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EVOLUÇÃO DA COSTA NORDESTE DO BRASIL NA REGIÃO DE PARNAÍBA DURANTE O PLEISTOCENO SUPERIOR E HOLOCENO

Dissertação apresentada por:

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Orientador: Prof. Dr. José Bandeira Cavalcante da Silva Junior (UFPA)

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Universidade Federal do Pará
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Como requisito parcial à obtenção do Grau de Mestre em Ciências na Área de GEOLOGIA, linha de pesquisa ANÁLISE DE BACIAS SEDIMENTARES

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O amor é sofredor, é benigno; o amor não é invejoso; o amor não trata com leviandade, não se ensoberbece, não se porta com indecência, não busca os seus interesses, não se irrita, não suspeita mal; não folga com a injustiça, mas folga com a verdade; tudo sofre, tudo crê, tudo espera, tudo suporta. O amor nunca falha; mas, havendo profecias, serão aniquiladas; havendo línguas, cessarão; havendo ciência, desaparecerá; porque, em parte, conhecemos e, em parte, profetizamos.

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RESUMO

Estudos prévios na região de Parnaíba estiveram focados no lineamento Pirapemas, na estabilização de um campo de dunas, na evolução do Delta do Parnaíba e em mudanças da linha de costa. No entanto, estudos adicionais ainda são necessários para desenvolver um modelo evolutivo no Pleistoceno Superior e Holoceno. A área de estudo está localizada na Bacia do Ceará, os depósitos quaternários estão sobrepostos a rochas do embasamento. Esses depósitos correspondem a areias eólicas, depósitos fluviais e depósitos de maré. Este estudo tem como objetivo propor um modelo evolutivo, com base nas seguintes técnicas: a) descrição de fácies; b) datação por luminescência oticamente estimulada (LOE); e c) sensoriamento remoto. Amostras foram coletadas para LOE, análise granulométrica e textural, catodoluminescência de quartzo (CL) e minerais pesados. Os depósitos quaternários mais antigos estão relacionados a campos de dunas cortados por rios entrelaçados. O cenário atual apresenta uma nova fase de formação de dunas com direção do vento NE-SW, as áreas interdunas são desenvolvidas próximas ao lençol freático, enquanto os manguezais estão presentes no Noroeste. O Rio Parnaíba é uma das feições mais importantes devido ao suprimento de sedimentos. Foram descritas 17 fácies, organizadas em 9 associações de fácies auxiliadas pelas unidades morfoestratigráficas. A AF1- rios entrelaçados é caracterizada por material grosso com alto conteúdo de clastos de quartzo e cimentação por ferro; AF2 - campo de dunas - ocupa a área sul e está associada às formas estabilizadas pela vegetação e aos depósitos eólicos atuais no Norte. A AF3 - área de deflação interduna - está associada à AF2, formada em áreas de depressão e com subsequente crescimento da vegetação. AF4 - canais de maré, AF5 - manguezais e AF6 - planície de maré, estão nos principais canais de maré com direção preferencial NW-SE. AF7 - *shoreline* - corresponde aos depósitos relacionados à ação das ondas. O rio meandrante AF8 está cortando todos os depósitos e é caracterizado por uma grande planície de inundação, o lacustre AF9 está associado a depósitos de sedimentos finos formados em canais represados. As amostras coletadas contêm quartzo com alta sensibilidade à luminescência. A taxa de dose varia de 0,585 ± 0,06 a 1,55 ± 0,07 Gy / ka. As idades obtidas variam de 2,1 ± 0,41 a 86,1 ± 6,4 ka e representam a evolução de um sistema eólico. Os sedimentos apresentaram formas subangulosas a subarredondadas com esfericidade média; a catodoluminescência do quartzo indicou uma fonte associada com rochas metamórficas e ígneas intrusivas o que é concordante com a assembleia de minerais pesados onde predominam os minerais ZTR e a cianita. Foi feito um modelo evolutivo para os últimos 86 ka, começando com a coalescência de processos fluviais e eólicos (>86 ka), represamento dos principais canais pela sedimentação eólica (86-20 ka), a estabilização das dunas por mudanças climáticas associadas à migração da Zona de Convergência Intertropical (20 a 10 ka), e a implementação de extensas áreas de manguezais desde os 10 ka até o presente. Essa configuração revela um modelo completo para o desenvolvimento de dunas transgressivas.

Palavras-chave: Associação de fácies. Delta do Parnaíba. Dunas Transgressivas. Luminescência Oticamente Estimulada. Mudanças climáticas.

ABSTRACT

Previous studies in the Parnaíba region were focused on the Pirapemas lineament, the stabilization of a dune field, the evolution of the Parnaíba Delta and changes in the coastline. However, further studies are still needed to develop an evolutionary model for the Upper Pleistocene and Holocene. The study area is located in the Ceará Basin, the Quaternary deposits are on the basement. These deposits correspond to wind sands, river deposits and tidal deposits. This study aims to propose an evolutionary model, based on the following techniques: a) facies description; b) dating by optically stimulated luminescence (OSL); and c) remote sensing. Samples were collected for OSL granulometric and textural analysis, quartz cathodoluminescence (CL) and heavy minerals. The oldest Quaternary deposits are related to dune fields cut by braided rivers. The current scenario presents a new phase of dune formation with NE-SW wind direction, interdune areas are developed close to the water table, while mangroves are present in the northwest, the Parnaíba River is one of the most important features due to the supply of sediments. 17 facies were described, organized into 9 facies associations assisted by the morphostratigraphic units. FA1- briaded rivers are characterized by coarse materials with a high content of quartz clasts and iron cementation; FA2 - dune field - occupies the southern area and is associated with parabolic dunes stabilized by vegetation and with the current wind dunes in the north. FA3 – deflation área - interdune - is associated with FA2, formed in depressed áreas with subsequent growth of vegetation. FA4 - tidal channels, AF5 - mangroves and FA6 - tidal flat, are associated to the main tidal channels with preferential direction NW-SE. FA7 - shoreline - corresponds to deposits related to wave action. The meandering river FA8 is cutting all deposits and is characterized by a large floodplain, the FA9 lake is associated with fine sediment deposition formed in dammed channels. The collected samples contain quartz with high sensitivity to luminescence. The dose rate ranges from 0.585 ± 0.06 to 1.55 ± 0.07 Gy / ka. The ages obtained range from 2.1 ± 0.41 to 86.1 ± 6.4 ka and represent the evolution of a wind system. The sediments presented subangular to sub-rounded shapes with medium sphericity; the quartz catodoluminescence indicated a source associated with intrusive metamorphic and igneous rocks, which is consistent with the assembly of heavy minerals where ZTR and kyanite predominate. An evolutionary model was made for the last 86 ka, starting with the coalescence of river and wind processes (> 86 ka), damming of the main channels by wind sedimentation (86-20 ka), the stabilization of the dunes by climate changes associated with migration of the Intertropical Convergence Zone (20 to 10 ka), and the implementation of extensive mangrove areas from 10 ka to the present. This setting reveals a complete model for the development of transgressive dunes.

Keywords: Facies Association. Parnaíba Delta. Transgressive Dunes. Optically Stimulated Luminescence. Climate Change.

LISTA DE ILUSTRAÇÕES

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1 INTRODUÇÃO

1.1 APRESENTAÇÃO

O litoral brasileiro tem sido foco de diferentes estudos relacionados principalmente à evolução geológica, dinâmica costeira nas últimas décadas e mudanças climáticas durante o Quaternário, as quais permitiram a modelagem de diferentes geoformas e a implementação de importantes ecossistemas como manguezais, pântanos, áreas de dunas, lagos, etc. Nesse sentido o estudo feito por Arz *et al.* (1999), baseado na assinatura isotópica de foraminíferos e radiocarbono, permitiu determinar as variações da circulação termohalina no Atlântico Tropical e Subtropical, atribuídas ás ultimas glaciações no hemisfério norte e que posteriormente durante a deglaciação, forneceu as condições necessárias para o desenvolvimento de extensas áreas de manguezais e colonização deste tipo de vegetação em áreas topograficamente mais altas como resultado do aumento do nível do mar e mudanças de outras condições ambientais como a temperatura, salinidade, química e aporte de nutrientes nas águas oceânicas (Cohen *et al*. 2018).

A foz do Rio Parnaíba limita os Estados de Piauí e Maranhão no nordeste do Brasil. Esta área é uma das poucas regiões do mundo nas quais a atividade humana é limitada (Szczygielski *et al.* 2014, Szlafsztein 2003), o que é confirmado por estudos que mostram que o sistema não atingiu níveis de concentração de elementos múltiplos capazes de afetar o equilíbrio dos ecossistemas locais (Paula Filho *et al.* 2014); porém, com porções do estuário nas quais a qualidade da água está mais degradada (Paula Filho *et al*. 2020). Neste setor estão localizados os limites entre as bacias geológicas de Barreirinhas, Parnaíba e Ceará sendo localmente esta última o foco do estudo. A sedimentação na porção *onshore* nesta área corresponde principalmente a uma sucessão sedimentar siliciclástica não consolidada que sobrepõe as rochas do embasamento do Paleoproterozoico (gnaisses localmente miloníticos) e do Neoproterozoico (granodioritos e sienitos), além das rochas paleozoicas da borda da Bacia de Parnaíba e das formações Pirabas e Barreiras (Ferreira 1964, Gonçalves *et al.* 2006, Távora *et al.* 2010, Sousa *et al.* 2012, Szczygielski *et al.* 2014), enquanto na porção *offshore* existe uma grande área de um antigo sistema eólico afogado e a presença de uma plataforma carbonática (Guedes *et al*. 2017, Mohriak 2003).

De acordo com o registro sedimentar, a área de estudo exibe principalmente depósitos costeiros e aluviais mapeados como depósitos eólicos continentais, paleodunas, depósitos de pântanos e mangues, depósitos aluvionares e depósitos litorâneos (incluindo os eólicos mais recentes), depositados no Pleistoceno Superior e Holoceno (Gonçalves *et al.* 2006, Sousa *et al.* 2012). Além disso, estudos de fácies feitos com testemunhos no lado oeste da foz do Rio Parnaíba (Szczygielski *et al.* 2014) sugerem uma deposição dominada principalmente por processos de maré, no entanto, os resultados estão restritos até uma idade aproximada de 4853 anos Bp (de acordo com o método de ^{14}C), o qual restringe esta interpretação à parte final do Holoceno. O trabalho desenvolvido por Guedes *et al.* (2017) permitiu determinar a idade de estabilização do campo de dunas mais extenso da América do Sul localizado ao sul dos Lençóis Maranhenses a qual é atribuída a um conjunto de mudanças climáticas relacionadas principalmente ao aumento da pluviosidade, redução da força do vento e aumento do nível do mar.

A ocorrência de campos de dunas tem sido descrita em diferentes localidades nos estados do Pará (Buynevich *et al.* 2010), Maranhão, Piauí (Aquino da Silva *et al.* 2019, Guedes *et al.* 2017), Ceará (Castro *et al.* 2017), Rio Grande do Norte (Caldas *et al.* 2006), Santa Catarina (Silva & Hesp 2010), Rio Grande do Sul (Milana *et al.* 2016), entre outros; nos quais foram estudados aspectos da dinâmica costeira como força do vento, fonte de sedimentos, variações na topografia, construção das formas eólicas e deriva litoral; porém ainda não foi desenvolvido um modelo conceitual que permita entender a relação dessas geoformas com outros ambientes de sedimentação na área de estudo.

Este estudo permitiu identificar as principais feições geomorfológicas e estratigráficas, bem como o desenvolvimento de um modelo evolutivo para a área de Parnaíba durante o Pleistoceno Superior e Holoceno. Esse modelo fornece uma base conceitual para futuros estudos relacionados à geologia do Quaternário, a distribuição de dunas transgressivas e também de importantes ecossistemas como os manguezais no litoral brasileiro.

1.2 ARÉA DE ESTUDO

A área de estudo está delimitada entre os Estados de Piauí (PI) e Maranhão (MA) no Nordeste do Brasil na Foz do Rio Parnaíba, distante aproximadamente 332 Km da capital do Piauí, Teresina, e 436 Km da capital do Maranhão, São Luís; nos municípios de Luís Correia, Parnaíba, Carnaubeiras (Macaco) e Araioses, ocupando uma área de 2450 Km^2 (Fig. 1.1). O acesso para esta localidade é feito pelas rodovias MA 315, MA 312, MA 345, PI 116 e PI 210, além de outros caminhos menores e canais. Os pontos de amostragem e afloramentos localizamse perto das rodovias e dos canais, enquanto os testemunhos foram feitos em proximidades de canais e lagoas (Lagoa do Portinho, Praia das eólicas, Ilha Canarias e Ilha Grande).

1.3 OBJETIVOS

Este trabalho teve como objetivo descrever os principais compartimentos morfoestratigráficos que ocorrem no limite entre os estados de Piauí e Maranhão na costa nordeste de Brasil levando em consideração as feições geomorfológicas (superficiais) e seu arranjo espacial, bem como estratigráficos (em profundidade) e seu arranjo vertical. Sequenciar os principais eventos de sedimentação que permitiram a construção das diferentes geoformas costeiras e determinar os processos dominantes para cada um dos tempos propostos. E finalmente, propor um modelo evolutivo para a área do Delta de Parnaíba fornecendo novas evidências das mudanças climáticas que ocorreram no Quaternário com suas implicações paleoambientais que exibem as diferentes fases de sedimentação que modelaram a paisagem nos últimos 86 Ka.

