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TESE DE DOUTORADO

"AVALIAÇÃO E APLICAÇÃO DE DADOS DE SENSORES REMOTOS NO ESTUDO DE AMBIENTES COSTEIROS TROPICAIS ÚMIDOS, BRAGANÇA, NORTE DO BRASIL"

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"AVALIAÇÃO E APLICAÇÃO DE DADOS DE SENSORES REMOTOS NO ESTUDO DE AMBIENTES COSTEIROS TROPICAIS ÚMIDOS, BRAGANÇA, NORTE DO BRASIL"

TESE APRESENTADA POR

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Aos meus eternos amores
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“Quem me dera, ao menos uma vez,
Explicar o que ninguém consegue entender:
Que o que aconteceu ainda está por vir
E o futuro não é mais como era antigamente”

SUMÁRIO

- ***Situação do Artigo:*** minuta concluída

- ***Situação do Artigo:*** minuta concluída

LISTA DE ILUSTRAÇÕES

Seção 4.1

Seção 4.2

Seção 4.3

Seção 4.4

LISTA DE TABELAS

RESUMO

Dados de sensores remotos orbitais foram avaliados e aplicados ao estudo de ambientes costeiros tropicais úmidos na Amazônia brasileira (Planície Costeira de Bragança, no nordeste do Pará) como parte do programa GLOBESAR-2, cujos objetivos eram construir e consolidar a capacitação de recursos humanos, bem como avaliar o potencial e a aplicabilidade do radar de abertura sintética SAR RADARSAT-1 na América Latina.

A área em estudo está inserida no contexto geológico da bacia costeira de Bragança-Viseu. A evolução holocênica desta área é marcada por progradação lamosa em uma costa de submersão, onde se desenvolveu um dos maiores sistemas de manguezal do planeta, com aproximadamente 6.000 km^2.

Este trabalho tem demonstrado que dados orbitais de sensores remotos podem fornecer excelentes informações geológicas e de uso das áreas costeiras. Imagens do RADARSAT-1 representam uma ferramenta poderosa para o estudo de ambientes costeiros tropicais úmidos, principalmente em costas de manguezal. Este fato está relacionado à radiação nas microondas poder ser interpretada para o mapeamento e monitoramento da zona costeira amazônica, pois imagens SAR constituem a única fonte de dados com capacidade de percepção remota em todas as condições de tempo, em resposta a dificuldade de se obter imagens no espectro óptico na Amazônia, devido a permanente cobertura de nuvens.

Imagens do sensor TM do satélite Landsat são excelentes dados para integração com o SAR RADARSAT, apresentando excelente performance na discriminação dos ambientes costeiros. Esta integração propiciou uma visão sinóptica da área, fornecendo informações geobotânicas (relação entre o ambiente costeiro e a vegetação sobrejacente) e de variações multitemporais. Adicionando os dados integrados a um sistema de informação geográfica foi possível ainda analisar simultaneamente as relações espaciais e temporais entre os vários ambientes costeiros, tornando a interpretação geológica mais compreensível, acessível, rápida e precisa dentro de uma filosofia organizacional para controle dos dados e posterior uso desta informação no gerenciamento da zona costeira.

As aplicações dos dados de sensores remotos no estudo de ambientes costeiros tropicais foram utilizadas em diversas abordagens. Em relação ao estudo da variabilidade na posição da linha de costa ao longo da Planície Costeira de Bragança, este estudo tem revelado que durante o Holoceno (últimos 5.200 anos) a planície é marcada por uma progradação lamosa da linha de costa. Entretanto, a partir da análise de imagens de sensores remoto, foi possível investigar a variabilidade da linha de costa em escalas de longo (72-98) e curto período (85 a 88, 88 a 90, 90 a 91), cujas variações morfológicas são caracterizadas por um recuo da linha de costa, provavelmente devido à variações climáticas, tais como El-Niño e La-Niña, que controlam a precipitação ao longo da zona costeira, onde os períodos de erosão mais severos (85-88) são acompanhados de elevadas taxas de precipitação (>4.000 mm/ano).

Do ponto de vista da análise espacial de ambientes costeiros, os manguezais constituem um dos melhores ambientes para análise a partir de sensores remotos, tanto no espectro eletro-óptico devido sua alta reflectância no infravermelho próximo, quanto nas microondas devido sua textura rugosa. Portanto, os manguezais tem mostrado ser um excelente indicador geológico para detecção e quantificação das variações morfológicas de curto e longo período.

Por fim, a integração de sensores remotos com GIS e dados de campo apresenta um papel fundamental para o gerenciamento integrado de zonas costeiras, avaliação de risco ambiental, caracterização local, mapas bases e geração de mapas temáticos e disseminação da informação de domínio público, que são fatores significantes no processo de tomada de decisão.

ABSTRACT

Orbital remote sensing data were used to evaluate its applications in the study of wet tropical coastal environments in the Brazilian Amazon (Bragança coastal plain, in the northeastern of the State of Pará). This work was developed as part of the GlobeSAR-2 Program, whose the objectives were build and consolidate the formation of human resources, as well as evaluate the potential and the applicability of the synthetic aperture radar (SAR) RADARSAT-1 in the Latin America.

The study site is situated in the Cretaceous Bragança-Viseu coastal basin. The holocenic evolution of this area is marked by muddy progradation over a submerging coast, where is developed one of the most mangrove system of the world, with almost 6,000 km^2.

This research has showed that orbital remote sensing data can provide excellent geologic and coastal land use information. The SAR RADARSAT-1 imageries represent a powerful tool to understand the coastal processes in the wet tropical environments, mainly in the mangrove coasts. This fact is related to microwave radiation can be interpreted for Amazon coastal zone mapping and monitoring, because SAR image constitutes in the unique source of data with all-weather remote sensing capability, in response to difficulty to get optical images in the Amazon, due to all-time cloud cover.

Landsat TM imageries are excellent data sources to integration with RADARSAT-1. They present a good performance in coastal environments discrimination. The remote sensing data integration allow a synoptic view of the area and provide geobotanic (relation between coastal environment and vegetation) and multitemporal information. In addition to integrated data, geographic information system (GIS) combines different data sets and simultaneously interprets the spatial and temporal relationship between various coastal environments. This way, GIS allows for a more comprehensive, accurate and easier interpretation of a geomorphologic mapping under an organizational philosophy to control data towards use the information to coastal zone management.

The application of remote sensing data in the tropical coastal studies was used in different approaches. In relation to spatial and temporal variability of the shoreline, this study has revealed that during the Holocene, the coastal plain is marked by a muddy progradation. However, from the analysis of the remote sensing images were possible investigate the shoreline variability under long (1972-1998) and short (1985-1988, 1988-1990, 1990-1991) term, which is characterized by shoreline retreat, probably due to climatic changes, such as El-Niño and La-Niña events. These climatic events control the rainfall along the coastal zone, where severe erosional period (1985-1988) are coupled with high precipitation rate (> 4,000 mm/yr.).

From the point of view of the spatial analysis of the coastal changes, the mangroves constitutes one of the most environments to be analyzed by remote sensing images, as in the electro-optical spectrum due to their high reflectance in the infrared, as in the microwave due to their rough surface responsible for high backscattering. Therefore, mangroves have showed to be an excellent geologic indicator to detect and to quantify short and long-term morphological coastal changes.

To conclude, remote sensing data integration, GIS and auxiliary fieldwork data present a fundamental role to the integrated coastal zone management, environmental risk assessment, local characterization of the study sites, base maps upgrading and information dissemination for public consultation, which are all significant factors in this decision-making process.

CAPÍTULO 1:

INTRODUÇÃO

1.1. APRESENTAÇÃO E OBJETIVOS

As regiões tropicais úmidas da Terra estendem-se do Equador até cerca de 15º N e S, representando menos de um quarto de toda a superfície terrestre, mas sendo responsável por mais da metade da água doce, partículas e solutos descarregados nos oceanos. Os trópicos úmidos são caracterizados por precipitação alta e constante (> 1.500 mm/ano), altas temperaturas (> 20º) com baixa variação térmica. Além disso, o oceano costeiro tropical apresenta outros fatores em comum, tais como radiação solar alta, grande "runnof" de água doce, ventos alísios de leste e fraca força de Coriolis (Nittrouer et al. 1995).

Os processos oceânicos costeiros nos trópicos tem grande relevância social, como demonstraram Glaser & Grasso (1998). A crescente necessidade de área para construção, devido o aumento na população humana, tem levado a destruição muitas florestas tropicais de manguezal nos últimos anos. No contexto da história geológica, cenários tropicais tem sido os precursores para muitos depósitos petrolíferos do mundo. Portanto, o entendimento dos processos costeiros nos trópicos úmidos tem ampla relevância científica, assim como importância social e econômica (Nittrouer et al. 1995).

A área em estudo encontra-se situada no maior e mais bem preservado ambiente tropical úmido do planeta, a Região Amazônica. A costa nordeste do Estado do Pará e noroeste do Maranhão estende-se por cerca de 480 km e ao longo desse trecho do litoral brasileiro ocorre um dos maiores sistemas de manguezal do mundo, com cerca de 6.000 km^2 (Herz 1991). Esta costa de manguezal é extremamente irregular e recortada, com inúmeras baías e estuários. Este setor do litoral brasileiro é caracterizado por um sistema de macromaré semidiurna, com variações médias de 4 m e máxima superior a 8 m, e correntes de marés máximas superiores a 4 m/s no Golfão Maranhense (Ferreira apud Rebelo-Mochel 1997). Os manguezais são desenvolvidos em clima equatorial quente e úmido, com estação chuvosa e seca muito bem definidas e precipitação média anual em torno de 2,500 mm. A temperatura do ar varia de 25º a 27º C e a umidade relativa de 80% a 91% (Martorano et al. 1993).

A área de estudo, a Planície Costeira de Bragança, está situada no setor nordeste do Estado do Pará, ao longo da costa de manguezais do norte do Brasil (Figure 1). Geologicamente, a área encontra-se situada na bacia costeira de Bragança-Viseu (Cretáceo), cuja evolução é controlada por falhamentos normais que alcançam a atual zona costeira. O arcabouço estrutural dessa bacia é responsável pela submersão da zona costeira (Souza Filho 2000), que apresenta baixo gradiente e alcança 45 km de largura na parte emersa. Tais características, aliadas a estabilidade ou queda relativa do nível do mar a partir de 5.200 anos B.P. e contínuo suprimento sedimentar fluvial tem permitido a progradação da planície lamosa e desenvolvimento do sistema de manguezal (Souza Filho & El-Robrini 1995).

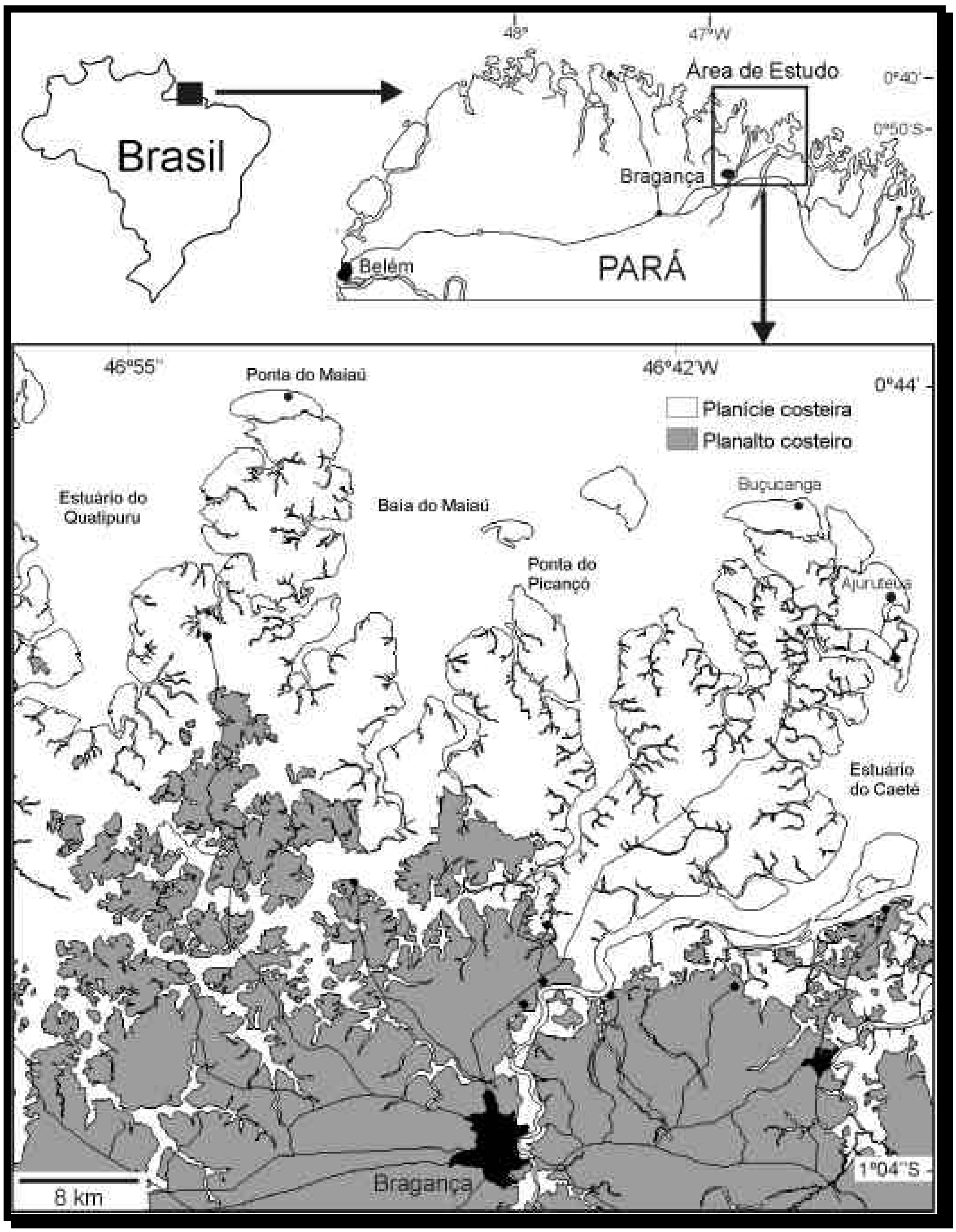

Figura 1- Mapa de localização da área de estudo.

Dentro desse contexto, esta pesquisa foi conduzida como parte do Programa GlobeSAR-2 para avaliar as aplicações do Radar de Abertura Sintética (SAR) do RADARSAT-1, suportado pelo Centro Canadense de Sensoriamento Remoto (CCRS), Agência Canadense para Desenvolvimento Internacional (CIDA), Centro de Pesquisa para Desenvolvimento Internacional (IDRC), Agência Espacial Canadense (CSA) and Instituto Nacional de Pesquisas Espaciais (INPE). Detalhes deste programa no Brasil podem ser encontrado em Paradella et al. (1997 a). Os outros projetos que deram suporte à esta tese foram Monitoramento da Dinâmica Costeira e Estuarina da Planície Costeira de Bragança, através de imagens de satélites e perfis de praia, financiado pela Universidade Federal do Pará (PROINT/98) e o Projeto de Financiamento (PROF) da CAPES

A área em estudo pode ser considerada um local em seu estado natural relacionado a dinâmica costeira. Ao longo desta zona costeira, não há atividades humanas que perturbem os processos costeiros. Assim, o entendimento dos processos geológico pode ser muito melhor compreendido através de dados de sensores remotos, aliados a dados morfológicos, geológicos, meteorológicos e oceanográficos. Outros importantes aspectos foram considerados na escolha da área de estudo, tais como grande diversidade de ambientes sedimentares costeiros, facilidade de acesso, ausência de trabalhos relacionados à geologia costeira, exceto os já desenvolvidos pelo autor desta tese, além da busca do entendimento das respostas humanas frente às variações costeiras, e a oportunidade de testar novas metodologias e sua aplicabilidade no estudo de zonas costeiras dominadas por manguezais de macromaré.

Os objetivos desta investigação foram: 1) caracterizar o cenário geológico regional da costa de manguezal de macromaré de Bragança, (2) reconhecer os ambientes sedimentares costeiros baseados em dados de sensores remotos ópticos e microondas, (3) avaliar a efetividade de realces de imagens, técnicas de fusão e integração de dados de sensores remotos para mapeamento geológico de ambientes costeiros na Região Amazônica, (4) mostrar aplicações de dados de sensores remotos integrados, processamento digital de imagens e técnicas de sistemas de informações geográficas (SIG) no estudo de ambientes costeiros, (5) examinar a dinâmica das formas costeiras através de dados de sensores remotos em escalas de curto e longo período em comparação com eventos na escala geológica, cuja evolução é refletida na estratigrafia dos ambientes costeiros, e (6) analisar o impacto de risco geológico no ambiente costeiro e suas implicações no assentamento da população costeira. Assim, esta pesquisa fornece importantes resultados para o gerenciamento integrado de zonas costeiras, combinando abordagens de diferentes escalas temporais e espaciais.

Esta tese foi concebida na forma de integração de artigos científicos organizados em seis capítulos e dois anexos. O Capítulo 1 inicia com as razões pelas quais estudou-se um ambiente tropical úmido, representado pela costa de manguezal do norte do Brasil (Seção 1.1), seguida por uma discussão do papel dos dados de sensoriamento remoto na pesquisa geológica costeira (Seção 1.2). O Capítulo 2 descreve o cenário geológico regional relacionado ao controle tectônico da geomorfologia da zona costeira do nordeste do Pará (seção 2.1), a geomorfologia da planície costeira de Bragança (Seção 2.2) e as variações do nível do mar e a evolução das seqüências estratigráficas da área em estudo.

O Capítulo 3 constitui a fundamentação desta tese. Descreve as técnicas de sensoriamento remoto relacionadas ao processamento digital de imagens e realces de ambientes costeiros tropicais dominados por manguezais de macromaré. Técnicas têm sido utilizadas para corrigir a geometria e realçar a imagem do RADARSAT-1 no reconhecimento de feições costeiras naturais e antropogênicas e detectar variações de longo período (Seção 3.1). As imagens RADARSAT-1 e TM Landsat são integradas a partir de diferentes processamentos digitais para realçar feições costeiras dentro da abordagem de multi-sensores (Seção 3.2). As imagens de sensores remotos também foram integradas em um SIG a fim de se executar o mapeamento geológico dos ambientes sedimentares costeiros (Seção 3.3). No final deste capítulo, dados do RADARSAT-1, Landsat TM e as combinações entre eles são avaliados quanto à sua efetividade no mapeamento de ambientes geológicos costeiros tropicais (Seção 3.4).

O Capítulo 4 apresenta diversas aplicações de dados de sensores remotos no estudo da geologia costeira. As imagens orbitais são usadas no estudo da dinâmica de curto e longo período da costa de manguezais (Seção 4.1). Manguezais são visto como indicadores geológicos de variações costeiras (Seção 4.2). Uma abordagem integrada é apresentada para a Praia de Ajuruteua, baseada na geomorfologia, uso da costa e impacto ambiental (Seção 4.3). Por fim, impactos naturais e antrópicos são reconhecidos ao longo da planície costeira de Bragança (Seção 4.4). No Capítulo 5 é apresentado um resumo dos resultados e conclusões e no Capítulo 6 é listada a literatura citada nesta tese. Em anexo ao texto principal é apresentado o mapa geológico-geomorfológico dos ambientes sedimentares costeiros da área de estudo e uma lista de artigos publicados dentro do escopo desta tese.

1.2. SISTEMAS DE OBSERVAÇÃO COSTEIRA: O PAPEL DOS SENSORES REMOTOS

Dado o interesse internacional e reconhecimento da importância da zona costeira, o programa LOICZ (Land-Ocean Interactions in Coastal Zones) juntamente com o IGBP (International Geosphere-Biosphere Program) tem sido implementado ao longo de todo o mundo. Além do mais, um módulo para monitoramento dos ambientes da zona costeira e suas variações costeiras são também um componente importante no GOOS (Global Ocean Observing System), estabelecido em 1993 (Johannessen 2000). Os objetivos desses esforços relacionados ao monitoramento da zona costeira podem ser perfeitamente alcançados através da utilização de dados de sensores remotos operacionais na faixa das microondas, óptico e infravermelho (Cracknell 1999).

Para muitos aspectos do estudo costeiro, a escala dos dados orbitais no passado não apresentava facilidades para o estudo de monitoramento costeiro (dados do Landsat MSS com resolução espacial de 80 m). Entretanto, desenvolvimentos recentes de sistemas de sensores remotos orbitais (SPOT, Landsat 5 e 7, RADARSAT-1 e IKONOS) tem permitido o uso de dados orbitais para diversos estudos costeiros. Assim, a partir de meados da década de 80, com o lançamento de plataformas modernas, imagens de satélite tem sido extensivamente usada em mapeamento geológico regional. Ao longo deste tempo, a fonte mais usual de dados orbitais ópticos para aplicações em geomorfologia tem sido as imagens do Landsat TM (Thematic Mapper). Levantamentos geomorfológicos costeiros através do Landsat TM tem sido executado em todo o mundo (Jones 1986, Gowda et al. 1995, Souza Filho 1995, Ciavola et al. 1999, Yang et al. 1999). Durante os últimos 10 anos, radares de abertura sintéticos vêm sendo utilizados com maior freqüência, principalmente em ambientes tropicais úmidos (Singhroy 1995, Singhroy 1996, Rudant et al. 1996, Prost 1997, Kushwaha et al. 2000), devido a versatilidade dos imageamentos nas microondas, que estende a capacidade dos sensores ópticos pela oportunidade de penetração em nuvens e chuvas, que são bastante comuns em áreas tropicais úmidas e iluminação independente de fonte solar.

Aspectos complementares na utilização dos dados de sensores remotos dizem respeito a integração de diferentes partes do espectro eletromagnético (microondas, infravermelho e visível). Tal abordagem já vem sendo utilizada em aplicações geológicas (Harrys et al. 1990, Rheault et al. 1991, Harrys et al. 1994, Paradella et al. 1997 b, Paradella et al., 1998) e em especial em geologia costeira (Singhroy 1996, Ramsey III et al. 1998, Souza Filho & Paradella submetido). Nesta abordagem, enquanto as energias nas microondas medidas pelos sistemas SAR fornecem informações das propriedades geométricas (macro e micro-topografia ou rugosidade superficial) e elétricas (relacionada ao conteúdo de umidade; Lewis et al. 1998, Raney, 1998), sensores ópticos tornam possível à extração de informações dos alvos relacionadas à composição físico-química dos materiais (Colwell 1983). Portanto, a sinergia dos dados SAR e óptico através de produtos integrados permite a detecção, caracterização e monitoramento dos ambientes costeiros e de suas feições, principalmente em ambientes tropicais úmidos, aonde a utilização de imagens SAR vem crescendo nos últimos anos, vindo a se constituir na principal fonte de informações espaciais de áreas tropicais úmidas.

Sistemas de informações geográficas (SIG) vêm sendo utilizados na cartografia de ambientes costeiros, onde imagens de sensores remotos são definidas como uma fonte de informação geográfica, fornecendo importantes feições no domínio do espaço e tempo (Burrough 1986). Deste modo, a habilidade dos SIGs para combinar um conjunto de dados (SAR, TM, litologia, etc) facilita a interpretação do relacionamento espacial e temporal de várias fontes de informação em uma base quantitativa, permite uma interpretação mais compreensiva da geologia costeira. Esta abordagem aliada a integração de dados multi-sensores pode ser considerada como uma das futuras direções do sensoriamento remoto aplicado a investigação de zonas costeiras

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CAPÍTULO 2:

GEOLOGIA COSTEIRA DA PLANÍCIE DE BRAGANÇA

2.1. TECTONIC CONTROL ON THE COASTAL ZONE GEOMORPHOLOGY OF THE NORTHEASTERN PARÁ STATE[1]

ABSTRACT

Based on the integration of geomorphologic, geophysical and structural data it was possible to characterize the large-scale distribution of the Quaternary sedimentary environments on the northeastern Pará coastal zone. Two geomorphological sectors are observed in the study area: sector 1, between Marajó and Pirabas Bay, presents a narrow, no more than 2 km wide coastal zone, developed over the Pará platform, and seems to be a very stable area. In sector 2, from Pirabas Bay eastward, the coastal zone becomes broader, almost 30 km wide, from inactive coastal cliffs to the shoreline. The evolution of this sector is related to the Bragança-Viseu coastal basin, which is controlled by normal faults that reach the present coastal zone. Therefore, the northeastern Pará coastal zone presents a stable coast associated to the Pará platform, and a submerging coast related to the Bragança-Viseu coastal basin.

Keywords: Coastal zone, geomorphology, tectonic control, Northern Brazil.

INTRODUCTION

The continental margin of northern Brazil has been studied to trace mid-ocean tectonic structures into the continental margins and into the continental interior (Gorini and Bryan 1976). Works discussing the geology and geomorphology at Atlantic type margins have emphasized the tectonic, stratigraphic, sedimentary and morphologic control of northern Brazilian passive margin evolution (Zembruscki *et al*. 1972, Campos *et al*. 1974, Asmus 1984). However, the coastal zone is an integral part of the continental margin, and its long-term evolution is controlled by thermo-tectonic evolution of passive margins (Gilchrist and Summerfield 1994).

The coastal zone evolution in Brazil has been traditionally studied with basis on sea level changes, sedimentary dynamics and landform features. However, the large-scale geomorphology of the northern Brazilian coastal zone is directly related to the structural and sedimentary evolution of the coastal basins. This area is clearly linked to the basement framework and to the tectonism that affected this basin and is related to the uplift and collapse that preceded the opening of the Equatorial Atlantic ocean (Aranha *et al*. 1990). The purpose of the present paper is to evince the tectonic control of coastal zone evolution with basis on the integration of geomorphologic, geophysical and structural data.

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GEOLOGIC SETTING

The general tectonic configuration of the northern Brazilian continental margins was established in the Early Cretaceous, during the opening of the Equatorial Atlantic Ocean (Rezende and Ferradaes 1971, Campos *et al*. 1974, Asmus 1984). Campos *et al*. (1974) noted that Precambrian lines of crustal weakness were reactived by tensional forces responsible for gravity-faulted structural pattern development (rifts) and coastal basins depressed in the basement. These faults show a stepped pattern from the continent to the ocean, forming a series of horsts and grabens (Gorini and Bryan 1976, Igreja 1992). According to Suguio and Martin (1996), the role of marginal basins, as a neotectonic agent in the evolution of the Brazilian coast, must be considered. Thus, the geotectonic activity in northeastern of Pará is controlled by E-W transcurrent faults connected through NW-SE normal faults, whereas the structural and sedimentary evolution of the area is clearly linked to the reactivation of basement framework (Costa *et al*. 1996).

Along the northeastern Pará coast, two structural frameworks can be observed (Figure 1): the Pará platform and the Bragança-Viseu basin (Gorini and Bryan 1976). The origin and evolution of these tectonic structures were explained through a model of Atlantic-type margins (Asmus 1984).

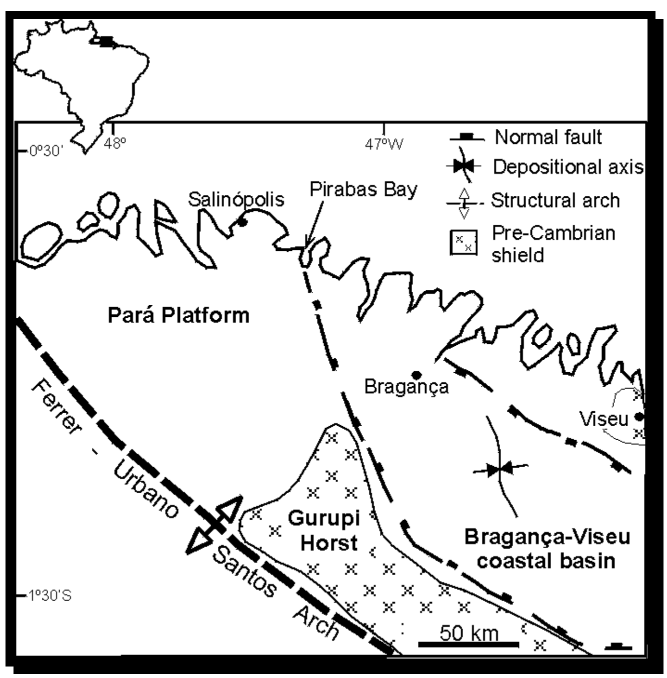

Figure 1- Localization and tectonic map of northeastern Pará State showing two geologic sectors in the coastal zone (based on Gorini and Bryan 1976).

During the Quaternary, the northeastern Pará coastal zone has been affected by regressive and transgressive episodes. Milliman and Barreto (1975) dated lagoon oolites at 17,400 years BP., which suggests that the continental shelf was exposed and sea level was located on the shelf break (-80 to -90 m lower than present sea level). Milliman and Emery (1968) believe that from 17.400 years BP, the sea level began to rise and coastline and transgressive sandy sheets migrated landward, eroding and onlapping the coastal plateaus to form active cliffs. Afterwards, under stillstand, or slower relative sea level rise, it is possible to observe a muddy progradation of the coastline seaward that marks the beginning of intertidal mangrove development. (Silva 1996, Souza Filho and El-Robrini 1996, Souza Filho and El-Robrini 1998). This sea level history has strongly controlled the Quaternary evolution of the coastal zone, which is characterized now by wide mudflat environments (mangroves).

DAT SET AND METHODS

Digital data from TM Landsat-5 imageries in orbit-point 222-61 and 223-60 were selected to cover the northeastern Pará coastal zone. The images were not geocoded to make the false color composition on a 1:250,000 scale. Details of the satellite data used are given on Table 1. Ancillary data such as plan-altimeter maps on a 1:250,000 scale, geological map on a 1:50,000 scale, bathymetric and sedimentological maps on a 1:5,000,000 scale and field observation were utilized for the study.

Table 1- Details of used satellite data.

Platform/ Sensor	Orbit/Point	Acquisition date	Spatial resolution
Landsat TM 5	222/61	August 24, 1985	30x30 m
Landsat TM 5	223/60	July 24, 1988	30x30 m

The geomorphologic study of the coastal zone was based on the interpretation of TM Landsat-5 satellite data in the form of false color composite (4R5G3B). Digitally enhanced products were carried out using standard keys such as tone/color, texture, patterns, form, size, shape and drainage. The accuracy of interpretation was also assessed through fieldwork. The geomorphologic map was integrated with gravity and tectonic maps to establish the relationships between coastal zone geomorphology and the tectonic framework of the northern Brazilian continental margin.

DIFFERENT GEOLOGIC SECTORS OF THE NORTHEASTERN PARÁ COASTAL ZONE

Along the Pará continental margin, two geologic sectors can be observed, according to Gorini and Bryan (1976). The Pará platform as defined by Rezende and Ferradaes (1971), constitutes areas of no more than 2,000 m of Cretaceous or Jurassic/Triassic deposits. The Tertiary sedimentary cover, almost 1,500 m thick, is not tectonically influenced by older centers of deposition, which reflects great tectonic stability compared to adjoining coastal basins (Rezende and Ferradaes 1971, Gorini and Bryan 1976). The other sector is represented by the Bragança-Viseu coastal basin, which constitutes a graben bounded by normal faults along the northwest-southeast structural trend. Sedimentary thickness reaches almost 4,500 m, deposited in two mega-sequences: Codó-Grajaú sequence (Late Aptian) and Itapecuru sequence (Early Albian to Early Cenomanian) (Aranha *et al*. 1990). The Cenozoic sequence is constituted by the Pirabas Formation, deposited under transgressive conditions, responsible for a carbonatic sedimentation, followed by Barreiras Group deposition under regressive conditions (Goes *et al*. 1990). Nowadays, the Barreiras Group forms coastal plateaus along the coast.

These geological sectors are controlled by the tectonic of the Pará continental margin (Figure 1). The Pará platform goes from Marajó to Pirabas Bay and constitutes the tectonic boundary of the continental margin. This platform represents a gravimetric high; easily identified on the Bouguer gravity anomaly map (Figure 2), which can explain the narrow geomorphologic expression of the coastal plain. The Bragança-Viseu coastal basin is completely developed in land and this geologic sector represents a gravimetric low developed from the Pirabas Bay to Gurupi River along a northwest-southeast direction and from coastline to continental fracture zone (Gurupi horst) in a northeast-southwest direction (Figure 2). According to Aranha *et al* (1990) and Igreja (1992), this basin is submitted to transtensive movimentation predominantly dextral, due to the displacement of the South American and African plates. Therefore, the coastal zone is located in a different geologic sector in relation to continental shelf, developed over the Pará platform.

COASTAL ZONE GEOMORPHOLOGY AND TECTONIC FRAMEWORK

Stretching out for 300 km, according to Franzinelli (1992), the northeastern Pará littoral constitutes a submergence coast subdivided in two sectors: sector 1, from Marajó Bay to Pirabas Bay, where the bays cut the active cliffs and; sector 2, from Pirabas Bay eastward, where the coastal plateaus stretch out southward to constitute inactive cliffs. This geomorphologic compartimentation can be observed in TM images; the coastal sedimentary environments (predominantly mangroves) widen considerably towards the east from Pirabas Bay (Figure 3). As the coastal plateaus extend southward, the coastal zone is wider and consequently this sector represents a lower topography, much more influenced by flooding and tidal action.

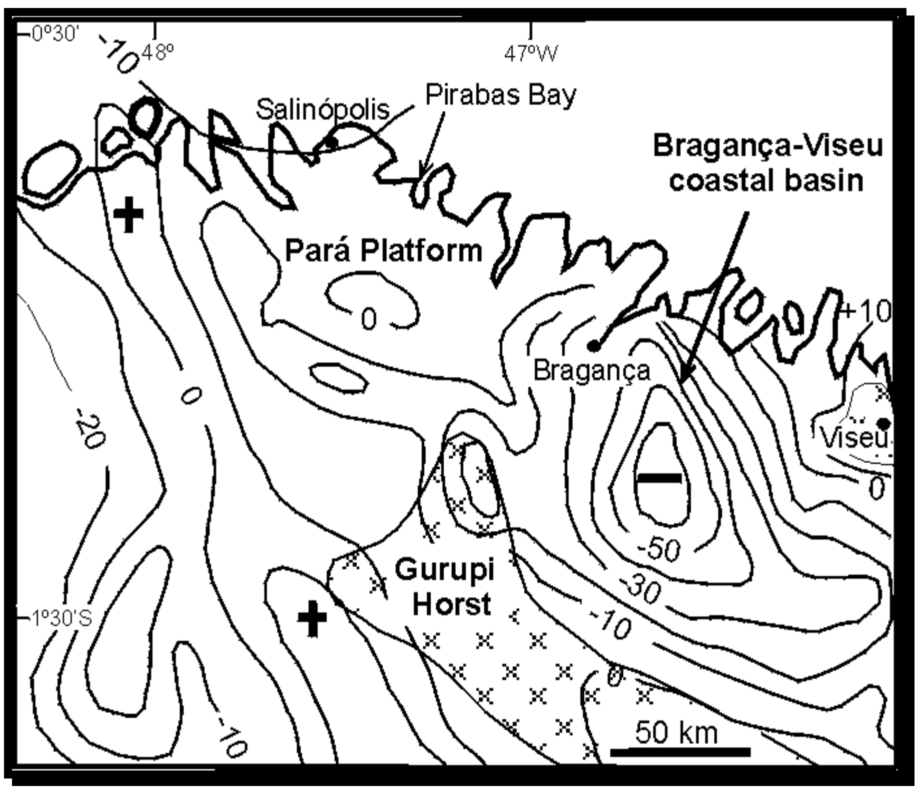

Figure 2- Bouguer gravity anomaly map of northeastern Pará State (Oliveira and Castro 1971).

The two geomorphologic sectors recognized by Franzinelli (1992) can be described in relation to morphostructural compartimentation of the northeastern Pará coastal zone. The sector 1 presents a narrow, no more than 2 km wide coastal zone, developed over Barreiras Group sediments, that reach the littoral to form active coastal cliffs. The cliffs constitute the outer boundary of the coastal plateaus exposed to erosion along the shoreline due to wave and tidal action. Estuaries incised in the coastal plateaus, extend for more than 70 km landward and mangrove deposits constitute the mud intertidal flat (Figure 3A). However, in the sector 2, the coastal zone becomes broader, reaching a width of almost 30 km from inactive coastal cliffs to shoreline (Figure 3B). The inactive cliffs are 1 m high in direct contact with the mud tidal flat represented by mangrove prograding environment and the estuaries extend for more than 100 km from shoreline to coastal plateaus.

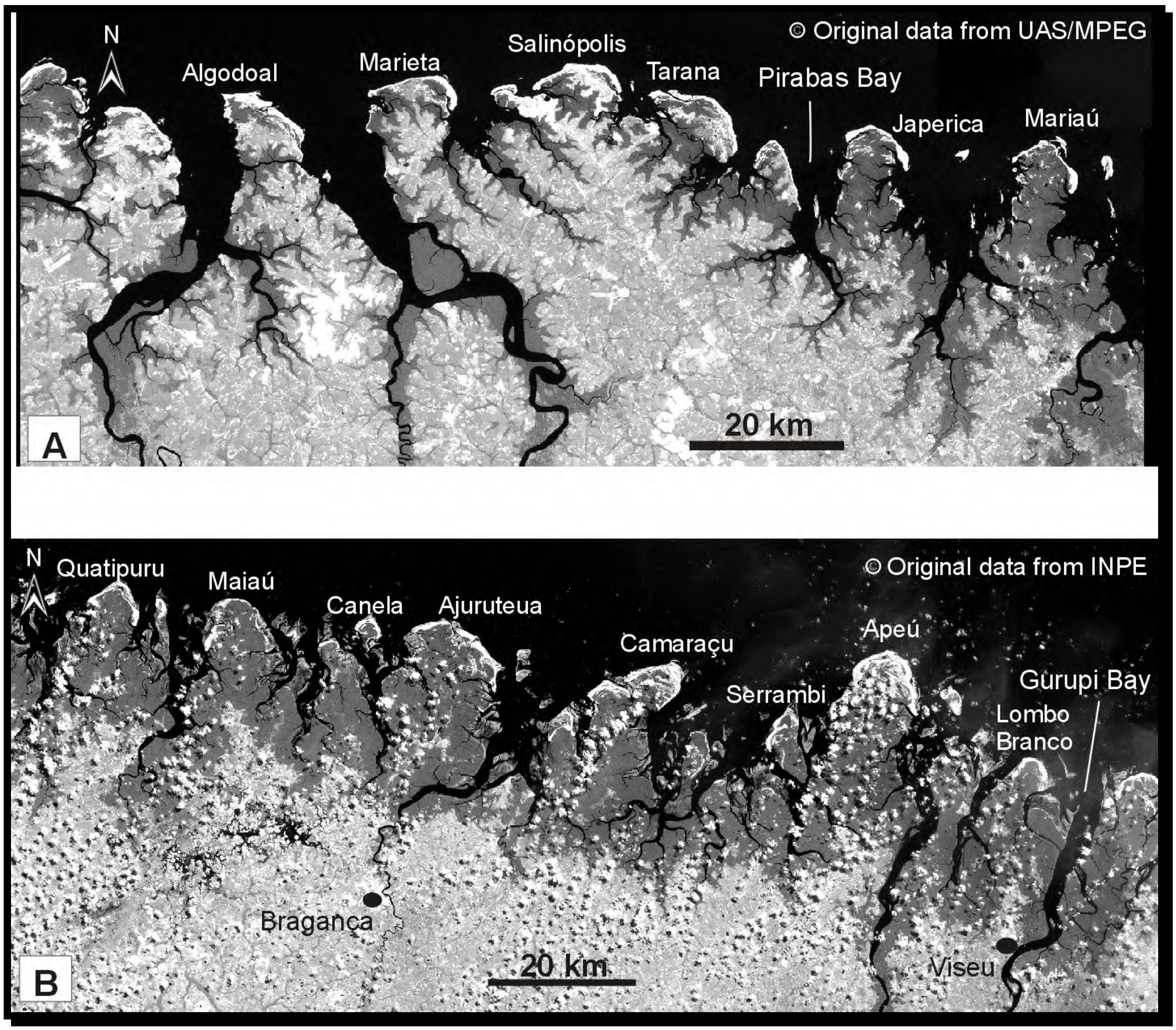

Figure 3- Band 5 of TM-Landsat imagery showing the coastal geomorphology of the northeastern Pará State. A) In the sector 1, note that coastal plateaus reach the shoreline and coastal plain is narrow. B) In the sector 2, observe that coastal plateaus stretch out southward to constitute inactive cliffs and coastal plain becomes wide, reaching more than 30 km of width.

DISCUSSION

Based on the integration of these data it is possible to state that sea level changes only could not explain the differences in sedimentary pattern and geomorphologic compartimentation between the western and eastern part of northeastern Pará State. In the sector 1, on the Pará platform, the higher relief developed with Tertiary deposits is found near the coastline forming active cliffs. Based on gravity map, this sector is found to be subject to stability or emergence processes. In the sector 2, in the Bragança-Viseu coastal basin, the relief along the coastline is lower and is related to Quaternary unconsolidated deposits. Gravity map analysis shows that this sector represents a submerging coast, where the sediment supply has been more important to build the coastal zone than in the sector 1, since the Bragança-Viseu basin represents a sink of sediments.

It is also interesting to verify that the transition between emerging and submerging zones is abrupt, which can be observed as well, in the gravity maps as in TM images. This seems to eliminate the hypothesis of morphological differentiation due to continental flexural mechanism described in the other sectors of the Brazilian coastline (Suguio and Martin 1976, Driscoll and Karner 1994, Bittencourt *et al.* 1999). Therefore, the tectonic interactions between fault blocks, separated by NW-SE normal faults developed as consequence of tectonic activity responsible for the Equatorial Atlantic Ocean opening, persist active during the Quaternary.

Sediment distribution along the coastal zone is also controlled by tectonic evolution of the continental margin. In the sector 1, the coastal plain is associated with the tidal flat along estuaries limited by Tertiary deposits (Figure 3A) that reach the coastline. In the sector 2, inactive cliffs mark the interior limit of the Quaternary plain, which possibly represents an ancient reactivated fault. From inactive cliffs, the Quaternary deposits prograde almost 30 km seaward (Figure 3B), probably due to continuous submergence of the coast during the Holocene.

In low elevation passive margins, such as in northeastern Pará, a broad continental shelf leads to a coastal plain, which rises gradually to a relatively low-lying interior surface (Gilchrist and Summerfield 1994). The continental shelf of the Pará is 220 km wide, with a smooth and gentle bathymetric surface, forming broad terraces (Zembruski *et al*. 1972). This morphologic characteristic of the continental shelf must be responsible for the control of the coastal plain morphology. However, two geomorphological sectors can be observed showing several different characteristics. Therefore, differences in the continental structures are reflected in the Quaternary coastal deposit distribution that is controlled by the tectonic framework.

SUMMARY AND CONCLUSIONS

The large-scale geomorphological evolution of northeastern Pará State is controlled by the tectonic setting of the passive margin developed since the Early Cretaceous during the opening of the Equatorial Atlantic Ocean. Two geomorphological sectors are observed in the study area. Sector 1 is developed over the Pará platform, which shows a wide Tertiary sedimentary cover represented by the Pirabas Formation and the Barreiras Group. The evolution of this sector is not tectonically influenced by older centers of deposition, seeming to be very stable (Rezende and Ferradaes 1971). Therefore, the coastal deposits are restricting to estuarine channels, prograding no more than 2 km seaward, constituting an emerging coast. Sector 2 has its evolution related to the Bragança-Viseu coastal basin that is controlled by normal faults that reach the present coastal zone. The structural framework of this coastal basin is responsible for a submerging coastal zone development, showing a wide mangrove ecosystem due to mudflat progradation.

The tectonic control of the coastal zone geomorphology has affected long-term and large-scale landscape development. Therefore, the tectonic framework of the Equatorial Atlantic margin controls large-scale geomorphic characteristics of the Quaternary sedimentary environments.

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2.2. GEOMORPHOLOGY OF THE BRAGANÇA COASTAL ZONE, NORTHEASTERN PARÁ, BRAZIL[1]

ABSTRACT

The area can be subdivided into three main geomorphologic compartments: (1) alluvial plain, with fluvial channels, levees and flood plain; (2) estuarine plain, with an estuarine channel subdivided into estuarine funnel segment, straight segment, meandering segment and upstream channel and; (3) coastal plain, with salt marshes (inner and outer), tidal flats (supratidal mangroves, intertidal mangroves and sandy tidalflats), chenier sand ridges, coastal dunes, barrier-beach ridges and ebb-tidal delta environments. The Bragança coastal zone is an active sedimentary region, which has been developed largely since the higher Holocene sea level (5,100 years BP). It has been concluded, based on geomorphology, lithostratigraphy and sedimentary processes that the coastal plain has evolved from mangrove progradation protected by dune-beach ridges with associated fluvial-estuarine-tidal channels. Therefore, the sedimentary model shows a complex depositional system, which is influenced by a broad tidal range.

Keywords: Coastal geomorphology, macro tidalflat, mangrove, remote sensing, Northern Brazil.

INTRODUCTION

Geomorphology is the science concerned with relationship between landforms and the processes currently acting on them (Summerfield 1991). Coastal zone environments are products of many complex interacting processes (transport, erosion and deposition), which continually modify rocks and sediments. According to Summerfield (1991), coastal zones are broad and reach from the landward limit of marine processes to the seaward limit of alluvial and shoreline processes. Therefore, coastal zone is the region between continental and marine environments where occur estuaries, deltas, tidal flats, salt marshes, barrier islands, cheniers, beaches and other coastal landforms.

In the Northeastern part of the State of Pará (Amazon Region) the coastal environments are dominated by macrotidal systems (6m ranges). The dominant geomorphologic features usually consist of wide muddy tidal flats (mangroves) with estuaries, shoals, salt marshes, cheniers, dunes, beaches and associated washover deposits (Silva 1996, Souza Filho and El-Robrini 1996).

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The morphology and sedimentary facies of coastal environments are the product of interactions between relative sea levels, coastal processes and sediment supply. Tidal coastal plains develop under conditions of rising sea level (transgressive coasts) or stable or falling sea level (prograding coasts) in response to different combinations of sea level changes history (Dalrymple *et al*. 1992). These settings are responsible for landward migration of the shoreline (transgression) and seaward migration of the shoreline (regression) and may be identified by geomorphologic mapping. Therefore, the recognition of shoreline deposits may be crucial to understand the sea-level changes and the stratigraphic sequence (Reading and Collinson 1996). The purpose of this study was to investigate the coastal zone geomorphology of Bragança plain to add to the understanding of the coastal evolution.

REGIONAL SETTING

The Bragança coastal zone is situated in the northeastern part of the State of Pará, in the Cretaceous Bragança-Viseu coastal basin (Cretaceous). Distribution and thickness of the Tertiary and Quaternary deposits have been controlled by the geometry of the basin and its paleotopography, and by recent tectonic movements. This coastal plain constitutes a macrotidal (6 m) depositional system, developed in a hot and humid equatorial climate, with dry and wet well-defined seasons and an annual precipitation averaging 3,000 mm; relative humidity varies from 80 to 91% (Martorano *et al*. 1993).

The Brazilian coastline is currently undergoing different tectonic, geomorphic, climatic and oceanographic processes. The Northern Brazilian Region is characterized by a wide continental shelf, the Northeastern Pará coastal zone being represented by an embayed coastline developed over Tertiary deposits, clastic and carbonatic sediments of the Barreiras Group and Pirabas Formation, respectively. These Tertiary deposits constitute the coastal plateaus which are continuous along the Northern Brazilian coast at elevations of about 50 to 60 m, decreasing progressively seaward, where it forms inactive and active cliffs along of shoreline and estuarine margins (Souza Filho and El-Robrini 1996).

The littoral zone from the Amazonas River to the Gurupi River has a width of about 600 km. In this region, Franzinelli (1992) could distinguish two primary geomorphological features on the coastline: (1) emergence coast, represented by Marajó Island, with a straight coastline, and (2) submergence coast, east of Marajó Bay to Gurupi Bay; the latter was subdivided in two sectors, a first one, from Marajó Bay to Pirabas Bay, where the bays cut active cliffs, and the second, east of Pirabas Bay, where the coastal plateaus extend southward as inactive cliffs (Figure 1).

METHODS

The coastal zone mapping was based on TM Landsat-5 imagery dated from 24/July/91, orbit-point 222-61 in digital format. The TM Landsat-5 data were digitally processed. Standard procedures were used, including geometric and radiometric corrections and image enhancement. The interpretation of satellite data in the form of false color Composite (TM4, TM5, TM3) and digitally enhanced products were made using standard key such as tone/color, texture, pattern, form, size, geometry, drainage and others. A detailed analysis of the spectral signatures of terrain associated with important elements both of geometric and textural characteristics of the coastal landforms, made it possible to identify different geomorphologic units.

Fieldwork was carried out to check the features observed in the image interpretation. During geomorphological mapping were identified vegetation, sediment texture and landforms of different coastal units, which were positioned through of global positional system (GPS). Each coastal unit was described and sampled by vibracorer technique and the sediments collected were analyzed.

GEOMORPHOLOGIC CLASSIFICATION OF THE COASTAL ZONE

The coastal zone geomorphic classification was based on landforms, sediment patterns, and dominant processes in operation (historical processes); some other factors, including geomorphological processes, land use and land cover, were also considered. Three large geomorphological compartments were mapped: coastal plain, estuarine plain and alluvial plain.

Coastal plain

The coastal plain is the most extensive of the three geomorphologic compartments. It extends north of the coastal plateaus for more than 20 km, occurring as wide tidal flats, until it reaches the shoreline dominated by marine processes (Figure 1). The major landforms observed are tidal mudflats (mangrove), salt marshes, tidal sandflats, chenier sand ridges, coastal sand dunes, barrier-beach ridges and ebb-tidal delta. Important observations in relation to geomorphological processes, sediment patterns, coastal processes, land use and land covers are highlighted below according to geomorphological classification.

TIDAL MUDFLATS (MANGROVE)

The tidal mudflats constitute a wide mangrove ecosystem with a width of about 20 km, densely covered by mangrove trees (Figure 2). They are located from the high spring tide to the mean tidal level. Organic muddy sediments are deposited on the tidal flats during the slack tidewater, when the currents decrease. Simple lenticular bedding with fine sand lenses, wavy bedding, tidal bundle and massive muddy sediments containing plant fragments and roots occur in the sedimentary mudflat deposits.

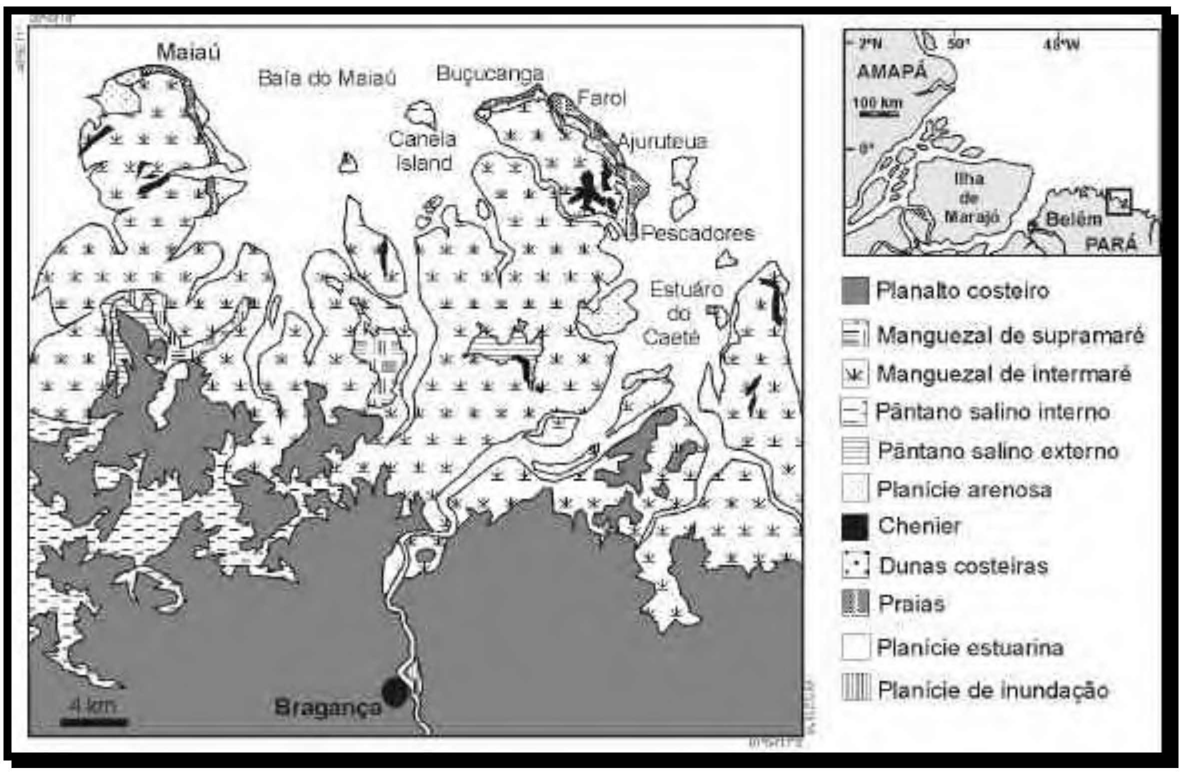

Figure 1- Map localization of study area and coastal zone geomorphologic map (Modified from Souza Filho and El-Robrini 1998).

Field studies have indicated that *Rhizophora* sp. and *Avicennia* sp. are the dominant species commonly found along this coast. The distribution of tidal flats is mainly controlled by topography. Therefore, based on relative altimetry and vegetation height, the tidal flats were subdivided in supratidal mangrove and intertidal mangrove. The supratidal mangroves are topographically higher with smaller trees and can be reached by water only during the spring tides, while the intertidal mangroves are topographically lower with progradacional and erosional areas.

Figure 2- Tidal mudflat sedimentary environments densely covered by mangrove trees

SALT MARSHES

The salt marshes are known in the area as "Campos de Bragança". The marshes are situated in the supratidal zone; sedimentation is marked by mud deposition carried from tidal fluxes along creeks (Souza Filho and El-Robrini 1996). They are subdivided in inner and outer salt marshes. The inner salt marsh occurs over the coastal plateaus and is flooded only during the rainy season and tidal waters influence its tidal creeks only during the dry season (Figure 3). The outer salt marsh occurs over old sandy beach ridge deposits along the tidal mudflat (Figure 4). Outer salt marshes are frequently flooded during the spring tides. The map in Figure 1 shows the spatial relationship between salt marsh, old beach ridges (cheniers) and tidal mudflats.

This unit is constituted by massive mud, but it is possible observe fine sand lenses intercalated by mud that characterize a lenticular bedding (Souza Filho and El-Robrini 1998).

TIDAL SANDFLATS

The tidal sandflats occur along the coast between mean tidal and low spring tidal levels. This unit is represented by sandy tidal shoals, which have many ripples, and megaripple marks and sand waves exposed at low tide (Figure 5). These tidal sandy deposits are characterized by plane-parallel and tangential cross stratification and simple flaser bedding with burrows filled by mud. Muddy balls reworked by tidal currents also occur along the sandflat.

Figure 3- Inner salt marshes flooded during the rainy season.

Figure 4- Outer salt marshes developed over old barrier-beach ridges (sandy ridge covered by trees).

CHENIER SAND RIDGES

The chenier sand ridges constitute old dune-beach ridges with associated washover fans. They are constituted by white fine sand covered by sparse vegetation. The cheniers have a very well characterized geometric linear and curved form whose boundary is marked by prograding tidal mudflats (Figure 5). The sedimentary processes responsible for its development are related to shoreline retreat during transgressive sea-level conditions followed by mud progradation. The mud progradation sometimes covered the sandy deposits, which allowed mangrove and salt marsh development. Foreset stratification and bioturbed structures deposited over intertidal muddy deposits characterize these coastal landforms.

COASTAL SAND DUNES

Sandy sediments of tidal shoals and beach reworked by the wind constitute the coastal sand dunes. Nowadays, the dunes are migrating landward over the mangrove deposits in the intertidal mudflats. Transverse and pyramidal dunes are partially or completely covered with vegetation and represent coastal dunes composed of very fine quartz sand, which is very well sorted, with few shell fragments and root marks. The transverse dunes present tabular cross stratification and the pyramidal dunes have beds dipping in opposite directions from the ridge, which is parallel to the trade winds direction (Souza Filho and El-Robrini 1996).

