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CONTROLES FÍSICOS NA EVOLUÇÃO DAS UNIDADES GEOAMBIENTAIS DA BACIA DO RIO ARAGUAIA, BRASIL CENTRAL

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Tese submetida ao Programa de Doutorado em Ciências Ambientais da Universidade Federal de Goiás, como um dos requisitos para a obtenção do título de Doutor em Ciências Ambientais.

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RESUMO

A bacia hidrográfica do Araguaia, situada no Brasil Central, drena uma área de aproximadamente 384.600 km² onde a cobertura de vegetação está representada por dois biomas brasileiros: o Cerrado e fragmentos do Amazonas. Esta região revela uma grande diversidade de ambientes biológicos, geológicos e geomorfológicos.

O objetivo geral desta pesquisa é fornecer uma revisão completa das Províncias Geológicas da bacia do Araguaia como suporte para a cartografia geomorfológica. Os objetivos específicos, em escalas local e regional, consistiram em: (*i*) definir a evolução tectono-geolólogica; (*ii*) datações radiométricas pelos métodos OSL (*Optically Stimulated Luminescence*), TL (*Thermoluminescence*) e ^{14}C (Radiocarbono) em sedimentos da Bacia Bananal; (*iii*) avaliar os controles das unidades morfo-vegetacionais do bioma Cerrado na planície da Ilha do Bananal.

Imagens digitais de sensoriamento remoto do SRTM (*Shuttle Radar Topography Mission*), MODIS (*Moderate Resolution Imaging Spectroradiometer*), ETM+ (*Enhanced Thematic Mapper Plus*) e dados aerogeofísicos foram processados no ENVI (*Environment for Visualizing Images*). Estes produtos de sensoriamento remoto foram interpretados, compatibilizados com dados de campo e integradas no ambiente GIS (*Geographic Information System*).

Seis Províncias Estruturais com padrões tectônicos e idades distintas foram identificadas: Tocantins, Carajás, Amazônia Central, Paraná, Parnaíba e Parecis. As principais Províncias e Unidades Geológicas regionais estão representadas por: terrenos arqueanos do Maciço de Goiás e do Domínio Rio Maria (terrenos TTG e *greenstone belts*). O Paleoproterozóico consiste de rochas dos domínios Iriri-Xingu e Porto Nacional-Nova Crixás. O Neoproterozóico está representada pelo Arco Magmático de Goiás e as faixas dobradas dos cinturões Araguaia e Paraguai. As bacias sedimentares Paleozóico-Mesozóicas do Paraná, Parnaíba e Parecis e a bacia fluvial Quaternária do Bananal constituem as mais importantes bacias intracratônicas da área do estudo.

Reativações tectônicas generalizadas, principalmente de movimento de soerguimento durante o Cenozóico, favoreceram os processos de denudação com a

geração de três Superfícies de Aplainamento Regional (RPSs). Estas superfícies de erosão estão escalonadas em diferentes altitudes em relação ao nível do mar, denominadas de RPSII (1000-750m), RPSIII (750-550m) e RPSIV (550-180m). Os processos denudacionais causaram a deposição da bacia intracratônica do Bananal, que representa o grande sistema de agradação Quaternária do Brasil Central, com área de aproximadamente 106.000 km². Internamente, esta bacia possui diversas unidades morfo-sedimentares depositadas durante o Pleistoceno Médio (240.000±29.000 a 159.600±18.542 anos) ao Pleistoceno Superior (121.000±15.000 a 17.200±2.300 anos) e durante o Holoceno (9.800±1.100 anos até o presente), quando ocorreram significativas mudanças paleohidrológicas e paleoclimáticas.

Os registros sedimentares em associação com as datações radiométricas (OSL e TL) obtidas em sedimentos fluvial da Formação Araguaia mostraram que a Bacia Bananal esteve dominada por avulsões de rios em dois períodos distintos: durante o Pleniglacial Médio (56.600±5.9000 a 34.000±4.600 anos) e no Pleniglacial Superior (26.400±3.100 a 17.200±2.300 anos). As reativações neotectônicas de falhas antigas (Pré-Cambrianas) que ocorrem associadas à Zona Sismogênica Goiás-Tocantins constituem os principais fatores que geraram avulsões de drenagem, paleocanais (canais abandonados), incisões de rios e a arquitetura sedimentar da Formação Araguaia durante o Pleistoceno Médio e Superior (240.000±29.000 a 17.200±2.300 anos).

A integração de dados multidisciplinares (vegetação, hidrologia, geomorfologia e geologia) indica que o crescimento e a distribuição espacial das fitofisionomias do bioma Cerrado estão controlados principalmente pelas pequenas variações altimétricas do relevo, com a influência da precipitação anual e prolongada inundação sazonal entre janeiro e maio.

As áreas pobremente drenadas e encharcadas nesse período favoreceram o crescimento de tipos de vegetação mais tolerantes à inundação, como as fisionomias mais herbáceas do bioma Cerrado (Campo Limpo e Campo Cerrado), enquanto as inundações por longo tempo inibem o crescimento dos tipos fisionômicos mais densos (Cerradão e Cerrado *stricto sensu*). Portanto, na Planície do Bananal existe uma relação entre unidades de vegetação com determinados tipos geomorfológicos (unidades morfo-vegetacionais).

ABSTRACT

The Araguaia River Basin, located in Central Brazil, drains an area of approximately 384,600km² where the vegetation cover is represented by two Brazilian biomes: the Cerrado and fragments of the Amazon. This region reveals a rich biodiversity and great geodiversity of geological and geomorphologic environments. The aim of this research in large-scale is to provide a thorough review of the geological provinces as a support for the geomorphologic cartography. In local and regional scales, the objectives consisted of defining the tectono-geological evolution, radiometric dating in fluvial sediments of river channels (abandoned and active) from the Quaternary Bananal Basin, and of assessing the morphovegetational controls of the Cerrado biome in the Bananal Island floodplain. Remote sensing images from SRTM (Shuttle Radar Topography Mission), MODIS (Moderate Resolution Imaging Spectroradiometer), ETM+ (Enhanced Thematic Mapper Plus), and aerogeophysical data were processed in ENVI (Environment for Visualizing Images) software, interpreted and compared with fieldwork data and integrated in GIS (Geographic Information System) environment for the geomorphologic mapping, and compatibilized with previous geological information. Six Structural Provinces with different tectonic patterns and distinctive ages were identified: Tocantins, Carajás, Central Amazônia, Paraná, Parnaíba, and Parecis. The main regional Geological Provinces and Geological Units are represented by Goiás Massif and Rio Maria Archean domains (TTG terrains and greenstone belts). The Paleoproterozoic consists of Iriri-Xingu and Porto Nacional-Nova Crixás domains. The Goiás Magmatic Arc and Araguaia and Paraguay belts represent the Neoproterozoic. The Paleozoic-Mesozoic sedimentary basins (Paraná, Parnaíba, and Parecis) and the Quaternary sedimentary basin (Bananal) constitute in large scale the main intracratonic basins of the study area. Generalized tectonic reactivations mainly of uplift movements on Precambrian basement rocks and Paleozoic/Mesozoic sedimentary basin rocks during the Cenozoic

favored the denudation processes with generation of three Regional Planation Surfaces (RPSs), scheduled in different altitudes: RPSII (1000-750m), RPSIII (750-550m), and RPSIV (550-180m above sea level). As a result, these erosive processes caused the deposition of the intracratonic Bananal Basin, which represents the great aggradation system with approximately 110,000km². Internally, this basin contains several morphosedimentary units deposited in the Quaternary and during the Holocene when significant paleohydrological and paleoclimatic changes occurred. Sedimentary registers in association with radiometric dating by OSL (Optically Stimulated Luminescence) and TL (Thermoluminescence) in fluvial sediments from Araguaia Formation showed that the Bananal Basin was dominated by river avulsions in two distinct periods: during the Middle Pleniglacial (56,6±5,9 to 34,0±4,6 ka BP) and in the Upper Pleniglacial (26,4±3,1 to 17,2±2,3 ka BP). Neotectonic reactivations from old faults of the Precambrian basements which occur in association with the GTSZ (Goiás-Tocantins Seismogenic Zone) constitute the main factors that generated drainage avulsions, paleochannels (abandoned channels), and incision of rivers as well as landforms and sedimentary architecture of the Araguaia Formation during the Middle and Upper Pleistocene (240±29 to 17,2±2,3 ka BP). The integration of multidisciplinary data (vegetation, hydrology, geomorphology, and geology) indicates that the growth and the spatial distribution of the phytophysiognomies of the Cerrado biome are controlled mainly by the small altimetric variations of the geomorphologic forms, with an influence of the annual rainfall and prolonged seasonal flooding between January and May. Poorly drained and soaked areas during a longer period favored the growth of more flood-tolerant vegetation such as the herbaceous physiognomies (Cerrado grassland and shrub Cerrado) and inhibited the growth of denser physiognomic types such as the woody plants (e.g. wooded Cerrado and Cerrado woodland). However, in the Bananal Plain exists a relationship between vegetation units with determined geomorphologic units (morphovegetational units).

INTRODUÇÃO GERAL

Esta pesquisa está inserida no Programa de Doutorado em Ciências Ambientais (CIAMB) da Universidade Federal de Goiás (UFG), na área da concentração de Estrutura e Dinâmica Ambiental. Entre muitas ações possíveis podem ser enfatizados o monitoramento e a análise de recursos naturais da geodiversidade e biodiversidade. Este programa tem como uma de suas bases o estudo científico a fim de subsidiar ações de políticas públicas e pesquisa ambiental de naturezas multidisciplinar e interdisciplinar da própria universidade, com ênfase aos aspectos físicos e bióticos do bioma Cerrado, conservação e gerenciamento da biodiversidade.

O Brasil, pais de dimensão continental, com aproximadamente 8.514.877 km², contem uma rica biodiversidade distribuída em seis biomas: Floresta Amazônica, Cerrado, Caatinga, Floresta Atlântica, Pantanal e Pampa. Estes biomas apresentam variações em termos de altitude, latitude, clima e geoambiente.

Neste contexto, a bacia hidrográfica Tocantins-Araguaia tem uma área de cerca de 800.000 km² e uma descarga média anual de aproximadamente 12.000 m^3s^{-1} (Latrubesse, 2003). Os rios deste sistema são os principais contribuintes de água doce que drenam a área do Cerrado. O bioma Cerrado é representado por formações de vegetação bastante complexas que mostram uma variação de fisionomias e composição florísticas, com cerca de 1.5% de plantas endêmicas, considerado como um dos 25 *hotspots* da Terra para a conservação da biodiversidade (Mittermeier *et al*., 1998; Myers *et al*., 2000).

As áreas objeto deste estudo compreendem quatro regiões: (i) toda a bacia hidrográfica do Araguaia; (ii) o médio e alto Bacia do Araguaia; (iii) a bacia sedimentar do Bananal e (iv) a Ilha do Bananal.

A bacia do rio de Araguaia, localizada na região central do Brasil, possui uma área de aproximadamente 384.600 km². Esta bacia é usualmente dividida em três segmentos: Alto, Médio e Baixo rio Araguaia. Nesta área é apresento o estado da arte da geologia através de uma revisão dos trabalhos pré-existentes da geotectônica e geologia com algumas modificações, além da evolução tectono-geológica da área de estudo. A área da bacia do rio Araguaia está representada por seis Províncias Estruturais: Tocantins, Carajás, Amazônia Central, Paraná, Parecis e Parnaíba. As unidades geológicas destas províncias são caracterizadas por uma grande variedade litológica, metamorfismo e deformação gerados desde o Arqueano ao Holoceno e foram desenvolvidas em diversos paleoambientes (marinho, fluvial, lacustrino, desértico e vulcanogênico).

A infracrosta Pré-Cambriana consiste de várias Províncias Geológicas (Maciço de Goiás; domínios Rio Maria, Iriri-Xingu e Porto Nacional-Nova Crixás; Arco Magmático de Goiás e os cinturões Araguaia e Paraguai). As rochas supracrustais estão representadas por três bacias sedimentares Paleozóico-Mesozóicas (Paraná, Parnaíba e Parecis) e uma bacia sedimentar Quaternária bem desenvolvida situada na região do médio rio Araguaia, denominada de Bacia Bananal, com aproximadamente 106.000 km². Na porção norte desta bacia sedimentar ocorre a Ilha do Bananal, com uma área de 20.000 km², que é sazonalmente inundada, considerada por diversos autores como a maior ilha fluvial do mundo.

Os processos de denudação e agradação do alto e médio Araguaia que atuaram durante o Quaternário geraram três Superfícies de Aplainamento Regional e um complexo mosaico de unidades morfo-sedimentares associado à Bacia Bananal. A planície desta bacia é inundada temporariamente, durante a estação chuvosa, por precipitação de águas locais e por saturação do nível freático, que pode ser classificada como *seasonal wetland*.