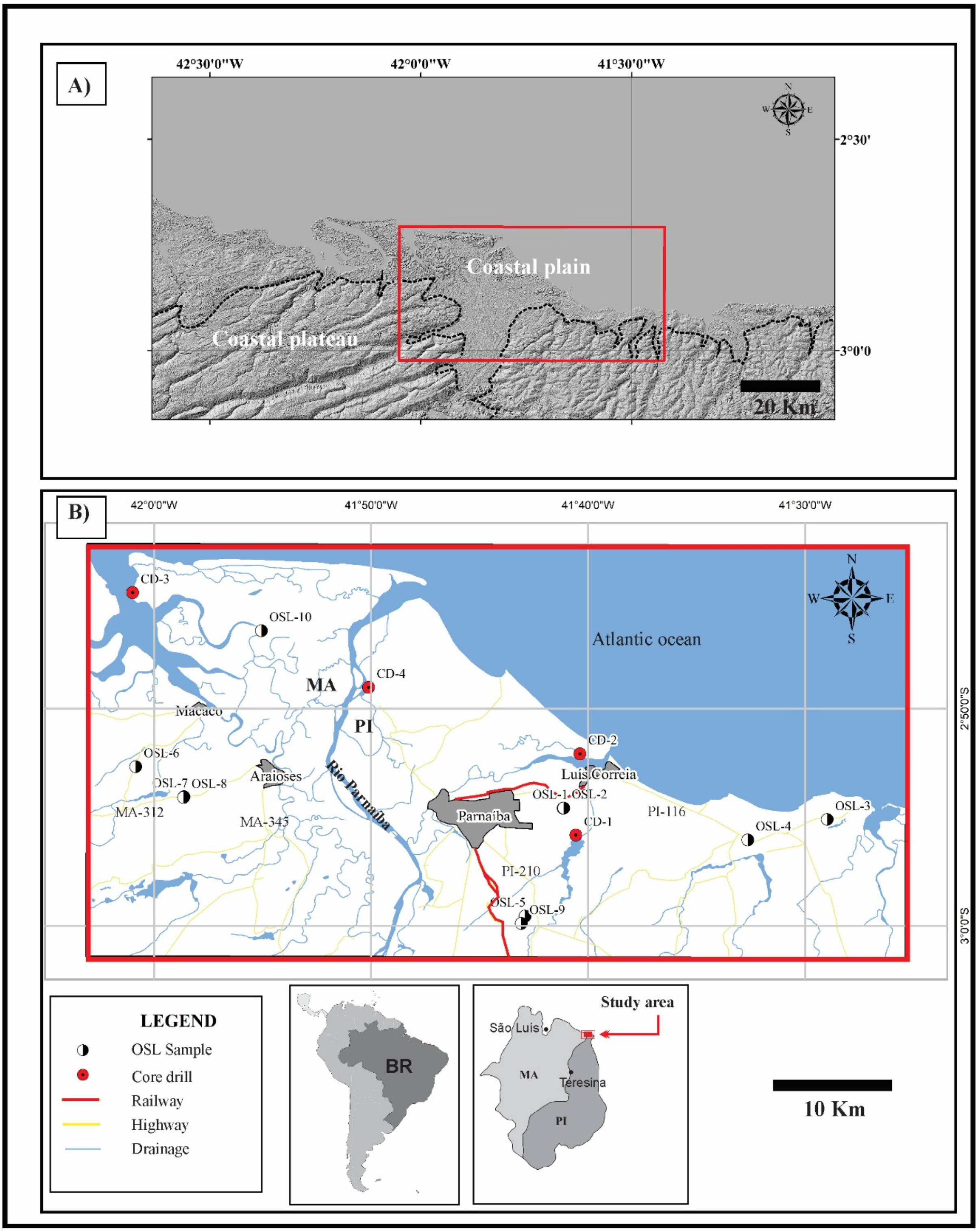

Figura 1. 1- Localização da área de estudo no limite entre os estados de Maranhão e Piauí no nordeste brasileiro. A) Modelo Digital de Elevação (*Hillshade*), mostrando diferenciação do planalto e a planície costeira (linha preta pontilhada). B) Indicação das principais localidades, rodovias, drenagens, pontos de perfuração e amostragem para LOE.

1.4 MÉTODOS

1.4.1 Análises de fácies sedimentares

Para cumprir com os objetivos propostos, foi feita a descrição de fácies de 3 afloramentos e 4 testemunhos de sondagem segundo a metodologia de Walker & James (1992) a qual inclui a individualização das fácies, determinação dos processos sedimentares e associação de fácies, que em conjunto, permitem determinar a ocorrência cogenética dessas fácies e comparação com um modelo preestabelecido para a determinação de ambientes e sistemas deposicionais. Os 4 testemunhos foram feitos usando o equipamento *Rammkernsonde* (RKS), atingindo profundidades de 6-7 m (Lagoa do Portinho, Praia das eólicas, Ilha Canarias e Ilha Grande), a descrição foi feita *in situ* e foram coletadas amostras para análises de laboratório.

1.4.2 Mapeamento geomorfológico

O mapeamento das principais feições geomorfológicas foi realizado a partir do processamento e interpretação uma imagem do satélite *Landsat 8* (8 de setembro do 2015) em composição RGB 432 (cor natural) auxiliado pelo modelo digital de elevação (DEM) da *Shuttle Radar Topography Mission*, complementado com o trabalho realizado em duas campanhas de campo e fotografias de drone para imagens com maior detalhe de certas feições de interesse, estes tipos de ferramentas têm sido úteis na definição da geomorfologia costeira em diferentes áreas da América do Norte (Cooper 1967, Swezey *et al.* 2013), Austrália (Woodroffe *et al.* 1989), China (Xu *et al.* 2015) e América do Sul (Aquino da Silva *et al.* 2019, Silva & Hesp 2010, Guedes *et al.* 2017). De acordo com os resultados, foram determinados os compartimentos morfoestratigráficos mais importantes a partir das características fisiográficas, sedimentológicas e da vegetação, as quais permitem definir modelos deposicionais detalhados (Souza Filho & El-Robrini 1996, Woodroffe *et al.* 1989) que são os instrumentos básicos para o entendimento da gênese e evolução da paisagem no passado geológico recente.

1.4.3 Datação por LOE

Alguns dos campos de dunas (atuais e abandonados) foram datados através de LOE que tem sido usada com sucesso em datações de dunas de areia e Loess (Lü & Sun 2011) em diferentes partes do mundo, tornando-se uma ferramenta útil no controle cronológico de sedimentos quaternários tardios (Duller & Wintle 2012). Este estudo foi realizado pelo Laboratório Datação, Comércio & Prestação de Serviços LTDA em Mogi Mirim no Estado de

São Paulo, no qual aplicaram a metodologia de luminescência oticamente estimulada / alíquota única (SAR) proposta por Murray & Wintle (2000), que é baseada na interação da radiação ionizante do cristal com um cristal natural (Sallun *et al*. 2007). A amostragem consistiu na utilização de tubos de pvc (30 cm de comprimento) para evitar que os sedimentos recebessem a luz solar e, posteriormente foram abertos em um ambiente de luz vermelha onde foi feito tratamento químico com água destilada, H_2O_2 (20%), HF (20%) e HCl (10%) para a eliminação da matéria orgânica, sílica deposicional e carbonatos. O material tratado foi secado e peneirado separando a fração granulométrica na faixa de 100-160 μm (100-60 Tyler), obtendo quartzo e feldspatos.

A idade (I) é calculada a partir da taxa de dose cumulativa (DA) e da taxa de radiação incidente (T) (Radiação γ, partículas β, partículas α e raios cósmicos) por ano (Equ. 1.1). A dose de carga consiste, então, na carga acumulada desde o momento em que a radiação solar incide no mineral (quartzo e/ou feldspato). Esta carga é retida na forma de impureza e/ou defeitos na rede cristalina. A emissão de LOE acontece a partir do momento em que o mineral é estimulado oticamente, esta radiação terá então um comprimento de onda diferente do utilizado na estimulação (Tatumi *et al*. 2008). Para cada amostra foram tomadas 15 alíquotas e suas correspondentes curvas de calibração foram feitas para a determinação da idade; devido a repetidas etapas de irradiação, pode correr uma queda ou aumento da sensibilidade dos grãos gerando uma resposta na luminescência, pelo qual devem ser aplicadas doses de teste (DT) com base no valor estimado de P (~10-20%), o que é necessário para a exatidão do protocolo SAR (Wallinga *et al.* 2000).

$$\mathbf{I}=(DA(G\gamma)) / (T\gamma+T\beta+T\alpha+T\text{rayos cósmicos } (GY/ano))$$

Equação 1.1- Determinação da Idade por LOE. Extraído de Tatumi *et al.* (2008).

2 FUNDAMENTAÇÃO TEÓRICA

2.1 CONTEXTO GEOLOGICO

2.1.1 Arcabouço tectônico e estratigráfico

A margem Brasileira foi originada por movimentos de extensão e deslizamento durante a abertura do Oceano Atlântico Sul (Almeida-Filho *et al.* 2009), nesse arcabouço a área do Delta de Parnaíba encontra-se localizada no limite entre as províncias fisiográficas de Cabo Orange e São Roque de acordo com as características batimétricas (Martins & Coutinho 1981), o que faz dela um ponto de interesse para a análises estrutural e tectônica da geologia costeira. A mais importante fase do *rift* nessa margem ocorreu no Jurássico Superior - Cretáceo Inferior (Martins & Coutinho 1981, Szatmari *et al.* 1987), mas a reativação das falhas foi dada durante o Quaternário o que poderia controlar a deposição dos materiais encontrados no litoral brasileiro (Almeida-Filho *et al*. 2009, Azevedo 1991).

Localmente, têm sido desenvolvidos estudos relacionados com a reativação da estrutura do embasamento associada com o lineamento Pirapemas na Bacia de Barreirinhas localizada aproximadamente a 80 Km em direção oeste da foz do Rio Parnaíba. Este lineamento divide dois terrenos com morfologia, padrões de drenagem e sedimentos com características diferentes indicando que é um fator importante no controle da sedimentação e deriva costeira como produto da presença do deslocamento da plataforma sobradinho e falhas que cortam rochas desde o Paleozoico até o Neógeno, o que gera mudanças locais na taxa de subsidência permitindo a acumulação de sedimentos com idades e espessuras diferentes (Almeida-Filho *et al.* 2009).

Outros estudos estiveram relacionados com perfis sísmicos de alta resolução mostrando a arquitetura estratigráfica do Pleistoceno Tardio e Holoceno na Plataforma continental na frente do Rio Parnaíba, fornecendo ferramentas para a delimitação de vales incisos na porção *offshore* tanto no leste como no oeste da foz do Rio Parnaíba variando só na morfologia (forma de U e V), indicando uma fase previa depositada no trato de sistema de mar baixo, permitindo determinar os processos de avulsão e preenchimento do canal principal no extremo inferior como consequência do aumento do nível do mar associado ao desgelo do período interglacial no trato de sistema transgressivo (Aquino da Silva *et al.* 2016). Essas mudanças também são descritas por Szczygielski et al., (2014) que identifica uma possível conexão entre o Rio Parnaíba e os canais de maré localizados no oeste da foz.

2.1.2 Bacias sedimentares

A área de estudo está localizada no limite entre as bacias do Barreirinhas, Ceará e Parnaíba (Fig. 2.1). A Bacia de Barreirinhas é uma das diferentes bacias costeiras do Brasil (Almeida-Filho *et al.* 2009) e está localizada ao oeste da foz do Rio Parnaíba. Morfologicamente é evidente a presença do lineamento denominado Pirapemas que tem uma direção preferencial NE-SW o que causa uma mudança nos padrões de drenagem, cobertura sedimentar e morfologia da região (Almeida-Filho *et al.* 2009). Esta mudança é comprovada com dados sísmicos e gravimétricos oferecendo uma ferramenta útil na definição da atividade desta estrutura do embasamento em tempos recentes. A parte marítima (*Offshore*) da Bacia do Barreirinhas está ligada à Bacia Pará – Maranhão, sendo caracterizada por falhas normais NW-SE (Aquino da Silva *et al.* 2016) e, é separada da Bacia do Ceará pelo Alto de Tutóia.

Por outro lado, a Bacia do Ceará estende-se da parte leste da Bacia do Barreirinhas e sua gênese está relacionada à abertura do Atlântico Equatorial durante o Cretáceo Inferior (Mohriak 2003) ocupando uma área de aproximadamente 34.000 Km^2 (Morais Neto *et al.* 2003). O registro sedimentar desta Bacia está formada por três Sequências: a) A primeira relacionada com um *rift* caracterizada por depósitos deltaicos, fluviais e lacustres; b) a segunda (Transicional) apresenta depósitos fluviais, deltaicos e lacustres com evaporitos e carbonatos subordinados; e c) terceira caracterizada pela deposição marinha (Pós-*rift*) (Mohriak 2003).

Finalmente, a Bacia de Parnaíba localizada no sul da área do estudo ocupa uma área de aproximadamente 600.000 Km^2 (Goes & Feijó 1994), e está composta principalmente por rochas sedimentares do Siluriano ao Triássico Inferior, com predominância de ambiente marinho, mas também de ambiente flúvio-deltaico, desértico e glacial.

