastic film, and stored in a PVC pipe under cool and dark conditions after return from the field and before sampling.

In total, two organic-rich bulk samples (1 cm thick) were taken for radiocarbon dating by accelerator mass spectrometry (AMS). Samples were dated at the Poznan Radiocarbon Laboratory in Poland. The derived age-depth model was used to guide intervals between subsamples taken for pollen analysis along the core. For pollen analysis, 26 subsamples (0.5 cm³ each) were taken at 2 cm intervals along the core for analyzing pollen, spores and non-pollen palynomorphs, and micro-charcoal particles. All samples were prepared using adopted methods including hydrofluoric acid treatment (Faegri and Iversen 1989), as well as acetolysis method by Erdtman (1952). It was added one tablet of exotic *Lycopodium clavatum* (20.848 ± 1.546) spores to each sample to determine the pollen concentration (grains/cm³) and pollen accumulation rate (grains/cm²/yr).

A minimum of 300 pollen grains were counted for each sub-sample. The pollen grains, spores, other palynomorphs were identified by optical microscopy (Axiostar plus, Carl Zeiss), using the objective of 40x, and with 100x when grains that could not be identified with a smaller magnification. The computer program Neotropical pollen (free to use) was used, and pollen keys of Carreira and Barth (2003), Colinvaux *et al.* (2005), Salgado-Labouriau (1973), Rivas (1978), Roubik and Moreno (1991) and a pollen reference collection at the Department of Palynology and Climate Dynamics (University of Göttingen, Germany) containing more than 3000 neotropical taxa were used to identify pollen grains.

The identified taxa were grouped by ecological affinities according to habitat, such as forest, floodplain forest, marsh/lacustrine, palm tree, savanna, algae, fern spores, and the sum of pollen groups. In addition, charcoal particles (5–150 µm) were counted on pollen slides and presented as charcoal concentration (particles/cm³)

The pollen sum includes trees, shrubs, and herbs and excludes aquatic taxa, fern and moss spores, and colonies of the algae *Botryococcus*. Pollen and spore data are presented in

pollen diagrams as percentages of the pollen sum. The software TILIA, TILIAGRAPH, and CONISS were used for illustration of the pollen and spore data, calculations, and cluster analysis (Grimm, 1987). The pollen diagrams include individual records of the most abundant pollen and spore taxa (Fig. 4) and records of the following groups: Forest, Floodplain Forest, Marsh/Lacustrine, Palm Trees, Savanna, Spores, Algae/Fungi as well as concentration and accumulation rate of pollen and a cluster analysis dendrogram (Fig. 5). The grouping is based on vegetation surveys in Central Brazil (e.g., Hueck, 1966; Klein, 1978 and 1981). The zonation of the pollen record is based on changes in the pollen assemblages and CONISS analysis.

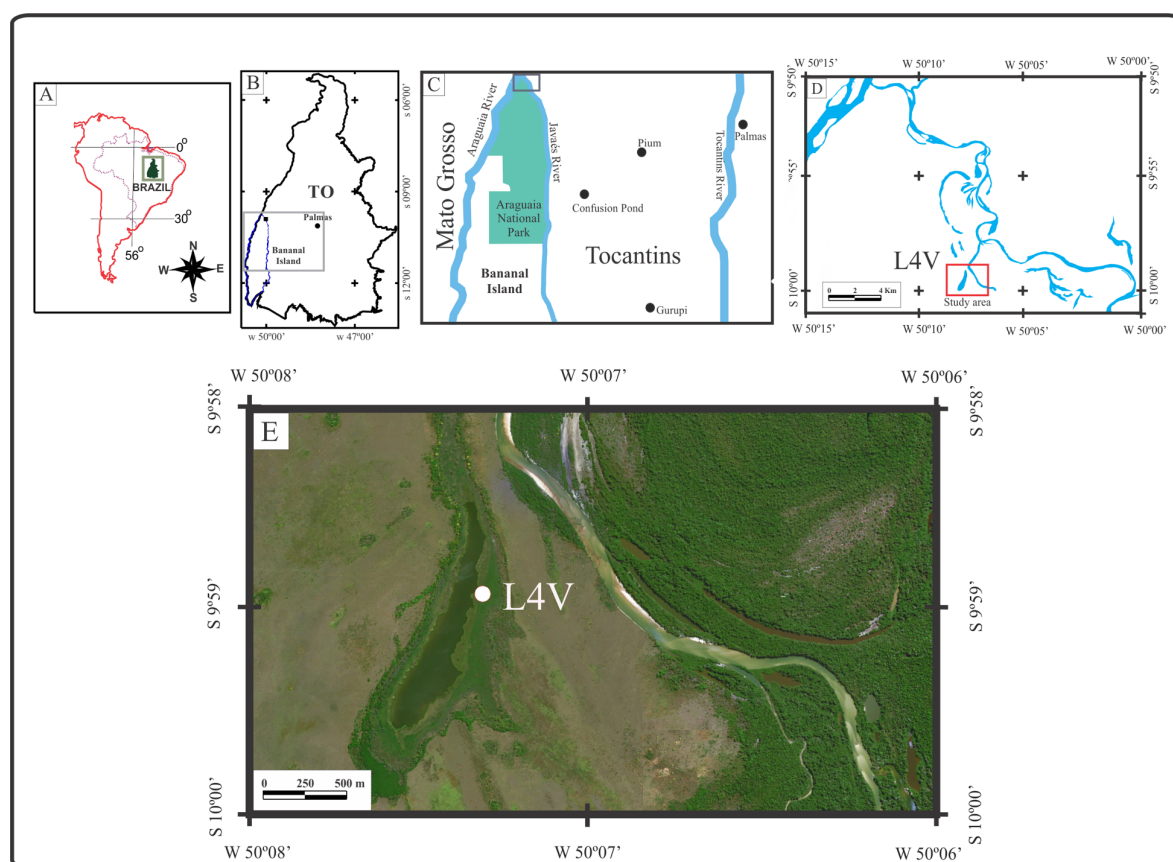


Figure 1. Localization map of the study area. A. Geographic location of Tocantins State. B. Bananal Island location. C. Detail of Araguaia National Park localized in the north of Bananal Island. D. Study area, the red square indicates the study area detail of the Lake Quatro Veados. E. Coring site in the Lake Quatro Veados.

4 RESULTS

4.1 Landscape, Core Stratigraphy and Radiocarbon dates

The Lake Quatro Veados landscape is locally constituted by an extensively flat relief slightly depressed towards the inner portion of the Bananal Island. The vegetation spatial arrangement follows the relief patterns. Thus, in the border of the island on more elevated topography (e.g. marginal dikes) occur wooded savanna with savanna trees and shrubs

scattering the herbaceous stratum which is dominant around the lake at swampy area and along the neighboring low and flattened surfaces. An isolated forest block occurs close to the sampled lake left margin on higher well-drained terrains. The local soil is composed by a superficial gray clayey horizon with 40 cm of thickness on average covering sandy sediments layers possibly old bars that were overlapped by a recent settled floodplain, nowadays under poor drainage conditions during the rainy season (Fig. 2). All these features were favorable to establishments of several stagnant water bodies like the Lake Quatro Veados whose morphological features indicate to be abandoned fluvial channels during avulsions processes very common in this landscape according Latrubesse (2015).

The L4V (Lake Quatro Veados) core was 50 cm long and 5 cm thick. Its constitution from the base to 40 cm was represented by sediment characterized as black sandy clay loam. Between 40 cm and the top the sediment comprises a black silty clay, being enriched in leaves and roots fragments from 20 cm to the top (Fig. 3).

Ages obtained by ^{14}C analysis indicated that the studied core deposition occurred entirely during the Late Holocene. The dating from the 40 cm revealed to be 1555 ± 30 years BP and the sample at 20 cm was dated in 365 ± 30 years BP. Samples obtained and calibrated ages from L4V core are shown in Table 1.

Depth	Lab. cod.	Conventional Age ^{14}C BP	Calibrated Age (cal yr BP)
20	Poz-97377	365 ± 30	429
40	Poz-97376	1555 ± 30	1465

Table 1. Radiocarbon dating and calibrated (cal) ages.

4.2 Description of the pollen and charcoal record

The record contains about 65 different pollen types dominated by Cyperaceae, Poaceae, *Bambusa*, *Mimosa*, *Sagittaria*, *Cecropia*, Moraceae/Urticaceae, *Byrsonima*, *Eichhornia* and *Sebastiania* (Fig. 4 and 5).

A total of 72 *taxa* of palynomorphs were identified along to the L4V core, including taxa of algae/fungi, pteridophytes and angiosperms. The concentration of carbonized particles was also analyzed. The pollen diagram (Figs. 4 and 5) shows the distribution of palynomorphs which were grouped according to their ecological affinities (habitat) The distribution was supported by Marchant *et al.* (2002) as well as based on local observations. The sum of environmental groups is shown in figure 6. The cluster analysis (CONISS) discriminate

analyses the major paleofloristic changes occurring in pollen groups. It was possible to establish four distinct ecological phases, L4V I, L4V II, L4V III and L4V IV, which are described below in an ascending stratigraphic order. Charcoal particles were frequent throughout the record.



Figure 2. Aspects of the Lake Quatro Veados landscape, showing the flat topography and vegetation around the lake.

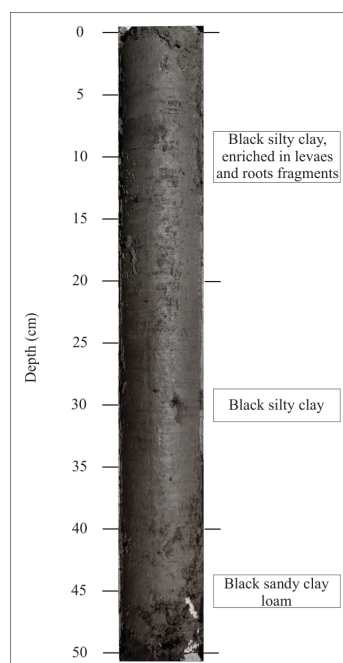


Figure 3. L4V core textural characteristics.

Phase L4V I (50 to 40 cm: 2.190 to 1.470 cal yr BP, 6 subsamples). This phase was characterized by the abundance of forest components (31-53%), which are dominated by pollen of *Bambusa* (3-20%), *Cecropia* (2-8%), Moraceae/Urticaceae (2-8%), *Sebastiana* (3-8%), Rubiaceae (0-4%), *Sloanea* (0-4%), *Mimosa* (0-3%), Melastomataceae/Combretaceae (0-3%), Fabaceae Cesalpinoideae and Fabaceae Mimosoideae (0-3%), Myrtaceae (0-2%), Anacardiaceae, Euphorbiaceae and *Mabea* (0-2%), *Piper* and other *taxa* are less than 2%. The savanna ecological group consists mainly of Poaceae (15-24%), *Byrsonima* (2-7%), Curcubitaceae (0-2%), *Roupala* (0-2%), *Anadenanthera*, *Borreria*, *Curatella* and *Solanum* pollen (0-1%), that presented pollen sum between 22 and 35%. The ecological group marsh/lacustrine showed percentages between 12 and 27%, dominated by Cyperaceae type 1 (6-22%), *Eichhornia* (1-7%) and *Sagittaria* (2-5%), Lentibulariaceae, *Ludwigia* and Polygalaceae (0-1%). The group of Palm trees pollen computed 0-2% and floodplain forest computed percentage of 0-1%. Algae amounted 23 to 28% almost composed by *Botryococcus*, and a Fungi identified as a type of *Bryophytomyces sp.* (5-10%), pteridophytes spores only 0,1%.

Phase L4V II (40 to 24 cm: 1.470 to 590 years cal BP, 6 subsamples). This phase was characterized by the abundance of forest components (34-63%), which are dominated by pollen of *Cecropia* (0-28%), *Bambusa* (8-19%), Moraceae/Urticaceae (2-7%), *Sebastiana* (1-5%), *Alchornea* (0-5%), Fabaceae Papilonoideae (0-4%), Melastomataceae/Combretaceae and Rubiaceae (0-4%), *Mimosa* (0-4%), Anacardiaceae and Myrtaceae (0-3 %), *Celtis* (0-3%) and other *taxa* are less than 2%. The savanna ecological group consists mainly of Poaceae, *Byrsonima*, *Roupala*, *Alibertia*, *Borreria*, Dilleniaceae and *Spermacoce*, presented pollen sum between 14 and 35%. The ecological group marsh/lacustrine showed percentages between 13 and 34%, dominated by Cyperaceae type 1 (6-15%), *Sagittaria* (3-15%) and *Eichhornia* (1-7%). The group of Palm trees computed 0-1% and floodplain forest does not appear. Algae amounted 23 to 38% almost composed by *Botryococcus*, and a Fungi *Bryophytomyces sp.* (6-14%), pteridophytes spores only 0,2%.