A Bacia Bananal é uma das mais importantes bacias sedimentares intracratônicas do Quaternário da América do Sul e preserva um bom registro de condições paleohidrológicas. A importância ecológica desta planície fluvial quanto à biota, aos sistemas lacustrinos e os cinturões das planícies fluviais têm chamado à atenção de pesquisadores nesta última década pela sua diversidade e fragilidade. Estes estudos sistemáticos abordaram as variações morfológicas do canal do rio Araguaia, visando quantificar o balanço de erosão/assoreamento do sistema fluvial, com a finalidade de oferecer subsídio científico aos estudos de planejamento ambiental.

Pouco se sabe sobre as interações que controlam a dinâmica paleohidrológica e morfo-sedimentares das planícies fluviais e aluviais durante o Quaternário, bem como os controles abióticos (geologia, geomorfologia e inundações periódicas por longo tempo) na distribuição espacial das unidades de vegetação do bioma Cerrado.

Os registros sedimentares fluviais da Bacia Bananal podem ser usados como indicadores de mudanças paleoclimáticas e paleohidrológicas que ocorreram no Pleistoceno. Durante os processos sedimentológicos e geomorfológicos, as avulsões foram os principais mecanismos que atuaram no Pleniglacial Médio e Superior, incluindo o Último Máximo Glacial (UMG). Conseqüentemente, as datações radiométricas pelos métodos de TL (*Termoluminescence*) e OSL (*Optically Stimulated Luminescence*), realizadas nos sedimentos arenosos da Bacia Bananal, nesta pesquisa, foram importantes porque estes registros constituem as primeiras idades obtidas em grande sistema fluvial tropical do território brasileiro.

Este estudo tem como objetivo geral uma revisão da geotectônica da área da bacia do rio Araguaia. Os objetivos específicos foram: (i) definir os diferentes movimentos tectônicos e a evolução tectono-geológica da área da bacia hidrográfica do Araguaia; (ii) cartografia das unidades geomorfológicas que compõem os sistemas denaducional e agradacional da área da bacia hidrográfica do alto e médio Araguaia; (iii) caracterizar os ambientes paleohidrológicos e os processos que controlam as avulsões de canais dos rios, datando os eventos usando técnicas de datação absolutas (TL e OSL) nos sedimentos da Bacia Bananal; (iv) introduzir a área da Bacia Bananal no contexto paleoambiental tropical da América do Sul; (v) delimitar a distribuição espacial das unidades da vegetação e os controles das unidades morfo-vegetacionais da Ilha do Bananal.

Esta pesquisa foi desenvolvida usando a análise e interpretação de imagens de sensoriamento remoto, tais como: SRTM (*Shuttle Radar Topography Mission)*, MODIS (*Moderate Resolution Imaging Spectroradiometer*), ETM+ (*Enhanced Thematic Mapper Plus*) e dados aerogeofísicos do PGBC (Projeto Geofísico Brasil-Canadá). A interpretação visual foi complementada com atividades de processamento digital de imagens através do *software* ENVI (*Environment for Visualizing Images*) e a integração dos dados foram realizados utilizando um GIS (ArcMap).

A extração das feições topográficas e padrões morfológicos de relevo foram identificados em imagem de relevo sombreado, com diferentes geometrias de iluminação, através de um Modelo de Elevação Digital obtida de imagens SRTM. Estes dados foram integrados com imagens ETM+ do satélite Landsat da estação seca de julho e setembro de 2000.

O mapeamento de tipos fisionômicos do Cerrado, na Ilha do Bananal, foi realizado através de imagens MODIS, do mês de setembro de 2003 (estação seca), utilizando o algoritmo de classificação digital pelo método de Paralelepípedo. A série temporal de imagens MODIS-VI foi adquirida a partir de MOD13Q1 (250m). Cinco recomposições bi-mensal da Ilha do Bananal foram filtradas com base nos meta dados NDVI (QA), para o período de março a outubro de 2003.

Para a coluna geológica foi utilizada a seqüência cronológica do ICS (*International Commission on Stratigraphy*), publicada em 2006, e ratificado pelo IUGS (*International Union of Geological Sciences*).

Três determinações pelo método de Radiocarbono (^{14}C) obtidas em amostras de matéria orgânica (madeira e folha) foram realizadas no *Radiocarbon Dating Laboratory at University of Waikato, Hamilton, New Zealand*. Enquanto quinze amostras de areia de canais de rios abandonados e de barrancos do rio Araguaia foram datadas pelos métodos de OSL e TL no Laboratório de Vidro e Datação da Faculdade de Tecnologia de São Paulo, Brasil.

O trabalho de campo foi realizado em duas etapas durante a estação seca, entre agosto e setembro 2005 e 2006. O estudo foi desenvolvido através de perfis em rodovias e em barco no rio Araguaia. Nesses períodos, foram executadas escavações de trincheiras, furos de trado, descrições de perfis nos barrancos de rios e amostragem de sedimentos para datação pelos métodos de ^{14}C, TL e OSL. A classificação das fisionomias do Cerrado, medidas de fraturas e falhas, bem como informações geológicas e geomorfológicas foram analisadas e estudadas no campo.

Esta tese foi organizada na forma de quatro *papers* científicos: O *paper* I é intitulado *"Geology and regional geomorphology of the Araguaia River Basin, Central Brazil: Part I - Geology"* e será submetido ao *Journal of South American Earth Sciences*. Este artigo constitui o estado da arte da geologia da área da bacia hidrográfica do rio Araguaia e apresenta uma revisão completa dos estudos precedentes de geologia, geotectônica e dos principais recursos minerais desta região.

Também é discutida a evolução tectono-geológica e as evidências dos eventos neotectônicos que ativaram falhas Pré-Cambrianas e que persistem até o presente.

O paper II é intitulado *"Geology and regional geomorphology of the Araguaia River Basin, Central Brazil: Part II - Geomorphology"* e será submetido ao *Journal of South American Earth Sciences*. Este artigo apresenta uma evolução metodológica da cartografia geomorfológica do território Brasileiro. Contempla os grandes sistemas geomorfológicos, isto é, os Sistemas denudacional e Agradacional, cujas evoluções são essencialmente genéticas e dinâmicas. No Sistema Denudacional as Superfícies de Aplainamentos Regionais (RPSs) são individualizadas e escalonadas em diferentes altitudes. Cada RPS pode conter duas ou mais subdivisões, com variados graus de dissecações (muito fortes, forte, médio, baixo e muito baixo), bem como as feições residuais resistentes à erosão (morros e colinas, estruturas dobradas, *hogbacks, inselbergs*, etc.). Entre duas RPSs geralmente ocorre uma Zona de Erosão Recuante.

O paper III, intitulado *"Paleohydrological characteristics and river channel avulsions during the Middle and Upper Pleniglacial in the Bananal Basin, Brazil"* foi submetido a *Quaternary Science Reviews*. Esta pesquisa estuda as avulsões de rios associadas às atividades neotectônicas e mudanças paleoclimáticas que ocorreram na bacia sedimentar do Bananal durante o Pleistoceno Médio e Superior. As datações radiométricas foram obtidas em amostras da areia através dos métodos OSL e TL. As idades de ^{14}C foram obtidas em amostras de matéria orgânica de estratos de barrancos do rio Araguaia.

O *paper* IV é intitulado *"Relationships between vegetation, geomorphology, and hydrology in the tropical wetland region of Central Brazil: the Bananal Island"*. Este artigo tem um caráter multidisciplinar e interdisciplinar e apresenta os relacionamentos entre as variáveis físicas que controlam a distribuição espacial dos tipos fisionômicos do bioma Cerrado na Ilha do Bananal. O uso de uma série temporal de imagens MODIS-VI e Landsat ETM+ suportados por dados de campo permitiram o mapeamento da distribuição espacial das fitofisonomias do Cerrado e a relação entre as unidades geomorfológicas e as unidades de vegetação.

CONCLUSÕES

A bacia hidrográfica do Araguaia, com uma área aproximada de 384.000 km², ocupa uma região de transição entre os biomas Cerrado e Amazônico, na região central do Brasil. Esta bacia apresenta evolução geológica, geomorfológica, paleohidrológica e morfo-vegetacional bastante complexa cujos processos ocorreram através de períodos geológicos de grande escala até os presentes dias.

Nesse contexto, a infracrosta Pré-Cambriana reflete histórias policíclicas do tectonismo e metamorfismo do seu embasamento na região de estudo. Os terrenos mais antigos consistem de rochas com idade e composição muito diversificadas, tais como os terrenos Arqueanos TTG e *greenstone belts* (~3.0-2.7 Ga); ortognaisses Paleoproterozóicos e seqüências vulcano-sedimentares (~2.2-2.0 Ga); cinturões dobrados metamórficos e arcos magmáticos Neoproterozóicos (~900-600 Ma).

O domínio supracrustal contém várias e extensivas bacias sedimentares intracratônicas geradas no Paleozóico e Mesozóico (Paraná, Parnaíba e Parecis), bem como a bacia Quaternária do Bananal depositada durante o Pleistoceno Médio e Inferior (~240.000 a 17.000 anos). Tanto as rochas da infracrosta como a supracrosta foram geradas em distintos paleoambientes (marinho, fluvial, lacustrino e desértico). Em particular, as rochas do embasamento foram afetadas por três eventos tectono-metamórficos do Pré-cambriano: Ciclo Jequié (~2.7 Ga), Ciclo Transamazônico (~2.0 Ga) e Ciclo Brasiliano (900-520 Ma). O ciclo orogenético Brasiliano, o mais expressivo na região, é caracterizado por orogenia relacionada a colisões associados à falhas de empurrão de baixo ângulo (Faixas Araguaia e Paraguai) e um expressivo sistema de falhas transcorrestes com direção N20-40E de alto ângulo, denominado de Lineamento Transbrasiliano.

Reativações tectônicas que atuaram nestes sistemas de falhas Pré-Cambrianas durante o Cenozóico se estenderam até o Neogeno. Essas atividades tectônicas podem ter sido o verdadeiro gatilho geomorfológico que favoreceram os processos de erosão e desenvolvimento de três unidades denudacionais, denominadas de Superfícies de Aplainamento Regional (RPSII, RPSIII e RPSIV) e Zonas de Erosão Recuantes. Associados às RPSs ocorrem estruturas dobradas, *hogbacks, inselbergs,* morros e colinas que representam remanescentes do embasamento resistentes à erosão, tais como: granitos, quartzitos, calcários, etc. Estas superfícies estão escalonadas em diferentes altitudes, com quotas que variam entre 1000 e 750 m (RPSII), 850 e 550 m (RPSIII) e 550 e 165 m (RPSIV).

O sistema agradacional, representado pela Bacia Bananal, é constituído por um complexo mosaico de unidades morfo-sedimentares que inclui as planícies fluviais e aluviais atribuídas ao Pleistoceno Médio e Superior (Formação Araguaia) e Holoceno (depósitos aluviais). As unidades geomorfológicas mais representativas deste sistema são constituídas por: (i) Planície Fluvial Ligeiramente Dissecada; (ii) Planície Fluvial com *Scrolls* de Meandro; (iii) Planície Fluvial com Padrão Meandrante; (iv) Cinturão Fluvial Abandonado; (v) Cinturão Fluvial Abandonado com Rio de Meandros Subadaptados (*Underfit Rivers*).

O alagamento na Planície Bananal é independente do transbordamento das grandes cheias do rio Araguaia. A inundação é resultado de três fatores: (i) alta precipitação entre janeiro e março; (ii) cobertura superficial da planície com predominância de solo argiloso (baixa permeabilidade); (iii) relevo muito plano com baixa altitude (baixo estrutural) que funciona como uma extensiva planície de acumulação de água tanto superficial como subterrânea.

As características litológicas, estruturais e hidrológicas conferem a Bacia Bananal, mais especificamente a Ilha do Bananal, o modelo de um grande reservatório de águas subterrâneas.

Mudanças tectônicas e climáticas que ocorreram desde o Ultimo Interglacial influenciaram na evolução da presente paisagem da Planície Bananal. O processo de sedimentação da Formação Araguaia foi importante durante o Pleistoceno Médio e Superior, entre 240.000±29.000 e 17.200±2.300 anos. Nesse contexto, idades OSL e TL obtidas em areias de canais abandonados de rios permitiram a interpretação de que as avulsões dos rios na Planície Bananal foram mais intensivas durante o Pleniglacial Médio ou estágio isotópico 3, entre 56.600±5.900 e 34.000±4.600 anos. Este processo avulsivo prolongou até o Pleniglacial Superior ou estágio isotópico 2, entre 26.400±3.100 e 17.200±2.300 anos. A maior concentração de pontos de avulsões ocorre na porção da baixa Bacia Bananal (região da Ilha Bananal), com 81% ou 56 pontos de avulsões. Avulsão foi o principal mecanismo nesse tempo, gerando um padrão *anabranching* de canais ativos, paleocanais e rios subadaptados (*underfit rivers*).