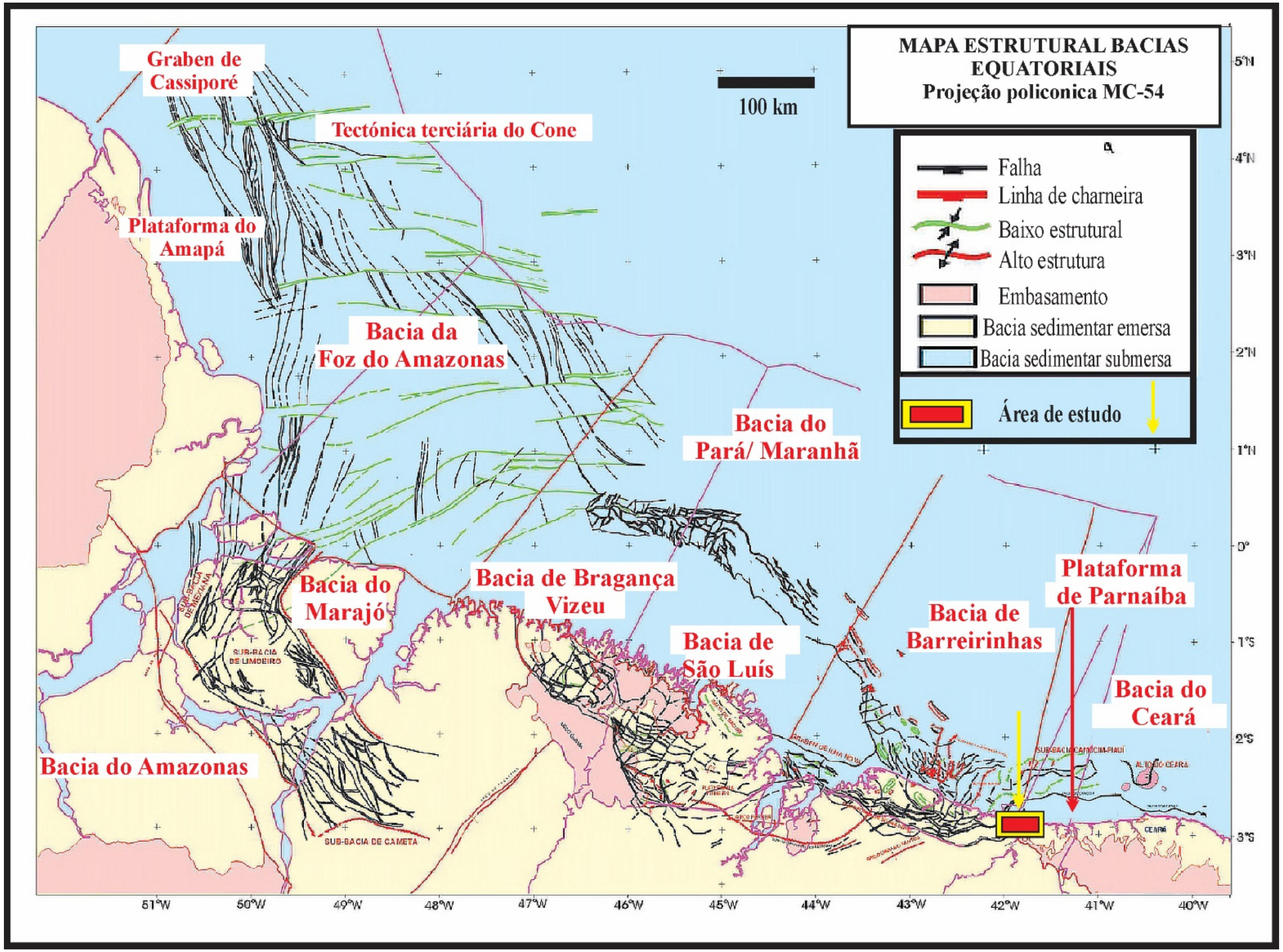

Figura 2. 1- Mapa geológico regional da margem equatorial entre o *gráben* de Cassiporé e a região oeste da Bacia do Ceará, mostrando as zonas de fraturas transformantes. A área de estudo se encontra localizada no limite entre as bacias de Barreirinhas, Parnaíba e Ceará e ocupa parte da plataforma de Parnaíba. Extraído de Mohriak (2003).

2.13 Bacia do Ceará

Localmente, a área específica de estudo encontra-se localizada na Bacia do Ceará. Esta Bacia teve sua origem com a abertura do Atlântico Sul no Mesozoico, na qual a sequência sedimentar foi registrada da seguinte forma: durante o Neocomaniano-Aptiano foram desenvolvidas falhas normais formando *semi-grabens* que permitiram a deposição dos conglomerados aluviais, arenitos fluvio-deltaicos e folhelhos lacustres da Formação Mundaú (Mohriak 2003), unidade basal da Bacia do Ceará. Durante o Neoaptiano ao Albiano Inferior foram depositados os arenitos fluviais, deltaicos e lacustres, além dos carbonatos e evaporitos subordinados, que compõem a Formação Paracuru (Mohriak 2003).

Do Albiano ao Santoniano, foram depositados os carbonatos da Formação Ponta do Mel e os folhelhos da Formação Ubaraná, enquanto no Campaniano se depositaram os folhelhos e arenitos turbidíticos da Formação Ubaraná que tem relação com os carbonatos de plataforma da Formação Guamaré e arenitos proximais da Formação Tibau (Mohriak 2003). A deposição na Bacia cessa com a Formação Barreiras (Durante o Mioceno) (Fig. 2.2), embora Bezerra *et al.* (2015) propõem a criação de uma nova Formação denominada Itaubal que corresponde à deposição durante o Pleistoceno para a Bacia da Foz do Amazonas e a qual poderia aparecer também nesta zona e corresponder com a sequência eólica e fluvial encontrada na base da sucessão estratigráfica descrita neste trabalho.

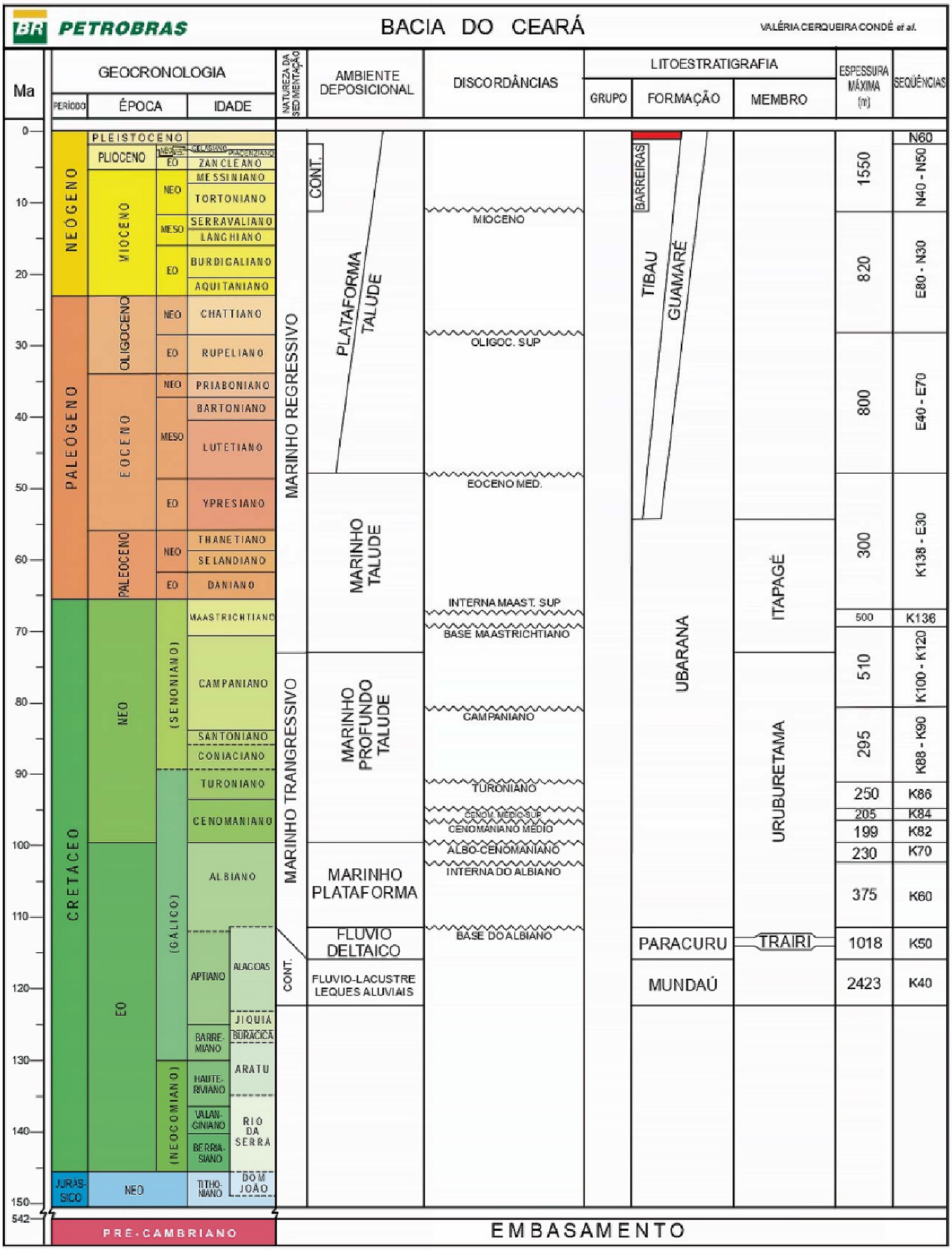

Figura 2.2- Carta estratigráfica da Bacia do Ceará. A caixa vermelha indica o intervalo estratigráfico de interesse. Extraída de Condé *et al.* (2007).

3 RESULTADOS

Artigo a ser submetido em Quaternary Research.

3.1 EVOLUTION OF THE BRAZILIAN NORTHEAST COAST IN THE PARNAÍBA REGION DURING THE LATE PLEISTOCENE AND HOLOCENE

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Abstract

An evolution model of the coastal area between Maranhão and Piauí states in Brazil during the late Pleistocene and Holocene was proposed using stratigraphy, dating by optically stimulated luminescence and remote sensing. In this way were found 17 sedimentary facies which were grouped in 9 facies associations defined as braided rivers, dune field, interdune- deflation areas, tidal channels, tidal flats, mangroves, shoreline, meandering rivers and lakes. Thus about 86 ka existed a coalescence between fluvial and aeolian systems developing and extensive dune field and braided rivers; with the sea level rise and the migration of the aeolian dunes the main drainages were dammed forming lakes. About 19 ka occurred a change in the climatic conditions like decrease in the wind strength and sediment supply and increase of precipitation generating the stabilization of the aeolian shapes by vegetation. From 10 ka to the present were developed mangroves and another generation phases of dune fields. The complex setting of this coastal system exhibits the final stage of transgressive dunes with backshore source for sediments and intermittent climatic conditions associated with changes in the intertropical convergence zone, increase in the sea surface temperature and rise of sea level.

Key words: Parnaíba, stratigraphy, optically stimulated luminescence (OSL) dating, paleoenvironments.

3.2 INTRODUCTION

The current setting of the northeastern Brazilian coast exhibits the integration of different sedimentological processes like waves, tides and wind, that associated with their respective paleoenvironments and environments modeled the morphology during the Quaternary. Previous studies in the Parnaíba region were focused in the structural setting of the Pirapemas lineament and its depositional implications (Almeida-Filho *et al.* 2009), the stabilization of an old dune field southward the Lençóis Maranhenses (Guedes *et al*. 2017), morphodynamic (Aquino da Silva *et al.* 2016; 2019), the evolution of the Parnaíba Delta (Szczygielski *et al.* 2014), trace elements and contaminants of sediments from the Parnaíba River (Paula Filho *et al.* 2014); however, additional studies are still necessary to develop an evolutionary model to explain the coastal dynamic in the Late Pleistocene and Holocene. The evolution of this coastal system could be related with different agents like geographic position, subsidence rate as product of the neotectonics activity (Almeida-Filho *et al.* 2009), rise of sea level (RSL) in interglacial periods (Giannini *et al*. 2007), oceanic and atmospheric circulation patterns (Jackson *et al.* 2019), wind strength (Hesp 2013), changes in the precipitation regime (Walker *et al*. 2018) and kind of vegetation. In this area the general distribution of morphostratigraphic compartments shows an active dune field migrating southwestward in the coast, stabilized dune fields in the south, tidal channels (with NW-SE direction) in the north; mudflats, mangroves and abandoned/active dune fields in the west (Szczygielski *et al*. 2014), all these cut by the most recent deposits of the Parnaíba River as well as the installation of its associated flood plain. This study aims to propose an evolutionary model for the late Pleistocene and Holocene based in facies description of core drills and outcrops (Walker & James 1992); dating with optically stimulated luminescence (OSL) which has shown accurate ages for fluvial terraces of the Solimões river (Soares *et al.* 2010), aeolian deposits in the Gobi desert in Mongolia and China (Lü & Sun 2011), abandoned dune fields associated with a fluvial system in United States of America (Swezey *et al.* 2013) and the coastal deposits in Brazil (Bezerra *et al*. 2015, Guedes *et al*. 2017, Tatumi *et al.* 2008) proving a good chronological control for Quaternary sediments (Duller & Wintle 2012); and remote sensing. With satellite images from Landsat 8 (natural composition color) and the digital elevation model (DEM) from the Shuttle Radar Topographic Mission (STRM) were identified the main surface features, defining the modern arrangement of the morphostratigraphic components and proposed a new and more detailed morphostratigraphic map.

3.3 STUDY AREA

The Parnaíba River is originated in the East Brazilian highlands and flows northward discharging sediments in the Atlantic Ocean, forming an asymmetric wave tide dominated delta according with its morphological features (Bhattacharya & Giosan 2003, Szczygielski *et al.* 2014). This river divides the states of Maranhão and Piauí and its course goes through the sedimentary basins of Parnaíba in the south and the Barreirinhas and Ceará in the north. Locally the study area is located in the Parnaíba River mouth, covering approximately an area of 2450 Km^2 (Fig. 3.1D). In the west, the zone is cut by numerous tidal channels and mangroves, while in the east, the area is dominated by the wave action with the formation of strand plains and beaches, the southern area is composed mainly by stabilized dune fields and some fluvial deposits.

This area is not affected by important human activities due the low population density in the NE of Brazil conserving the natural ecosystems (Szczygielski *et al.* 2014, Szlafsztein 2003). Previous studies in this area were focused on the structural setting of the Pirapemas lineament, the aeolian system associated with the Lençóis Maranhenses, the evolution of the Caçó lake and the evolution of the Parnaíba river mouth in the Holocene (Almeida-Filho *et al.* 2009, Guedes *et al.* 2017, Sifeddine *et al*. 2003, Szczygielski *et al.* 2014). According with Suguio & Martin (1981), the Holocene evolution of deltas at the Brazilian coast began with a constructive phase followed by a destructive phase related with tides and waves, however in the study area this last phase could extend to late Pleistocene showing an initial phase of the transgressive system tract recorded by aeolian deposits, tidal channels and fluvial deposits (Aquino da Silva *et al.* 2016).