Phase L4V III (24 to 8 cm: 590 years cal BP to the present, 10 subsamples). This phase was characterized by the rise of marsh/lacustrine vegetation (30-48%), which are dominated by *Sagittaria* (10-25%), Cyperaceae type 1 (11-24%), *Eichhornia* (1-6%), Lentibulariaceae (0-4%) and *Cuphea* pollen (0-2%). Forest continues being abundant (27-44%) and dominated by *Bambusa* (7-15%), *Mimosa* (1-13%), *Cecropia* (2-11%), Moraceae/Urticaceae (1-8%), *Sebastiana* (0-6%), Euphorbiaceae (0-4%), Flacoutiaceae, *Psicotrya* and Rubiaceae (0-3%), Myrtaceae (0-2%), *Alchornea* and Melastomataceae/Combretaceae (0-2%), Anacardiaceae,

Annonaceae, *Celtis* and Fabaceae Papilionoideae (0-2%), and other taxa are less than 2%. The savanna ecological group consists mainly of Poaceae (7-22%), *Byrsonima* (1-9%), *Borreria* (0-2%), and other less than 2% presented pollen sum between 15 and 30%. The group of Palm trees and floodplain forest computed percentage of 0-1% each one. Algae amounted 26 to 32% almost composed by *Botryococcus*, and fungi *Bryophytomyces sp.* (0-9%) and pteridophytes spores only 0,6%.

Phase L4V IV (8 to 0 cm: present day, 4 subsamples). In this phase the marsh/lacustrine vegetation continues to be dominant (38-54%) showing a peak at the top of the core, but now it is dominated by Cyperaceae type 1 (31-38%), Cyperaceae type 2 (0-19%), *Sagittaria* (0-5%), *Eichhornia* (0-3%) and *Cuphea* pollen (0-1%). Forest taxa are abundant (31-45%) and dominated by *Mimosa* (9-29%), *Bambusa* (2-6%), *Cecropia* (3-5%), Rubiaceae (1-4%), Moraceae/Urticaceae (0-4%), Asteraceae (0-3%), Myrtaceae (0-3%), Melastomataceae/Combretaceae (0-3%), and other taxa are less than 2%. The Savanna ecological group decreased, being Poaceae (7-22%), *Byrsonima* (1-9%), *Borreria* (0-2%), *Roupala* (0-2%), *Acalypha* (0-1%) and the presented pollen sum is between 15, and 30%. The group of Palm trees and floodplain forest computed percentage of 0-1% each one. Algae amounted 26 to 32% almost composed by *Botryococcus*, and a fungi *Bryophytomyces sp.* (0-1%), pteridophytes spores only 0,6%.

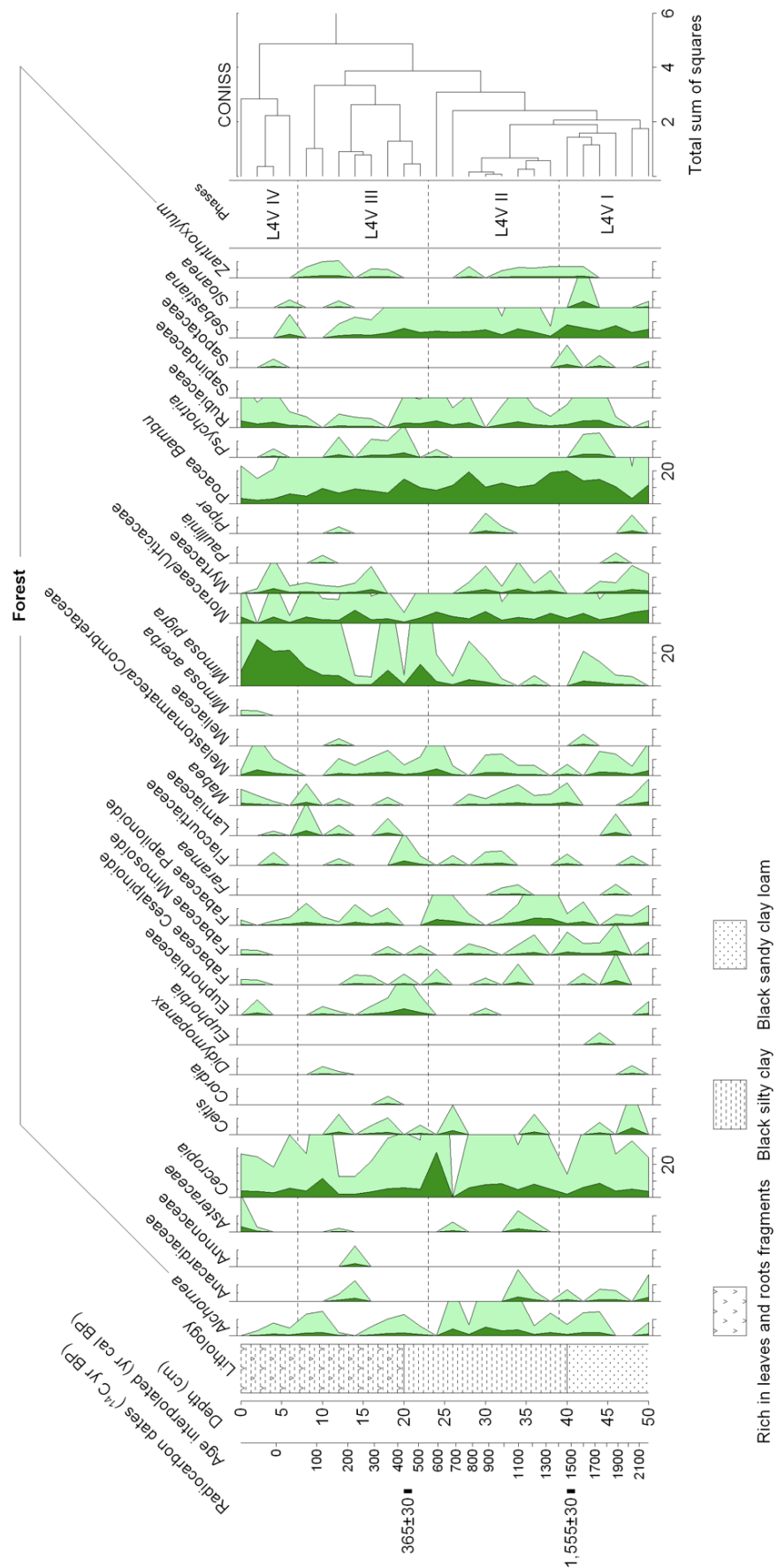


Figure 4. Pollen diagram percentages of L4V core with *taxa* included in ecological groups such as Forest. It features a 7x exaggeration to better visualization of pollen types with low percentages.

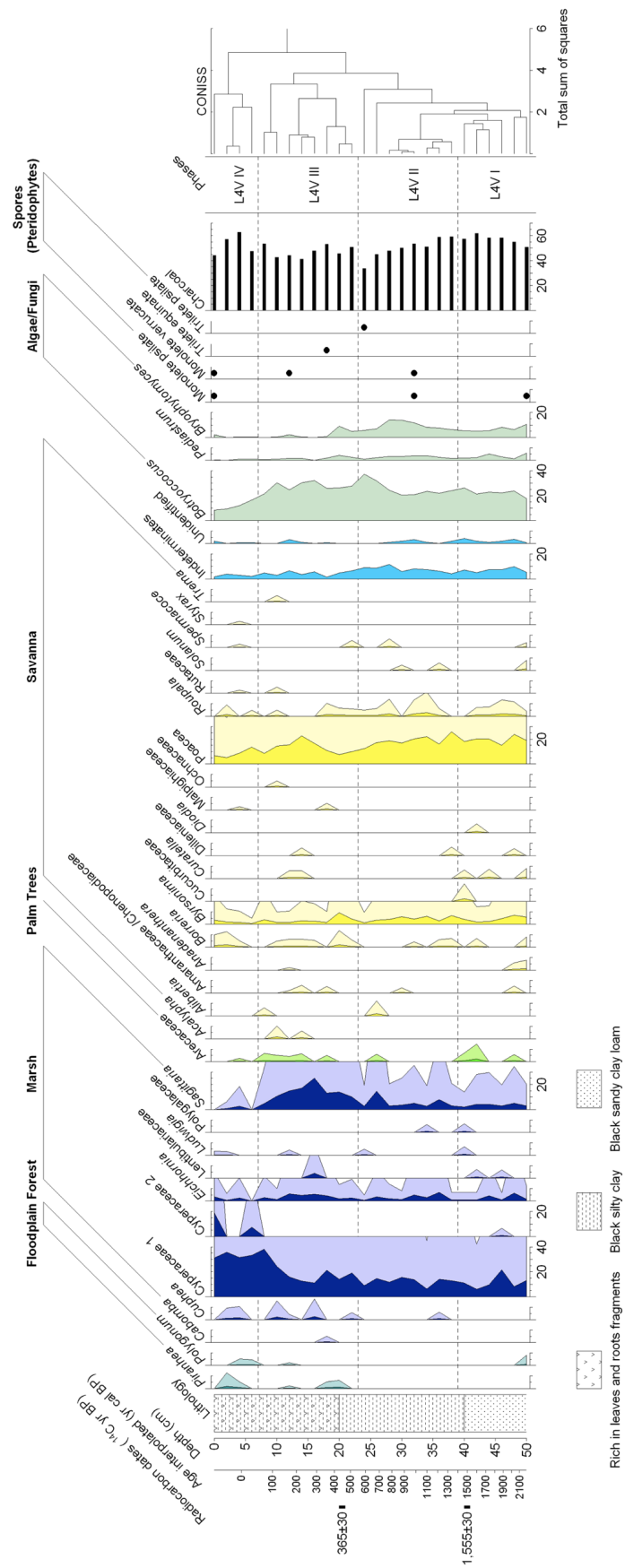


Figure 5. Pollen diagram percentages of L4V core with *taxa* included in ecological groups such as Floodplain Forest, Marsh/Lacustrine, Palm Trees, Savanna, Algae/Fungi, Spores (Pteridophytes). It features a 7x exaggeration to better visualization of pollen types with low percentages.

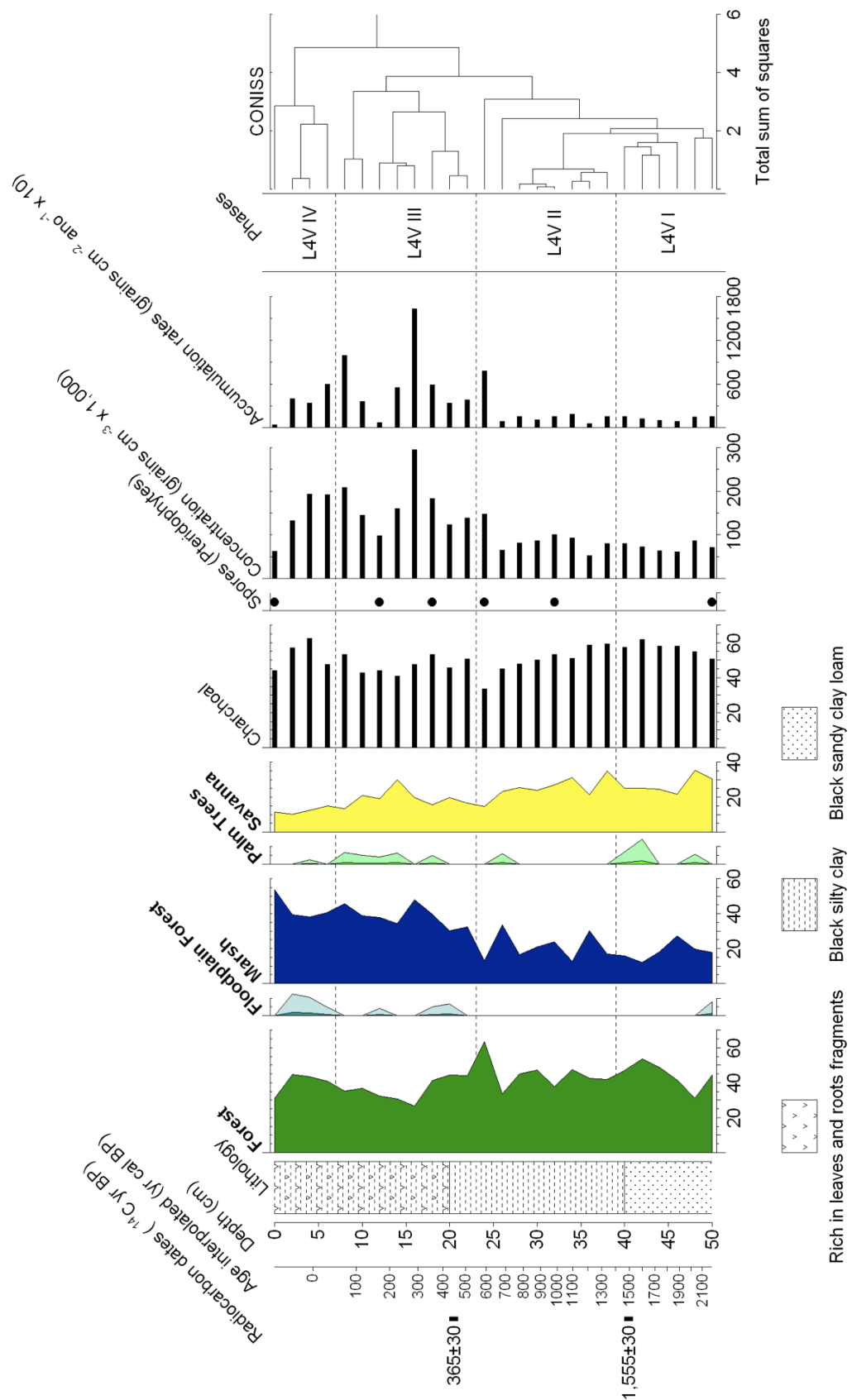


Figure 6. Summary pollen diagram showing radiocarbon ages, interpolated and extrapolated ages, lithology, ecological groups, pollen concentration and accumulation rate, charcoal concentration, pollen phases and cluster analysis (CONISS).