Nas áreas mais baixas da Planície Bananal, como na Ilha do Bananal, onde a superfície plana é pobremente drenada e encharcada por um longo período (dezembro a maio) favorece o desenvolvimento de vegetação mais tolerante à inundação, como os tipos herbáceos do bioma Cerrado (Campo Limpo e Campo Cerrado). Consequentemente, esse ambiente encharcado inibe o crescimento dos tipos fisionômicos mais densos (Cerrado s.s. e Cerradão). Desta forma, a distribuição espacial das fitofisionomias do bioma Cerrado na Ilha do Bananal é controlada, principalmente, por inundações prolongadas, variações das formas geomorfológicas e secundariamente por avulsões dos cinturões fluviais (eventos neotectônicos).

Finamente, os registros obtidos na Planície Bananal lançam novas luzes para o entendimento das condições paleohidrológicas do Brasil Central e fornecem importantes informações para a área de transição entre os biomas Cerrado e Amazônico.

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PAPER I

Geology and regional geomorphology of the Araguaia River Basin, Central Brazil: Part 1 – Geology*

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Geology and regional geomorphology of the Araguaia River Basin, Central Brazil: Part 1 - Geology

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Abstract

A general review of existing data with some updates and modifications on geotectonics and geology of the Araguaia River Basin in Central Brazil region is presented. In this region, the geology consists of rocks with ages, evolution and distinctive structural patterns, which were generated in varied paleoenvironments (marine, fluvial, lacustrine, desertic, and volcanogenic). The oldest rocks consist of Archean to Paleoproterozoic ensialic basement (Goiás Massif, Rio Maria, Iriri-Xingu, and Porto Nacional-Nova Crixás). The Neoproterozoic supracrust rocks comprise the magmatic island arcs (Goiás Magmatic Arc) that limit these old nuclei and metasedimentary folded belts (Araguaia and Paraguay belts). These mobile belts were amalgamated during the Brasiliano Cycle (630-899 Ma) through the continental collision between the Amazon and the São Francisco cratons. Fault systems control the gold, copper-gold, and emerald deposits associated to the greenstone belts and metavolcano-sedimentary sequences. The geological development of the intracratonic sedimentary basins of Paraná and Parnaíba provinces evolved during the Paleozoic and Mesozoic with a deposition that was influenced by the geodynamics of the Gondwana. Fluvial sediments of the Bananal Basin characterize the Quaternary in the region. The Precambrian regional structure is made up of several continental blocks limited by major crustal sutures that are associated with strike-slip faults and thrust fault systems. Evidences of neotectonic events are related to a shear zone reactivated in Paleozoic and Cenozoic, whose movements persist up to the present day through the Goiás-

Tocantins Seismogenic Zone (GTSZ). Digital data from Landsat ETM, SRTM, and aerogeophysical images were processed, interpreted and compared with field data and integrated in GIS environment for the geological and tectonic mapping. This study has as its main objective the use of interpretation techniques of remote sensing products in the definition and characterization of the geological and deformational properties of the Araguaia River Basin region.

Keywords: Geology; Geotectonics; Araguaia River Basin

1. INTROCUCTION

Significant advancements were obtained on the geology of Brazil during the last decades. From the cartographic viewpoint the information was united in the recent work of the Geological Survey of Brazil, published in 2003 through the Geology, Tectonics and Mineral Resources of Brazil, with maps at 1:2.500.000 and 1:1.000.000 scales, in GIS environment. It synthesizes the geological information amassed over 30 years by this company, universities, and mining companies.

Despite these significant advancements, the geology of Brazil's central region generally possesses fragmented and punctual information and in many areas the scientific knowledge is quite scarce. In particular, the geological environments of economic interest have received greater attention due to high mining potential, for example, the Greenstone Belt areas (Crixás, Goiás Velho, Guarinos) and the Mafic-Ultramafic Complexes of Goiás (Barro Alto, Niquelândia, and Canabrava).

On the other hand, the Araguaia River is the biggest fluvial system that drains the Cerrado biome. One must be reminded that 75% of the Cerrado savanna has suffered deforestation that has been accelerated due to the expansion of the agricultural frontier since the 1970s.

Moreover, inside the Araguaia fluvial basin can be found the intracratonic basin constituted by Quaternary sediments, called Bananal Basin, with approximately 106,000km² that extends along 800km of length. In the north portion of this fluvial basin stands the Bananal Island plain with 20,000km². Bananal Island is an area of environmental conservation that contains Araguaia's National Park and some aboriginal reserves, where valuable information on the paleoenvironment of the Quaternary and of the present can be found; therefore, it represents the last still preserved regions of the Cerrado biome.

A good part of the existing information on the geology of the Araguaia Basin and of the Center-West, in general, is not available in the international literature. Generally, they are internal reports or published in regional symposia or national congresses by government agencies, mining companies and universities, including academic theses.

The geographic clipping in the Araguaia fluvial basin is justified from the geological viewpoint because it allows for the understanding of the geological reorganization of the landscape of the Late Cenozoic until acquiring the present physiognomy, which caused the formation of the biggest Brazilian intracratonic sedimentary basin in recent times, the Bananal Basin. Apart from that, the geographic clipping is also justified because, in Brazil, hydrographical basins represent a basic element in the management of natural resources and the territorial order where the geological study is a fundamental part.

The presentation of a review of the existing data of the entire geological column and their geotectonic characteristics is fully justified in order to supply the international scientific community with an integrated vision of this enormous and important region in a succinct form and a set of bibliographical references of Brazil to be divulged.

In this form, this study has as general objective a review of the preexisting works of geology with some data updates. The specific objectives were to characterize the main evidences of the different tectonic movements and to define the tectono-geological evolution.

2. STUDY AREA

This study was developed in the Araguaia River Basin, in Brazil's central region. With an area of approximately 384,600 km² (Fig. 1), it is located between meridians

47º47`34`` and 55º24`08`` of west longitude and parallels 5º22`15`` and 18º17`12`` of south latitude.

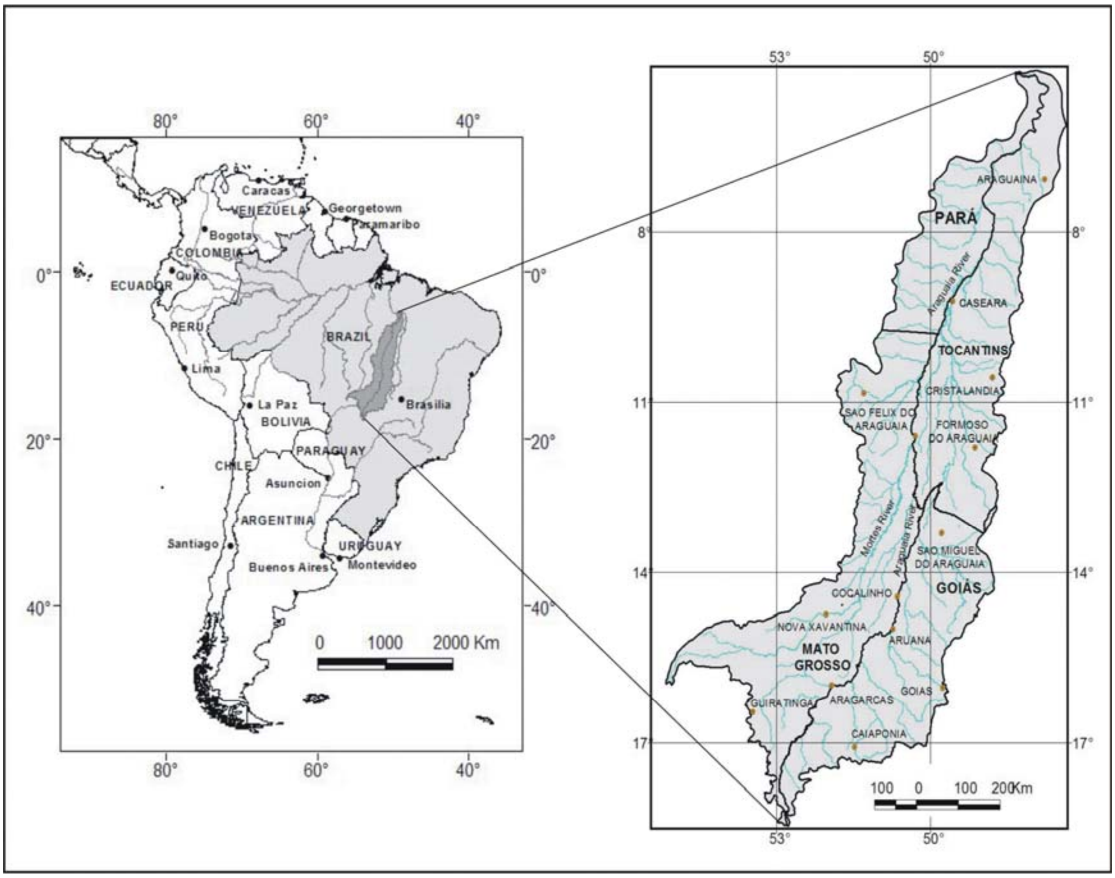

Fig. 1 - Location of the study area in Central Brazil.

In the study region there is vegetation of the Cerrado and Amazon biomes. The tropical rainforest of the Amazon biome is dominant in the southeast of Pará state. The Cerrado is more expressive and consists of Cerrado woodland, wooded Cerrado, shrub Cerrado and Cerrado grassland physiognomies, as well as gallery forest along the floodplain belts. This region underwent an intense occupation process during the 70s and 80s, with deforestation of the Cerrado and Amazon biomes for the implantation of agriculture and cattle breeding.

The climate corresponds to the Aw in Koppen´s Climatic Classification. It is characterized by two well-defined seasons: six months of wet condition, from November to March, and six months of dry condition, from April to September. The annual mean rainfall of the region varies from 1,400 to 2,200 mm/year. The annual mean temperature increases northward, varying between 22ºC and 26ºC, with the maximum (38º) occurring in August and September and the minimum (22ºC) in June.

The Araguaia River is usually divided into three main parts, according to the hydrologic conditions and river regimes: Upper, Middle, and Lower Araguaia. Phanerozoic sedimentary rocks of the Paraná Province characterize the geology in Upper Araguaia Basin. The Middle Araguaia is constituted predominantly by Quaternary Bananal Basin sediments and subordinately by Precambrian basements of the Goiás Massif, Goiás Magmatic Arc, Porto Nacional-Nova Crixás, and Araguaia and Paraguay Belts. The Low Araguaia is represented by Araguaia Belt and Paleozoic/Mesozoic covers of the Parnaíba Province, as well as Precambrian basements of the Amazon Craton (Rio Maria and Iriri-Xingu Domains).

3. MATERIALS AND METHODS

The cartographic representation of the structural provinces was obtained mainly from GIS Project of Brazil (Bizzi et al., 2003), at 1:1.000.000 scale, with some adaptations and data updates. For the vertical or chronologic sequence of geological units in a region, we used the geological column from International Commission on Stratigraphic (ICS) and published in 2006.

For the elaboration of the geotectonic and structural maps, we used visual interpretation techniques of the image spatial attributes of Landsat ETM+ (Enhanced Thematic Mapper Plus) and interferometric data from SRTM (Shuttle Radar Topography Mission), as well as aerogeophysical data (magnetometry, gamma-ray spectrometry, and gravimetry). This interpretation was complemented with activities of digital processing of images (ENVI) and integration with a Geographic Information System (ArcMAP). Through the StereoNet for Windows Version 3.03 was constructed rose diagrams of the structural lineaments extracted from remote sensing products and field data.

Fieldwork was developed during 35 days in the dry season, in order to know and describe characteristics of the morphological features, types of rocks and fracture data, excavation of trenches, drill holes and profiles in Araguaia River with the support of a boat. This fieldwork was carried out in two periods, the first from August to September 2005 and the second in August 2006.

4. STRUCTURAL PROVINCES

Almeida et al. (1977, 1981) introduced the concept of Structural Province and identified ten provinces in the Brazilian territory. Six structural provinces cover the study area and are discussed herein, namely Tocantins, Carajás, Central Amazônia, Paraná, Parecis, and Parnaíba (Fig. 2). These provinces were individualized according to geochronological and geophysical-structural models. Their distributions are in agreement with the geochronological provinces established in previous works (Cordani *et al.*, 1979; Almeida *et al.*, 1977, 1981; Pimentel et al., 1991; Pimentel and Fuck, 1992; Tassinari et al., 1997; Cordani and Sato, 1999; Lacerda Filho et al., 1999; Pimentel et al., 2000, 2003; Santos, 2000, 2003; Bizzi et al., 2003).