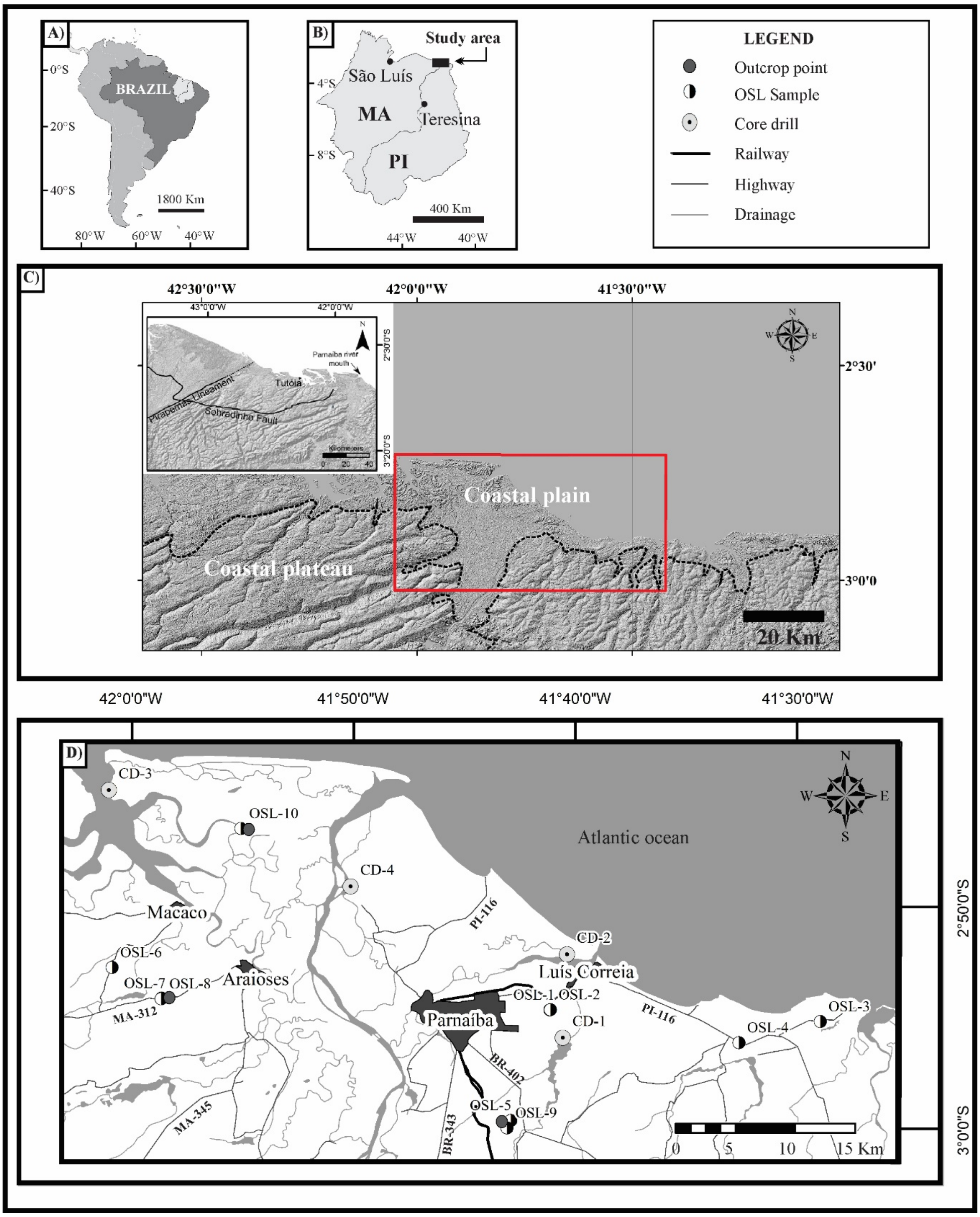

Figure 3.1. Location map of the work area. A) Figure of South America showing location with respect to Brazil. B) State of Maranhão and Piauí with positioning of the study area to the northeast. C) Hillshade highlighting the coastal plateau and the coastal plain with the Pirapemas lineament and the study area, red rectangle. D) Positioning of drilling cores, outcrops and samples dated by OSL.

3.4 GEOLOGICAL FRAMEWORK

The Ceará Basin is located in the Brazilian coast covering an approximate area of 34000 Km^2 (Morais Neto *et al.* 2003). In the study area, the Ceará and Barreirinhas Basins are separated by the Tutoia High (Almeida-Filho *et al.* 2009). The genesis of this Basin is related with the Equatorial Atlantic Ocean opening during the Necomanian-Aptian (Mohriak 2003); in this context were deposited the fluvio-deltaic sandstones and lacustrine shales of the Mundau Formation. The Piracuru Formation is formed by fluvial, deltaic and lacustrine sandstones and subordinated limestones and evaporites that make up the Neoaptian-Albian succession.

The Ubaraná Formation began its deposition during the Albian to Pleistocene and represents deep water deposits, while the Guamaré and Tibau Formations were deposited from the Eocene to Pleistocene and were formed in a transitional to shallow platform (Mohriak 2003); Finally, in the Miocene were deposited the Pirabas and Barreiras Formations composed by limestones and a sandy - muddy succession; however, these formations, some rocks of the edge of the Parnaíba Basin and the crystalline basement are overlaying by Quaternary deposits which are present in whole coastal system (Fig. 3.2) (Guedes *et al*. 2017, Szczygielski *et al*. 2014). Locally, the Quaternary deposits are overlaying the basement in the east of the Parnaíba River while in the west these ones are overlaying Cenozoic rocks of the Pirabas Formation and the edge of the Parnaíba Basin (Fig. 3.2). The Quaternary sediments correspond with aeolian sands and tidal/fluvial channel deposits mainly, however in the north of the area are being implemented extensive areas of mangroves along of the main tidal channels. These deposits were classified as Unit A and Unit B and chronologically are separated by a stabilization phase of the aeolian shapes that occurred during the uppermost part of the Late Pleistocene (Fig. 3.2) (Guedes *et al*. 2017). The unit A is formed mainly by an ancient aeolian deposits and remnants of braided rivers that were dammed by a younger aeolian sedimentation, generating in some parts of the area lakes with fine sedimentation. The unit B is formed by aeolian deposits, a group of tidal channels that cut the coast from NW to SE and the mangrove deposits associated with these ones. According with the morphological setting, the development of the Parnaíba River occurred just in the Holocene being and explication of the contact of this unit with another deposits and rocks.

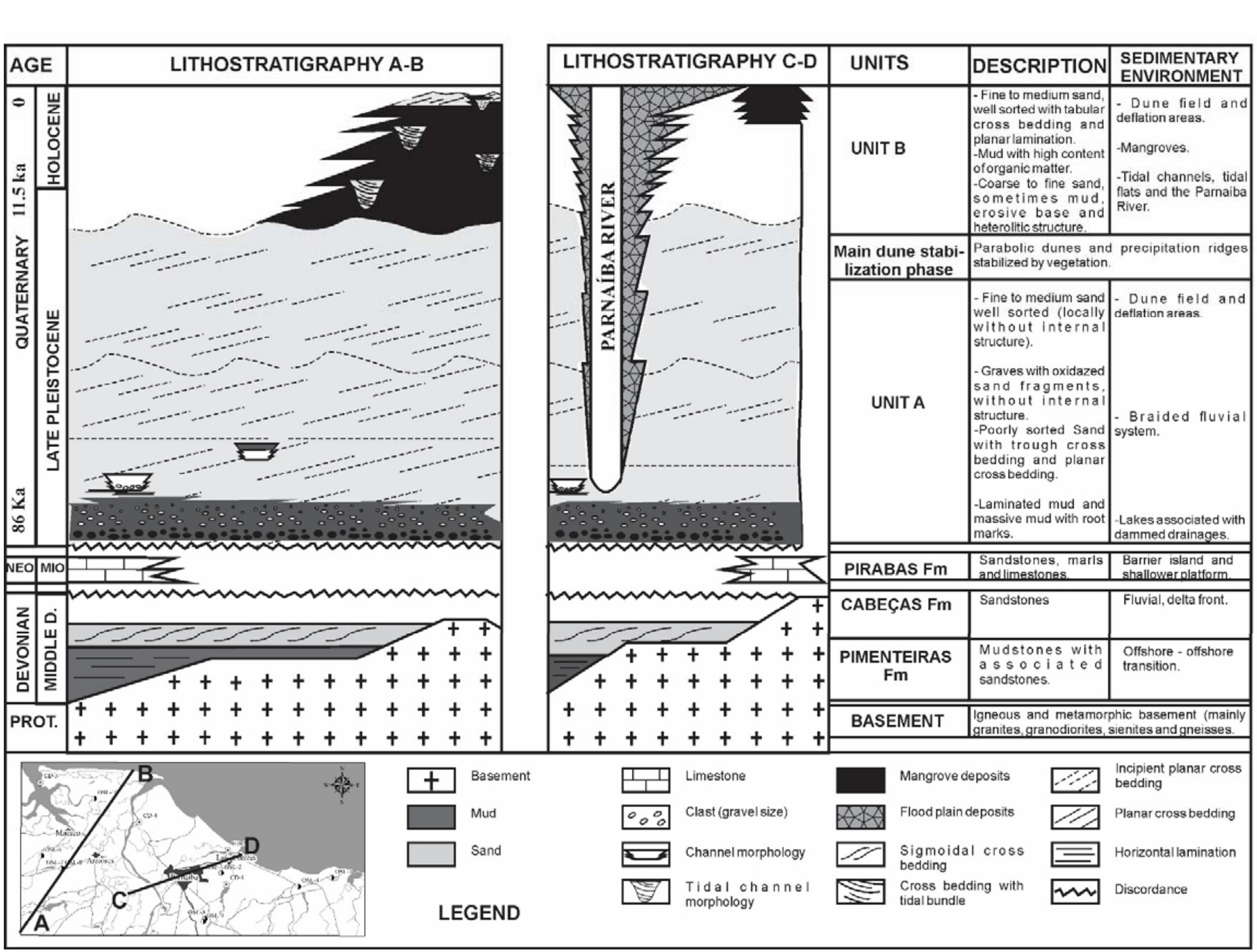

Figure 3.2. Lithostratigraphic chart of the Parnaíba region. Summary of facies association for the Quaternary deposits.

3.5 MATERIAL AND METHODS-

3.5.1 Geomorphology and Stratigraphy

The geomorphological compartments were mapped using a Landsat 8 satellite image from September 8 of 2015 download from the Earth Explorer Platform tied with a digital elevation model (DEM) made with a mosaic of images from STRM. Some images were taken with Drone Phantom 4 (dji) and data were corroborated in 2 two field campaigns on October of 2018 and March of 2019. According with this distribution, were selected four locals for drilling using the Rammkernsonde (RKS), each core drill reached a depth from 6 to 7m. The description of these core drills was made using the methodology of Walker & James (1992) to define the most important features like lithology, grain size, mineralogical composition, sedimentary structures, fossils and bioturbation. Also were described 4 outcrops in which were taken samples for granulometric analysis and OSL dating. The samples were taken in different stratigraphic positions to define the last time when sediments get the solar light avoiding the shallower portions that could resetting the quartz clock (Chase 2009).The environments of deposition were interpreted using a link between the current disposition of these ones as well as the facies association described in outcrops and core drills to define the morphostratigraphic units (Souza Filho & El-Robrini 1996, Woodroffe *et al.* 1989).

3.5.2 OSL dating

To get the OSL data, samples of sediments were taken in 10 locals with pvc tubes to avoid the incidence of solar light, grains of quartz were selected and preparing using the single aliquot regenerative-dose (SAR) which measuring the interaction between the ionizing radiation from a crystal with a natural crystal (Murray & Roberts 1998, Murray & Wintle, 2000, Sallun *et al.* 2007), for this methodology the tubes were opened in a red light environment and treated chemically with H_2O, H_2O_2 (20%), HF (20%) and HCl (10%), after this treatment the samples were dried and sieved separating the granulometric fraction of 100 to 160 µm getting quartz and feldspars without organic matter and heavy metals. To determine the middle age were analyzed 15 aliquots and elaborated the respective calibration curves to determine the paleodose (P), this value have to be corrected using the test doses (DT) with a normal value between 10% P (Wallinga *et al.* 2000). To find the equivalent dose (De) is used the average of De or the lower values; the age (A) is calculated dividing De by T (corresponding to the radioactive isotopes of U, Th, K and cosmic radiation, calculated with gamma spectroscopy).

3.6 RESULTS

3.6.1 Geomorphology

Most of the study area is covered by a stabilized dune field which corresponds with an advanced phase of transgressive dune formation, indicating that they are the oldest Quaternary deposits in this region. The development of these geomorphological features is related with the stabilization by vegetation, sediment supply and climatic conditions; superficially are recognized by parabolic shapes (southwestern area) and differences of height with the surrounding terrain (Figs. 3.3A, 3.3F, 3.3G, 3.3H, 3.3I). In the east, these shapes are not recognized maybe by the chaotic appearance due the cannibalization of older dune shapes by blowouts patterns and precipitation ridges (Hesp 2013, Semeniuk *et al.*1989).