5 DISCUSSION

5.1 Vegetational changes in the Bananal Island during the last 2,000 cal years BP

The pollen record sampled from a lake L4V situated of the in a wetland forest-forest ecotone inside the Bananal Island provided information about the vegetation changes as well as the fire history and revealed few changes in the vegetational composition occurred during the last two thousand years.

The lowermost radiocarbon date shows which the deposition process establishment in the lake started at around 2,190 cal yr BP. In this period until 1,470 cal yr BP forest rich in *Bambusa*, *Cecropia*, Moraceae/Urticaceae, Melastomataceae/Combretaceae and *Sebastiania* occurred close to this lake. In this period, the savanna vegetation also was present, probably occurring around the lake. The proportion of savanna decreased from middle to end of this period. The pollen grains typical for marsh/lacustrine environments like Cyperaceae and *Sagittaria* also decreased suggesting a size reduction of the surroundings flooded areas. The forest vegetation by other hand expanded as result of the lowered water table and reduced soil saturation caused by lower rainfall rates (if compared to present day) or more probably to a short rainy seasons with shorter duration of the flooding. This interpretation is based on studies carried out in Bananal Island by Valente *et al.* (2013). According these authors who studied the relationship between the abiotic factors and the modern vegetation spatial distribution pattern, soaked soils inhibit the growth of the woodland formations. Thus, the duration of flooding events controls the vegetation dynamics, for example, periodic flooding that persists for a long time avoid the forest and woody expansion. In this context, a wetter climate situation is not favorable to forested formations development, except by few species adapted to these extreme environmental conditions.

Similar situation was noticed in an Amazonian forest-savanna ecotone situated in the north portion of Roraima State, Brazil by Meneses *et al.* (2013 and 2015). The authors studied the vegetational dynamics during the late Holocene and their findings shown that hydromorphic conditions are one of the factors that block the expansion of the forest formations even under modern wet climate.

During the period between 1,470 and 590 cal yr BP, the nearby forest continues being abundant, however, retreat moments are observed as well as peak at the end of this period due increase of the pioneer *Cecropia* indicating forest regeneration. Simultaneously to forest retreat moments, peaks of marsh/lacustrine elements, mainly Cyperaceae and *Sagittaria* are seen. This scenery suggests that occurred fluctuation between drier and wetter periods with shorter and

longer rainy seasons respectively. Therefore, longer rainy seasons produced increase of the flooded areas catchment which diminished the forested areas being restricted to more elevated terrains like the fluvial belt or other well-drained local. On the other hand, shortened rainy seasons caused reduction of the flooded areas and lower lake water level which permitted expansion of the forested areas towards the lake surroundings. However, a long duration of drought season would be not favorable to forest expansion and possibly arboreal savanna would settle in this area.

Since 590 cal yr BP until the present day the vegetation cover changes were marked by decrease in the forested area occurred in the middle of this period while the marsh/lacustrine components increased with presence of Cyperaceae and *Sagittaria*. The proliferation of the *Botryococcus* algae reinforces the presence of an extensive lake and expansion of the flooded areas with stagnant water body added. These indicators support the occurrence of wetter climate conditions with rainy seasons similarly to nowadays.

For the last recorded phase that corresponds to the present day, the pollen spectrum reflects a scenery marked by increased forested areas being in this turn *Mimosa pigra* the main taxa. *Mimosa pigra* is well-known invasive species in tropical wetlands that is reduced when the lake water level abruptly increases at the final of the phase. Savanna vegetation maintain lower representation occurring around the lake as observed now in the local.

The almost lack of pteridophytes and bryophytes spores meaning that ferns were absent as result of nonexistence of shadow in the environment, indicating that forest vegetation did not occur locally and the pollen types came from the adjacent gallery forest. This pollen record shows vegetational stability along the recorded period with few environmental changes due to humidity fluctuations with longer and shorter flooding duration under a wet climate. Despite of moist climate predominance the forest formations did not expand over the savanna area as it is waited and also probably did not establish around the lake too. Besides the climate, several other environmental variables may influence floristic variation, including relief, geology, water table fluctuations, fire events and edaphic factors. According to Gibbs *et al.* (1983), the variations in soil water table, fire, herbivory and human disturbances are considered important factors in the determination of the floristic heterogeneity of the South American savannas. In case of the Bananal Island we understanding that a team of factors are responsible by the vegetation control especially the flooding caused by rainy seasons and rising of water table which causing hydromorphic situations inhibits the forest installation. Thus, the existence of a wetter climatic conditions is not favorable for forest growth once the presence of wetlands

that can become longer and reaches bigger areas and then favoring the kept or expansion of savanna instead rainforest.

About the fire frequency we consider these charred particles counted at the sedimentary sequence are suggestive for natural origin once no other anthropogenic indicators (e.g. presence of palms) were recorded in the studied area during this recorded time. In fact, the flooded areas conditions become this region non attractive for people establishments. At present days, that area belongs to National Park of Araguaia protected area. The vegetation in the Bananal Island is one of the few remaining large and intact areas in Central Brazil without any anthropic interference.

These results are partially comparable to the previous and single pollen record studied by Mendes *et al.* (2015) from Bananal Island. The lake studied by the mentioned authors is also located in the north portion of Bananal Island, nevertheless, it is now surrounded by forest instead savanna as occur in Lake Quatro Veados, and its pollen record counted the vegetational and climate history for the last millennium.

The Mendes *et al.* (2015) findings revealed that the last millennium was dominated by forest reflecting a wet climate and three different phases were recognized. Thus, at the beginning of the record between 920 and 770 cal yr BP the wet climate and high rainfall produced flooding during long rainy seasons that maintained the Javaés River connected to the studied lake, and hence, this environment was marked by the presence of a homogenous forest rich in Moraceae/Urticaceae. In the Lake Quatro Veados this time interval (zone L4V II) was marked by lower lake water level and dominance of forest too. Supposedly the lake was in its initial phase indicating increase of humidity and the forest was closer than the following phases. Comparing both sites, it is possible to infer that climate was wet.

During the following period (770-300 cal yr BP) the reduced rainfall and shortening of the rainy seasons isolated the lake from the Javaés River for long period which caused a diversification of the forest and gave rise to the appearance of the components of floodplain forest and marsh vegetation adapted to waterlogged soils. During this period Poaceae and Cyperaceae settled the lake margins, while the *Pediastrum*, a genus of Algae colonized the water surface evidencing the lacustrine trait of this environment. Thus, drier conditions were observed that shortened rainy seasons and diminished the flooded areas allowing the expansion of forested areas and higher diversity in its floristic composition as seen in the pollen diagram. In Lake Quatro Veados area, for this period that is corresponding to L4V II and entire L4V III phases we observed fluctuation between dry and moist periods responsible by growth and decrease of forest plants. However, these types were especially the short-lived *Cecropia* and

Bambusa that are well-known pioneers in forest regeneration. No clear evidence was found for supporting drier climatic conditions at the Lake Quatro Veados. On the contrary, especially from the 590 years an increasing moisture trend is noticed due growth of aquatic plants suggesting enlargement of the wetland area.

During the last 300 years cal yr BP that environment remained dominated by this diverse forest and the lacustrine conditions with a slight increase of moisture at the end of this phase that caused the increase of *Piranhea* a genus typical of Amazonian floodplain forests (Wittmann *et al.*, 2004). In the Lake Quatro Veados we observed an increase of humidity at the uppermost core corresponding to present day situation. In a general way our results are coincident with the study carried out previously in Bananal Island. As about the occurrence of the fires, Mendes *et al.* (2015) did not register particles of charcoal along the sedimentary sequence, possibly due the local forest was buffering the input of particles into the lake. Our results, by other hand, shown a constant occurrence of charred particles along the core, however, it is attributed to natural origin, probably resulting of the dry seasons savanna burning and apparently did not have much importance in the vegetation dynamics. Although some works revealed the importance of fire frequency in the control of vegetation, avoiding for example, the forest expansion over the savanna lands (Meneses *et al.*, 2015).

5.2 The Late Holocene in South American wetlands and forest-savanna ecotones

The Late Holocene history has been reconstructed in several environments along the South America places. To correlate the data from Bananal Island history we are considering the similar places conditions such as wetlands and forest-savanna ecotone regions. The Bananal Island is placed in one of the biggest wetlands in the South America that is the Araguaia river basin. In regions like that, according to Junk *et al.* (1989), the flooding is the main force in wetlands systems, because it controls the production patterns, influences decomposition and nutrient cycles in water and soil. Thus, the effects depend on the duration and hydrologic energy of the flood events. According them, the highest rates of production occur within periodic floods of short duration (oxidant conditions) due to the subsiding of nutrients and water, whereas stagnant flooding of long duration (anoxic conditions) causes physiological stress and results in lower production.

In order to understand the climate changes along the geological time and their effects in every landscape is necessary to comprehend the vegetation composition and its ecological behavior face to environmental changes as the nature and duration of floods, presence of

humans, fire events, among others. According to Urrego *et al.* (2006), the vegetational composition is severally influenced by river water levels and drainage conditions. In Colombia, for instance, the studied floodplain forests show increase of *Mauritiella* and *Camposperma* populations during the Late Holocene as result of flooding with better drainage. The increasing abundance of palms verified around 3,500 ^{14}C yr BP in Laguna Piusbi (Behling *et al.*, 1998), and around 3,000 ^{14}C yr BP in Pantano de Monica area (Behling *et al.*, 1999), located in Colombian Amazon lowlands region, were response to markedly wetter climatic conditions and also human disturbance. In the region of Bolivian lowlands, also a probable increase in precipitation facilitated an expansion of the Amazon rainforest, especially during the last 3,000 years (Mayle *et al.*, 2000; Burbridge *et al.*, 2004).

In the Central Amazon forested areas during the Holocene period a moister climate was documented in Lake Tapajós, in the eastern Amazon, due presence of unchanged forest around the lake (Irion *et al.*, 2006), since the last 4,300 years BP. However, the abundance of Poaceae and *Cecropia* suggested an increase in human activity in the region according them.

Studies carried out in a region of ecotone savanna/forest located in north portion of the Roraima State (Meneses *et al.*, 2013 and 2015) showed expansion of forest over the savannas cover during the Late Holocene in response to wetter climate dominance. According the authors, despite wetter climate situation, cycles of the forest contraction occurred related to fire events and from the last 300 years BP the forest expanded due to reduction of fire events. Besides, increase of forest over savanna, the spread of *Mauritia* palms swamps authors is another indicative of humidity increase in the region during the Late Holocene. In Bananal Island the probable high water levels are not good for *Mauritia* palm swamps establishments, because this type of vegetation does not tolerate permanently inundated conditions as occur in this region during long periods. About the fires, we consider the found charred particles as result of natural fires since grasses are burnt during the seasonal drought and its occurrence is not the reason for forest expansion hampering.

In summary, all these studies carried out in different regions of savanna-forest ecotones and wetlands indicated the dominance of a wetter climate during the late Holocene comparable to the present, as shown in this study for the Bananal Island.

6 CONCLUSIONS

The pollen and charcoal record show that during the last 2,200 cal yr BP the climate conditions were wet in the north region of the Bananal Island. Alternations between periods of

longer and shorter rainy seasons and duration of flooding events caused retreat and advance cycles of the forest along the studied period with few changes in vegetation composition due to increase or decrease of the lake water level or waterlogged soils. Even though of moist climate being favorable to forest expansion, environmental characteristics such as low waterproof terrains due superficial clayey soils, flattened and low surface added to long rainy seasons and high rainfall rates cause water table elevation and inhibits the establishment of forest formations, because of persistent hydromorphic conditions. So, the maintenance of savanna vegetation types can be explained by a long duration of the flooding with a longer soil saturation situation.

In spite of the data provided by this project and other previous studies carried out in this region, the diversity of environments and features found across that and wetland forest-savanna areas requires more investigations, in order to identify accurately the mechanisms that built this regional landscape environmental changes which probably occurred. It is extremely necessary to accomplish multi-proxy studies in other localities of this region in Bananal Island and surroundings which will allow distinctions between local effects and regional trends related to climatic changes.