BARRIER- BEACH RIDGES

The barrier- beach ridges are the most dynamic coastal environments. They extend from low spring tidal levels to dune-beach scarps that represent the higher spring tidal level in the intertidal beach. The beaches have a linear and elongated form along an east-west direction, with curved spits in the longshore sediment transport direction (Figure 5). This barrier-beach ridges form protected backward areas where muddy sediments are deposited during the slack water and so salt grasses and mangrove trees are installed.

The barrier-beach ridges are dominated by macrotidal conditions and they were subdivided in supratidal zone (backshore), intertidal zone and subtidal zone based on relative tidal level (Wright et al. 1982). The supratidal zone extends above the high spring tide level that coincides with the topographic boundary (dune-beach scarp). The intertidal zone occurs between high and low spring tide level. This zone is subdivided in three sub-zones based on morphologic and sedimentologic characteristics, flooding time and dynamic regimes. The high intertidal zone extends from high spring tide to high neap tide level; the mean intertidal zone is centered between high neap tide and low neap tide level, while the low intertidal zone extends from low neap tide to low spring tide level. The lower area, named subtidal zone, occurs under low spring tide level and extends to the breaker zone.

EBB-TIDAL DELTA

The size and shape of ebb deltas are directly related to the relative influence of waves and tidal currents on barrier-beach ridges (Davis Jr. 1992). Where the tidal energy is dominant, ebb deltas extend seaward in the form of large deltas; shore normal sand bodies (Figure 5). The ebb delta morphology has shallow ebb channels exposed during low spring tide, flanked by sandy bars. These ebb deltas contain a very complex system of bedform such as different types of ripples, megaripples and sand waves on intertidal sandy bodies. The sediments are very fine to fine, well sorted, with shells and micaceous mineral fragments.

Estuarine plain

The estuarine plain extends upstream to the southward, as far as the tidal limit of the Caeté and Taperaçu rivers (Figure 1), to the north its boundary is dominated by marine processes. The river channel is influenced by fluvial, tidal and marine processes. Souza Filho and El-Robrini (1996) observed that geomorphology of the estuarine plain changes between downstream and upstream limits. According to Woodroffe *et al*. (1989), this is a reflex of progressive change of the river and its wet season flood profile. Souza Filho and El-Robrini (1996) recognized four estuarine channel types in the Caeté River: estuarine funnel, straight segment, meandering segment and upstream tidal channel.

Alluvial plain

The alluvial plain extends south of the tidal limit, forming the floodplain of the freshwater parts of the Caeté and Taperaçu rivers. The fluvial channels are meandering with longitudinal and point bars, and box morphologic anomalies. The floodplain is bounded by levees and it is flooded during the wet season.

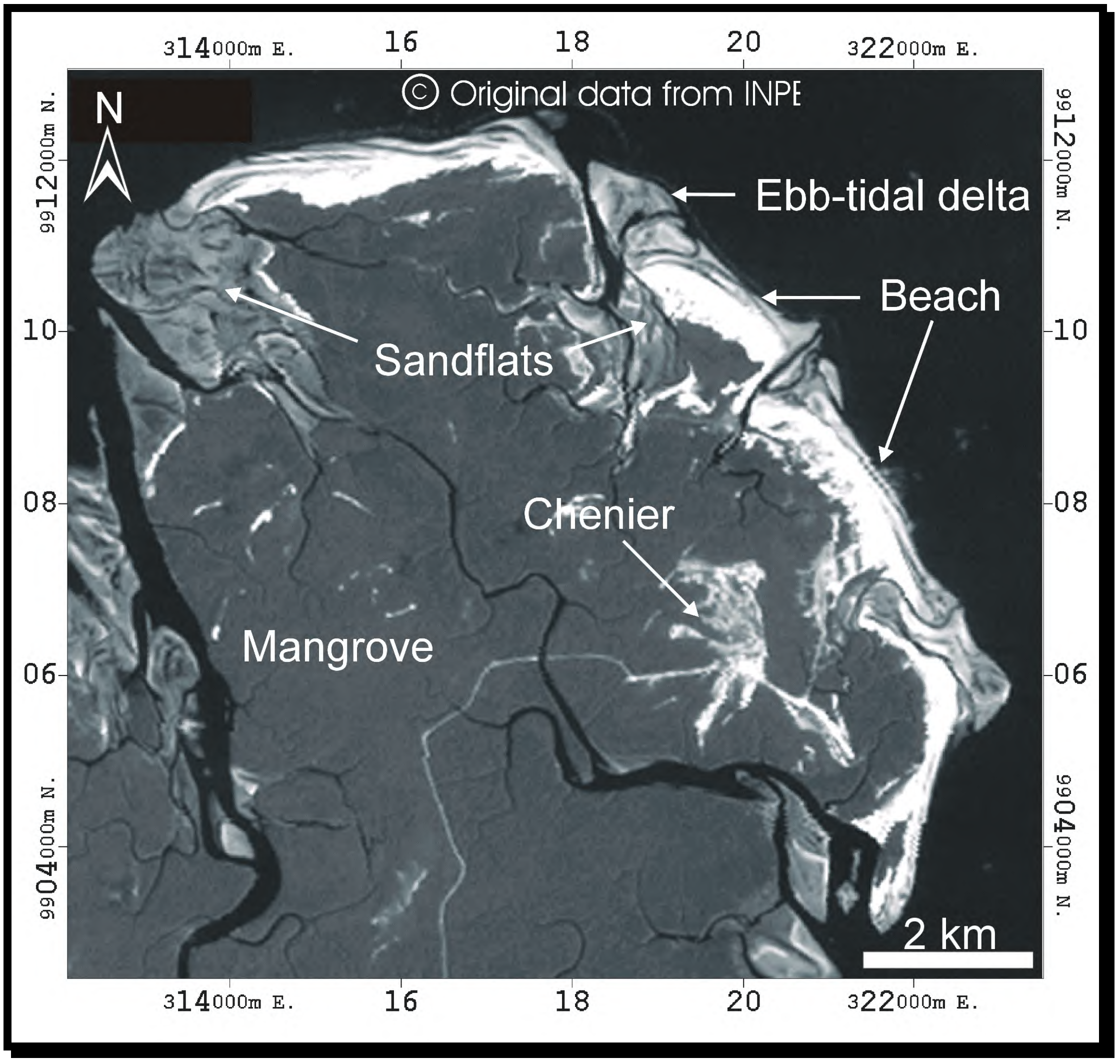

Figure 5- Band 5 of TM Landsat imagery showing geomorphologic features in the Ajuruteua Island, Bragança coastal plain.

SUMMARY AND CONCLUSIONS

TM Landsat imagery and fieldwork have been used for the study of the coastal zone geomorphology of the Bragança plain. Geomorphologically, the investigated area was subdivided into three majors compartments: 1) coastal plain; 2) estuarine plain; and 3) alluvial plain.

The tidal mudflats have been deposited under progradacional conditions since 5,100 years BP, when mangrove replaced a coastal forest ecosystem (Behling et al. 1999). Inner salt marshes are related to incised-valley fill, while outer salt marshes have its evolution associated to mangrove evolution (Souza Filho and El-Robrini 1998). Tidal sandflats represent one of the most dynamic intertidal zones where tidal currents are responsible for transport, deposition and erosion. Chenier sand ridges mark old beach ridges in the coastal zone showing the great displacement of the shoreline seaward during the Holocene period. Coastal sand dunes are partially or completely covered with vegetation, an evidence of the presence, in the recent past, of a period of dune formation with intense reworking of the sands by wind. However, nowadays, the dunes have been dissipated and waves and tidal currents have eroded dunes along the coast. The beach ridges have been developed under macrotidal conditions and work as barriers, which reduce coastal erosion. These barriers are responsible for the development of protected areas where occurs mud progradation with an increase of the mangrove area. The ebb-tidal delta represents the most dynamic area, where the tidal channels have migrated considerably along time. This constant displacement is responsible for intense erosion.

Inactive cliffs bound the coastal plateaus representing older shoreline position developed during the last Holocene transgression (5,100 years BP). Simões (1981) obtained this age through midden datation along the coastal plateaus. Afterwards, the shorelines have been submitted to extensive progradation well defined by the position of chenier beach ridges and by mangrove development.

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2.3. AS VARIAÇÕES DE NÍVEL RELATIVO DO MAR E A ESTRATIGRAFIA DE SEQÜÊNCIAS DA PLANÍCIE COSTEIRA BRAGANTINA, NORDESTE DO PARÁ, BRASIL[1]

ABSTRACT

The integration of geomorphologic, sedimentologic, stratigraphic and remote sensing data collected on the Bragança Coastal Plain allowed the detection of three stratigraphic successions that were correlated to relative sea-level changes during the Holocene.

The Holocene stratigraphy of the Bragança Coastal Plain show: (a) a basal retrogradational Succession S_1 constituted by beach and estuarine sands and salt-marsh mud; (b) an intermediate progradational Succession S_2 developed by mud progradation on tidal flats (mangroves) and; (c) an upper retrogradacional sandy Succession S_3 represented by coastal dunes, beaches, chêniers and sand shoals.

The Holocene evolution in the Northern Brazil, began when sea level reached the present position 5,200y BP (maximum of Holocenic Transgression). This event was characterized by the development of a retrogradational Succession S_1 (transgressive sand sheet). During sea level stillstand conditions, the seaward muddy progradation took representing the beginning of the Succession S_2 development, whose boundary with the coastal Succession S_1 is flat and well defined as a consequence of subaerial progradation, which was interrupted by short transgressive pulses, responsible dune-beach ridge deposition that was isolated due to shoreline muddy progradation forming chêniers. The Succession S_3 is characterized by retrograding sandy coast succession (dune-beach ridge and sandy tidal shoal) situated on the progradational muddy Succession S_2, which characterizes the present transgressive episode, responsible for Succession S_3 development.

The interpretation of the sedimentary and stratigraphic patterns of the Bragança Coastal Plain, based on sequence stratigraphy concepts is the first tentative of application of this concepts on Holocene coastal environments in the Northern Brazil.

Key-Words: morphostratigraphy, stratigraphic facies, relative sea-level changes, sequence stratigraphy, Holocene.

INTRODUÇÃO

Os ambientes costeiros brasileiros têm sido intensa e extensivamente estudados nas regiões nordeste, sudeste e sul, onde as costas são dominadas por ondas e submetidas a um regime de micro (0 a 2m) a mesomarés (2 a 4 m de amplitude). As seqüências costeiras são progradantes, desenvolvidas sob condições de nível de mar descendente (Dominguez 1982; Dominguez *et al*. 1987; Villwock 1987; Martin & Suguio 1989; Dominguez *et al*. 1992; Martin *et al*. 1993; 1996; Tomazelli & Villwock 1996; Angulo & Lessa 1997).

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[1] Artigo publicado no Boletim do Museu Paraense Emílio Goeldi, Série Ciências da Terra, Vol. 10, p. 45-78

Toda a linha de costeira do norte do Brasil é dominada por macromarés com feições geomorfológicas características, com extensos depósitos de planície de maré (manguezais), com estuários, baixios, pântanos salinos, chêniers, dunas, praias e leques de lavagens associados (Souza Filho 1995; Souza Filho & El-Robrini 1996a; Santos 1996; Silva 1996; Souza Filho & El-Robrini 1996c). Estas planícies costeiras dominadas por maré são desenvolvidas sob condições de subida (costas retrogradacionais), de estabilidade ou mesmo de queda do nível relativo do mar (costas progradantes), em resposta às diferentes combinações de história das variações de nível relativo do mar, largura e gradiente da plataforma continental, incidência de ondas, nível de energia, amplitude de maré e suprimento sedimentar (Dalrymple *et al*. 1992).

Deste modo, seqüências costeiras são assumidas como sendo depositadas, principalmente, durante condições de nível de mar estável e transgressivo, enquanto quedas relativas do nível do mar estão geralmente relacionadas a eventos não-deposicionais, com superfícies erosivas amplamente desenvolvidas (Allen & Posamentier 1993).

Vários trabalhos têm sido realizados na Região Norte com o intuito de esclarecer os ambientes sedimentares e as sucessões estratigraficas holocênicas, associadas às feições morfológicas (Souza Filho 1995; Souza Filho & El-Robrini 1995, 1996c; Silva 1996; Santos 1996). Deste modo, Souza Filho & El-Robrini (1996a; 1996b) analisaram pela primeira vez as sucessões estratigráficas à luz do conceito da estratigrafia de seqüências.

O objetivo deste artigo é apresentar: (a) a interrrelação entre as unidades morfoestratigráficas e as fácies estratigráficas da Planície Costeira Bragantina, com às variações de nível relativo do mar e; (b) a provável evolução holocênica da Planície Costeira Bragantina baseada no conceito de estratigrafia de seqüências.

METODOLOGIA

Os métodos e os equipamentos utilizados durante a execução deste trabalho incluíram sensoriamento remoto, geo-processamento, testemunhagem à vibração, análises sedimentológicas e faciológicas.

A cena do sensor TM do satélite LANDSAT-5, datada de 24/07/1991 (órbita-ponto 222-61), foi processada digitalmente através do Sistema de Tratamento de Imagens (SITIM-340), quando foi obtida a composição colorida 5R 4G 3B, definida como a melhor para o estudo das áreas de manguezais.

Os levantamentos de campo foram realizados para a identificação da vegetação, da textura sedimentar e dos ambientes de sedimentação. Foram realizados 35 testemunhagens à vibração, cujas amostras foram marcadas e processadas, segundo as técnicas descritas por Figueiredo Jr. (1990). Na descrição dos testemunhos, foram identificadas as estruturas e texturas sedimentares e cor dos sedimentos, utilizando a tabela da Rock-Color Chart Committee (1984), coletando-se também amostras sedimentológicas para análises granulométrica e morfoscópica.

Os estudos granulométricos foram realizados somente em amostras predominantemente arenosas, utilizando-se métodos clássicos descritos por Suguio (1973).

CENÁRIO REGIONAL

A Planície Costeira Bragantina, no nordeste do Estado do Pará, apresenta cerca de 40 km de linha de costa, estendendo-se desde a Ponta do Maiaú até a foz do Rio Caeté (Figura 1). Ela está inserida na Bacia Costeira de Bragança-Viseu (Cretáceo) e sua geometria e paleotopografia estão associadas às movimentações tectônicas, que tem controlado as espessuras dos depósitos terciários e quaternários (Igreja 1991; Costa *et al*. 1993, Costa & Hasui 1997).

Regionalmente, a área está inserida em uma costa indentada transgressiva dominada por macromaré que, Franzinelli (1982, 1992) subdividiu em dois setores: (1) a oeste da Baía de Pirabas, onde as baías delimitam as falésias ativas do Planalto Costeiro e; (2) a leste, o Planalto Costeiro que recua rumo ao sul, constituindo falésias mortas e as baías recortam a planície costeira.

Souza Filho (1995) compartimentou geomorfologicamente a geomorfologia da Planície Costeira Bragantina em três domínios: (a) planície aluvial, com canal fluvial, diques marginais e planície de inundação; (b) planície estuarina, com canal estuarino subdividido em funil estuarino, segmento reto, segmento meandrante e curso superior, canal de maré e; planície de inundação e; (c) planície costeira, com ambientes de pântanos salinos (interno e externo), planície de maré (manguezais de supramaré, manguezais de intermaré e planície arenosa com baixios de maré), chêniers, dunas costeiras e praias (Figura 1).

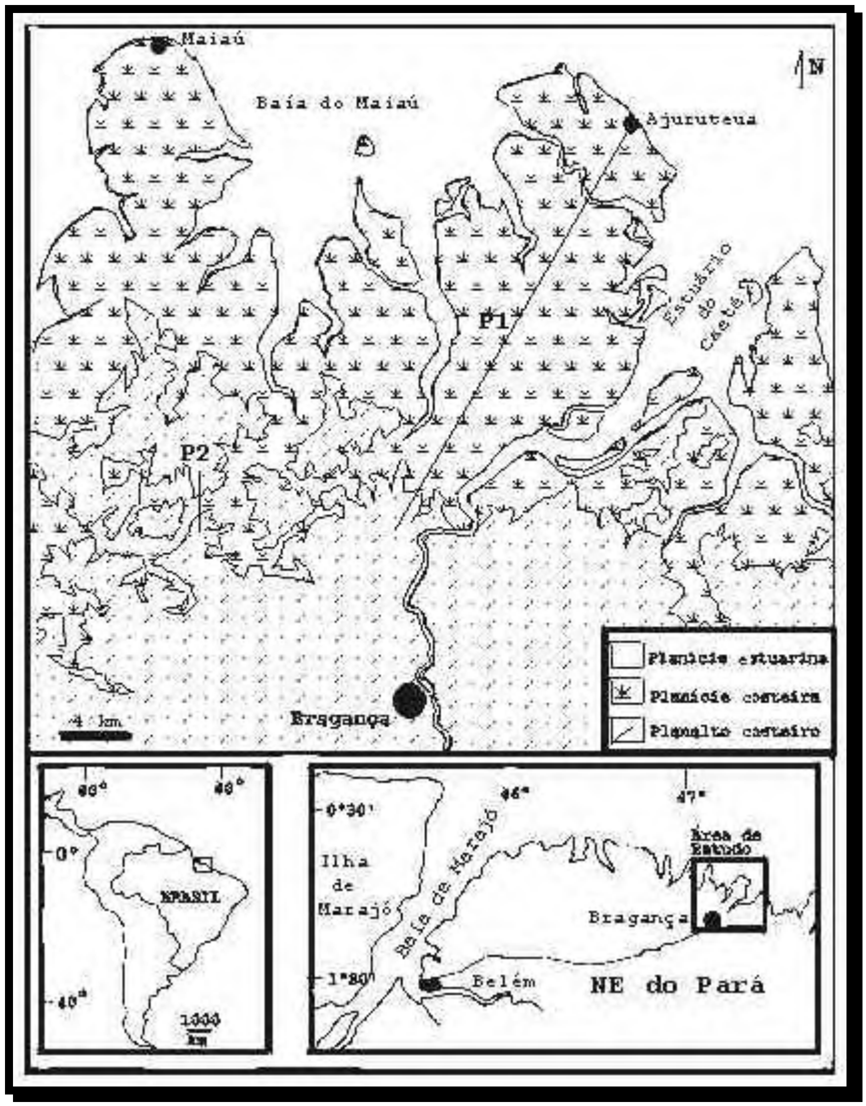

Figura 1 - Mapa de localização da planície Costeira Bragantina. Observar a compartimentação morfológica e a posição dos perfis P1 e P2.

O clima da área é equatorial quente e úmido (Amw de Köppen), com estação muito chuvosa de dezembro a maio e precipitação anual de 3.000 mm, com umidade relativa do ar oscilando entre 80 e 91% (Martorano *et al*. 1993). As condições hidrodinâmicas são caracterizadas por macromarés semidiurnas, que durante os períodos de sizígia chegam a alcançar amplitudes de até 6m (DHN 1995).

AMBIENTES SEDIMENTARES, MORFOESTRATIGRAFIA E FÁCIES SEDIMENTARES

O estudo dos ambientes sedimentares da Planície Costeira Bragantina (Figura 2) foi realizado pela aplicação do conceito de unidades morfoestratigráficas introduzido por Frey & Williman (1960) no mapeamento de depósitos glaciais pleistocênicos do Lago Michigan (Estados Unidos). As unidades morfoestratigráficas foram definidas pelas características morfológicas superficiais, pela estratigrafia de subsuperfície e pelos processos sedimentares atuantes e, portanto, têm uma conotação genética, sendo descritas a partir da planície aluvial rumo à planície costeira. Este conceito morfoestratigráfico tem sido amplamente utilizado na geomorfologia costeira por Rhodes (1982), Woodroffe *et al*. (1986, 1989), Woodroffe & Mulrennan (1993) e outros autores na planície costeira da Austrália.

No entanto, o conceito estratigráfico é referido aos depósitos subsuperficiais que não podem ser interpretados em termos dos ambientes atuais. A história deposicional e as mudanças ambientais associadas são reveladas a partir da análise faciológica dos depósitos, definidas em termos texturais, mineralógicos, estruturas sedimentares e conteúdo fossilífero.

Onze unidades morfoestratigráficas e cinco fácies estratigráficos foram definidas na Planície Costeira Bragantina, estando suas principais características sintetizadas nas Tabelas 1 e 2 respectivamente.

UNIDADES MORFOESTRATIGRÁFICAS

Planície aluvial

Planície de inundação

Apresentam espessuras em torno de 1m sobre o Planalto Costeiro (sedimentos basais) (Figura 3A), sendo constituídas por lama oxidada de coloração cinza oliva claro (5Y 5/6), sem estrutura sedimentar aparente, fitoturbada, com marcas e fragmentos de raízes. Lentes milimétricas de areia fina estão intercaladas a este pacote de lama, provavelmente relacionados aos períodos de grandes inundações, quando a água do canal fluvial transborda e deposita os sedimentos finos por decantação na planície de inundação (Figura 3B).

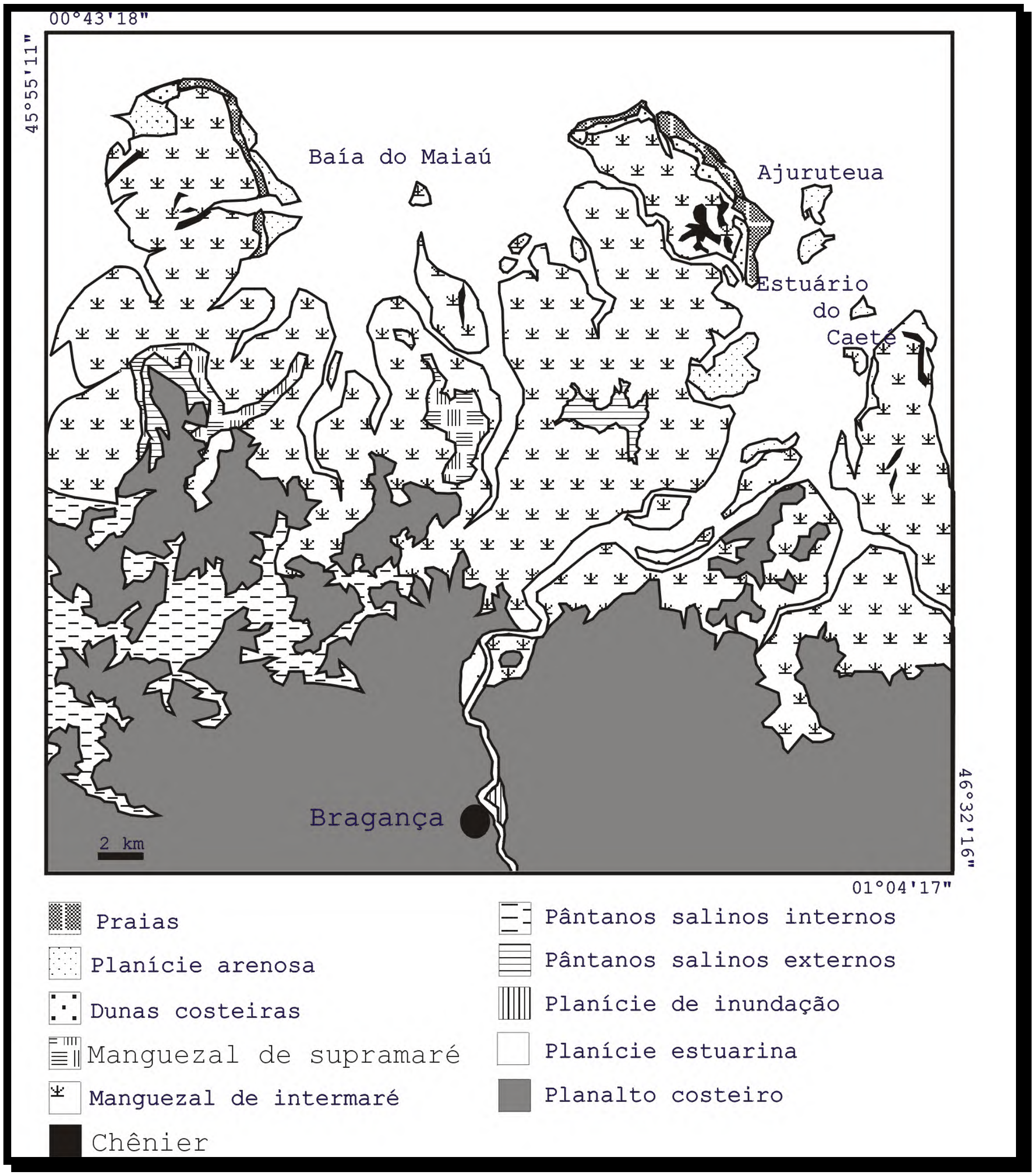

Figura 2 - Mapa dos ambientes sedimentares da Planície Costeira Bragantina (Modificado de Souza Filho, 1995).

Tabela 1 - Principais características das unidades morfoestratigráficas

Unidades Morfoestratigráficas	Características dos Sedimentos	Morfologia	Tempo de Inundação	Vegetação
Planície de Inundação	Lama cinza oliva claro rica em fragmentos orgânicos e fitoturbações	Áreas planas limitadas por levees e pelo planalto costeiro	Somente durante os períodos de grandes cheias	Herbácea (Aleucharias sp.)
Levee	Areia lamosa cinza oliva claro, fitoturbada e rica em fragmentos orgânicos	Diques vegetados ao longo do canal fluvial	Somente durante os períodos de grandes cheias	Mangue sp. Aleucharias sp
Barra de Canal	Areias fina a média de cor amarelo pálido, com marcas onduladas	Barras arenosas longitudinais de meio de canal e barras arenosas em pontal	Constantemente inundados	________
Manguezal de Supramaré	Lama superficial oxidada, cinza acastanhada, fitoturbada com marcas e fragmentos orgânicos. Seguida de lama cinza médio, intercalada com fragmentos de matéria orgânica	Planície de supramaré, colonizada por mangue de pequeno porte	Inundação irregular durante as marés de sizígia mais altas (5-6m)	Mangue
Pântano Salino	Camada superficial rica em fragmentos orgânicos pretos acastanhados escuros, seguida de lama oxidada de cor marrom amarelada e por lama cinza médio, maciça, com areias formando acamamento lenticular	Planície de supramaré encaixada em uma paleo rede de drenagem colmatada, limitada pelo planalto costeiro e recortada por córregos de marés	Inundação irregular durante as marés de sizígia mais altas (5-6m) e durante todo o período chuvoso	Herbácea (Aleucharias sp.)
Manguezal de Intermaré	Lama superficial oxidada, cinza acastanhada, seguida de lama cinza médio, sem estruturação aparente, fitoturbada com marcas e fragmentos orgânicos	Planície de intermaré colonizada por mangue de grande porte	Inundado regularmente pela maré semidiurna	Mangue
Planície Arenosa	Areias quartzosas, finas, cinza muito claro, com estruturação maciça, estratificação plano-paralela, cruzada tangencial de pequeno porte, acamamento flaser e clastos de argila retrabalhados	Extensas áreas planas, recortadas por canais de marés, com "sand waves", (mega) ondulações e barras expostas durante a maré baixa	Inundado regularmente pela maré semidiurna	________
Barra em Pontal	Areias quartzosas, finas, cinza muito claro, intercaladas com lama, formando estrutura heterolítica inclinada...	Forma lunada	Constantemente inundados	________
Dunas Costeiras	Areias quartzosas, muito fina, amarelo pálido, com estratificação cruzada tabular de grande porte e estratificação oblíqua	Dunas longitudinais e piramidais	________________	Arbustiva
Chênier	Areias quartzosas cinza amarelado a cinza muito claro, finas a muito finas, com estrutura mosqueada no topo e cruzada de médio porte na base	Cordões com cristas irregulares e cordões com cristas alongadas, limitados por manguezais	Inundado somente no período chuvoso	Arbustiva
Praia	Areias quartzosas finas, com fragmentos de conchas, cinza muito claro, com estratificação plano-paralela	Extensas áreas planas, inclinadas 2º rumo ao mar, recortadas por sistema de calha e crista ("ridge e runnel")	Inundado regularmente pela maré semidiurna	________

Tabela 2- Principais características das fácies estratigráficas

Fácies estratigráficas	Característica dos Sedimentos	Paleoambiente	Prof. (m)
Areia Fluvial	Areias quartzosas, médias a grossas, muito mal selecionadas	Fundo de canal fluvial	5
Areia e lama estuarina/ maré	Areias quartzosas, com fragmentos de conchas, bem selecionadas, com estratificação plano paralela, marcas onduladas e estrati-ficação cruzada de baixo ângulo e pequeno porte, intercalada com lamas cinza médio, que constituem acamamentos de maré e flaser	Sedimentos do face praial (“shoreface”) e de barras arenosas de foz estuarina	2.5 - 4
Areia e lama de barra em pontal	Areias quartzosas finas, cinza claro, intercalado com lama e/ou fragmentos orgânicos, formando estrutura heterolítica inclinada	Canal estuarino e/ou de maré	2-4
Areia marinha	Areias quartzosas finas, cinza claro, com estratificação plano-paralela e cruzada de baixo ângulo	Face praial	2-5
Sedimentos basais	Lama arenosa azulada, com manchas marrom claro e vermelho moderado, com grânulos e seixos ferruginosos	Leques aluviais do Grupo Bar-reiras	____

Diques marginais

São constituídos por areias finas a muito finas, com intercalações milimétricas de lama. Os sedimentos estão oxidados, com coloração marrom oliva claro (5Y 5/6), fitoturbados com marcas e fragmentos de raízes. Devido à intensa fitoturbação, as laminações estão completamente obliteradas, dando ao pacote aspecto mosqueado.

Barras de canal

As barras longitudinais e em pontal são as mais comuns no canal fluvial do Rio Caeté. As barras longitudinais formam corpos arenosos no meio de canal e são constituídas por areias finas a médias de coloração cinza muito claro (N8). As barras em pontal ocorrem nas porções convexas dos meandros, sendo constituídas por estratos arenosos centimétricos (2 cm) de coloração cinza muito claro (N8) recobertos por lâminas lamosas (“mud drapes”) milimétricas.

Planície estuarina

Barra em pontal

Dois tipos de barras em pontal ocorrem na área: barras em pontal arenosas, situadas a jusante do sistema estuarino e barras em pontal lamosas situadas a montante do estuário.

As barras em pontal arenosas são superpostas por depósitos lamosos de manguezal de intermaré. São constituídas por pacote inferior (150-254 cm) marcado pela alternância de níveis arenosos de 1 a 10 cm de espessura, de coloração cinza muito claro (N8), limitadas por lâminas lamosas de 5 mm a 5 cm de espessura, de coloração cinza médio (N5), com 20º a 25º de mergulho, caracterizando uma estratificação heterolítica inclinada. O pacote superior (0-210 cm) é caracterizado por areias quartzosas finas, bem selecionadas, com poucos fragmentos de conchas e coloração cinza muito claro (N8), sem estruturação interna, intercalado com lentes milimétricas de matéria orgânica cominuída ("coffee ground") e lâminas lamosas com 10º de mergulho. Blocos e seixos de lama retrabalhados por correntes de maré também ocorrem.

O pacote superior das barras em pontal está associada às porções mais rasas da barra, que sofre maior retrabalhamento pelas correntes de maré e migram rumo ao eixo do canal principal a medida que o meandro desloca-se lateralmente.

As barras em pontal lamosas são constituídas por pacotes ("bundles") milimétricos de areia fina, bem selecionada, recobertos por camadas lamosas com até 5 cm, inclinadas de 30º, constituindo a estratificação heterolítica inclinada.

Planície costeira

Pântano salino

Apresenta espessura máxima de 600 cm e recobre depósito de canal abandonado, representado pelo fácies areia de canal fluvial (Figura 3C e 3D). Os 500 cm basais são constituídos por lama de coloração cinza médio (N5), sem estrutura sedimentar aparente. Observam-se lentes de areia fina intercalada a lama, caracterizando acamamento lenticular simples. Feições de bioturbação também ocorrem ao longo do pacote lamoso. Segundo Bouma 1962 (in Frey & Basan 1978), a espessura do pacote lamoso depende da deposição de argilas na forma de flocos ou de grânulos de granulometria maior. Os sedimentos subseqüentes (30 a 10 cm) são constituídos por lama oxidada de coloração cinza oliva claro (5Y 6/1), superposta por lamas ricas em matéria orgânica fragmentada, de coloração preto acastanhada (5YR/6).

Manguezal de supramaré

A espessura do depósito é superior a 500 cm, sendo o intervalo basal (65-430 cm) marcado pela intercalação de estratos de lama e matéria orgânica de 2 a 10 mm de espessura, com mergulho de 20º, caracterizando estratificação heterolítica inclinada, onde a areia é substituída por matéria orgânica; enquanto o pacote superficial (0-65 cm) é constituído por lama orgânica de coloração cinza médio (N5), sem estrutura sedimentar aparente, representativa da planície de supramaré lamosa, seguida de lama orgânica oxidada, de cor cinza amarelada (5Y 7/2), com manchas oliva claro acastanhadas (5Y 5/6), fitoturbada com marcas e fragmentos de raízes.

Manguezal de intermaré

A espessura desses depósitos varia de 300 a 600 cm. De 430 a 40 cm, ocorre um pacote de lama orgânica, de coloração cinza médio (N5), sem estrutura sedimentar aparente, fitoturbado com marcas e fragmentos de raízes, representativo da planície de intermaré lamosa. O pacote superior (40-0 cm) é constituído por lama orgânica oxidada, de coloração amarelo escuro (5Y 6/4), com manchas marrom claro (5 YR 5/6), bastante fitoturbada por fragmentos de raízes. Esta unidade representa o episódio de progradação lamosa holocênica da planície costeira.

Dunas costeiras

As dunas longitudinais e piramidais vegetadas são compostas por areias quartzosas angulosas, muito finas, bem selecionadas e com poucos fragmentos de conchas. As dunas longitudinais apresentam estratificação cruzada tabular de grande porte, mergulhando 26º/210º Az e marcas de raízes, enquanto as dunas piramidais (Goldsmith 1978) apresentam camadas que mergulham em sentidos opostos à linha de crista da duna, que é paralela a direção dos ventos alísios (270º Az), resultando na estratificação cruzada obliqua. Dunas barcanóides e piramidais não fixadas, ocorrem sobre a pós-praia, constituindo um campo de dunas móveis com 0,5 a 1m de altura, que migram rumo ao continente (Figura 3G).

Esta unidade é formada pelo retrabalhamento eólico dos sedimentos das planícies arenosas e das praias. As dunas migram rumo ao continente, soterrando os depósitos de manguezal da planície lamosa (Souza Filho & El-Robrini 1996c).

Chêniers

Apresenta espessura máxima de 5,5 m, cujo pacote arenoso repousa em discordância erosiva sobre um pacote lamoso de 130 cm de espessura, com topo exibindo tubos biogênicos preenchidos por areias finas, evidenciando uma superfície de exposição subaérea. Um nível de conchas de *Mytela sp*. em posição de vida e fragmentos de conchas são observados neste intervalo. O intervalo basal (130 - 100 cm) é marcado por estratificação inclinada, mergulhando 23º rumo ao continente, com alternância de estratos milimétricos de areia fina e matéria orgânica, caracterizando a estratificação de camadas frontais (“foreset”) da porção distal do leque de lavagem, superposta por intervalo de 100-0 cm, onde ocorrem sedimentos arenosos finos, de coloração castanho amarelado pálido (10YR 6/2) a laranja muito pálido (10yr 8/2), bem selecionados, bastante bioturbado e com estrutura mosqueada, característica da porção proximal do leque de lavagem e/ou depósito de estirâncio (“foreshore”), que apresenta estratificação horizontal (Figura 3G) (Souza Filho & El-Robrini 1997b). Os 3 m superiores deste depósito de chêniers são constituídos por dunas vegetadas, de areias muito finas, de coloração marrom pálido (10 YR 6/2), bem selecionadas, cujas estruturas primárias estão completamente obliteradas por processos pedogenéticos.

Este depósito é típico de chêniers, sendo semelhante aos descritos por Penland & Suter (1989) no Delta do Mississipi, diferenciando-se deste modo dos depósitos de cordão de praia e esporões arenosos (“spits”).

Planície arenosa

Apresenta espessura superior a 400 cm. O intervalo basal (430 - 350 cm) é caracterizado por areias finas a muito-finas, de coloração cinza muito claro (N8), bem selecionadas, com estrutura maciça, com alguns fragmentos de conchas e micas; enquanto o intervalo subseqüente (350 - 200 cm) apresenta estratificações plano-paralelas, cruzadas tangenciais e marcas onduladas, além de acamamento flaser simples, tubos biogênicos preenchidos por lama e clastos de argila retrabalhados. O pacote superior (200 - 0 cm) é constituído por areias quartzosas finas, cinza muito claro (N8), bem selecionadas, com estrutura aparentemente maciça (Figura 3H).

Estirâncio (Foreshore)

A espessura varia de 50 cm a 300 cm, tendo sido depositada sobre manguezais de intermaré. Na zona de espraiamento, próximo a escarpa de praia, observam-se estratificações cruzadas de baixo ângulo, desenvolvidas por migração de marcas onduladas. São constituídas em profundidade por areias quartzosas finas, bem selecionadas, com estratificação cruzada planar de baixo ângulo, que caracteriza os depósitos de estirâncio (Figura 3I). Os sedimentos arenosos migram sobre a unidade morfoestratigráfica manguezal de intermaré, constituindo, deste modo, praias transgressivas.

FÁCIES ESTRATIGRÁFICOS

Areias de canais fluviais

Ocorrem sob sedimentos lamosos de pântanos salinos a 520 cm de profundidade. Estas areias fluviais são essencialmente quartzosas, angulosas, de granulometria média a grossa, mal selecionadas, de coloração cinza claro (N7) e por vezes recobertas por uma fina película de hidróxido de ferro de cor castanho amarelo pálido (10YR 6/2). Estes sedimentos são típicos de depósitos de fundo de canais fluviais, que foram progressivamente preenchidos por depósitos lamosos de pântano salino (Figura 3C).

Areia e lama estuarinas e de planície maré

Esta fácies está amplamente distribuída sob as unidades morfoestratigráficas de pântano salino (externo), a uma profundidade que varia de 250 a 400 cm. As areias são quartzosas, finas a muito finas, angulosas, de coloração cinza muito claro (N8), bem selecionadas, com estruturas maciças, plano paralelas, marcas onduladas e cruzadas de pequeno porte intercaladas com lentes milimétricas de matéria orgânica. As lamas são de cor cinza médio (N5) e ocorrem intercaladas às areias, constituindo acamamentos de maré, estrutura flaser e heterolítica inclinada, evidenciando influência da maré nesta fácies estratigráfica.

Areia e lama de barra em pontal estuarina

Esta fácies encontra-se interdigitada com os depósitos lamosos das unidades morfoestratigráficas de pântano salino e manguezal de intermaré. É constituída pela alternância de pacotes ("bundles") arenosos com mergulho de 10 a 30º, recobertos por lâminas lamosas, constituindo estratificação heterolítica inclinada, representativa da migração lateral de barras em pontal em canais de maré lamosos (Figura 3D).

Areia marinha

Esta fácies está amplamente distribuída sob a unidade morfoestratigráfica manguezal de intermaré a profundidade que varia de 2 a 4 m. As areias são quartzosas, finas a muito finas, de coloração cinza muito claro (N8), bem selecionadas, com fragmentos de conchas, estruturas maciças, plano-paralelas, marcas onduladas e cruzadas de pequeno porte, caracterizando o ambiente de face praial, cujas areias tem origem na plataforma continental interna (Figura 3G).

Sedimento basal

Esta fácies foi encontrada próxima ao contato do planalto costeiro com a unidade morfoestratigráfica Manguezal de Intermaré. É constituída por lama arenosa maciça, de coloração cinza azulado claro (5B 7/1), com manchas marrom claro (5YR 5/6) e vermelho moderado (5R 4/6). Grânulos e seixos ferruginosos apresentam-se dispostos na matriz (Figura 3A). Esta fácies estratigráfica é interpretada como sendo a fácies areno-argilosa superior do Grupo Barreiras (Rossetti et al. 1989), que constitui o embasamento da planície costeira.

INFLUÊNCIA DAS VARIAÇÕES DO NÍVEL DO MAR NA SEDIMENTAÇÃO COSTEIRA

Souza Filho & El-Robrini (1997a) admitem que a história evolutiva holocênica no norte do Brasil, iniciou-se quando o nível relativo do mar alcançou a posição atual há cerca de 5.200 anos A.P (Simões 1981), que representaria o máximo da Transgressão Holocênica. Durante este evento transgressivo, a subida do nível do mar provocou erosão dos depósitos do Grupo Barreiras na Planície Costeira Bragantina formando falésias ativas, além da migração de um lençol transgressivo constituído por depósitos de baixios de maré, praias e cordão de duna e praia. Este evento afogou a rede de drenagem, que foi progressivamente colmatada, evoluindo para uma seqüência de preenchimento de paleoestuários, representada pelo Pântano Salino, além de esculpir as falésias mortas de 1m de altura, preservadas no contato do planalto com a planície costeira, representativa da linha de costa deste período.

Durante este evento transgressivo, ocorreu o desenvolvimento da sucessão retrogradacional S_1. Esta sucessão estende-se na forma de lençol arenoso transgressivo no sentido de costa afora (Figura 4), onde as fácies estratigráficas, predominantemente arenosas, foram desenvolvidas em condições de ambiente praial de águas rasas, influenciado por ondas e correntes de marés, enquanto os sedimentos lamosos dos pântanos salinos, preenchem os canais estuarinos, superpondo-se aos sedimentos fluviais de fundo de canal (Figura 5).

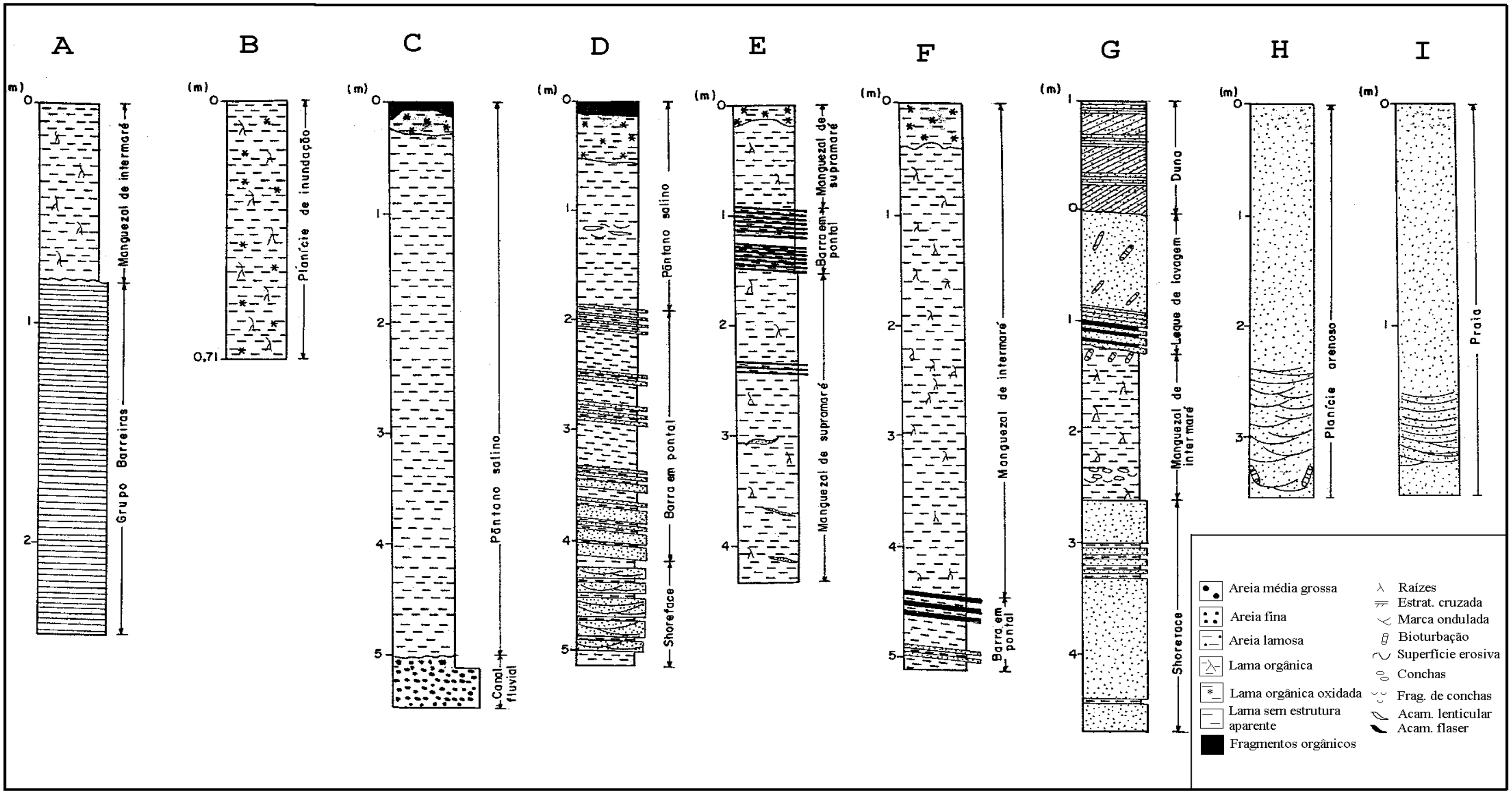

Figura 3- Seções estratigráficas das unidades morfoestratigráficas e das fácies estratigráficas da Planície Costeira Bragantina: A- sedimentos basais, B- planície de inundação, C- pântano salino interno sotoposto pelo fácies areia-fluvial, D- pântano salino externo sotoposto pelo fácies areia e lama estuarina-maré; E - manguezal de supramaré; F- manguezal de intermaré sotoposto pelo fácies areia marinha; G- chênier sotoposto pela unidade manguezal de intermaré; H- planície arenosa; I- praia.

Sob condições de nível de mar estável, observa-se a progradação lamosa da linha de costa rumo ao mar, marcando o início de desenvolvimento do manguezal de intermaré. O contato do lençol arenoso transgressivo, com os depósitos da frente de progradação lamosa é aplainado e bruscamente definido (Figura 4), resultado de progradação subaérea, truncando sucessivos cordões de praia, à medida que a linha de costa avança rumo ao mar (Souza Filho & El-Robrini 1997a).

Os sedimentos depositados durante este evento (sucessão S_2) evidenciam a natureza progradante da sedimentação costeira, que está associada a uma estabilização ou descida relativa do nível do mar (Allen & Posamentier 1993). Deste modo, de acordo com Souza Filho & El-Robrini (1996c) a sedimentação deixa de ser retrogradante e passa a ser progradante, marcada pela planície de maré e barras arenosas (Figura 4).

Durante a fase de progradação, ocorreram fases de erosão, responsáveis pelo retrabalhamento dos sedimentos costeiros, com deposição de cordões de dunas e praias (“dune-beach ridge”) com leques de lavagem associados.

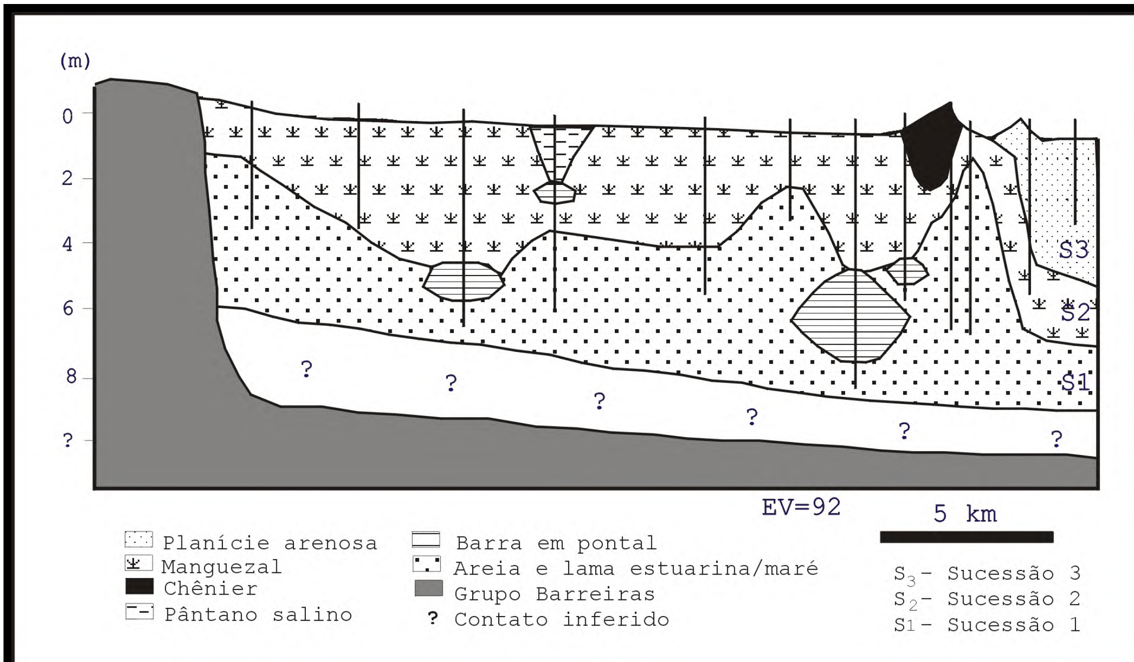

Figura 4- Seção estratigráfica generalizada Bragança-Ajuruteua, mostrando as sucessões estratigráficas S_1, S_2 e S_3 e as unidades morfoestratigráficas e as fácies estratigráficas (ver localização na Figura 1)(Souza Filho & El-Robrini, 1997b).

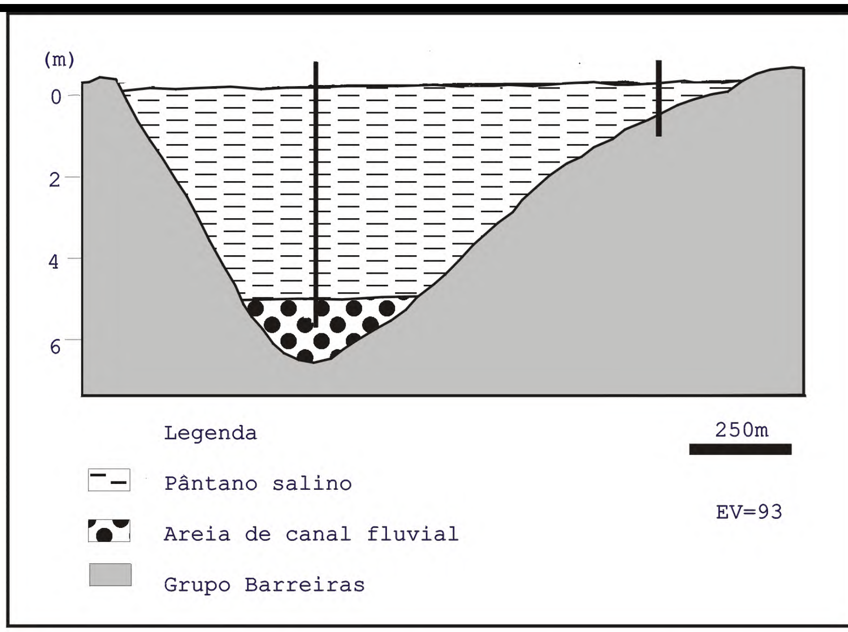

Figura 5- Seção estratigráfica da unidade pântano salino. Notar o limite de seqüência basal sob o depósito fluvial sobreposto por lamas estuarinas, enquanto os interflúvios estão expostos à erosão subaérea (Ver localização na Figura 1).

O evento seguinte é representado pela sucessão S_3, que marca uma nova situação de nível relativo de mar transgressivo, onde o lençol arenoso transgressivo (baixios de maré e cordões de dunas e praias) migra sobre os depósitos lamosos de manguezal e erode a linha de costa (Figura 4). Este novo evento transgressivo já foi reconhecido por Souza Filho (1995) e Silva (1996) no litoral nordeste do Pará e por Tomazelli *et al*. (1997) na costa do Rio Grande do Sul.

ESTRATIGRAFIA DE SEQÜÊNCIAS DA PLANÍCIE COSTEIRA BRAGANTINA

A interpretação do padrão estratigráfico de sedimentação da Planície Costeira Bragantina, baseado nos conceitos de estratigrafia de seqüências proposto por Posamentier et al. (1988) e Posamentier & Vail (1988), é uma tentativa de se aplicar e discutir tais conceitos em ambientes costeiros holocênicos do Norte do Brasil.

Qual é o limite de seqüência basal dos depósitos quaternários da Planície Costeira Bragantina?

A Planície Costeira Bragantina pode constituir, aproximadamente, uma seqüência deposicional tipo 1, no sentido de Van Wagoner *et al*. (1988) e Posamentier & Vail (1988), embora o limite de seqüências basal expresso por discordância erosiva sobre os depósitos terciários do Grupo Barreiras, marcada na parede dos vales incisivos e seus interflúvios, seja inferida, uma vez que não foi possível caracterizar toda a geometria do sistema de vales incisos.

Segundo Posamentier *et al*. (1988) e Posamentier & Vail (1988), a seqüência tipo 1 inclui o limite de seqüência basal (SB), o trato de sistema de nível de mar baixo (TSMB), o trato de sistema transgressivo (TST), a superfície transgressiva (ST), o trato de sistema de nível de mar alto (TSMA) e a superfície de inundação máxima (SIM). Além do mais, outras importantes superfícies, como a superfície de ravinamento por maré e/ou onda pode ser observada. No entanto, na área em estudo as superfícies acima mencionadas ainda não foram amplamente reconhecidas.

O limite de seqüência dos depósitos quaternários está esculpido em depósitos Mio-pleistocênicos do Grupo Barreiras, sendo superposto por depósitos areno-argilosos pós-Barreiras que, de acordo com Rossetti *et al*. (1989), são representativos de antigas dunas costeiras. Nos interflúvios, este limite de seqüências permanece exposto e a superfície de discordância continua sofrendo processos de erosão subaérea.

Essa discordância é interpretada como formada quando a taxa de queda eustática do nível do mar excede a taxa de subsidência na quebra da plataforma continental, produzindo uma queda relativa do nível do mar nesta posição (Van Wagoner *et al*. 1988). Assim, este limite de seqüência é desenvolvido pela combinação da incisão fluvial que formou os vales e pela exposição subaérea dos interflúvios, constituídos por depósitos terciários do Grupo Barreiras.

Trato de Sistema e as Sucessões Estratigráficas S_1, S_2 e S_3

Duas são as possibilidades de se relacionar às sucessões estratigráficas S_1, S_2 e S_3 aos tratos de sistemas. Na primeira, as sucessões S_1 e S_3 representariam um trato de sistema transgressivo, enquanto a sucessão S_2 constituiria o trato de sistema de nível de mar alto. A segunda hipótese aqui discutida associa as sucessões S_1, S_2 e S_3 a um único trato de sistema, o de nível de mar alto, dentro do qual ocorrem variações do nível do mar, relacionadas a pulsos transgressivos, regressivos e de nível de mar estável responsável por eventos de sedimentação retrogradacional (sucessão S_1 e S_3) e progradacional (sucessão S_2).

A sedimentação transgressiva, (Sucessão S_1), é iniciada com a sedimentação de lamas estuarinas, representadas pelos depósitos de pântanos salinos (Souza Filho & El-Robrini 1996b). Com a contínua subida do nível do mar até 5.200 anos A.P. (Simões 1981), as areias e lamas estuarinas e de planície de maré e areias marinhas migram rumo ao continente, superpondo os depósitos lamosos dos pântanos salinos, causando o recobrimento transgressivo do Planalto Costeiro, vindo a constituir um extenso lençol arenoso transgressivo. Caso os depósitos estuarinos e marinhos venham a recobrir os depósitos fluviais e os depósitos terciários (Grupo Barreiras), esta discordância viria a marcar uma superfície transgressiva que representaria a base do trato de sistema transgressivo, ou simplesmente a base de uma parasseqüência transgressiva (Posamentier *et al*. 1988).

A sucessão S_2 é caracterizada por aumento de espessura dos depósitos progradacionais, interpretados como sendo depositados durante nível relativo de mar estável (Souza Filho 1995; Souza Filho & El-Robrini 1996c), onde o recuo da linha de costa dá lugar à progradação generalizada da planície costeira. Assim, a sedimentação deixa de ser retrogradacional e passa a ser progradacional, representada pelos depósitos lamosos da planície de maré (manguezais de intermaré) e barras arenosas. Segundo Allen & Posamentier (1993), estes depósitos não parecem ter se acumulado durante a fase transgressiva, pois eles apenas se formam em períodos de progradação geral da costa.