The current morphological setting presents a new phase of dune field formation which is located in the north of the area (Figs. 3.3 B, 3.3C). This geomorphological feature extends from coast line about 7.6 Km covering other deposits (Fig. 3.4). In the study area are visible transverse, sinuous and barchan shapes showing the wind direction from NE to SW. Inland, these shapes are building precipitation ridges along the downwind margins or around the dune field boundary (Figs. 3.3A, 3.3B). Texturally, the deposits are formed by whitish quartz grains with a granulometry mainly of fine sand (Hesp 2011, 2013, Martinho *et al*. 2006). The interdune areas are developed closer to the water table or deflation bases (soil, rock, ancient dune filed, etc.) facilitating the development of vegetation and allowing the formation of vegetated flats or bush pockets (Figs. 3.3D, 3.3E) (Cooper 1967, Hesp 2013, Hesp & Thom 1990). Associated with this large-scale dune migration are formed large deflation plains in the upwind area, characterized by deflation ponds, slacks, wetlands and barchanoid ridges (Hesp 2013). The ridge morphology of the dune field is crenate due the migration of sand into an area with dense vegetation and could be formed parabolic shapes (Hesp 2013).

Mangroves are developed in the north area (Fig. 3.4) associated with tidal influence and their proximity with important drainages. This kind of coastal plants are restricted with intertropical areas (30° N and 30 °S) and the colonization could be related with RSL and another climatic changes as temperature, sediment supply and oceanic currents (Godoy & Lacerda 2015, Spalding *et al.* 1997). According with the current configuration is possible to interpret a dominance of destructive processes (tidal and waves) that define local features as damming of rivers increasing salinity and the migration of mangroves inland (Godoy & Lacerda 2015).

The Parnaíba River is one of the most important geomorphological feature in the study area (Figs. 3.3F, 3.4) due the sediment supply for the construction of other geoforms that modeling the landscape, this river presents low sinuosity bends and formation of different kind of bars (Fig. 3.3F), its flood plain is narrower in the west and more extensive in the east due the presence of tributaries like the Igaraçu River. Other features are related with the possible connection between this fluvial system with other channels in past time as well as the migration of the main distributary channel by the presence of abandoned meanders and the implantation of the flood plain.

3.6.2 Stratigraphy

The older rocks in the northern area of Maranhão and Piauí states correspond with Orthogneisses TTG (PP1g) associated with banded migmatites locally mylonitic (2355 Ma U-Pb), intruded by the Chaval Suit (NP3g 2ch) composed by granodiorites and quartz-syenites (591 Ma U-Pb), forming the crystalline basement of the study area (Gonçalves *et al*. 2006, Sousa *et al*. 2012). There are outcrops of the edge of the Parnaíba Basin of the Canindé Group (Associated with Pimenteiras and Cabeças Formations) in the south of area with expositions of shales and fine sandstones deposited in a delta and a platform dominated by waves with a Mesodevonian age according with the presence of trilobites, brachiopods and ichnofossils (Della Favera 1990, Barbosa 2014).

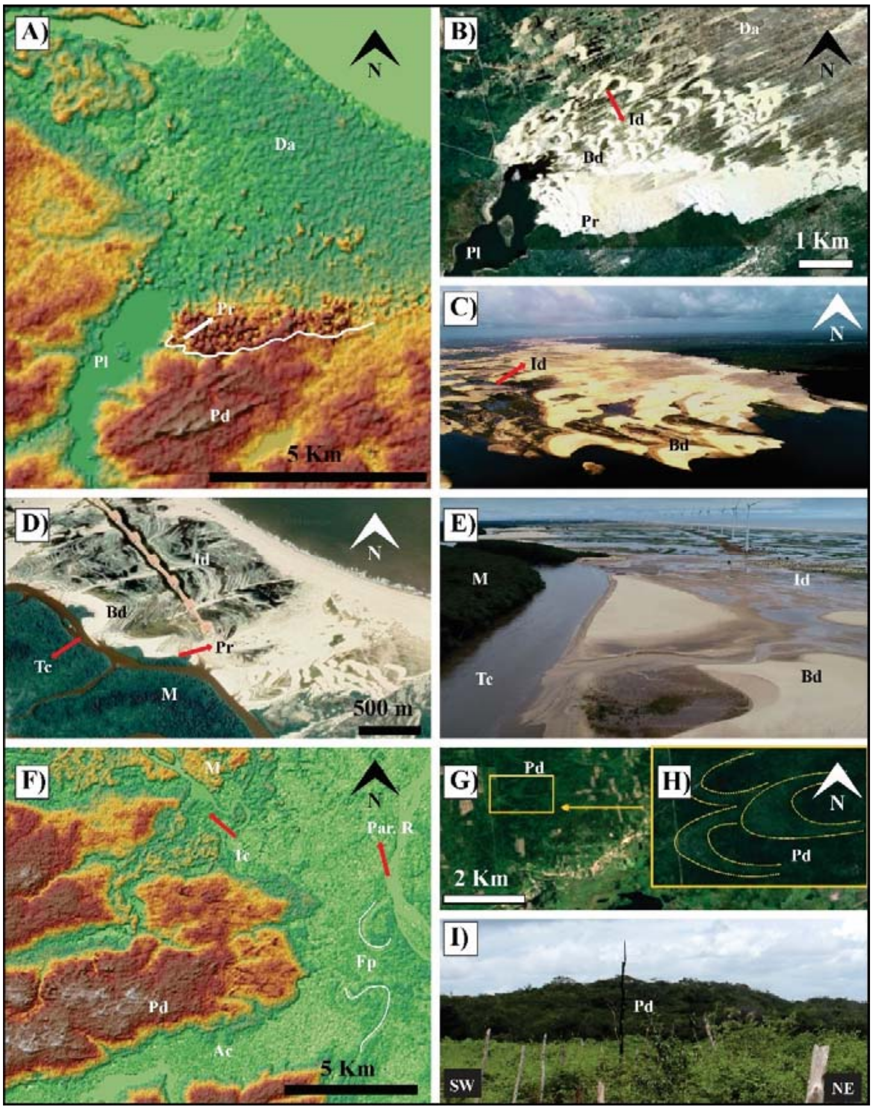

Figure 3.3. Geomorphology. A) DEM showing the current dune field migrating above an ancient channel (Pl). Precipitation ridges begin to be sinuous and there are parabolic shapes in the south. B) Satellite image in natural color composition, showing the direction of migration (NE to SW) forming a big deflation area and interdune areas; are observed barchan shapes. C) Drone image showing a zoom from A and B, more detailed image of barchan shapes and interdune features formed by the proximity with the groundwater level. D) Migration of barchan dunes leaving marks in the deflation areas, development of a tidal flat (mangroves) associated with the tidal channel. E) Drone image showing a detailed image from D, migration of barchan dunes and formation of interdune areas. F) DEM showing the higher relief from the ancient dune field with parabolic shapes, in the north is present a big area covered by mangroves associated with tidal channels with direction from NW to SE. Are showed other features like the flood plain exhibiting migration of channels and abandoned meanders associated with the Parnaíba River. G) parabolic dune stabilized by vegetation, migration pattern from NE to SW. H) detailed image from G, indicating difference of vegetation above de parabolic dunes. I) Photography of a stabilized dune, showing the difference of height. Da: Deflation area, Pr: Precipitation ridge, Pl: Portinho lake, Pd: Parabolic dunes, Id: Interdune, Bd: Barchan dune, Tc: Tidal channel, M: Mangrove, Ac: Abandoned channel, Fp: Flood plain, Par R: Parnaíba river.

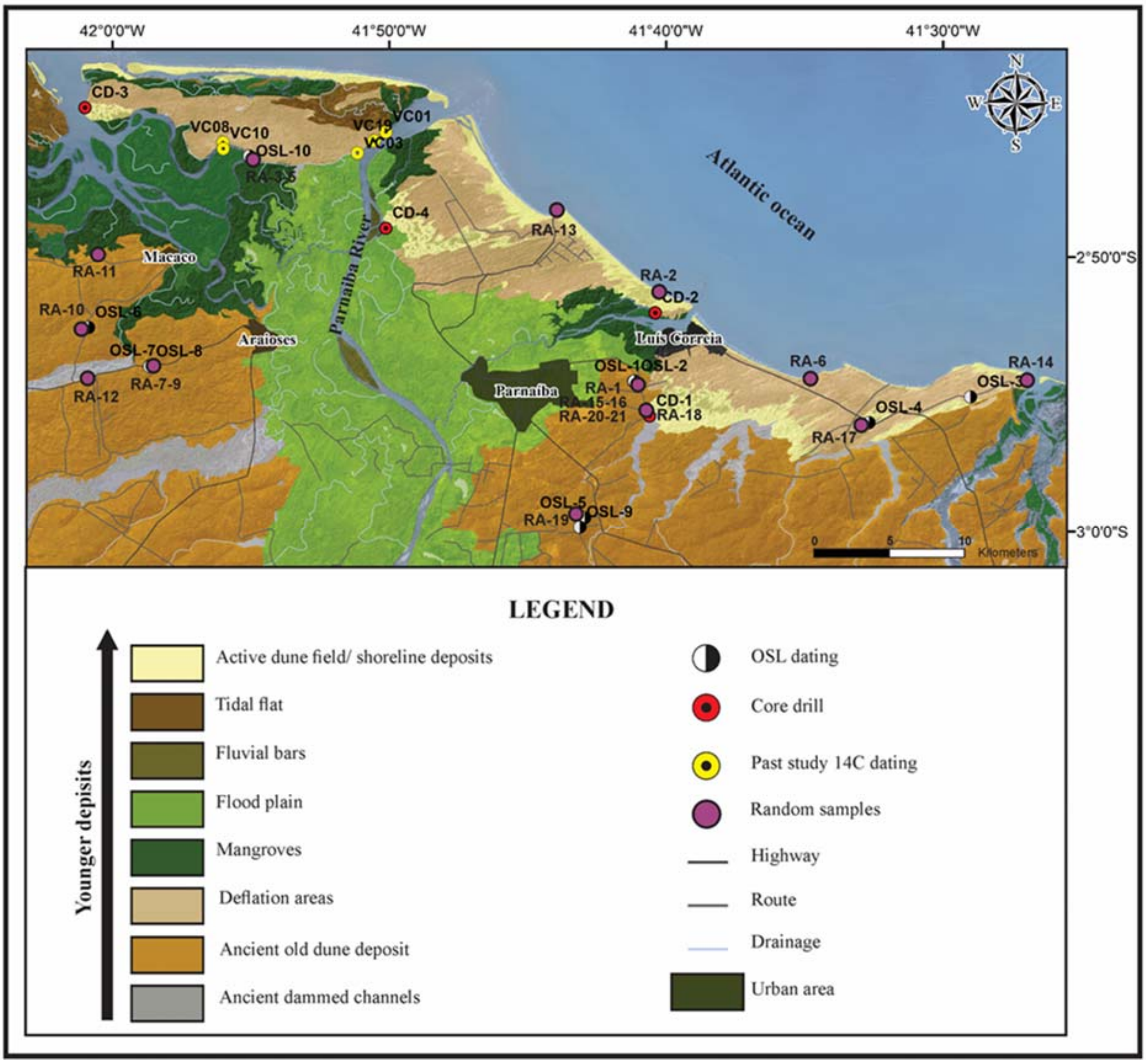

Figure 3.4. Morphostratigraphic map. Location of the geomorphological units in the study area. The different points indicate the core drills and OSL samples.

According with Ferreira (1964) exist outcrops of the Pirabas Formation located in Luis Correia and 20 Km away from Parnaíba City, exhibiting limestones, marls, sandstones and mudstones deposited in a barrier island system associated with a large carbonatic platform during the Late Oligocene to Early Miocene (Nogueira & Nogueira 2017, Nogueira *et al.* 2018, Petri 1957). Gonçalves *et al.* (2006) and Sousa *et al.* (2012), described occurrences of the Barreiras Formation (Neogene) formed mainly by sandstones and conglomerates interbedded with siltstones, claystones and a ferricrite layer in the top. Near from the study area has been described some occurrences of this unit mainly in the south and other ones near from the Lençóis Maranhenses area (Guedes *et al*. 2017). The Quaternary setting corresponds with a large stabilized dune field formed by parabolic dunes, deflation areas, active dune fields, flood plain deposits, mangroves, tidal flats and shoreline.

3.6.3 Facies description

Were described 17 sedimentary facies (Tab. 3.1, Figs. 3.5, 3.6) according with sediment textures, sedimentary structures and geometry, varying in lithology from gravels to mud indicating changes in the depositional processes, energy, sediment supply, currents, etc. The facies were arranged in 9 facies associations (AF) (Fig.3.6), aided by the morphostratigraphic units; each one represents a distinctive depositional environment. FA1(braided river) is deposited in the profile base (older deposit), it is characterized by coarse material (gravel to coarse sand) with high content of clasts with a metamorphic and igneous origin and an early stage of cementation by iron oxides. FA2 (dune field) occupies the southern area and it is associated with the stabilized shapes by vegetation and the current aeolian deposits in the north, its base, at least locally, is over the braided fluvial deposits with high content of iron oxides and closing channels. FA3 (interdune-deflation área) is associated with FA2 formed in depression areas (flooded) and subsequent growing of vegetation, is the first stage of the deflation area compartment. FA4 (tidal channel), FA5 (tidal flat) and FA6 (mangroves), are related with tidal processes, are present in 2 phases of development, the first one overlayed by the basal fluvial deposits with preferential direction NE-SW according with paleocurrents and the current residual shapes, while current tidal channels are active and have a preferential direction from NW-SE. The FA7 (shoreline) corresponds with the coastal deposits. The FA8 (meandering river) is the younger deposit and it is cutting all deposits, is characterized by a big flood plain, the FA9 (lacustrine) is associated with fine sediment deposits formed by dammed channels.

FA1. Braided river

FA1 is yellow to dark red in color, it is located underlaying the older dune field succession with thickness about 3-4 m. It is formed by beds of gravels sometimes matrix or clast supported and a finning upward sequence (Figs. 3.5A, 3.5B). The conglomeratic clasts are formed mainly by reworked cemented sandstones with iron oxides (probably hematite) in the base and a quartz rich gravel in the top grading to sand with trough and planar cross bedding indicating deposition in an energetic environment. This association is formed by Gcmf, Gmm, Gh St and Sp facies. The distribution of clast as well as the presence of matrix indicated a nearby source area associated with the basement. The contact with the tidal deposits is erosive while with the aeolian sands is net.