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Appendix

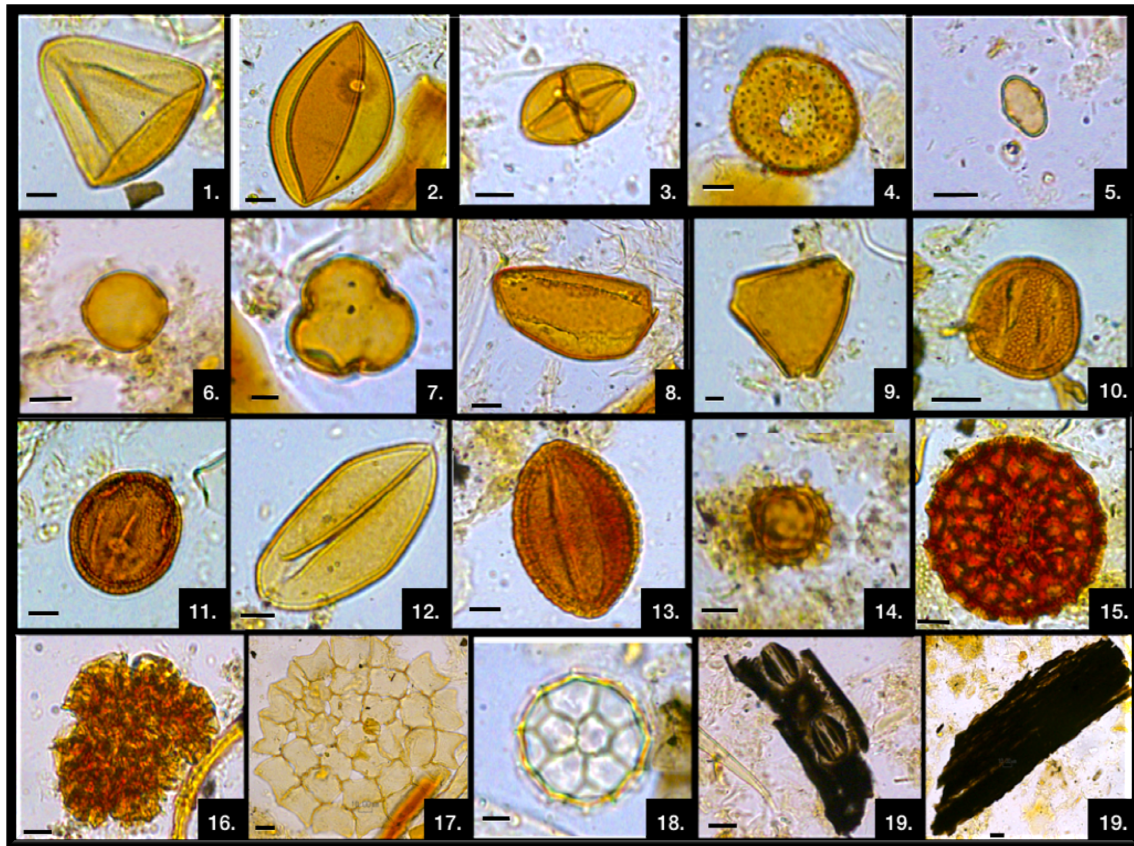


Figure 7. 1. Cyperaceae, 2. *Bambusa*, 3. *Mimosa*, 4. *Sagittaria*, 5. *Cecropia*, 6. Moraceae/Urticaceae, 7. *Sebastiania*, 8. *Eichhornia*, 9. *Roupala*, 10. *Borreira*, 11. Rubiaceae, 12. Arecaceae, 13. *Mabea*, 14. Asteraceae, 15. *Polygonum*, 16. *Botryococcus*, 17. *Pediastrum*, 18. *Bryophytomyces* sp., 19. Charcoal. Scale: 10µm.

4.3 ARTIGO 3: MODERN AND FOSSIL POLLEN RECORD FROM REGION OF THE MIDDLE ARAGUAIA RIVER FLOODPLAIN, TOCANTINS STATE (BRAZIL)



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#5757 Sinopse

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MODERN AND FOSSIL POLLEN RECORD FROM REGION OF THE MIDDLE ARAGUAIA RIVER FLOODPLAIN, TOCANTINS STATE (BRAZIL)

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Abstract

The Araguaia river is one of the most important hydrographic basin in Brazil. Its drainage system reaches two dominant Brazilian biomes that are Amazon Rainforest and Brazilian Cerrado (savanna). This study was carried out in a zone of ecotone between rainforest and savanna formations, in the Middle Araguaia River basin, specifically at the floodplain of Javaés River its tributary by right margin, in the State of Tocantins. The goal of this present study was to provide information about the vegetational succession in this forest-savanna ecotone area, in order to contribute to the understanding of this landscape dynamics. For this reason, a sedimentary core collected from a lake (Lago da Mata Verde) was submitted to palynological and radiocarbon dating analyses. The results showed that during the last 400 years this site was bordered by forest reflecting a wet climate with some increase of the flooded margins in the present day. The modern pollen rain and local vegetation data supported in the interpretation of the fossil pollen results. Our findings are according to other studies carried out in the similar ecotone zones and floodplains in Amazonian regions during the Late Holocene.

Keywords: Lacustrine Sediments, Late Holocene, Pollen Analysis.

Resumo

O rio Araguaia constitui uma das mais importantes bacias hidrográficas brasileiras. Seu sistema de drenagem atravessa dois dominantes biomas brasileiros a saber o bioma Amazônico e o Cerrado brasileiro (savanas). Este estudo, foi realizado em uma zona de ecótono entre as formações de floresta tropical e savana, na bacia do Médio Rio Araguaia, especificamente na planície de inundação do rio Javaés, seu tributário pela margem direita, no estado do Tocantins. O objetivo deste estudo foi fornecer informações sobre a sucessão vegetal nesta área de ecótono floresta-savana, visando contribuir para o entendimento da dinâmica desta paisagem. Dessa forma, um testemunho sedimentar coletado no Lago da Mata Verde foi submetido às análises palinológicas e de datação radiocarbônica. Os resultados mostraram que durante os últimos 400 anos este ambiente foi cercado por floresta refletindo um clima úmido, com um ligeiro aumento de margens inundadas nos dias atuais. Os dados de chuva polínica atual e de vegetação local fundamentaram a interpretação dos resultados palinológicos fósseis. Os resultados obtidos são similares a outros estudos realizados em outras áreas de ecótonos e planícies de inundação em regiões da Amazônia durante o Holoceno Tardio.

Palavras-chave: Sedimentos Lacustres, Holoceno Tardio, Análises Palinológicas

1 Introduction

Palynological data have been useful to reconstruction of past vegetation and their related paleoclimates during the Quaternary around the South American landscapes. One of the most studied is the Amazon region, where several studies allowed draw the different sceneries and their environmental changes throughout Pleistocene and Holocene. Therefore, studies carried out by Colinvaux *et al.* (1996), Colinvaux and De Oliveira (2000), Haberle and Maslin (1999) and Bush *et al.* (2004) evidenced an undisturbed forest cover occurrence with establishing of cold climate and mountain adapted species. On the contrary direction, Absy *et al.* (1991) and Van der Hammen and Absy (1994), identified periods of retreat and fragmentation of the rainforest vegetation due drier climate conditions in Serra dos Carajás, southern of Amazon region. In zone of ecotones between forest and savanna vegetation several works recognized changes in the vegetation caused by climate fluctuations during the Pleistocene and Holocene (Gouveia *et al.*, 1997; Pessenda *et al.*, 1998; Freitas *et al.*, 2001; Meneses *et al.*, 2015).

The Brazilian Cerrado (a biome of savannas type) also have been relatively well studied as about the Pleistocene and mainly Holocene periods (Ferraz-Vicentini and Salgado-Labouriau, 1996; Salgado-Labouriau *et al.*, 1997; Barberi *et al.*, 2000). All of these records revealed a trend in increased moisture during the Late Holocene with a climate comparable to the present day.

The Tocantins state is situated in southeastern Amazon region and hosts diverse vegetation types including both amazon and savanna biomes. Despite the ecological and geographic importance, the studies about the past vegetation dynamics are scarce. There are only two record using pollen analysis: the first one was carried out by Behling (2002), who examined sediments collected from a small rounded lake named Lagoa da Confusão (10°38' S, 49°43' W), recognizing the changes in vegetation occurred during the Late Pleistocene and Holocene. The second pollen work was performed by Mendes *et al.* (2015) in the Bananal Island located 145 km from far the Lagoa da Confusão that counted the last millennium history of the local vegetation. In this context, the objective of this work is supply information about the past vegetation, climate and environmental changes occurred in this region during the Late Holocene aiming to contribute with the knowledge about these zones of forest-savanna ecotone in Amazon region. In order to interpret the fossil pollen data, we also intend to determine the modern pollen rain signatures, examining the spatially variability of the pollen rain and source of pollen of different sites along the lake neighboring forest and then to compare the pollen rain data with floristic composition to discover the modern pollen-vegetation relationships.

2 Study Area

The Lago da Mata Verde ($9^{\circ}58'41.80''$ S and $50^{\circ}1'2.10''$ W) is located in the region of the Middle Araguaia River basin, specifically in the Javaés river floodplain that by its turn is one of the most important tributary of Araguaia River by right margin. This lake has an elongated shape and is connected to other lake (Lago do Arrozal) during the rainy season throughout an intermittent inflowing channel (Fig. 1, 2 and 3).

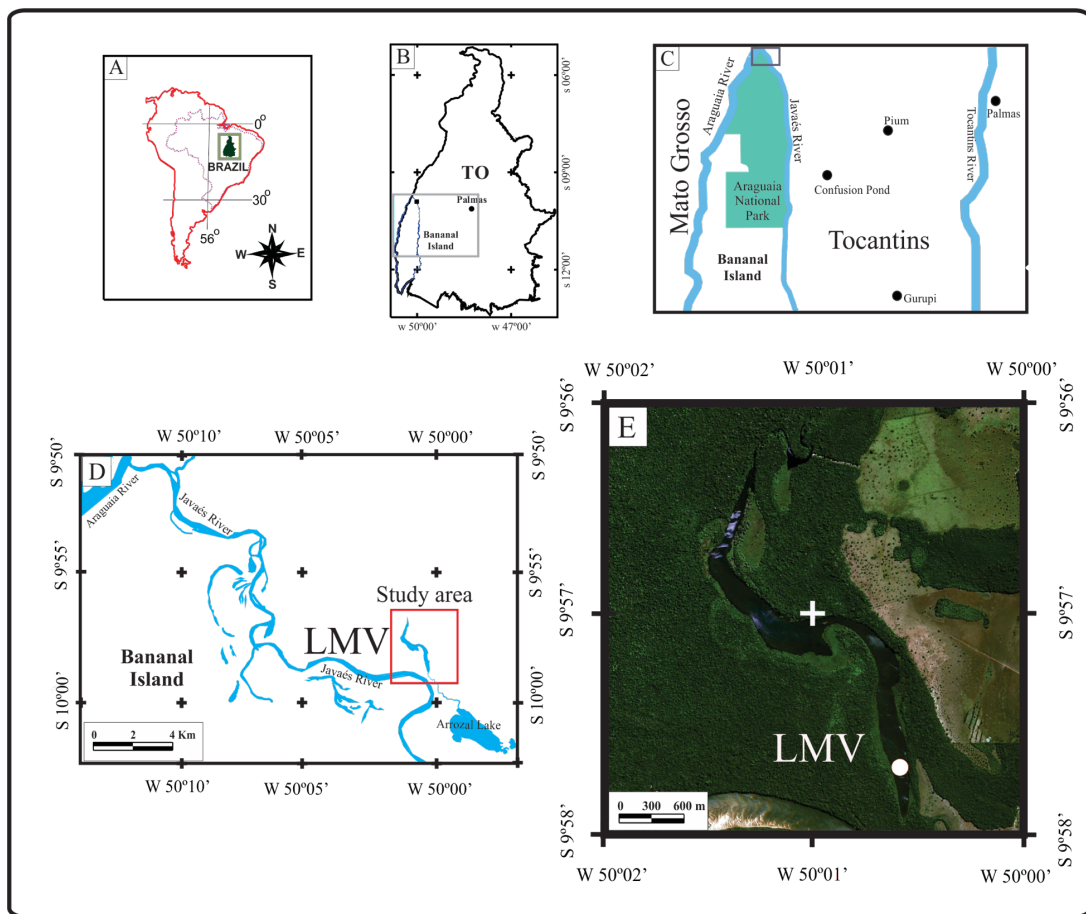


Figure 1. Localization map of the study area. A. Geographic location of Tocantins State. B. Bananal Island location. C. Detail of Araguaia National Park localized in the north of Bananal Island. D. Study area, the red square indicates the study area detail of the Lago da Mata Verde. E. Coring site in the Lago da Mata Verde.

The modern regional climate is hot and semi-humid. The average annual precipitation is between 1,400 and 2,200 mm. The rainy season occurs from November to April. The dry season is marked by very low or no precipitation, and the driest months ranges from June to September. The average annual temperature is 26°C , the maximum temperatures of 38°C occurring during the months of August and September.

The regional modern vegetation is composed by forest and savanna mosaic. However, locally the lake is surrounded by an extensive block of riparian forest that accompanies all the

Javaés River course. The savannas formations vary from grassland where the Poaceae family is dominant to wooded savanna which presents bushes and trees scattered along the herbaceous stratum or forming denser groups. *Byrsonima* sp. and *Curatella americana* are the shrubs or trees types dispersed along the herbaceous stratum.