A superfície entre as sucessões S_1 e S_2 é marcada por uma superfície de recobrimento regressivo (Posamentier & Vail 1988) reconhecida pelo contato marcante entre as areias e lamas estuarinas e de planície de maré e areias marinhas da sucessão S_1, superpostas por lamas orgânicas dos manguezais de intermaré da sucessão S_2 (Figura 4).

Sobre as unidades de manguezais de intermaré, representativa da progradação costeira, repousam os depósitos de chêniers. De acordo com Hoyt (1969), corroborado por Augustinus (1989), os chêniers delimitam períodos erosivos da linha de costa, responsáveis pela interrupção da progradação lamosa e formação de uma superfície de ravinamento por onda e/ou maré (Demarest & Kraft 1987). Esta superfície é uma importante feição que marca períodos de nível de mar transgressivo, responsável pelo recuo erosivo da linha de costa, formando esta superfície de ravinamento.

No nordeste do Pará, o processo de formação dos chêniers é dominado pela ação de ondas, durante eventos de marés de sizígia, quando se intensificam as correntes de deriva litorânea e de marés, que retrabalham os sedimentos, removendo os sedimentos pelíticos e concentrando as areias. Esta variação periódica de energia no ambiente litorâneo produz uma variação episódica no suprimento de sedimentos arenosos marinhos oriundo da plataforma contiental interna que, associada à progradação lamosa da planície de maré, é responsável pelo desenvolvimento dos chêniers.

No entanto, a progradação lamosa da planície de maré, relacionada à formação dos chêniers, é resultado também de variações do nível do mar. Tal proposta é corroborada por Souza Filho & El-Robrini (1996c), que admitem um modelo sedimentar atual resultante da progradação da linha de costa durante uma fase de nível de mar estável, com sedimentação dos extensos depósitos lamosos de manguezal da planície de maré lamosa, intercalada com eventos transgressivos de curta duração, quando se deu o desenvolvimento dos chêniers, que marcam uma fase retrogradacional atual da linha de costa, onde vários ambientes sedimentares atuais estão evoluindo.

Atualmente, a porção distal dos estuários está sendo transformada em deltas (Souza Filho 1995), enquanto sua porção proximal já está completamente preenchida. Além do mais, minerais pesados euedrais de fontes fluviais estão sendo depositados na plataforma continental interna (El-Robrini et al. 1992), resultado da progradação da linha de costa e eventual agradação fluvial. A linha de costa vem sofrendo, novamente, processos erosivos e os ambientes litorâneos vem migrando sobre os manguezais de intermaré e uma nova superfície de ravinamento por onda e/ou maré está erodindo os depósitos progradacionais da sucessão S_2, o que indicaria que as sucessões S_2 e S_3 poderiam ser sincrônicas.

CONCLUSÕES

As variações do nível do mar e a história estratigráfica da Planície Costeira Bragantina iniciada a partir de 17.400 anos A.P. (Milliman & Barreto 1975), está intimamente associada a construção de uma antiga barreira recifal constituída por areias biogênicas (Silva 1993) e bancos carbonáticos com algas coralíneas, hexacorais e ostreídeos (Vital *et al*. 1991) desenvolvida sob condições de nível de mar baixo. Esta barreira recifal foi formada quando a plataforma continental estava exposta e o nível relativo do mar estaria 80 a 90 m abaixo do atual, beirando a quebra do talude. Sob esta condição de queda do nível relativo do mar, vales fluviais foram escavados no Planalto Costeiro, formando um sistema de vales incisivos (Dalrymple *et al*. 1994), que recortavam a plataforma continetal exposta rumo ao mar (Souza Filho 1993). A erosão fluvial seria a responsável pela formação do limite de seqüência basal erosivo, sobre o qual depositaram-se os sedimentos.

Milliman & Emery (1968) e El-Robrini & Souza Filho (1993) acreditam que a partir de 17.400 anos A.P., o nível relativo de mar começou a subir e a extremidade distal (jusante) dos vales fluviais foi sendo transgredida e convertida em um estuário. Durante este evento, grande quantidade de sedimentos fluviais foi aprisionada no estuário e os sedimentos arenosos reliquiares da plataforma continental foram retrabalhados por ondas ao longo da linha de costa (Faria Jr. *et al*. 1987; El-Robrini et al. 1992). A ocorrência de depósitos estuarinos acumulados sobre areias grossas fluviais, indica que não ocorrem significante agradação fluvial durante rápida subida do nível relativo do mar (Allen & Posamentier 1993). Conseqüentemente, o suprimento sedimentar oriundo do curso superior dos rios, foi depositado por agradação, enquanto os depósitos estuarinos influenciados por maré, recobriram (“onlap”) os sedimentos fluviais, sendo o vale fluvial, progressivamente transformado em estuário.

Segundo Allen & Posamentier (1994), os sedimentos lamosos (pântanos salinos) acumulados entre a foz do paleoestuário (limite planalto/planície costeira) e seu curso superior viriam a constituir a primeira fase da transgressão e representaria o limite mais inferior de uma seqüência ou sucessão transgressiva.

Durante a subida do nível relativo do mar no Holoceno, os sedimentos arenosos e lamosos (fácies areia e lama estuarina e de planície de maré) formavam as barras arenosas de maré, a planície arenosa de foz de estuários e os depósitos de face praial (fácies areia marinha) que recobrem o Planalto Costeiro e migraram em direção ao continente, constituindo a sucessão S_1.

A sucessão S_1 foi interpretada como sendo de ambientes estuarino, parálico (pântano salino) e de face praial (“shoreface”), constituindo uma sucessão retrogradacional, cuja evolução está intimamente relacionada a um período de nível de mar transgressivo. Tal situação proporcionou a migração destes ambientes costeiros rumo ao continente sob ação de ondas e correntes de marés, que erodiram o Planalto Costeiro formando falésias, atualmente distantes 25 km da linha de costa. Com a contínua subida do nível relativo do mar, os estuários foram progressivamente preenchidos, e os depósitos lamosos preencheram os antigos cursos fluviais delineando uma paleorrede de drenagem (Figura 2), onde ocorre o ambiente de pântanos salinos. Segundo Souza Filho & El-Robrini (1997a), este evento transgressivo pode ser correlacionável ao nível de mar mais alto do Holoceno, conhecido na costa leste brasileira como Transgressão Holocênica (5.100 anos A.P.), responsável pelo afogamento de cursos fluviais que foram transformados em estuários (Dominguez 1982; Suguio *et al*. 1985; Martin & Suguio 1989, Martin *et al*. 1996). Estas evidências são observadas, na área de estudo, além de sambaquis datados de 5.200 anos A.P. (Simões 1981) localizados na base das falésias. Estes indicadores levam a concluir que a sucessão retrogradacional S_1 pode vir a representar o estágio final de sedimentação sob condições de nível de mar transgressivo.

Posteriormente, sob condições de nível de mar estável ou com taxa de subida mais lenta, desenvolve-se a sucessão S_2, constituída pelo ambiente de planície de maré (manguezais de intermaré e supramaré), que vem a representar uma sucessão progradacional desenvolvida sob condições de nível de mar alto estável. O limite desta sucessão S_2 com a sucessão S_1 é marcado por uma superfície de recobrimento regressivo bem definida, resultado da progradação lamosa subaérea sobre os depósitos arenosos (Figura 4 e 5), a medida que a linha de costa avança em direção ao mar. Assim, admite-se que estes depósitos lamosos da planície de maré tenham se acumulado durante período de progradação geral da linha de costa, sob condições de nível de mar alto estável.

A sucessão S_3 foi interpretada como de ambiente litorâneo (dunas costeiras, praias e chêniers") e estuarino, representando eventos transgressivos de curta duração, responsável pela fase retrogradacional atual da linha de costa, onde vários ambientes sedimentares atuais estão evoluindo.

Desta maneira, pode-se concluir que a aplicação dos conceitos de estratigrafia de seqüências na Planície Costeira Bragantina é possível, mas para que se estabeleça com precisão os limites das sucessões e sua geometria interna, se faz necessária a utilização de novas ferramentas como a sísmica de alta resolução, perfilagem de raios gama, testemunhagens mais profundas e datações isotópicas. Tais resultados viriam contribuir para melhor entendimento da estratigrafia de seqüência costeira e sua relação com as variações do nível do mar, sendo possível então se definir com precisão os limites de seqüências e a individualização dos tratos de sistemas.

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CAPÍTULO 3:

TÉCNICAS DE SENSORIAMENTO REMOTO PARA MAPEAMENTO DE AMBIENTES COSTEIRAS TROPICAIS

3.1. COASTAL GEOMORPHOLOGICAL STUDY AND LARGE-SCALE EVOLUTION OF BRAGANÇA COASTAL PLAIN (BRAZILIAN AMAZON) FROM SAR IMAGERIES

ABSTRACT

A RADARSAT-1 Fine Mode image acquired in 1998 over a study site located on the North of the Brazilian Amazon Region was evaluated aiming at mapping and assessing the large-scale evolution of this wet tropical coastal environment. With SAR's side viewing geometry, longer wavelengths, and almost all-weather sensing capability, RADARSAT-1 imagery has been extensively used as monitoring tool for coastal changes in the moist tropics. In this investigation, RADARSAT Fine Mode data acquired in 1998 was combined with airborne SAR X-HH GEMS acquired in 1972 during the RADAM Project and it was possible to evaluate the large-scale coastal changes occurring over the past three decades.

The orbital SAR data was digitally geometric corrected (ortho-rectified) and filtered for speckle noise. The airborne SAR data, originally available on mosaic format was scanned and geometrically corrected through polynomial method. The results have shown that the RADARSAT-1 image represents a powerful tool for geomorphological mapping and land use assessments in the Amazon Region, mainly in environmental characterization of macrotidal mangrove coast such as the Bragança coastal plain. Thus, it was possible to map mangroves, salt marshes, chenier sand ridges, dunes, barrier-beach ridges and shallow water morphologies based on this kind of orbital SAR data. Furthermore, a simple method to estimate shoreline changes was carried out based on the superimposition of shoreline vectors extracted from the airborne radar and related features present on the RADARSAT data. The results of the investigation have allowed characterizing changes in the area associated with shoreline retreat and accretion. In addition, the mapping of the tidal current and wave attack direction, estuarine and tidal channel displacements have also provided an understanding of the coastal sedimentary dynamic, marine transgression and sea-level changes in this sector of the Northern Brazilian coast.

Key words: coastal mapping, coastal changes, orbital (RADARSAT-1) SAR and airborne (RADAMBRASIL) SAR data.

INTRODUCTION

The Bragança coastal plain situated along the northeast of the State of Pará (northeastern Brazilian Amazon) is part of one of the largest macrotidal mangrove coast of the world, with almost 6,000 km^2 (Herz, 1991). Geologically, the Amazon coastal zone is poorly mapped. The RADAMBRASIL Project, in the beginning of the 70', carried out the first regional mapping project in the area. With the SAR´s side viewing geometry, longer wavelengths, airborne X-HH band SAR imagery from the RADAMBRASIL were extensively used as an operational tool for regional mapping in the coastal Amazon environments. The area is associated with perennial cloud cover that restricts the use of airborne or spaceborne-based optical sensors. In addition, the high sun-angle in the tropics also provides limited shadowing and poor topographic contrast. Over the past 26 years (1972-1998), only six Landsat-TM acquisitions are available with less than 40% cloud cover over the Pará State coast. Based on this kind of optical orbital data, Souza Filho (1995) produced the just coastal plain map in the scale of 1:100.000, describing the geologic and geomorphologic coastal features of the area.

A recent RADARSAT Fine Mode acquisition campaign was undertaken during September 1998 in the area. In contrast with optical data, orbital SAR imageries (ERS-1, JERS-1, RADARSAT-1) have been extensively used for mapping and monitoring wet tropical coastal environments (Singhroy, 1992; 1995; Rudant et al. 1996; Singhroy, 1996; Conway, 1997; Barbosa et al. 1999; Johannessen, 2000; Kushwaha et al., 2000). This paper presents a guide to digital image processing and interpretation of RADARSAT-1 data in tropical coastal environment mapping and assesses the large-scale coastal evolution during the last three decades. It also emphasizes the importance of using SAR images for coastal zone mapping purposes. In addition, the integration of information got from old and new SAR imageries has allowed an excellent evaluation of the shoreline changes and mapping of areas at risk related to coastal erosion.

STUDY AREA

The study area extends for 50 km of coastline between Caeté and Quatipuru estuaries (Figure 1). The climate is marked by a wet season from December to May and a dry season from June to November. Located at 1º S of the Equator line, trade winds blow from northeast throughout the year, most strongly during the dry season. The average annual rainfall reaches

2,500 mm and the mean tidal ranges measures around 4 m in a semi-diurnal cycle, and the range during the spring tides is locally as high as 6 m. Thus, during the spring tides, large areas of the low land are inundated by water as a result of both high rainfall-runoff rates and tidal inundation (Kjerfve et al. 2000). Strong tidal currents and waves are responsible for the erosion of mangroves along the coast, estuaries and bays, where lines of fallen mangroves trees mark the eroded places. On the other hand, new mangrove fringes are prograding seaward in response to muddy sedimentation.

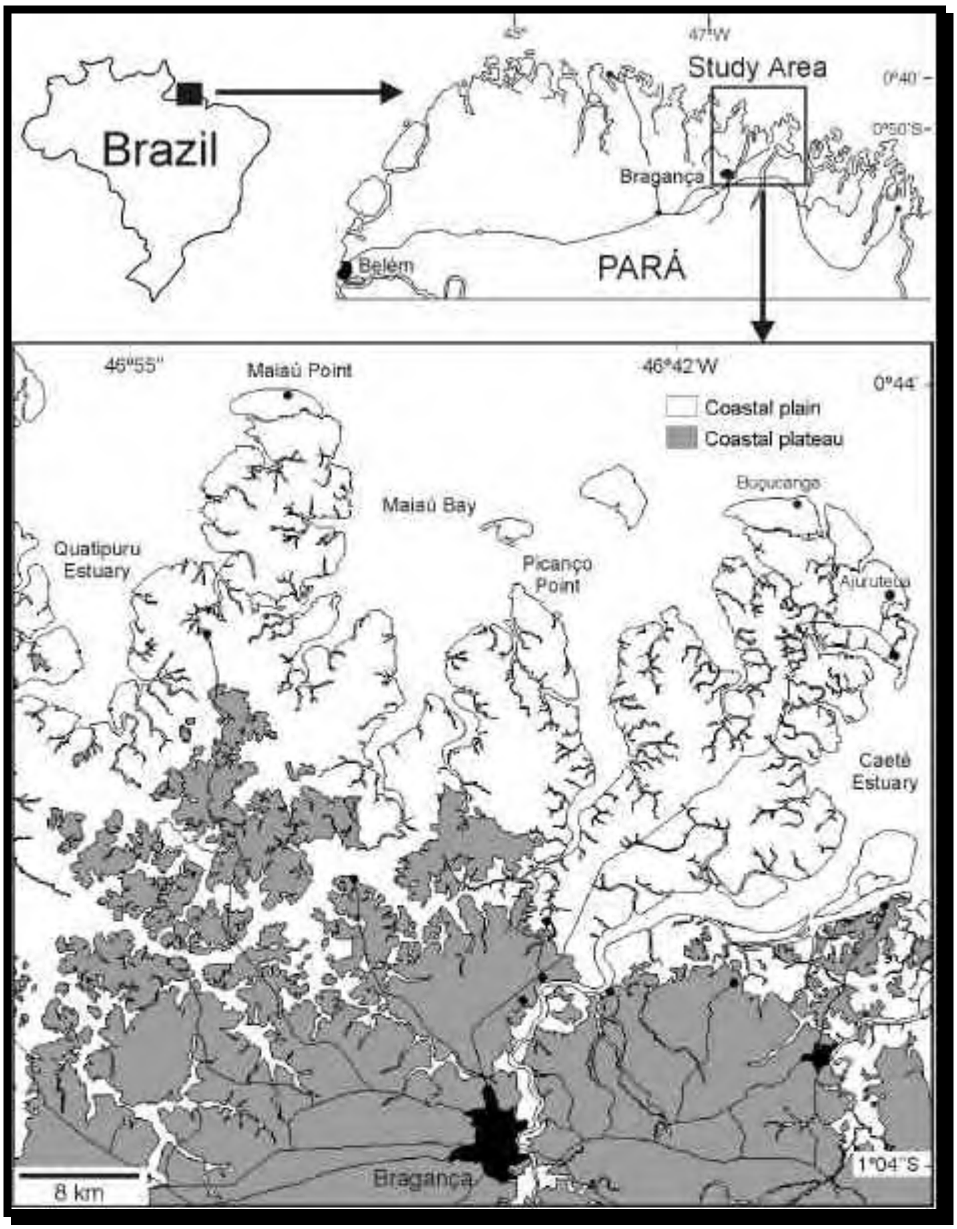

Figure 1- Location map of study area of the Bragança coastal plain.

The geology and geomorphology of the Bragança coastal plain were described in various publications (Souza Filho, 1995; Souza Filho and El-Robrini, 1996; 2000). The area can be subdivided into three main geomorphologic compartments: (1) alluvial plain, with fluvial channels, levees and flood plain; (2) estuarine plain, with an estuarine channel subdivided into estuarine funnel segment, straight segment, meandering segment and upstream channel; and (3) coastal plain, with salt marshes (inner and outer), tidal flats (supratidal mangroves, intertidal mangroves, muddy and sandy tidal flats), chenier sand ridges, coastal dunes, barrier-beach ridges and ebb-tidal delta environments. The coastal plain is extremely irregular, with jagged nature of this low gradient coast. The Bragança coastal zone is an active sedimentary region, which has been developed largely since the higher Holocene sea level (5,100 years BP) (Souza Filho and El-Robrini, 1998).

Topographically, the study site presents a low gradient. The tidal flat, including mangrove system, have slopes around 1:3000 (0.033%), being dissected by creeks. Salt marshes constitute the higher areas of the coastal plain. They are situated 3 m above the mean tidal level, while intertidal mangrove occurs from 2 to 2.6 m and supratidal mangrove develop between 2.6 to 2.8 m above the mean tidal level. Consequently, the salt marshes are inundated only 28 day/yr., while mangroves remained flooded from 51 day/yr. (supratidal mangrove) to 233 day/yr. (intertidal mangrove) (Cohen et al. 2000).

The original vegetation over the coastal plateaus is constituted by tropical rain forest. This vegetation cover has been affected by anthropogenic activities (agriculture and human settlement). Mangrove forest is found on the tidal flat, grasses occur along the marshes and arbustive vegetation occupies the chenier sand ridges, dunes and backshore zone of the barrier-beach ridges.

DATA SET AND IMAGE PROCESSING

The investigation was based on airborne and spaceborne SAR images. The airborne X-HH band SAR data was acquired in 1972, during the RADAM Project. The spaceborne C-HH band RADARSAT Fine Beam Mode 1 (descending orbit) was acquired in 1998, under the GLOBESAR-2 Program (Paradella et al., 1997). Details of the SAR remotely sensed data used in this study are presented in the Table 1.

Table 1. Characteristic of the remotely sensed data.

Platform	**Sensor**	**Acquisition Date**	**Angle of *Incidence***	**Spatial Resolution (m)**	**Image Format**	**Azimuth Direction**
RADARSAT-1	Fine Beam Mode 1	September 08, 1998	37-40º	9,1 x 8,4	16-bits	282º
Aircraft	GEMS 1000	1972	45-77º	16 x 16	Analogic	270º

The digital image analysis was carried out based on the EASI-PACE package (PCI, 1999). Antenna pattern correction (APC) and speckle suppression filtering were applied to the Fine Mode image as radiometric corrections. The initial processing steps for the RADARSAT data included the scaling of the image from 16 to 8 bits. Afterward, an adaptive enhanced-Frost filter (3 x 3 window) was used in order to reduce speckle effects (Lopes et al., 1990) during the ortho-rectification process. Due to the facts that the study area presents a low relief and no digital elevation model was available, the ortho-rectification process was applied assuming a flat terrain model. The ortho-rectification model was based on twenty-five ground control points acquired from Global Position System (GPS) on the terrain. The statistics of the ortho-rectification for the Fine Mode data has indicated a pixel size of 12 meters based on the RMS accuracy. Further, the RADARSAT-1 Fine image was linearly stretched in order to enhance the contrast for the coastal environment features. The main steps of the RADARSAT image processing are presented in the flow chart shown in Figure 2.

The airborne SAR data was initially scanned and digitally rectified to a common UTM coordinates. Twenty-two ground control points were collected and the RMS accuracy for the geometric correction (first order polynomial method) was around 16 meters. This value was selected as pixel size. In order to extract the shoreline position in 1972, the airborne SAR image was classified in two classes: emerging coastal areas and coastal water. Afterwards, the raster data was converted to vectors and superimposed to the RADARSAT-1 scene. The RADARSAT-1 image was visually interpreted and the coastal environments were mapped based on standard photo-interpretation keys such as tone, texture, pattern, form and size. Black-white air photos and field information were also used during this process. Finally, the extracted information was compared to the airborne SAR information and an estimate of coastline changes was possible.

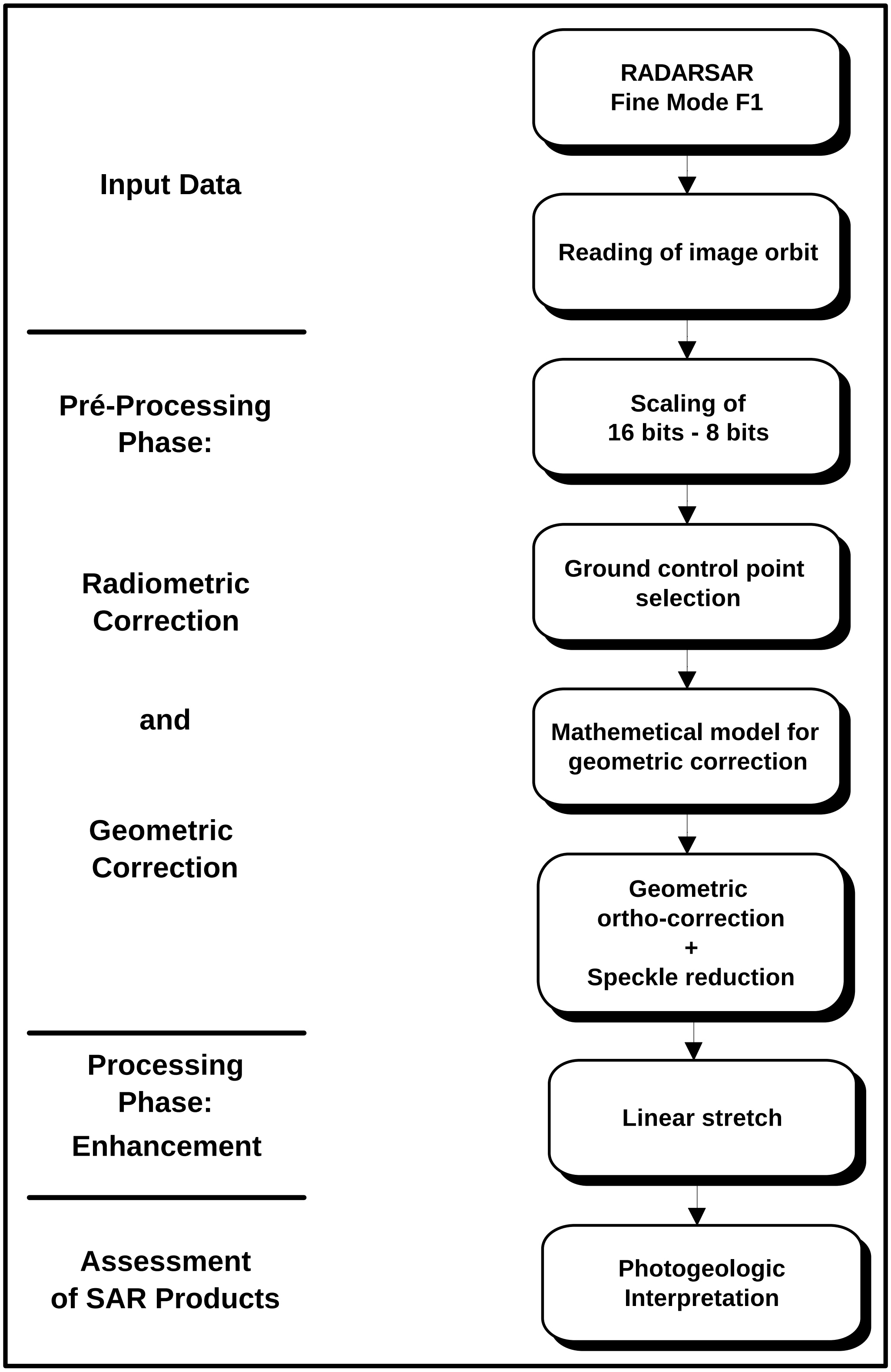

Figure 2- Flow chart with the main steps of RADARSAT image processing

RESULTS AND DISCUSSIONS

Coastal geomorphology from RADARSAT Fine 1

The backscattered microwave energy from the Earth's surface measured by a SAR system provides information of geometry (macro and micro-topography) and electrical properties (moisture content) (Lewis et al., 1998; Raney, 1998). Based on these characteristics, six prominent geological coastal features in the study area were examined in detail, using the information gathered from the RADARSAT Fine image. The orbital SAR data was evaluated to identify coastal environment features and shallow water morphology related to the tidal current and incidence wave direction in the coastline (Figure 3 and 4).

Mangroves

The tidal mudflats constitute a wide mangrove ecosystem with a width of about 20 km, densely covered by mangrove trees, principally *Rhizophora* sp. and *Avicennia* sp. They are located from the high spring tide to the mean tidal level, whose distribution of tidal flats is mainly controlled by topography. Therefore, based on relative altimetry and vegetation height, the tidal flats were subdivided in supratidal mangrove and intertidal mangrove. The supratidal mangroves are topographically higher with smaller trees and can be reached by water only during the spring tides, while the intertidal mangroves are topographically lower with progradacional and erosional areas (Souza Filho and El-Robrini, 2000).

The interpretation of the RADARSAT Fine image in the mangrove environment has indicated that intertidal mangrove forest (trees with a height around 20m) are related to microwave responses controlled, probably, by volumetric scattering and double-bounce mechanism. This particular condition is responsible for a very rough texture and light-gray tone allowing the discrimination of this coastal environment (Figure 3). The smooth, flat, high dielectric constant surface of the water increases the amount of backscattered radiation toward the radar, due to tree-ground double-bounce interaction. The supratidal mangrove presents a similar behavior of the intertidal mangrove, however the mangrove trees are smaller and spaced, reducing the double-bounce effect. Hence, the target appears less rough and with dark-grayish tone.

Salt marshes

The marshes are situated in the supratidal zone. The sedimentation is marked by mud deposition carried from tidal fluxes along creeks (Souza Filho and El-Robrini 1996). They are subdivided in inner and outer salt marshes. The inner salt marsh occurs over the coastal plateaus and is flooded only during the rainy season and tidal waters influence its tidal creeks only during the dry season. The outer salt marsh occurs over old sandy beach ridge deposits along the tidal mudflat.

The RADARSAT-1 Fine image clearly outlines the salt marshes. The inner salt marsh, completely flooded in the rainy season, presents a specular scattering behavior when the microwave radiation reaches the water table on the surface. Thus, this target appears as very dark tone in the image (Figure 3). However, for the sectors where the inner salt is covered by grasses, the radiation interaction produces a slightly rougher surface with lighter gray tones. Finally, for the outer salt marsh a similar scattering mechanism related to the inner vegetated salt marsh is characterized, but its geometry and spatial distribution are typical.

Chenier sand ridges

The chenier sand ridges constitute old dune-beach ridges with associated washover fans. They are constituted by white fine sand covered by sparse vegetation. The cheniers have a very well characterized geometric linear and curved form whose boundary is marked by prograding tidal mudflats (Souza Filho, 1995). The sedimentary processes responsible for its development are related to shoreline retreat during transgressive sea-level conditions followed by mud progradation. The mud progradation sometimes covered the sandy deposits, which allowed mangrove and salt marsh development (Souza Filho and El-Robrini, 2000).

From the SAR RADARSAT-1 Fine image, the chenier sand ridges present a smooth surface and dark tones. These SAR image characteristics appear to be controlled by presence of dry sandy sediments of old dune-beach ridges and washover fans (cheniers; Figure 3). This morpho-sedimentary characteristic is responsible for absorption of the microwave radiation. As intertidal mangrove around cheniers presents a double-bounce effects and light gray tone, this behavior favours its image discrimination (Souza Filho and Paradella, submitted).

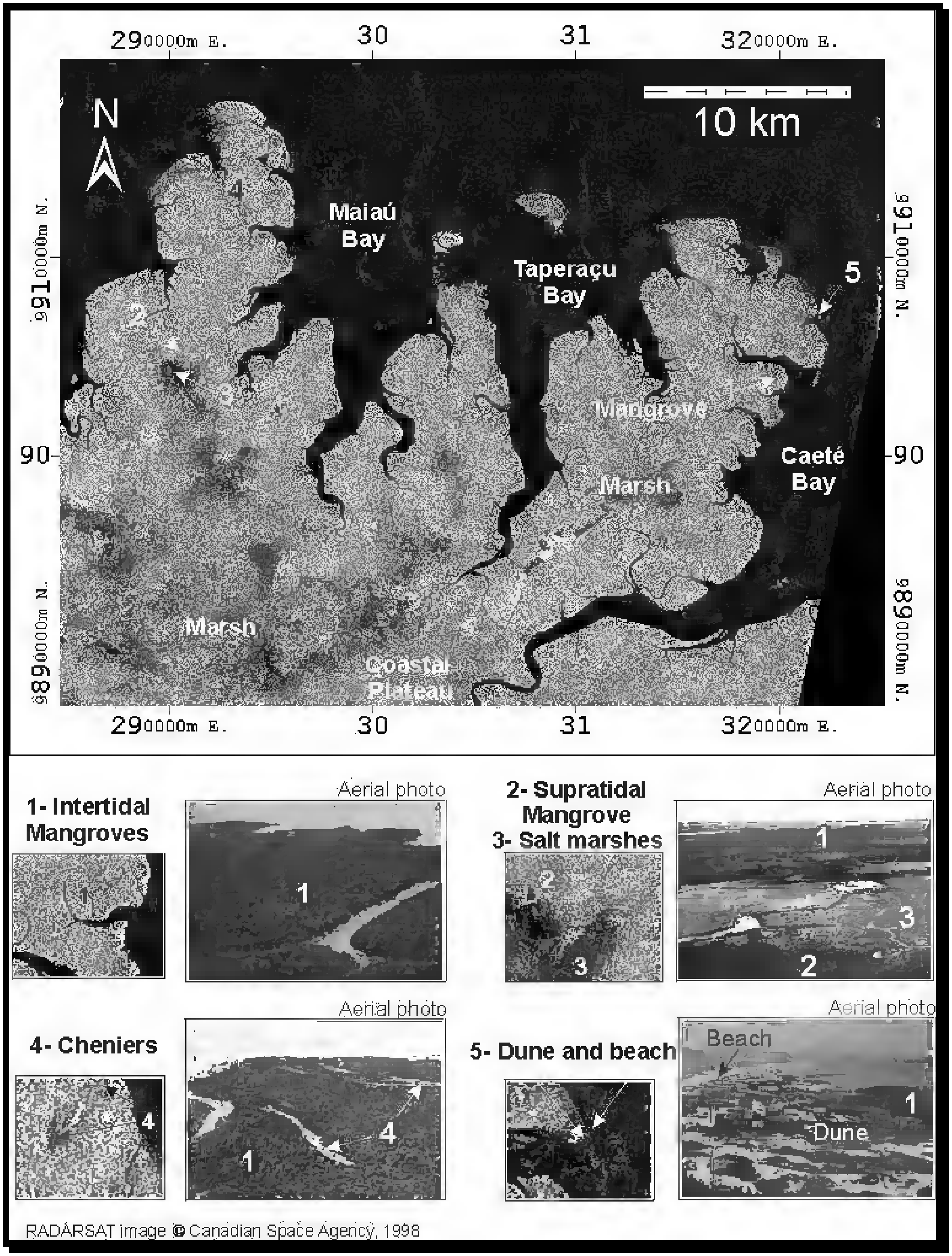

Figure 3- Detailed coastal geomorphology of Bragança plain from the RADARSAT-1.

Coastal dunes

Sandy sediments of tidal shoals and beach reworked by the wind constitute the coastal sandy dunes. Nowadays, the dunes are migrating landward over the mangrove deposits in the intertidal mudflats. Transverse and pyramidal dunes are partially or completely covered with vegetation and represent coastal dunes composed of very fine quartz sand, which is very well sorted, with few shell fragments and root marks (Souza Filho and El-Robrini, 1996)

Coastal dunes in RADARSAT-1 image are well defined in response to dry sandy sediments covered by sparse arbustive vegetation. This characteristic attributes to the scene moderated rough and dark-gray tones, compared to adjacent mangrove forest (Figure 3).

Barrier-beach ridges

The barrier-beach ridges are one of the most dynamic coastal environments. They extend from low spring tidal levels to dune-beach scarps that represent the higher spring tidal level in the intertidal beach. The beaches are constituted by fine white quartz sand and present a flat morphology with linear and elongated forms and curved spits in the direction of the longshore sediment transport (Souza Filho and El-Robrini, 2000).

In response to sedimentologic and morphologic characteristics, barrier-beach ridges in SAR image present a smooth surface and very dark tones (Figure 3), due to specular scattering of the microwave radiation.

Shallow water morphology

Along the study area, Souza Filho and Paradella (submitted) have mapped submerse sandy banks and estuarine tidal channel from integrated remote sensed data. From SAR image, underwater morphology is inferred through the radar signature of ocean surface current changes and corresponding modulations of the shorter gravity-capillary waves (Johannessen, 2000). These SAR characteristics are responsible for wave front mapping in the surf zone and tidal current interactions with bottom features to locate and orient submerse sandy banks (Figure 4h).

Based on research results, assessment of coastal environments mapping and RADARSAT-1 interpretation note is summarized in Table 2.

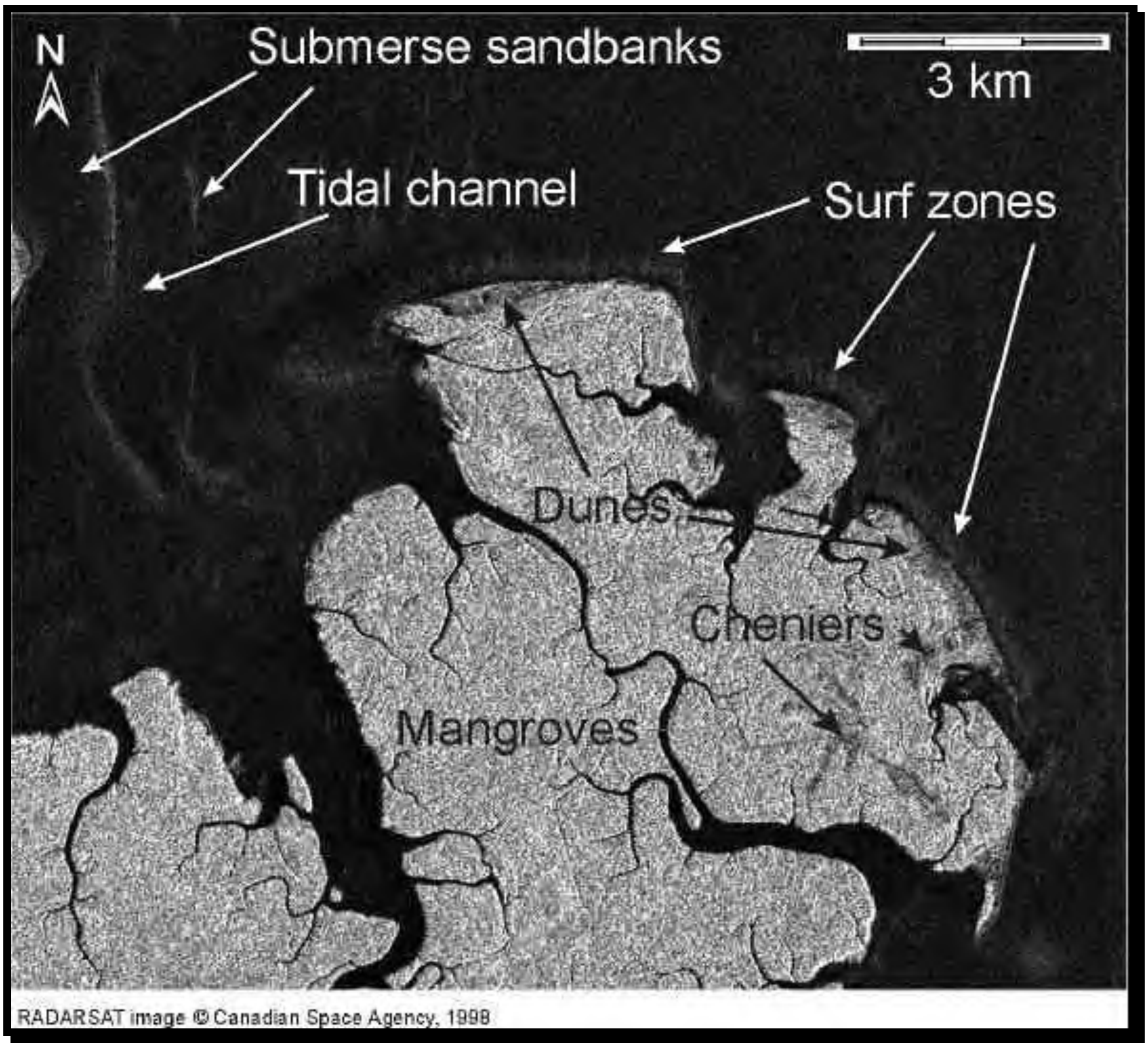

Figure 4- Shallow water morphology from RADARSAT-1.

Table 2- Interpretation of SAR RADARSAT-1 imagery for coastal geological mapping

Coastal geological features and land cover	**SAR image interpretation results**
A. Coastal environments	
Mangrove	• Coastal areas dominated by forest with average trees of 20 m high. Mangroves are associates with rough surface and medium-light tones (double-bounce).
Salt marsh	• Coastal low-lying and water logged terrain covered by grasses. Slightly rough surface and dark tones on the SAR image.
Chenier sand ridge	• Linear features with until 4 m high covered by arbustive vegetation. It is bounded by mangrove forest and presents rough surface and medium tones.
Coastal dunes	• Linear features with until 6 m high covered by arbustive vegetation. Slightly rough surface and dark tones on the SAR image.
Barrier-beach ridge	• Linear and flat features in the intertidal zone without vegetation. Smooth surface and very dark gray tones on the SAR texture.
Shallow water morphology	• Smooth surface with very dark tones intercalated with light tones defined by shorter gravity-capillary waves.
B. Erosional settings	
Coastal forms	• From 500 to 1000 m of erosional forms mainly identified in the open coast as curved shoreline.
Estuarine forms	• From 30 to 400 m of straight erosional forms.
C. Depositional forms	
Mangrove progradation	• Coastal prograding areas covered by young mangrove forest with until 1,000 km of shoreline accretion Rough texture and light gray tones on the SAR image.
D. Land cover	
Regenerated mangrove	• Coastal mangrove forest deforested and now subjects to regenerative process. Rough texture and highlight tones due to corner reflection.
Deforested mangrove	• Muddy soil exposed with smooth surface and very dark gray tones

Mapping of coastal land cover

The RADARSAT-1 imagery has shown to be valorous in providing information to produce and update coastal land cover maps in this tropical environments, covered by clouds during all time. The Bragança Coastal Plain has suffered fast and dramatic changes in the landscape. The anthropogenic impacts are most related to the opening of roads over the mangroves to access the beaches and unplanned coastal land use, as well as the drops of solid wastes and groundwater contamination (Souza Filho, 2000a). Along the Bragança-Ajuruteua road, it was detected areas where the mangrove ecosystems are completely deforested and in same places are subject to regeneration.

The interpretation of the RADARSAT-1 image has allowed the mapping of changing land cover. Flat and linear features bounded by mangrove forest characterize the roads, thus appear as a smooth surface with very dark tones. Specular scattering is observed too in the deforested mangrove areas, where salt and wet muddy sediments are exposed in the flat terrain (Figure 5). The natural regenerated mangrove sites present sparse and short vegetation distributed over flat muddy morphology. These factors favor the backscattered signal strength controlled by corner reflector mechanisms, producing high radar returns. Thus, this target shows a rough texture with high light gray tones (Figure 5). In a specific place, an artificial lake was formed due to a tidal creek damping by road (Figure 5). Table 2 summarizes the land cover characteristics in SAR imagery.

Spatial and temporal analysis of shoreline change from SAR

A number of potential shoreline datum or geomorphic features can be used to monitor historical shoreline changes. However, in most situations, the high water line, represented in study site by the spring high tide level (SHTL), has been demonstrated to be the best indicator of the land-water interface for historical shoreline comparison study (Dolan et al., 1980; Crowell et al., 1991). The SHTL delineates the landward extent of the last high tide, hence it is easily recognizable in the field and it can usually be detected from airborne and spaceborne remote sensed data. The landward extent is represented by mangrove forest easily discernible in SAR imageries and according Souza Filho (2000b), mangroves are one of the best geoindicators for evaluating shoreline changes associated to erosional and depositional processes in muddy coast.

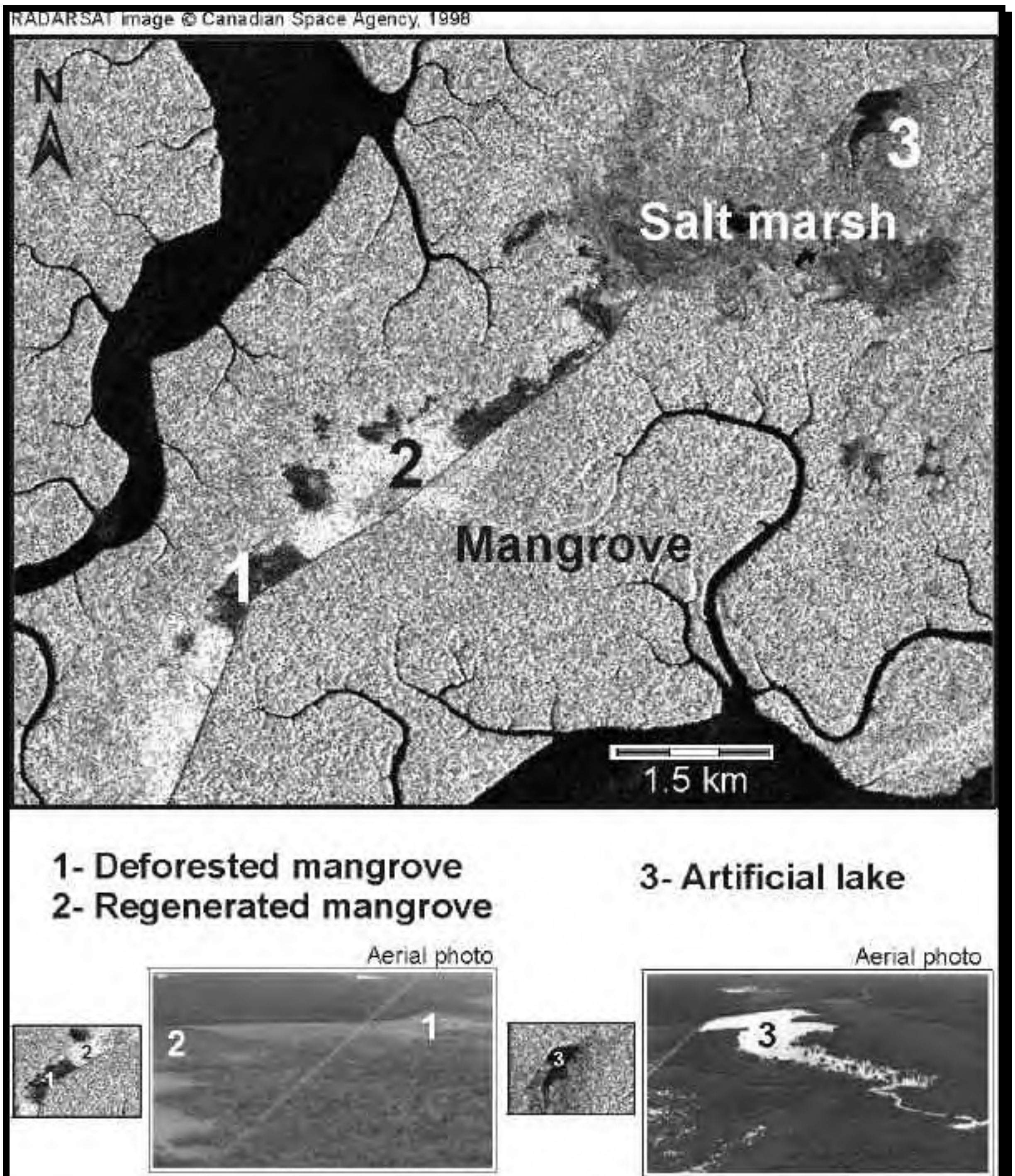

Figure 5- Land cover mapping from RADARSAT-1.

The mid-term changes in shoreline position were measured between 1972 and 1998 using SAR data from airborne GEMS and spaceborne RADARSAT-1, respectively (characteristics are presented in table 1). The shoreline position accuracy was determined by surveying ground control points. Reference points consisted of the corner of discernible structures, road driveway fluvial intersections. After geometric correction, the GEMS RMS error was around 16 m, while RADARSAT-1 RMS error reached 12 m, based on statistics of the ortho-rectification. Therefore, the maximum error due to the shoreline position change was estimated at ± 28 meters.

The impact of the natural dynamics in the Bragança Coastal Plain has made fast and dramatic changes in the shoreline position during the last three decades. From microwave remote sensing imageries, critical observations of large-scale coastal evolution provide clues to the natural history. The comparison between 1972 airborne SAR GEMS and 1998 spaceborne SAR RADARSAT-1 has shown that the shoreline has been subjected to severe erosion and accretion processes. In any specific coastal sites, some sectors remained unchanged. In the ocean setting, the mid-term shoreline recession reached maximum distance of 1,500 m and 1,250 m ±28 m in the Maiaú Point and Buçucanga Beach, respectively (Figure 6A and 6B). These erosional settings represent the most seaward boundary of the coastal plain, which receive little or no muddy sediment. The main sedimentary process responsible for the shoreline retreat is related to sandflats migration landward over the mangrove deposits due to tidal currents and large wave action. Mangrove vegetation has been killed by rapid sand deposition over it and mangrove terrace has been eroded. Hence, great parts of the shoreline, principally beaches, are characterized as transgressive deposits (Souza Filho, 1995). The shoreline accretion sectors are well represented by the Picanço Point, where the shoreline position has migrated around 1,250 m seaward (Figure 6C). In this area, the continuous sediment supply and the geomorphological positions, protected of wave attack, favor the accretion of sandbanks, muddy deposition and mangrove vegetation establishment. Therefore, mangrove trap sediments to build a depositional mud terrace in the upper intertidal flat and successive zones of pioneer vegetation (*spartina sp*.) and other mangrove species migrate seaward. Migration of islands is observed along the Maiaú Bay in response to oceanographic and sedimentary processes. For example, the Maciel Island migrated almost 1 km from 1972 to 1998 (Figure 6C).

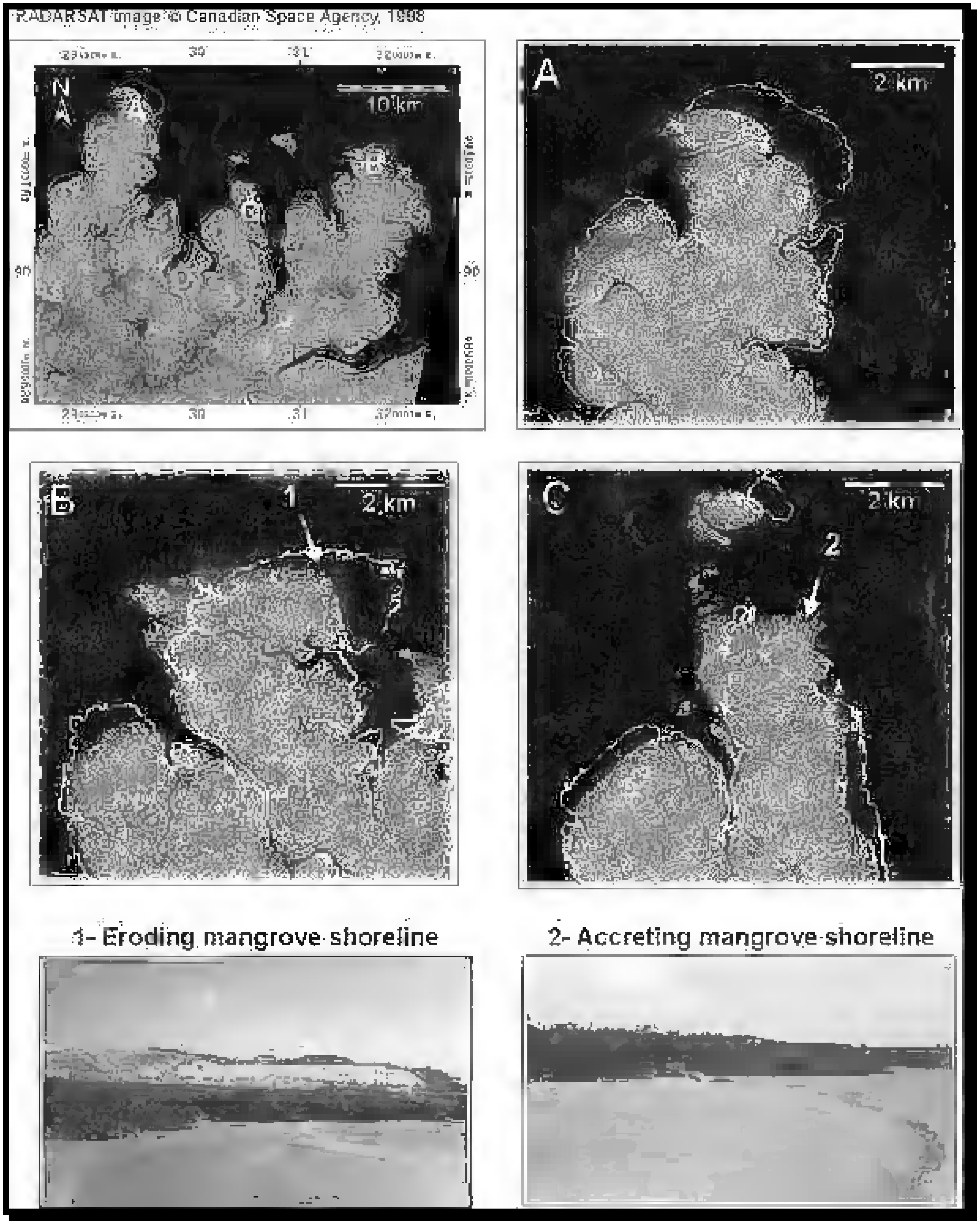

Figure 6- 1998 RADARSAT image and superimposed vector showing shoreline changes since 1972, coastal erosion and accretion, island migration and geomorphologic features. Maiaú Point (A) and Buçucanga Beach (B) erosional sector; and Picanço Point (C) accretionary sector showing an island migration process.

Other coastal setting is related to estuarine processes, where tidal currents and tidal channel position have controlled the coastal evolution. Based on integrated remote sensed products (RADARSAT and TM composites, Souza Filho and Paradella, submitted), is possible to observe that erosional sectors are strongly controlled by estuarine and tidal channel positions. These tidal channels play a key role in the shoreline recession; due to the severe coastal Erosional processes caused by channels running near the shoreline boundary (Figure 7). On the other hand, favorable areas are formed for shoreline accretion (Figure 7), where sandbanks are situated along the coast and the tidal channels do not reach the land-water boundary.

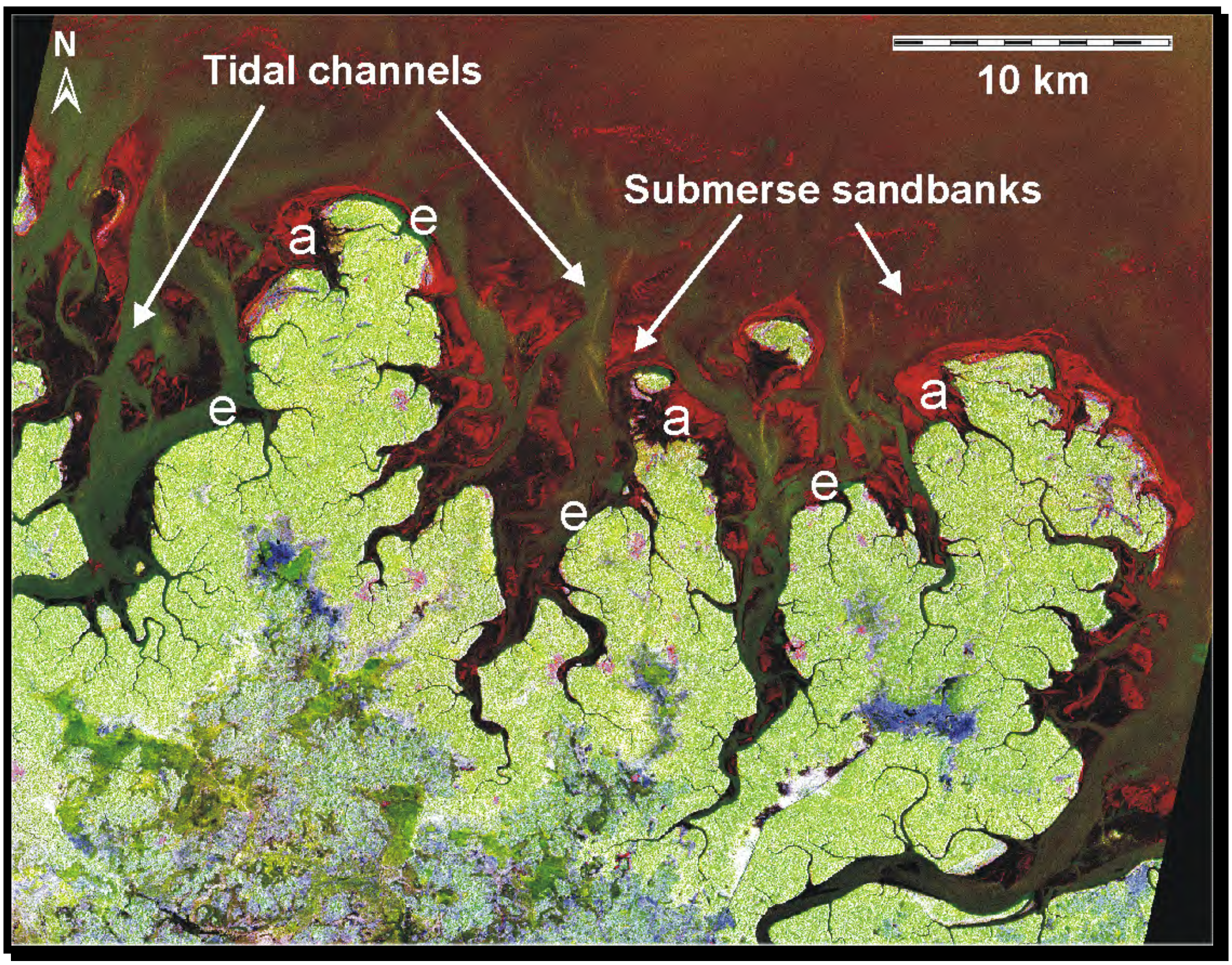

Figure 7- RADARSAT-1 and Landsat TM composite showing the coastal geomorphology and shallow water morphology. a = accretion and e = erosion.

CONCLUSIONS

The SAR imageries represent a powerful tool for the tropical coastal environments study, mainly in a macrotidal mangrove coast such as Bragança coastal plain, where the capability of SAR data to penetrate cloud cover provides a unique opportunity to map and monitor coastal changes in the Amazon Region. This paper illustrates RADARSAT's capability to provide geomorphological and land uses information. Furthermore, the integration of this kind of information with ancillary data has allowed detecting coastal changes related to shoreline retreat and accretion. Sedimentary dynamic, tidal current, wave action and estuarine and tidal channel displacement have played an important role in controlling of these coastal changes.