4.1. Tocantins Province

The Tocantins Province is the most extensive geotectonic unit ca. 63% of the study area, situated in the eastern part of the area (Fig. 2). The Province corresponds to a large Neoproterozoic orogenic zone related to the Brasiliano-Pan African orogenesis. This orogeny was formed between 1.0 Ga and 0.6 Ga and is represented by the Brasília, Araguaia, and Paraguay belts and by large juvenile magmatic arcs with ca. 0.9-0.64 Ga, like Mara Rosa and Arenópolis arcs (Pimentel et al., 2000; Dardenne, 2000). The main characteristics of the structural and geological provinces are summarized in Table 1 and discussed below.

The basement of the study area is made up of Archean granite-greenstone (Goiás Massif) and Paleoproterozoic terrains (Porto Nacional-Nova Crixás and Rio dos Mangues Complex). These cratonic fragments took part in the collision between the large continental masses of the Amazonian and São Francisco cratons (Cordani and Sato, 1999; Pimentel et al. 2003). Several works consider the subdivision of the Tocantins Province (Almeida et al., 1977; Fuck et al., 1993; Fuck, 1994; Pimentel et al., 2000). However, in this paper we used the division of the Geological Survey of Brazil (Bizzi et al., 2003) with adaptations and some alterations.

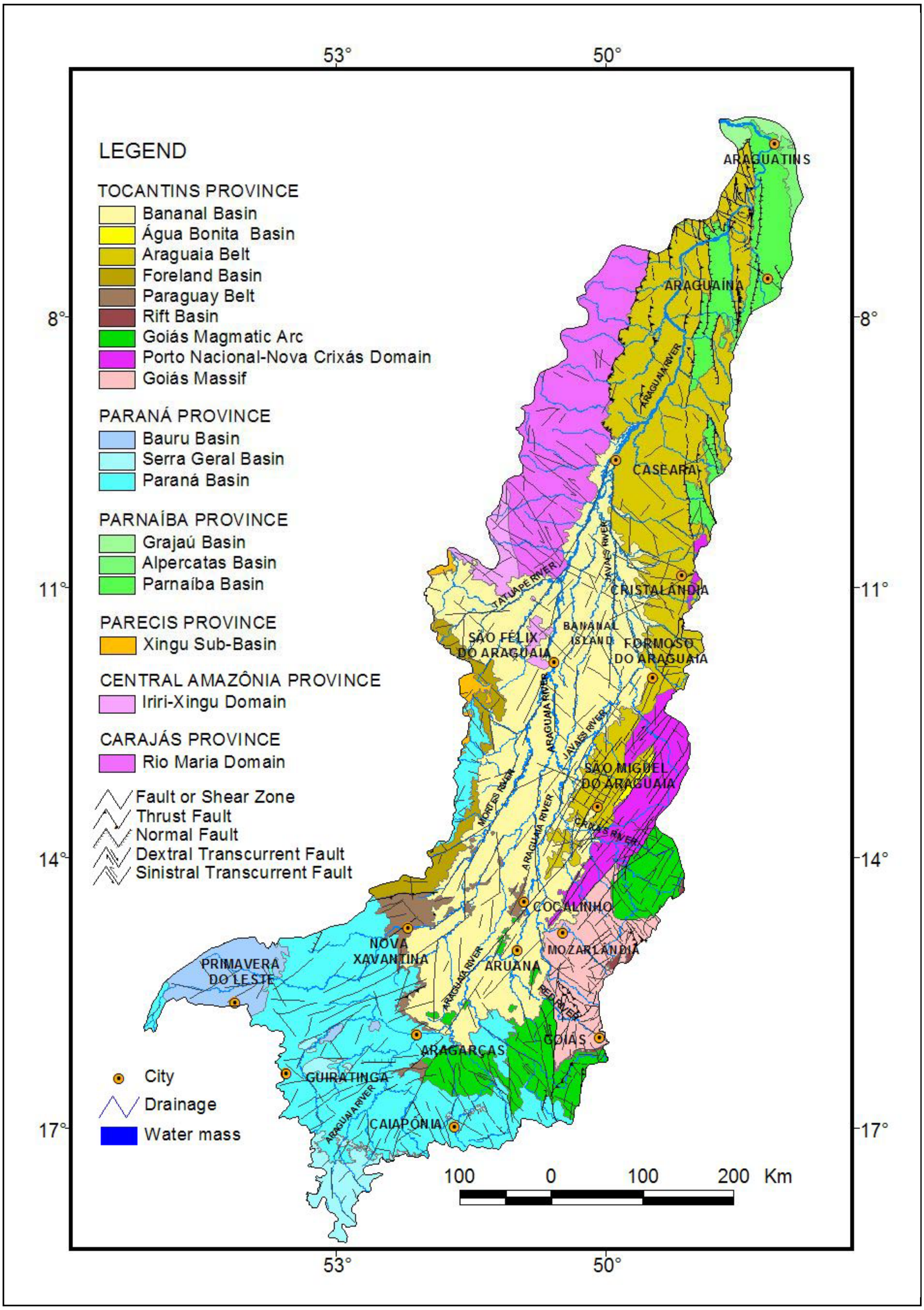

Fig. 2 - Tectonic and geological domains in the Araguaia River Basin.

Table 1 - The main characteristics of the structural provinces of the study area.

STRUCTURAL PROVINCES	GEOLOGICAL PROVINCES	GEOLOGICAL UNITS	PERIOD/EPOCH/ AGE	AREA (Km^2)	(%)
TOCANTINS	Bananal Basin	Araguaia Formation	Quaternary	105.965	27,46
	Água Branca Basin	Agua Bonita Formation	Silurian/Devonian	608	0,16
	Araguaia Belt	Couto Magalhães, Morro do Carom, and Xambioá formations	Neoproterozoic (Tonian)	55.865	14,75
	Foreland Basin	Diamantino Formation	Neoproterozoic	11.475	2,73
	Paraguay Belt	Cuiabá and Nova Xavantina groups	Neoproterozoic (Cryogenian)	11.285	2,92
	Goiás magmatic Arc	Orthogneissis of the West of Goiás and Metavolcanosedimentary Sequences (Bom Jardim, Iporá-Amorinópolis, Arenópolis-Piranhas, Jaupaci, Anicuns-Itaberaí, Mara Rosa) and Syn-Late orogenetic granites	Neoproterozoic 630-899 Ma U-Pb (SHRIMP)[1,2]	21.342	5,53
	Rift Basin	Serra da Mesa Group	Paleoproterozoic	481	0,12
	Porto Nacional-Nova Crixás Domain	Campo Maior and Rio dos Mangues complexes	Paleoproterozoic 2.12-2.0 Ma (Pb-Pb)	14.237	3,69
	Goiás Massif	Greenstone belts and TTG terrains: Granitic-Gneiss Complexes (Uvá, Caiçara, Anta, Caimar, Hidrolina, Muquém) and greenstone belts (Crixás, Goiás, Pilar de Goiás, and Guarinos groups).	Meso to Neoarchean 2.85-2.70 Ga U-Pb (SHRIMP)[1,2] 3.0 ± 0.14 Ga (Sm-Nd)[3]	21.352	5,52
PARANÁ	Bauru Basin	Bauru Formation	Cretaceous	9.824	2,54
	Serra Geral Basin	Botucatu and Serra Geral formations	Jurassic-Cretaceous	7.548	1,95
	Paraná Basin	Aquidauana, Corumbataí, Furnas, Ponta Grossa, and Vila Maria formations	Silurian-Triassic	64.045	16,59
PARNAÍBA	Grajaú Basin	Itapecuru and Codó formations	Cretaceous	1.790	0,46
	Alpercatas Basin	Pastos Bons and Corda formations (Mearim Group) and Mosquito Formation	Jurassic	1.395	0,36
	Parnaíba Basin	Pimenteiras, Cabeças, Longá, and Poti formations (Canindé Group). Piauí, Pedra-de-Fogo, Motuca, and Sambaíba formations (Balsas Group)	Devonian-Carboniferous	18.724	4,85
PARECIS	Parecis Basin	Salto das Nuvens and Ronuro formations	Cretaceous-Neogene	1.728	0,45
CENTRAL AMAZONIA	Iriri-Xingu Domain	Iriri Group, Xingu Complex, and Tarumã Granite	Paleoproterozoic 1.8-1.7 Ga U-Pb (SHRIMP)[4]	4.960	1,28
CARAJÁS	Rio Maria Domain	TTG intrusons, Quixadá, and Tocandera formations and Sapucaia Group	Mesoarchean 3.0-2.8 Ga U-Pb (SHRIMP)[4,5]	33.752	8,74

References by ages: [1]Pimentel et al. (2000); [2]Pimentel and Fuck (1994); [3]Fortes et al. (2002); [4]Santos et al. (2000); [5]Santos (2003)

4.1.1. Goiás Massif

Goiás Massif constitutes the oldest tectonic unit in the study area. This Meso to Neoarchean basement covers an area of ca. 21.300km^2 or 5,5% of the Tocantins Province. Goiás Massif is constituted by several greenstone belts (Crixás, Pilar de

Goiás, Guarinos, and Goiás Velho groups). This geotectonic unit presents the following units from base to top: (a) komatiitic and tholeiitic ultramafic metavolcanic rocks; (b) tholeiitic metabasaltic rocks; (c) detrital and chemical metamorphic sedimentary rocks, sometimes associated with pyroclastic rocks (Kuyumijian and Dardenne, 1982; Danni and Jost, 1986; Fortes and Nilson, 1991; Magalhães and Nilson, 1993; Jost et al. 1995). The komatiitic rocks of these greenstone belts were dated and produced Sm-Nd isochronic ages of 2.82 ± 0,098 Ga (Arndt et al., 1989) and 3.00 ± 0,09 Ga (Fortes et al., 2002) **.**

The Crixás greenstone belt is the most preserved, revealing pillow lava structures and spinifex textures. The main deposits of Au occur in association with Crixás greenstone belt, called Mine III/New Mine with 65t Au and exploited since 1990 with an annual output of 4,5t Au (Yamaoka and Araújo, 1988).

The greenstone belts are limited by TTG (tonalite, trondhjemite, and granite) allochthonous blocks through shear zones or thrust faults of mainly NW-SE trend, named Uvá, Caiçara, Anta, Caimar, Muquém, and Hidrolina. These granite-gneissic complexes presented U-Pb ages varying between 2.84-2.70 Ga (Queiroz et al., 1999; Pimentel et al., 2000) and were affected by three tectono-metamorphic events with U-Pb ages at 2.7 Ga and 2.01 Ga (Pimentel et al., 2000) and 590 Ma (Queiroz et al., 1999) which correspond, respectively, to Jequié, Transamazonian, and Brasiliano orogenic cycles.

4.1.2. Porto Nacional-Nova Crixás Domain

The interest area of this study occupies part of the Porto Nacional-Nova Crixás Domain, situated in the eastern portion of the researched area. This domain covers a middle and high-grade gneiss belt of NE-SW trend, which is mostly unknown in the south segment. Porto Nacional-Nova Crixás Domain is represented by the following units: (1) gneiss and granulite rocks of the Porangatu Complex; (2) orthogneiss and calci-sillicate rocks of the Rio dos Mangues Complex with a U-Pb SHRIMP age of 2.2 Ga (Fuck et al. 2001) and Pontal Orthogneiss with a U-Pb age at 2.15 Ga, dated by Gorayeb et al. (2000); (3) the volcano-sedimentary sequence of the Rio do Coco

Group and granitoids of the Serrote Suite of extensional environment with an age of 1.85 Ga (Souza and Moura, 1996).

In the Gurupi region, the Rio dos Mangues Complex is constituted by granodiorite and tonalite rocks that are generally mylonitized and deformed by ductile shear zone of N20º-40ºE direction, related to dextral strike-slip fault from Transbrasiliano Lineaments (Frasca et al., 2005). These rocks reveal calci-alkaline affinity, interpreted as accretionary magmatic arc to the Sanfranciscana microplate, with important mineralizations of tourmaline, garnet, and cyanite generated during the Brasiliano Cycle at 551±4 Ma in garnet (Frasca et al., 2005).

4.1.3. Rift Basin

The Rift Basin related to Statherian taphrogenesis evolved towards an intracratonic basin in Paleo to Mesoproterozoic, during which it was filled by sediments and continental bimodal volcanism with intrusions of anorogenic granites (Pimentel et al., 1991). This basin is characterized by important post-rift marine transgressions, constituted by beds of quartzite and metapelites deposited in shallow platform, related to Serra da Mesa and Serra Dourada groups that constitute the metamorphic equivalent of the marine sediments of the Araí Group (Braun and Baptista, 1978; Marini et al., 1984; Dardenne, 2000) and of the Natividade Group (Gorayeb et al., 1988).