The riparian forest vegetation occurs as an extensive patch that consists of the perennial forest alongside of Javaés River. According to Kurzątkowski *et al.* (2017), who carried out a floristic inventory in this region, a number of 69 species of trees belonging to 30 families are found locally and the main representative are Fabaceae, Myrtaceae, Anacardiaceae, Rubiaceae and Annonaceae families.

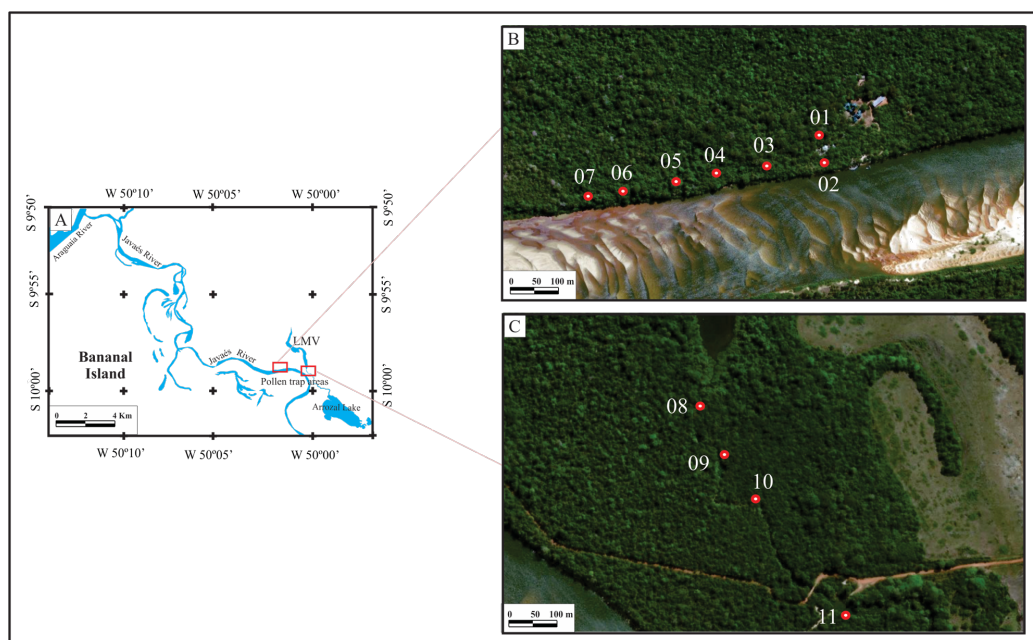


Figure 2. Localization map of artificial pollen traps. A. Study area, the red square indicates the study area details of the artificial pollen traps. B. Location of artificial pollen traps in the margin of Javaés River. C. Location of artificial pollen traps in the margin of the intermittent channel near the Lago da Mata Verde (LMV).

The study site is geologically placed in the Bananal Basin. It is a well-developed Quaternary sedimentary basin, located in the region of the Middle Araguaia River with approximately 106,000 km² in the Amazon forest-savanna ecotone region. The Bananal Basin, formed by quaternary alluvial deposits of the Araguaia Formation, is temporarily flooded during the rainy season by both local rainfall waters and a saturated water table (Valente, 2007).



Figure 3. Aspects of the Lago da Mata Verde landscape, showing vegetation around the lake.

3 Material and Methods

A 63 cm long sediment core was recovered from the lake so-called Lago da Mata Verde (LMV) using a Russian corer. In total, two organic-rich bulk samples (1 cm thick) were taken for radiocarbon dating by accelerator mass spectrometry (AMS). Samples were dated at the Poznan Radiocarbon Laboratory in Poland. The derived age-depth model was used to guide intervals between subsamples taken for pollen analysis along the core. For pollen analysis, 32 subsamples were taken at 2 cm intervals along the core for analyzing pollen, spores and other palynomorphs, and charred particles. All samples were prepared using adopted methods

including hydrofluoric acid treatment (Faegri and Iversen, 1989), as well as acetolysis method by Erdtman (1952). It was added one tablet of exotic *Lycopodium clavatum* ($20,848 \pm 1,546$) spores to each sample to determine the pollen concentration (grains/cm³) and pollen accumulation rate (grains/cm²/yr).

A minimum of 300 pollen grains were counted for each sub-sample. The pollen grains, spores, other palynomorphs were identified by optical microscopy (Axiostar plus, Carl Zeiss), using the objective of 40x, and with 100x when grains that could not be identified with a smaller magnification. The computer program Neotropical pollen (free to use) was used, and pollen keys of Roubik and Moreno (1991), Carreira and Barth (2003), Colinvaux *et al.* (2005), and a pollen reference collection at the Department of Palynology and Climate Dynamics (University of Göttingen, Germany) containing more than 3000 neotropical taxa were used to identify pollen grains.

The identified taxa were grouped by ecological affinities according to habitat, such as forest, marsh/lacustrine, palm tree, savanna, algae, fern spores, and the sum of pollen groups. In addition, charcoal particles (5-150 µm) were counted on pollen slides and presented as charcoal concentration (particles/cm³).

The pollen sum includes trees, shrubs, and herbs and excludes aquatic taxa, fern and moss spores, and algae. Pollen and spore data are presented in pollen diagrams as percentages of the pollen sum. The software TILIA, TILIAGRAPH, and CONISS were used for illustration of the pollen and spore data, calculations, and cluster analysis (Grimm, 1987).

The pollen diagrams include individual records of the most abundant pollen and spore taxa (Fig. 4 and 5) and records of the following groups: Forest, Marsh/Lacustrine, Palm Trees, Savanna, Spores, Algae/Fungi as well as concentration and accumulation rate of pollen and a cluster analysis dendrogram (Fig. 6). The zonation of the pollen record is based on changes in the pollen assemblages and CONISS analysis.

For modern pollen rain analysis 11 artificial pollen traps were installed along the forest patch close to the studied lake for a 12 months period (2016-2017). The preparation of the pollen traps was performed as described by Bush (1992).

The chemical treatment of the samples followed the same standard method used for sediment core samples (Faegri and Iversen, 1989). Pollen and spores were calculated as percentages of the pollen sum and concentration (grains/cm³). The pollen rain results were compared with regional floristic inventory carried out in this region.

4 Results

4.1 Lithology and Chronology

The Lago da Mata Verde sedimentary core from the base 63 cm to 58 cm is composed by black sand. From 58 cm to 37 cm the material is black silt loam being substituted by black loamy sand between 37 and 35 cm. From 35 to 33 cm an interval of silt loam is found. Between 33 and 31 cm a fine layer of black sand is found. From 31 cm to the top of the core, the material is composed by very dark brown loam.

Ages obtained by ^{14}C analysis indicated that the studied core fine sediments deposition occurred recently. The dating from the 55 cm revealed to be 320 ± 30 years BP and the sample at 30 cm was dated in 114.35 ± 0.38 pMC representing modern age. Samples obtained and calibrated ages from LMV core are shown in Table 1.

Table 1. Radiocarbon dating and calibrated (cal) ages.

Depth	Lab. cod.	Conventional Age ^{14}C	Calibrated Age
30	Poz-93934	114.35 ± 0.38 Modern	1846* yr cal AD
55	Poz-93775	320 ± 30	382 yr cal BP

4.2 Description of the pollen and charcoal record

The pollen record contains about 83 different pollen types dominated by *Cecropia*, Cyperaceae, Melastomataceae/Combretaceae, Poaceae, Moraceae/Urticaceae, *Alchornea*, *Byrsonima*, *Sebastiania*, *Sagittaria*, *Celtis*, Fabaceae, *Mabea*, *Psichotrya*, *Roupala* (Fig. 4 and 5).

A total of 93 *taxa* of palynomorphs were identified along to the LMV core, including taxa of algae/fungi, pteridophytes and angiosperms. The concentration of carbonized particles was also analyzed. The pollen diagram (Fig. 4 and 5) shows the distribution of palynomorphs which were grouped according to their ecological affinities (habitat) The distribution was supported by Marchant *et al.* (2002), Kurzątkowski *et al.* (2017), as well as based on local observations. The sum of environmental groups is shown in Figure 6. The cluster analysis (CONISS) discriminate analyses the major paleofloristic changes occurring in pollen groups. It was possible to establish five distinct ecological phases, LMV I, LMV II, LMV III, LMV IV and LMV V, which are described below in an ascending stratigraphic order. Charcoal particles were frequent throughout the record showing concentration between 11,000 and 390,000 particles/cm³ presenting the lowest values towards to the top of the core, in LMV IV and LMV

V phases. The pollen concentration values were very low in the phase LMV II and become higher in the last phases LMV IV and LMV V (Fig. 6).

Phase LMV I (63 to 59 cm: 500 to 415 cal yr BP, 2 subsamples). These samples did not present fine and organic material and then this interval is characterized by the non-preservation of pollen grains, ferns spores, as well as algae *taxa*.

Phase LMV II (59 to 33 cm: 415 to 148 cal yr BP, 13 subsamples). This phase is characterized by the abundance of forest components (59-76%), which are dominated by pollen of *Cecropia* (4-27%), Melastomataceae/Combretaceae (6-19%), Moraceae/Urticaceae (3-15%), *Alchornea* (2-15%), *Sebastiania* (0-10%), *Celtis* (0-8%), Fabaceae (1-8%), *Mabea* (0-8%), *Psychotria* (0-8%), Flacoutiaceae (0-6%), Myrtaceae (0-5%), *Mimosa* (0-5%), Rubiaceae type 1 (0-4%), Anacardiaceae, *Euphorbia*, Sapotaceae and Euphorbiaceae (0-3%), *Clusia*, Asteraceae, *Chamaesyce*, *Guettarda*, Rubiaceae type 2 (0-2%) and other *taxa* are less than 2%. The savanna ecological group consists mainly of *Byrsonima* (0-12%), Poaceae (0-11%), *Roupala* (0-8%), *Curatella* and *Trema* (0-3%), Malpighiaceae, *Caryocar* and *Styrax* (0-2%), Apocynaceae, *Borreria*, Curcubitaceae and Dilleniaceae less than 2%, that presented pollen sum between 6 and 26%. The ecological group marsh/lacustrine showed percentages between 10 and 22%, dominated by Cyperaceae type 1 (8-22%), Cyperaceae type 2 (0-5%), *Eichhornia* (0-3%) and *Sagittaria* (0-2%), *Cuphea*, Polygalaceae, *Cabomba*, Lentibulariaceae presented less than 1%. The group of Palm trees pollen computed 0-1%. Algae amounted 1 to 5% almost composed by *Botryococcus* (1-5%), pteridophytes spores only 1%.

Phase LMV III (33 to 31 cm: 148 to 104 cal yr BP, 1 subsample). This phase is characterized by the non-preservation of pollen grains due sandy sediments layer. Few ferns spores, as well as algae *taxa*, were poorly preserved and presented some charcoal.

Phase LMV IV (31 to 15 cm: 104 cal yr BP to the present, 8 subsamples). This phase is characterized by the abundance of forest components (66-70%), which are dominated by pollen of *Cecropia* (16-30%), *Alchornea* (3-10%), *Sebastiania* (1-9%), Melastomataceae/Combretaceae (3-8%), Moraceae/Urticaceae (3-7%), Flacoutiaceae (0-6%), Myrtaceae (1-5%), *Euphorbia* (0-5%), *Celtis* (0-4%), Asteraceae (0-4%), Fabaceae (1-3%), Euphorbiaceae (1-2%), Anacardiaceae, Rubiaceae type 1 and 2, *Bambusa*, and *Mimosa* (0-3%), other *taxa* are less than 2%. The savanna ecological group consists mainly of Poaceae (6-12%), *Byrsonima* (0-3%), *Trema* (1-3%), *Roupala* (1-2%), Apocynaceae, *Sapium* (0-2%), *Styrax*, Rutaceae, Convolvulaceae, Dilleniaceae, *Alibertia*, *Curatella*, *Caryocar* and others presented less than 1%, that presented pollen sum between 14 and 24%. The ecological group marsh/lacustrine showed percentages between 8 and 19%, dominated by Cyperaceae type 1 (4-

13%), *Sagittaria* (1-4%), *Cuphea* (0-3%), Cyperaceae type 2, *Eichhornia* (0-2%) and *Ludwigia*, *Cabomba*, Lentibulariaceae and Araceae presented less than 1%. The group of palm trees pollen computed 0-2%. Algae amounted 5 to 6% almost composed by *Botryococcus* (4-6%), pteridophytes spores only 1%.