The SAR imagery has an important role to play in environmental assessment, site characterization and base maps updating, which are all significant and useful factors for an integrated coastal zone management program. Hence, the SAR interpretation in tropical coastal environment can be used to:

- Map the coastal sedimentary environment;
- Determine the position of submerse sandy banks in estuarine shallow waters;
- Map the directions of superficial tidal currents and waves in the surf zone;
- Determine the accurate position of the shoreline and to estimate its changes;
- Identify sectors subject to erosion, accretion or stability along the shoreline allowing the localization of areas subjected to coastal geologic risk;
- Locate areas subject to mangrove regeneration and deforestation related to coastal land-use.

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3.2. INTEGRATION OF REMOTELY SENSED DATA FOR COASTAL GEOMORPHOLOGICAL MAPPING IN BRAGANÇA, AMAZON REGION, BRAZIL

ABSTRACT

This work shows the application of integrated microwave and optical data for coastal geologic study in one of the largest mangrove system of the world, along the Pará and Maranhão State coasts (northern Brazil). The study site, in the Bragança Coastal Plain, is a macrotidal depositional system, whose evolution is related to fall in the relative sea level during Holocene. In this research, it was evaluated and compared a series of Landsat TM data digitally integrated with RADARSAT-1 Fine Mode imagery. Two different image enhancements were applied to the TM scenes: decorrelation stretch (DEC) of TM 4, 5, 3 bands, and selective principal components analysis (SPC) from the PC1 of TM 1, 2, 3, TM4 and PC1 of TM 5, 7. The integration of the SAR with optical data was based on the IHS transformation.

The SAR data has allowed enhancing differences between coastal vegetation heights and areas showing different moisture content. On the other hand, TM Landsat images have contributed to enhance vegetation and sedimentary environments based on the spectral response of the targets. The SPC-SAR integrated product was considered the best product for coastal geological mapping, providing additional information about geobotany (vegetation and coastal sedimentary environment relationship), emerge and submerge coastal geology and also insights regarding multi-temporal dynamics.

Keywords: Remote sensing, tropical environment, RADARSAT-1, Landsat TM, and SAR integrated products.

INTRODUCTION

The Brazilian Amazon coast along the states of Pará and Maranhão extends, for almost 480 km and represents the largest mangrove system of the world, measuring almost 6,000 km^2 (Herz, 1991). This mangrove coast is extremely irregular and jagged with numerous bays and estuaries. The broad coastal plain presents a low gradient and reach 45 km as a result of falling relative sea level, associated to rapid muddy progradation of the coast in response to the riverine sediment supply. Geologically, the region has been locally mapped from optical remote sensing data (Souza Filho, 1995). However, due to the mixed spectral response of the sediments, vegetation and water in the coastal environments, part of the geological features has been very difficult to be discriminated. In addition, the constant cloud cover over mangrove system restricts the data acquisition based on optical sensors. On the other hand, Synthetic Aperture radar (SAR) with side viewing geometry, longer wavelength and all-weather sensing capability has been extensively used as an operational tool for coastal mapping, playing an important role in the acquisition of information in tropical rain forest environments (Rudant et al., 1996; Singhroy, 1996; Kushwaha et al., 2000).

The process of digital integration based on different sources of remote sensing data is a promising alternative for solving problems regarding geological mapping of coastal environments, such as undistinguished features and coastal changes. The nature of this approach is based on the pixel fusion of complementary remote sensing and geosciences data, producing accurate and color image maps on which colors and textural attributes can meaningfully be interpreted (Harris et al., 1994; Paradella et al., 1997a).

The main purpose of this study was to investigate the use of different TM digital processing techniques integrated with RADARSAT Fine Mode data for coastal environmental geological mapping in this complex coastal environment of the Brazilian Amazon Region.

STUDY SITE AND GEOLOGICAL SETTING

The Bragança Coastal Plain is located on the northeastern part of the State of Pará along the macrotidal northern Brazilian mangrove coast (Figure 1). Geologically, the area is related to in the Bragança-Viseu coastal basin (Cretaceous), and shows an evolution mainly controlled by normal faults. The tectonical and structural framework of the basin is responsible for a submergence of the coastal zone (Souza Filho, 2000). This submerging coast coupled with falling relative sea level, during the Holocene and riverine sediment supply, have allowed the muddy flat progradation and development of one of the largest mangrove system of the world (Kjerfve et al., 2000).

The study area is related to Tertiary deposits of the Barreiras Group and Pirabas Formation. These deposits constitute the coastal plateau along the north of Brazil, which forms inactive and active cliffs in the coastal plain (Souza Filho and El-Robrini, 2000).

The coastal plain extends northward of the coastal plateaus for more than 20 km, and is characterized by a macrotidal mangrove coast. The major coastal features observed are tidal mudflats (mangrove), salt marshes, tidal sandflats, chenier sand ridges, coastal sand dunes, barrier-beach ridges and ebb-tidal delta (Figure 1). The estuarine plain extends southward upstream as far as the tidal limit of the Caeté, Maiaú and Tapera-Açu estuaries. The climate in the area is hot, typical of the humid equatorial climate, marked by a wet season from December to May and a dry season from June to November. The annual precipitation is around 2,500 mm and the relative humidity ranges from 80 to 91%.

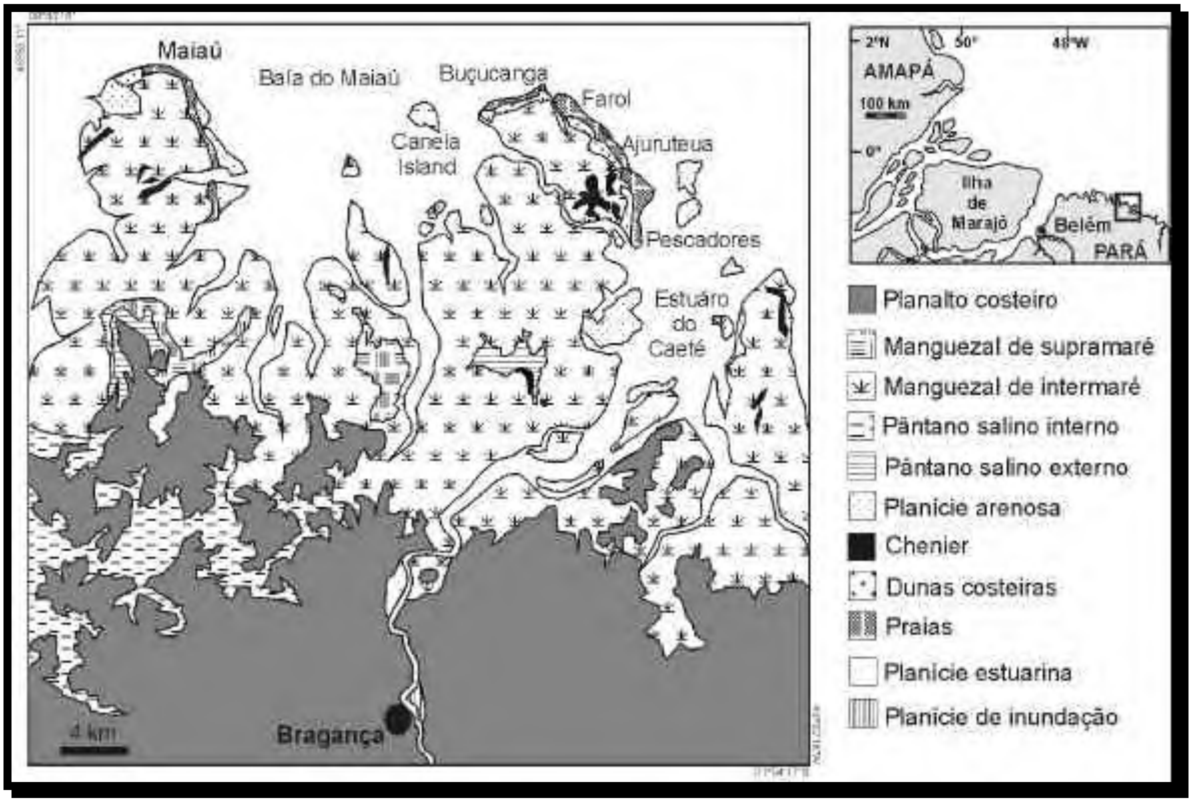

Figure 1- Location of study area and the coastal zone geomorphologic map (Modified from Souza Filho and El-Robrini 1998).

REMOTE SENSING DATASET

The investigation was based on a RADARSAT Fine Mode (Beam 1) image, acquired on a descending pass in 1998, under the Globesar-2 Program. Details about this program can be found in Paradella et al. (1997b). Spaceborne optical data were represented by the Landsat TM reflective bands (path 222, row 61), acquired in 1991 under INPE auspicious. Table 1 provides details of the remotely sensed data used in the investigation.

Table 1. Characteristics of the remotely sensed data.

Platform	Sensor	Acquisition Date	Angle of Incidence	Spatial Resolution (m)	Pixel Size (m)	Number of Looks	Image Format
RADARSAT-1	Fine Beam Mode 1	September 08, 1998	37-40º	9,1 x 8,4	6,25x6,25	1x1	16-bits Path Image
Landsat-5	TM Bands 1,2,3,4,5,7	December 31, 1991	_____	30 x 30	30 x 30	_____	8-bits

DIGITAL IMAGE PROCESSING

Geometric Correction

The main steps of the methodological approach are presented in the flow chart shown in Figure 2. The methodology essentially has involved multisensor data fusion and visual interpretation of the enhanced products for detection and characterization of the tropical coastal environments. The digital analysis was carried out based on the EASI-PACE package (PCI 1999). The optical and SAR data were geometrically corrected to a common UTM format, thus ensuring data standardization on a spatial sense, and allowing data manipulation and comparison on a pixel-to-pixel basis (Toutin, 1995). An ortho-rectification scheme was used to correct induced terrain distortion, which is a major factor in radar geometric correction due to the off-nadir viewing. Distortions due to relief in optical and even SAR images can be considered negligible over low-relief terrain. In the study area, variations of elevation are less than 4 m and due to the absence of a previous digital elevation model (DEM); the ortho-rectification correction was applied assuming a flat terrain model along the coastal plain. Based on the statistics of the ortho-rectification for the TM and the SAR data (RMS accuracies around one cell resolution for each data). In order to keep a balance of the geometric and the radiometric integrities in the data fusion, a 30-meter pixel size was selected as common pixel size for the data integration.

Digital Enhancement Techniques and Data Integration

The digital integration was based on the Intensity-Hue-Saturation (IHS) transform (Harris et al. 1990). For the RADARSAT-1 Fine image, antenna pattern correction (APC) and speckle suppression filtering were applied as radiometric processing. The APC was based on the procedures designed by Pietch (1993). An Enhanced-Frost filter was chosen to reduce speckle effects (Lopes et al., 1990) and applied during the ortho-rectification process. The RADARSAT-

1 Fine image was further linearly stretched and used as the Intensity channel in the reverse IHS-RGB transformation.

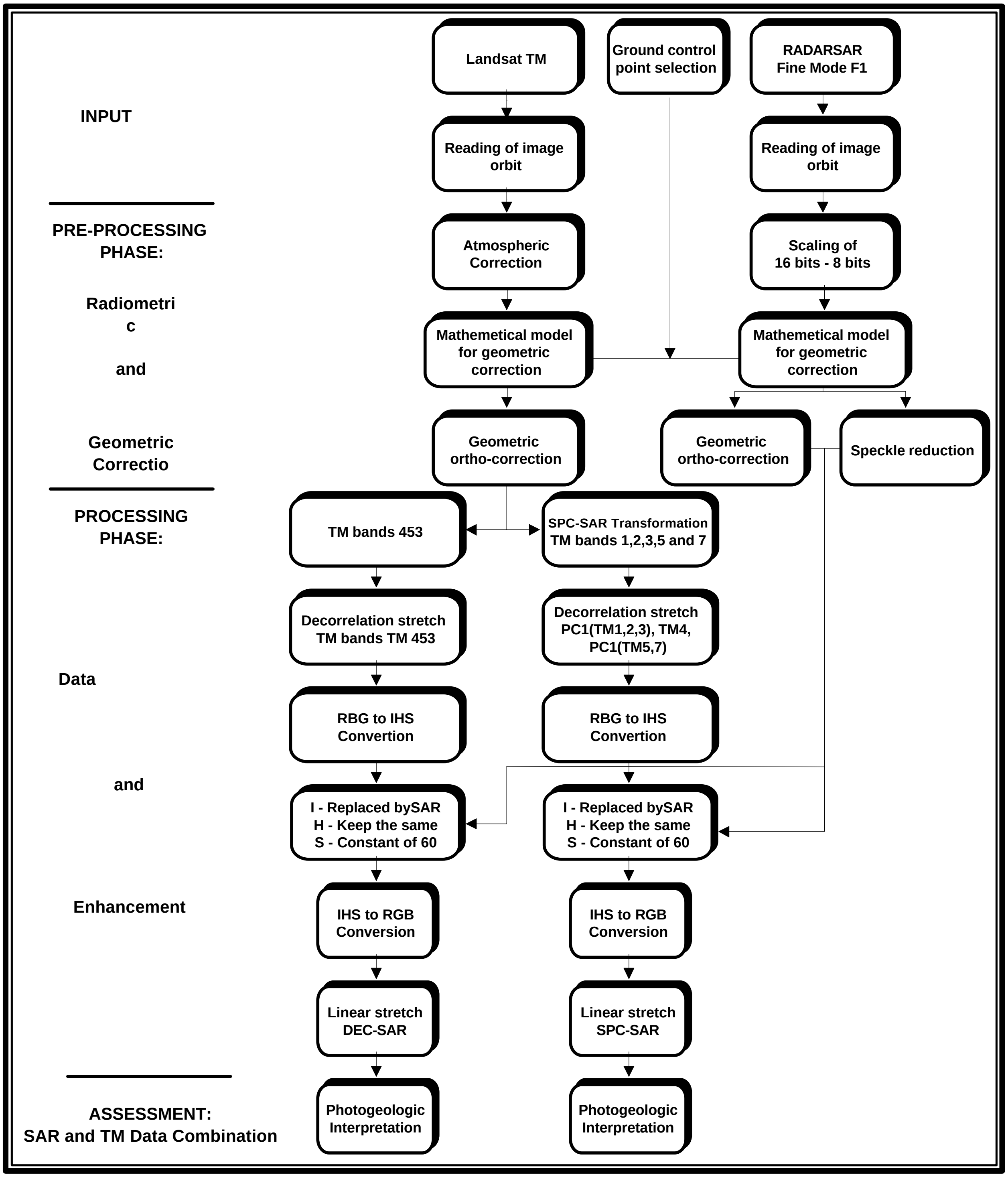

Figure 2- Flow chart with the main steps in the RADARSAT F1 and Landsat TM data fusion.

The pre-processing technique applied to the TM data has involved the radiometric correction related to the attenuation of atmospheric effects and was based on the minimum histogram pixel (Chavez, 1988). A feature selection approach based on the optimum index factor-OIF (Chavez et al., 1982) was also used to select triplets of the TM bands for color composites. The RGB color composite TM4, TM5 and TM3 was chosen based on this triplet was used as input for the integration (modulation of hue in the IHS transform).

Two different image enhancements were applied to the TM bands before the digital integration with SAR data: 1) decorrelation stretch of a set of TM bands (TM 3, 4 and 5); and 2) selective principal components (SPC) based on the PC1 of TM 1, 2, 3, and PC1 of TM 5, 7, plus the use of the original TM4.

Decorrelation stretch is a spectral enhancement technique based on the use of principal component transformation. Normally, a set of three original bands is transformed to a new and decorrelated coordinate system (Gillespie et al. 1987). The purpose of using decorrelated images is mainly to maximize spectral contrast given by color nuances. Several examples of the effective use of decorrelation stretching of the Landsat TM, previously to SAR integration, have been published in the literature (Harris et al., 1994; Paradella et al. 1997a; 1998).

The "SPC-SAR Integrated Product" used in this research constitutes a new approach, and was originally proposed by Paradella et al. (1999) for the integration of RADARSAT and TM data in the geological mapping of the Carajás Mineral Province (Amazon Region). Basically, a principal component transform is independently applied to two distinct sets of the TM bands (TM 1, 2 and 3; and 5 and 7). The two first eigen channels obtained (PC1 of TM 1, 2, 3 and PC1 of TM 5 and 7), retained the maximum variance of the visible and the mid-infrared parts of the TM spectrum (Table 2). In addition, TM 4 band was used as one of the three input channels in the RGB/IHS transform. In order to maximize the variance of these channels, a decorrelation stretch can be also applied to the channels, previously to the RGB/IHS transform. A synthetic image (image with a constant value) with a digital number 60 was used as the saturation channel in the reverse IHS-RGB transform.

Table 2: Eigenvector loadings and variance (in %) of the selective principal component images obtained: a) for TM 1, 2 and 3 bands, and b) for TM 5 and 7 bands.

a)

	PC1	PC2	PC3
TM1	**0.69**	**0.42**	**0.59**
TM2	**-0.61**	**-0.09**	**0.78**
TM3	**-0.38**	**0.90**	**-0.20**
Var. (%)	**95.11**	**4.42**	**0.47**

b)

	PC1	PC2
TM5	**0.08**	**-0.99**
TM7	**-0.99**	**-0.08**
Var. (%)	**64.44**	**35.56**

RADARSAT WITH LANDSAT TM DATA INTEGRATION

The complementary aspects of integrating radar and optical imageries have already been demonstrated aiming at geologic applications (Harrys et al., 1990; Harrys et al., 1994; Singhroy, 1996; Paradella et al., 1997a; Paradella et al., 1998). While backscattered microwave energy from the Earth's surface measured by a SAR system provides information the geometry (macro and micro-topography) and electrical properties (particularly related to the water content) (Lewis et al., 1998), optical sensors provide information controlled by physical-chemical properties of the targets (Colwell, 1983). Thus, the synergism of SAR and optical data through integrated products improve the detection and the characterization of coastal environments and features, mainly in tropical coastal environments.

Two types of integrated products were produced using SAR and TM data acquired from the Bragança Coastal Plain. The evaluation of these products was based on visual interpretation taking into account color and textural attributes. Table 2 provides a ranking of the performance of the integrated products, based on a criterion of interpretability (range of color-texture, effectiveness of integration, ability to combine more than three bands of Landsat TM with SAR data).

The RADARSAT-TM integrated based on the Fine image and the three TM decorrelated bands (DEC 453) was no so effective to discriminate the different coastal environments, mainly along the shoreline and the estuarine plain. The interpretability and detection of image patterns are poor, probably in response to the combination of only three TM bands. This product provides, principally SAR information related to macro-topography (low local slopes), micro-topography (superficial roughness), and water content of the coastal sedimentary environments. The intertidal mangrove forest (Figure 3a) can only be separated from the secondary vegetation of the coastal plateau due to rougher texture, without exposed soil. The supratidal mangrove (Figure 3b) with a more spaced coastal forest is partly confused with the salt marsh, and is only discriminated due to its spatial distribution. Backscattered responses controlled by the water content, has allowed subdivided the salt marsh in: (1) inner salt marshes (Figure 3c), constituted by wet muddy sediment, densely covered by grasses along tidal creeks, showing a dark green colors; and (2) outer salt marshes (Figure 3d), covered by a grasses in a wet muddy sediments, responsible for light greenish patterns. Cheniers sand ridges (Figure 3e) are discernible based on textural patterns and spatial position, characterized by a smooth surface and dark tones in response to absorption of the microwave radiation by dry sandy sediments. Barrier-dune-beach ridges, ebb-tidal deltas, tidal sandflats, submerse sandy banks and tidal estuarine channel are difficult to be discriminated on this integrated product.

Table 3- Evaluation of the integrated products

Qualitative Factors	**Integrated Products**	
	SAR x TM (SPC)	**SAR x TM (DEC)**
Interpretability of patters	G	P
Color-texture range	G	P
Combination of more than three TM bands	Y	N
Shoreline delineation	G	G
Coastal environment recognizing	G	M
Subjective Ranking	1	2

DEC = Decorelated stretch SPC = Selective principal component

P = Poor M = Moderate G = Good N = No Y = Yes

1 = Highest ranking 4 = Lowest ranking

The RADARSAT-TM integrated product produced from the Fine Mode image and the selective principal component of the six TM reflective bands has shown much better results for the coastal geological mapping. This product has favoured the visual interpretability (better range of color-texture), showing effectiveness of integration, and ability to combine information from more than three bands of the Landsat TM with SAR data. Hence, the complementary aspects of integrating radar and visible and infrared imageries were reached, allowing a much more accurate and easier and more consistent interpretation of the remote sensing data. According to Souza Filho and

Paradella (submitted), with the "SAR-SPC Integrated Product", three relevant aspects have been embedded in this integration: 1) powerful tool for visual analysis; 2) geobotany; and 3) multi-spectral and multi-temporal analysis.

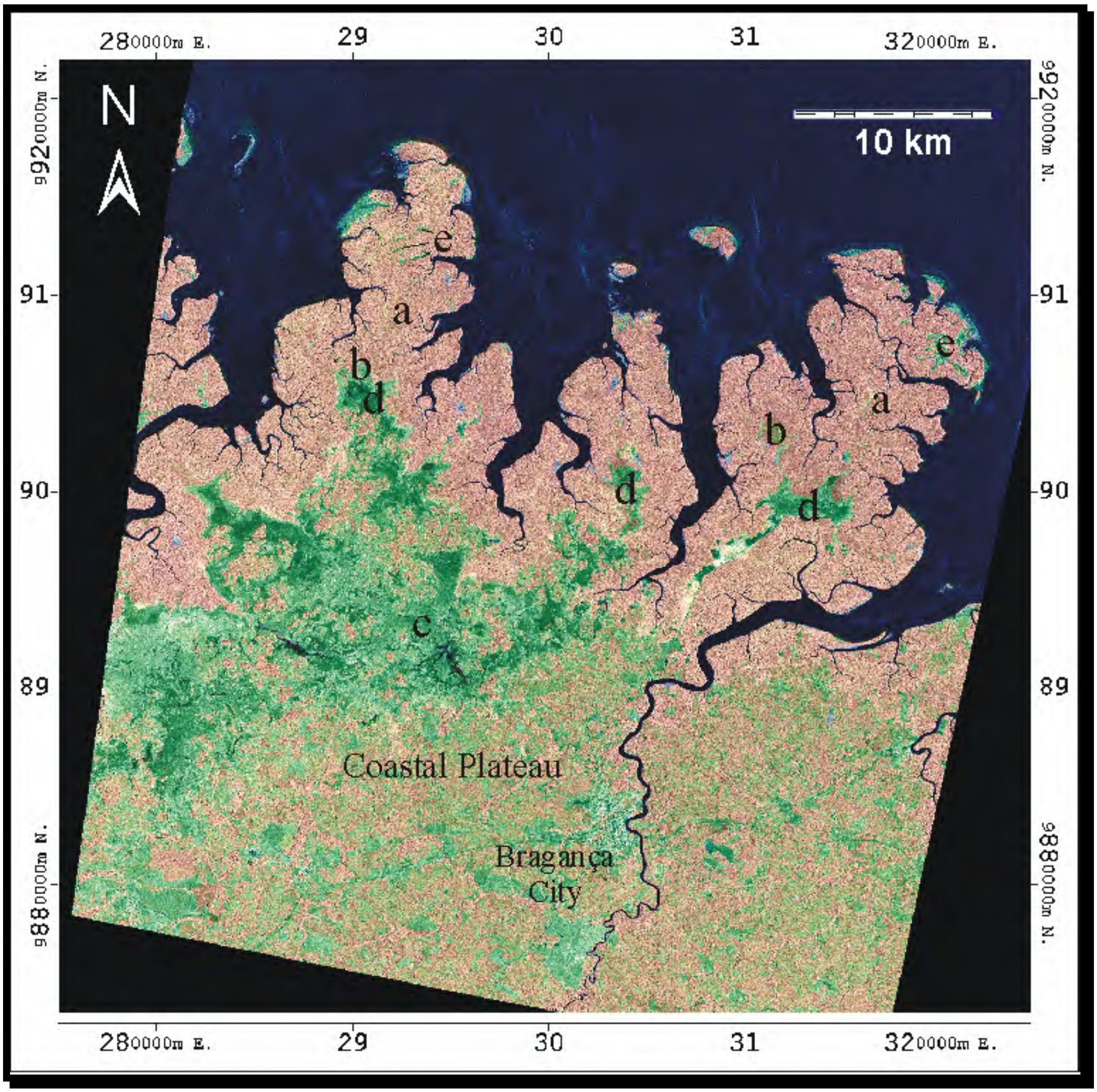

Figure 3- RADARSAT (F1) and Landsat TM (decorrelation stretch) integrated product from the Bragança Coastal Plain. The letters are discussed in the text (a = intertidal mangrove, b = supratidal mangrove, c = inner salt marsh, d = outer salt marsh, e = chenier sand ridge).

The spectral TM and textural SAR integrated responses can be related to topographic differences (elevation) closely related to variations in sedimentology, water content and geobotanical controls. Thus, intertidal mangrove forest associated with wet muddy sediments, flooded twice per day by tides, is expressed by a greenish pattern and a rough texture (Figure 4a). The supratidal mangrove forest related to muddy sediments, and flooded only during high spring tides, is characterized by a more spaced mangrove forest showing bluish colors (Figure 4b).

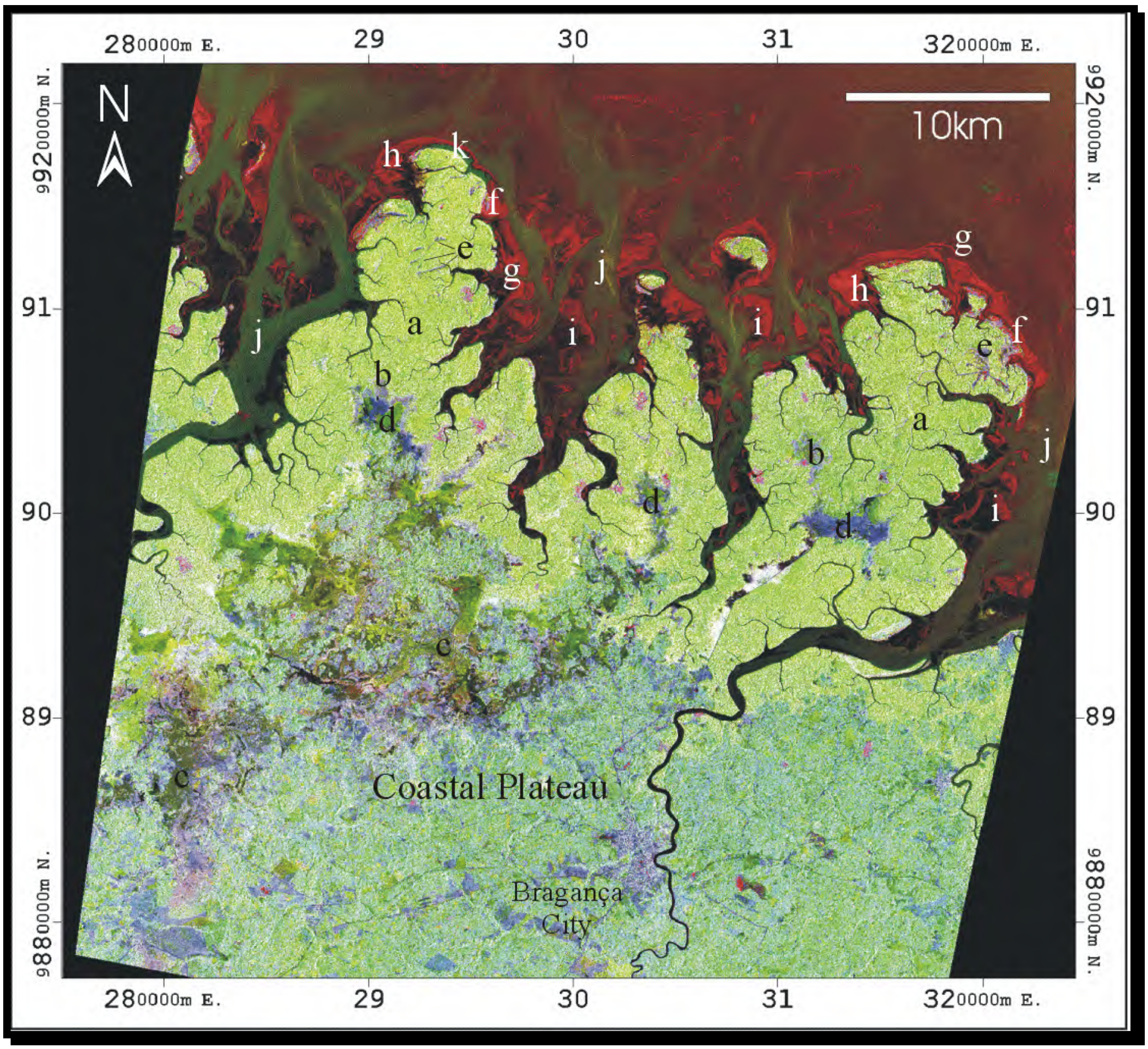

Figure 4- RADARSAT (F1) and Landsat TM (selective principal component) integrated product from the Bragança Coastal Plain. The letters are discussed in the text (a = intertidal mangrove, b = supratidal mangrove, c = inner salt marsh, d = outer salt marsh, e = chenier sand ridge, f = barrier-dune beach ridge, g = ebb-tidal delta, h = tidal sandflat, i = submerse sandy bank, j = tidal estuarine channel, k = coastal change).

The vegetated inner salt marsh is constituted by wet muddy sediment, densely covered by grasses expressing as dark green colors (Figure 4c), while outer salt marshes, covered by a more spaced grasses with muddy exposed sediments, are depicted as bluish patterns (Figure 4d). Cheniers sand ridges, topographically higher, dry and covered by arbustive vegetation, are related to reddish hues (Figure 4e). The shoreline and estuarine environments, such as barrier-dune-beach ridges (Figure 4f), ebb-tidal deltas (Figure 4g), tidal sandflats (Figure 4h), submerse sandy banks (Figure 4i) and tidal estuarine channel (Figure 4j), almost not perceptible in the SAR data are easily mapped in the "SPC-SAR integrated Product" due to the spectral TM contribution (hue), expressed as reddish colors.

Finally, a multi-temporal analysis can be done based on a single color composite product since images of different dates are integrated, and provide information about coastal accretion or retreating. This is a fundamental aspect to be addressed when dealing with coastal dynamic studies (Figure 4k).

CONCLUSIONS

This research has demonstrated how the spaceborne SAR integrated with optical remote sensing data can be used to support coastal geological mapping in tropical macrotidal environments. The "SPC-SAR Integrated Product" has proved to be a powerful toll for the integration of RADARSAT with Landsat TM data, showing the best performance in the discrimination of units in this kind of coastal environment. This superior performance was mainly related to the information content provided by the six reflective TM bands. The first eigen channel (PC1) obtained from the TM bands 1, 2 and 3 was responsible for the enhancement of the shoreline and submerse coastal features. The first eigen channel (PC1) generated from the TM bands 5 and 7 has enhanced exposed soils in the coastal environments and allowed the spectral discrimination between inner and outer salt marshes and supratidal mangroves. The contribution of the TM band 4 was related to the discrimination of dense mangrove forest from secondary vegetation of the coastal plateaus, whose spectral response is mixed with exposed soil produced by human activity. The SAR data was responsible by the enhancement of distinct coastal vegetation height, geometry and water contents. In addition, the digital fusion of RADARSAT Fine with TM images also provided a synoptic view of the area, and favored planning for field campaigns and the integration of previous disperse information. Finally, the use of SAR image integrated with optical data must be recognized by coastal geologist as an extremely important tool for mapping and purposes monitoring of the coastal zones. The "SPC-SAR integrated product" has provides information about geobotany (vegetation and coastal sedimentary environment relationship), emerge and submerge coastal geology, and also allowed the detection of changes in coastal areas over periods of years to decades, which cannot be done from field investigations alone.

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3.3. REMOTE SENSING DATA AND GEOGRAPHIC INFORMATION SYSTEM INTEGRATION FOR COASTAL GEOMORPHOLOGICAL MAPPING IN A MACROTIDAL MANGROVE COAST, BRAZILIAN AMAZON REGION

ABSTRACT

The geomorphologic mapping in a macrotidal coastal plain in the Amazon region is complex. Firstly, as these lowland coast environments are formed by large and heterogeneous landforms, and secondly, these landforms are submitted to rapid and significant changes along the coastline. The coastal environments spatial changes, in the inner sectors of the coastal plain, are related to a long-term time scale. Therefore, the geomorphologic mapping does not have to be updated in relation to geologic and morphologic attributes, except to monitor and manage coastal environments. This study suggests that integrated spatial analysis of remote sensing data (RADARSAT-1 and Thematic Mapper™ images) with Geographic Information System represents a new approach to geomorphologic mapping in wet tropical coastal plains. This approach became possible with the integration of a complete sequence of acquisition, processing, storage and management of the spatial data. Based on spatial, spectral and textural attributes, the coastal environments were mapped and validated with field observations, such as sediments, stratigraphy, vegetation, topography, land cover and land use characteristics. This research has revealed that integrated remote sensing data and GIS for geomorphologic coastal mapping provided valuable, rapid and accurate methods for the study of coastal landforms. Remote sensing data provides great details of the coastal configuration and associated with the organizational philosophy of GIS allow the site characterization, base maps and thematic maps generation and information dissemination for public consultation, which are all significant factors in this decision-making process.

Key words: RADARSAT-1, Landsat TM, GIS, coastal geomorphology, northern Brazil.

INTRODUCTION

The coastal zone is a broad zone that reaches from the landward limit of marine processes to the seaward limit of alluvial and shoreline processes, situated between continental and marine environments where occur estuaries, deltas, tidal flats, salt marshes, barrier islands, cheniers, lagoons, beaches and others (Summerfield, 1991). Coastal environments are products of many complex interacting processes (transport, erosion and deposition), which are continually modifying the landscape.

Geomorphologic mapping is concerned with the Earth's surface representation and shows the shape, form, spatial distribution, constituent material, age and other planimetric features of the landforms and give important keys to the processes, which led to their development (Cook and Doornkamp 1990). The morphology and sedimentary facies of the coastal environments are the product of interactions between tectonic controls, relative sea level, coastal processes and sediment supply responsible for geomorphologic coastal evolution. Landform mapping in tropical macro-tidal coastal plain environment is complicated due to a number of factors. Firstly, macro-tidalflats form lowland areas, where relief information is often scarce and the spatial planimetric representation becomes dominant. According to Yang et al. (1999), this often causes problems in landform interpretation if spectral elements and other indirect features, such as vegetation pattern, hydrographic features, and land use, are not effectively utilized. Secondly, the tidal range reaches around 6 m, producing dramatic changes in coastal sedimentary environment boundaries, estuary water line and shoreline position in response to wide vertical and lateral displacement of the tide. Thirdly, the coastal geomorphological changes are very intense and rapid in many coastal landforms. Therefore, these characteristics are limiting factors for coastal landform mapping in the study site, along the Bragança coastal plain.

Orbital remotely sensed data has been extensively used in regional geomorphologic mapping when a modern satellite platform was launched in the 1970's. Since this time, the most useful source of satellite optical data for geomorphologic application is images from the Landsat Thematic Mapper (TM). Coastal geomorphologic survey through TM Landsat has been carried out elsewhere (Jones 1986; Gowda et al. 1995; Prost 1997; Ciavola et al. 1999; Yang et al. 1999). During the last 10 years, Synthetic Aperture Radar (SAR) has been used more widely, mostly in tropical coastal environments (Singhroy, 1995; 1996; Rudant et al., 1996; Prost, 1997; Kushwaha et al. 2000). With SAR's side viewing geometry, longer wavelengths, and almost all-weather sensing capability, RADARSAT-1 imagery has been extensively used as an operational tool for geomorphological mapping in the moist tropics.

The complementary aspects of integrating radar, visible and infrared imageries have already been demonstrated to geologic applications (Harrys et al., 1990; Rheault et al. 1991; Harrys et al., 1994; Singhroy, 1996; Paradella et al., 1997a; Paradella et al., 1998; Ramsey III et al. 1998). While backscattered microwave energy from the Earth's surface measured by a SAR system provides information the geometry (macro and micro-topography) and electrical properties (particularly related to the water content) (Lewis et al., 1998), optical sensors provide information controlled by physical-chemical properties of the targets (Colwell, 1983). Thus, the synergism of SAR and optical data through integrated products improve the detection and characterization of coastal environments and features, mainly in wet tropical coastal environments.

According Burrough (1986), remote sensing and geographic information system (GIS) can be treated as general framework of integrated spatial analysis. Hence, the remote sensing data represents the source of geographical information, providing important features in the space and time domains. The ability to combine a data set (remote sensing and geosciences data) and simultaneously interpret the spatial relationship between various sources of information allows for a more accurate and comprehensive interpretation (McGregor et al., 1999).

The purpose of this research was to integrate remote sensing data, digital image processing and GIS techniques to geomorphologic mapping in a wet tropical mangrove coast. Based on remotely sensed data and GIS integrated approach, coastal landforms have been mapped to provide a better understanding of the geomorphologic coastal evolution of the Bragança coastal plain.

STUDY AREA

The study area is located along the Pará-Maranhão Coast, northern Brazil (Figure 1), which represents one of the larger mangrove systems of the world, with almost 6,000 km^2 (Herz, 1991). Geologically, the area is located in the Bragança-Viseu coastal basin of Cretaceous age, whose tectonic evolution is controlled by normal faults. The structural framework of this coastal basin is responsible for a submergence of the coastal zone (Souza Filho, 2000). This submerging coast coupled with a falling relative sea level during the Holocene. The riverine sediment supply has allowed the muddy flat progradation and development of the coastal sedimentary environment during the last 5,1000 years B.P. (Souza Filho and El-Robrini, 2000).

The coastal study site is developed over Tertiary deposits of the Barreiras Group and Pirabas Formation. These deposits constitute the coastal plateau along the northern Brazilian coast, which is bounded by inactive and active cliffs (Souza Filho and El-Robrini 1996). The coastal plain extends northward of the coastal plateaus for more than 20 km, where are found wide tidal flats. The major coastal environments observed are tidal mudflats (mangrove), salt marshes, tidal sandflats, chenier sand ridges, coastal sand dunes, barrier-beach ridges and ebb-tidal delta (Souza Filho, 1995).

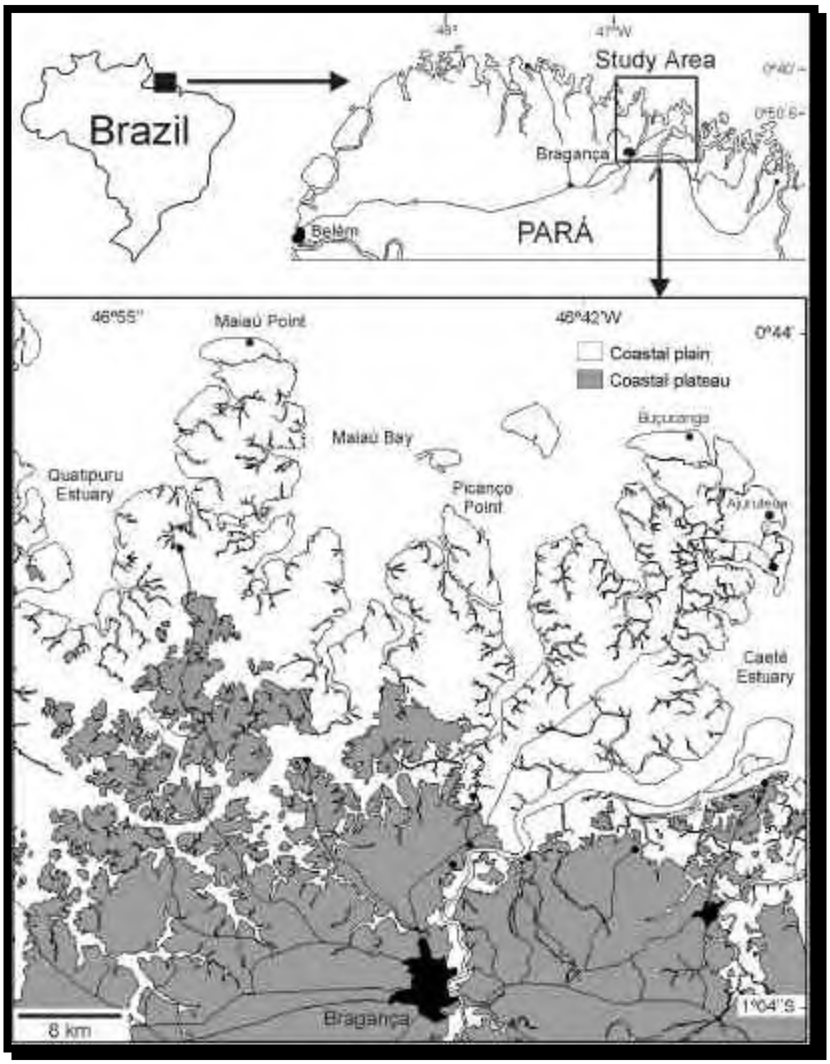

Figure 1- Location map of the Bragança Coastal Plain.

The estuarine plain extends southward upstream as far as the tidal limit of the Caeté, Maiaú and Tapera-Açu estuaries and it is bounded northward by marine processes. The climate in the area is a hot and humid equatorial climate, with rainy season from December to May and a dry season from June to November, with an annual precipitation averaging 2,500 mm and relative humidity of the air ranging from 80 to 91%.

METHODOLOGICAL APPROACH

The use of a GIS for coastal geomorphological mapping has revealed to be a success in lowland environments (Lyon and Adking, 1995; Yang et al., 1999). An integrated method combining digital image processing and geographical information system (GIS) was used for data collection, processing, analysis and displaying of the results. The use of GIS for coastal geomorphological identification consisted of the following working procedures:

Data acquisition: SAR and optical data were used for coastal geomorphological mapping. The SAR image is represented by RADARSAT-1 Fine C-HH band, acquired in a descending orbit on September 08 1998, under Globesar-2 Program (Paradella et al., 1997b). The incident angles ranging from 37º to 40º, with 16-bit image processed to a 1-look resolution, 9.1 and 8.4-meters spatial resolution and 6.25 x 6.25-meters pixel size. The Landsat TM image was acquired on December 31 1991, in path 222 and row 61. The TM sensor records the intensity of reflection in six bands from visible to short wave infrared, presenting spatial resolution and pixel size of 30 x 30-meters.

Data processing: The digital analysis was carried out based on the EASI-PACE package (PCI 1999). The methodology essentially has involved multisensor data integration and visual interpretation for detection and characterization of the tropical coastal environments. The optical and SAR data were geometrically corrected to a common UTM format, thus ensuring data standardization on a spatial sense, and allowing data manipulation and comparison on a pixel-to-pixel basis (Toutin, 1995). An ortho-rectification scheme was used to correct induced terrain distortion, which is a major factor in radar geometric correction due to the off-nadir viewing.

For the RADARSAT-1 Fine image, antenna pattern correction (APC) and speckle suppression filtering were applied as radiometric processing. The APC was based on the procedures designed by Pietch (1993). An Enhanced-Frost filter was chosen to reduce speckle effects (Lopes et al., 1990) and applied during the ortho-rectification process. The RADARSAT-1 Fine image was further linearly stretched and used as the Intensity channel in the reverse IHS-RGB transformation.

The pre-processing technique applied to the TM data has involved the radiometric correction related to the attenuation of atmospheric effects and was based on the minimum histogram pixel (Chavez, 1988). Selective principal components (SPC) transform based on the PC1 of TM 1, 2, 3, and PC1 of TM 5, 7, plus the use of the original TM4 was applied in the TM reflective bands to before the digital integration with SAR data.

The "SPC-SAR Integrated Product" used in this research constitutes a new approach, and was originally proposed by Paradella et al. (1999) for the integration of RADARSAT and TM data in the geological mapping of the Carajás Mineral Province (Amazon Region). Basically, a principal component transform is independently applied to two distinct sets of the TM bands (TM 1, 2 and 3; and 5 and 7). The two first eigen channels obtained (PC1 of TM 1, 2, 3 and PC1 of TM 5 and 7), retained the maximum variance of the visible and the mid-infrared parts of the TM spectrum. In addition, TM 4 band was used as one of the three input channels in the RGB/IHS transform. In order to maximize the variance of these channels, a decorrelation stretch can be also applied to the channels, previously to the RGB/IHS transform. A synthetic image (image with a constant value) with a digital number 60 was used as the saturation channel in the reverse IHS-RGB transform.

The main steps of the digital image processing methodological approach are presented in the flowchart showed in the Figure 2, while the RADARSAT-TM integrated product produced from the Fine Mode image and the selective principal component of the six TM reflective bands is showed in the Figure 3.

Analysis and interpretation: The interpretation of the "SPC-SAR Integrated Product" was carried out using standard keys such as tone/color, texture, pattern, form, size, geometry, drainage and others. A detailed analysis of the coastal geomorphology is associated with important elements, such as spectral, textural and geometric characteristics of the coastal landform. The subsequent systematic interpretation was performed with on-screen digitizer provided by an Arc-View GIS Software, version 3.1 (ESRI, 1996). The "SPC-SAR Integrated Product" was used to map on a 1:70.000 scale. A polygon file was initially generated to illustrate the coastal landform boundary, while line files were used to show the drainage and roads, and point files were generated to show towns and villages.

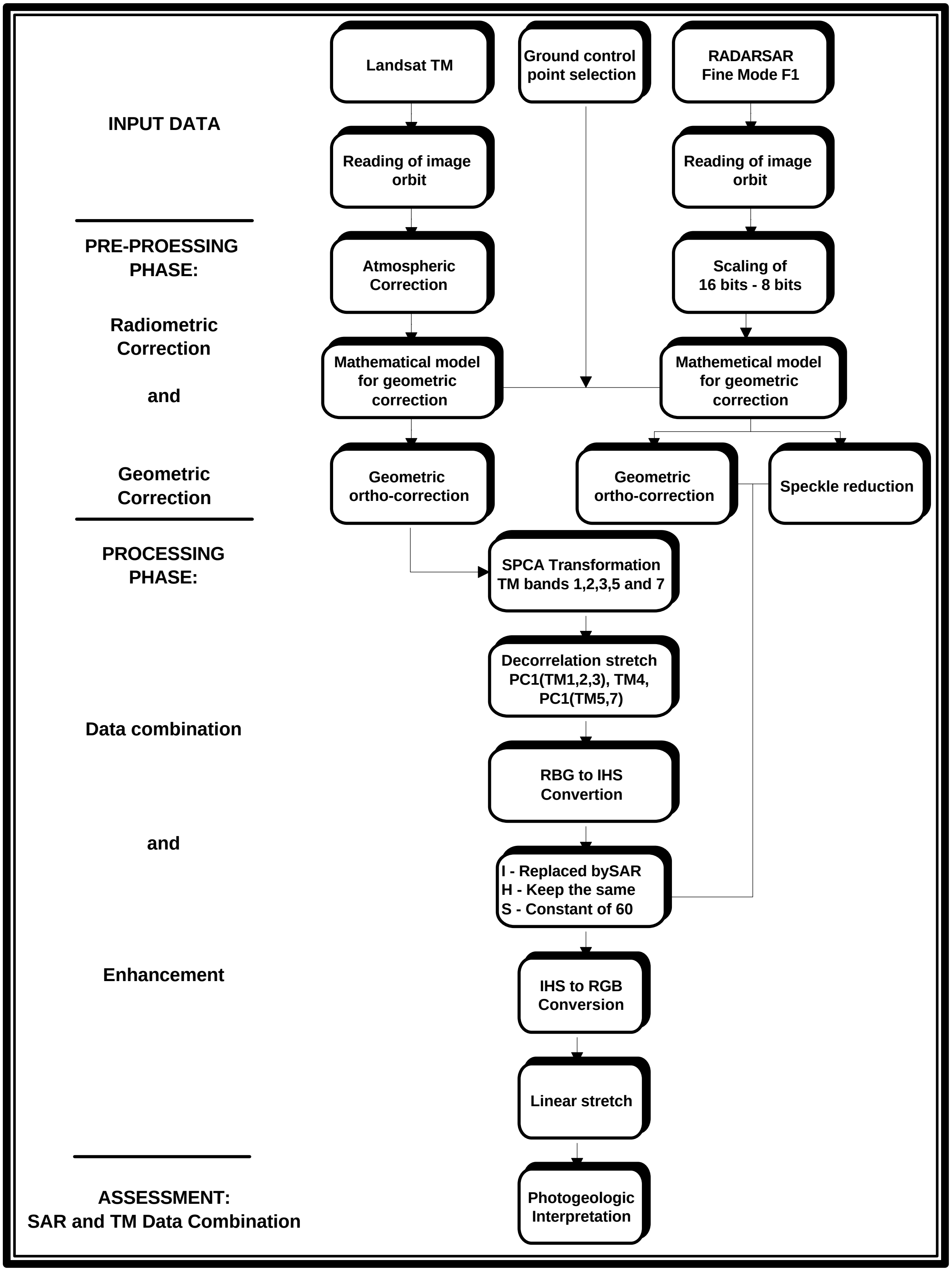

Figure 2- Flow chart with main steps in the SAR and TM integration.

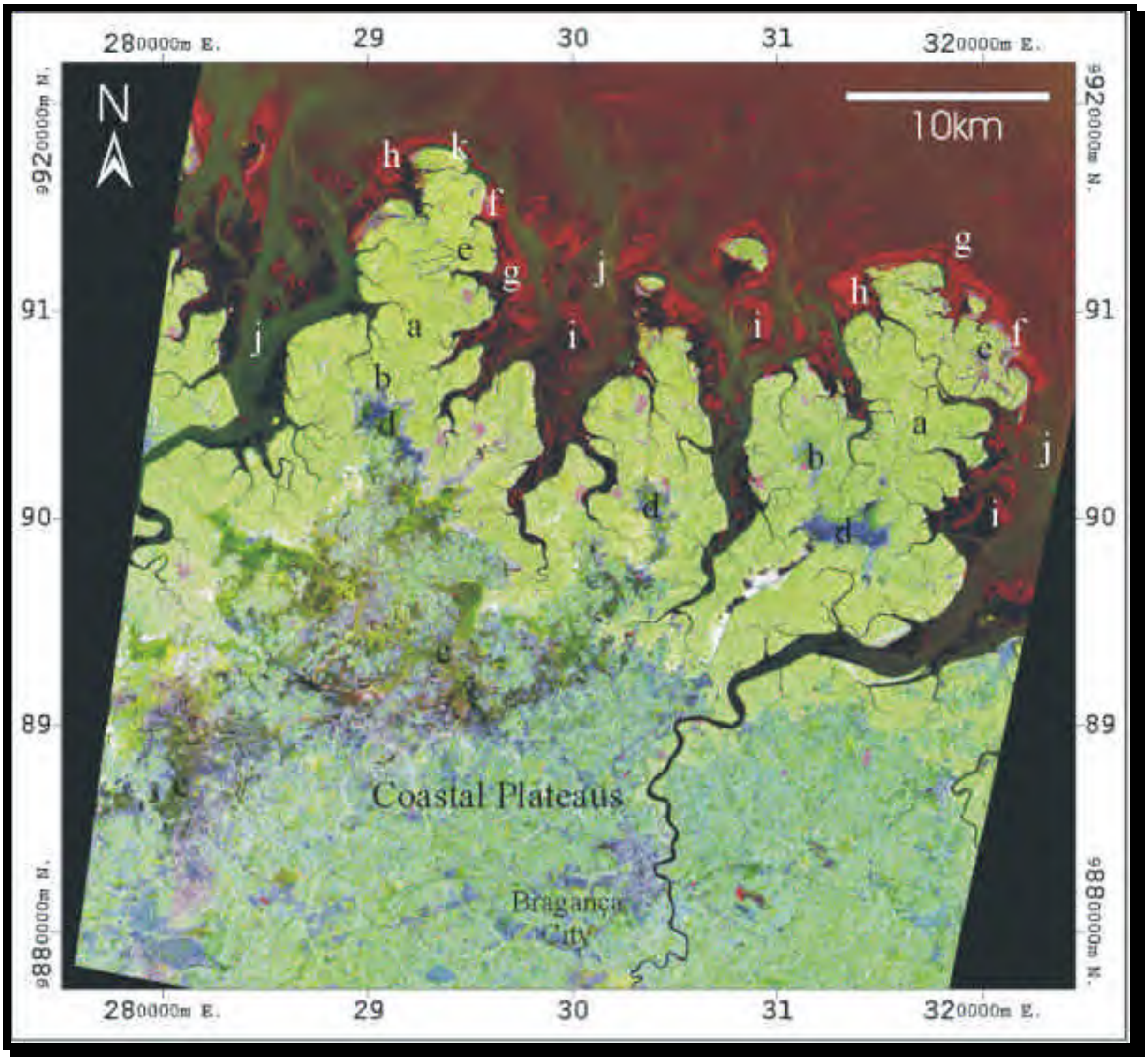

Figure 3 - SPC-SAR integrated product in the Bragança Coastal Plain. The letters are discussed in the text (a = intertidal mangrove, b = supratidal mangrove, c = inner salt marsh, d = outer salt marsh, e = chenier sand ridge, f = barrier-dune beach ridge, g = ebb-tidal delta, h = tidal sandflat, i = submerse sandy bank, j = tidal estuarine channel, k = coastal change).

Field working and observations: The field survey was carrying out to check the initial features observed in the image interpretation. During the geomorphological mapping were identified vegetation, sediment texture, stratigraphy, vegetation, age, topography and features of different coastal landforms, which were positioned through the global positional system (GPS). Each coastal unit was described and sampled through vibracorer techniques, whose sediments were collected and analyzed from genetic facies approach.

Map integration and cartographic presentation: Based on fieldwork data, the preliminary polygon file was further modified and refined, together with the attribute database to calculate the area of each coastal landform. The final map was cartographically designed with output, including text placement, legend and hardcopy printing.

RESULTS AND DISCUSSIONS

Geomorphological mapping of the coastal zone

The landforms classification system adopted in this study is modified of ITC system of geomorphologic survey (Verstappen and Van Zuidam, 1991). This is based on geomorphologic principles, i.e. a classification on the basis of landform, sedimentary patterns, and the dominant processes in operation related to historical processes. Some other factors, including land use and land covers, were used for classification. Those coastal parameters were largely extracted from digital image processing through manipulation of spectral-textural and spatial of the image data, whose principal aim was to enhance the coastal landforms.

The "SPC-SAR Integrated Product" allowed the identification of various colors and textures patterns. Along the coastal plain, a greenish pattern and a rough texture (Figure 3a) express intertidal mangrove environment. A more spaced mangrove forest showing bluish colors (Figure 3b) characterizes the supratidal mangroves. The vegetated inner salt marshes are expressed as dark green colors (Figure 3c), while outer salt marshes are depicted as bluish patterns (Figure 3d). Cheniers sand ridges are related to reddish hues (Figure 3e). The shoreline and estuarine environments, such as barrier-dune-beach ridges (Figure 3f), ebb-tidal deltas (Figure 3g), tidal sandflats (Figure 3h), submerse sandy banks (Figure 3i) and tidal estuarine channel (Figure 3j), almost not perceptible in the SAR data are easily mapped in the "SPC-SAR integrated Product" due to the spectral TM contribution (hue), expressed as reddish colors.

The geomorphologic map realized under a GIS environment is illustrated in Figure 4. The characteristics of each coastal landform unit are summarized in Table 1, while detailed description of morphologic, stratigraphic and sedimentary attributes can be found in the work of Souza Filho (1995) and Souza Filho and El-Robrini (1998). This map represents the recent status of the coastal plain in relation to morphology of sedimentary environment, vegetation conditions and land use due to the more dramatic impacts, which were caused during the building of the Bragança-Ajuruteua road in the early 1980's.

Coastal landforms description and interpretation

The major landforms observed in the Bragança Coastal Plain are tidal mudflats, mangroves, salt marshes, tidal sandflats, chenier sand ridges, coastal dunes, barrier-beach ridges and ebb-tidal delta (Figure 4).

Important observations in relation to geomorphologic processes, sediment pattern, coastal processes, land cover and anthropogenic environmental impacts in the coastal plain are highlighted below according to geomorphologic classification.