The more expressive outcrops occur in Serra Dourada, located in the southern to southwestern regions of Goiás city, where metasediments constitute mountains in NE-SE to E-W trend limited by thrust faults. In this region can be found the basal unit of the Serra Dourada Group that consists of quartzite, arkose-quartzite and levels of intraformational metaconglomerate.

4.1.4. Goiás Magmatic Arc

The Neoproterozoic Goiás Magmatic Arc comprises a series of juvenile magmatic arcs defined mainly by frontal trusting and lateral ramp systems of more than one episode of deformation during the Brasiliano Orogenic Cycle, between 900 and 630 Ma (Pimentel and Fuck, 1992, Pimentel et al., 1991, Pimentel et al., 1997; Junges et al., 2002). These arcs are mostly formed by Neoproterozoic island-arc terrains consisting of tonalitic to granodioritic orthogneisses, volcano-sedimentary associations and late- to post-orogenic intrusions of granites and gabbros (Pimentel et al., 1999).

According to Delgado et al. (2003) there are three large-scale tectonic episodes in the Brasiliano Cycle: (i) The Brasiliano Orogenic System I (900-700 Ma), with a collisional peak at 790 Ma, encompasses the first subduction-related plutono-volcanic intra-oceanic accretionary arcs; (ii) The Brasiliano Orogenic System II (640-610 Ma) is characterized by collision-related orogens with a metamorphic peak at 632 Ma with recycling of crustal material and limited juvenile accretion; (iii) The Brasiliano Orogenic System III (600-520 Ma) comprises the most recent system of orogens. This system marks the transition to a stable environment in the South American Platform.

The Goiás Magmatic Arc has been identified in two localities, separated by Neoarchean granite-greenstone terrains (Fig. 2), called Mara Rosa Arc in the northern segment and Arenópolis Arc in the southern segment (Pimentel et al., 2000; 2003). The Goiás Magmatic Arc contains several deposits of Au and Au-Cu originated in the diverse periods of evolution. Oliveira et al. (2000) included these mineralizations in the Arenópolis-Mara Rosa Gold-Copper Belt, where occur the deposits of Au (Posse and Fazenda Nova), Cu-Au (Chapada and Bom Jardim), Au-Bi (Mundinho), and Au-Ag-Ba (Zacarias). In addition, in the Mara Rosa Magmatic Arc contains important emerald “garimpos” (Santa Terezinha de Goiás) that have been exploited since 1981 with an output estimated at 150 to 200t of emeralds and green beryls (Biondi, 1990).

In this context, the Mara Rosa Magmatic Arc is formed by metatonalite and metadiorite affinity rocks associated with narrow NW-SE belts of volcano-sedimentary sequences; these are constituted of basic to felsic metavolcanic rocks and detrital to chemical metasedimentary rocks metamorphosed in greenschist to amphibolite facies conditions (Arantes et al. 1991). Pimentel et al. (1997), by means of the U-Pb SHRIMP method, dated the Posse Gold Mine with values of 862 ± 8 Ma (crystallization age for the felsic rock) and 632 ± 4 Ma in titanite (metamorphic age of the Brasiliano II). The dominant structural pattern of the Mara Rosa Arc is oriented in the N20-30E trend, where the rocks are folded and deformed by thrust fault and strike-slip-faulting of the Transbrasiliano Lineaments.

The Arenópolis magmatic arc is known in southwestern and southern regions of Goiás city and contains a series of coalescent arcs and volcano-sedimentary sequences. These sequences occur as narrow bodies that are elongated parallel to the NNW and NNE strike-slip faults between Bom Jardim de Goiás and Firminópolis (Pimentel et al., 2000).

These belts are separated by orthogneiss terrains (granite, tonalite and granodiorite) generally with mylonitic structure. In this region are represented from west to east by the following sequences: Bom Jardim de Goiás and Arenópolis-Piranhas with U-Pb age of 928±8 Ma (Pimentel et al., 1991) and metamorphic age of 594 Ma; Iporá-Amorinópolis encompasses the zircon U-Pb age of 636 ± 6 and 597 ± 5 Ma (Rodrigues, 1996) which represents the end of the Brasiliano II; Jaupaci Sequence reveals a zircon U-Pb age dated by Pimentel and Fuck (1994) at 764±14 Ma; it represents a formation age and 600 Ma metamorphism age of the Brasiliano II and Anicuns-Itaberaí with an age of 860 Ma.

4.1.5. Araguaia Belt

The Araguaia Belt in the context of the Tocantins Province is located in its northern portion and reveals a general N-S direction, with a dimension around 1,000 km of length and 150 km of average width. It constitutes the north extension of the Paraguay-Araguaia Belt bordering the eastern part of the Amazon Craton (Central Amazon and Carajás provinces). In the area of study, the Araguaia Belt is represented by its southern segment, where it is constituted mainly by pelite-psammite metasedimentary rocks, locally with carbonate facies, attributed to the Baixo Araguaia Group (Couto Magalhães, Xambioá, Pequizeiro, and Campo Maior formations). The metamorphic grade varies from low greenschist to amphibolite facies conditions (Souza and Moreton, 1995; Frasca and Araújo, 2001; Alvarenga et al., 2000).

Remnants of Proterozoic oceanic crust occur in restricted areas that are constituted by mafic-ultramafic rocks of the Serra do Tapa and Quatipuru (Souza e

Moreton, 1995), as well as diverse granitic intrusions. Colméia, Lontra, and Xambioá complexes represent dome structures of gneissic basement. The Xambioá Complex presents a Pb-Pb age of 2,85 Ga (Moura e Souza, 1996; Moura e Gaudette, 1999).

This orogenic belt possesses a prominent planar foliation, generated by progressive tangential efforts, directed westwards against the Amazon Craton. This tectonic movement provided the development of the ductile shear zone with a displacement of surfaces and shear structure of low angle (frontal ramps of N-S direction) developed during the Brasiliano Orogenic System II (650-600 Ma). Structural analyses suggest a westward crustal shortening and tectonic transport towards NW, indicating an oblique collision (Brito Neves et al., 1999).

4.1.6. Paraguay Belt

It constitutes a mobile belt situated in the occidental portion of the Tocantins Province (Almeida et al. 1977), deposited in the border to the south of the Amazon Craton and to the east of the Apa River Block, in Mato Grosso do Sul. This geological province is characterized by a sequence of metasedimentary rocks that are folded and deformed by high angle reverse faults during the Brasiliano Orogenic System III, between 590-500 Ma, with post-orogenic granitic magmatism represented by granites of the São Vicente Suite (550-500 Ma).

Alvarenga and Trompette (1993) separate these metasediments of low-grade metamorphism (Cuiabá Group) into two structural zones: lower detrital unit and claciomarine/turbiditic unit. The lower unit is composed of graphitoid phyllite, phyllite, quartzite, and dolomite; and the upper unit represented by a stratigraphic sequence deposited during the glaciation of the end of the Upper Proterozoic, formed for dyamictite and turbidite.

In the area under study, metasedimentary rocks of this geological province occur in a narrow belt between the sediments of the Paraná and Bananal basins, located in the south portion of the study area. In the New Xavantina region occurs a sequence of metavolcano-sedimentary rocks correlated to the basal portion of the Cuiabá Group. This sequence consists of metavolcanic rocks of mafic to intermediate compositions, intercalated with cherts and BIFs in the base, while the upper portion is dominated by pelitic-psammitic metasediments. According to Martinelli (1998), important auriferous mineralizations in the “Garimpo” Araés (Nova Xavantina) can be found in quartz veins associated to the dextral transcurrent fault, with an ENE-WSW trend. However, the gold quartz veins in the “Baixada Cuiabana” (Jardim Itália, Casa de Pedra and “Garimpos” of CPA, Mineiro, and Abdala, among others) occur filling fractures along the NW-SE direction in phyllite, siltstone, and quartzite attributed to the Cuiabá Group.

4.1.7. Foreland Basin

In the Cuiabá-Província Serrana region, the foreland basin is oriented around N60-70E in its northern portion and passes gradually to N25E in the southern portion. It consists of a carbonate sequence (Araras and Guia formations) that is under the upper detrital sequences (Raizama and Diamantino formations). The rocks of this domain were affected by a low-grade metamorphism (Alvarenga 1990) characterized by ruptile tectonics that is itself manifested by normal faults and by open folds, with subvertical axial plans, that moves towards the Paraguay Belt through inverse folds to isoclines. The axial plans exhibit low-dips for southeast with a northward vergence, in the direction of the Amazon Craton (Almeida, 1984; Luz et al., 1980; Alvarenga, 1990; Alvarenga et al. 2000). The representative unit is the Diamantino Formation constituted by shales, argillites, siltstones, and arkoses.

4.1.8. Água Bonita Basin

The sediments of this basin are confined inside the lineament system of the NE-SW trend, located between the Porto Nacional-Nova Crixás Domain and the Araguaia Belt. These sediments occur in a narrow area around 7km of width and 83km long parallel to these lineaments, called Transbrasiliano Lineaments. The reactivation of these structures in the graben system allowed the preservation of sedimentary units, mainly molassic. The Água Bonita Formation of the Silurian-Devonian period

(Schobbenhaus et al., 1975) is constituted by medium to coarse sandstone, with intercalations of siltstone and locally with conglomeratic facies.

4.1.9. Bananal Basin

The Bananal Basin, represented by Pleistocene alluvial sediments of the Araguaia Formation, is a flat surface of low slope with an area close to 106,000km² and corresponds to 27% of the surface of the study area.

The pioneering work of Barbosa et al. (1966) defined the Araguaia Formation as being formed by a succession of continental sediments that are initiated by a basal conglomerate (with thickness of up to 3m) covered by yellowish sands or brownish, silty, ferruginous, consolidated to unconsolidated ones, with varied colors and textures

Pena et al. (1975) executed a drill hole 47,90m of deep in the Bananal Basin (in Canada farm). In this locality the Araguaia Formation is 45,50m thick with metrical to decimetrical intercalations of sands, silts, and clays. The sandy sediments are predominant among the coarse textures. These sediments present a generally yellowish to reddish coloration with a variation of white and gray. In the interval of the profile between 25,00 to 29,00m of depth, there is a level of fine to medium sand with intercalations of clay and of indurated sandy sediment enriched in iron oxide.

Fieldwork executed by Valente and Latrubesse (2007) in the Bananal Island plain and in the Araguaia River bank showed that the Araguaia Formation is constituted by an upper stratum of indurated gray-clear clay up to 3,00 m which overlaps sandy sediment strata of fine to medium textures with clay intercalations. The occurrence of indurated sand layers enriched in iron oxide of reddish colouring is common.

Tertiary to Quaternary lateritic crusts occur in several localities, for example, in the Bananal Island and in the western region of the Cocalinho and Aruanã, as product of intense weathering made up of mineral assemblages with rich concretions in Fe-Al oxides. These laterites developed in a drier climatic environment than the present one.

4.2. Paraná Province

The Paraná Province is located in southern Brazil, with an area of about 1,050,000km² and a NNE-SSW-trending elliptical shape that evolved during the Paleozoic and the Mesozoic. In the study area, the Paraná Province occurs in the southern part with an area of 81,417km² or 21,08%.

It is a flexural intracratonic basin of polycyclic evolution. The deposition began in the Ordovician within an intracratonic rift of the basement as an Interior Fracture (IF) type basin. The known tectono-stratigraphic record suggests that the orogenic activity in the boundaries of the South American Plate had influenced the intraplate regime regarding to the events of subsidence, uplift and magmatism. Zalán et al. (1990) suggest that the Paraná River Basin corresponds to the overlapping of some basins on the same plate. According to Milani and Thomaz Filho (2000), this province includes three areas of independent sedimentation, separated by deep discordances: The Paraná, Serra Geral and Bauru basins (Fig. 3).

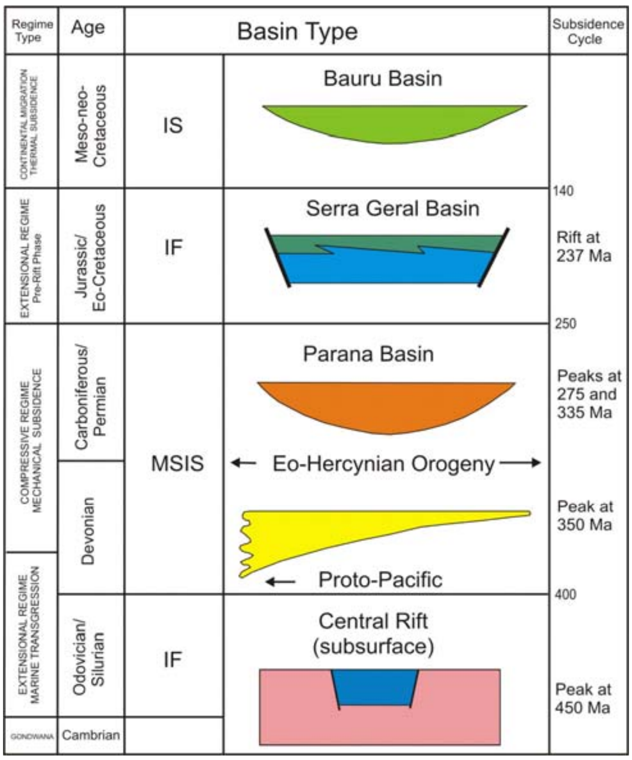

Fig. 3. Tectonic evolution of the Paraná Province (modified from Pedreira et al., 2003). IF-Interior Fracture, IS-Interior Sag, MS-Marginal Sag, MSIS-Marginal Sag/Interior Sag.