Phase LMV V (15 to 0 cm: present day, 8 subsamples). This phase is characterized by the abundance of forest components (54-62%), which are dominated by pollen of *Cecropia* (9-23%), *Alchornea* (2-11%), *Sebastiania* (3-10%), Melastomataceae/Combretaceae (5-9%), Moraceae/Urticaceae (2-9%), *Bambusa* (0-6%), *Zanthoxylum* (0-5%), Flacoutiaceae, *Celtis* and Fabaceae (0-4%), *Euphorbia* (0-4%), *Mimosa* (1-3%), *Sloanea*, *Psychotria*, (0-3%), Sapotaceae, *Chamaesyce*, Meliaceae and Myrtaceae (0-2%), Asteraceae and other *taxa* are less than 2%. The savanna ecological group consists mainly of Poaceae (8-16%), *Trema* (0-4%), *Byrsonima* (0-2%), *Roupala* and Amaranthaceae/Chenopodiaceae (0-2%), *Solanum* and Ochnaceae (0-1%), Apocynaceae, *Sapium*, Rutaceae, *Caryocar*, *Spermacoce*, *Cassia*, Acanthaceae, *Diodia* and others presented less than 1%, that presented pollen sum between 13 and 19%. The ecological group marsh/lacustrine showed percentages between 21 and 31%, dominated by Cyperaceae type 1 (9-22%), *Sagittaria* (3-8%), Cyperaceae type 2, *Eichhornia* (0-4%), Araceae (0-2%), *Cabomba*, *Cuphea* and Polygalaceae presented 1%. The group of palm trees pollen computed 0-1%. Algae amounted 4 to 12% almost composed by *Botryococcus* (4-12%), pteridophytes spores only 1%.

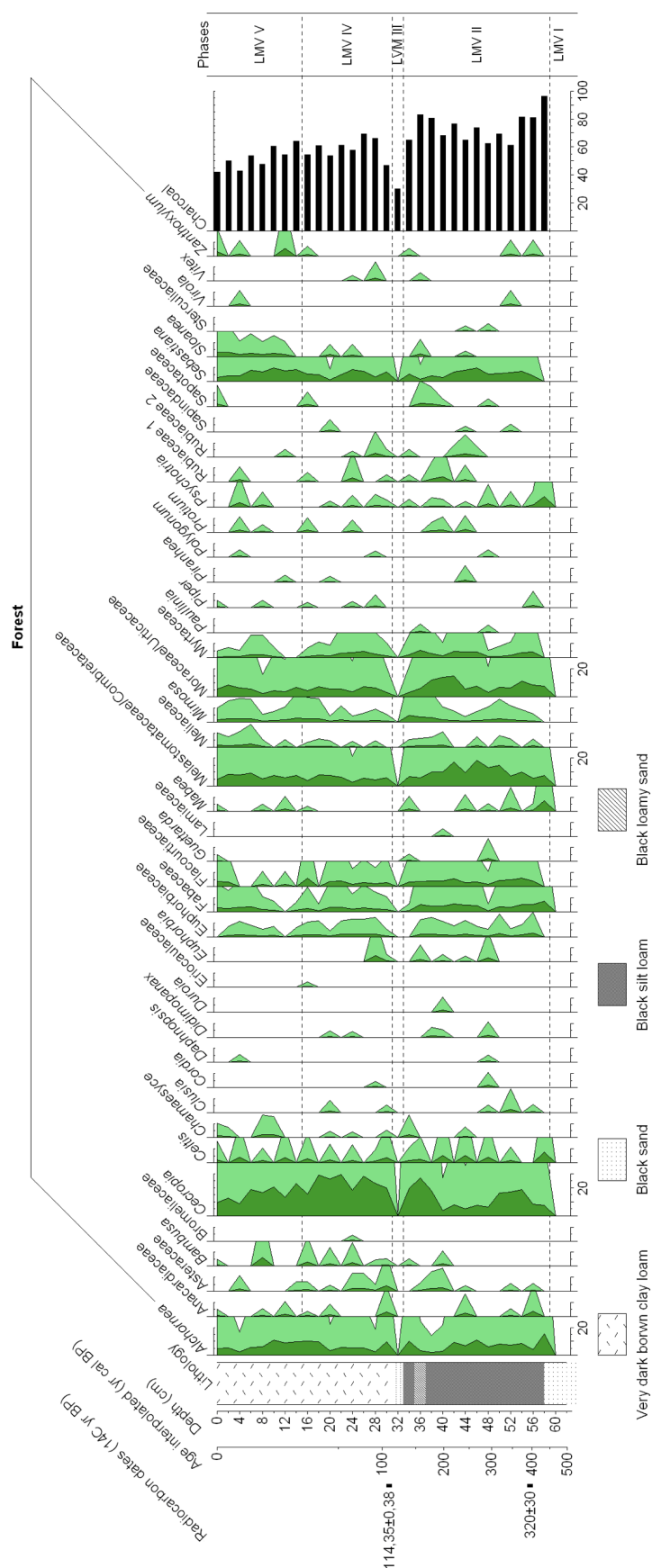


Figure 4. Pollen diagram percentages of LMV core with *taxa* included in ecological groups such as Forest and charcoal. It features a 7x exaggeration to better visualization of pollen types with low percentages.

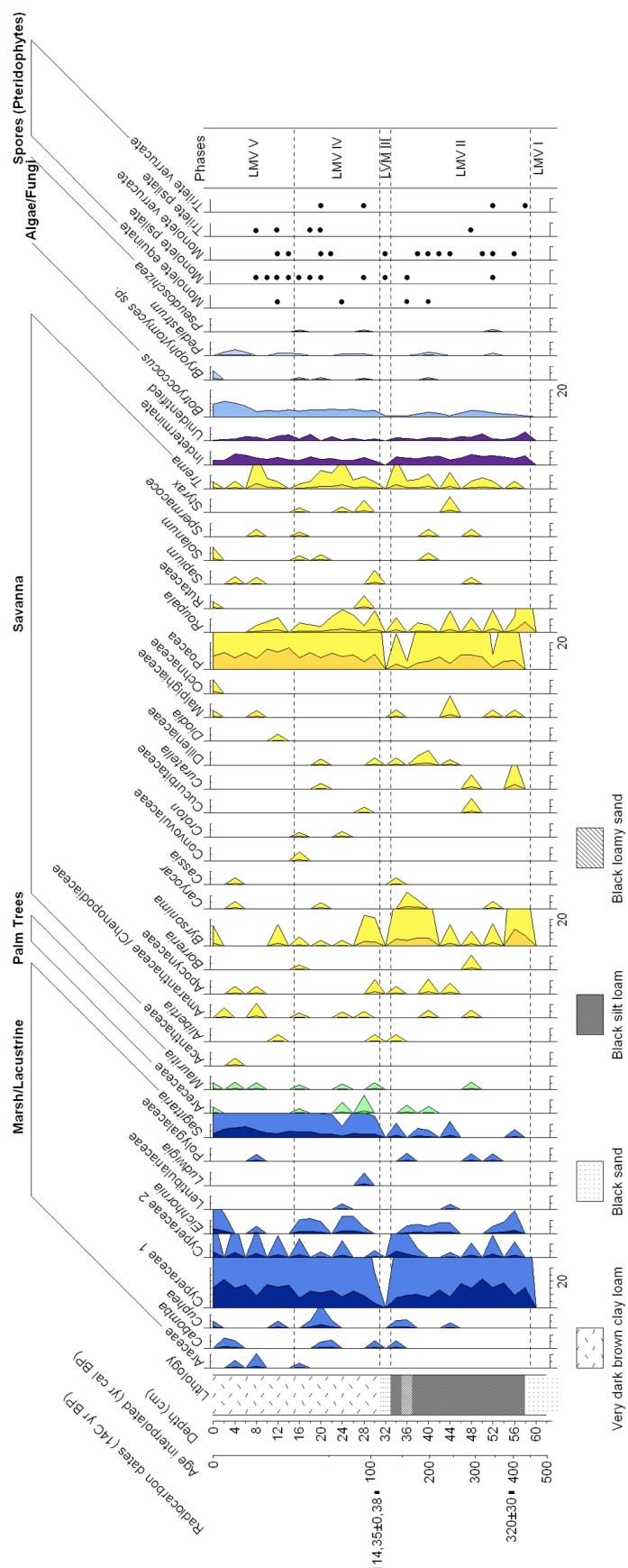


Figure 5. Pollen diagram percentages of LMV core with *taxa* included in ecological groups such as Marsh/Lacustrine, Palm Trees, Savanna, Algae/Fungi, Spores (Pteridophytes). It features a 7x exaggeration to better visualization of pollen types with low percentages.

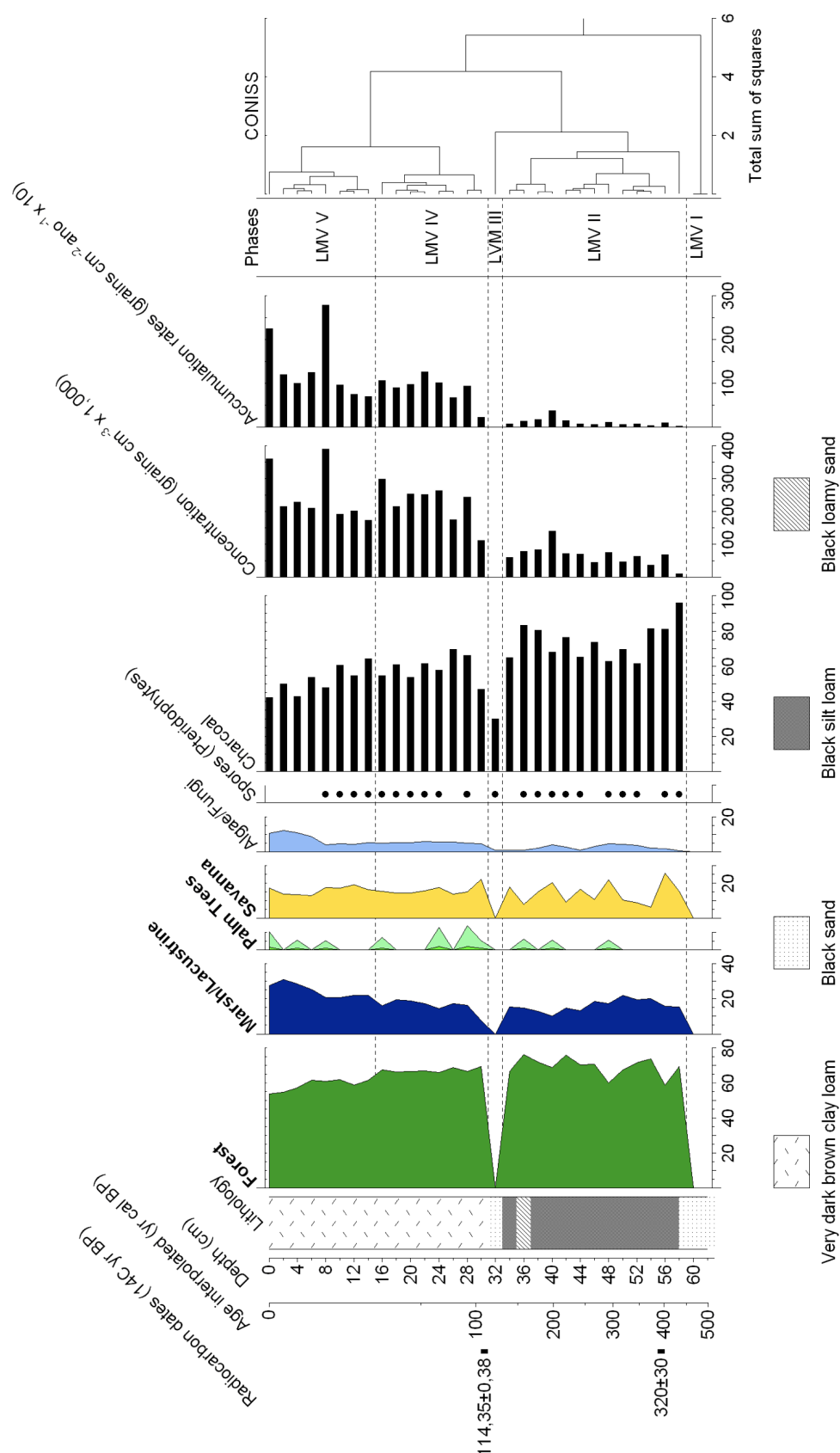


Figure 6. Summary pollen diagram showing radiocarbon ages, interpolated and extrapolated ages, lithology, ecological groups, pollen concentration and accumulation rate, charcoal concentration, pollen phases and cluster analysis (CONISS). It features a 7x exaggeration to better visualization of pollen types with low percentages (Palm Trees).

4.3 Description of Modern Pollen Rain Diagram

The modern pollen assemblages from the 11 artificial pollen trap samples across the studied forest patch vegetation are presented in Figure 7 and 8. The modern pollen rain diagram shows the most frequent and important 65 taxa including 10 unidentified pollen types which are arranged according to the preferential ecological groups.