Coastal plateau

The Coastal Plateau is developed over Tertiary deposits of Barreiras Group and is marked by land cover with secondary vegetation, such as pasture and also exposed soil. In response to these characteristics, this target is very well distinguished by texture and mixed spectral response of secondary vegetation and exposed soil (Figure 2).

Tidal mudflats (mangrove)

The tidal mudflats are easily mapped due to strong spectral response and rough texture of the mangrove vegetation (Figure 2). The tidal mudflats constitute wide mangrove system. They are located from the high spring tide to the mean tidal level. Organic muddy sediments are deposited on the tidal flat during the slack tidewater, when the currents decrease. The field studies have indicated that *Rhizophora* sp. and *Avicennia* sp. are the dominant species commonly found along this coast.

The distribution of mangrove is mainly controlled by topography (Coehn et al. 2000). Based on relative altimetry and vegetation height, the tidal flats were subdivided in supratidal mangrove and intertidal mangrove. The supratidal mangroves are topographically higher with smaller trees and reached by water only during the spring tides, while the intertidal mangroves are topographically lower with high trees (almost 30 m) and progradational front's seawards.

Table 1 - Characteristics of the coastal mapping features

Morphostratigraphic Unit	Sediments	Morphology	Land cover/ Use	Image characteristics (SPC-SAR Integrated Product)	Inundation time (day/yr.) Cohen et al., 2000)	Area (km^2)	Area (%)
Estuaries and tidal channels	Fine sand, silty clay	Erosion and accretion of the channel margins	_________	Smooth surface with greenish tones	365	305	____
Submerse sandbank	Fine sand	Longitudinal banks with lateral shifting	_________	Smooth surface with reddish tones	365	92	10.05
Sand flat	Fine sand	Intertidal flat erosion and accretion	_________	Smooth surface with reddish tones	300	93	10.17
Mudflat	Silt, silty clay	Intertidal flat deposition	_________	Smooth surface with dark tones	300	1.5	0.16
Ebb-tidal delta	Fine sand	Intertidal flat, erosion and accretion	_________	Smooth surface with reddish tones	300	3.6	0.40
Old estuarine sanbanks	Fine sand	Supratidal flat accumulation	_________	Smooth surface with bluish tones	Without field data	0.2	0.02
Barrier-beach ridges	Fine sand	Intertidal flat erosion	Arbustive	Linear features, smooth surface with reddish tones	233	15	1.63
Coastal dunes	Very fine sand	Transverse, longitudinal and pyramidal dunes, erosion	Arbustive	Rough surface with reddish tones	0	1,7	0.18
Chenier sand ridges	Fine sand	Transverse dunes with washover fans	Arbustive	Linear features, rough surface with reddish tones	28	8	0.92
Young intertidal mangrove	Silt, silty clay	Recent prograding zone	Mangrove trees	Rough surface with light greenish tones	300	12	1.32
Intertidal mangrove	Silt, silty clay	Accretion and erosion	Mangrove forest	Very rough surface with light greenish tones	100	480	52.47
Supratidal mangrove	Silt, silty clay	Flooding and accumulation	Mangrove forest	Rough surface with green-bluish tones	28	34	3.73
Outer salt marsh	Silt, silty clay	Flooding and accumulation	Grassland	Rough surface with bluish tones	0	67	7.29
Inner salt marsh	Silt, silty clay	Flooding and accumulation	Grassland	Slightly rough surface with greenish tones	Without field data	79	8.63
Fluvial flood plain	Fine sand, silt	Flooding, accumulation and marginal erosion	Grassland	Rough surface with greenish tone	Without field data	24	2.60
Regenerated mangrove	Silt, silty clay	Flooding and accumulation	Mangrove trees	Very rough surface with light tone		2.5	0.28
Degraded mangrove	Silt, silty clay	Flooding and accumulation	_________	Smooth surface with dark tones	100	1.2	0.13
Artificial lake	Silt, silty clay	Flooding and accumulation	Water body	Smooth surface with dark tones	365	0.2	0.02
Urban areas	Ferruginous silty sand	Hill relief	Buildings	Very rough surface with bluish tones	__________	____	____

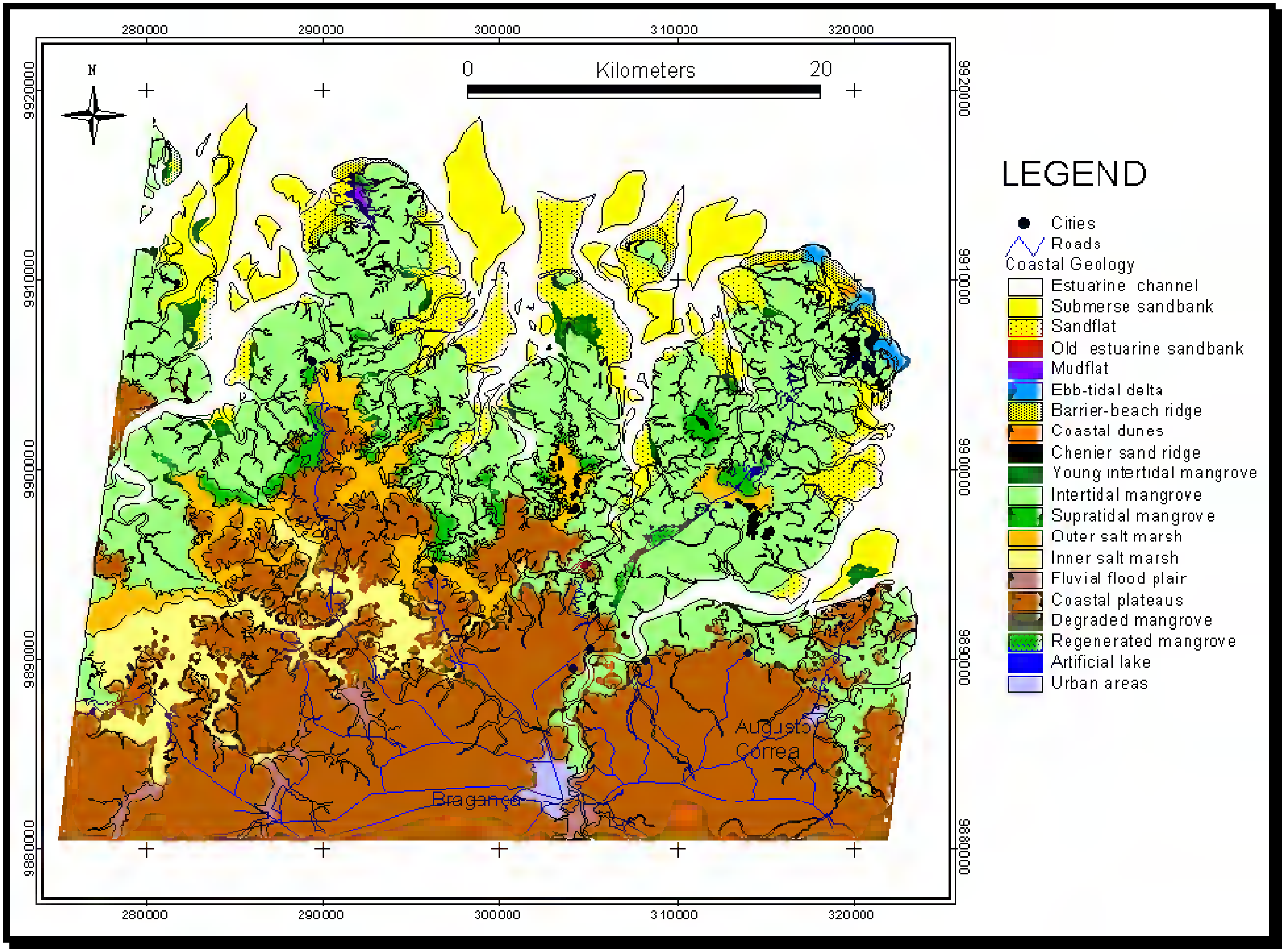

Figure 4- Geomorphologic map of the Bragança coastal plain.

Salt marshes

The salt marshes are known in the area as "Campos de Bragança". They are clearly discernible due to the distinct characteristics of wetland area, which support grasses (*Eleucharias* sp.) adapted for saturated soils. The marshes are situated in the supratidal zone and its sedimentation is marked by mud deposition carried from tidal fluxes along creeks (Souza Filho and El-Robrini 1996). They are subdivided in inner and outer salt marshes. The inner salt marshes occur bounded by the coastal plateaus and are flooded during the rainy season, while the outer salt marshes occur along the tidal mudflat boundary and are frequently influenced by spring tides (Figure 5).

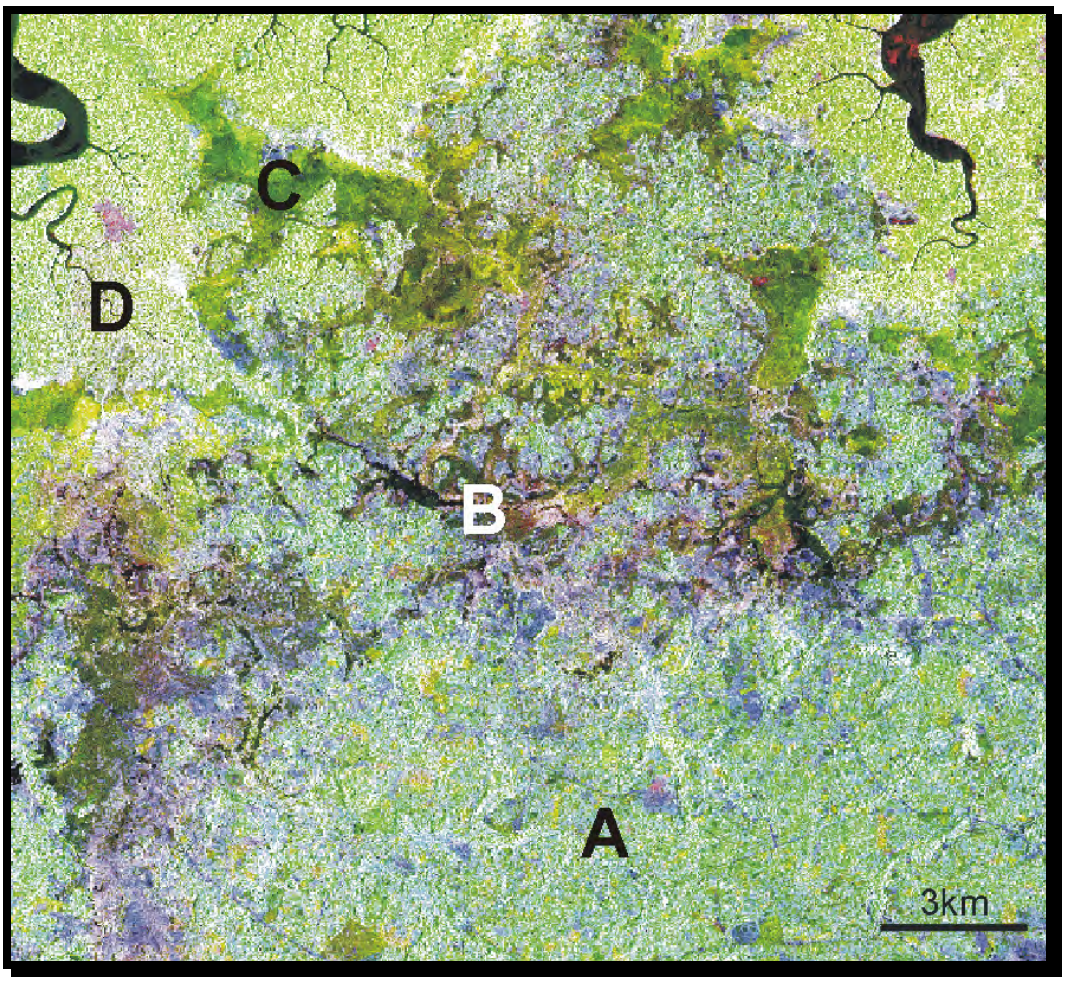

Figure 5- Transition between coastal plateau (A), inner salt marsh (B), outer salt marsh (C) and intertidal mangrove (D) showed in an SPC-SAR integrated product.

Chenier sand ridges

The chenier sand ridges constitute old dune-beach ridges with associated washover fans. It is easy to identify this feature in the image due to high spectral response of white fine sand covered by sparse arbustive vegetation and geometric boundary. The cheniers have a well-defined linear and curved form, whose boundary is the prograding tidal mudflats (Figure 6).

Coastal dunes

Coastal sandy dunes occur in restricted areas along the Ajuruteua Island. From SPC-SAR integrated product was possible to separate dry sands of vegetated dunes from wet sand of the beaches (Figure 6). Nowadays, the dunes are migrating landward over the mangrove deposits in the intertidal mudflats. Transversal sandy dunes are partially or completely vegetated and they are composed by very fine quartz sand.

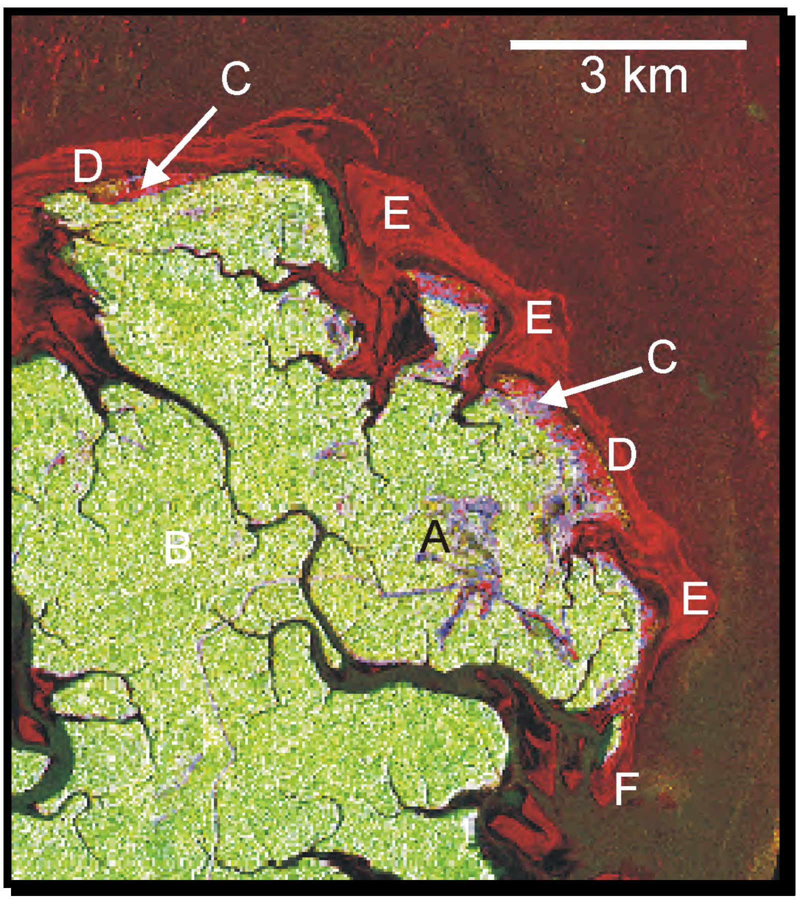

Figure 6- SPC-SAR integrated product displayed along the Ajuruteua Island. Observe the chenier sand ridge (A) bounded by intertidal mangroves (B), the coastal dunes (C), the transgressive barrier-beach ridge (D), and ebb-tidal deltas (E) in the tidal channel mouth and spits (F).

Barrier-beach ridges

Barrier- beach ridges extend from low spring tidal level to the dune-beach scarp that represents the higher spring tidal level in the intertidal beach. This coastal landform was easily identified from the TM imagery contribution, due to the high spectral response of white sands. The beaches show a linear and elongated form with curved spits in the longshore sediment transport direction (Figure 2 and 6). These barrier-beach ridge forms transgressive beaches, which migrate over intertidal mangroves.

Ebb-tidal delta

Ebb-tidal deltas are the most dynamic coastal landform, whose size and shape are directly related to the relative influence of waves and tidal currents on barrier-beach ridge (Davis Jr. 1992). Its detection from TM imagery is due to the same spectral attributes observed in sandflats landform, but it presents peculiar spatial features. As the tidal energy is dominant, ebb deltas extend seaward in the form of large deltas, and shore normal sand bodies. The ebb delta morphology presents shallow ebb channels exposed during low spring tide, flanked by sandy bars (Figure 6).

Tidal sandflats

The tidal sandflats occur between mean tidal and low spring tidal levels along the coast. Sandy tidal shoals show many ripple and megaripple marks and sand waves exposed at low tide. Due to these characteristics, the mapping of this coastal landform is a direct response of sandbanks in shallow waters (Figure 2). In these areas, it is possible to map the prograding zone by mangrove colonization (Figure 7).

Estuarine channel and submerse sandy tidal banks

Estuarine channel and submerse sandy tidal banks are not usually mapped from remote sensed data, principally in waters with great concentration of suspended sediments. However, the selective principal component analyses of six TM bands allowed the discrimination of submerse coastal features (Figure 2 and 8). Estuarine channel appears a smooth surface and greenish tones very well defined in the SPC-SAR integrated product. Submerse sandy tidal banks are in reddish tones, whose surface is well enhanced.

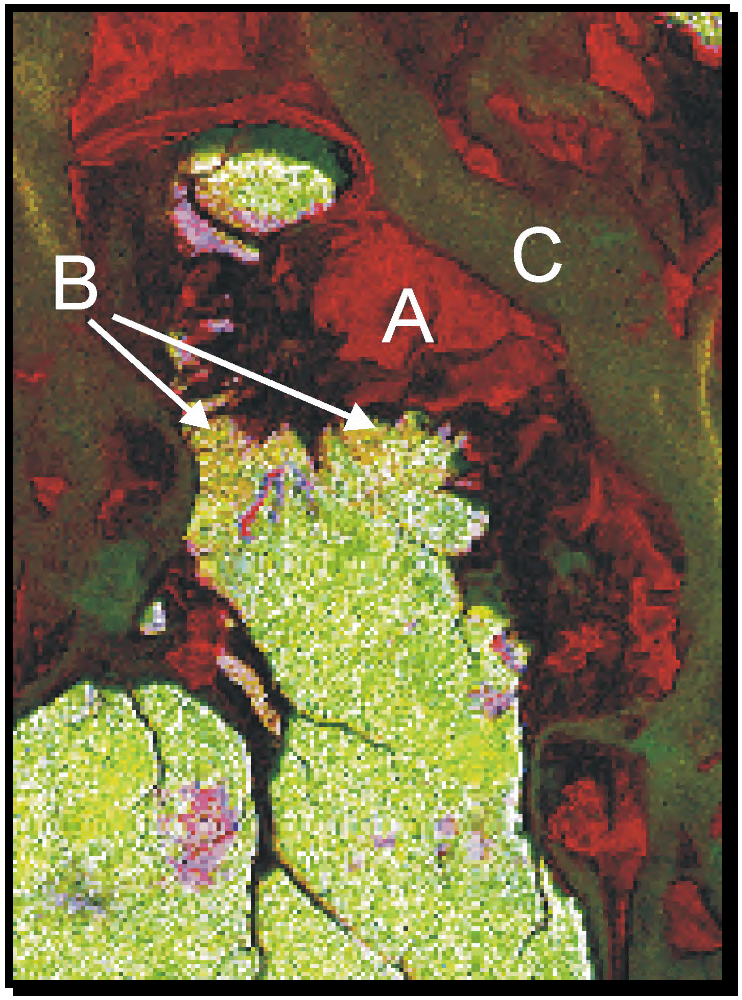

Figure 7- Mangrove prograding over tidal sandflat along the Picanço Point from the SPC-SAR integrated product. Note the extension of sandflat exposed during the low tide (A) that is progressively colonized by mangrove vegetation (B). Observe the tidal channels bounding the sandflat (C).

Degraded areas by human activities

Along the Bragança coastal plain there are many human settlements. In these villages are developed agricultural and fishery activities. Agricultural villages are located in the coastal plateau and salt marshes areas, while fishery villages are situated along the estuarine margins, mangroves and beaches. Extensive areas affected by human activities have been mapped with success from SPC-SAR integrated product, such as roads along mangrove system, deforested mangrove areas and artificial lakes (Figure 8).

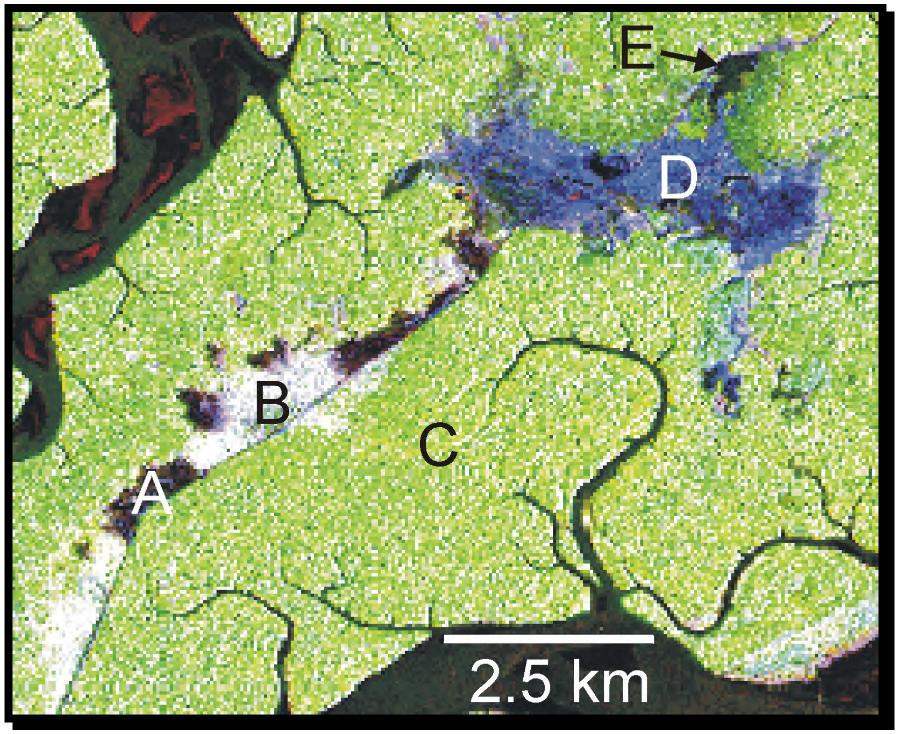

Figure 8- Human activities mapped from SPC-SAR integrated product. Deforested mangrove area (A); mangrove-regenerated areas (B); native mangrove forest (C); grasses of salt marsh (D); and artificial lake (E).

Coastal landform boundaries and coastline delineation

Due to great variations of oceanographic processes such as macro-tidal range, wave directions, longshore drift, river discharge, rainfall, and rapid morphologic coastal changes, the landform boundaries and coastline delineation are difficult to establish in coastal zone geomorphologic mapping.

The inner coastal landform boundaries are very well defined in the SPC-SAR integrated product because the texture, geometry and spectral responses of the targets are different in intensity and spatial distribution. The inner coastal plain boundary is defined by contact between coastal plateaus and mangrove or inner salt marsh. The contact between coastal plateaus and mangrove is marked by abrupt lithologic, vegetation and morphologic changes, which can be observed in the Figure 2. The contact between coastal plateaus, inner and outer salt marshes and mangroves shows an environmental succession controlled by topography and tidal inundation (Figure 5). Other landform boundaries such as cheniers and mangroves, dunes and mangroves, beaches and mangroves, beaches and tidal sandflats are also easily recognized in the images and in the field.

The coastline delineation was very well defined along the inner part of estuarine channel dominated by tidal currents. In this sector, the boundaries between coastal plateaus and water, and mangrove and water were easily recognized (Figure 2). In the distal sectors of estuarine plain influenced by waves action and lateral tidal range, the boundary between water and land was established with more difficult. Due to relative changes in tidal ranges, this boundary was defined based on dry sand (high spectral response) or intertidal mangrove line. Thus, the coastline mapped in this work represents the high tide line. As remote sensed images present different dates (1991 Landsat TM and 1998 RADARSAT-1) the multitemporal coastal changes could be well mapped from SPC-SAR integrated product (Figure 9).

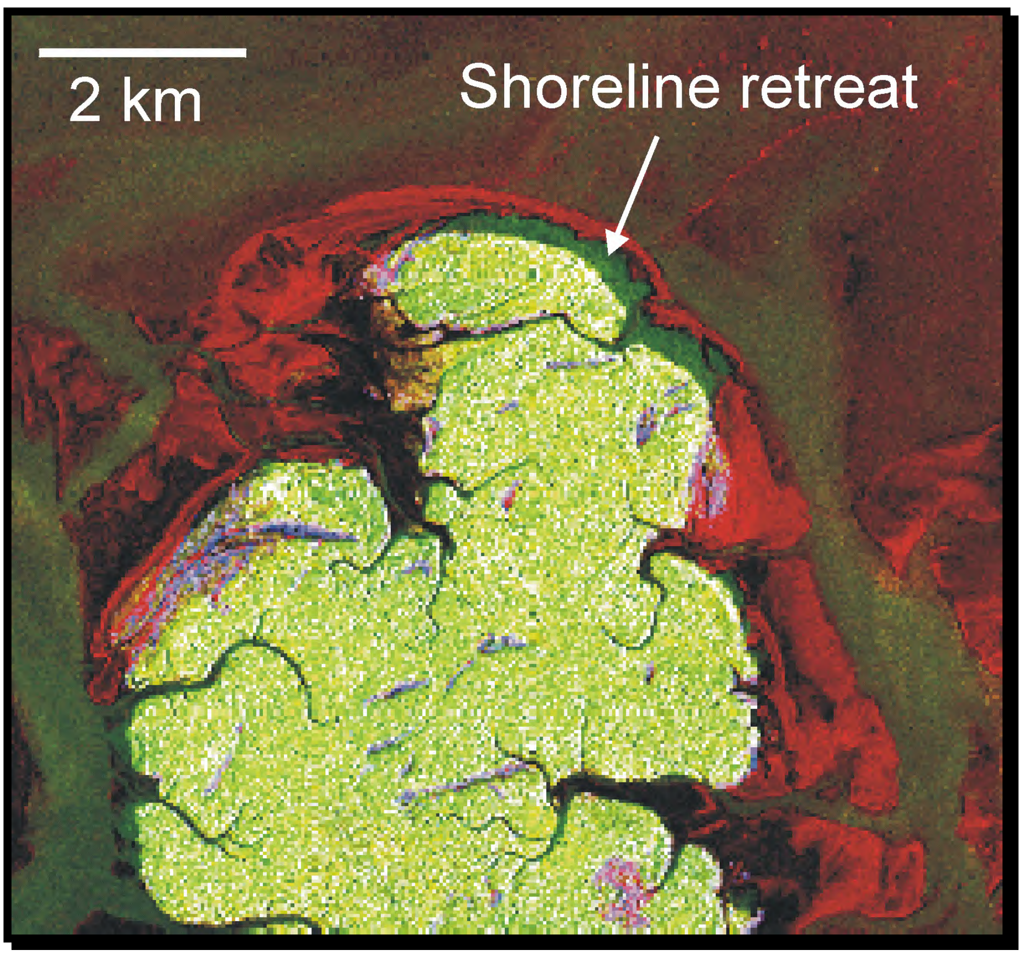

Figure 9- SPC-SAR integrated product showing coastal changes from 1991 to 1998.

CONCLUSIONS

Several conclusions have been reached with regard to integrated remote sensing data and the use of GIS for the purpose of site characterization within a Bragança Coastal Plain.

The geomorphologic mapping of tropical macro-tidal coastal environments is complex owing to tide, wave, longshore drift, fluvial discharge action and rapid morphologic changes. The use of SPC-SAR integrated product imagery in the geomorphologic mapping showed it to be an excellent tool to extract morphologic features of coastal landforms. Many techniques of digital image processing are available in the literature and they can be used to enhance different targets, i.e. different coastal landforms with specific spectral response displayed in the space. However, the integration of RADARSAT and TM data in geological mapping presents, at least, three relevant aspects:

1) The visual analysis of integrated products is related to the ability of the SAR to enhance topographic features and differences in the vegetation heights. In addition, the Landsat TM data provided more information on the land cover types and land use and changes in vegetation signatures, which indicated the sites of coastal environments transitions; 2) the SAR and TM data integration involves the geobotany, were coastal vegetation is closely related to coastal sedimentary environments; and 3) the SAR and TM integration is related to multi-temporal analysis. When images of different dates are integrated, a multi-temporal attribute is also added to the product, providing information about coastal accretion or retreat.

The integration of the remote sensed data with a GIS constitute the more general framework of integrated spatial analysis and makes possible the complete sequence of acquiring, processing, storing and managing spatial data (Star and Estes 1990). Thus, the ability of GIS to combine different data sets and simultaneously interpret the spatial relationship between several coastal environments allows for a more comprehensive interpretation of a geomorphologic mapping.

The study has revealed that integrated remote sensing data and GIS for geomorphologic coastal mapping provided valuable, rapid and accurate methods for the study of coastal landforms. The GIS represents an organizational philosophy to control data towards uses the information to coastal zone management. Hence, for a coastal zone management program, remote sensing and GIS technologies have important roles to play in environmental assessment, site characterization, base maps and thematic maps generation and information dissemination for public consultation, which are all significant factors in this decision-making process.

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3.4. EVALUATION OF LANDSAT THEMATIC MAPPER AND RADARSAT-1 DATA TO GEOMORPHOLOGICAL MAPPING ON A MANGROVE COAST, BRAGANÇA, PARÁ, BRAZILIAN AMAZON REGION[1]

ABSTRACT

Orbital remote sensing data were evaluated for geological mapping on a Mangrove Coast, along the Bragança Region, in the Pará State, Brazilian Amazon Region. This study aimed at a detailed reconnaissance of the coastal environments (wetlands - mangroves and salt marshes, sandflats, chenier sand ridges, coastal sand dunes, barrier-beach ridges and ebb-tidal delta) and the coastal features (plateaus and coastal plain boundary, depositional and erosional features, coastline form, suspended sediments and submerse sandy banks) based on Landsat-5 Thematic Mapper and RADARSAT-1 Fine-mode data. In addition, the effectiveness of various image enhancement techniques was also evaluated in the context of coastal depositional systems detection. With Landsat TM data, it was possible to detect distinct coastal environments based on the spectral responses controlled by physical-chemical composition of water, vegetation and sediments. On the other hand, the RADARSAT-1 image has provided complementary information related to the electric-geometrical characteristics of the environment. Finally, multisensor data fusion based on the optical and SAR images has allowed to characterize geobotanical controls due to changes in the vegetation cover, closely related to variations in flooding frequency and sedimentology of the area. An important aspect involving the optical-SAR data fusion is related to the multi-temporal information providing additional insights about the coastal dynamic. The result of the investigation has shown the importance of using orbital remote sensing integrated products as a powerful tool for coastal geomorphological mapping in the Amazon Region, particularly in the wetland environments of mangrove coasts.

Keywords: Brazilian Amazon Region, coastal mapping, Landsat TM, mangrove, multi-sensor data integration, RADARSAT-1, salt marsh.

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INTRODUCTION

Wetland low-lying areas that are flooded at a sufficient frequency to support vegetation adapted for life in saturated soils, include mangroves forest and salt marshes (Clarck, 1996). Coastal wetlands exhibit extreme variations in area extent, temporal duration, and spatial complexity (Ramsey III et al., 1998). The transition of continental and coastal environments is marked by a water table near or above the surface, hydric soil and hydrophytic vegetation. The development of monitoring tools for this kind of complex environment is necessary, mainly in the discrimination of wetland types and in the identification of seasonal alterations caused by natural and anthropogenic processes.

In general, three approaches have been used to extract geological and geomorphological information from remote sensing data: spectral, photo-geological and digital integration methods (Singhroy, 1992). The spectral approach involves differences in target reflectance, which is used to multispectral classification schemes. The photo-geological technique uses topographic features, textures, tones and drainage patterns to delineate geological, geomorphological and lithologic units. Finally, integration methods use remote sensing data integration techniques as a complement to the spectral and photo-geologic interpretation. Therefore, the synoptic view of the coastal wetland environments from space has been used for accurate mapping of coastal wetland systems. Distinct sensors exploring the optical spectra, such as the Landsat TM, have a long history of successful mapping of wetland types through different techniques of digital image processing (Ramsey III and Laine, 1997; Ramsey III et al., 1998; Smith et al., 1998). One of the major drawbacks related to the usage of spaceborne optical data is the presence of perennial clouds in the equatorial coastal zone, particularly during the wet season. Synthetic Aperture Radar (SAR) technology has advanced during the last 10 years with the advent of global observation system based on imaging radar (ERS-1, JERS-1, ERS-2, and RADARSAT-1). SAR could extend the capability of optical sensor for mapping of coastal zone wetlands, due to its all-weather imaging capability, since microwaves can penetrate cloud, and to a high degree, rain. Furthermore, imaging radar also operates independently of sun illumination. These factors have opened a new dimension in the use of spaceborne sensors for coastal zone applications, particularly in the assessment and management of the natural resources during the wet season (Lecont and Pultz, 1991; Rudant et al., 1996; Adams et al., 1998; Kushwaha et al., 2000). On the other hand, data integration using the concept of multisensor synergy is becoming a common trend in applications in geosciences (Harris et al., 1994; Singhroy, 1996; Wald, 1998).

Taking into account these aspects, this investigation had two main objectives: (1) a detailed reconnaissance of a coastal wetland environment located in the Northern part of Brazil, based on spaceborne optical and SAR data, and (2) to evaluate the effectiveness of image enhancement and data integration techniques for mapping and characterization of this complex tropical environment.

STUDY SITE

The Bragança Region, located on the northeastern Brazilian Amazon (Figure 1) is influenced by a macrotidal coastal environments. The area, part of the Pará-Maranhão Coast, represents one of the larger mangrove ecosystems of the world with almost 6,000 km^2 (Herz, 1991). The Holocene sedimentary evolution of the Bragança coastal plain began at 5,100 years B.P, when the sea level reached the maximum relative level (Souza Filho and El-Robrini, 1998; Behling et al. 1999). From 5,100 years B.P to the moment, the sedimentary model is a result of coastline progradation with development of a mangrove system, intercalated to short-term retrogradation events responsible for coastal erosion and deposition of old and recent barrier dune-beach ridges. These features mark old and recent coastlines that interrupted the mangrove progradation.

Along the Mangrove Coast, the major landforms observed are salt marshes, tidal sandflats, chenier sandy ridges, coastal sandy dunes, barrier-beach ridges and ebb-tidal deltas (Figure 1) (Souza Filho and El-Robrini, 2000). The distribution of tidal flats is mainly controlled by topography. Therefore, based on the relative altimetry and vegetation height, the tidal flats were subdivided in supratidal mangrove and intertidal mangrove. The supratidal mangroves are topographically higher with smaller trees and can be reached by water only during the spring tides, while the intertidal mangroves are lower in elevation with progradacional and erosional areas.

According to Souza Filho (2000), the coastal zone geomorphology of the northeast of the Pará State presents a tectonic control. The study area occurs along the Bragança-Viseu coastal basin, with Quaternary deposits controlled by the geometry of the basin and its paleo-topography. This coastal plain constitutes a macrotidal (>4 m) depositional system, developed in a hot and humid equatorial climate, with dry and wet well-defined seasons and an annual precipitation averaging 2,500 mm, while relative humidity varies from 80 up to 91% (Martorano et al., 1993).

REMOTE SENSING DATASET

The investigation was based on the C-HH band RADARSAT-1 Fine Beam 1, (descending orbit) with acquisition occurring in 1998, under the GlobeSAR-2 Program. Details of this program in Brazil can be found in Paradella et al. (1997a). Spaceborne optical data were represented by Landsat TM data (path 222, row 61) acquired in 1985 and 1991. Table 1 provides details of the remotely sensed data used in the research.

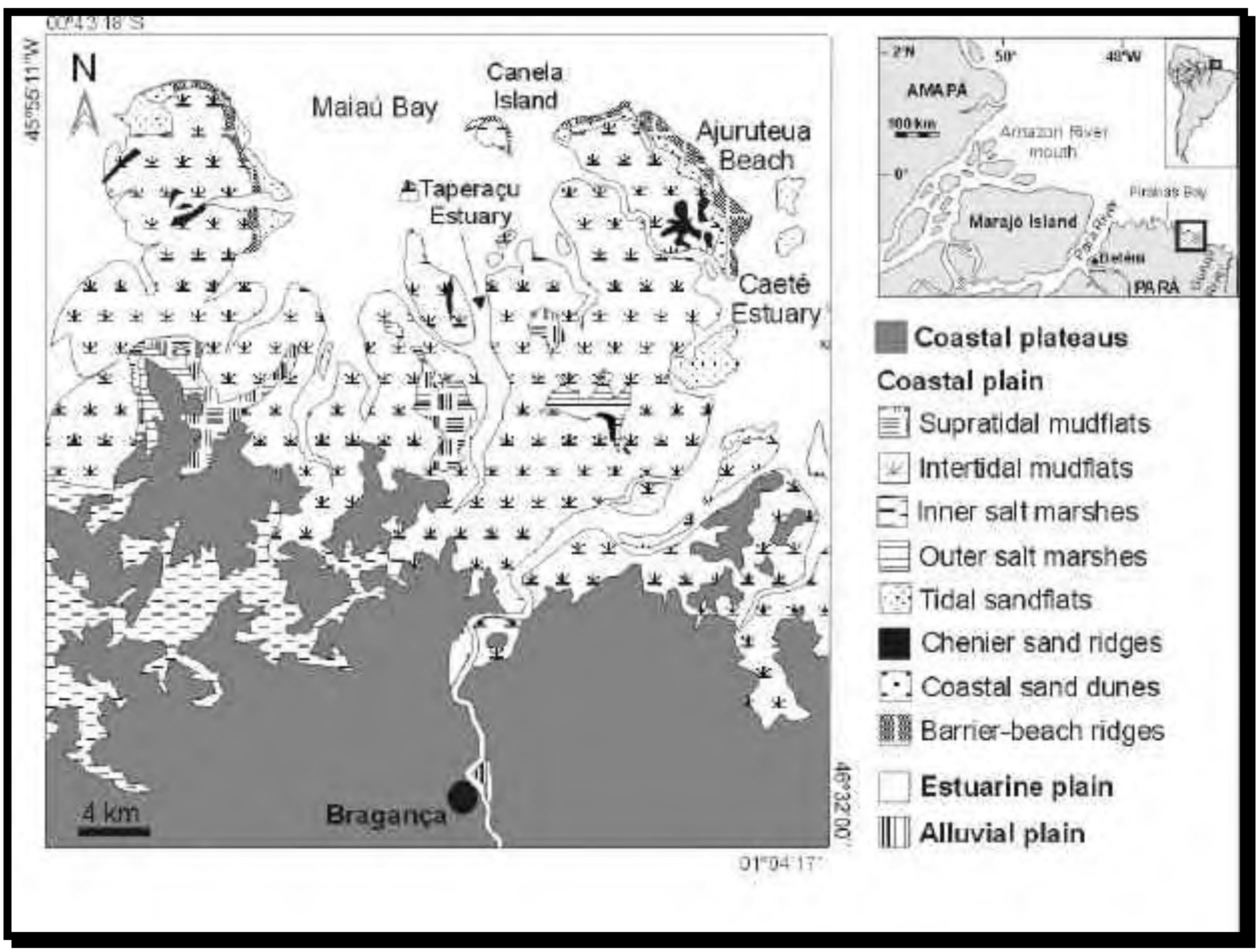

Figure 1- Location of the study area and coastal zone geomorphologic map (Modified from Souza Filho and El-Robrini 1998).

Table 1- Characteristics of the remotely sensed data.

Platform	Sensor	Acquisition Date	Angle of Incidence	Spatial Resolution (m)	Pixel Size (m)	Number of Looks	Image Format
Radarsat-1	Fine Beam Mode 1	September 08, 1998	37-40º	9,1 x 8,4	6,25x6,25	1x1	16-bits Path Image
Landsat-5	TM Bands 1,2,3,4,5,7	December 31, 1991	_____	30 x 30	30 x 30	_____	8-bits
Landsat-5	TM Bands 1,2,3,4,5,7	August 24, 1985	_____	30 x 30	30 x 30	_____	8-bits

METHODOLOGICAL APPROACH

The methodology essentially has involved: (1) the analysis of the RADASAT-1 Fine and the Landsat TM data through digital image processing techniques, (2) multisensor data integration, and (3) the visual interpretation of the enhanced products for detection and characterization of the coastal wetland environments. The digital analysis was carried out with PCI software (PCI 1999). Both data-set were geometrically corrected to a common UTM format, thus ensuring data standardization on a spatial sense, and allowing data manipulation and comparison on a pixel to pixel basis (Toutin, 1995).

Landsat TM-5 imagery

The pre-processing techniques applied to the TM data have involved radiometric and geometric corrections. The radiometric correction was related to the attenuation of atmospheric effects based on the minimum histogram pixel (Chavez, 1988). A rigorous geometric correction based on an ortho-rectification scheme was applied to the TM bands in order to assure correction for terrain distortions (Toutin, 1995). Image enhancements were also applied based on linear and equalization stretches. A feature selection approach based on the optimum index factor- OIF (Chavez et al., 1982) was also used to select triplets of the TM bands for color composites. The RGB color composite based on TM4, TM5 and TM3 was selected based on this statistical criterion and chosen for visual interpretation.

RADARSAT-1 imagery

Antenna pattern correction (APC) and speckle suppression filtering for the Fine Mode image was applied as radiometric corrections. The APC was based on the procedures designed by

Pietch (1993). An Enhanced-Frost Filter was applied to reduce speckle effects (Lopes et al., 1990) during the ortho-rectification process. Based on the statistics of the ortho-rectification for the TM and the SAR data (RMS accuracies around cell resolution for each data) and in order to keep a balance of the geometric and radiometric integrities in the data fusion, a 30-meters pixel size was selected as common pixel size for the data integration.

Multisensor integration (RADARSAT with TM)

IHS (Intensity, Hue and Saturation) transform combined with enhanced techniques (linear, decorrelation stretches, etc.) have been commonly used for remote sensing data integration (Harris et al., 1994; Paradella et al., 1997b; Paradella et al., 1998; Pohl, 1998, among others). A new approach, the "SPC-SAR (Selective Principal Component) Integrated Product", as proposed originally by Paradella et al. (1999) for the integration of RADARSAT and TM data in the geological mapping of the Carajás Mineral Province (Amazon Region), was also evaluated. Basically, a Principal Component Transform is independently applied to two distinct sets of the TM bands (TM 1, 2 and 3; and 5 and 7). The two first eigen channels obtained (PC1 of TM 1, 2, 3 and PC1 of TM 5 and 7), retained the maximum variance of the visible and the mid-infrared parts of the TM spectrum (Table 2). In addition, TM 4 band was used as one of the three input channels in the RGB/IHS transform. In order to maximize the variance of these channels, a decorrelation stretch can be also applied to the channels, previously to the RGB/IHS transform. A synthetic image (image with a constant value) with a digital number 60 was used as the saturation channel in the reverse IHS-RGB transform.

Visual analysis

The visual analysis of the digitally enhanced products were carried out using standard keys such as tone/color, texture, pattern, form, size, geometry, drainage and others. The TM bands provided the spectral attributes of the landforms; while the geometric and textural characteristics of the terrain were highlighted through the SAR backscattered responses. The application of these techniques has provided an integrated, detailed and more accurate geomorphological interpretation map of coastal wetland areas.

RESULTS AND DISCUSSIONS

The coastal geomorphology classification for the study area was mainly based on landforms, sedimentary and stratigraphic patterns, and dominates processes in action (evolutionary processes) (Souza Filho and El-Robrini, 1996). In addition, factors such as geomorphological processes, land use and land cover, were also considered. Six coastal sedimentary environments were mapped: tidal flats (mangroves and sandflats), salt marshes, chenier sand ridges, coastal sand dunes, barrier-beach ridges and ebb-tidal delta (Souza Filho and El-Robrini, 2000).

Landsat TM

In the color composite of the Landsat TM images acquired on August 1985 (Figure 2). The intertidal mangrove is depicted as reddish hue, with strong infrared spectral response caused by the contribution of the dense mangrove forest in the TM 4 band (Figure 2a). The supratidal mangroves appear as green-reddish colors due to mixed response of muddy sediments and mangrove trees (Figure 2b). Field information has indicated that Rhizophora sp. and Avicennia sp. are the dominant species commonly found along this coast.

The salt marshes are situated in the supratidal zone, with sedimentation marked by mud deposition carried from tidal fluxes along the creeks (Souza Filho and El-Robrini, 1996). They are subdivided in inner and outer salt marshes. TM image shows the inner salt marsh in dark tones in TM bands 3, 4 and 5 at the end of the rainy season, in response to the spectral behavior of clean water (Figure 2c). The outer salt marsh marks the transitional zone between the coastal plateaus and the mangrove system, and shows green-reddish colors due to the mixed spectral response of muddy sediments and grasses (Figure 2d). Therefore, it presents the same spectral response of the supratidal mangrove.

The chenier sand ridges constitute old dune-beach ridges with associated washover fans. They present light-bluish colors in response to the spectral reflectance of dry white fine sand covered by sparse vegetation in TM 3 and 4 (Figure 2e). The cheniers have a well-characterized geometry given by linear and curved forms with boundaries marked by prograding tidal mudflats. The chenier's appearances are typical in the images. They are discernible from recent beaches by form and spatial distributions rather than by color attributes.

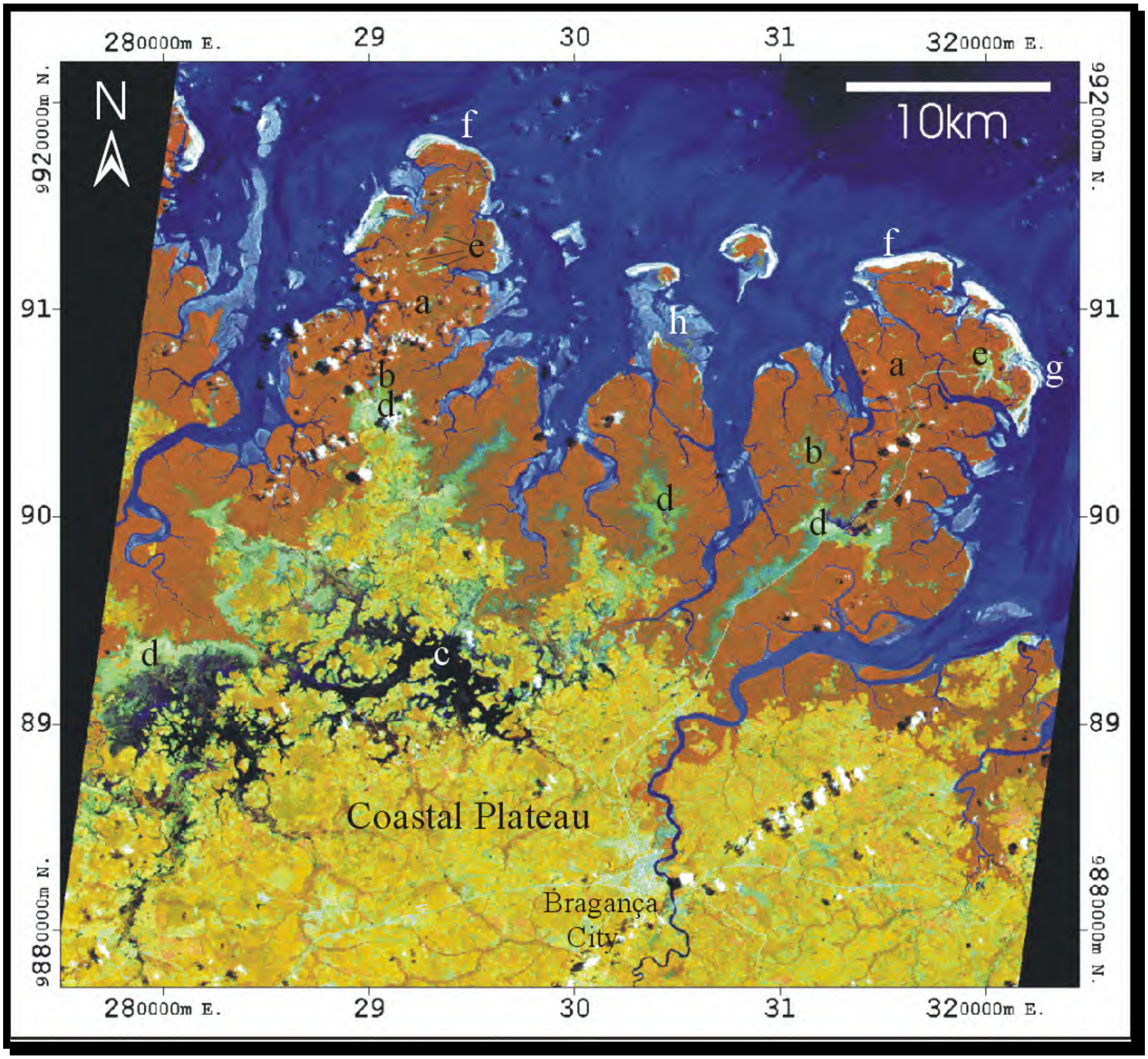

Figure 2- Landsat TM false color composite (4R5G3B) from the Bragança Coastal Plain. The letters are discussed in the text (a = intertidal mangrove, b = supratidal mangrove, c = inner salt marsh, d = outer salt marsh, e = chenier sand ridge, f = barrier-dune beach ridge, g = ebb-tidal delta, h = tidal sandflat).

Barrier-dune-beach ridges (Figure 2f), ebb-tidal deltas (Figure 2g) and tidal sandflats (Figure 2h) are associated with white colors due to the high spectral response in all three TM bands caused by the presence of dry fine white sandy deposits in dunes and intertidal beaches. Coastal features, such as coastal plateaus and coastal plain boundary, prograding depositional features, suspended sediments and submerse sandy banks, are well discernible in the images due to the spectral response of the these targets.

RADARSAT-1

The interpretation of the RADARSAT Fine image in the mangrove environment has indicated that intertidal mangrove forest (trees with a height around 20m) are related to microwave responses controlled, probably, by volumetric scattering and double-bounce mechanism. This particular condition is responsible for a very rough texture and light-gray tone allowing the discrimination of this coastal environment (Figure 3a). The smooth, flat, high dielectric constant surface of the water increases the amount of backscattered radiation toward the radar, due to tree-ground double-bounce interaction. The supratidal mangrove presents a similar behavior of the intertidal mangrove, however the mangrove trees are smaller and spaced, reducing the double-bounce effect. Hence, the target appears less rough and with dark-grayish tone Figure 3b).

The RADARSAT-1 Fine image clearly outlines the salt marshes. The inner salt marsh, completely flooded in the rainy season, presents a specular scattering behavior when the microwave radiation reaches the water table on the surface. Thus, this target appears as very dark tone in the image (Figure 3c). However, for the sectors where the inner salt is covered by grasses, the radiation interaction produces a slightly rougher surface with lighter gray tones Figure 3d). Finally, for the outer salt marsh a similar scattering mechanism related to the inner vegetated salt marsh is characterized, but its geometry and spatial distribution are typical (Figure 3e).

From the RADARSAT-1 Fine image, the chenier sand ridges and dunes (Figure 3f) present a smooth surface and dark tones. These SAR image characteristics appear to be controlled by presence of dry sandy sediments of old dunes. This morph-sedimentary characteristic is responsible for absorption of the microwave radiation (Souza Filho and Paradella, submitted).

Barrier-beach ridges and ebb-tidal deltas are constituted by wet fine sandy deposits and present a flat morphology. In response to sedimentologic and morphologic characteristics, these coastal features in RADASAT image present a smooth surface and very dark tones (Figure 3), due to specular scattering of the microwave radiation. As a consequence, the mapping of these coastal features is difficult. On the other hand, other coastal features, e.g. coastal plain and estuaries boundary, erosional features and coastline forms, are very well discriminated based on the SAR data.

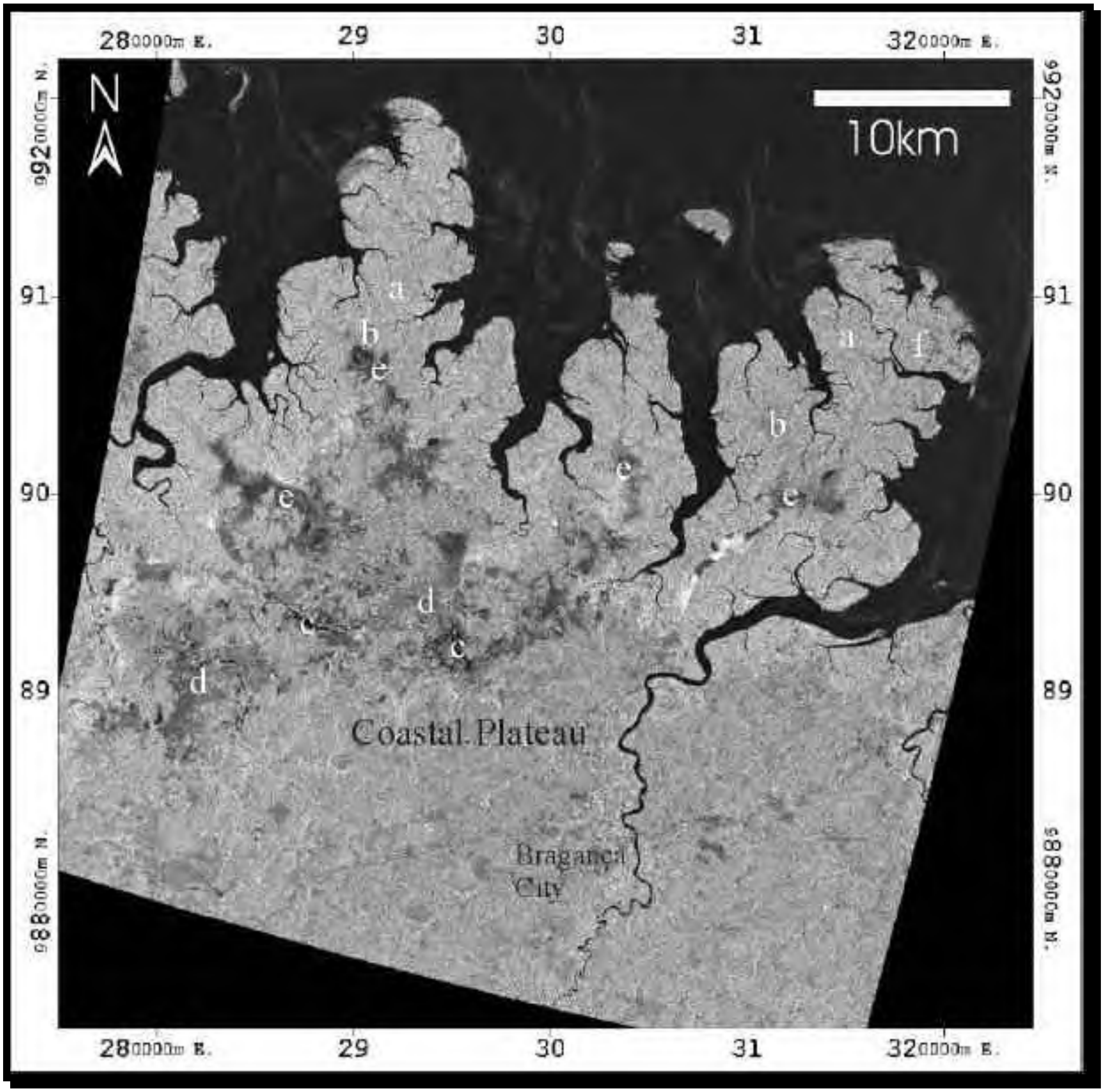

Figure 3- RADARSAT Fine Bean Mode (F1) from the Bragança Coastal Plain. The letters are discussed in the text. (a = intertidal mangrove, b = supratidal mangrove, c = inner salt marsh, d = outer salt marsh, e = chenier sand ridge, f = barrier-dune beach ridge).

RADARSAT-1 with TM integrated product

The backscattered microwave energy from the Earth's surface measured by a SAR system provides information the geometry (macro and micro-topography) and electrical properties (particularly related to the water content) (Lewis et al., 1998; Raney, 1998). On the other hand, optical sensors provide information controlled by physical-chemical properties of the targets (Colwell, 1983). Thus, the synergism of SAR and optical data through integrated products improve the detection and the characterization of coastal environments and features, mainly in tropical coastal environments (Figure 4).