FA2. Dune field

This facies association is yellow to orange in color (Figs. 3.5C, 3.5D), it represents the 2 dune fields (ancient to current), some structures are not present in the older deposits due the vegetation stabilization and collapse processes (just incipient planar cross bedding and massive sands). At the base, the contacts are net while in the top commonly has erosive contacts associated with the tidal channels. It is formed by Sp, Sh, Sl, Sm (Fig. 3.4C, 3.4D) facies and the thickness of deposit usually is higher than 10 m. Texturally, is composed by fine to medium sand, well to moderately sorted. Rarely presents clast >2mm which are associated with rains and rise in the proximate drainages during the wetter period. In the current setting are observed listric faults due to the instability and high rate of sedimentation and the ancient deposits are covered by vegetation and are recognized parabolic shapes and precipitation ridges.

FA3. Interdune- Deflation areas

This environment is associated with FA2, is deposited in areas with low energy and represents the development of paleosols and deflation areas indicating rise in precipitation or groundwater level, and decrease of sediment supply. The contact with the dune field is defined by flat surfaces. This association is composed by Sh, Sm, Srm, Fl, Frm facies (Fig. 3.5E). Its morphology is characterized by flooded and extensive deflation areas with grown of vegetation and dune migration marks in soils. It is more frequent in the north.

FA4. Tidal channel

This facies association corresponds a several tidal channels in the west part of the study area (Figs. 3.3D, 3.3E). These have a preferential direction from NW to SE. It is formed by Stb, Sm and Scm facies, reworked shell fragments and mud drapes are common indicating an energetic environment and occasional lack waters, however. Its base represents an erosive contact with the older dune field and it is covered partially by the younger aeolian deposits. Locally some of these deposits turned in close lakes, in this way some muddy deposits are recognized with this association.

FA5. Mangrove

This environment is dark brown to black in color, it is characterized by muddy deposits with high content of organic matter and coarsening upward cycles being sometimes sandy. This facies association is composed by Srm, Fl, and Frm facies; wood and bioclast fragments (fish fragments) are found in this environment (Fig. 3.6). Associated with reducing environments and high content of Sulphur allowing the conservation of the organic matter and the formation of organic pyrite.

Table 3.1**.** Sedimentary facies descriptions and interpretations.

CODE	NAME	DESCRIPTION	PROCESS
Gcmf	Ferruginized massive gravel	Massive gravel supported by clasts. High content of reworked gravel clast (sandstone with hematite) and early iron oxide cement (mainly goethite and limonite). Erosive base.	Pseudo plastic debris flow (inertial bedload, turbulent flow) with high content of clasts (Ferreira Junior & Castro 2001, Miall 1996).
Gmm	Massive gravel	Massive gravel supported by matrix. Formed mainly by rounded polycrystalline gravel quartz and an early oxide iron cement.	Plastic debris flow (high strength, viscous), recurrent floods (Delcaillau *et al*. 2016, Miall 1996,).
Gh	Gravel with horizontal bedding	Gravel supported by clasts with horizontal bedding, imbrication of pebbles.	Longitudinal bedforms or residual deposits (Ferreira Junior & Castro 2001, Miall 1996).
Gb	Gravel with bioclast fragments	Gravel with shell fragments and entire organisms. Presence of muscovite and an early cementation phase.	Deposited by reworked sediment by energetic currents, associated with a carbonate beach (Boggs 2006).
St	Sand with trough cross bedding	Medium to coarse sand sometimes conglomeratic (reddish to grayish), moderately to poorly sorted. Presence of granulometric segregation. In sets approximately of 30 cm.	Migration of subaquatic sinuous crest bedforms in a low regime flow (Ferreira Junior & Castro 2001, Reineck & Singh 1975).
Sp	Sand with tabular cross bedding	Fine to medium sand with tabular cross bedding, associated with wind and subaquatic transport, sometimes massive and incipient by presence of bioturbation (stabilized facies). Continue laterally.	Migration of large-scale, straight-crested ripples and dunes. It forms during lower flow regime conditions (Boggs 2006).
Stb	Sand with tangential cross bedding and tidal bundle	Fine to medium sand with cross bedding and tidal bundles.	Deposition of bundles related with neap-spring tidal cycles. Limited by slack water deposits (mud layers) (Boersma 1969, Visser 1980).
Sl	Sand with low angle cross lamination	Fine to coarse sand, well to poorly sorted with foresets <15°. Associated with dune field (well sorted and fine grain) and beach environments (locally coarser grain and sometimes with shell fragments and foraminifera).	Filling depressions and attenuated dunes associated with interdune migration (translatant) or beach deposits (Rodrigues 2014, Walker & James 1992).
Scm	Conglomeratic massive sand	Conglomeratic sand with high content of pebbles <4mm. Without internal structure. Erosional base. Sometimes presence of shell fragments.	Viscous debris flow (Ferreira Junior & Castro 2001, Miall 1996).
Sm	Massive sand	Fine to medium sand, moderately sorted with occasional clasts >2mm. Sometimes presence of organic matter. Some deposits indicate incipient planar and cross bedding. Locally with translatant climbing ripples.	Probably dune deposits, increasing of grain size associated with rainfall and massive structure due to initial instability and subsequent fixation by vegetation destroying the initial stratification (Boggs 2006).
Sh	Sand with horizontal lamination	Fine to medium sand with horizontal lamination, well to poorly sorted, sometimes with clasts >2mm and carbonaceous fragments. Locally with high content of organic matter and associated with mud layers.	Migration of bedforms by high velocity wind. Occasionally obstacles could generate a scour and localized deposition (Boggs 2006, Hunter 1977).
Srm	Massive sand with root marks	Massive sandy layers (orange to gray) with presence of organic matter (root marks).	Destroyed bedding by bioturbation (root marks) associated with paleosols, wetting cycles (Boggs 2006, Retallack 1988).
SMw	Sand-mud with wavy cross bedding	Reddish medium sand with deposition of mud in troughs (whitish).	The mud layers overlie ripple crests and more or less fill the ripple troughs, so that the surface of the mud layer only slightly follows the concave or convex curvature of the underlying ripples, could be associated with ephemeral streams (Martin 2000, Reineck & Wunderlich 1968).
Sihs	Sand with inclined heterolytic bedding	Inclined coarse-to-fine couplet (sand-mud layers). Presence of root traces and bioturbation.	Lateral growth of "active", large-scale "bedforms" (Thomas *et al*. 1987).
Fsl	Mud with linsen cross bedding	Sandy discontinuous linsens in a mud matrix.	Formed where a thin sand layer on a rigid surface is shared by currents. Patterns of isolated long-crested small-scale ripples are generated travelling over the rigid layer (mud) with subsequent mud deposition (Reineck & Singh 1975, Terwindt & Breusers 1972).
Fl	Laminated mud	Layers of mud with organic matter content.	Deposition by precipitation in low energy environments (Boggs 2006).
Frm	Massive mud with root marks and trunks	Massive mud with high content of organic matter and presence of roots and trunks.	Deposition of suspension material in low energy conditions, formation of paleosols with low sediment supply (Retallack 1988).

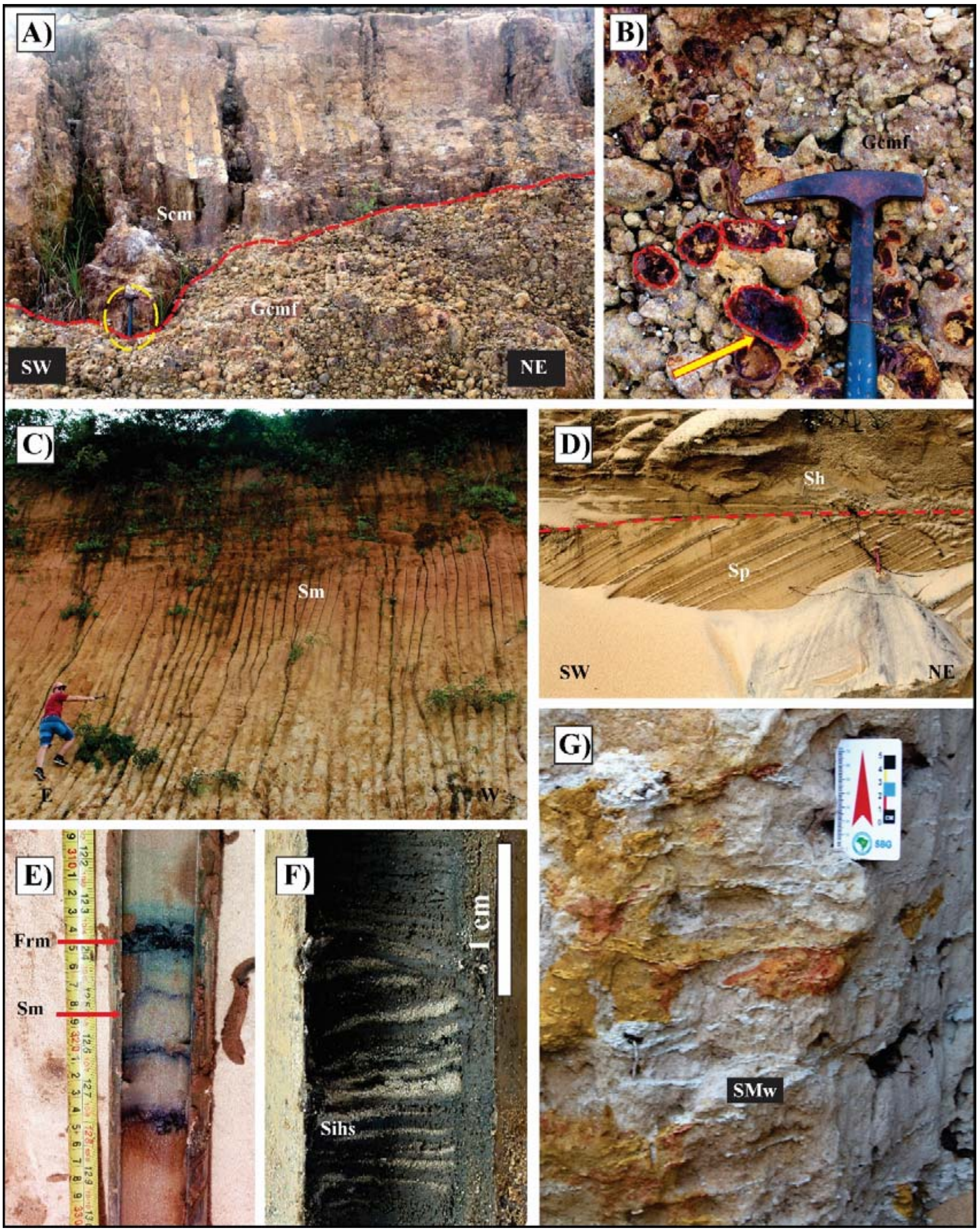

Figure 3.5. Sedimentary facies. A) Outcrop showing the relation between Gcmf and Scm facies, the dotted line indicates an erosional contact. B) Detail of Gcmf facies exhibiting fragments of ferruginized sandstone. C) outcrop of a sand deposit associated with the Sm facies, showing the stabilization by vegetation covering the outcrop. D) Sp and Sh facies in active dune, the dotted line represents the planar limit between the cossets. E) relation between Frm and Sm facies in a core drill indicating the formation of paleosols during the wetter conditions in the dune field. F) Sihs facies in a core drill indicating the alternance between muddy and sandy layers. G) Outcrop showing the SMw facies indicating a fluctuation in the hydraulic condition during the tidal deposition.

FA6. Tidal flat

FA6 consists in muddy to sandy deposits. It occurs in areas next to tidal channels mainly in the west part of the study area. This association is formed by SMw and Fsl facies related with fluctuant hydraulic conditions produced by tides. The proportion Sand - mud indicates a deposition in a mixed tidal flat.

FA7. Shoreline

This association is related with current beach deposits, it includes medium to coarse sand, well sorted and beach rock (high content of fragmented shells) associated with carbonate precipitation of the Parnaíba platform. It is covered rocks of the basement in Pedra do Sal and Coqueiro beaches and it is the source of sediments for the younger dune field. It is formed by Sh, Sl and Gb facies and occurs parallel with the coast line affected mainly by the wave action exhibiting a more pronounced morphology west to the Parnaíba River (Fig. 3.4). Were found porcelain foraminifera in deposits of the Macapá beach where the granulometry is coarser.

FA8. Meandering river

This facies association includes the channel, point bar and flood plain deposits forming a fining upward sequence. It is associated with the Parnaíba river and it is formed by Sihs, Sm, Fl, Srm, Frm, and Sp facies. This environment indicates the development of a paleosol with bioturbation of continental organisms (thalassionoides), locally is covered by active dune field deposits with net contacts (Figs. 3.5F, 3.6). The Parnaiba River forms an erosive contact (Channel deposits) with rocks of the basement and the ancient Quaternary deposits

FA9: Lacustrine

This facies association represented by dammed ancient drainages with a net contact. It is formed by Fl and Frm facies overlaying conglomeratic facies associated with braided rivers. It is deposited under low energy conditions exhibiting in some cases formation of paleosols (Fig. 3.6).