In Paraná Province there are kimberlitic provinces of the Upper Cretaceous which are related to Lineaments AZ-125º (Gonzaga and Tompkins, 1991). In the Diorama region there is several diamond "garimpos" in alluvial deposits along the Caiapó and Pilões rivers that are oriented in Lineaments AZ-125º. In Arenópolis/Nortelândia the diamond deposits with 400,000 carats and content of 2 to 4 points/m³ are resultant from the erosion and concentration of diamonds in placer type deposits during the Tertiary-Quaternary (Fleischer, 1998).

4.2.1. Paraná Basin

Paraná Basin consists of four cycles of subsidence that correspond to the second-order allostratigraphic units or supersequences: the rift phase represents the Rio Ivaí Supersequence and the syneclise phase corresponds to Paraná, Gondwana I, and Gondwana II supersequences (Milani, 1997). This last basin occurs outside of the study area.

The top of this Supersequence is defined by a discordance surface that deeply eroded the package and established a wide and regular peneplain (Milani and Ramos, 1998). The Rio Ivaí Supersequence constitutes a transgressive cycle that in the study area is represented by the Vila Maria Formation (Rio Ivaí Group), which is made up of dimictites, shales, fossiliferous siltstones, and sandstones. The rocks of this formation are distributed along a narrow belt between the Neoproterozoic basement (Goiás Magmatic Arc and Paraguay Belt) and the Paraná Basin (Furnas Formation).

The Paraná Group is constituted, in its northern portion, by the Furnas (base) and Ponta Grossa (top) formations. The basal contact with the Rio Ivaí Group and the upper one with the Aquidauana Formation are erosive discordances.

The Devonian record in the Paraná Basin begins with the Furnas Formation, a sandy package of accumulated tabular geometry on a wide and stable peneplain post-ocloyic orogeny (Milani and Ramos, 1998). It represents a transgressive-regressive cycle and is made up of a predominance of rocks deposited in fluvial and transitional environments that encompass sandstones and conglomerates, with abundant icnofossils. The Ponta Grossa Formation is mainly constituted by shales and divided into three members, of which the lowest one, marine, corresponds to the surface of maximum flooding of the Devonian.

The Aquidauana Formation that occurs in the study area is an integrant part of the Gondwana I Supersequence and represents the widest sedimentary area of the Paraná Basin. This formation, attributed to Late Carboniferous-Early Permian glaciation of Gondwana, has been divided into three stratigraphic units (Schneider et al., 1974): (a) Lower unit formed by red to whitish sandstones, diamictites and conglomerates; (b) Middle unit is constituted by siltstones, shales, sandstones, and diamictites; (c) Upper unit consisting of red sandstones with cross stratification. The depositional environment interpreted by Schneider et al. (1974) is continental, with fluvial and lacustrine deposits and glacial influence.

4.2.2. Serra Geral Basin

The Serra Geral Basin is constituted by Botucatu and Serra Geral formations (São Bento Group). According to Scherer (2002), this basin can be divided into two genetic units: a lower unit, with maximum thickness of 100 m, corresponding to the Botucatu Formation. The Botucatu desert is constituted by aeolian sand deposits forming sets and cosets of cross-bedded strata and deposits of conglomerates and conglomeratic sandstones related the local occurrence of ephemeral rivers.

The upper unit consists of volcanic rocks of the Serra Geral Formation. It encompasses a succession of flows around 1.500m thick constituted by a bimodal tholeiitic sequence where basalt to andesitic basalt rocks (> 90% in volume) are predominant, overlapped by rhyolite and rhyodacite rocks. The Serra Geral Formation marks the end of the Eocretaceous magmatic episode of infillings this geological province which corresponds to one of the biggest volcanic events in the world (Saunders et al., 1992). It is related to the fragmentation of west Gondwana through the generation and extraction of magma that is linked to mantle dynamics of the Tristão da Cunha plume. Ar-Ar radiometric dating sets its beginning at 137,4 Ma and the end at around 128,7 Ma (Turner et al., 1994).

4.2.3. Bauru Basin

The sedimentary Bauru Basin is essentially constituted by sandy continental deposits, with subordinate volcanic rocks, installed on the area of occurrence of basaltic lavas of the Serra Geral Formation during the Neocretaceous (Fúlfaro et al., 1982; Fernandes, 1992; Coimbra and Fernandes, 1994). This basin consists of two chronocorrelate units (Fernandes and Coimbra, 2000). The Bauru and Caiuá groups are representative of the same environment, under a hot climate that is semi-arid in the borders, and desertic in the interior of the basin. The Upper Cretaceous Bauru Group is a package of alluvial, fluvial, and eolian sedimentary rocks that closed the depositional history of the Paraná Basin (Milani and Zalán, 1999).

4.3. Parnaíba Province

Góes and Feijó (1994) divide the Parnaíba Structural Province into four basins separated by unconformities: Parnaíba, Alpercatas, Grajaú, and Espigão-Mestre basins. According to the global classification of basins of Kingston et al. (1983), these sedimentary basins were classified by Pedreira et al. (2003) in: the first of the IF/IS-type (Interior Fracture/Interior Sag), the second of the IF-type (Interior Fracture), the third of the MS-type (Marginal Sag) and the fourth of the IS-type (Interior Sag). This last basin does not occur in the study area.

4.3.1. Parnaíba Basin

The Paleozoic/Mesozoic Parnaíba Basin, in the area under study, is oriented as a SW-NE belt. This basin was implanted on the Cambrian-Ordovician rifts of Jaibaras, Jaguarapi and others (Brito Neves, 1998), therefore being a basin of the IF/IS type (Pedreira et al., 2003) represented in the study area by Canindé, Balsas, and Mearim groups, as well as by Mosquito, Codó, and Itapecuru formations.

The Canindé Group is formed from base to top by Pimenteiras, Cabeças, Longá, and Poti formations. The Pimenteiras Formation consists of sandstone with levels of shales, deposited in an environment which is dominated by tides and storms. The Cabeças Formations consists of sandstones with diamictite intercalations that are interpreted by Góes and Feijó (1994) as neritic platformal environment deposits, with a periglacial influence. The Longá Formation consists of fine sandstones and siltstones. The Poti Formation is represented by sandstones, shales, siltstones, argillites, and conglomerates. Góes et al. (1997) interpreted this formation as deposited in environments of upper and lower sub-tide, fluvio-estuarine channel and tidal plain, under climatic conditions of dryness.

The Balsas Group is formed by Piauí, Pedra-de-Fogo, Motuca and Sambaíba formations that are attributed to the Carboniferous-Triassic. The Piauí Formation consists of aeolian dune deposits; inter dunes and deflation plains, containing sandstone, argillite, shales, siltstones, and limestones. The Pedra-de-Fogo Formation is constituted by sandstones, shales, siltstones, limestone, evaporate, and silexite deposited in tide plains. The Motuca Formation consists of red shales with levels of siltstones, locally with dome stromatolite representing lacustrine environment. Finally, the Sambaíba Formation is formed by aeolian fine sandstone.

4.3.2. Alpercartas Basin

This unit represents an intracratonic basin with sedimentary rocks and volcanic masses of flows, tuffs and other materials, brought to the surface through faults and forming piles. The Alpercatas Basin is located between the Parnaíba and Grajaú Basin. It is formed by a system of rifts which are filled by the Jurassic supersequences, formed by the Pastos Bons and Corda formations (Mearim Group) limited by the Mosquito Formation.

The Pastos Bons Formation is a sequence of shales and sandstones that is interpreted as fluvial and aeolian environment deposits. The Corda Formation consists of reddish sandstones with bimodal granulometry in sequences separated by surfaces where clay deposition occurs. The environment of sedimentation is interpreted as desertic. The Mosquito Formation is formed by black tholeiitic basalt that occasionally possesses intercalations of sandstones. The associated dikes were dated by Ar-Ar at 198 Ma (Marzolli et al. 1999).

4.3.3. Grajaú Basin

This basin is located to the north of the Alpercatas Basin. It is attributed to the Cretaceous and includes, in the study area, the Codó and Itapecuru formations.

The Codó Formation is composed of shales, limestones, and evaporites (Paz and Rossetti, 2001). In the Itapecuru Formation, the predominant lithologies are sandstones in metric beds or in lenses and layers of pelites (shales), deposited in an environment with deltas, tides, and storms.

4.4. Parecis Province

4.4.1. Xingu Sub-Basin

The continental sediments of the Cretaceous Supersequence of the Parecis Basin, of interest to this study, made up of Salto das Nuvens Formation of the Upper Cretaceous that occurs in the escarpment of the Serra do Roncador, a region to the east of the Mato Grosso state. According to Pedreira et al. (2003), the Parecis Basin is of the IF-type (Interior Fracture) evolving to IS-type (Interior Sag). The Salto das Nuvens Formation is constituted by conglomerates and red immature sandstones with meddle to large-scale cross stratification, with intercalated lenses of reddish argillites and siltstones that are deposited in an aeolian fluvial environment (Costa et al., 1975). The Upper Cretaceous age is demonstrated by the presence of fossils, such as the *Mesosuchidae* (*Notosuchidae*). The Salto das Nuvens Formation is covered predominantly by sandy sedimentary rocks that are little consolidated and represented by sand, silt, clay, and gravel, called Ronuro Formation, associated to the Alto Xingu Sub-Basin and attributed to the Neogene age (Tertiary).

4.5. Carajás Province

This Province was subdivided by Santos et al. (2000) and Santos (2003) into two distinct domains: Rio Maria (Mesoarchean) and Carajás (Neoarchean). The Rio Maria domain, located in the southern portion of the Amazon Craton, is the subject of this study

4.5.1. Rio Maria Domain

The Rio Maria Domain is essentially constituted by granite-greenstone that represents two recognized periods of addition of youthful crust: between 3,05-2,96 Ga and 2,87-2,85 Ga. This domain corresponds to the greenstone belts grouped in the Andorinhas Supergroup (Souza et al. 2001). It is represented by the Lagoa Seca Group (metaturbidites and calc-alkaline volcanic rocks) and Babaçu Group (mafic and ultramafic volcanics). These units are cut by TTG intrusions (tonalite, trondhjemite, and granite) of the Caracol and Arco Verde types, with slightly younger ages between 2,924±2 Ma (Leite, 2001) and 2,957±21 Ma (Macambira and Lancelot, 1996), and represent primitive island arcs in the evolution of the region.

The second association, according to Santos (2003), congregates the greenstone belts that consist of metasedimentary rocks (graywackes, turbidities, and iron formations) and a great volume of mafic and ultramafic volcanic rocks, common to the Tucumã and Gradaús groups, with an age of 2,868 ± 8 Ma (Avelar et al. 1999). TTG granitoids, for example, Trondhjemite Mogno and Parazônia Tonalite types present ages of 2,871 Ma and 2,858 Ma, respectively (Pimentel and Machado, 1994). The calc-alkaline rocks are predominantly granodiorites and monzogranites, for instance, Xinguara Granite and Rio Maria Granodiorite), generated between 2,87 and 2,85 Ga.

4.6. Central Amazon Province

Santos et al. (2000) separated the Carajás Province from the Central Amazon Province based on differences in rock types and in structural trends. It was defined previously as a single Archean province by Tassinari (1996), onto which several younger Proterozoic mobile belts were accreted.

The basement rocks of the Amazon Central Province comprises of a poorly known basement (Santos, 2003). It is divided into two segments: the Mapuera–Tumucumaque rocks of the Guianense Complex represent the northern segment, while the Iriri-Xingu Domain of the Xingu Complex represents the south segment. The latter occurs in the study area.

4.6.1. Iriri-Xingu Domain

The Archean basement of this domain is similar to a TTG association composed by granodioritic and tonalitic gneiss. This basement was metamorphosed into amphibolite facies attributed to the Xingu Complex that possess ages of 2,851 ± 4 Ma U-Pb in zircon (Machado et al., 1991).