The first relevant aspect in the visual analysis of integrated products is related to the ability of the SAR to enhance topographic features and differences in the vegetation heights. The mangrove coast in the Bragança Region is characterized by a low and flat terrain, segmented by estuaries and tidal channels and colonized by different vegetation types, whose structures varies from forest to natural fields. Variations in the vegetation height are expressed by distinct textural patterns (mesoscale roughness), while variations in the vegetation structures control the gradations in tone (microscale roughness) in the SAR data. Thus, mangrove forests are easily discriminated from marsh grasses. In addition, this discrimination is favoured by the presence of distinct moisture content in the mangrove forests. It is also important to mention that Landsat TM data provides the colors in the integrated products, with hue variations closely related to the spectral responses of the targets. The product's interpretation is much more accurate and easier to be done.

The second relevant aspect in the SAR and TM data fusion involves the geobotany (Paradella and Bruce, 1990; Paradella et al., 1994; Paradella et al., 1998). Spectral TM response can be related to topographic differences (elevation) closely related to variations in sedimentology, water content and geobotanical controls. Intertidal mangrove forest is related to wet muddy sediments flooded twice per day by tides and is represented by a greenish pattern and rough texture (Figure 4a). The supratidal mangrove forest is related to muddy sediments flooded only during high spring tides and are associated with more spaced mangrove forest with bluish colors (Figure 4b). The vegetated inner salt marsh is constituted by wet muddy sediment, densely covered by grasses showing a dark green colors (Figure 4c); while outer salt marshes are covered by more spaced grasses with muddy exposed sediments, responsible for the observed bluish patterns (Figure 4d). Cheniers sand ridges, topographically higher, dry and covered by arbustive vegetation, are related to reddish tones (Figure 4e). Barrier-dune-beach ridges (Figure 4f), ebb-tidal deltas (Figure 4g) tidal sandflats (Figure 4h) and submerse sandy banks (Figure 4i) and tidal estuarine channel (Figure 4j) almost not perceptible in the SAR data, in response to their flat morphology, are mapped in the scenes due to the spectral TM responses (hue), showing a reddish colors. The other coastal features previously mentioned in the TM and SAR scenes are also well discriminated in the integrated products.

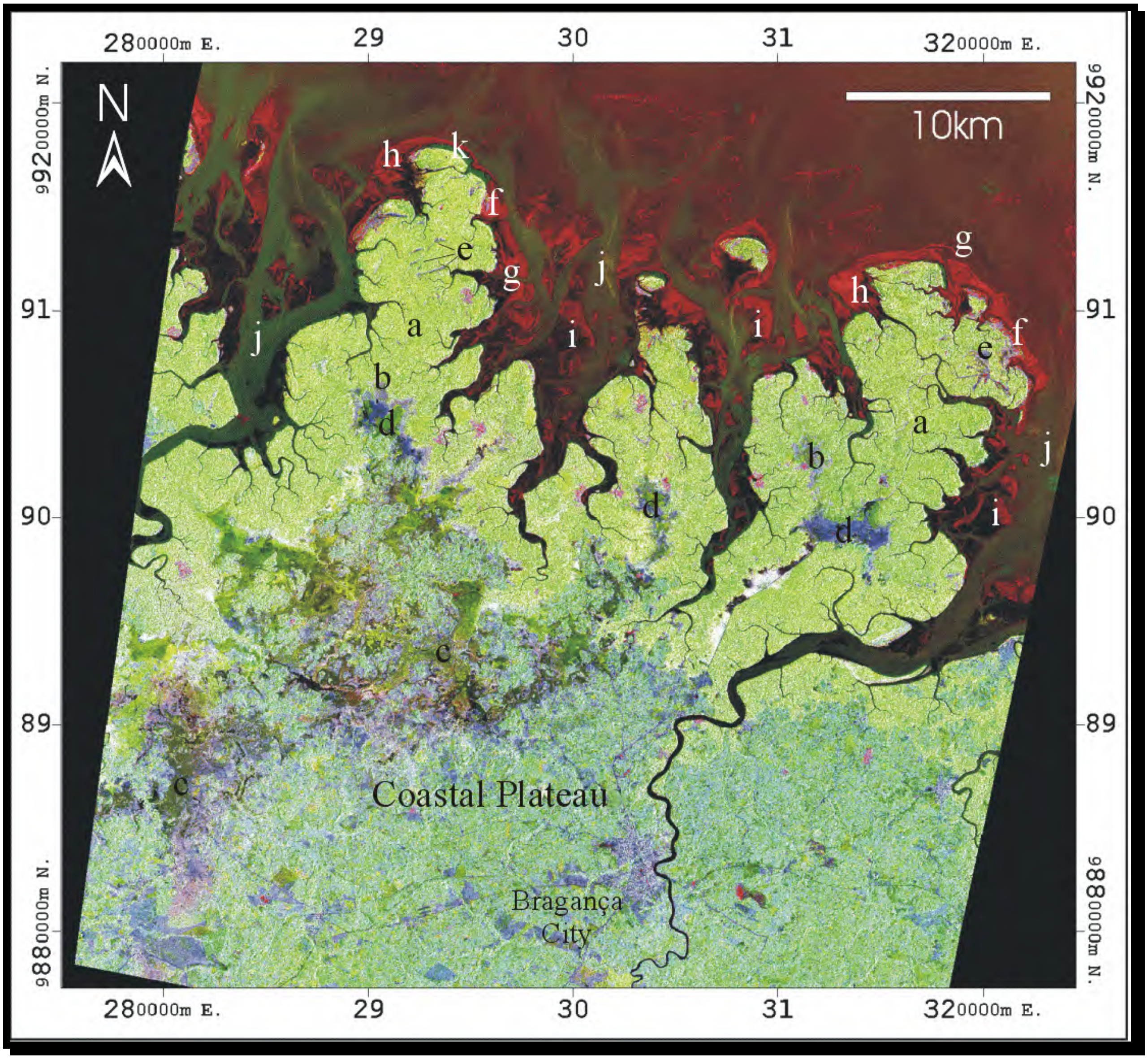

Figure 4- RADARSAT (F1) and Landsat TM (selective principal component) integrated product from the Bragança Coastal Plain. The letters are discussed in the text (a = intertidal mangrove, b = supratidal mangrove, c = inner salt marsh, d = outer salt marsh, e = chenier sand ridge, f = barrier-dune beach ridge, g = ebb-tidal delta, h = tidal sandflat, i = submerse sandy bank, j = tidal estuarine channel, k = coastal change).

Finally, the third relevant aspect involving the SAR/TM fusion is related to multi-temporal analysis. When images of different dates are integrated, a multi-temporal attribute is also added to the product, providing information about coastal accretion or retreating. This is a fundamental aspect to be addressed when dealing with coastal dynamic studies (Figure 4k). Thus, the relationships of hue coupled with morphological changes of the terrain on different dates will provide a more accurate geomorphological interpretation than that based solely on the individual SAR or TM scenes.

Based on research results, assessment of the different remote sensing data applied to coastal environments study is summarized in Table 2.

Table 2- Remote sensing product evaluation.

Coastal environments and features	**Image interpretation results**			**Recognizing level**		
	SAR	TM	SARxTM	SAR	TM	SARxTM
Intertidal mangrove	Very rough surface, light tones, covered by mangrove forest	Enhanced by the TM data due to the vegetation cover	Very rough surface with light greenish tones	M	G	G
Supratidal mangrove	Rough surface, gray tones, covered by spaced mangrove forest	Enhanced by the TM data due to the vegetation cover and soil exposed.	Rough surface with green-bluish tones	M	G	G
Inner salt marsh	Slightly rough surface, medium tones, covered by grasses	Recognized on TM as dark tones due to wet exposed sediments	Slightly rough surface with greenish tones	G	G	G
Outer salt marsh	Slightly rough surface, medium tones, covered by grasses	Recognized on TM as light tones due to spectral response of dry sediments and grasses	Rough surface with bluish tones	M	G	G
Water bodies in salt marshes	Smooth surface, dark tones	Recognized on TM as dark tones due to spectral response of clean waters	Smooth surface with dark tones	G	G	G
Chenier sand ridges	Linear features, rough surface, dark tones, covered by arbustive vegetation	Enhanced by the TM data due to white sand exposition	Linear features, rough surface with reddish tones	G	G	G
Barrier dune-beach ridges	Linear features, smooth surface, dark tones	Enhanced by the TM data due to white sand exposition	Linear features, smooth surface with reddish tones	M	G	G
Ebb-tidal deltas	Smooth surface, dark tones	Enhanced by the TM data due to white wet sand exposition	Smooth surface with reddish tones	P	G	G
Tidal sandflats	Smooth surface, dark tones	Enhanced by the TM data due to white wet sand exposition	Smooth surface with reddish tones	P	G	G
Plateaus and coastal plain boundary	----------	----------	----------	M	G	G
Coastal plain and water boundaries	----------	----------	----------	G	M	G
Erosional landforms	----------	----------	----------	G	M	G
Depositional landforms	----------	----------	----------	G	G	G
Coastline forms				G	M	G
	G = good	M = moderate	P = poor			

CONCLUSIONS

(1) This research has demonstrated the importance of using digital image processing for geomorphological mapping of mangrove coast based on orbital SAR and optical remote sensing.

(2) The geometrical correction through ortho-retifications was a fundamental step in the digital processing. It assures that optical and SAR data can be integrated under a more consistent and robust modeling.

(3) The SPC Integrated Product has shown to be a powerful toll for the integration of RADARSAT with Landsat TM with the best performance in the discrimination of classes.

(4) The research has also demonstrated the importance of the usage of orbital remote sensing data in the coastal environment studies, mainly in the wetland areas. The TM sensor has contributed with spectral response to enhance the chemical characteristics of the materials, while SAR data was responsible by enhancement of distinct coastal vegetation height, geometry and water contents. In addition, the digital fusion of SAR with TM also provided a synoptic view of the area which favors planning for field campaigns and the integration of previous disperse information.

(5) The Mangrove Coast along the Northern Brazil is a large area, poorly mapped. The results of this investigation offer a real possibility of using spaceborne optical and SAR data for coastal geomorphological mapping and monitoring purposes. This is first step aiming an environmental protection program of this complex but extremely fragile moist tropics ecosystem.

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CAPÍTULO 4:

APLICAÇÃO DE DADOS DE SENSORIAMENTO REMOTO NO ESTUDO DA GEOMORFOLOGIA COSTEIRA

4.1. SATELLITE IMAGES FOR STUDY OF DYNAMIC OF THE BRAGANÇA MANGROVE COAST, NORTHERN BRAZILIAN AMAZON

ABSTRACT

Diverse coastal macrotidal environments characterize the Bragança mangrove coast in the State of Pará lying on the northern coast of Brazil. In order to understand the geologic evolution of the coastal zone, its coastal landforms, and their seasonal and mid-term dynamics, multidate satellite data from 1972 (airborne SAR GEMS 1000), 1985, 1988, 1990, 1991 (Landsat TM) and 1998 (RADARSAT-1) were used for visual interpretation of the coastal area around Bragança. The satellite images were integrated in a geographic information system for interpretation and evaluation of shoreline changes. The Bragança mangrove coast represents a submerging coast, whose geologic evolution is related to sea level rise since 5,200 years B.P, followed by stillstand conditions responsible for mangrove fringe progradation. Therefore, the geologic coastal evolution of the study area is controlled by relative sea level changes. The mid-term morphological changes from 1972 to 1998 are marked by shoreline recession. The dynamic changes observed along the coastal features are thus mainly controlled by the combined effects of waves, tides and currents operating in the area, coupled with nature, type, composition of the material, orientation of the coast and variation in the tidal channel positions. The short-term evolution has revealed few modifications at local level, well recognized at specific place mainly from 1985 to 1988. These short-term coastal changes are, principally related to anomalous rainfall times, associated to La-Niña events and responsible for severe coastal erosion periods.

Key words: remote sensing, Landsat TM, RADARSAT-1, coastal erosion, El-Niño event.

INTRODUCTION

The landforms along the Bragança macrotidal mangrove coast in Pará State (northern Brazil) are complex and dynamic in nature. The interactive processes that are operating in the evolution of these coastal landforms are mainly controlled by waves, wind, tides and currents coupled with geology and lithology of the area. The coastal processes of erosion, deposition and transport, flooding and relative sea level change continuously modify the shoreline. Thus, the understanding of coastal landform development and their spatial and temporal changes is very important to characterize the coastal evolution.

Orbital remotely sensed data has been extensively used in regional geomorphologic mapping when modern satellite platform was launched in the 1970's. Useful source of satellite optical data for geomorphologic application are images from the Landsat Multispectral Scanner (MSS) and Thematic Mapper (TM), SPOT HRV and other higher resolution sensor. The TM sensor of Landsat 5 allows a variety of use, notably in natural resources survey, land cover and land use, coastal geomorphologic changes and environmental monitoring (Jones 1986; Loughlin 1991; Gowda et al. 1995; Prost 1997; Ramsey III et al. 1998; Ciavola et al. 1999; Yang et al. 1999). During the last 10 years, Synthetic Aperture Radar (SAR) has been used with more frequency, principally in tropical coastal environments (Singhroy, 1995; 1996; Rudant et al., 1996; Prost, 1997; Barbosa et al. 1999; Johannessen, 2000; Kushwaha et al. 2000). Nowadays, the RADARSAT-1 Fine Mode is a useful data for coastal dynamic studies. This SAR emphasizes the importance of using microwave images for coastal zone mapping, and the integration of information got from older and new SAR has an excellent evaluation of the shoreline changes and mapping of areas at risk from coastal erosion.

The principal objectives of this paper are to examine the dynamic of coastal landforms over seasonal and mid-term changes in comparison to the holocenic events and to consider the possible role of direct rainfall related to El Niño-La Niña events in producing coastal erosion.

REGIONAL SETTING

The study area is located in the northeast of the State of Pará, around 1º S and 46º W (Figure 1). A continuous mangrove belt of around 20 km wide fringes the shoreline with elevation from 1 to 2 m above mean tide level (Cohen et al. 2000). A wet season from December to May and a dry season from June to November mark the climate. Trade winds blow from northeast throughout the year, most strongly during the dry season. The average annual rainfall reach 2,500 mm and the mean tidal range measures around 5 m in a semi-diurnal cycle, and during the spring tides is locally as high as 6 m. Thus, during spring tides large areas of the low land are inundated as a result of both high rainfall and runoff rates and tidal inundation (Kjerfve et al. 2000). Strong tidal currents and waves are responsible for erosion of mangroves along the coast, estuaries and bays, where lines of fallen mangroves trees mark the eroded places. On the other hand, new mangrove fringes are prograding seaward in response for muddy sedimentation (Souza Filho and El-Robrini, 1998).

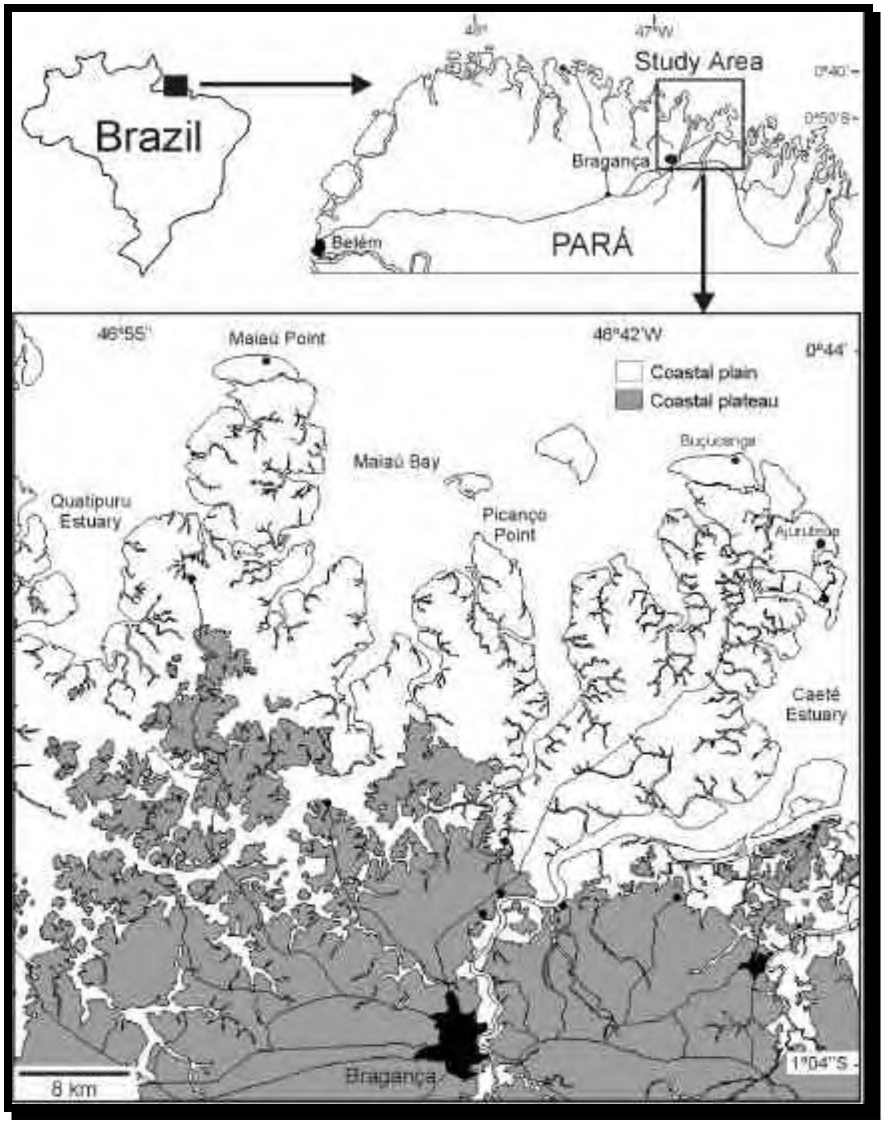

Figure 1- Localization map of the study site.

The detailed knowledge of the coastal environments (mangroves, salt marshes, sandflats, chenier sand ridges, coastal sand dunes, barrier-beach ridges and ebb-tidal delta) and the coastal features (plateaus and coastal plain boundary, depositional and erosional features, coastline form and suspended sediments) is observed in the color composite of the Landsat TM images acquired on August 1985 (Figure 2; Souza Filho and Paradella, submitted). Intertidal mangrove is depicted as reddish hue, with strong infrared spectral response caused by the contribution of the dense mangrove forest in the TM 4 band (Figure 2a). Supratidal mangroves appear as green-reddish colors due to mixed response of muddy sediments and mangrove trees (Figure 2b). Salt marshes are situated in the supratidal zone, with sedimentation marked by mud deposition carried from tidal fluxes along the creeks (Souza Filho and El-Robrini, 1996). They are subdivided in inner and outer salt marshes. TM imagery shows the inner salt marsh in dark tones in TM bands 3, 4 and 5 at the end of the rainy season, in response to the spectral behavior of clean water (Figure 2c). The outer salt marsh marks the transitional zone between the coastal plateaus and the mangrove system, and shows green-reddish colors due to the mixed spectral response of muddy sediments and grasses (Figure 2d).

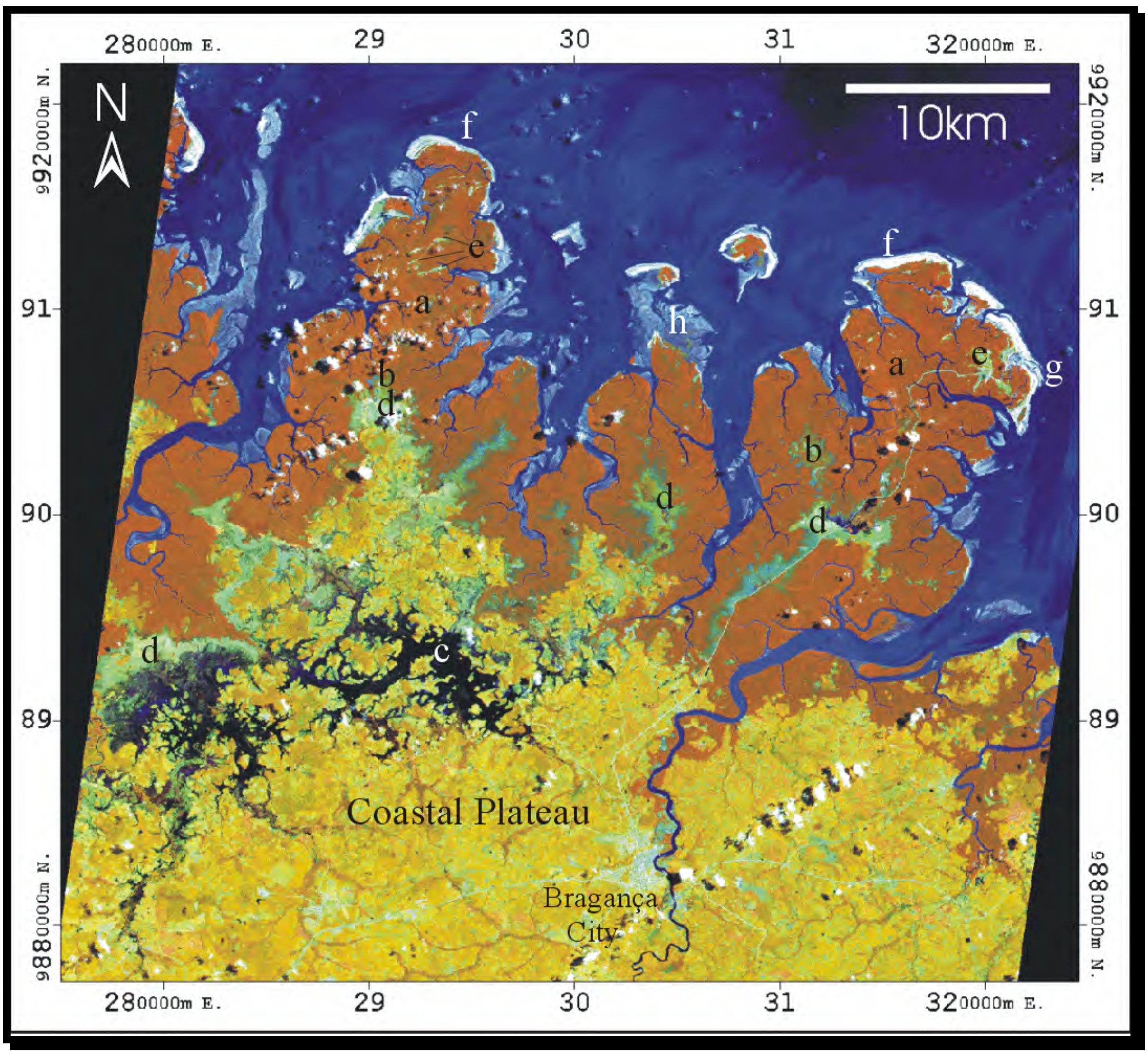

Figure 2- 1985 Landsat TM false color composite (4R5G3B) showing landforms of the Bragança macrotidal coast. The letters are discussed in the text (a = intertidal mangrove, b = supratidal mangrove, c = inner salt marsh, d = outer salt marsh, e = chenier sand ridge, f = barrier-dune beach ridge, g = ebb-tidal delta, h = tidal sandflat, i = submerse sandy bank, j = tidal estuarine channel, k = coastal change).

The chenier sand ridges constitute old dune-beach ridges with associated washover fans. They present light-bluish colors in response to the spectral reflectance of wet white fine sand covered by sparse vegetation in TM 3 and 4 (Figure 2e). The cheniers have a very well characterized geometry given by linear and curved forms with boundaries marked by prograding tidal mudflats. The chenier's appearances are typical in the images. They are discernible from recent beaches by form and spatial distributions rather than by color attributes.

Barrier-dune-beach ridges (Figure 2f), ebb-tidal deltas (Figure 2g) and tidal sandflats (Figure 2h) are associated with white colors due to the high spectral response in all three TM bands caused by the presence of dry fine white sandy deposits in dunes and intertidal beaches. Coastal features, such as coastal plateaus and coastal plain boundary are very well discernible in the images due to the spectral response of the targets. The suspended sediments and tidal currents responsible for sediment dispersion are much more recognizable in Landsat TM band 3 (Figure 3). Note the high turbidity near the coast and tidal current line orientated along north-south direction defining a singular turbidity distribution pattern.

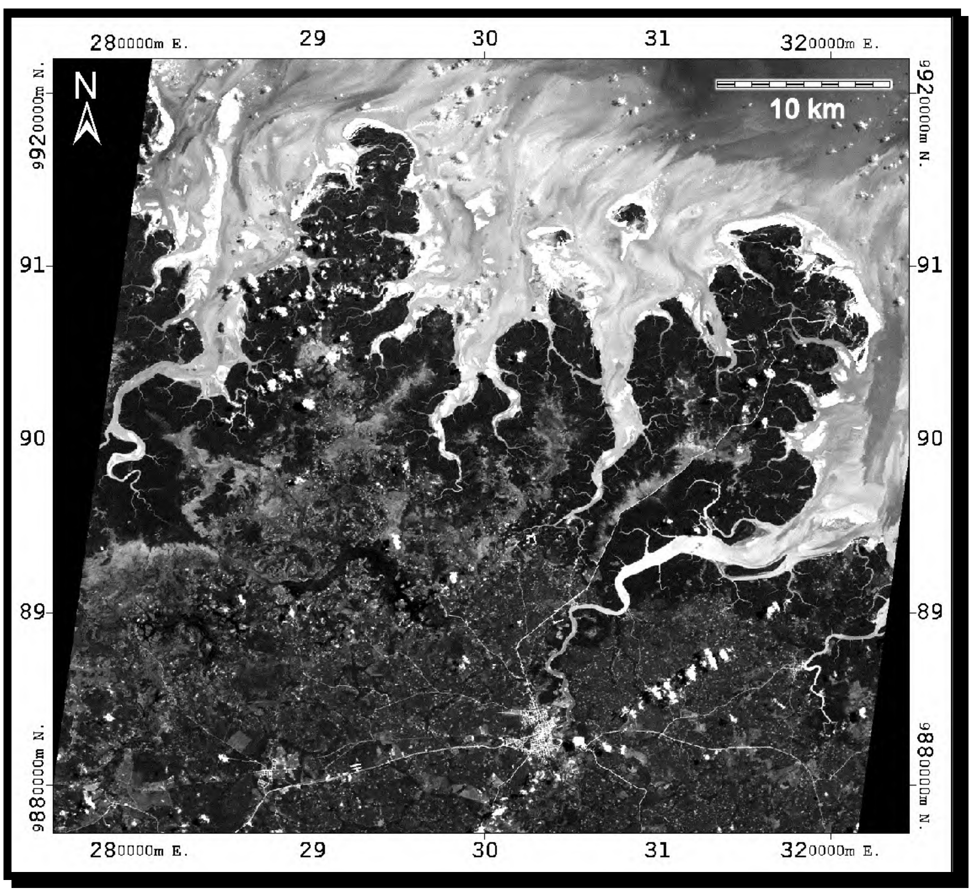

Figure 3- 1985 Landsat TM band 3 showing turbidity distribution patterns and tidal current lines.

DATA SET AND METHODS

Historical investigation of the shoreline positions was based on remote sensing data represented by GEMS 1000 acquired in 1972, Landsat TM (path 222, row 61) acquired in 1985, 1988, 1990, 1991 and 1995 and C-HH band RADARSAT-1 Fine Mode 1, (descending orbit) acquired in 1998. Table 1 provides details of the remotely sensed data used in this research.

Table 1. Characteristics of the remotely sensed data.

Platform	**Sensor**	**Acquisition Date**	**Angle of Incidence**	**Spatial Resolution (m)**	**Pixel Size (m)**	**Image Format**
Aircraft	GEMS 1000	1972	13-36º	16x16	16	Analogic
Landsat-5	TM Bands 1,2,3,4,5,7	August 24, 1985	_____	30 x 30	30 x 30	8-bits
Landsat-5	TM Bands 1,2,3,4,5,7	October 03, 1988	_____	30 x 30	30 x 30	8-bits
Landsat-5	TM Bands 1,2,3,4,5,7	July 05, 1990	_____	30 x 30	30 x 30	8-bits
Landsat-5	TM Bands 1,2,3,4,5,7	December 31, 1991	_____	30 x 30	30 x 30	8-bits
Landsat-5	TM Bands 3,4,5	June 08, 1995	_____	30 x 30	30 x 30	8-bits
RADARSAT-1	Fine Beam Mode 1	September 08, 1998	37-40º	9,1 x 8,4	6,25	16-bits Path Image

The digital image analysis was carried out based on EASI-PACE package (PCI, 1999). The TM data were radiometric and geometric corrected. Radiometric correction was related to the attenuation of atmospheric effects based on the minimum histogram pixel (Chavez, 1988). A rigorous geometric correction based on an ortho-rectification scheme was applied to the TM bands in order to assure correction for terrain distortions (Toutin, 1995). The initial processing steps for the RADARSAT data included the scaling of the image from 16 to 8 bits. Afterward, a 3 x 3 adaptive enhanced-Frost filter window was applied to reduce speckle effects (Lopes et al., 1990) during the ortho-rectification process. Based on the statistics of the ortho-rectification for the TM and the SAR data, the RMS accuracy was around 1 pixel size. Hence, the minimum detectable change works out to be 60 m for TM data and 18 m for SAR data.

The mid-term shoreline change was examined from airborne SAR data that was initially scanned and digitally rectified to common UTM coordinates (RMS accuracy was around one pixel size through first order polynomial method). In order to extract the shoreline position in 1972, the airborne SAR image was classified in two classes: emerging coastal areas and coastal water. Afterwards, the raster data was converted to vector and superimposed to the RADARSAT-1 scene. Finally, the extracted information was compared to the airborne SAR information and an estimate of coastline changes was possible.

The short-term shoreline change was analyzed from digital image enhancement of Landsat TM and superimposition of different dates in the same scene. The shoreline positions were gathered in an ArcView GIS (ESRI, 1996).

The shoreline position used to monitor historical changes is represented here by spring high tide level (SHTL), which has been demonstrated to be the best indicator of the land-water interface for historical shoreline comparison study (Dolan et al., 1980; Crowell et al., 1991). The SHTL delineates the landward extent of the last high tide, hence it is easily recognizable in the field and it can usually be approximated from remote sensed data.

GEOLOGIC SHORELINE CHANGES

The large-scale geomorphological evolution of northeastern Pará State is controlled by the tectonic setting of the passive margin developed since the Early Cretaceous during the opening of the Equatorial Atlantic Ocean. Bragança mangrove coast has its evolution related to the Bragança-Viseu coastal basin that is controlled by normal faults that reach the present coastal zone. The structural framework of this coastal basin is responsible for a submerging coastal zone development, showing a wide mangrove ecosystem due to mudflat progradation (Souza Filho, 2000). According Bird (1993), submerging coast is presently confined and has been subsiding along the geologic history.

Souza Filho & El-Robrini (1997) suggest that holocenic evolution in the Northern Brazil begun when the sea level reach the present position around 5, 100 years B.P (Simões, 1981), which represent the maximum of the Holocenic Transgression. During this event, the sea level rose and eroded the Tertiary deposits developing active cliffs along the shoreline. The transgressive sand sheet migrated landward forming sand tidal shoal, estuarine mouth bars, beaches and dune-beach ridges. This environment constitute a retrogradational succession that is found 3-5 meters depth, where the sand stratigraphic facies were developed under shallow water conditions, influenced by tidal current and waves, while the salt marsh mud facies filled the estuarine channels.

Under stillstand sea level conditions since 5,100 years B.P occur a muddy progradation of the coastline in direction to seaward marking the beginning of mangrove development at 2,100 years B.P (Behling et al, 1999). The contact between the transgressive sand sheet and the mud mangrove deposits is flat and very well defined, as result of subaerial progradation (Souza Filho and El-Robrini, 1998). During this progradation occurred erosional phase responsible by reworking of coastal sediments and deposition of dune-beach ridge with washover fans associated that will evolve to Chenier deposits. Therefore, these sediments deposited during the stillstand conditions represent the progradational succession. The boundary between the transgressive sand sheet and the muddy progradation deposits is plane and define a downlap surface that represents a maximum flooding surface (MFS). Therefore, this surface characterizes a progradation responsible for coastline accretion.

The last sedimentary event is marked by a new transgressive condition, where the transgressive sand sheets (sand tidal shoal and beach-dune ridges) migrates over muddy mangrove deposits and erodes the coastline. Souza Filho (1995) and Silva (1996) characterized this transgressive event in the coast of Pará State and by Tomazelli et al (1998) in the coast of the State of Rio Grande do Sul.

HISTORICAL SHORELINE CHANGES

Mid-term morphological changes

The mid-term changes in shoreline position were measured between 1972 and 1998 using SAR data from airborne GEMS and spaceborne RADARSAT-1, respectively. The impact of the natural dynamics in the Bragança Coastal Plain has made fast and dramatic changes in the shoreline position during the last three decades. A comparison between 1972 and 1998 in the shoreline position has shown that shoreline has been subjected to severe erosion and accretion, and some sector remains unchanged in any specific coastal site. In the oceanic setting, the mid-term shoreline recession reaches maximum distance of 1,500 m and 1,250 m ± 28 m in Maiaú Point and Buçucanga Beach (Figure 4), with average recession rate for these sites were 57.7 m/yr. and 48 m/yr. for the 26-year period, respectively. These erosional settings represent the most seaward boundary of the coastal plain, which receive little or no muddy sediment. The main sedimentary process responsible for shoreline retreat is related to sandflats migration landward over the mangrove deposits due to tidal currents and large waves action. Mangrove vegetation has been killed by rapid sand deposition over it and mangrove terrace has been eroded. Hence, great parts of the shoreline, principally beaches, are characterized as transgressive deposits (Souza Filho, 1995).

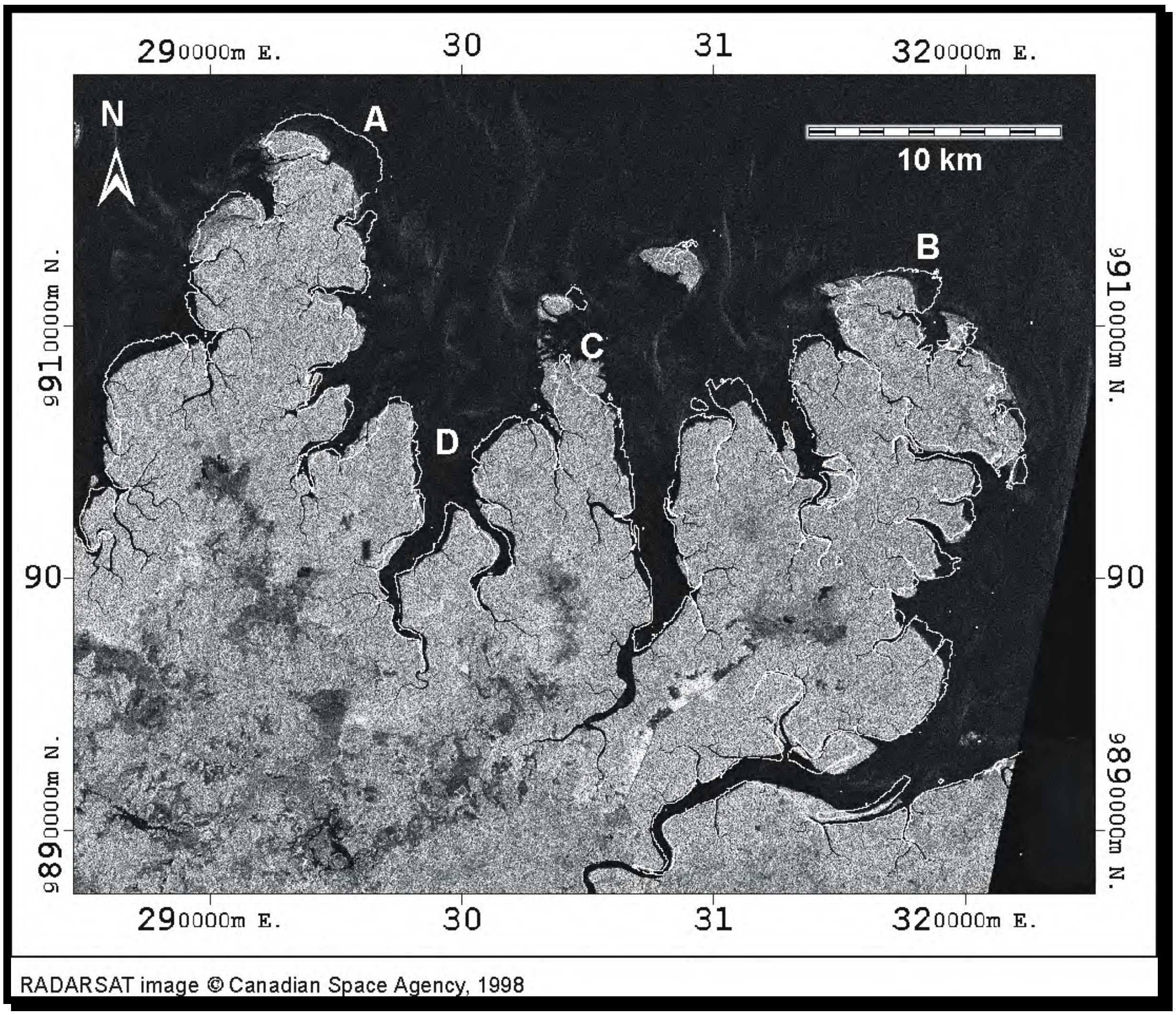

Figure 4- Lon-term morphological changes observed through 1972 shoreline vector superimposed to 1998 RADARSAT-1 image. A) Maiaú Point; B) Buçucanga Beach; C) Maciel Point; and D) Atalaia Estuary.

The shoreline recession sectors are very well observed in the Maciel Point, where shoreline position migrated 1,250 m seaward (Figure 4). This is about 48 m/year of coastal progradation. In this area, the continuous sediment supply, geomorphological positions and protection of wave attack favor the accretion of sandbanks, muddy deposition and mangrove vegetation establishment. Therefore, mangrove trap sediments to build a depositional mud terrace in the upper intertidal flat and successive zones of pioneer vegetation (*spartina sp*.) and other mangrove species migrate seaward. Migration of islands is observed along the Maiaú Bay in response to oceanographic and sedimentary processes. For example, the Maciel Island migrated almost 1 km from 1972 to 1998, with average migration rate of 38.5 m/year (Figure 4).

Other coastal setting is related to estuarine processes, where tidal currents and tidal channel position have controlled the coastal evolution. Based on integrated remote sensed data, SAR and TM composite (Souza Filho and Paradella, submitted), is possible to conclude that erosional sectors are strongly controlled by estuarine and tidal channel position and ebb-tidal delta evolution. Where tidal channels run near the shoreline boundary are observed the specific places subject to severe coastal erosion, such as the Maiaú, Picanço and Buçucanga Point. On the other hand, where sandbanks are situated along the coast and the tidal channels do not reach the land-water boundary, favorable areas are formed for shoreline accretion, such as the Maciel Point.

Short (seasonal) morphological changes

The study of short-term changes through Landsat TM data of August 1985 vs. October 1988, October 1988 vs. July 1990 and July 1990 vs. December 1991 has showed no major changes only few modifications at specific places. Hence, four sites were selected for detailed analysis of short-term coastal changes based on places submitted to greater mid-term changes (Figure 4). The two most prominent points (Maiaú and Buçucanga) are being eroded. In Maiaú Point, the principal coastal process is related to erosion, responsible for shoreline retreat of approximately 300 ± 48 m from 1985 to 1988, 75 ± 46 m from 1988 to 1990 and 130 ± 47 m from 1990 to 1991 (Figure 5). In this place, tidal currents along the coast and wave attack mainly control the coastal erosion. In the Buçucanga Beach, the coastal erosion is associated to ebb-tidal delta migration that is responsible for sandbanks migration over mangrove deposits. Moreover, ebb and tidal currents coupled with waves of northeastward favor the shoreline retreat that reaches values of 530 ± 48 m from 1985 to 1988, less than 60 m from 1988 to 1990 and 260 ± 47 m from 1990 to 1991 (Figure 6).

Protected areas such as Maciel Point and Atalaia Estuary were analyzed. The Maciel Point represents one of the few sites dominated by depositional processes related to stabilization of sandbanks and posteriori colonization by mangroves and muddy deposition (Figure 7). The geographical position of this site besides the estuarine island and behind two estuaries allowed the development and emerging of sandbank protected of wave attack and tidal current erosion (Figure 3). The Atalaia Estuary is marked by little erosion along its margins (Figure 8). The tidal channels and submerse sandy banks has been subjected to severe coastal changes, however due to macrotidal conditions is difficult to quantify the real geomorphic changes.

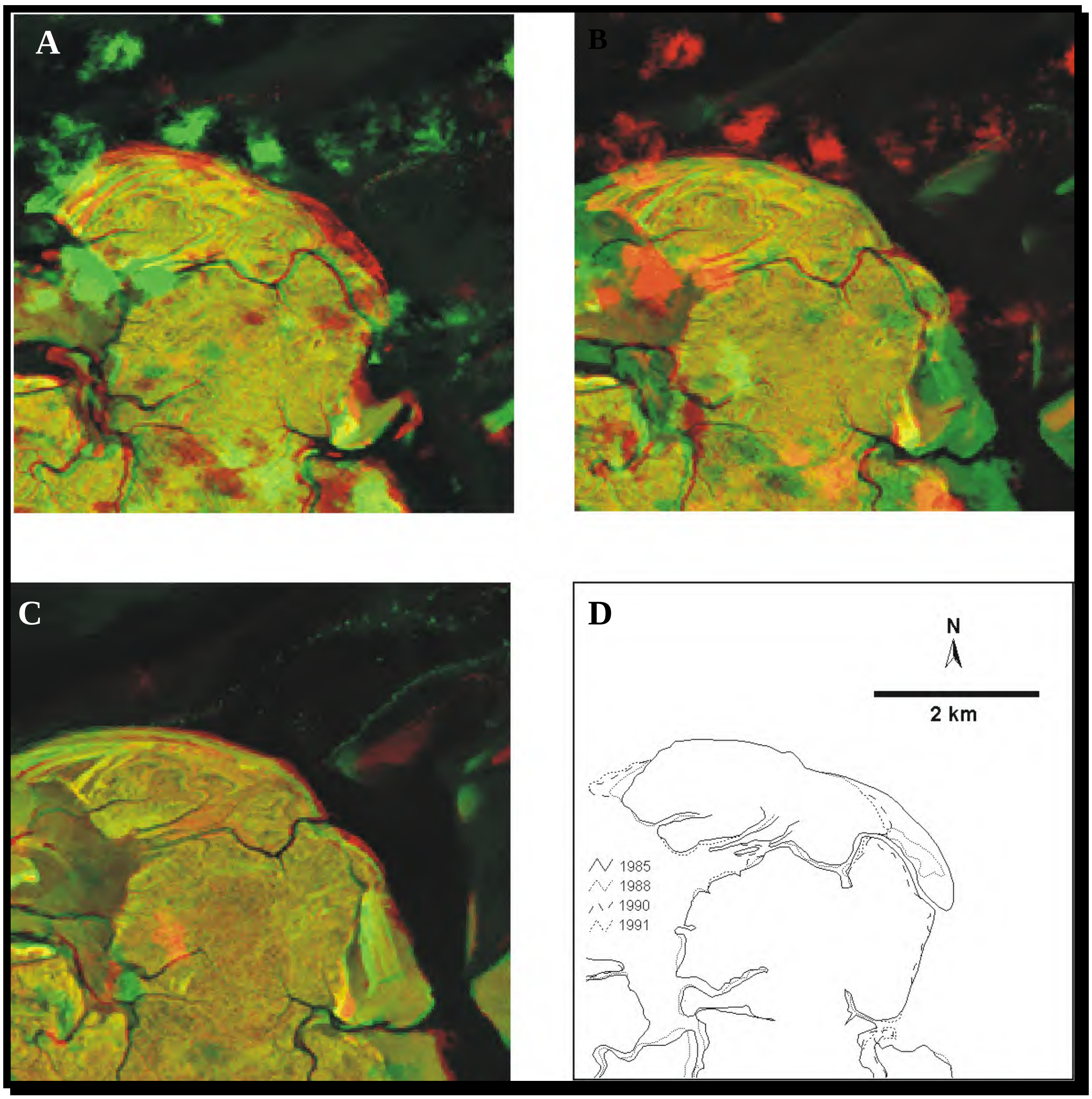

Figure 5- Short-term morphological changes in positions of shoreline in the Maiaú Point. A) 1985-1988; B) 1988-1990; C) 1990-1991; and D) map showing the shoreline changes from 1985 to 1991.

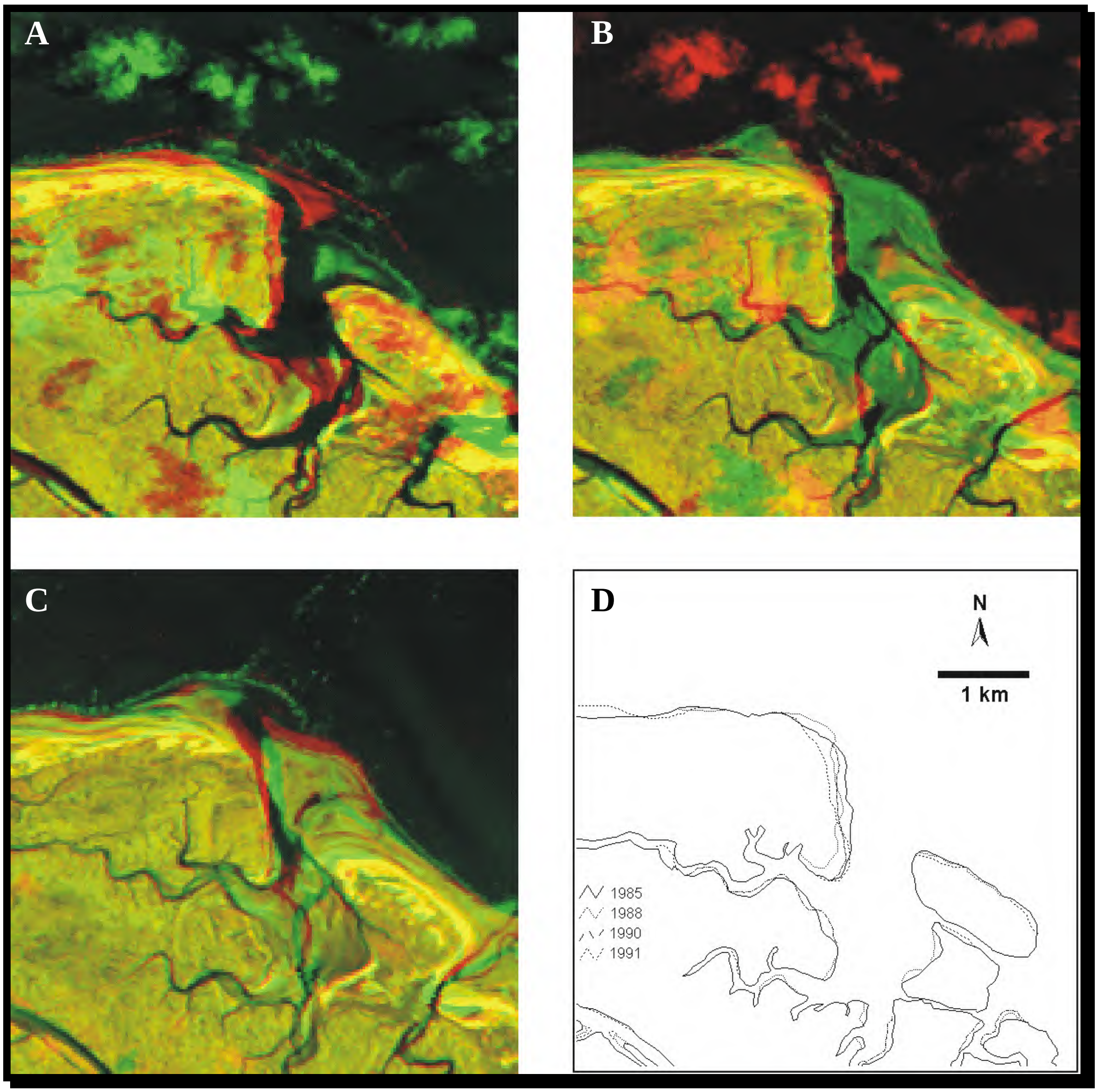

Figure 6- Short-term morphological changes in positions of shoreline in the Buçucanga Beach. A) 1985-1988; B) 1988-1990; C) 1990-1991; and D) map showing the shoreline changes from 1985 to 1991.

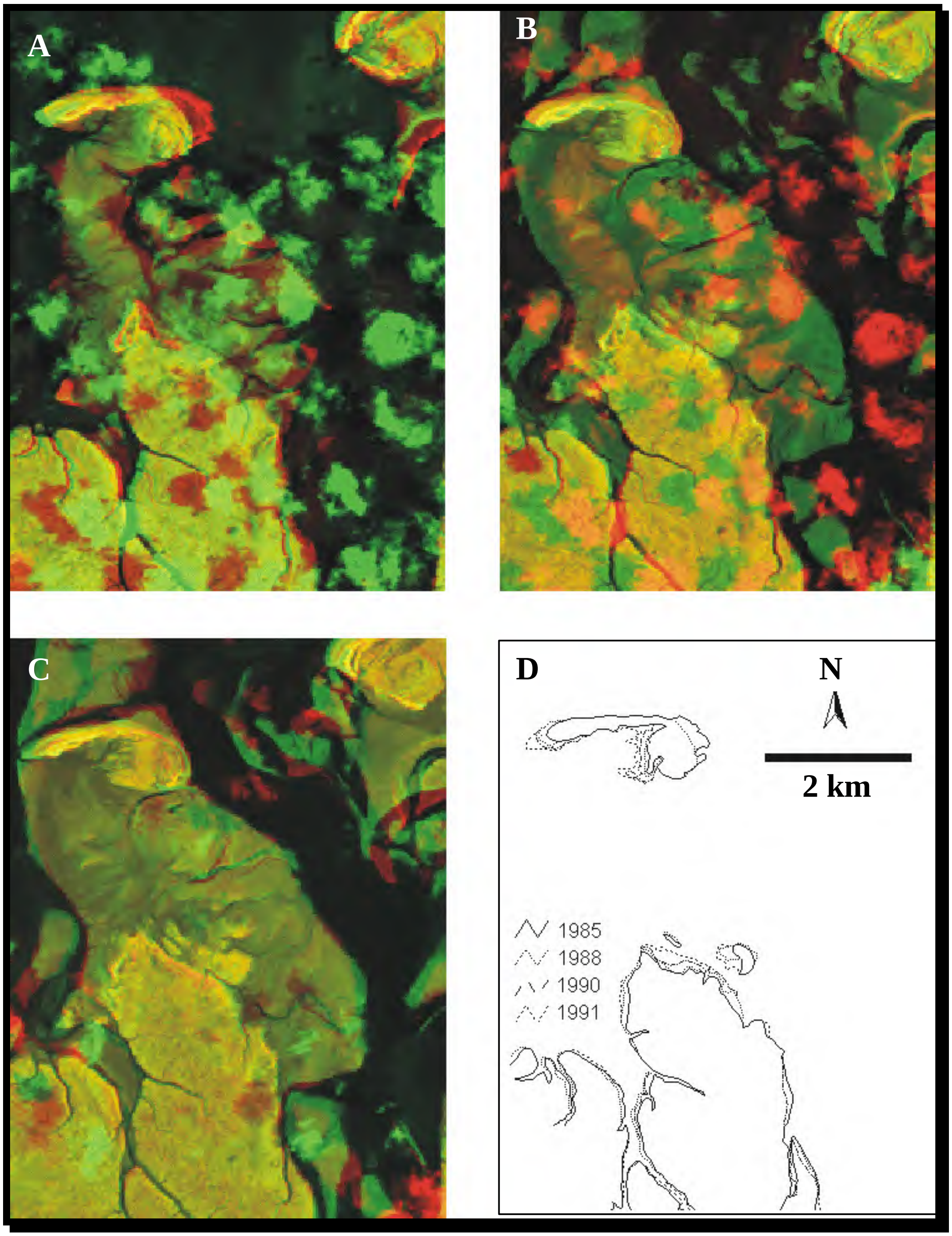

Figure 7- Short-term morphological changes in positions of shoreline in the Maciel Point. a) 1985-1988; b) 1988-1990; c) 1990-1991; and d) map showing the shoreline changes from 1985 to 1991.

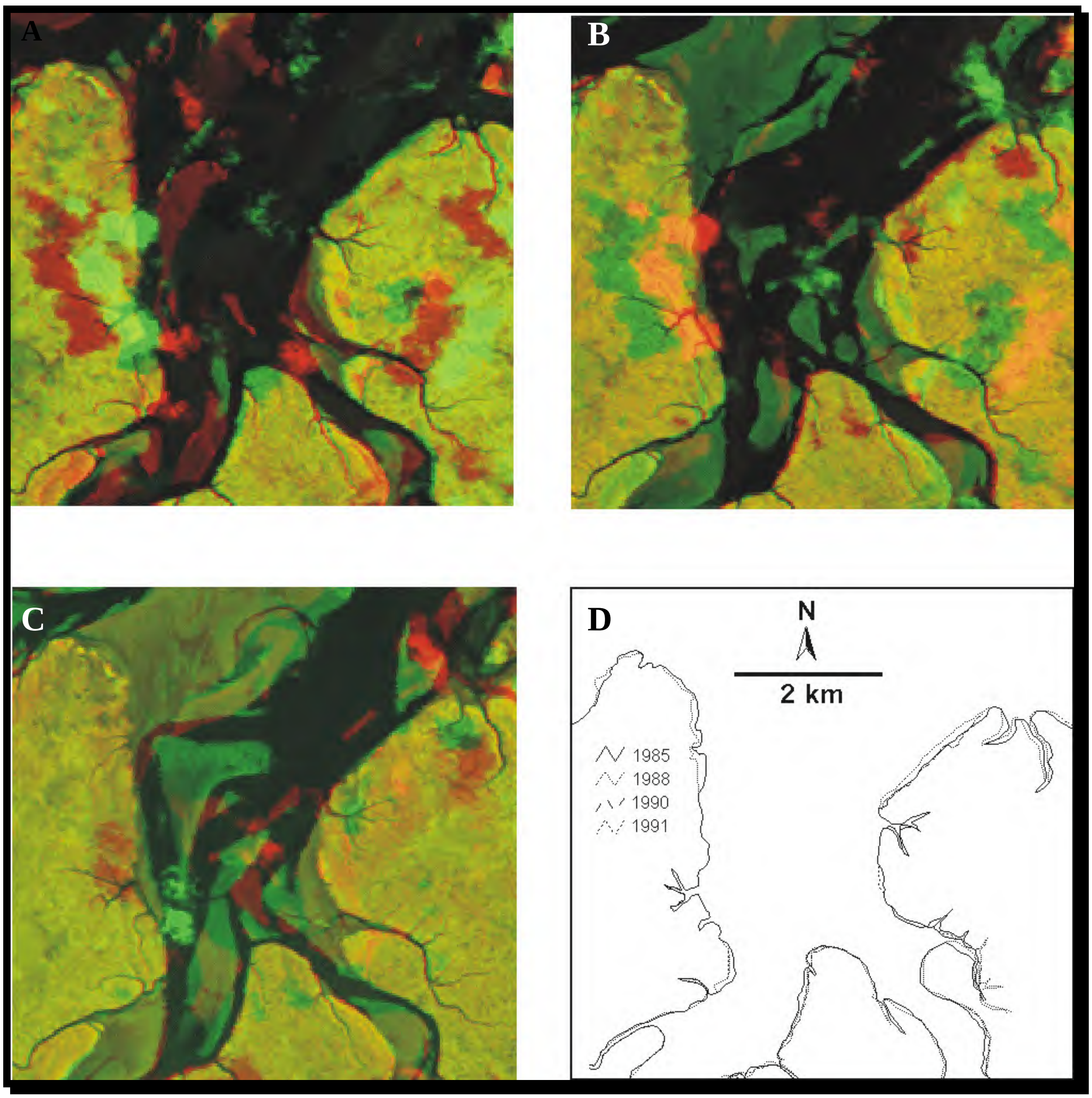

Figure 8- Short-term morphological changes in positions of shoreline in the Atalaia Estuary. A) 1985-1988; B) 1988-1990; C) 1990-1991; and D) map showing the shoreline changes from 1985 to 1991.