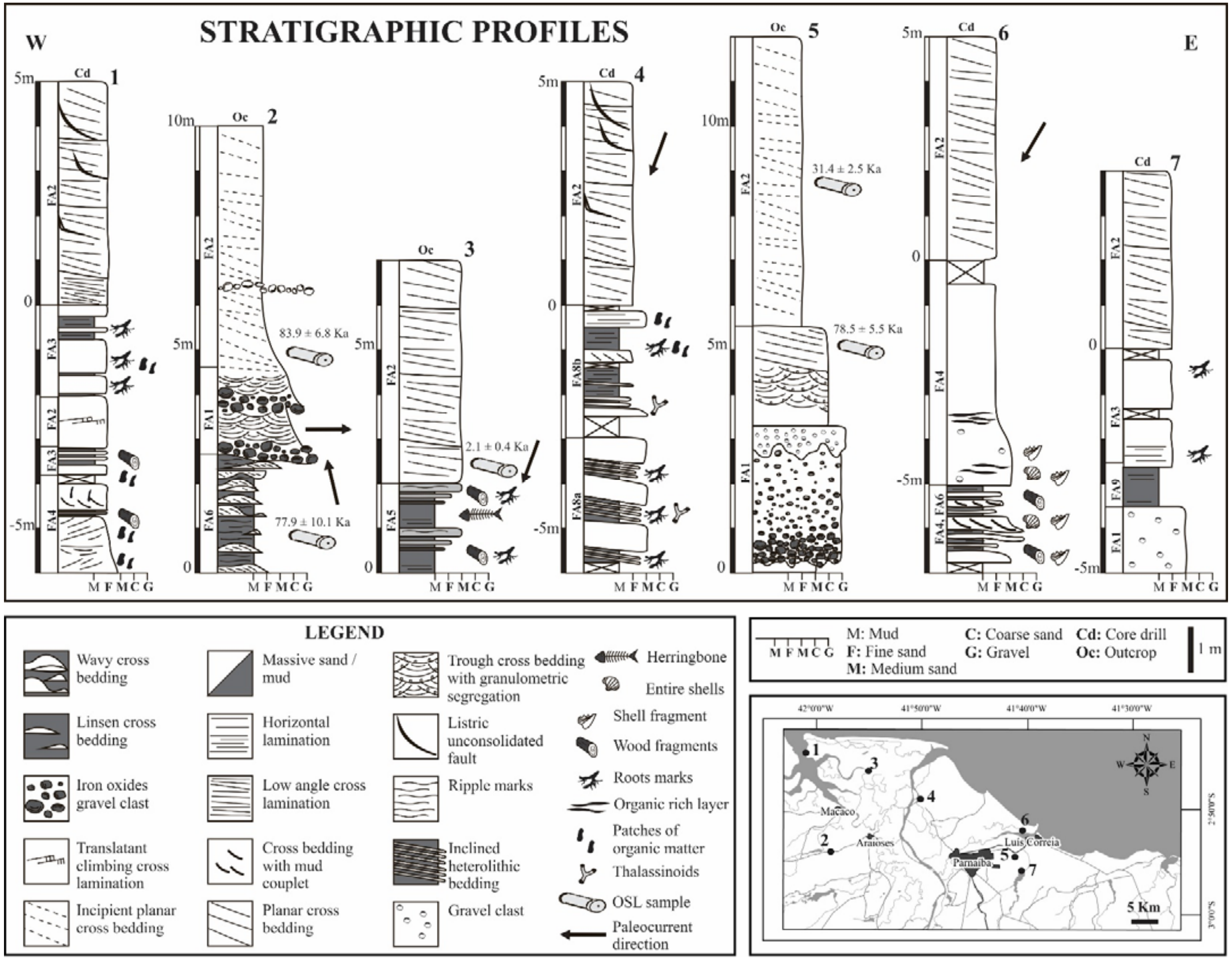

Figure 3.6. Facies description of outcrops and core drills. Facies association located in the left part of each profile as well as its location in the study area. Age in ka (corresponding with OSL dating).

3.6.4 Optically stimulated luminescence (OSL)

The samples contain quartz with high luminescence sensitivity, low recuperation and recycling ratios between 0.90 and 1.10 for all aliquots. These features of quartz are suitable for equivalent dose estimation. The low dose rate ranging from 0.585 ±0.06 to 1.55±0.07 Gy/ka and it is related with the low potassium, uranium and thorium contents at burial environment; according with these results the cosmic dose had a relatively high contribution to the total dose rate (Guedes *et al.* 2017) because the variation of this parameter over time is not expected due the high sedimentation rates and surface stabilization of paleodunes, however older sediments buried by younger aeolian sediments could show changes in the burial depth and age uncertainty (OSL 10).

The burial ages obtained for the deposits range from 2.1 ±0.41 to 86.1±6.4 ka (Tab. 3.2) and represent the evolution of the coastal system emphasizing in several phases of aeolian sediment accumulation and preservation. According with morphology and stratigraphy of deposits, could be proposed two mains generation/stabilization phases of aeolian dunes, the first one about 86 ka to 19 ka, the second one about 19 to present.

Table 3.2. Optically stimulated luminescence age results using SAR protocol.

SAMPLE	DEPTH (m)	Th (ppm)	U (ppm)	K (%)	ANNUAL DOSE (µGy/year)	P (Gy)	STANDARD DEVIATION	Moisture (%)	AGE (ka)
OSL1	7	4.12 ± 0.24	0.79 ± 0.08	0.47 ± 0.07	1100 ± 55	86.10	4.20	5.30	78.50 ± 5.55
OSL2	3.5	9.58 ± 0.46	1.87 ± 0.11	0.24 ± 0.07	1550 ± 70	48.70	3.20	2.40	31.40 ± 2.50
OSL3	5	6.68 ± 0.34	1.079 ± 0.10	0.25 ± 0.07	1160 ± 60	59.90	4.50	2.90	51.65 ± 4.78
OSL4	4	7.97 ± 0.39	1.52 ± 0.10	0.34 ± 0.07	1430 ± 60	54.40	4.40	3.30	37.94 ± 3.50
OSL5	6	5.81 ± 0.32	0.98 ± 0.09	0.18 ± 0.07	970 ± 65	69.10	4.10	4.50	71.14 ± 6.28
OSL6	5	5.00 ± 0.29	1.23 ± 0.10	0.19 ± 0.08	1010 ± 65	45.80	2.50	4.30	45.25 ± 3.85
OSL7	5	2.90 ± 0.23	0.60 ± 0.09	0.65 ± 0.08	1155 ± 70	89.90	13.70	1.40	77.9 ± 10.10
OSL8	9	4.74 ± 0.28	1.06 ± 0.10	0.25 ± 0.08	1000 ± 65	84.30	4.20	4.60	83.9 ± 6.78
OSL9	7	5.24 ± 0.30	0.88 ± 0.09	0.30 ± 0.07	1050 ± 65	90.40	3.80	4.30	86.10 ± 6.40
OSL10	5	1.13 ± 0.18	0.43 ± 0.09	0.24 ± 0.07	585 ± 60	1.30	0.20	12.40	2.1 ± 0.41

3.7 DISCUSSION

3.7.1 Morphostratigraphic setting and facies description

The normal setting of a transgressive dune field is the stabilization by vegetation but the evolution to reach this distribution could be different in each region; in this case, the system displays crenate, wavy and trailing precipitation ridges. Hesp (2013) indicates that in this setting, the current arrangement of this system could be only a partial remnant of the original dune field due the action of cannibal shapes like parabolic dunes and blow outs modifying and eliminating the former dune field phases. The tie of the satellite image interpretation and the field work made possible the formulation of a new morphostratigraphic map in which were separated the units according with the morphological and textural features of each one. In the fig. 3.4 is showed like the ancient aeolian phase is located in the south of the area where are still recognized some dammed channels that are periodically flooded. In previous studies of the Piauí and Maranhão states (located in the east and west of the Parnaíba River) this unit was interpreted as Barreiras Formation (Gonçalves *et al.* 2006, Guedes *et al*. 2017), however, the OSl dating revealed a Pleistocene age for the ancient aeolian deposits and one more sample recollected below the fluvial record (Fig. 3.6). The petrographic description of that basal fluvial unit showed reworked clasts of a ferruginous sand which could be interpreted as the ferricrite that is common in the top of the Barreiras Formation (Armand *et al.* 1983, Rossetti *et al*. 2012, Siqueira *et al.* 2014) nevertheless is not observed a lateritic profile and the iron oxide content is not enough to classify that feature as a ferricrite.

In the northwest of the area were implemented mangrove deposits, this feature indicates a change in the hydrodynamics conditions alongshore which is concordant with the development of these ecosystems during the Pleistocene and Holocene in the Brazilian coast (França *et al.* 2018, Schaeffer *et al.* 2000,). An important geomorphological feature is the change of direction from SW-NE to NW-SE of the main drainages in comparison with the older ones which could be attributed with local tectonics or coastal drift. The growth of this kind of vegetation could be initialized at the same time of stabilization of the ancient dune field due sea level rise, increase of precipitation and nutrient supply from the continent and changes in the local topography and magnitude of tides that generated an expansion of tidal flats in protected areas. The implementation of a new aeolian system is present in the north indicating availability of sediments and an increase of wind strength generating barchan shapes in the east of the Parnaíba River (Fig. 3.4).

3.7.2 OSL Dating

The OSL ages displays activity of dune fields in different periods of time related with paleoclimatic conditions. According with these results, the oldest age corresponds with the interglacial period between Marine Isotope Stages (MIS) 5 and 4, however previous studies reveal that the dune system associated with the Lençóis Maranhenses may have formed even in the MIS 7 (Guedes *et al.* 2017) in relation with the coastal dune field formation in the south hemisphere as result of the RSL (Bateman *et al.* 2011, Giannini *et al.* 2007, Guedes *et al*. 2017, Lees 2006) which is corroborated by the facies association where fluvial deposits are covered and/or eroded by other shapes like transgressive surfaces. The conservation of this dune field system could be related with the formation of sand deposits in heights of about 90 m above the current sea level and a paleoshoreline about 65 Km from the current position composed mainly by sandy deposits in offshore environments suggesting a drowned aeolian dune field (Guedes *et al.* 2017, Kowsmann & Costa 1979). The presence of older aeolian deposits located stratigraphically above fluvial deposits indicates coexistence of the two systems for the same period of time (between 86- 78 Ka), in this context those ancient drainages had a preferential direction from SW-NE and were developed over aeolian dunes as result of uplift of the basement in the south (possibly associated with the Pirapemas lineament and the Sobradinho fault), increase in precipitation and more availability of sediments.

The youngest ages correspond with a sample collected near from a tidal channel (OSL10 – 2.5 Ka) in the north of the study area, this result indicates that exist a new phase of mobilization of dune fields that in this case is beginning in the north of the area suggesting a rise in the sediment supply from the foreshore, these morphologies are synchronous with a big mangrove system which obstacles the migration of dunes downwind generating extensive deflation areas. Dating and sedimentological studies with ^{14}C and in the west of the Parnaíba river mouth (Fig. 3.4) exhibited the development of tidal flats and mangrove paleosols in the last 4.8 ka Bp which suggest the decrease of the fluvial action at least in the north (Szczygielski *et al*. 2014). According with Guedes *et al.* (2017) the last phase of stabilization of the paleodune system occurred narrow time from 19 to 14 ka ago, however currently is developing a new phase of stabilization (2.5 ka) which corresponds dunes localized in the north of the study area (near to coast) which are cut by different tidal channels with a preferential direction from NW to SE.

The existence of a sedimentary cover associated with the Parnaíba River overlaying the aeolian deposits indicates that the development of the flood plain corresponds just with the last stage of evolution of the coastal system, the heavy mineral assemblage of the aeolian deposits exhibit differences with the Parnaíba river assemblage (Guedes *et al*. 2017, Hilbert *et al.* 2016) and similar with the assemblage of the Barreiras Formation indicating reworked sediments of this unit corroborating the OSL dating and the interpretation of the southern deposits.

3.7.3 Paleoclimatic conditions

Some climatic factors as precipitation, temperature and strength-direction wind in South America are related with the Intertropical Convergence Zone (ITCZ) which generates variations in the trade winds in northeastern Brazil (Guedes *et al*. 2017, Tsoar *et al.* 2009,). Data from different climate changes during Holocene and Pleistocene in the Northern Brazilian coast is based in marine sediment studies (Arz *et al.* 1999, Behling *et al.* 2000, Guedes *et al.* 2017, Zhang *et al.* 2015), palynological record (Sifeddine *et al.* 2003), mangroves dynamics (Asp *et al.* 2018, Cohen *et al*. 2018, Franca *et al.* 2019), ^{14}C dating (Mahiques *et al.* 2019, Szczygielski *et al.* 2014) and isotopic relations (Szczygielski *et al.* 2014). However, information about climatic changes in the study area is limited (Guedes *et al.* 2017), in this context, dynamics of the ITCZ could control the building and stabilization of aeolian morphologies due the sediment supply and transport alongshore (Guedes *et al.* 2017, Tsoar *et al.* 2009). At the present time could be observed the coalescence of stabilized and active phases of the aeolian systems indicating that seasonal changes allow the formation of this scenario, in drier periods exist more availability of sediments that could be transported by wind; while during wetter periods increase the precipitation and decrease the wind strength enabling the growth of vegetation. According with Guedes *et al.* (2017) conditions for the remobilization of the stabilized phases have not yet been fully developed at least inland since around 13.9± 1.2 ka. The difference of time for the stabilization of an aeolian system depends mainly of the size of the dune fields and the magnitude of the climatic factors that generate these changes related with variation of precipitation, sediment supply, RSL, tectonics, etc.

Data for the Caçó lake and Lençóis Maranhenses suggest that during about 27 to 21 ka Bp the paleodune system was active indicating that this lake was originated by damming of a preexistent drainage at the same time of the last glacial maximum (Guedes *et al*. 2017) what concord with dammed drainages in the Parnaíba region (Fig. 3.4), according with these data, the stabilization of the of paleodunes occurred about 19 to 14 Ka which is coincident with some geomorphological shapes such as deflation areas and parabolic dunes found in the south of the study area, indicating low supply of sediments for aeolian transport, increase of water table and precipitation, and vegetation growth (Guedes *et al.* 2017). The works of Sifeddine *et al.* (2003) and Jacob *et al.* (2004) pointed that after Heinrich stadial 1 (HS1) (about 18 Ka) started a wetter period in the NE of the Brazilian coast due the southward shift of the ITCZ in South America and Africa and the weakening of the Atlantic meridional circulation (AMOC) (Barker *et al.* 2009, Mulitza *et al*. 2017, Stager *et al.* 2011, Weldeab *et al.* 2006) increasing the sea surface temperature (SST) in the Equatorial Atlantic.