The Uruará Tonalite was studied by SHRIMP U-Pb and revealed an Archean crystallization age of 2,503 ± 10 Ma and a population inherited with 2,581 ± 6 Ma. However, part of those "complexes" was possibly formed in the Paleoproterozoic (Santos, 2003). The supracrustal rocks are represented by felsic to intermediate volcanics (Iriri Formation), A-Type granites (Maloquinha Intrusive Suite), with a sedimentary cover dominated by fluvial braided deposits (Gorotire Formation). The volcanics of the Iriri Formation and the granite of the Maloquinha Suite were generated by the Uatumã Magmatism (Santos and Reis Neto, 1982), evolving between 1,88 to 1,70 Ga.

5. REGIONAL TECTONIC SETTING OF DEFORMATION

The South American Platform encompasses a succession of orogenic episodes involving crustal accretion and reworking which are intercalated by taphrogenic events dated from the Mesoarchean to the Neoproterozoic.

The tectonic setting of the Brazilian Platform in the study area is characterized by two main orogenic cycles: Transamazonian (2.1 to 1.9 Ga) and Brasiliano (900 to 550

Ma). The first corresponds from Archean to Paleoproterozoic terrains of the Goiás Massif (greenstone belts and TTG terrains) generated between 2.8 and 2.7 Ga (Queiroz et al., 1999; Pimentel et al., 2000) and orthogneiss of the Porto Nacional-Nova Crixás Domain with a U-Pb SHRIMP age of 2.2 Ga (Fuck et al. 2001). These old terrains were affected by tectono-metamorphic events at 2.01 Ga (Transamazonian Cycle) and subsequently deformed with shear zones from 590 to 551 Ma (Brasiliano Cycle). The second younger cycle (Neoproterozoic) comprises the Brasiliano Orogenic System that is constituted by the Goiás Magmatic arc (Mara Rosa-Arenópolis intra-oceanic arcs), and Araguaia and Paraguay belts.

The regional structural picture consists of ancient collisions of several continental blocks which are limited by major crustal sutures in association with transcurrent shear belts and thrust faults. Although the region represents a continental crust that is relatively stable and has strain rates that are believed to be low, the majority of faults which show evidence for neotectonic movement are related to crustal discontinuities of Precambrian or Paleozoic heritage.

5.1. Evidences of the different tectonic movements

The expressive occurrences of rocks with ages that vary from the Archean to the Quaternary, deformed, in the majority of cases, in consequence of several tectonic cycles that acted in the region shows a complex deformation geometry.

For the knowledge and extraction of lineaments, the criteria are the expressions of the linear elements of the relief, such as crest segment lines, elongated depressions, rectilinear lake and drainage patterns, vegetation belts, linear variation of soil tonality, and so forth. Fractures (including faults, shear zones, and joints) in the terrestrial crust affect the topography or the features of the land in some way.

The various linear elements that exist in nearly all landscapes are controlled by subsurface tectonics and can significantly affect morphology and hydrology temporarily or permanently by triggering avulsions.

In order to represent and classify variations in the orientation of the structural lineaments, rose diagrams were constructed. The diagrams show the variations of the orientation grouped in classes, according to the frequency of occurrence in determined trends. The extraction of the lineaments was obtained from field data, remote sensing products (Landsat ETM and SRTM) and aerogeophysical (magnetometry and gamma-ray spectrometry) data. Three main shear zone trends were distinguished: N20-40E, N50-60W and N15-30W (Fig. 4).

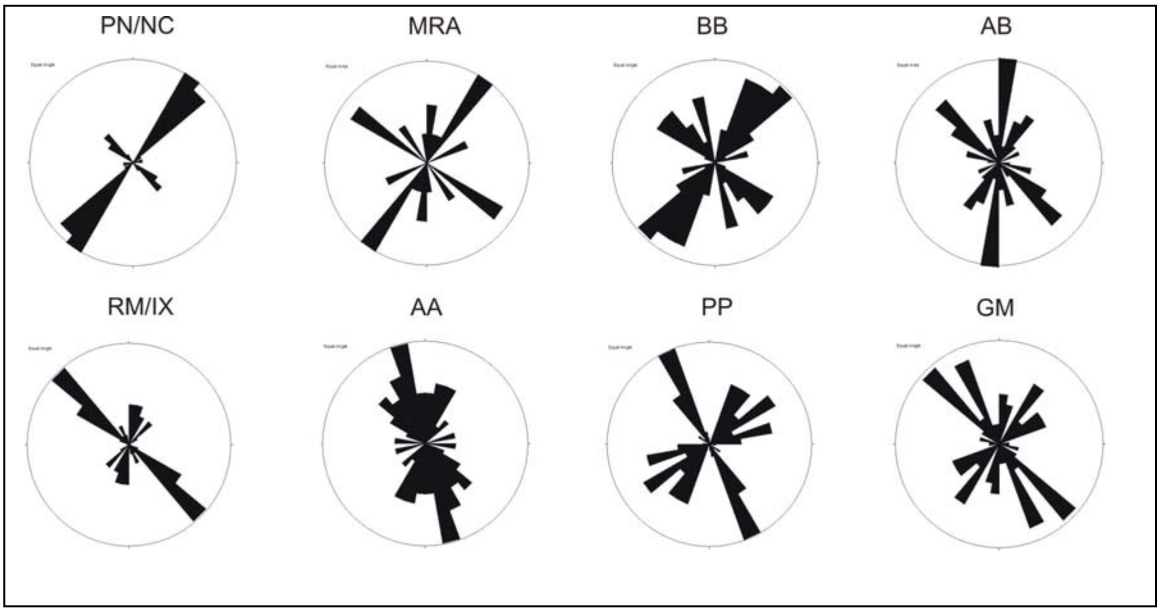

Fig. 4. Rose diagrams of structural lineaments of the main tectonic domains. PN/NC-Porto Nacional-Nova Crixás Domain, MRA-Mara Rosa Arc (Goiás Magmatic Arc), BB-Bananal Basin, AB-Araguaia Belt, AA-Arenópolis Arc (Goiás Magmatic Arc), PP-Paraná Province, RM/IX-Rio Maria/Iriri-Xingu Domains (Amazon Craton) and GM-Goiás Massif.

The first, the dextral N20-40E-trending shear zone, is called Transbrasiliano Lineament (Schobbenhaus et al., 1975). It is characterized by a strike-slip fault system of high angle associated to transpressional and transtensional regimes of nature, predominantly ductile-brittle and brittle. The deformation geometry is compatible with the Riedel model, with a compressive effort from west for east (direction of $\sigma 1$). This deformation of continental dimension is recorded at almost all the geological provinces, with greater evidence in PN/NC (Porto Nacional-Nova Crixás), MRA (Mara Rosa Arc), and in the south segment of the AB (Araguaia Belt). This shear zone exerts strong control into the plutonism/volcanism, sedimentation/erosion, and deformational aspects during the geological and geomorphologic evolutions.

The second is a sinistral N50-60W shear zone trend. In the northern part of the Araguaia Belt there are compressive and tangential efforts, directed westwards against the Rio Maria Domain (Amazon Craton). The compressive regime developed displacement surfaces and a shear zone of low angle (thrust fault) with a N-S trend that is cut by sinistral shear zones trend with around N50W, both in AB (Araguaia Belt) and in RM/IX (Rio Maria and Iriri-Xingu domains). The southern segment of the Araguaia Belt is transposed by the N30-40E shear zone trend of the Transbrasiliano System.

The third, sinistral N15W to N30W-trending shear zone is sub-parallel to Anápolis-Itauçu Granulitic Belt that occurs in the south of Goiás state. This fault system represents a progressive deformation, with tectonic transport from west to east against the São Francisco Craton. This tectonic stress was responsible for the development of an extensive shear zone with ductile and ductile-brittle regimes that deformed rocks both in infrastructure as in suprastructure. The sinistral N15W to N30W shear zone trend is represented in domains of AA (Arenópolis Arc) and GM (Goiás Massif). However, this fault system occurs in PP (Paraná Province) as a reactivation of old basement faults.

5.1.1. Neotectonic Faulting

Neotectonics is the study of young tectonic events that occurred or are still occurring in a given region, after its orogenesis or after the most significant tectonic readjustment (Pavlides, 1989). Hasui (1990) used the term 'resurgent tectonics' for the reactivation of Precambrian faults during the Cenozoic. This author relates the origin of neotectonism in Brazil to the migration of the South American continent and consequent opening of the South Atlantic, whose movements occur until the present day.

Tectonically active areas have a direct relation between natural seismicity and neotectonism (Hasui and Ponçano, 1978; Schumm et al., 2000; Oswald and Wesnousky, 2002; Goodbred Jr. et al., 2003).

In this context, there are some localities in Brazil with concentration of seismic activity, named seismotectonic provinces, for example, Fortaleza and São Francisco Craton seismogenic zone, in the Northeast; Mantiqueira and Serra do Mar seismogenic zone, in the Southeast; and Goiás-Tocantins seismogenic zone, in the central region of the country (Ferreira and Assumpção, 1983; Hasui, 1990; Riccomini, 1990; Bezerra, 1999).

Seismogenic zones in Brazil are invariably associated with the regions where Precambrian geossuture reactivations occur. Those reactivations would occur owing to epirogenetic movements since the end of the Cretaceous to the Pleistocene. According to Hasui et al. (1978), the continental taphrogenic basins of the Brazilian Southeast developed since the Brasiliano Cycle (Upper Proterozoic) and culminated with the implementation of continental basins in the Late Tertiary and/or Pleistocene by the reactivation of old faults.

The main seismogenic area of Central Brazil, the object of this study, is located between the Amazon and São Francisco cratons, being the interaction between them the main responsible for significant neotectonic and seismic activities in the area, called Goiás-Tocantins Seismogenic Zone (GTSZ). In the region there are several seismic activities, with a magnitude that ranges from 2,9 to 4,1 (Richter scales) along the NE-SE trend (Transbrasiliano Lineament); its dimensions are 700km long and 200km wide (Veloso, 1997), originated on continental tectonic structures. Fig. 5 shows the regional epicenter distribution in the GTSZ.

This suture zone evolved to frontal, oblique and directional ramps, which placed the high-grade terrain (Porangatu Granulitic Complex) on one side and metavolcano-sedimentary belts on the other. In this context, there is the Água Bonita Graben (Silurian/Devonian) limited by faults of the Transbrasiliano Lineaments.

Evidences of this tectonic regime were presented by Hales (1981) from geophysical data (magnetometry and seismics) carried out in the Middle Araguaia River region, between the south of Bananal Island and the confluence of the Araguaia-Crixás rivers. This author stated that the Bananal Basin finds itself structured in horst and graben systems with a predominance of NE-SW trend faulting (Figure 6).

In this sense, Rabelo and Soares (1999) described an active NE fault zone that crosses the central Pantanal Basin, in Mato Grosso state, related to the reactivation of the Transbrasiliano Lineament, in the basement. The northern border of the Paraná Basin and the Bananal Basin were affected by faulting that was reactivated by the Arenópolis Magmatic Arc basement (Fig. 7).