Forest taxa vary between from 76 to 90%, primarily due to higher pollen frequencies of Moraceae/Urticaceae (5-50%), *Tetrapteryx* (0-35%), *Alibertia* (0-39%), *Chamaesyce* (0-23%), Malpighiaceae and *Euphorbia* (0-20%), Meliaceae (0-15%), Anacardiaceae (0-14%), *Celtis* (0-13%), Melastomataceae/Combretaceae (2-11%), Fabaceae, *Cecropia* and *Alchornea* (0-9%), *Bertiera* and *Piranhea* (0-7%), *Protium* and Sapindaceae (0-6%), *Mimosa* and Flacourtiaceae (0-5%), Sapotaceae (0-4%), *Mabea* (0-3%) and other taxa less than 3%. This forest group was absolutely dominant in all sampled sites, being more abundant near to the Lago da Mata Verde margin (around 90%), with the *Tetrapteryx* (35%), Meliaceae (15%) and Moraceae/Urticaceae (14%) as the most representative taxa. At the margin of the Javaes River, in samples 3 and 9, the forest group was less abundant (76%), with Moraceae/Urticaceae (13%), *Celtis* (13%), Melastomataceae/Combretaceae (11%), *Cecropia* (9%) and Anacardiaceae (7%), as well as in the margin of the intermittent channel (77%), with Moraceae/Urticaceae (24%), *Tetrapteryx* (10%), *Bertiera* (7%), *Celtis* and Melastomataceae/Combretaceae (6%) each one. Anomalous peaks were observed for some samples that occurred in high amounts in a unique sample, for instance *Alibertia* in sample of number 6 that reached 39%, *Chamaesyce* (23%) in sample number 7 and *Euphorbia* (20%) in sample number 2.

The Marsh/Lacustrine group is represented just by Cyperaceae, that appears in all pollen traps (1-4%), and by *Sagittaria* (0-1%), that appears only in two samples near Canguçu Research Center.

The group of Savanna vary between 5 to 17%, with the most common taxa: *Roupala* (0-10%), *Byrsonima* (1-16%), *Solanum*, *Styrax* and *Sapium* (0-4%), *Trema* and Poaceae (0-3%), Amaranthaceae/Chenopodiaceae and Dilleniaceae (0-2%), and others present less than 2%. The Savanna types are more abundant in the pollen trap 9 (in the margin of the intermittent channel), where *Roupala* (10%), *Trema* (3%) and Dilleniaceae (2%) are the most abundant types. And it is less represented in the in the margin of the intermittent channel near Lago da Mata Verde margin (pollen trap 8), which *Byrsonima* (2%), *Trema* and Apocynaceae (1%) are the most abundant types.

Palm taxa represent just 1% of all of the recorded pollen in the traps. Arecaceae appearing in the sample 7 (in the margin of Javaés River) and in the sample 8, collected near Lago da Mata Verde.

5 Environmental Changes in the Lago da Mata Verde

The results obtained from the pollen analysis of Lago da Mata Verde core shown few changes in the vegetational composition during the last 400 years on the forest-savanna ecotone in Tocantins State and revealed unchanged wet climate conditions. Bellow 59 cm depth the sandy material and absence of preserved palynomorphs indicates a high dynamic at the water body probably lotic conditions when the lake probably kept permanent link with Javaés River before to become isolated from this. The elongated morphology of the Lago da Mata Verde and its position among vegetation covered bars indicates that this lake is an abandoned channel formed due lateral accretion of bars.

The lacustrine environment of Lago da Mata Verde was performed since 415 cal yr BP and since then until 148 cal yr BP the environment was rounded by heterogeneous forest cover dominated by *Cecropia*, Melastomataceae/Combretaceae, Moraceae/Urticaceae, *Alchornea* and others. Some savanna vegetation rich in shrubs and trees like *Byrsonima sp* and *Curatella americana* did not occur so close, probably was surrounding this forest patch. The savanna pollen grains were probably transported by wind over some distance into the lake and also perhaps brought by the inflowing channel. The inflowing channel came from a lake called Lago do Arrozal that is located in a savanna area. Marsh/lacustrine plants like Cyperaceae and *Sagittaria* settled the lake margins while *Eichornia* occupied the shallow portions. Charred particles concentration were high indicating regional fires coming from neighboring savanna burning.

In the following identified phase (LMV III) from 148 to 104 cal yr BP the sediments core was marked by a thin layer of sandy sediments, and preserved pollen grains were not found. It was probably due entrance of terrigenous material carried by runoff waters during frequent flooding episodes, or it was brought by the inflowing small channel discharge. It also possible that the lotic conditions returned, because this hiatus lasted almost 50 years. In a general way, the sedimentation process was not continuous or regular, because the sediments texture changed several times along the core, reflecting variations in the hydrological dynamics.

Figure 7. Pollen diagram percentages of Pollen traps with *taxa* included in ecological groups such as Forest, Marsh/Lacustrine, Savanna, Palm Trees.

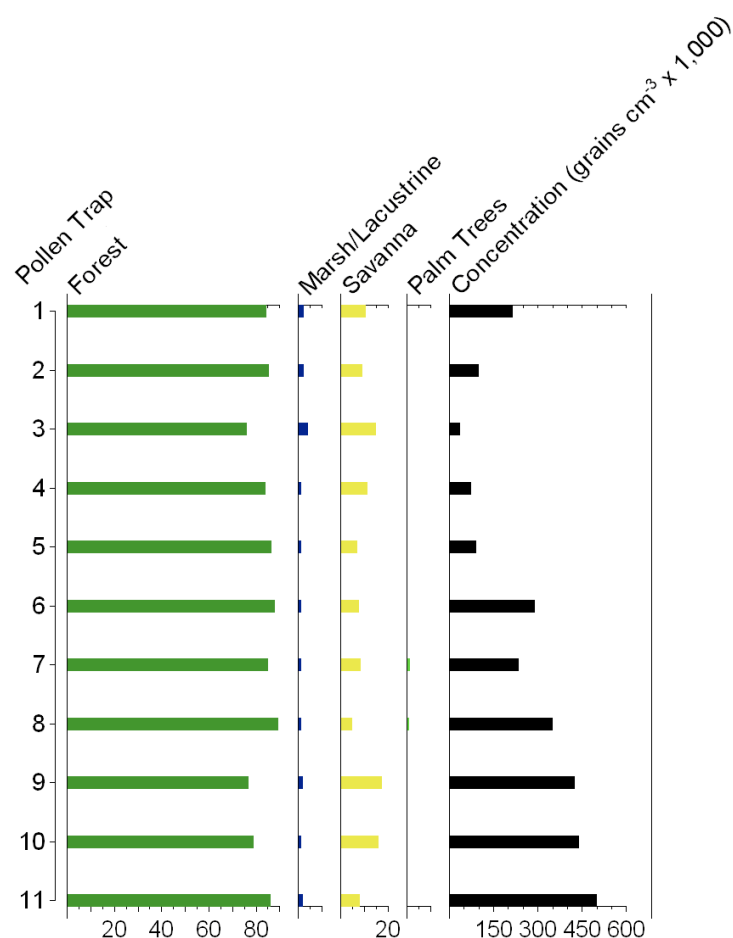


Figure 8. Summary pollen diagram showing ecological groups and pollen concentration.

From 104 cal yr BP to the present-day (LMV IV) the dominance of forest over savanna cover was maintained. However, the savanna became poorly scattered by trees and shrubs as shown by decrease of *Byrsonima* in relation to previous phase (LMVII). The human occupation likely is responsible for remove this trees replacing for grasses for cattle raising and installation of agriculture farms. Charred particles concentration were lower if compared to previous phases. Probably because the human occupation, once the agriculture farms and cattle usually does not make use of fires controlling (Meneses *et al.*, 2013).

The last phase that corresponds to modern time, forest and savanna slightly reduces while the marsh/lacustrine vegetation increases relation to other vegetation formations. This fact suggests that the lake area was enlarged as confirmed by increase of algae/fungi group especially *Botryococcus* suggesting shallow water conditions due expansion of flooded areas.

6 Modern Pollen-Vegetation Linkage

In order to establish modern pollen-vegetation relationships, the data of pollen rain were compared to floristic data from the present vegetation along the riparian forest in Javaés

River floodplain. Pollen analyses from 11 artificial pollen traps samples revealed good relationship between modern pollen assemblages and this forest formation.

The found pollen assemblage reflects mostly the local forest elements such as Moraceae/Urticaceae that is absolutely dominant, followed by Melastomataceae/Combretaceae, Malpighiaceae, *Tetrapteryx*, Anacardiaceae, Fabaceae, Euphorbiaceae, *Alchornea*, *Piranhea*, *Protium*, *Cecropia*, and *Celtis* which were the most frequent types. Comparing the pollen data with local forest vegetation, it is possible to observe that the most important families are represented in the pollen spectra. However, Fabaceae and Myrtaceae that are the richest families in number of species in this forest area presenting 15 and 5 species respectively are not so abundant in the pollen rain spectra as expected. The pronounced richness of Fabaceae species matches the floristic composition of many tropical moist forests of Central Amazonia (Wittmann *et al.*, 2013). According them, in inundated forests of Central Amazonia, Fabaceae and Euphorbiaceae normally have been recorded to be dominant. In the Araguaia forest, following Felfili (1995), besides Fabaceae, additional species-rich families are Myrtaceae and Rubiaceae. Locally Kurzątkowski *et al.* (2017), highlighted the dominance of Moraceae, Rubiaceae, Annonaceae, Picrodendraceae and also Myrtaceae as the most representative families in richness of species.

Considering the mentioned forest floristic composition and its representation in the pollen rain assemblage, Euphorbiaceae are represented especially by *Alchornea*, *Chamaesyce* and *Sebastiania*; Rubiaceae types were *Alibertia* and *Bertiera* only. Picrodendraceae appears like *Piranhea* which was very frequent in the samples.

According to Kurzątkowski *et al.* (2017), the most frequently occurring species in this forest patch are *Alibertia edulis*, *Inga marginata*, *Mouriri guainensis*, *Protium heptaphyllum*, *Protium paniculatum* and *Brosimum rubescens*. Among these species, only *Inga marginata* was not recorded in the modern pollen rain. *Mouriri guainensis* might have been counted as Melastomataceae/Combretaceae and *Brosimum rubescens* as Moraceae/Urticaceae that were the families with the most abundant pollen grains.

In case of Annonaceae described as one the most important family in the local forest, its pollen grains were not recorded in the modern pollen rain spectra, probably because it has very fragile pollen grains (Salgado-Labouriau, 1973). According to Behling and Negrelle (2006), several families with abundant occurrence in forests such as Annonaceae, Lauraceae and Chrysobalanaceae, are missing in the pollen assemblages and specific particularities in the pollen production, dispersal power and preservation conditions could be responsible for such

anomalies. The same reasons could be pointed for explaining the registered low representation of Fabaceae and Myrtaceae families in the pollen trap samples.

Then, except for Annonaceae, the main families recorded in the forest around the lake Lago da Mata Verde are represented in the modern pollen rain spectra, indicating good relationship between them. However, the modern pollen signal has local representativeness. Poaceae and other savanna types appear in very low percentages because riparian forests are dense, and then, pollen dispersed from regional grasslands cannot easily enter into these forests. Moreover, the pollen signal of entomophilous plants may record only the community that actually grows locally (Colinvaux *et al.*, 1999). Consequently, grasslands pollen signal, of wide regional occurrence is under-represented in the pollen spectra from samples taken inside the studied riparian forest, although they consist mostly of trees and shrubs with zoophilous pollination. Exceptions may be observed for frequent *Alchornea*, and *Cecropia* that have anemophilous pollination and might have been brought from out the studied locals. Nevertheless, both genus in fact occur in the local forest patch.

Sagittaria and Cyperaceae (marshes/lacustrine group) appeared in low quantity, only as single grains. Cyperaceae pollen is accepted as one of the most representative elements found in marshes and lake margins, being generally associated to freshwater areas and humid environments, locally developed during the Holocene. However, some species occur in well drained grasslands and it difficult the interpretation (Absy *et al.*, 2014). So, it is necessary take into account the pollen associations to infer the occurrence or increase of humid terrains based in the presence of Cyperaceae pollen grains. At the present study is assumed that this family settle the lakes margins and swamps, based on local observations. Accordingly, the forest from the Javaés River floodplain matches the modern pollen signal except for some anomalies, as for instance, the over representation of *Alibertia*, (39%), *Chamaesyce* (23%) and *Euphorbia* (20%) which appeared restricted to unique trap sample location each one. This fact, however, is probably due to entrance of flowers or pollinator insect into the trap or due to the proximity of the installed trap with the individual plant source.

When compared the modern pollen rain assemblages with the lacustrine fossil pollen from Lago da Mata Verde, it is possible to observe that the families and pollen types are shared in both results and its frequency are almost similar, however, with some differences. Moraceae/Urticaceae pollen grains are the most abundant in the modern pollen rain from the traps than in the lacustrine sediments, reflecting in this context the forest vegetation where is widely occurring. On the other hand, *Cecropia* pollen is more frequent in the recorded sediments into the lake than in the pollen trap. Probably, because this genus occurs locally

settled in borders of forest and due anemophilous pollination, it is coming from beyond of growth local.

In a general way, by these results we conclude that the lake since all the recorded time was surrounded by forest and the savanna vegetation was at the neighboring similarly to nowadays. In this context, the lacustrine sediments recorded the local and regional pollen signal and, therefore, the savanna pollen grains found in the lacustrine sediments were carried into the lake by wind and also by the small inflowing channel during the rainy season. Because this mentioned channel cross savanna vegetated areas.