The increase of the Parnaíba River sedimentation in the Younger Dryas (YD) (12-13 Ka) and the record in the Caçó lake as a humid period does not provide evidences of another important phase of reactivation of the dune system in this time, probably because the rise of sea level continued until the present, Guedes *et al.* (2017) suggested that in the Lençóis Maranhenses and Parnaíba areas could have formed a new aeolian system during Bølling-Allerød that subsequently was submerged and eroded with the Holocene rise sea level and that only in modern times is being developed a new aeolian phase next to the coast.

3.7.4 Depositional environment

The study area is interpreted as a complex coastal plain formed by the integration of waves, tidal and fluvial processes. This interpretation was made according with the facies description, morphostratigraphic analyses and dating stablishing its vertical and lateral distribution. The main depositional environment consists in a stabilized dune field with parabolic forms (u and v shapes) preserved by vegetation in the south of the area showing a wind direction from NE to SW. This kind of environments needs sand availability (sediment supply), unidirectional winds and vegetation cover (Hugenholtz 2010, Hugenholtz *et al*. 2008, Lancaster 1995, McKee & Bigarella 1979) which could be related with the proximity with Parnaíba and Igaraçu rivers as possible sources of sediment indicating that is possible the remobilization of fluvial and marine materials by wind (Swezey *et al* 2013). The concordant age between aeolian, fluvial and tidal facies indicated a concurrent activity from wind, rivers and tides with a variation of mud content and moisture probably product of coastal dynamics (Aquino da Silva *et al.* 2019). With the dune migration for NE to SW and the decrease of wind velocity there was a stabilization of these forms like an answer for the increase of vegetation and the sea level rise (Muhs & Holliday 1995, Swezey *et al*. 2013).

According with Gracia *et al*. (2006), Hesp (2013) and Thom (1984), during the late Pleistocene and Holocene started a sea level rise where the shoreline erosion occurred and the transgressive dune field formation started in different places of the world such as Australia, Spain, Poland and Brazil (Barboza *et al.* 2011, Borowka 1990, Dillenburg & Hesp 2009). The development of a complex transgressive dune field model in the region of Parnaíba could followed the next stages (Fig. 3.7):

- In the first stage older than 86 Ka (Fig. 3.7A), existed the coalescence of fluvial and aeolian systems, the source of sediments for this scenario could be related with the development of mobile dunes which avoided the development of vegetation backshore (Hesp 2013). In this way the implementation of this dune field could start as sand sheet or dune fields that later developed transverse, sinuous and barchanoid shapes landward and precipitation ridges in the downwind margins (Hesp 2011, Hesp 2013, Martinho *et al*. 2006).
- In the second stage (from 80 to 20 Ka) (Fig. 3.7B), the migration of dunes continued downwind. in this context the main channels were dammed by sand deposits generating a distinctive geomorphological feature characterized by flats areas between dune fields in the south revealing a preferential direction from SW to NE. In this scenario, the formation of interdune areas allowed the proximity of the water table with another deflation surfaces generating interdune lakes mainly seaward enabling the growth of vegetation in the wetter portions and deposition of fine sediments. The distribution of these aeolian shapes could explain why were not founded stabilized dune shapes in the north and record of fine sediments associated with interdunes in the south.
- In the third stage (between 20 and 10 Ka) (Fig. 3.7C), were developed transverse dunes, trailing ridges, deflation ponds and wetlands, the ridge morphology could be wavy or crenate, exist the buildup of a more extensive precipitation ridge according with the new limits of the dune field. In this stage were formed parabolic dunes migrating ahead the remainder of the dune field (Hesp 2013). Guedes *et al*. (2017) proposed a stabilization age of the aeolian shapes from 19 to 14 Ka, for this time existed a change in the ITCZ, reduction in the wind strength and reduction in the sediment’s availability for the aeolian transport which generated the implementation of the Parnaíba River and mangroves. The stabilization of dunes was stronger in the south while in the north existed a more dynamic system due the action of waves and tides.

- Currently (between 10 Ka to present) (Fig. 3.7D), presents fully vegetated dune fields. The more representative shapes are parabolic but are common imbricated and elliptic dunes, the presence of parabolic dunes is an evidence of the evolved transgressive dune field in the final stage (Hesp 2013). The absence of another kind of shapes could be related with parasitic shapes that eliminated the original geoforms such as blowouts and parabolic shapes. When the sediment supply down, the first dune field is formed landward and an extensive deflation area is developed seaward (Borowka 1990, Cooper 1958, Cordero *et al*. 2006, Hernández & Suárez 2006, Hesp 2013, Hunter *et al.* 1983,) that together with the increase of precipitation, nutrients and salinity (Szczygielski *et al.* 2014), allowed the installation of mangroves extended in both east and west of the Parnaíba River. The presence of paleosols associated with mangroves below dune deposits (Fig. 3.6) indicates a new phase of aeolian migration which concords with the current morphology and the evolution for the Holocene of the Parnaíba River Mouth (Szczygielski *et al.* 2014).

Currently, there is an increase of the sediment availability in the shoreline, with the formation of discrete and active phase of dune fields which concord with another dune fields in Brazil (Barbosa & Dominguez 2004, Hesp 2013, Guedes *et al*. 2017), America (Hesp 2011, Hesp 2013) and Europe (Garcia *et al.* 1997), where exist a similar geomorphological settings. A new phase of mobilization of dunes was developed at least 2.5 Ka ago in which the aeolian active dunes are in contact with mangroves and the ancient aeolian system, the deflation area could be associated with the ancient aeolian system according with OSL ages (samples OSL3 and OSL4), moreover shallower sand deposits could be associated with younger dune fields. In the north of the area are present new sand deposits with barchan and transverse dunes due the increasing of sediment supply, in this way they are developed as sand separated shapes in the seaward margin and in contact with the ancient aeolian deposits (Luna *et al*. 2012, Hesp 2013).

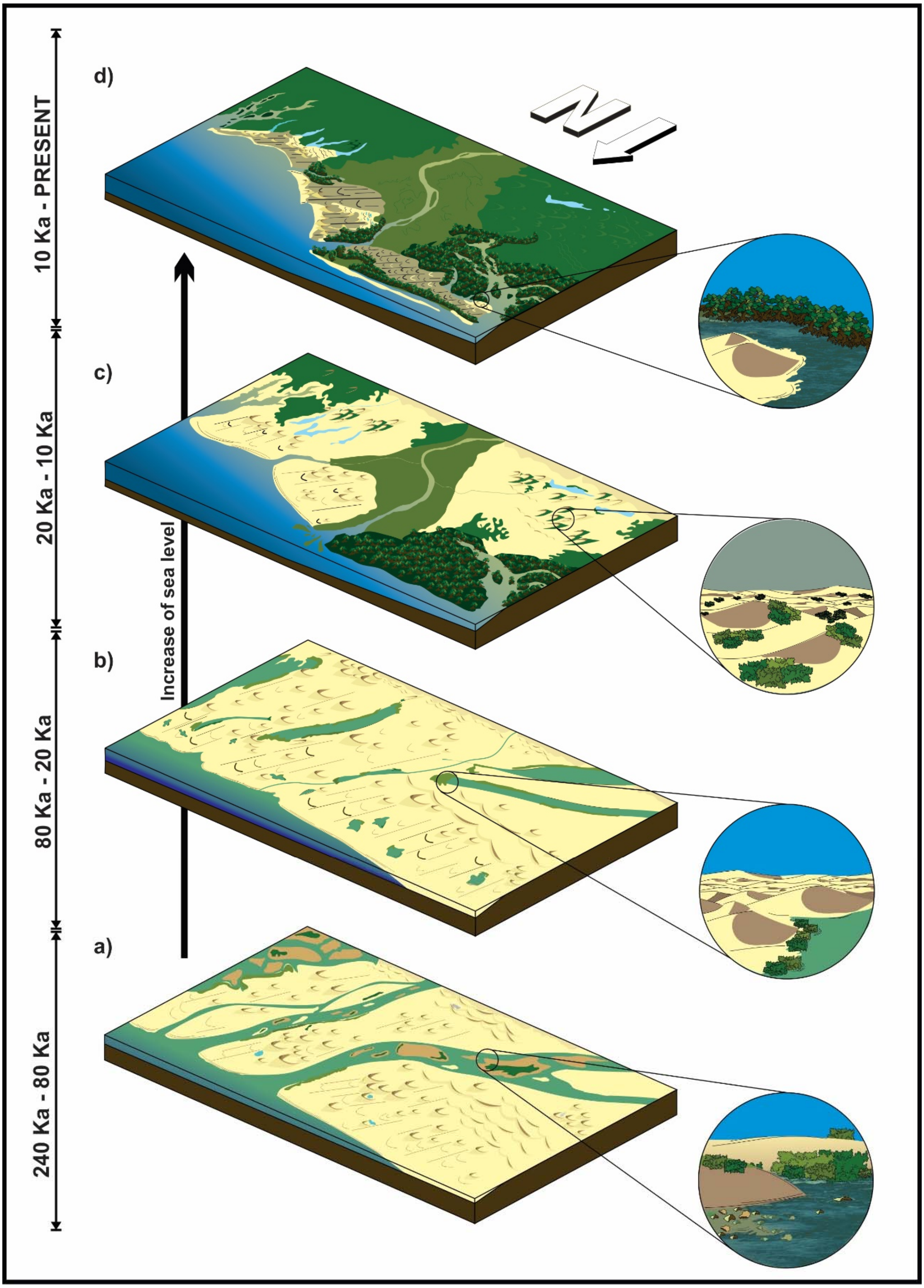

Figure 3.7. Depositional model for the Parnaíba Region during the Late Pleistocene and Holocene.

3.8 CONCLUSIONS

The facies description and OSL ages allowed to determine the morphological evolution of a coastal system recorded during the late Pleistocene and Holocene. This system includes a complex set of tidal channels, beaches, mangroves, tidal flats, rivers, flood plains and active/stabilized dune fields. According with another studies, the formation of one of the largest dune field in South America started at least 240 Ka. The evolution of the system for the study area was recorded, initially by facies associated to braided rivers and the oldest dune field while the final events are associated with deflation plains, mangroves and active dune fields, the OSL ages and the facies analysis allowed determine that what was previously described as Barreiras Formation in the coast of the Piauí state are really fluvial reworked deposits with high iron oxide content and not remnants of the formation of a lateritic paleosol which were coalescent with an ancient aeolian deposits.

The stabilization of this dune system is related with the increase of precipitation, grown of vegetation and decrease of wind strength related with the sea level rise, change in the ITCZ and increase of SST during the HS-1, allowing the preservation mainly in the south of the area recording the biggest dune field in South America. The distribution and morphology of the Quaternary deposits exhibits the developed of an extensive transgressive dune system with different stages of activation/reactivation which just is possible the recognition of some shapes due the cannibalization of the parabolic dunes and blowouts.

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5 CONSIDERACOES FINAIS

Foi realizado um modelo evolutivo para o final do Pleistoceno e Holoceno na região de Parnaíba no limite entre os estados de Piauí e Maranhão. A descrição de fácies, bem como as idades obtidas com LOE e as imagens de sensores remotos permitiram formular um novo mapa morfoestratigráfico no qual são separadas as principais unidades de acordo com a sua ocorrência e disposição vertical e lateral, indicando que os depósitos mapeados como Formação Barreiras no litoral do Estado de Piauí realmente correspondem a dunas eólicas estabilizadas pela vegetação. Este sistema costeiro apresenta diferentes geoformas que incluem canais de maré, praias, manguezais, planícies de maré, rios, áreas de deflação e campos de dunas. De acordo com dados cronológicos prévios pode-se assumir que a formação desse sistema eólico começou pelo menos há 240 Ka onde era síncrono com canais entrelaçados que depois foram fechados com a migração eólica, gerando lagos em localidades dentro do continente. Posteriormente com a diminuição da força do vento e aporte sedimentar, e aumento da precipitação e nível do mar associados à mudança da zona de convergência intertropical, as dunas foram estabilizadas pela vegetação deixando apenas remanescentes superficiais dessas formas. Durante o final do Pleistoceno e início do Holoceno foram implementadas extensas áreas de manguezais ao longo dos principais canais de maré que cortam a área em direção NW-SE. Este novo arcabouço é concordante com a formação de extensas áreas de pântanos em zonas de deflação pela proximidade com o nível freático e com a evolução do Rio Parnaíba durante o Holoceno e sua respectiva planície de inundação. As morfologias encontradas são concordantes com o modelo de dunas transgressivas no estágio final associado com formas parabólicas, *blowouts* e *precipitation ridges* que mascaram as morfologias originais. A granulometria das amostras também corrobora com a hipótese de que aquela unidade corresponde com dunas eólicas devido ao tamanho de grão predominante e ausência de partículas com granulometria maior de 0.500 mm e menores a 0.063 mm. Da mesma forma, texturalmente estes sedimentos apresentam uma morfologia dominante de grãos de esfericidade média com moderado grau de arredondamento o que indica uma fonte próxima ao lugar de deposição relacionada possivelmente com o *foreshore* e *backshore*. A catodoluminescência do quartzo indicou também que a fonte está relacionada com rochas metamórficas e plutônicas principalmente, o que gera evidências de sedimentos transportados ao longo do litoral relacionados aos tipos de rochas aflorantes na costa dos estados de Piauí e Ceará principalmente. Portanto, a assembleia de minerais pesados difere daquela dos Lençóis Maranhenses a qual exibe predominância de minerais ZTR e que pode estar associado com maior maturidade textural pelo local de acumulação. Da mesma forma, essa assembleia é diferente com a da Formação Barreiras que tem sido descrita em diferentes localidades do Brasil e na que aparecem outros minerais pesados como epidoto e granada os quais são ausentes na área de estudo.

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