The short-term coastal changes observed along the study area are well marked from 1985 to 1988. All sites examined during this period revealed the major shoreline changes. The analysis of meteorological data has shown that there were abnormalities in precipitation during this period. Only in 1985, the annual precipitation totaled 4,069 mm after voluminous rainfall compared to the annual average of approximately 2,500 mm (Figure 9). In March the precipitation amounted 761 mm and during the wet season (January to June) rainfall reached 3386 mm with average of 564 mm/month, which is much greater than month average (Figure 10). 1986 and 1988 were also characterized by heavy rainfall (Figure 8) with annual precipitation of 3423 and 2878 mm, respectively. During the wet season, the month average remained above the mean (Figure 10).

The period between 1988-1990 is characterized by stabilization in the shoreline position. During this same time, the precipitation in marked by index under the annual average (2,331 and 1,848 mm, respectively; Figure 9). The month average remained under the mean along the almost all month (Figure 10). From 1990 to 1991 small shoreline changes are observed in combination to increase in the precipitation that reached 3,487 mm in 1991.

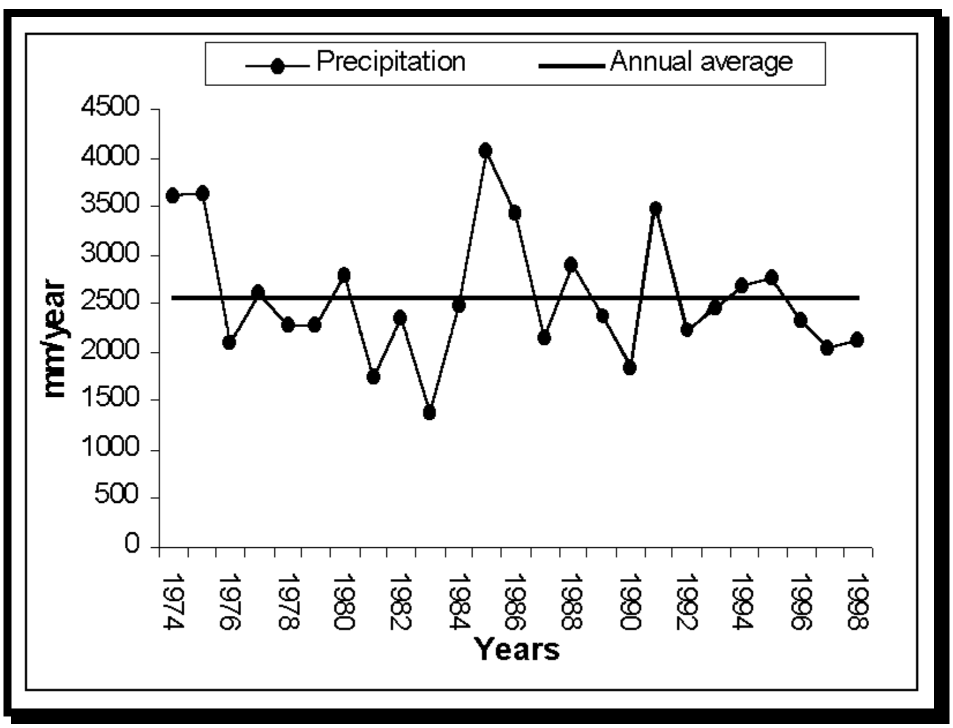

Figure 9- Annual precipitation in the Traquateua hydro-meteorological station from 1974 to 1998. Note the years with precipitation higher than annual average.

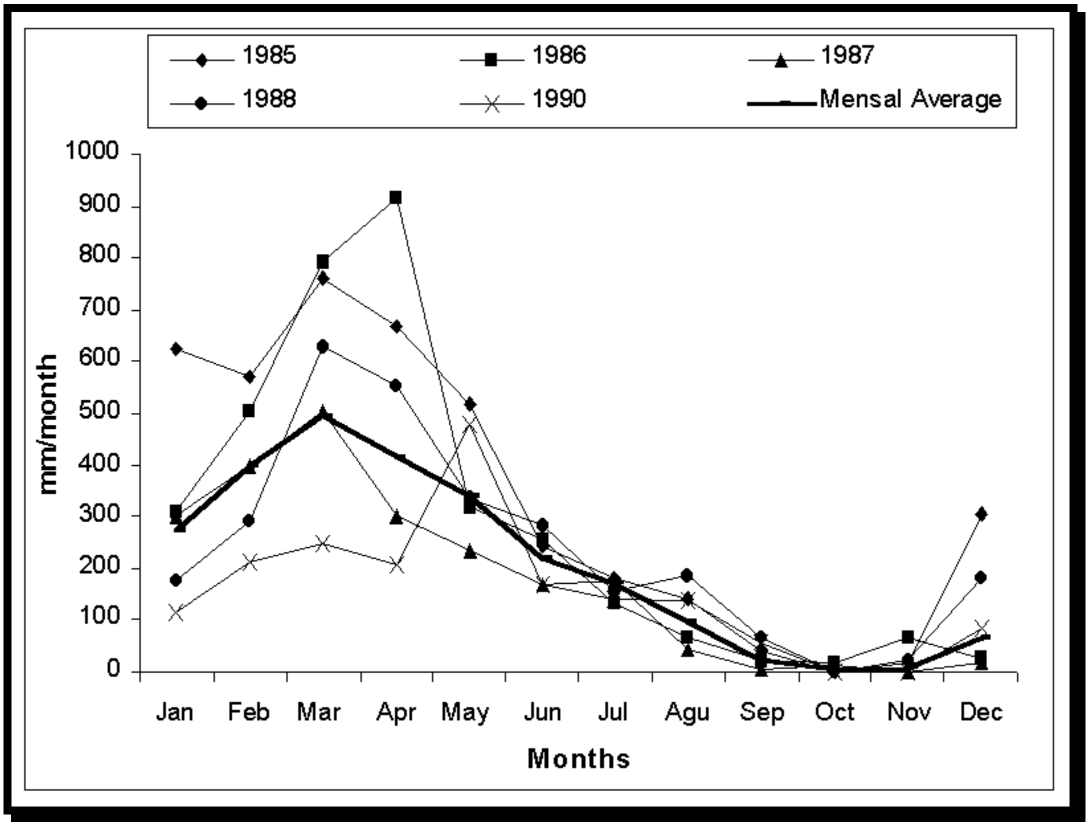

Figure 10- Month precipitation in the Traquateua hydro-meteorological station during the period of short-term shoreline analysis.

DISCUSSION

The Bragança mangrove coast geologic evolution was initiated during the Holocene transgression at 5,200 years B.P, when rise in sea level partly eroded and drowned the coastal plateaus. During this event, extensive transgressive sandy sheets and barrier-beach ridges were formed. From 2,100 years B.P (Behling et al, 1999), a wide mangrove coast was developed under drop in sea level favoured by seaward progradation of the coastline. The stillstand sea level also exposed estuaries, which were replaced by brackish water wetlands, such as salt marshes. Presently, a new transgressive condition is observed along the coastal zone. Stratigraphic records show transgressive sandy sheets migrating over muddy mangrove deposits and producing a coastline retreat.

In view of Holocene history, the general tendency that would be expected in the study coast would be the mangrove shore progradation. However, the mid-term morphological changes from 1972 to 1998 are marked by shoreline recession, which represents the dominant morphological change along the coast with showed recession rates of until 57.7 m/yr. The dynamic changes observed along the coastal features are thus mainly controlled by the combined effects of waves, tides and currents operating in the area, coupled with nature, type, composition of the material and orientation of the coast. Also variation in tidal channel positions has contributed to changes in coastal landforms

The short-term evolution has revealed small modification at local level. This few morphological changes are related to shoreline recession, well recognized at specific place mainly from 1985 to 1988 during a La-Niña event. This period is marked by high precipitation that probably resulted in flooding, high river discharge, severe tidal currents, high tidal range and high wave energy. Hence, theses coastal processes must have been responsible for shoreline retreat during this short-term scale. Ulbricht and Heckendorff (1998) also characterized this climatic event in the coast of João Pessoa (northeastern Brazil). This fact suggest that flooding phenomena from 1985 to 1988 had a regional scale producing short-term shoreline retreat along the northern and northeastern Brazilian coast.

CONCLUSION

This investigation has revealed that this mangrove-fringed coast is very sensitive and susceptible to changes as a result of natural dynamic processes. The Bragança mangrove coast represents a submerging coast, whose geologic evolution is related to sea level rise since 5,200 years B.P, followed by stillstand conditions responsible for mangrove fringe progradation. However, the mid-term and short-term landscape development is marked by shoreline retreat, probably related to climate changes. Therefore, climatic changes associated with El-Niño and La-Niña events that controlled the annual precipitation, must be one of important factors in producing coastal erosion from 1985 to 1988 in the Bragança Coastal Plain.

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4.2. MANGROVES AS GEOLOGICAL INDICATOR OF COASTAL CHANGES IN BRAGANÇA, PARÁ, NORTHERN BRAZIL

ABSTRACT

Mangrove ecosystems show close links between geomorphology and vegetation assemblage. In addition, the vegetation can change through time as landforms accrete or erode what is a direct response to coastal sedimentary processes. This demonstrates that significant changes can occur on short time scales and mangroves provide very well register of these modifications. Therefore, mangrove morphology and sediments are good indicators of interactions between relative sea level, coastal processes and sediment supply. These interactions are responsible for landward migration of the shoreline (transgression) and seaward migration of the shoreline (regression) that is possible to detect from field observation and geomorphologic mapping. Mangroves are one of the best geoindicators in global change research and they are an excellent procedure to detect and quantify coastal modifications.

Keywords: Mangroves - geoindicators - coastal changes - remote sensing - Northern Brazil

INTRODUCTION

Mangroves are the most prominent tropical ecosystem in the Northern Brazilian coast where geomorphologic, sedimentary and oceanographic processes have controlled the landscape evolution. Natural processes and human activities have extensively modified mangrove communities, and economic and social impacts have increased along the last two decades. Therefore, natural and anthropogenic impacts on mangroves ecosystem have contributed to the rapid coastal changes.

In recent years, there has been much discussion about the natural (physical, chemical and biological) environment to know what is its integrity state? What is the pressure both natural and anthropogenic that it is undergone? What is the significance of the changes? And how are we responding to the changes - what are we doing about them? (Berger 1996). Based on geoindicators' approach, the aim of this paper is to establish mangrove as environmental indicator able to detect and quantify the short-term changes in Bragança coastal plain.

ENVIRONMENTAL SETTING

Mangrove shorelines occur in a number of different environmental settings that comprise geophysical (climate, tides and sea level) and geomorphological (dynamic history of the land surface and contemporary processes and biological components, Woodroffe 1992).

The Bragança coastal plain presents a hot and humid equatorial climate, with a dry and wet well-defined seasons and an annual average precipitation of 3,000 mm. The study area is a tide-dominated setting characterized by a semidiurnal macrotidal regime (6 m high tidal range). There is an extensive (more than 20 km wide) and low gradient intertidal zone available for mangrove colonization that forms a fringe wetland vegetation zone between coastal plateaus and sea (Figure 1). Mangrove vegetation is composed of forest with trees reaching up to 30 m high and brackish or marine waters as a result of tidal action that regularly overflow them. Strong bi-directional tidal currents characterize the Caeté Estuary, which presents funnel-shaped mouth, straight, and meandering segments and up-stream tidal channel (Souza Filho and El-Robrini, 1996).

DATA SETS AND METHODOLOGY

The investigation was based on spaceborne SAR, TM Landsat and aerial photograph data. Table 1 provides details of the remotely sensed data. The methodology applied to assess the geomorphologic changes was based on multidate satellite data. An ortho-rectification process was necessary in order to correct terrain distortion and compare different images (Toutin 1995). This geometric correction was based on cubic convolution and UTM geo-referencing. The images were digitally enhanced through different imaging processing. The mangrove ecosystems were mapped through SAR Radarsat (1998) and TM Landsat 5 (1985) imageries and scanned aerial photographs (1975), auxiliary data and field observations. Fieldwork was carried out to detect the sedimentary processes responsible for coastal changes and geomorphologic modifications observed in the imageries.

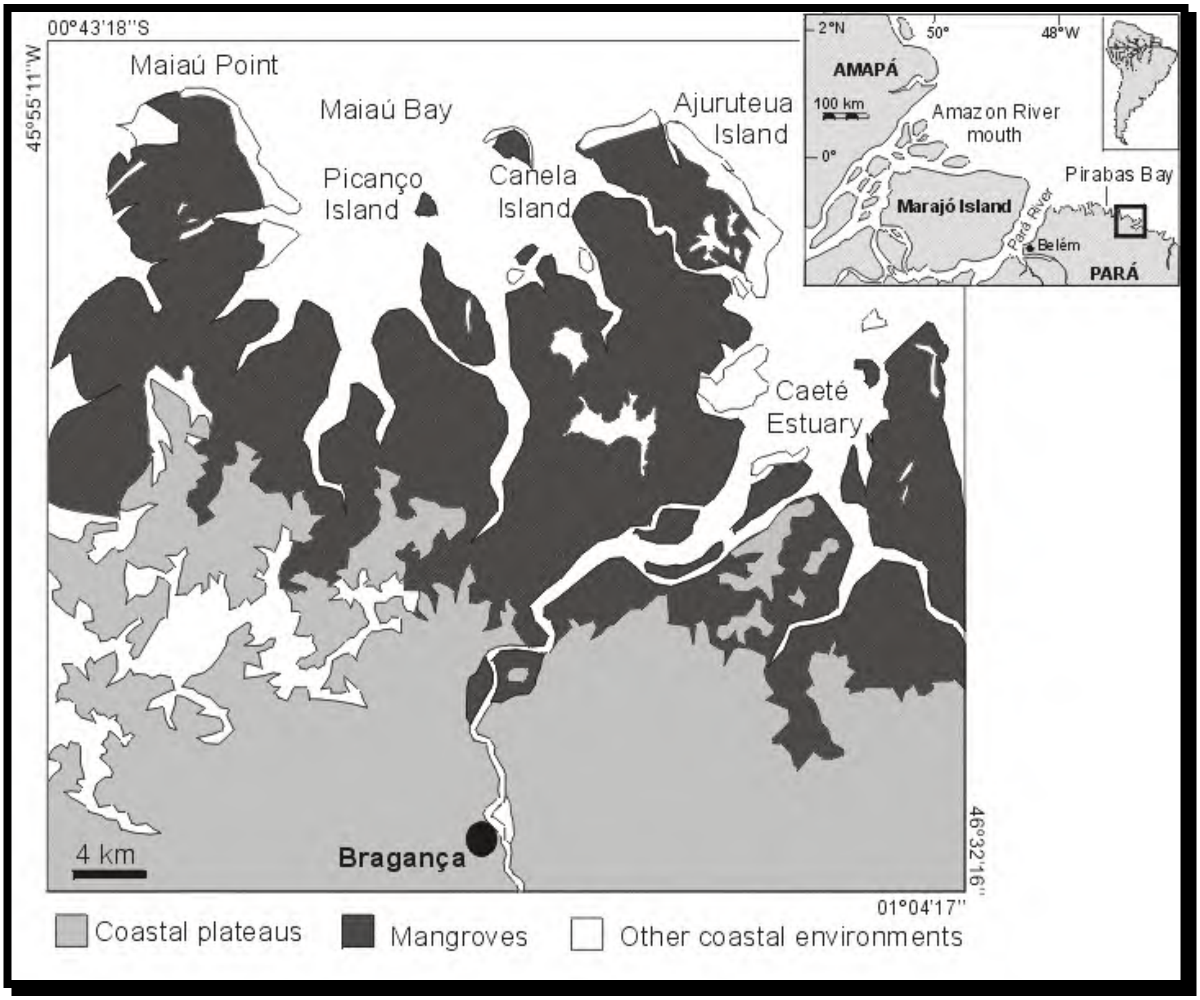

Figure 1- Location map of the study area and mangroves distribution in the Bragança coastal plain.

Table 1- Characteristics of remotely sensed data.

Platform/ Sensor	Acquisition date	Tide condition	Incidence angle	Spatial resolution
Radarsat F1	September 08, 1998	High tide	37-40º	9.1 x 8.4 m
Landsat TM	August 24, 1985	Low tide	----	30x30 m
Aerial photos	1975	High tide	----	2.5 x 2.5 m

MANGROVES AS GEOLOGICAL INDICATOR

Geoindicators are measures of surface or near-surface geological processes and phenomena that significantly over periods of less one century and that provide information that is meaningful for environmental assessment (Berger 1996). They measure (mainly abiotics) variations including those related to climate changes, shoreline positions and geomorphologic and sea level changes. Geoindicators measure both catastrophic and gradual events related to natural and anthropogenic activity.

Coastal sedimentary landforms can be used as geomorphological indicators of the environments and processes that shape the coastal zone. Coastal zones are very sensitive to environmental change, but multiple linkages, feedback mechanisms, nonlinearly and possible chaotic effects combine to produce uncertainty in the meaning of these indicators (Forbes and Liverman, 1996). There is a wide selection of potential geoindicators in the coastal zone, but in the Bragança coastal plain, mangroves cover approximately 471 km^2, almost 76.5 % of the coastal study area (Souza Filho and El-Robrini1998). And besides, mangrove ecosystem is very sensitive to shoreline position and rate of change, erosional and depositional processes, climate and sea level change.

Assessing of mangrove shoreline position

Indicator of shoreline position is derived from remotely sensed imageries that were used to detect the shoreline changes between 1975 and 1998. Water line positions depend on water level at the time of observations, what is very difficult to establish in satellite imageries in macrotidal environments. Therefore, mangrove boundary was used as reference line to detect the shoreline changes.

The overview of the shoreline position shows stability, but in the restricted sectors as tidal channels and estuaries mouths, the coastal erosion is very strong. Shoreline recession, of almost 600 m, is observed in the Maiaú point in response to rapid and strong sedimentary dynamic in macrotidal coast setting (Figure 2). On the other hand, in protected barrier-beach ridge areas, it is possible to observe wide and shallow tidal shoals where mangroves spread directly out to accreting tidal mudflats (Figure 3). These progradational processes are responsible for the formation of mangrove fringes and island over the tidal sand shoals. A good example of this it is the island formed in the Rombada Creek between 1975 and 1985 in response to sandy tidal shoal accretion (arrow in Figure 3). Afterward, sandbanks are colonized by pioneer vegetation (*spartina sp*.) that increases the rate of mud sedimentation allowing the vegetated estuarine mouth bar formation.

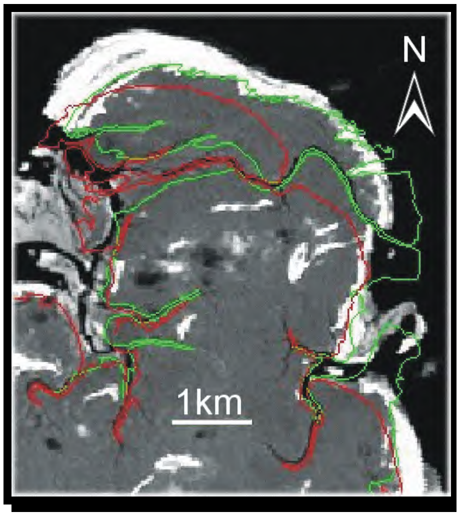

Figure 2- Shoreline recession by barrier overwash and mangrove erosion at Maiaú Point, from 1975 to 1998. Remotely sensed data was ortho-rectified to UTM coordinates. Mangrove line position in 1975 (green), 1985 (Band 5 of TM Landsat) and 1998 (red) was digitized in Arc View GIS, from air photographs, TM Landsat and SAR Radarsat imageries, respectively. Observe de strong coastal erosion eastward and the tidal mudflat prograding westward

Shoreline position changes can be observed widely in the study area. Barrier-beach ridges are overlaying the mangrove deposits. Islands have modified their positions due to sedimentary dynamic in response to tides, waves and current processes.

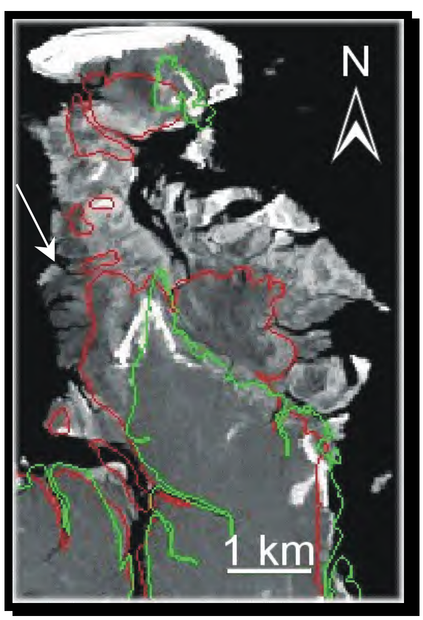

Figure 3- Shoreline accretion by tidal mudflat progradation from 1975 to 1998. Remotely sensed data was ortho-rectified to UTM coordinates. Mangrove line position in 1975 (green), 1985 (Band 5 of TM Landsat) and 1998 (red) was digitized in Arc View GIS, from air photographs, TM Landsat and SAR Radarsat imageries, respectively. Note that mudflat is prograding over sand tidal shoals that is being progressively colonized by mangrove vegetation.

Evaluating of erosional and depositional settings

Mangroves are one of the best geoindicators for evaluating shoreline changes associated to erosional and depositional processes in muddy coast. On sectors with continuous sediment supply or favorable geomorphological positions, mangroves trap sediments to build a depositional mud terrace in the upper intertidal flat, where successive zones of pioneer vegetation (*spartina sp*.) and other mangrove species migrate seaward (Figure 4A). On coastal sectors that receive little or no muddy sediment, mangrove terrace has been eroded (Figure 4B). In areas where intertidal sandflats migrate landward over the mangrove deposits due to tidal currents and large waves action, the mangrove has been killed by rapid sand deposition. Mangrove forests die due to sand deposition, producing the shoreline recession (Figure 4C).

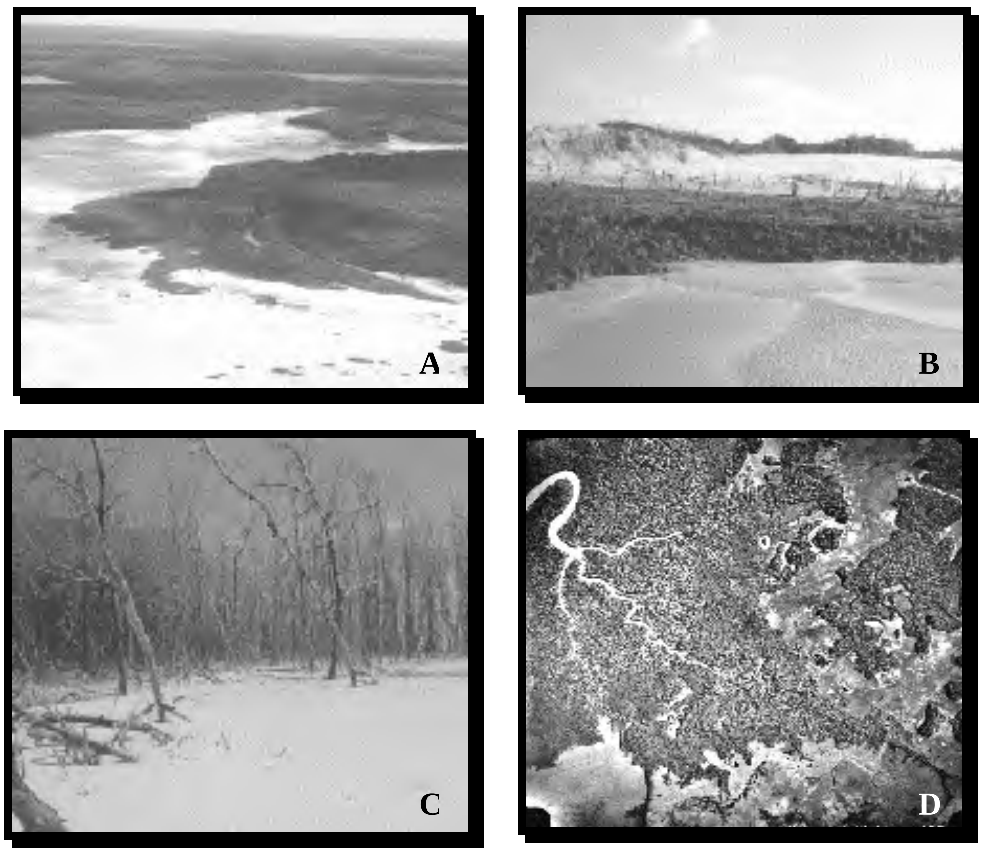

Figure 4- Assessment of mangroves as geological indicator to detect coastal changes. A) Mangrove succession in response to mud progradation. B) Mangrove terrace formed by strong tidal current and wave attack that produce the shoreline recession. C) High mangrove forest died due to rapid sand deposition over muddy substrata. D) Environmental succession marked by salt marsh, supratidal and intertidal mangrove prograding seaward in response to sea level changes.

Implications of sea level changes in mangrove and salt marsh evolution

Evolution of the mangrove and salt marsh during the last 5,100 years BP suggest that these environments are able to achieve sustained vertical and lateral growth under rising or stillstand sea level conditions. Mangroves grow in the upper intertidal flat seaward in response to high muddy sediment input. However, in the inner sectors of the coastal plain in contact with coastal plateaus, mangrove has been less influenced by tidal action that has allowed the development of salt marshes followed by supratidal mangrove. Therefore, salt marsh represents the geomorphologic, sedimentary and vegetational evolution of mangrove ecosystem situated in the supratidal zone inundated only by the equinoctial spring tides. This environmental succession can be observed in Figure 4D.

Mangroves have spread seaward in front of salt marshes and other continental vegetation on terraces formed by muddy sediment accretion. This is due to the existence of sufficient muddy sediment supply to accrete and maintain the seaward edge, while salt marshes spread in direction to mangrove (Figure 4D).

Evaluating risk from coastal hazards

The impact of the natural dynamics and anthropogenic activities in the Bragança Coastal Plain has made fast and dramatic changes in the landscape. Critical observations of large and small-scale coastal geomorphology and vegetation provide clues to the natural history, erosion and accretion degree of the shoreline and potential risk of associated natural hazards for any specific coastal site. (Young et al. 1996).

Souza Filho (2000) suggests that natural clues have presented coastal-hazard risk assessing. Coastal erosion and overwash are among the most intense short-term processes that have affected the coastal area. As mangroves constitute low and flat areas bounded by estuaries and barrier-beach ridges. Their morphology, vegetation and drainage have been strongly affected by destructive tidal current and wave attack. On Ajuruteua Island, the barrier-beach ridge has been strongly eroded and the shoreline recession has changed the high spring tide line landward. This process is responsible for houses' exposure to waves and longshore current action in the intertidal zone (Figure 5A). These natural processes have disturbed the daylife of fishermen, hotel owners and tourists, due to severe coastal erosion and shoreline recession. Therefore, in erosional barrier-beach ridges, the mangrove ecosystems will be reached and eroded too.

The anthropogenic impacts are most related to the opening of roads over the mangroves to access the beaches (Figure 5B) and unplanned coastal land use, as well as the drops of solid wastes and groundwater contamination (Souza Filho 2000). Along the Bragança-Ajuruteua road there is an area where the mangrove ecosystems were deforested and the geological, chemical and biological characteristics were completely modified. These environmental changes are responsible for climatic modifications on mangrove ecosystems that will be very difficult to discern from modifications due to anthropogenic actions and episodic natural events (Kjerfve and Macintosh, 1997). Moreover, because mangrove proximity to coastal settlements, they have been subject to dramatic human stressors responsible for decrease in mangrove area (Schaeffer-Novelli and Citrón-Molero 1999).

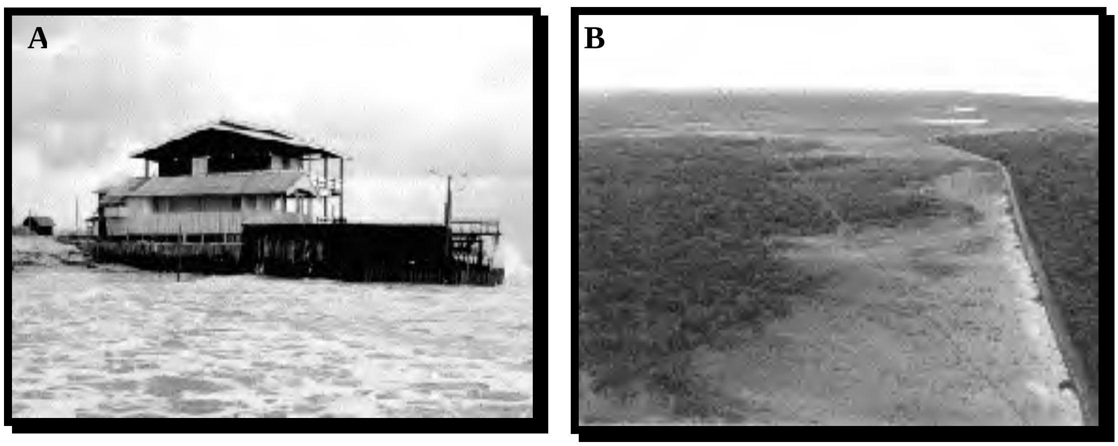

Figure 5- Natural and anthropogenic impacts on coastal area. A) Shoreline recession from Ajuruteua Beach, where houses are situated in the intertidal zone underwent to waves and currents attack. B) Mangrove ecosystem deforestation along Bragança-Ajuruteua road.

DISCUSSION AND CONCLUSION

Mangrove ecosystems have showed be an excellent geological indicator in the coastal zones to detect and quantify short-term changes. They are a good marker of shoreline changes in macrotidal dominated setting due to be easily recognized in aerial photographs, airborne and spaceborne SAR and orbital optical sensor imageries. The ortho-rectification of the remote sensing data allows comparing images from different sensors (optical and microwave) on various platforms (airborne and spaceborne) showing an absolute accuracy. The digital image processing permitted the recognizing of the coastal sedimentary environments what became possible the mangrove mapping associated to field survey.

Mangroves as geological indicator usually represent the integrated response of the coastal zone to a number of interacting geological parameters and environmental variables. It may be difficult to establish a single cause of a change in coastal positions, morphology, erosion, human impacts, or a change in the rates; frequency or intensity of coastal processes (Forber and Liverman 1996). However, the effective use of mangrove as indicator depends on a thorough understanding of coastal processes operating in the study area, such as waves, tides, currents and sedimentary dynamic.

There is no doubt that sensibility of mangrove ecosystem to register coastal changes from years to decades time scales become it a potential geological indicator able to detect and quantify the modification along the coastal zone. Mangrove may be used as qualitative indicator for managing a particular stretch of coastline related to natural and human action. Therefore, mangrove as geological indicator should help to assess environmental changes important for the attainment of sustainability, and for ecosystem management, environmental impact and risk/hazard assessment.

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4.3. GEOMORPHOLOGY, LAND-USE AND ENVIRONMENTAL HAZARDS IN AJURUTEUA MACROTIDAL SANDY BEACH, NORTHERN BRAZIL.

ABSTRACT

The Ajuruteua macrotidal sandy beach in northern Brazil extends along one of the largest mangrove coast of the world, with almost 6,000 km^2. The coastal zone evolution is related to a submerging coast, coupled with falling relative sea level from 5,200 years B.P. and muddy flat progradation from riverine sediment supply. The Ajuruteua Beach has a flat, linear and elongated form and is bounded by ebb-tidal deltas. Based on relative tidal level, the barrier-beach ridge was subdivided in three zones: supratidal zone, where are found dunes and berm, intertidal zone (high, mean and low intertidal zone) and subtidal zone. The Ajuruteua shoreline is subject to two distinct coastal processes and can be subdivided in two sectors: 1) Northwestern (NW) Sector, very vulnerable to shoreline recession with rates of -2.21 m/month; and 2) Southeastern (SE) Sector, which remains stable or with shoreline accretion with rates of +1.46 m/month. Building displacement from shoreline to coastal dunes owing severe coastal erosion in the NW Sector marks the present beach use. The risks of coastal hazards are related to shoreline change rating and the NW Sector is considered as a high risk area, while the SE Sector is considered as a moderate risk area. The coastal land use has not been regulated, and is occurring an unsustainable exploitation of the natural landscape. In response to this beach settlement, the natural process of shoreline retreating has been an emergent coastal problem.

Additional Index Words: Coastal geomorphology, mangrove coast, remote sensing, beach profiles, beach erosion.

INTRODUCTION

The Ajuruteua Island is located near the northern Brazilian coast in the State of Pará. This area occurs along one of the largest mangrove systems of the world, with almost 6,000 km^2 (HERZ, 1991), along the coasts of the states of Pará and Maranhão. This coast has macrotidal beaches, which show visible changes over periods of time ranging from hours, days, months and years. They also represent one of the most important natural and economic resources of northeastern region of the State.

During the last three decades, dunes and beaches became settlement area due to the increase of tourism, which depends largely on the beaches. An important fact was the building of 36 km of the PA-458 Road over a mangrove system, between the town of Bragança and Ajuruteua Beach, which created serious environmental problems for both beach and mangrove. Beaches can be viewed as systems in dynamic equilibrium, where the sea level, wave and tidal energy, beach sediment supply and position in space are interdependent factors, which control the coastline development (PILKEY, 1991).

The study site constitutes a submerging coast coupled with falling relative sea level during the Holocene and riverine sediment supply has allowed the muddy flat progradation (SOUZA FILHO and EL-ROBRINI, 1998). However, nowadays the shoreline is subject to retreat and coastal problems associated to erosion has been emergent. Problems related to natural dynamics and land occupation have been very well studied along the Brazilian coast (ANGULO, 1996; SOUZA and SUGUIO, 1996; MENDES *et al*., 1997; SOUZA FILHO, 2000a). This study is believed to become helpful in beach use planning, zoning and regulation. The main objectives are the following: 1) provide an overview of the geomorphology of the Ajuruteua macrotidal sandy beach; 2) describe its present land-use; and 3) analyze the hazard impacts in the coastal environment and their implications on the coastal population settlement.

STUDY SITE

The Bragança Coastal Plain is situated in the northeastern part of the State of Pará along the northern Brazilian mangrove coast (Figure 1). Geologically, the area is located in the Bragança-Viseu coastal basin of Cretaceous age, whose its evolution is controlled by normal faults reaching the present coastal zone. The structural framework of this coastal basin is responsible for a submergence of the coastal zone (SOUZA FILHO, 2000b).

The coastal study site is developed over Tertiary deposits of the Barreiras Group and Pirabas Formation. These deposits constitute the coastal plateaus near the northern coast of Brazil, which forms inactive and active cliffs in the coastal plain (SOUZA FILHO and EL-ROBRINI, 2000). The coastal plain extends northward of the coastal plateaus for more than 20 km, where occur wide tidal flats, to the shoreline dominated by marine processes. The major coastal environments observed in the Ajuruteua Island are tidal mudflats (mangrove), sandflats, chenier sand ridges, coastal dunes, barrier-beach ridges and ebb-tidal deltas (Figure 2).

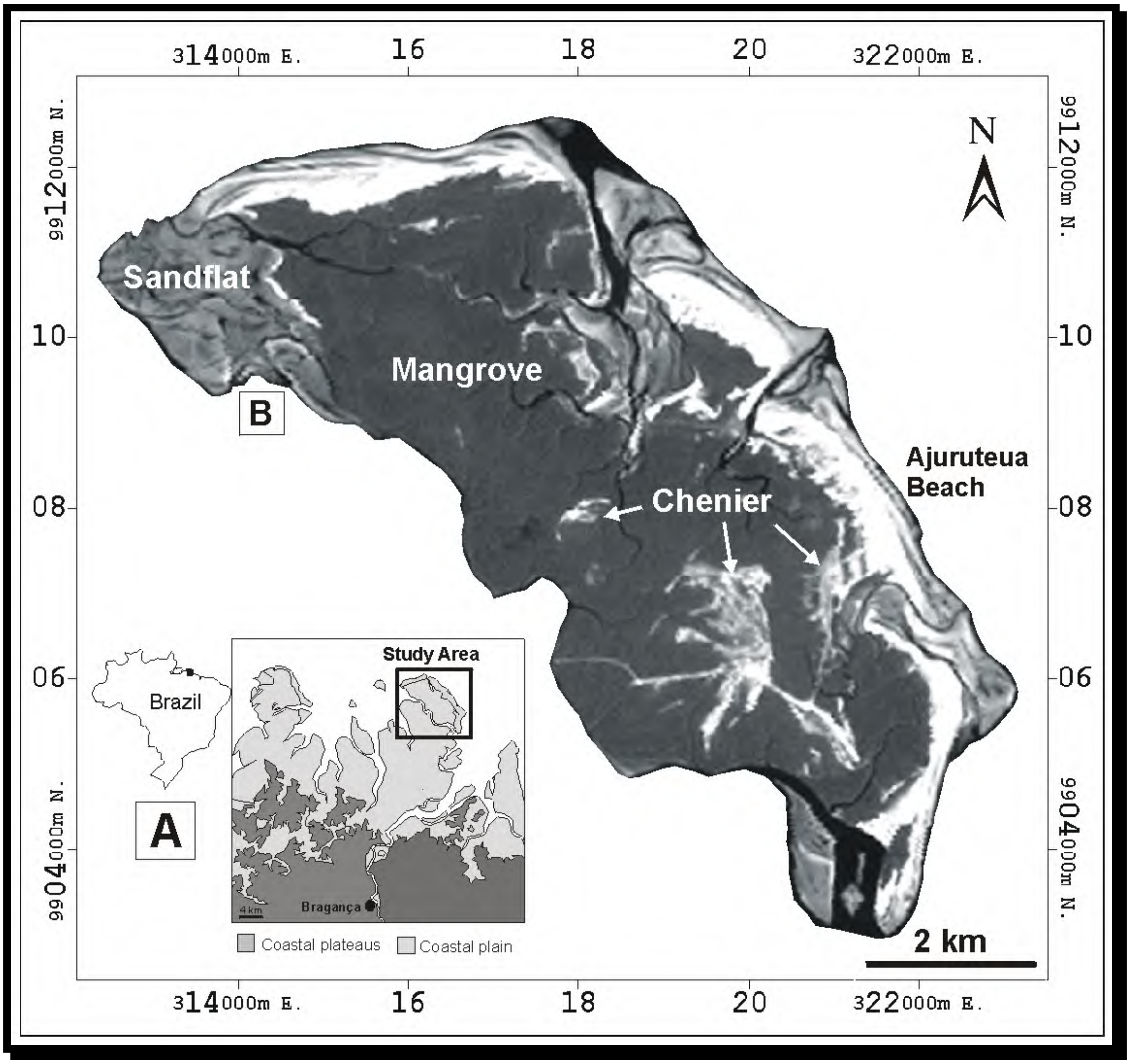

Figure 1- Localization map of the study area based on Landsat TM band 5.

A wet season from December to May and a dry season from June to November mark the climate. Geographically, the are is located 1º S of the equator, trade winds blow from the northeast throughout the year, more strongly during the dry season. The average annual rainfall reaches 2,500 mm and the mean tidal range measures around 4 m in a semi-diurnal cycle, although this range during the spring tides is locally as high as 6 m. Thus, during the spring tides large areas of the low land are inundated by water as a result of both high rainfall-runoff rates and tidal inundation (KJERFVE *et al*. 2000). Strong tidal currents and waves are responsible for erosion of mangroves along the coast, estuaries and bays, where lines of fallen mangrove trees mark the eroded places. On the other hand, new mangrove fringes are prograding seaward in response to muddy sedimentation. The net shore drift direction responsible for sediment transport along the coast presents two main directions along the Ajuruteua Island (Figure 2). In the Ajuruteua Beach, shore drift direction changes from one coastal sector to another due to the variations in coastal orientation and nearby oceanographic conditions.

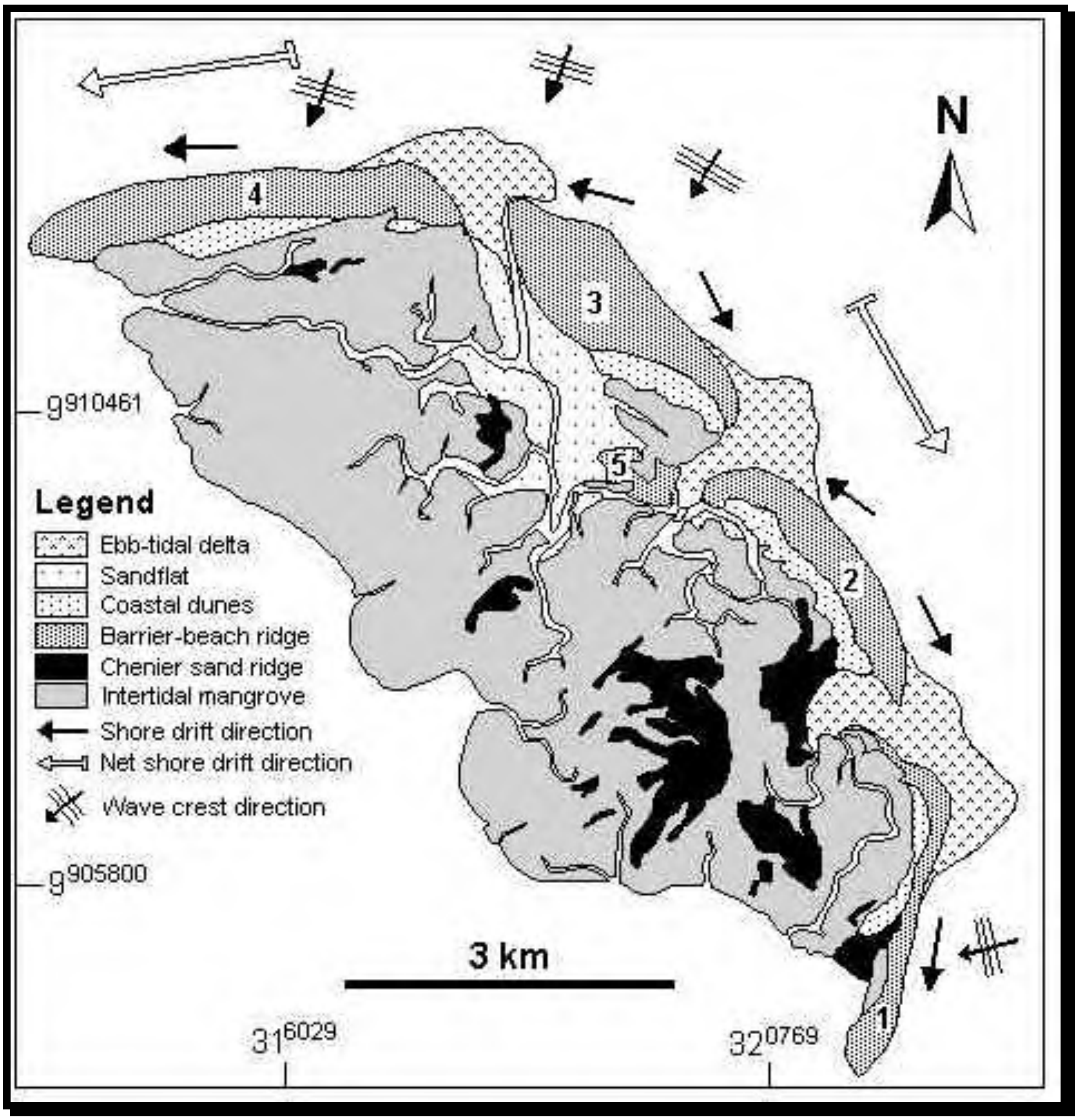

Figure 2- Geomorphologic landforms and shore drift directions on the Ajuruteua Island. Observe the beach localization 1) Pescadores, 2) Ajuruteua, 3) Farol, 4) Buçucanga and 5) Chavascal beaches.

METHODS

The coastal zone mapping was carried out in Geographical Information System (GIS-ArcView Software) from TM Landsat and RADARSAT-1 image processing. The land-use was mapped and monitored with obliquous air photographs and panoramic photographs from 1995 to 1999, while the coastal environmental hazard impacts were described and monitored along the same period. Topographic profiles to characterize the beach morphology and evaluate the short-term coastal changes were gathered normal to coastline from tidal flat (mangrove) to low spring tidal level. Hence, each littoraneous feature was measured and positioned in relation to tidal level. The analysis of short-term variability in shoreline position was quantified through five sets of monthly beach profile measurements. Five benchmarks were established at approximately 400 m intervals along the 3.0 km of Ajuruteua shoreline (Figure 3). The beach profiles were carried out at approximately spring low tide from March 1998 to March 1999 through the EMERY (1961) method of beach profiling.

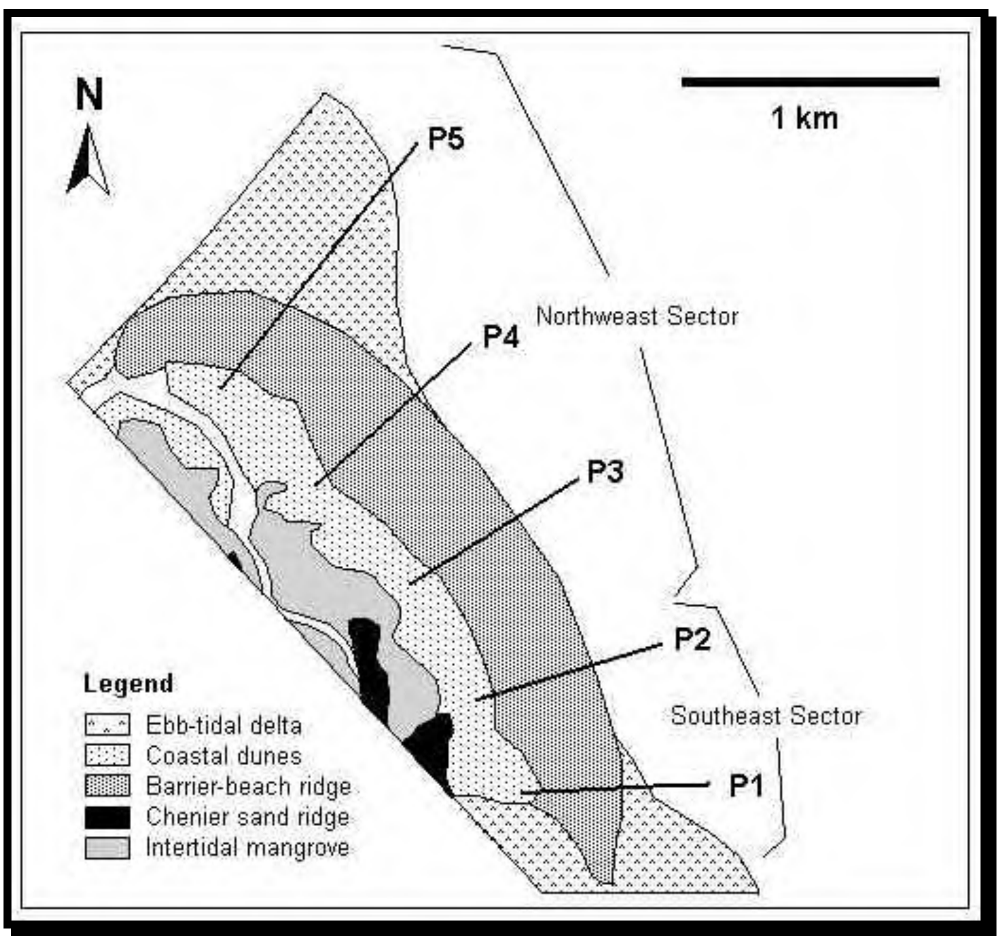

Figure 3- Localization of shore-normal transects used to measure short-term changes in shoreline position.

The shoreline datum used to monitor historical changes is represented here by spring high tide level (SHTL), that has been demonstrated to be the best indicator of the land-water interface for historical shoreline comparison studies (DOLAN *et al*., 1980; CROWELL *et al*., 1991). The SHTL delineates the landward extent of the last high tide, hence it is easily recognizable in the field and it can usually be approximated from remote sensed data. Oceanographic conditions related to wave crest propagation and net shore drift direction were determined from satellite images and field surveying (Figure 1).

AJURUTEUA MACROTIDAL SANDY BEACH MORPHOLOGY

Coastal morphology is controlled by a wide range of geologic factors and processes operating in a variety of scales. According to YOUNG *et al*. (1996), frequency, intensity and location of active physical processes are controlled by factors which can be regional (e.g. plate tectonic setting and latitude), local (such as coastal configuration, lithology), and specific site (such as elevation and land cover).

The Ajuruteua macrotidal beach presents a linear and elongated form along a northwest-southeast direction with curved spits in the longshore sediment transport direction (Figure 3). Wide mangrove system and ebb-tidal deltas bound this beach. According to SOUZA FILHO and EL-ROBRINI (2000), the Ajuruteua beach was classified as a barrier-beach ridges that extend from low spring tidal level to dune-beach scarp, which represents the higher, spring tidal level in the intertidal beach zone (Figure 4).

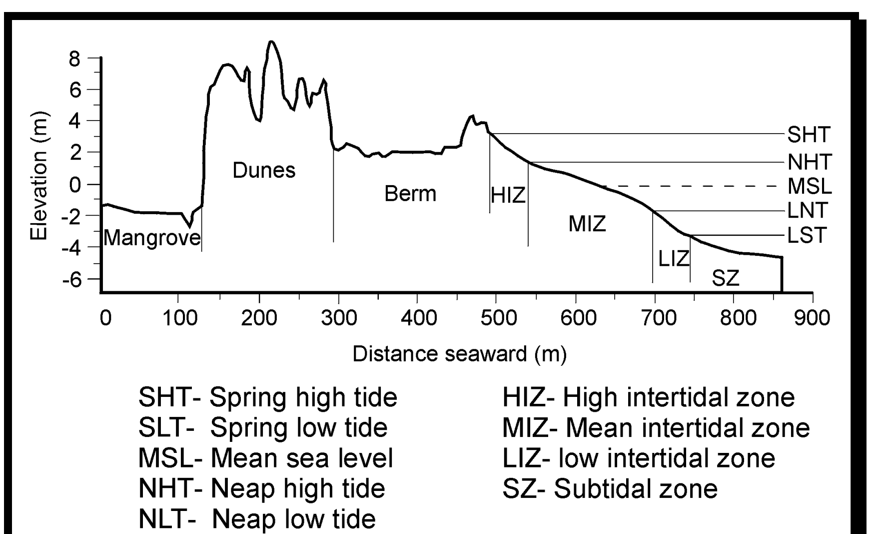

Figure 4- Morphologic details of the Ajuruteua macrotidal sandy beach.

Based on relative tidal levels (WRIGHT *et al*. 1982), the barrier-beach ridge was subdivided in three zones (Figure 4):

1) Supratidal zone (backshore): extends above the high spring tide level that coincides with the topographic boundary (dune-beach scarp). This zone is constituted by transverse vegetated coastal dunes 7 m high, followed by berm situated 1m under spring high tide level (SHTL). However, it is separated from the high intertidal zone by berm crest 1 m above SHTL.

2) Intertidal zone: occurs between high and low spring tide level. This zone is subdivided in three sub-zones along of 1,100 km^2. The high intertidal zone extends for almost 50 m from spring high tide to neap high tide level with mean gradient of 1:23; the mean intertidal zone with almost 160 m is centered between neap high tide and neap low tide level (gradient of 1:53), while the low intertidal zone extends for around 50 m from neap low tide to spring low tide level with a gradient of 1:27.

3) Subtidal zone: represents the lower area of the beach profile and occurs under spring low tide level, extending to the breaker zone with a gradient of 1:86.

SHORT-TERM BEACH CHANGES

Beach morphology and shoreline changes could be very well documented by topographic profiling techniques that involved repeated measurements along the transect oriented perpendicularly to the shoreline. Short-term beach profile measurements indicated that the shoreline position along the study site presented two distinct behaviors during the 13 months study (Figure 5). Figure 5 shows the variability of shoreline position for each month, measured from dune to beach scarp in the berm crest, because the beach width (distance between beach scarp and high water level-HWL) during the spring tide is zero. The shoreline variability occurs mainly during equinoctial period (March and September), when the tidal ranges are higher, reaching up to 6m.

During the period of study, the end point rate (EPR) method was used to calculate rates of shoreline change (DOLAN *et al*., 1991). The method involved measurements of the differences between shoreline positions with time based only in two shoreline positions (the earliest and latest dates).

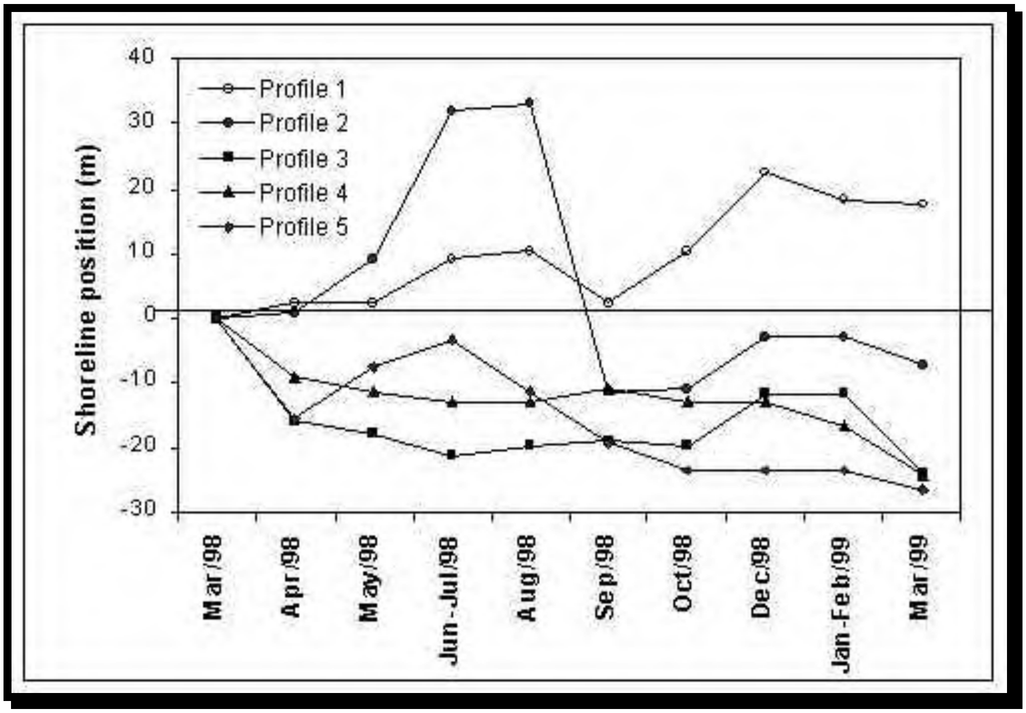

Figure 5- Relative shoreline position along the Ajuruteua Beach.

Figure 6 shows the EPR rates of each monitored beach profile. Hence, it was possible to observe that the shoreline is subjected to an accretion process with rate of +1.46 m/month in Profile 1, and for shoreline retreat with rates of -0.58 (Profile 2), -1.98 (Profile 3), -2.02 (Profile 4) and -2.21 m/month in Profile 5. This behavior allows the inference that Ajuruteua shoreline is subjected to two distinct coastal processes and so could be subdivided in two sectors: Northwestern (NW) Sector and Southeastern Sector.

The SE Sector is subjected to the accretionary shoreline process (Figures 5 and 6) with volume changes of -6.35 and +0.27 m^3/m in profiles 1 and 2, respectively (Figure 7). The NW Sector is subjected to severe shoreline retreat (Figures 5 and 6) associated with dramatic volume changes of -136, -74 and -131.5 m^3/m in profiles 3, 4 and 5, respectively (Figure 7).

Therefore, the SE Sector remains unchanged or with few variations in respect to shoreline position and volume change, while the NW Sector is very vulnerable to shoreline recession, characterized by a loss of sediments along the beach profiles.

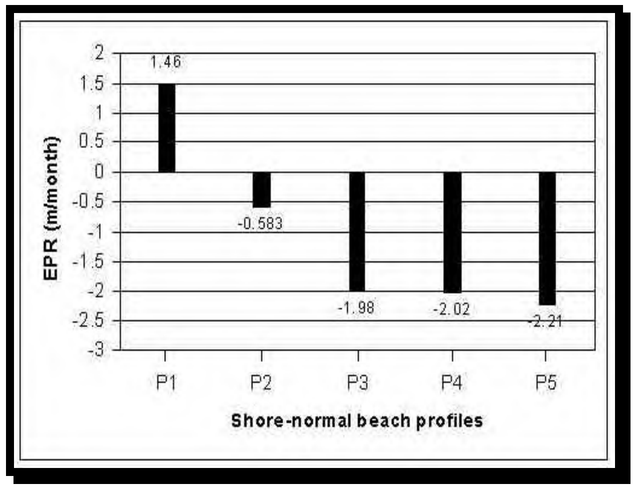

Figure 6- Plot of shoreline rate of change values for the Ajuruteua Beach.
Rates were calculated using EPR method.