7 The Late Holocene in Amazonian Forest-Savanna Ecotones Areas and Floodplains

Our findings about this site show that the climate was wet and did not change along the small reached time. They are accordingly similar to results obtained by the previous studies in this region. For instance, in a lake called Lagoa da Confusão, during the Late Holocene the climate was wetter than in the Early Holocene as observed by Behling (2002). This author found an increase of aquatic plants which he attributed to the expansion of the lake due to a probable increase in rainfall. In the record achieved by Mendes *et al.* (2015), in Bananal Island, the last millennium was marked by wet climate as indicated by unchanged forest vegetation. However, periods with minor flooding events was noticed. However, since 304 cal yr BP until the present day this environment continued dominated by this diverse forest, and the lacustrine conditions with a slight increase of moisture in the last 84 years as indicated by increase of *Piranhea*.

Studies carried out in Amazon forest-savanna ecotone areas similarly shown the occurrence of wetter climate during the Late Holocene. In Humaitá-AM Freitas *et al.* (2001) and Pessenda *et al.* (2001) observed an expansion of the forest over the savanna for the last millennium. In Roraima state, situated in northern of Amazon region Meneses *et al.* (2013) and (2015), identified periods of expansion and contraction of forest related to fire events and the last cycle 300 years BP was marked by the expansion of the forest due to a wetter climate and reduction of fire events.

In the zone *Llanos Orientales* in Colombia (northwestern Amazon rainforest/savanna ecotone) at Laguna Loma Linda rainforest expansion is documented since 6,850 cal BP and was more intensified after 3,200 cal BP (Behling and Hooghiemstra, 2000). In southwestern Amazonia, (Laguna Bella Vista and Chaplin, Bolivia) there is evidence of Amazon rain forest expansion during the late Holocene at least since 3,200 cal BP (Mayle *et al.*, 2000).

In zones of wetlands and floodplains the pollen studies allowed to recognize periods of higher moisture during the Late Holocene times. According to Behling *et al.* (2001), in Lake

Calado (Central Amazonia) after 4,610 cal BP the area of várzea/igapó forests increased because the Amazonian water levels must have been higher than before and the period of the annual high water stands was probably longer. Especially since 2,060 cal BP, the largest proportion of várzea/igapó forests is recorded, reflecting the highest Amazonian water level or also indicate that the cyclic annual period of the Amazonian high water level was the longest since then. Pollen studies carried out in Curuá River located in eastern Amazonian region, shown that at 3,340 cal BP, occurred an expansion of inundated várzea and igapó forest area, as indicated by increase of *Virola*, *Euterpe/Geonoma* and *Macrolobium*, trees which are common in flooded forests. Since about 2,560 cal BP, the pollen data reflect the largest extension of seasonally inundated forests and Curuá River reached a water level similar to that of present.

Behling (2011), compared several studies carried out by himself and co-workers in the Amazon lowlands and concluded that the marked increase of flooded areas of várzea (seasonally flooded) and igapó (permanently flooded) forests is apparently related to the late Holocene sea-level rise and practically the whole Amazon Basin lowland seem to have experienced this change. Then, huge areas of non-flooded Amazon rainforest were replaced by várzea and igapó during the Late Holocene. This fact was interpreted as indicators of climate change to wetter late Holocene periods if compared to early and middle Holocene times.

Differently, from other mentioned Amazonian sites, in the Lake Cabaliana situated on the Solimões River basin, palynological and sedimentological data revealed two dry periods in the Late Holocene (2,800-2,550 cal yr BP and 1,450-550 cal yr BP) separated by a wetter phase (2,550-1,450 cal yr BP) (Sá *et al.*, 2016). According to the authors the successional dynamics that occurred in Lake Cabaliana indicate that the present varzea forest was established recently (last 550 cal yr BP), and is composed of a mosaic of different successional stages that are controlled by the intensity of the flood pulse in response to variations in local and regional precipitation.

So, the increasing humidity verified in Amazon region during the Late Holocene especially the last two millennia also is confirmed in its southeastern portion. In fact, a studies compilation organized by Flantua *et al.* (2016) show that fossil pollen records from the lowland Amazon basin indicates continuously wet climate throughout the last two millennia, however, centennial-scale shifts are observed in terms of forest composition attributed to hydrological changes.

8 Conclusions

The Lago da Mata Verde is a lake situated at the floodplain of Javaés River and it was formed due isolating from a channel (*paraná*), caused by intense process of deposition of sandbars posteriorly vegetated. The lacustrine conditions started around 400 cal yr BP. No significant vegetational changes were noticed during the recorded period and the scenery was almost similar to present day. Thus, a dense forest vegetation is found bordering the lake, whilst savanna formation occurs eastwards surrounding the forest. Few changes in the savanna floristic composition occurred during the last 100 years possibly due human impact like planting of grasses for cattle ranches. The lake experienced increasing of flooded areas as pointed increase of marsh and lacustrine plants as well as algae *Botryococcus*. The modern pollen rain presented good relationship with local forest vegetation, and reflects the local riparian forest. Thus, the savanna pollen grains found into the lake is coming from regional savanna covered areas brought by channel waters during the rainy season or by wind transport. The wet climate recorded in this area is local and regionally similar the other Amazonian sites with trend to increasing humidity.

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5 CONCLUSÕES

A Ilha do Bananal está localizada na região do Médio Curso do Rio Araguaia, situando-se entre este rio e seu afluente pela margem direita, o rio Javaés. O presente estudo foi realizado na porção norte desta ilha, onde ocorre um emaranhado de feições geomorfológicas (diques marginais, meandros abandonados, paleocanais e lagos) e geobotânicas contrastantes (florestas e savanas), que refletem a intensa atividade hidrodinâmica nesta região, que é sazonalmente inundada pelas águas pluviais e pela elevação do lençol freático, por isso, é considerada uma *seasonal wetland*.

Os registros palinológicos e cronológicos obtidos a partir dos sedimentos lacustres aliados às características texturais, mineralógicas e químicas de solos e sedimentos coletados em barrancos e barras de canal ao longo dos rios Javaés e Araguaia possibilitaram pontuar importantes transformações de caráter geomorfológico, pedológico e botânico ao longo da histórica geológica recente dessa complexa paisagem, indicando que a principal força motriz foram as mudanças climáticas e hidrodinâmicas decorrentes destas. Com base nestes dados, em observações de campo e ainda em informações obtidas por estudos anteriores na área de estudo tornou-se possível estabelecer tecer algumas conclusões sobre a dinâmica dessa paisagem.

Do ponto de vista geológico-geomorfológico, a porção norte da Ilha do Bananal e áreas adjacentes (leito e planície de inundação do rio Javaés), apresentaram uma evolução flúvio-lacustre durante o Pleistoceno Tardio e principalmente Holoceno que compreende pelo menos 4 eventos principais:

Assim, uma fase fluvial meandrante se instalou sobre um sistema fluvial provavelmente já existente e contou com a formação de uma ampla planície de inundação. A partir daí uma extensa e intensa precipitação química de hidróxidos de ferro parcialmente cimentaram os corpos arenosos (barras de canal e de pontal) formando crostas que dificultaram um subsequente processo erosivo em fase posterior.

Esta paisagem foi o cenário de uma extensa cobertura pedológica formada por gleissolos que representam um típico ambiente pantanoso ou *wetland* que levou a uma remobilização parcial de hidróxidos de ferro levando a formação de frentes ocre de hidróxidos de ferro. Este foi um momento de densa cobertura vegetal (floresta).

Uma fase de condições secas atingiu a paisagem de gleissolos como indicado pela intensa formação de faturamento vertical e disjunção colunar. E finalmente, esta paisagem foi retomada no Holoceno Tardio pela nova atividade fluvial meandrante começando com um processo de ferruginização indicado pela intensa formação de géis de hidróxido de ferro

amorfo. As águas fluviais carregam em solução Fe complexado e sílica, permitindo a formação de hidróxidos de Fe e diatomáceas, respectivamente, e provavelmente Ca, Mg e K, dando origem a algumas neoformações de esmectita e clorita.

A composição mineralógica e química geralmente similar entre os solos e sedimentos analisados, variando apenas em função da fração granulométrica dominante (areia e/ou silte/argila), mostra que os sedimentos e solos investigados têm uma fonte comum, provavelmente rochas ácidas aluminosilicatadas submetidas ao intemperismo tropical, que na ilha do Bananal experimentou localmente condições redutoras promovidas pelos processos de hidromorfismo e gleização nos pântanos e depressões das barras arenosas.

Com relação à dinâmica e sucessão vegetacional, na porção norte Ilha do Bananal, os registros palinológicos obtidos em sedimentos do Lago Quatro Veados revelaram que durante os últimos 2.200 anos cal AP as condições climáticas foram úmidas. Entretanto, alternâncias entre períodos com maior ou menor duração da estação chuvosa e dos eventos de inundação causaram ciclos de recuo e avanço da floresta ao longo desse período, que ocasionaram algumas mudanças na composição da vegetação devido ao aumento ou diminuição do nível da água e/ou redução e ampliação de solos brejosos. Dessa forma, ao longo do Holoceno Tardio, observou-se um controle climático, mas, sobretudo edáfico, uma vez que, essa área é sazonalmente alagada, fato este favorecido pela natureza argilosa dos horizontes superficiais dos solos, das altas taxas de pluviosidade como estação chuvosa prolongada (em média 6 meses) e da topografia baixa e plana dos terrenos. Assim, fatores como a duração das inundações e das condições de hidromorfismo decorrentes, são responsáveis por controlar a instalação de florestas. Assim, a manutenção da vegetação de savana em detrimento da floresta pode ser explicada pela longa duração dos eventos de inundação e saturação dos solos.

No Lago da Mata Verde localizado na planície de inundação do Rio Javaés, em sua margem direita (fora dos limites insulares), apenas os últimos 400 anos foram registrados através das análises palinológicas. Este lago como muitos outros encontrados nessa região foi formado a partir da acreção lateral de barras arenosas que isolou um canal (*paraná*) do canal principal do rio Javaés. Dessa forma, as condições lacustres tiveram início por volta de 400 anos AP e desde este período até os dias atuais o cenário registrado tem sido o mesmo. Assim, uma densa cobertura florestal ocorre em volta de todo o lago, enquanto formações savânicas ocorrem imediatamente a oeste justapostas a esse bloco de floresta ripária. Nos últimos 100 anos houve redução de savana arbórea e aumento de savana graminosa como indicam os dados polínicos. Essas mudanças podem estar relacionadas a ocupação humana e atividades agro-pastoris que podem ter removido a vegetação original para implantação de pastos. Nos últimos

anos observou-se aumento das áreas inundadas atestado pelo aumento de plantas de ambientes aquáticos e brejosos bem como de algas. Os dados para a chuva polínica atual obtidos ao longo da floresta em torno do lago refletiram a vegetação local e subsidiaram as interpretações paleoambientais. Nesse contexto, os grãos de pólen encontrados nos sedimentos do Lago da Mata Verde são provenientes da savana que ocorre regionalmente e foram carregados pelas águas do canal intermitente que durante a estação chuvosa liga o lago estudado ao Lago do Arrozal que por sua vez localiza-se em ambiente savânico, ou ainda podem ter sido transportados pelo vento, dado o caráter anemófilo, especialmente de Poaceae. As condições climáticas úmidas com tendências ao aumento de umidade registradas nessa área são local e regionalmente similares àquelas descritas em outros locais da Amazônia.

De um modo geral, esta pesquisa trouxe contribuições para entender a dinâmica funcional dessa paisagem frente as mudanças climáticas e ambientais ocorridas na região, bem como para ampliar o conhecimento sobre os ambientes de *wetlands* e sobre a dinâmica das paisagens de transição entre a floresta amazônica e as savanas, cujo conhecimento paleoambiental ainda é restrito.

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PARECER

Sobre a Defesa Pública da Tese de Doutorado de LAÍS AGUIAR DA SILVEIRA MENDES

A banca examinadora da Tese de Doutorado de **LAÍS AGUIAR DA SILVEIRA MENDES** orientanda do Prof. Dr. Marcondes Lima da Costa (UFPA), composta pelos professores doutores Maria Ecilene Nunes da Silva Meneses (UFT), Soraia Girardi Bauermann (ULBRA-RS), José Francisco Berredo Reis da Silva (MPEG) e Marcelo Cancela Lisboa Cohen (UFPA), após apresentação da sua tese intitulada "**DINÂMICA DA PAISAGEM NA PORÇÃO NORTE DA ILHA DO BANANAL E ADJACÊNCIAS DURANTE O QUATERNÁRIO TARDIO**", emite o seguinte parecer:

A candidata realizou sua apresentação de forma clara e bem organizada. Na arguição mostrou domínio das questões relacionadas à mineralogia e geoquímicas dos sedimentos e vegetação atual e passada da sua área de estudo. O trabalho foi apresentado na forma de três artigos redigidos em inglês e atende as exigências para uma tese de doutorado.

A banca examinadora decidiu por unanimidade aprovar a tese de doutorado.

Belém, 30 de agosto de 2019.



Prof. Dr. Marcondes Lima da Costa (Orientador – UFPA)



Prof.ª Dr.ª Maria Ecilene Nunes Meneses (UFT)



Prof.ª Dr.ª Soraia Girardi Bauermann (ULBRA)



Dr. José Francisco Berredo Reis da Silva (MPEG)



Prof. Dr. Marcelo Cancela Lisboa Cohen (UFPA)