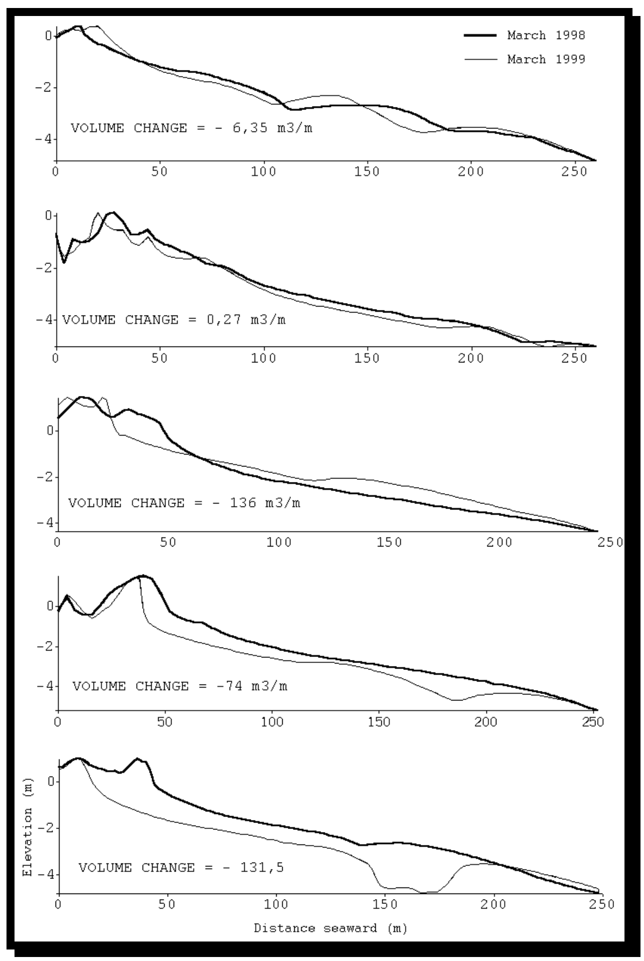

Figure 7- Beach profiles and volumes changes on the Ajuruteua Beach.

PRESENT BEACH USE

The Ajuruteua Beach is located 36 km far from Bragança. The land use in this beach begun from 70's, when Buçucanga and Chavascal beaches were destroyed by intense erosive processes responsible for shoreline retreat. The waves and tides eroded the backshore zone and the intertidal zone migrated landward reaching the dunes. Hence, the land use area in those beaches was removed and people who lived there moved to Ajuruteua, and tourism also began at this time.

Today, the Ajuruteua Beach constitutes the more important tourism point of the Bragança area. The population of Ajuruteua is almost 200 people, however during the summer holiday more than 20,000 people way arrives in Ajuruteua by excursion buses and cars during a single weekend. From the GIS it was possible determine that Ajuruteua dune-barrier beach ridge has an area of 1,100 m^2 and an perimeter of 6,851 km. Therefore, during the summer the beach remains completely crowded.

With the development of "wild area" tourism, a lot of vocation wood houses and hotels have been built over dunes and backshore zone along all shoreline for tourists to stay and rest from the beach (Figure 8). However, due to short-term shoreline retreat in the NW Sector, buildings have been constantly moved from shoreline to coastal dunes due to severe coastal erosion (Figure 9). On the other hand, in the SE Sector, characterized by shoreline stabilization, the buildings have been built at least 10 m backward from the shoreline. Owing to this temporary stability, it was observed an increase in buildings during the last 3 years and the berm crest with vegetated dunes began to be destroyed. Moreover, due to the macrotidal characteristics of the beach, the intertidal zone is usually used by tourists for parking cars during the low water level. Therefore, the present coastal use in Ajuruteua Beach is based on geomorphological characteristics. Where seaside resorts have been subjected to shoreline retreat, people have moved or abandoned structures that have been built for recreational use and tourist accommodation (Figure 9).

NATURAL PROCESSES TO COASTAL-HAZARD RISK ASSESSMENT

When human developments are placed in the path of coastal processes, natural events become geologic hazards from the human perspective (YOUNG *et al*. 1996). Hence, coastal problems are made by man, because if no one lived on the shore, there would be no problem (PILKEY, 1991).

Figure 8- Overview of coastal land use in the Ajuruteua Beach

Figure 9- The Ajuruteua Beach under high spring tide conditions. Observe the beach width and the remains of houses in the high intertidal beach zone destroyed owing to shoreline retreat.

Along the Ajuruteua Beach, a considerable number of environmental features provide information to the active physical processes in the shoreline, its natural history, and the associated natural hazards. Therefore, the parameters for evaluating site-specific risks from coastal hazards along the Ajuruteua shoreline are related to elevation, area landward of site, each width and morphology, coastal shape, dune and berm configuration, overwash, site position in relation to ebb-tidal deltas, incidence angle of waves, shore drift and shoreline change rates.

The general parameters are related to elevation and area landward of site, represented by mangroves. The study site is constituted mainly of flat lowland areas, whose high spring tidal level reaches the dune scarp northeastward and mangrove backward. During this tidal conditions, only 506 m^2 of total areas of dunes and berm remain emerged.

The Ajuruteua barrier-beach ridge forms an arc along a NW-SE direction. This coastal shape and presence of ebb-tidal deltas are responsible for generation of shore drift in two opposite directions (Figure 2). The evolution of the Chavascal ebb-tidal delta is related to a shore drift direction from SE to NW, which produces sedimentary transport in direction to the tidal channel, while the shore drift southeastward is responsible for sedimentary development of the spit in the Barca ebb-tidal delta that established the shoreline along the SE Sector. Therefore, the net shore drift controls the evolution of ebb-tidal delta, whose position migrates along the time changing the coastal shape configuration, representing a specific-site risk of coastal hazard.

Overwash processes occur frequently along the shoreline where berm crest is absent. For instance, in the NW Sector, the shoreline is submitted to severe erosion and there are no berm crests. However, in the SE Sector, where the berm crest is well-developed erosion is not observed, what is evidence of coastal stability.

The main parameter to evaluate areas of risk of coastal hazard is related to shoreline change rates. In the NW Sector, the shoreline is rapidly retreating at a rate of up to -2.21 m/month. In this sector, the buildings have suffered from strong coastal erosion and wave and tidal current power. Hence, the houses had to be moved landward or abandoned. In this case, the cesspools of houses stay exposed in high intertidal beach zone in response to coastal retreat (Figure 9), while the waste is disposed in the backshore near the mangrove ecosystem. Therefore, this sector is considered as high-risk area.

In the SE Sector, the shoreline change rates are around +1.46 m/month. Hence the beach is submitted to an accretionary process, where buildings are located near from dune ridges. Hence, this sector is considered as moderate risk area.

CONCLUSIONS

Ajuruteua sandy beach has a particular morphology associated to macrotidal environments with wave action. In the last two decades, activities in Ajuruteua beach have been considerably increased owing to the building of the Bragança-Ajuruteua road. During this time, the coastal land use has not been regulated, and an unsustainable exploitation of the natural landscape occurs. In addition, natural processes related to sediment supply, wave and tide energy and sea level are the primary causes of coastal changes, whereas human activities are catalysts that cause disequilibrium conditions, which accelerate changes (MORTON *et al*. 1996). Moreover, the physical characteristics of the coastal plain such as lowland coastal topography, mangrove occurring landward of the beach, flat morphology, concave coastal shape, dune and berm configuration, site position in relation to ebb-tidal deltas, shore drift, and principally shoreline change rates make Ajuruteua Beach a place of high risk for coastal hazards assessment and very susceptible to sea level rise. Hence, the shoreline recession rates and negative volume changes observed along the beach have shown an emergent problem of coastal erosion.

An effective coastal management plan must be implemented based on geologic frameworks and on an understanding of changes in natural processes on both geologic and historical scales. A possible future land use planning can be based on coastal setbacks provisions, which would establish a safety distance between buildings and the active coastal zone, characterized by wide mangroves and macrotidal beaches. Hence, there would be a guaranty of space for the beach move naturally, both during neap and spring tides.

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4.4. IMPACTOS NATURAIS E ANTRÓPICOS NA PLANÍCIE COSTEIRA DE BRAGANÇA

ABSTRACT

The impact of the natural dynamics and anthropogenic activities in the Bragança Coastal Plain has made fast and dramatic changes in the landscape. The erosion and accretion of the shoreline are affecting both the mangroves and daylife of the local population. The anthropogenic impacts are most related to the opening of roads to the beaches and unplanned coastal land use, as well as the drops of solid wastes and groundwater contamination.

The integration of the several parameters studied here allowed to suggest some important rules to the future coastal land use. This was also based on the concepts of geo-environmental units. It is suggested that a strong coastal management directed to the sustainable development of this area represents one of the main points that could allow the future reduction of the anthropogenic impacts.

Key words: coastal dynamics, anthropogenic impacts, land use, Bragança region.

INTRODUÇÃO

As áreas litorâneas possuem uma riqueza significativa de recursos naturais, que apresentam um grande potencial turístico. Contudo, a intensidade de ocupação desordenada vem colocando em risco este frágil ecossistema costeiro.

Os ambientes costeiros na área de Bragança vem sofrendo constantes modificações naturais, como a migração de barras arenosas e canais de maré, formação de novas áreas costeiras devido a progradação de depósitos de manguezais, desenvolvimento de áreas pantanosas colonizadas por gramíneas e erosão e acreção de praias.

Atualmente, o homem está continuamente interagindo com o ambiente natural, produzindo modificações no sistema costeiro, como por exemplo, a degradação de manguezais, através da construção de estradas de acesso às praias; utilização de areias de dunas na construção civil; construção de casas sobre os campos de dunas e a pós-praia, entre outras formas de agressão. Portanto, tentar entender a relação entre as atividades antrópicas e os processos naturais nos ecossistemas costeiros é importante para planejar um desenvolvimento sustentável.

Conhecer melhor a dinâmica de funcionamento dos ambientes costeiros e estuarinos permitirá trazer novos dados científicos e tecnológicos necessários para o monitoramento e manejo dessas áreas, uma vez que não se pode conservar adequadamente ambientes sem conhecê-los e sem entender a relação que existe entre ele e o homem. Assim, este trabalho tem como objetivo fornecer informações sobre a região costeira de Bragança relacionadas às modificações causadas por fatores naturais e antrópicos, além de utilizar tais informações com o intuito de propor um melhor uso das áreas costeiras baseado em um planejamento geoambiental.

CENÁRIO REGIONAL

O embasamento da planície costeira é formado por sedimentos terciários do Grupo Barreiras que constitui o Tabuleiro Costeiro. Os tabuleiros apresentam uma superfície plana arrasada, suavemente ondulada e fortemente dissecada, com cotas entre 50 e 60m, que diminuem progressivamente em direção à planície costeira, a norte. Este contato é marcado por uma mudança litológica (sedimentos areno-argilosos avermelhados do Grupo Barreiras e lamosos da planície costeira), vegetacional (floresta secundária e mangue) e morfológica brusca (falésias mortas de até 1m de altura) (Souza Filho & El-Robrini 1996; 1997).

A Planície Costeira Bragantina, no nordeste do Estado do Pará, apresenta cerca de 40 km de linha de costa, estendendo-se desde a Ponta do Maiaú até a foz do Rio Caeté (Figura 1). Está inserida em uma costa embaiada transgressiva dominada por macromaré, cuja compartimentação geomorfológica apresenta três domínios (Souza Filho 1995): (1) Planície Aluvial, com canal fluvial, diques marginais e planície de inundação; (2) Planície Estuarina, com um canal estuarino subdividido em funil estuarino, segmento reto, segmento meandrante e canal de curso superior, canal de maré, e planície de inundação; e (3) Planície Costeira, com os ambientes de pântanos salinos (interno e externo), planície de maré (manguezais de supramaré e intermaré e planície arenosa com baixios de maré), *cheniers*, dunas costeiras e praias (Figura 1).

A vegetação da Planície Costeira Bragantina é caracterizada pela ocorrência de mangues, que ocupam 95% de toda a área costeira. Os gêneros dominantes são *Rhyzophora. Avicenia* e *Laguncularia.* Associada a esta vegetação ocorre *Spartina sp.* e C*onocarpus L.* A vegetação de campo nos pântanos salinos é predominantemente *Aleucharias sp.* (juncos), enquanto que nos *cheniers* e campos de dunas, observa-se uma vegetação arbustiva (Souza Filho & El-Robrini, 1996).

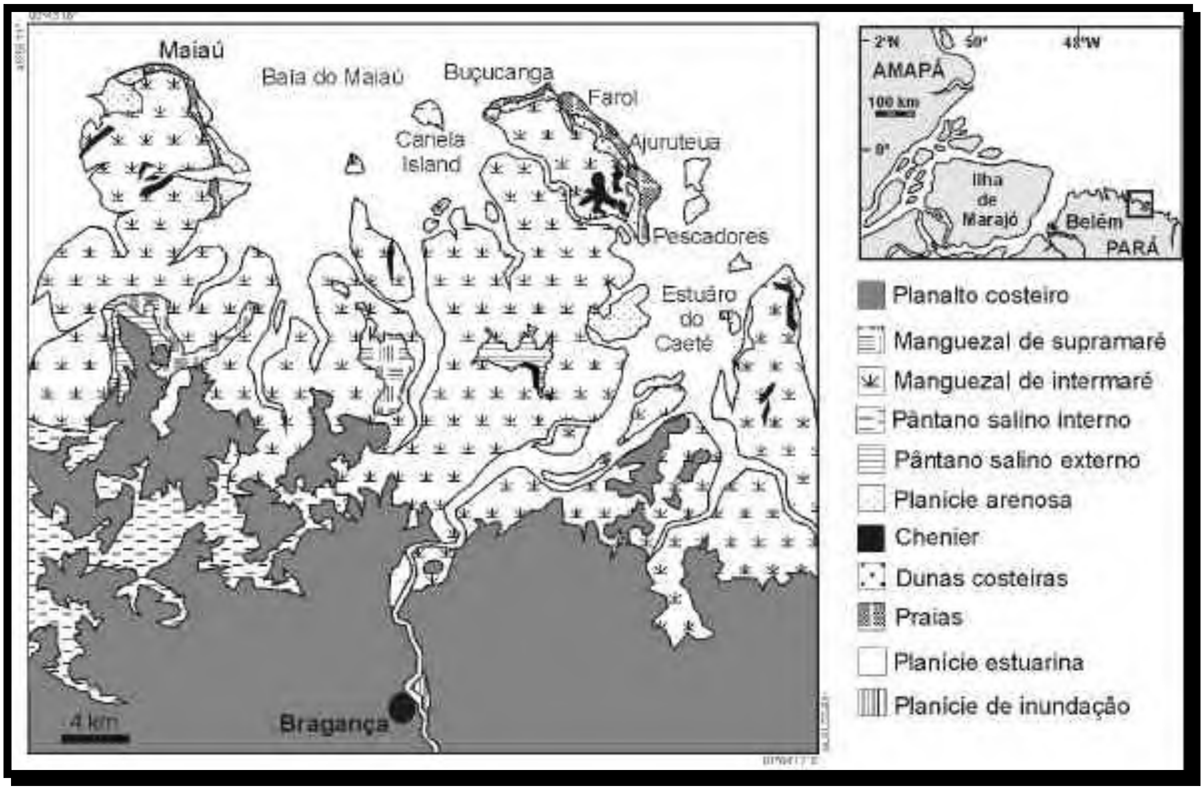

Figura 1- Mapa geomorfológico e de localização da Planície Costeira de Bragança

O clima da área é equatorial quente e úmido (Amw, de acordo com a classificação de Köppen), com uma estação muito chuvosa de dezembro a maio e precipitação anual em torno de 3.000 mm; a umidade relativa do ar oscila entre 80 e 91% (Martorano *et al*. 1993).

METODOLOGIA

Os métodos e equipamentos utilizados durante a realização deste trabalho incluíram sensoriamento remoto, geoprocessamento, testemunhagem a vibração, perfis de praia e caracterização dos parâmetros oceanográficos.

As cenas de satélite (TM do LANDSAT-5 datada de 24/07/1991, órbita-ponto 222-61) foram processadas digitalmente, obtendo-se a composição colorida 5R 4G 3B, definida como a melhor composição para o estudo da área costeira. Deste modo, foram cartografados os diferentes ambientes de sedimentação, sendo elaborado o mapa geológico-geomorfológico. Além do mais, foram cartografados os vetores de impactos ambientais instalados (p. ex. ocupação urbana e estradas, áreas desmatadas) e as alterações morfológicas e da cobertura vegetal ocorridas ao longo do tempo.

Os levantamentos de campo foram realizados para identificação da vegetação, ambientes de sedimentação, processos costeiros naturais, além de um levantamento completo da ocupação e uso do solo, localização, descrição e registro das ações antrópicas causadoras da degradação ambiental.

A partir da integração dos dados obtidos nas etapas anteriores foi elaborada a carta temática geoambiental, cujos objetivos básicos, segundo Mendes *et al*. (1997) são: (1) registrar as unidades geológicas-geomorfológicas que retratam o meio físico; (2) registrar o quadro atual da ocupação antrópica e sua influência sobre o ambiente natural; e (3) apresentar as áreas para as mais diferentes formas de ocupação das áreas costeiras, respeitando suas particularidades geológicas, geomorfológicas, botânicas e processos costeiros atuantes, além da legislação ambiental vigente.

IMPACTO DOS PROCESSOS NATURAIS NA ZONA COSTEIRA BRAGANTINA

Os processos naturais atuantes na zona costeira Bragantina são extremamente energéticos, o que vem propiciando intensas modificações na paisagem costeira. Segundo Souza Filho (1995), a posição geográfica do NE do Estado Pará (0º-1º S), aliada a seus embaiamentos costeiros e grande extensão da Plataforma Continental do Pará/Maranhão, proporciona o desenvolvimento de um ambiente de alta energia, dominado por macromarés semi-diurnas com amplitudes variando de 4 a 6 m (DHN 1997), com ondas de até 2 m de altura geradas pelos ventos alísios de NE e correntes de maré vazante no sentido de SE para NW e correntes de maré enchente no sentido de NW para SE (DHN 1986). Estes fatores são, em grande parte, responsáveis pelo transporte de sedimentos, assim como pela orientação dos canais estuarinos do litoral norte do Brasil. Tais condições hidrodinâmicas influenciam consideravelmente a sedimentação e a dinâmica das áreas costeiras, tornando-as incomparáveis com os demais setores da costa brasileira.

Erosão da Linha de Costa

Embora o monitoramento das áreas costeiras através da utilização de perfis de praia não esteja sendo realizado em todas as praias da área de estudo, pode se afirmar, com segurança, que todas as praias têm sido afetadas por processos erosivos decorrentes, principalmente, da ação das marés de sizígia de equinócios, que têm provocado o recuo da linha de costa da ordem de até 50 m em um ano de observação (março/1998 a março/99).

Na Praia dos Pescadores, eventos erosivos sucessivos vêm afetando constantemente a vida dos moradores locais. Nos últimos cinco anos, cerca de 500 m da Vila dos Pescadores voltada para o canal estuarino foram erodidos, sendo os moradores deslocados para outra área mais segura e livre da ação dos processos costeiros. Na área da praia voltada para o mar, a taxa de erosão é mais lenta, devido ao perfil de praia dissipativo e o ângulo de incidência das ondas ser aproximadamente paralela à linha de costa, com ondas com alturas nunca superiores a 1 m.

Na Praia de Ajuruteua, o setor NW vem sendo submetido a um forte processo erosivo devido sua posição às margens de um canal de maré, ângulo de incidência de ondas em torno de 7º com a linha de costa, alturas próximas a 2m e amplitude de maré variando de 4 a 6,5 m durante os meses de março e abril. Tais condições propiciaram o recuo de 22 m da linha de costa no último ano, expondo as casas de veraneio e pousadas à erosão na zona de intermaré (Figura 2A).

Nas praias do Farol e Buçucanga, a ação de ondas e correntes de maré provocam também o recuo da linha de costa, desenvolvendo escarpas de praia de até 10 m de altura, esculpidas em dunas longitudinais costeiras, onde ainda é possível observar linhas de deixa formadas por troncos de árvores de 10 m de altura, que evidenciam a grande energia hidrodinâmica do ambiente (Figura 2B).

Acreção da Linha de Costa

Enquanto a maioria das praias vem sendo submetida à erosão, um pequeno setor da linha de costa, com cerca de 1,5 km de extensão, acrescem, devido seu posicionamento as margens de um canal de maré, onde um amplo delta de maré vazante funciona como uma barreira hídrica e sedimentar, propiciando a progradação da praia em direção ao mar. Deste modo, graças ao processo deposicional relacionado ao retrabalhamento de areias da zona de intermaré da praia pelo vento durante a maré baixa, observa-se a formação de pequenas dunas na base da escarpa de praia, provocando o alargamento do berma praial e, por conseguinte, a acreção da linha de costa.

Mudanças na Vegetação Costeira

Com a ação dos fortes processos hidrodinâmicos na zona litorânea, o efeito na vegetação costeira tem sido significante. Mediante a ação de processos deposicionais associados à migração de bancos de areia sobre os depósitos de manguezais, observa-se à destruição da floresta de mangues que, mesmo morta por asfixia de suas raízes, permanece em posição de vida, formando bosques de paliteiros com até 10 m de altura, que em seguida são derrubados pela ação energética de ondas e correntes de maré, propiciando assim o recuo da linha de costa (Figura 2B).

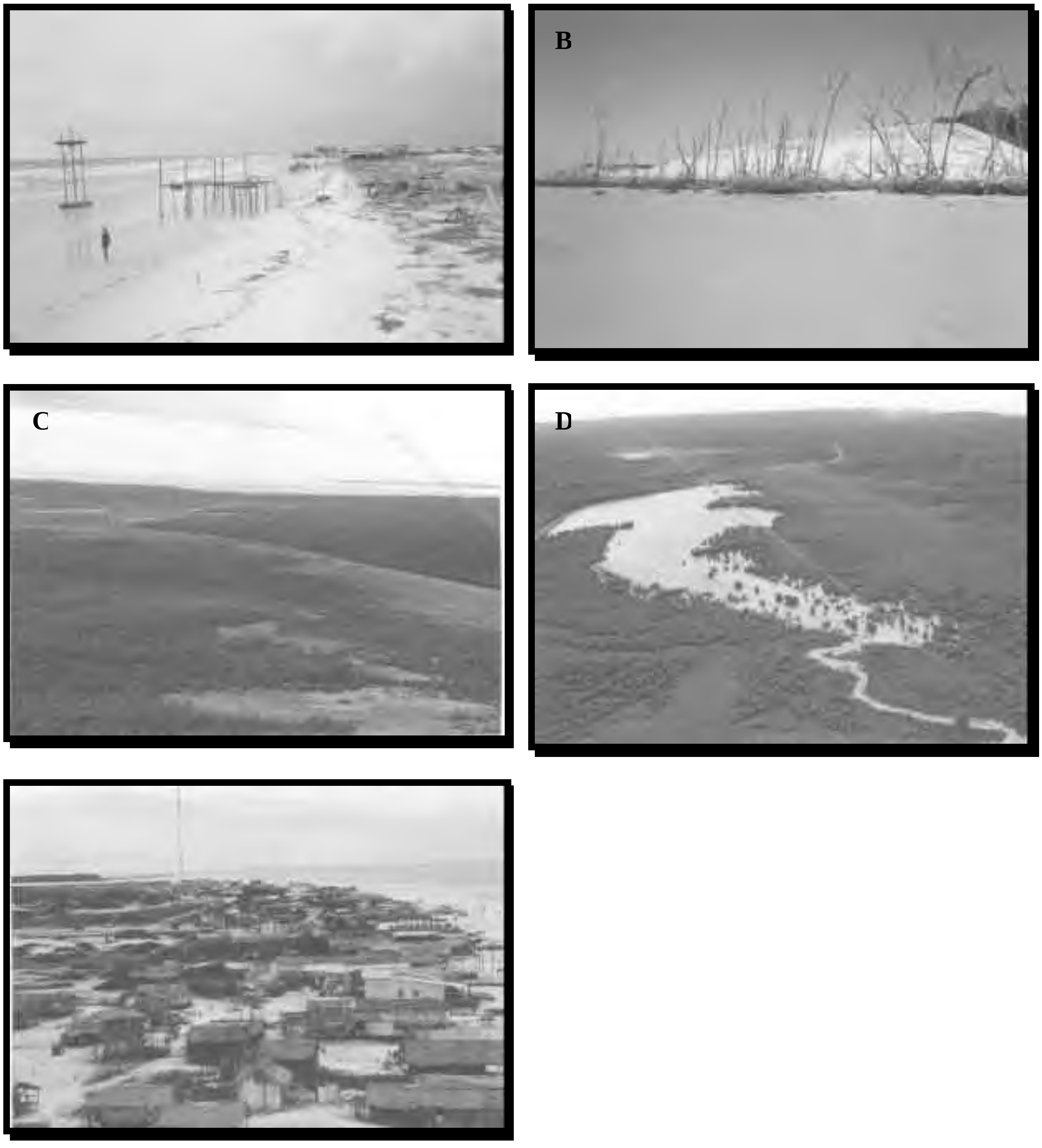

Figura 2 - A) Setor NW da Praia de Ajuruteua submetido a erosão, expondo as casas na àzona de estirâncio. B) Processo natural de erosão na Praia do Buçucanga e o impacto na vegetação costeira. C) Impacto antrópico causado pela construção da estrada sobre o manguezal. Notar a área em que a floresta foi completamente removida e o solo encontra-se exposto. D) Barragem de um canal de maré causado pela construção da estrada. E) Ocupação desordenada da Praia de Ajuruteua.

Em áreas onde predominam os processos de progradação lamosa, a vegetação de mangue expande-se sobre o substrato lamoso, inicialmente colonizado por *spartina sp*. gerando uma clara zonação da vegetação costeira.

IMPACTO DAS ATIVIDADES ANTRÓPICAS NA ZONA COSTEIRA BRAGANTINA

Segundo Nichols & Corbim (1997), para se entender como as áreas costeiras têm sido afetadas por atividades antrópicas, é necessário saber primeiro qual é a origem dos sedimentos costeiros, que por sua vez está relacionada à erosão de áreas continentais e ao transporte fluvial destes sedimentos, e quais são as fontes de sedimentos marinhos que suprem as áreas costeiras. Portanto, quando analisamos os impactos antrópicos em processos costeiros, se faz necessário saber que os ambientes costeiros da Planície Bragantina constituem um sistema dinâmico, e assim, qualquer impacto antrópico que modifique a dinâmica natural, como a construção de estradas, residências, hotéis e pousadas afetarão os processos costeiros atuantes.

Construção de Estradas de Acesso às Praias

Até o final da década de 70, a falta de acesso às praias da Planície Costeira Bragantina era visto como um sério problema ao desenvolvimento do turismo na região. No entanto, no início da década de 80, foi construída a estrada que liga a Cidade de Bragança a Praia de Ajuruteua, o que sem dúvida alguma deu um grande impulso ao turismo, além de facilitar a vida dos pescadores locais. Contudo, esta estrada foi construída sobre extensos depósitos da planície de intermaré lamosa, densamente colonizada por mangue, secionando deste modo, 25 km de manguezais. Assim, veio a constituir a maior obra de impacto antrópico em áreas costeiras do norte do país, cujos danos ainda não foram quantificados.

Ao longo dessa estrada, observa-se áreas cuja vegetação de mangue já foi completamente removida, estando o solo lamoso exposto à incidência direta dos raios solares, que provocam a formação de gretas de contração, além de desencadear modificações das condições físico-químicas do solo, que geram certamente prejuízos à atividade biológica (Figura 2C).

Outro problema observado está relacionado à desestruturação de parte da rede de drenagem, uma vez que diversos canais de maré, responsáveis pela circulação dos nutrientes no ambiente de manguezal, foram cortados pela estrada, que em alguns trechos funciona como barragem ao fluxo das marés, gerando enormes áreas com água represada (Figura 3D). Tal modificação tem gerado novas condições ambientais que alteram o funcionamento do ecossistema de manguezal, desde o processo de sedimentação, condições físico-químicas das águas até a fauna e flora vivente.

As demais praias da área de estudo (Farol, Chavascal, Buçucanga, Pilão, Picanço, Canela e Maiaú) encontram-se completamente preservadas, sendo o acesso feito somente por meio fluvial ou a pés durante as marés baixas.

Ocupação Desordenada das Praias

Os 535 km^2 de áreas costeiras em estudo estão pouco ocupados pelo homem. A ocupação se dá, na maioria das vezes, sobre "ilhas" de terrenos terciários aflorantes em meio à planície de intermaré lamosa (manguezais). Nas praias a ocupação é desordenada, exceto na Vila dos Pescadores, onde a grande maioria das casas localiza-se atrás do cordão de dunas fixo; e apenas uma minoria encontra-se sobre a escarpa de praia, sujeita à ação erosiva de ondas e marés, o que leva os moradores a desmontarem suas casas, construindo-as posteriormente em áreas mais protegidas, não influenciadas pela dinâmica praial.

Na praia de Ajuruteua, a forma de uso é inversa, uma vez que toda a linha de escarpa de praia do setor NW está ocupada por casas e pousadas. Para conter a erosão, alguns moradores construíram muros de madeira que vem afetando a dinâmica morfo-sedimentar, influindo na evolução natural do ambiente praial (Figura 3E). Entretanto, o setor SE, submetido a um processo de acreção da linha de costa, apresenta todas as construções situadas à pelo menos 10 m da escarpa de praia.

Estudos de monitoramento realizados nestas praias permitirão em breve quantificarmos exatamente a relação destas formas de ocupação com os processos erosivos e deposicionais ocorrentes em todas as praias da Planície Costeira Bragantina.

Impacto dos Resíduos Sólidos no Ambiente Costeiro

O volume de lixo sólido depositado no ambiente costeiro constitui uma séria ameaça ao ambiente praial e manguezal da Planície Costeira Bragantina. Ao longo dos 25 km da planície costeira, não existe nenhum sistema de coleta de lixo, sendo este depositado regularmente nos campos de dunas. Seus impactos variam desde a poluição da linha de costa até influências na saúde da população, e problemas estéticos e econômicos que abalam o turismo da área. Alguns destes impactos foram muito bem descritos por Simmons (1997) como:

Impactos na Fauna e Flora

Estima-se que os resíduos plásticos constituem 60% dos detritos inorgânicos que entram no ambiente marinho. A degradação deste produto é muito lenta, permanecendo em suspensão no mar ou retido no fundo por um longo período de tempo. Estes resíduos representam uma ameaça aos animais marinhos, como pássaros, tartarugas, peixes, crustáceos, etc.

Degradação Física

O grande depósito e a lenta degradação de plásticos (400 anos), vidros (200 anos), borracha (100 anos), metais (2 anos) e alumínio (não degrada) proporcionam a acumulação dos resíduos sólidos nos estuários e praias, que são posteriormente retrabalhados e depositados juntamente com os sedimentos, formando camadas de lixo intercaladas a camadas sedimentares recentes, marcando períodos de grande acumulação de resíduos (Figura 3A).

Impactos Estéticos e Econômicos

A presença de lixos em áreas costeiras, principalmente, nas praias não é bem visto, particularmente em áreas onde o turismo é altamente dependente da beleza da praia e de um ambiente saudável. Logo, um aumento no acúmulo de lixo poderá diminuir a qualidade e beleza do ambiente e, por conseguinte, diminuir o fluxo de turistas, visitantes e usuários da praia, sendo isto traduzido em perdas econômicas para pousadas e empresas de turismo, sem contar com os prejuízos de moradores, pescadores e donos de embarcações.

Impactos na Saúde

Garrafas, copos e latas lançadas nas praias e estuários constituem uma ameaça a banhistas e demais usuários, que sofrem constantes acidentes. O conteúdo destes detritos em contato com a pele ou se ingeridos acidentalmente representam um perigo real se tratados de forma imprópria e inadequada pelos usuários das praias. Além do mais, o lixo e as fossas contaminam os lençóis freáticos, tornando a água utilizada pela população imprópria ao consumo. Devido a forte erosão costeira, diversas fossas são encontradas na zona de intermarés das praias (Figura 3B).

Figure 3- Impacto dos resíduos sólidos na Praia de Ajuruteua. A)Depósito de lixo (lata, plástico, tijolo, etc) intercalado a camadas de sedimentos arenosos de dunas costeiras; B) Fossas de antigas residências (setas) expostas na zona de intermaré devido ao recuo da linha de costa. Essas fossas representam um perigo a saúde dos banhistas, pois contaminam os lençóis freáticos superficiais, cuja água é utilizada pelos moradores locais.

ESTRATÉGIA DE OCUPAÇÃO DA ÁREA COSTEIRA

A partir da integração dos mapas geológico-geomorfológicos com os processos naturais e antrópicos observados na área costeira, foi possível identificar e caracterizar áreas apropriadas ou não ao uso e ocupação do solo, as quais Mendes *et al*. (1997) denominaram de Unidades Geoambientais.

Com base no mapa geoambiental (Figura 4), elaborado para a área de estudo, é proposta uma forma de uso e ocupação da zona costeira, baseado em um planejamento que permita um desenvolvimento sustentável, conforme descrito abaixo:

Áreas de Preservação Permanente

De acordo com a Resolução nº 004/85 do CONAMA, essas áreas são consideradas Reservas Ecológicas, sendo representadas na Planície Costeira Bragantina pelos ecossistemas de manguezal, pântanos salinos, dunas costeiras incluindo os cheniers, planícies arenosas e praias e, os ecossistemas estuarinos (canal estuarino e planície de inundação). Além das características ecológicas peculiares destes ecossistemas, essas áreas são inadequadas à urbanização por estarem sujeitas a processos naturais como erosão, deposição, inundação, marés, ondas, ação eólica, etc., os quais dificultam sobremaneira a construção de obras de engenharia.

Áreas Adequadas à Ocupação

Representam áreas cujas características geológicas-geomorfológicas e ambientais atuais (a floresta nativa já foi destruída nos primórdios da década de 60) favorecem sua urbanização, principalmente por estarem localizadas sobre o Tabuleiro Costeiro, sustentado por sedimentos terciários do Grupo Barreiras. Há a necessidade de avaliação do impacto sobre a cobertura vegetal e rede de drenagem a ser atingida.

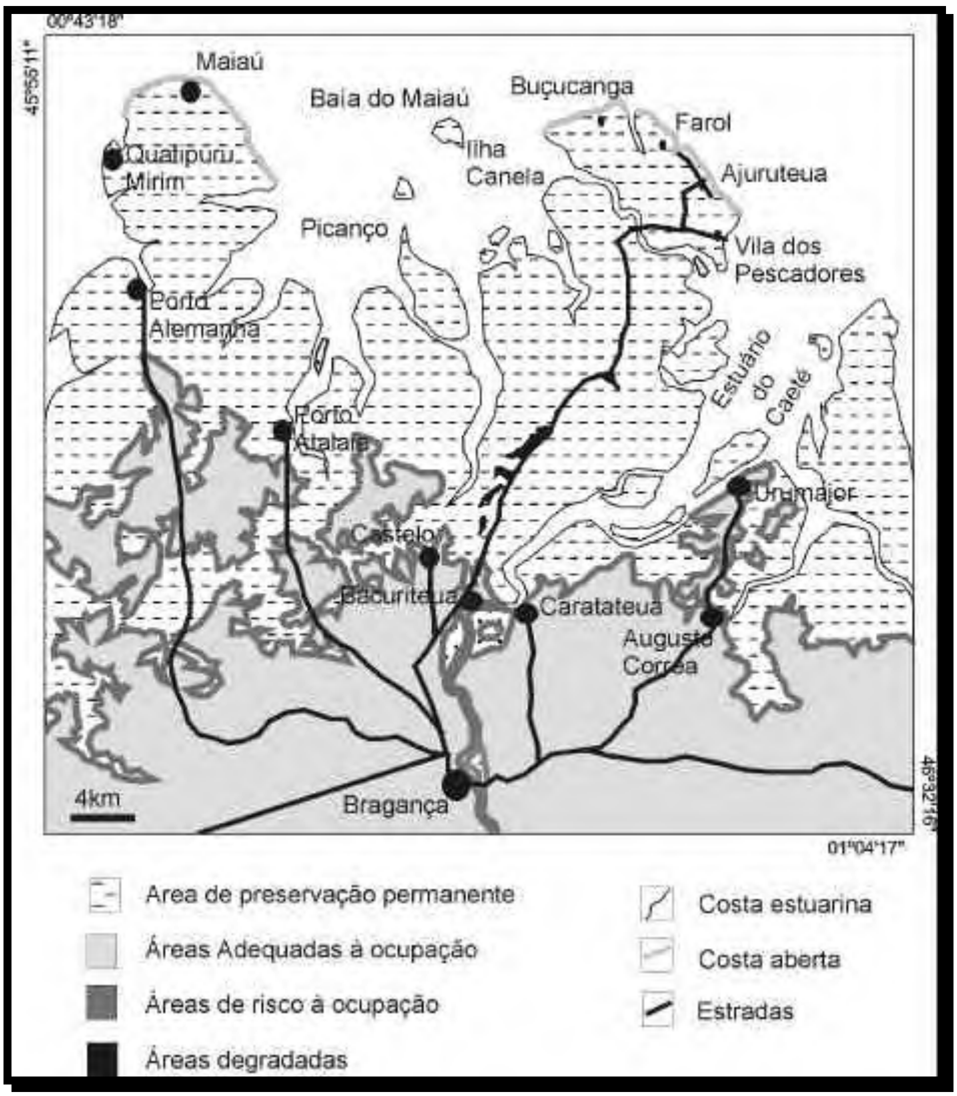

Figura 4- Mapa geoambiental da Planície Costeira de Bragança.

Áreas de Risco à Ocupação

Correspondem às áreas que apresentam restrições ao uso do meio físico, dispondo apenas de condições parciais de suporte a projetos de urbanização. São necessários cuidados especiais a fim de se evitar problemas ambientais, geológicos e geotécnicos que possam ocorrer nas áreas de risco, como as margens das paleofalésias, dos rios e estuários. Existe ainda a preocupação com a emissão dos efluentes nos sistemas estuarinos e costeiros, devido a sua proximidade.

Áreas Degradadas

Constituem áreas situadas na unidade geoambiental de preservação permanente, submetidas a impactos antrópicos que degradaram o meio físico. Essas áreas são representadas pela ocupação desordenada das praias, devastação de florestas de mangue, formação de novos ambientes (lagos) e estradas que seccionam os manguezais. Entretanto, caso essas ações tivessem sido planejadas, seus impactos ambientais poderiam ter sido minimizados.

RECOMENDAÇÕES PARA REDUZIR A VULNERABILIDADE DA ÁREA COSTEIRA

Para se reduzir à vulnerabilidade das áreas costeiras sujeita, tanto a processos naturais, quanto os antrópicos, se faz necessário à tomada de decisões, cujas atribuições são do setor público, responsável pela preservação do patrimônio de uso público e coletivo.

Portanto, para reduzir o impacto ambiental nas áreas costeiras, é preciso a implantação de alguns programas como:

- monitoramento dos processos costeiros para constituir um banco de dados a fim de predizer a dinâmica costeira;
- priorizar a proteção dos manguezais, dunas costeiras e praias;
- regenerar áreas costeiras já destruídas pela ação antrópica;
- estabelecimento de uma linha de recuo (“setback”) para o uso e desenvolvimento de áreas costeiras. Esta linha de recuo será definida como a distância prescrita da linha de maré baixa para uma feição costeira, preferencialmente a linha de vegetação do campo de dunas, na qual todos ou certos tipos de desenvolvimento serão proibidos;
- determinação de uma zona entre a linha de maré baixa e a faixa de ocupação costeira, na qual a zona de praia pode acrescer ou recuar naturalmente;
- controlar a emissão de efluentes domésticos e industriais nos rios, estuários e linha de costa;

- estabelecimento de um programa de coleta de resíduos sólidos adequado ao ambiente costeiro, com a finalidade de reciclar o lixo quando possível.

Estas medidas devem ser tomadas o quanto antes, uma vez que a grande maioria dos impactos antrópicos responsáveis pela vulnerabilidade das áreas costeiras ainda são reversíveis. Deste modo, planejar nesse momento um desenvolvimento sustentável para a região é bastante pertinente, sendo possível evitar danos ambientais irreparáveis, como aqueles observados na área de Salinópolis (Mendes et al. 1997), também localizada no litoral do Estado do Pará.

CONCLUSÕES

Este artigo representa uma tentativa de se abordar os muitos problemas envolvidos no gerenciamento de áreas costeiras, com o intuito de planejar um desenvolvimento sustentável para a Planície Costeira Bragantina. A implementação de uma política de gerenciamento deve ser de longo período, iniciando-se com o reconhecimento das características do meio abiótico e biótico, para que se possa então monitorar e em seguida gerenciar o ambiente.

Os principais problemas ambientais na Planície Costeira Bragantina estão relacionados à erosão costeira e a ocupação desordenada de áreas de preservação permanente, sem que haja nenhum estudo prévio dos impactos ambientais decorrentes de tal ação. Deste modo, o primeiro passo é reconhecermos a erosão costeira como um problema que vem afetando a população local, causando sérios prejuízos econômicos e sociais. Em seguida, é necessário se rever à forma de ocupação atual da planície costeira e adequá-la a proposta geoambiental de uso e ocupação do solo, a fim de que se possa reduzir a vulnerabilidade das áreas costeiras aos processos naturais atuantes. Vale ressaltar ainda a necessidade de estabelecimento de uma política de gerenciamento costeiro, onde o planejamento do meio físico seja de responsabilidade de órgãos ambientais, que juntamente com a comunidade, a iniciativa privada e organizações não governamentais fomentem e incentivem o turismo e o desenvolvimento da região de modo efetivo.

Portanto, ainda a tempo de evitarmos problemas ambientais mais graves na Planície Costeira Bragantina, que só passam a existir quando o homem ocupa de forma desordenada e irracional o ambiente em que vive.

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CAPÍTULO 5:

CONCLUSÕES GERAIS

5.1. EVOLUÇÃO DA ZONA COSTEIRA

A evolução geomorfológica em grande escala da costa nordeste do Estado do Pará é controlada pelo arcabouço tectônico das margens continentais passivas desenvolvidas desde o Cretáceo Inferior durante a abertura do Oceano Atlântico Equatorial. Dois domínios geomorfológicos são observados ao longo do nordeste do Pará. O Domínio 1 é desenvolvido sobre a Plataforma do Pará, que apresenta uma vasta cobertura sedimentar, representada pela Formação Pirabas e pelo Grupo Barreiras. A evolução deste setor não é tectonicamente influenciada por antigos centros deposicionais, parecendo ser muito estável. Assim, os depósitos costeiros são restritos a canais estuarinos e frentes de progradação com largura inferior a 2 km, vindo a constituir uma costa emergente. O Domínio 2, situado mais à leste, tem sua evolução relacionada à bacia costeira de Bragança-Viseu, controlada por falhas normais que alcançam a zona costeira atual. O arcabouço estrutural desta bacia costeira é responsável pelo desenvolvimento de uma zona costeira de submersão, onde se instalou um dos maiores sistemas de manguezal, devido a progradação lamosa.

Inserida no contexto da bacia costeira de Bragança-Viseu, observa-se a Planície Costeira de Bragança, cujas características geomorfológicas permitiram sua subdivisão em três compartimentos distintos: (1) planície aluvial, com canal fluvial, diques marginais e planície de inundação; (2) planície estuarina, com um canal estuarino subdividido em funil estuarino, segmento reto, segmento meandrante e canal de curso superior, canal de maré e planície de inundação e; (3) planície costeira, com os ambientes de pântanos salinos (interno e externo), planície de maré (manguezais de supramaré, manguezais de intermaré e planície arenosa com baixios de maré), cheniers, dunas costeiras e praias.

A evolução geológica da Planície Costeira de Bragança durante o Holoceno é marcada por progradação da linha de costa desde 5.100 anos BP. Falésias inativas esculpidas no planalto costeiro representam esse nível de mar mais alto durante a última transgressão. Durante a subida do nível relativo do mar no Holoceno, os sedimentos arenosos e lamosos (fácies areia e lama estuarina e de planície de maré) formavam as barras arenosas de maré, a planície arenosa de foz de estuários e os depósitos de face praial (fácies areia marinha) que recobrem o Planalto Costeiro e migraram em direção ao continente, constituindo a sucessão S_1, interpretada como sendo uma sucessão retrogradacional, cuja evolução está intimamente relacionada a um período de nível de mar transgressivo. Em condições de nível de mar estável ou com taxa de subida mais lenta, desenvolve-se a sucessão S_2, constituída pelo ambiente de planície de maré (manguezais de intermaré e supramaré), que vem a representar uma sucessão progradacional desenvolvida sob condições de nível de mar alto estável. O limite desta sucessão S_2 com a sucessão S_1 é marcado por uma superfície de recobrimento regressivo bem definida, resultado da progradação lamosa subaérea sobre os depósitos arenosos, à medida que a linha de costa avança em direção ao mar, datada em 2.100 anos BP. Assim, admite-se que estes depósitos lamosos da planície de maré tenham se acumulado durante período de progradação geral da linha de costa, sob condições de nível de mar alto estável.

A sucessão S_3 foi interpretada como de ambiente litorâneo (dunas costeiras, praias e cheniers) e estuarino, representando eventos transgressivos de curta duração, responsável pela fase retrogradacional atual da linha de costa, onde vários ambientes sedimentares atuais estão evoluindo.

5.2. MAPEAMENTO DE ZONAS COSTEIRAS TROPICAIS ÚMIDAS DOMINADAS POR MANGUEZAIS POR SENSORES REMOTOS ORBITAIS

Este trabalho tem demonstrado que dados orbitais de sensores remotos podem fornecer excelentes informações geomorfológicas e de uso da terra. Imagens do radar de abertura sintética RADARSAT-1, no modo de alta resolução, representam uma ferramenta poderosa para o estudo de ambientes costeiros tropicais úmidos, principalmente em costas de manguezal de macromaré, onde a capacidade da radiação eletromagnética nas microondas, penetra a cobertura de nuvens, fornecendo uma oportunidade unívoca para o mapeamento e monitoramento de áreas costeiras amazônicas. Assim, o processamento digital das imagens SAR seguida de sua interpretação pode ser usada no mapeamento de ambientes sedimentares costeiros, na determinação da posição de bancos arenosos submersos em águas rasas, na determinação das direções das correntes de marés superficiais, na determinação da posição precisa da linha de costa e a estimativa de sua variação ao longo do tempo, na identificação de setores sujeitos a erosão, acreção ou estabilidade, na localização de áreas sujeitas ao desflorestamento e regeneração das florestas de mangue e por fim na localização de áreas de risco geológico costeiro.

Esta pesquisa tem demonstrado também como imagens orbitais SAR combinadas a sensores remotos ópticos podem ser úteis no mapeamento geológico costeiro em ambientes tropicais úmidos. Produtos integrados a partir de componentes principais seletivos (SPC) das bandas do sensor TM do satélite Landsat são excelentes dados para integração com o RADARSAT, apresentando a melhor performance na discriminação dos ambientes costeiros. Este aspecto está relacionado à habilidade da análise por SPC tornar possível o uso das seis bandas reflectivas do TM. Assim, o primeiro auto canal (PC1) obtido a partir das bandas TM 1, 2 e 3 é responsável pelo realce da linha de costa e das feições costeiras submersas, uma vez que a PC1 contém 95,11% da variância do espectro visível do TM. Além do mais, o primeiro auto canal (PC1) obtido a partir das bandas TM 5 e 7 realça as áreas com solos expostos, permitindo a discriminação espectral entre os pântanos salinos internos e externos e manguezais de supramaré. Enquanto a banda TM 4 é responsável pelo realce da floresta costeira de manguezal da vegetação secundária sobre o planalto costeiro. Os dados SAR foram responsáveis pelo realce de feições topográficas, diferenças na altura da vegetação, geometria dos corpos e conteúdo de umidade, enquanto os dados TM forneceram mais informações da cobertura vegetal e variações no tipo vegetal.

A integração digital das imagens SAR e TM propiciaram uma visão sinóptica da área, fornecendo informações geobotânicas (relação entre o ambiente costeiro e a vegetação sobrejacente) e de variações multitemporais. Deste modo, tal técnica de processamento pode ser reconhecida pelos geólogos costeiros como uma poderosa ferramenta para mapeamento e monitoramento costeiro.

A partir deste estudo é possível concluir que a integração de dados de sensores remotos com um sistema de informação geográfica (GIS) constitui a melhor estrutura de análise espacial integrada. A habilidade do GIS de combinar diferentes conjuntos de dados e a possibilidade de se interpretar simultaneamente as relações espaciais entre os vários ambientes costeiros permitiu uma interpretação mais compreensível do mapeamento geológico costeiro. Esta pesquisa revelou que este sistema de mapeamento costeiro constitui um método acessível, rápido e preciso e o GIS representa uma filosofia organizacional para controle dos dados e posterior uso desta informação no gerenciamento da zona costeira.

5.3. APLICAÇÃO DE DADOS DE SENSORIAMENTO REMOTO NO ESTUDO DA GEOLOGIA COSTEIRA

As aplicações dos dados de sensores remotos no estudo de ambientes costeiros tropicais além de estarem relacionadas ao mapeamento geológico estão associadas a processo de monitoramento das modificações costeiras. Estas estão relacionadas à dinâmica natural do ambiente e a influência antrópica exercida sobre ele.

O estudo da variabilidade na posição da linha de costa ao longo da Planície Costeira de Bragança, revela que durante o Holoceno (últimos 5.200 anos), a planície foi marcada por uma progradação lamosa da linha de costa. Entretanto, a partir da análise de imagens de sensores remotos, foi possível investigar a variabilidade da linha de costa em escalas de longo (1972-1998) e curto período (85 a 88, 88 a 90, 90 a 91), cujas variações morfológicas são caracterizadas por recuo da linha de costa, provavelmente devido às variações climáticas, associadas á eventos El-Niño e La-Niña, que controlam a precipitação ao longo da zona costeira, onde os períodos de erosão mais severos (1985-1988) são acompanhados de elevadas taxas de precipitação (>4.000 mm).

Do ponto de vista da análise espacial de ambientes costeiros, os manguezais constituem um dos melhores ambientes para análise a partir de sensores remotos, tanto no espectro eletro-óptico devido sua alta reflectividade no infravermelho próximo, quanto nas microondas devido sua textura rugosa. Portanto, os manguezais têm mostrado ser um excelente indicador geológico para detecção e quantificação das variações morfológicas de curto e longo período. Eles são os melhores marcadores das posições de linha de costa em ambientes dominados por macromaré, devido seus limites serem facilmente reconhecidos tanto no campo como em imagens de sensores remotos. Não há dúvidas de que a sensibilidade do sistema de manguezal para registrar variações nos processos costeiros (erosão, deposição e transporte) em diferentes escalas de tempo e espaço, o torna um indicador geológico em potencial para ser monitorado a partir de sensores remotos orbitais.

Por fim, a integração de sensores remotos com o GIS e dados de campo apresenta um papel fundamental para o gerenciamento integrado de zonas costeiras, avaliação de risco ambiental, caracterização local, mapas bases e geração de mapas temáticos e disseminação da informação de domínio público, que são fatores significantes no processo de tomada de decisão.

CAPÍTULO 6:

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ANEXO A – LISTA DE TRABALHOS PUBLICADOS E SUBMETIDOS À PUBLICAÇÃO

Souza Filho P.W.M. and El-Robrini M. 1998. As variações do nível do mar e a estratigrafia de sequências da Planície Costeira Bragantina - Nordeste do Pará, Brasil. Boletim do Museu Paraense Emílio Goeldi, Série Ciências da Terra, 10: 45-78.

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Souza Filho, P.W.M. and El-Robrini, M. 2000. Coastal zone geomorphology and sedimentology of Bragança Area, Amazon Region, Brazil. In: International Geological Congress, 31, Rio de Janeiro, Brasil, Shell, Abstracts Volume, CD ROM.

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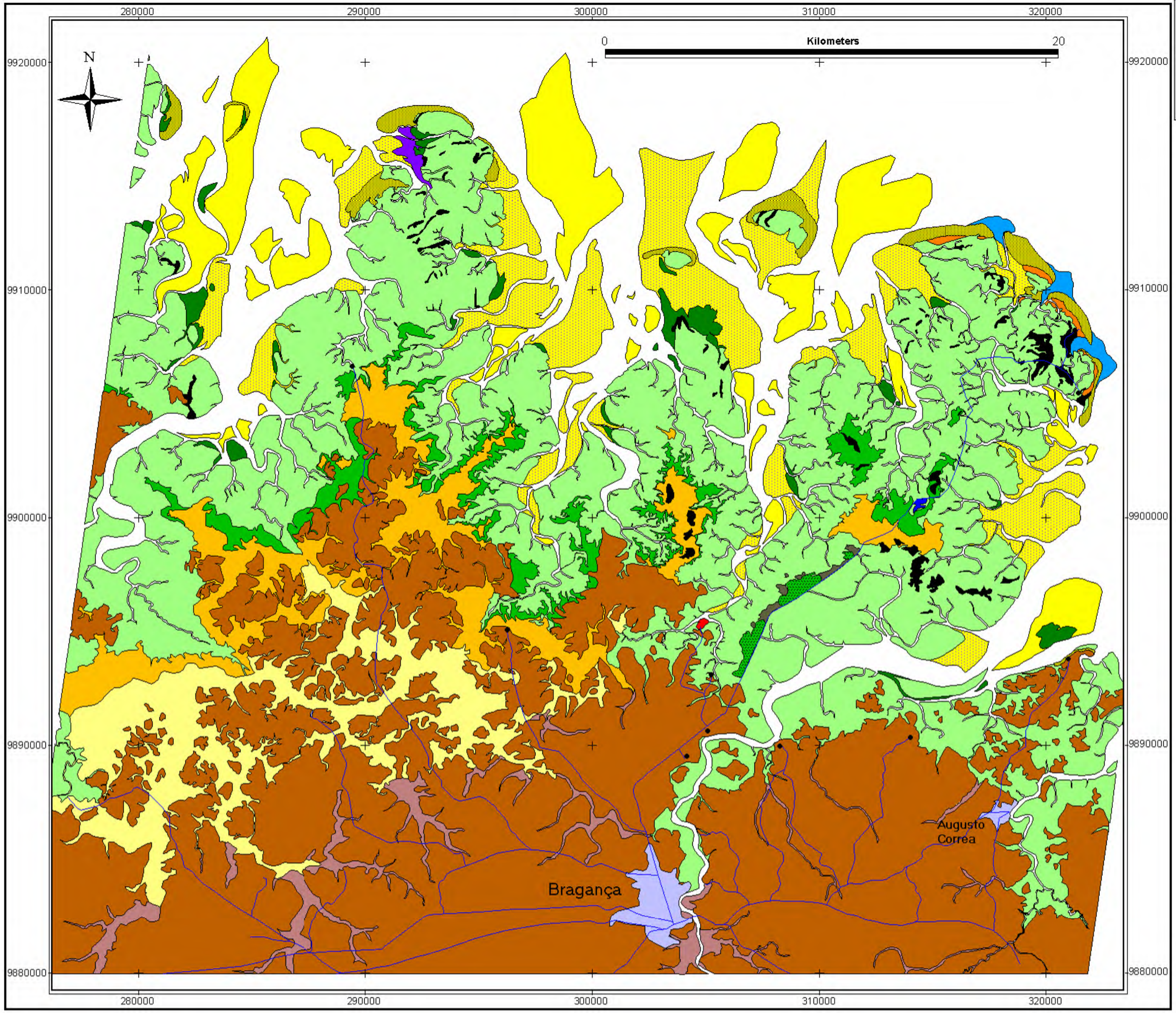
ANEXO B

Mapa Geomorfológico da Planície Costeira de Bragança



Mapa geomorfológico elaborado a partir da interpretação de produtos integrados RADARSAT F1 e Landsat TM . Parte integrante da tese de doutorado de P.W.M. Souza Filho (2000).