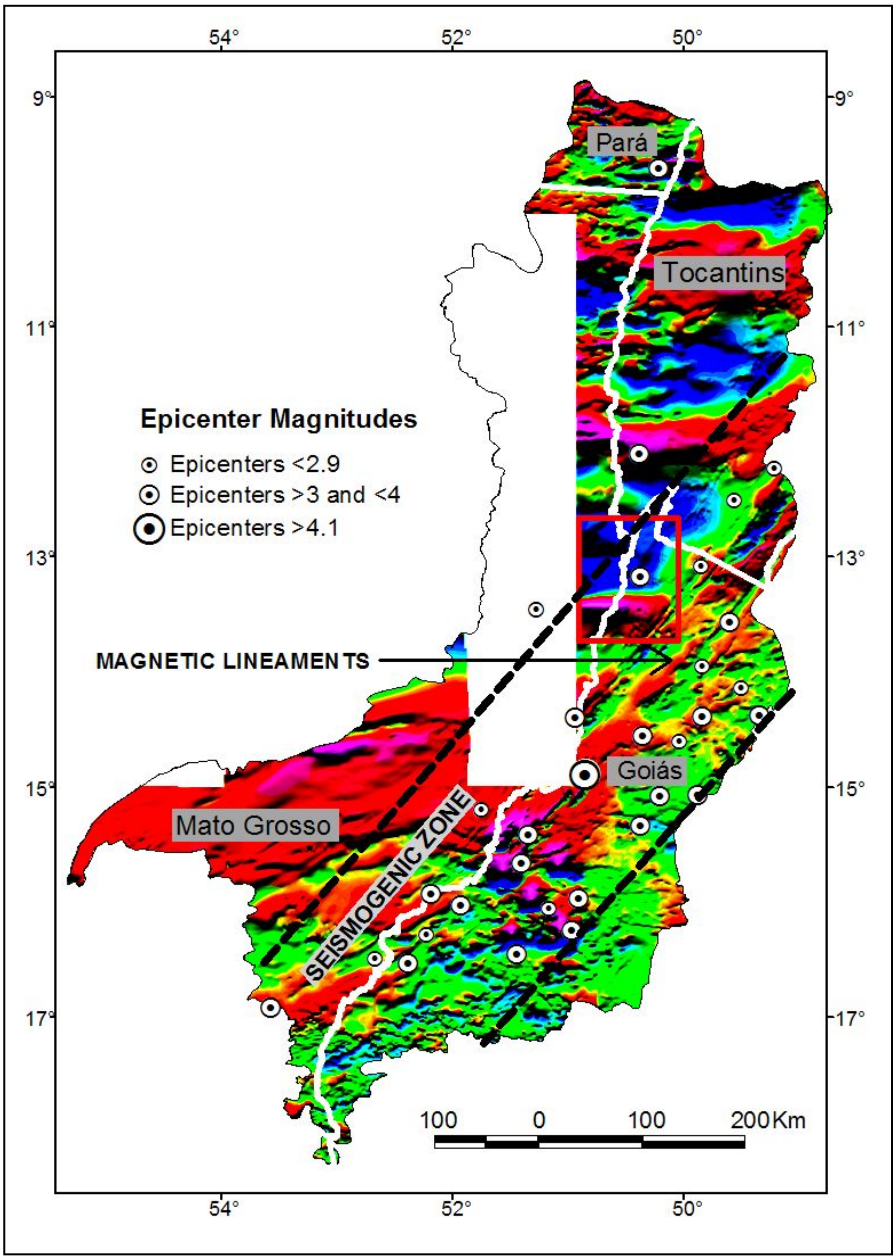

Fig. 5. Relation between seismic activity and magnetic lineaments along Goiás-Tocantins Seismogenic Zone (GTSZ) in the Upper and Middle Araguaia River Basin. Seismic data are from the Seismological Observatory of the University of Brasília. The magnetic anomaly image is a total field reduced from IGRF (International Geomagnetic Reference Field), generated from Aero database of Geological Survey of Brazil. The area of the rectangle in the image corresponds to Fig. 6.

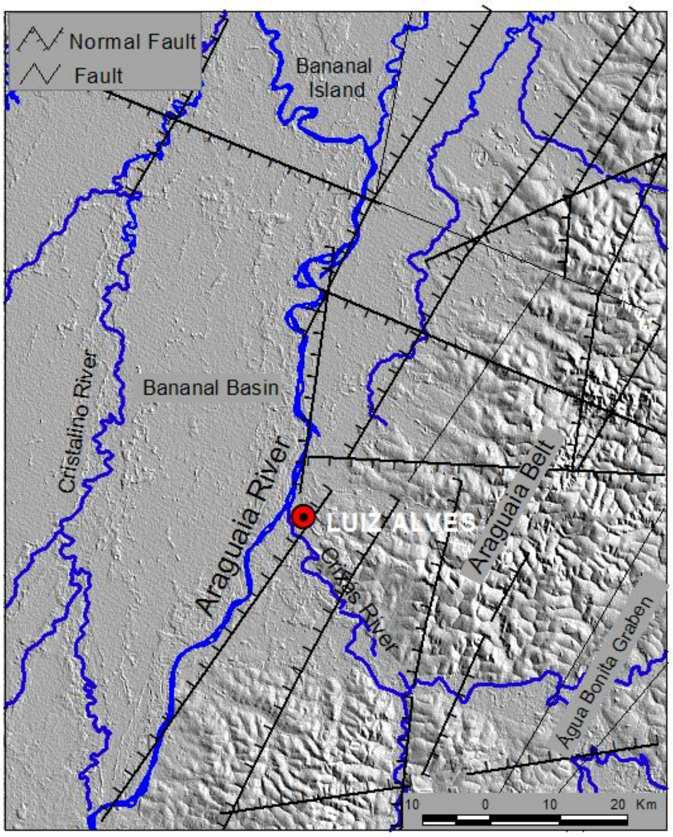

Fig. 6. Faulting system in horst and graben in the Bananal Basin interpreted from magnetometric data (modified from Hales (1981). SRTM 3D shaded relief image.

Therefore, tectonic features of the basement influenced the development of the major Brazilian Phanerozoic interior basins. These basins are result from the extensional regime of Neoproterozoic transcurrent fault lines, reactivated by neotectonic processes during the fracturing of the Gondwana. For example, there are the Cenozoic intracratonic basins of Central Brazil (Bananal and Pantanal), Southeast Brazil (Volta Redonda, Resende, Taubaté, São Paulo, Curitiba), and Paleozoic rift and strike-slip basins of Northeast Brazil (Recôncavo, Tucano, Jatobá, Araripe, Iguatu, Rio do Peixe).

Surely, the multidisciplinary study that involves neotectonic features such as fault kinematics, geochronological dating, morphogenesis, areas of erosion and sedimentation, seismicity, intraplate tensions, source, and thermal flow. These researches will allow the necessary knowledge of the phenomena and of the geological-tectonic processes in regional and global scales of Central Brazil. Such information is still quite scarce.

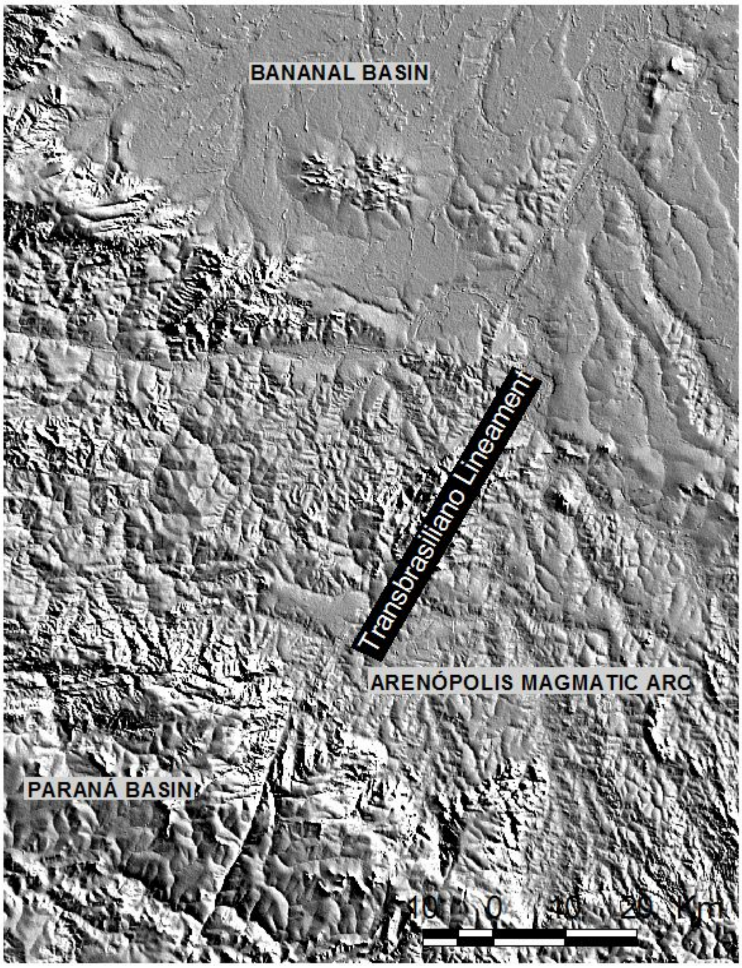

Fig. 7 – Fault of the Transbrasiliano Lineament System cutting rocks of the Quaternary (Bananal Basin), Devonian (Paraná Basin) and Neoproterozoic basement (Arenópolis Magmatic Arc).

6. TECTONO-GEOLOGICAL EVOLUTION

The Structural Provinces of the study area in the context of the South American Platform have a complex composition, reflecting a polycyclic history of its basement, and varying from the Mesoarchean (3.0-2.8 Ga) to the Cambrian/Ordovician (500-480 Ma). Paraná and Parnaíba Province basins (Paleozoic/Mesozoic) and Bananal Basin (Pleistocene) dominantly represent Phanerozoic sedimentary covers.

Archean units are constituted by TTG (tonalite, trondhjemite, and granite) blocks of continental crust (Goiás-Crixás and granitoids of the Vila Maria Domain) which evolved in successive episodes of crustal accretion that were associated with several greenstone belts; these were generated in an extensional-oceanic environment.

The Paleoproterozoic comprises mostly TTG terrains (Xingu Complex) with felsic to intermediate volcanic rocks (Xingu-Iriri Domain) and granite-gneissic terrains (Porto Nacional-Nova Crixás Domain) which were generated during the Trans-Amazonian orogenic Cycle (2.25-2.01 Ga). The abortion of the Statherian Taphogenesis, outside the area (Serra da Mesa-Araí groups), originated expansion in the Mesoproterozoic between the Calymmian and Ectasian (1.6-1.2 Ga) of ample syneclises with sedimentary deposits of marine and transitional environments that encompass the Rift Basin of the Serra Dourada Group.

The last orogenic collage in the area corresponds to the Brasiliano Orogenic System and comprises a series of intra-oceanic magmatic arcs. Three large-scale episodes have been defined (Pimentel *et al.* 1999, Silva et al., 2000; Delgado et al., 2003): (i) Brasiliano Orogenic System I (900-700 Ma) consists of the Arenópolis-Anicuns-Itaberaí-Mara Rosa arcs with a collisional peak at 790 Ma; (ii) Brasiliano Orogenic System II (640-610 Ma) with the Jaupaci-Iporá-Amorinópolis magmatic arcs and Araguaia and Paraguay belts, as well as sedimentary rocks which are deposited in a foreland basin (Alto Paraguay). It is the main orogenic episode of the Brasiliano collage, characterized by juvenile accretion with a metamorphic peak at 632 Ma; (iii) Brasiliano Orogenic System III (600-520 Ma) comprises the most recent system of orogens which marks the transition to a stable environment in the South American Platform at ca. 520 Ma.

The deformation style with thrust and fold belts associated to the strike-slip fault system is dominant in Neoproterozoic rocks of the Tocantins Province. The first two systems are associated with the metasedimentary rocks with N-S trend (Araguaia Belt) and N70E trend (Paraguay Belt and Foreland Basin). Sinistral transcurrent faults around N50W control the structuring of the Archean terrains (Goiás Massif, Rio Maria, and Xingu-Iriri Domains) and the southern segment of the Neoproterozoic Goiás Magmatic Arc (Arenópolis Arc).

The dextral N20-40E-trending shear zone has a ductile-brittle and brittle nature with a tensional fracture around 90º direction for $\sigma 1$. This faulting presents verticalized plans and horizontal to sub-horizontal relative movements. It constitutes the orientation of the main shear zone of the study area and corresponds to the Transbrasiliano Lineament of continental dimension that extends 2,700km in Brazilian territory, revealing continuity in the oceanic fracture zones such as the Patos and Pernambuco lineaments. This shear zone has registers at almost all the geological provinces, with greater evidence in the south portion of the Araguaia Belt, in Porto Nacional-Nova Crixás Domain and Mara Rosa Magmatic Arc (Figs. 2 and 4).

These shear zone directions represent crustal weakness zones that were reactivated during the Phanerozoic time. The beginning of the Mesozoic, from a tectonic point of view, represents a continuation of the conditions prevailing during the Paleozoic that was called Intracratonic Cycle by Sampaio and Northfleet (1973). In Paleozoic, the Brazilian structures were active from the Cambro-Ordovician in an extensive regime of the IF-type (Interior Fracture) with implantation of grabens that originated from the sedimentary deposits of the Parnaíba and Paraná Provinces. The shapes of the intracratonic sedimentary basins, e.g. the Paraná and Parnaíba provinces seem to be controlled by the N20-40E (Transbrasiliano Lineament), N50-60W, and around N-S-trending Precambrian structures.

The Parnaíba Province consists of four successive basins: IF-type Jaibara Graben and others (Cambro-Ordovician); IS-type Parnaíba Basin (Silurian-Triassic) has marine, fluvial-deltaic and desertic environments; IF-type Alpercatas Basin (Jurassic-Cretaceous) is essentially continental with fluvial-lacustrine and eolian deposits and basaltic flows; IS/MS-type Grajaú Basin (Cretaceous) has both sedimentary rocks that were deposited in closed marine environments and eolian deposits.

On the other hand, the Paraná Province encompasses three successive basins: MSIS-type Paraná Basin (Devonian) presents marine and fluvial deposits; IF-type Serra Geral Basin (Jurassic-Eo-Cretaceous) was deposited in marine, fluvial, and desertic environments with glacial incursions and continental flood basalts; IS-type Bauru Basin (Upper Cretaceous) presents two phases of deposition: the first is essentially desertic and the second is of a fluvial-eolian environment.

In Quaternary time, the Bananal Basin developed due to the reactivation of the Transbrasiliano structures in horst and graben, according to geophysical studies presented by Hales (1981). Recent apatite fission-track dating suggests an increase in the rate of crustal uplift after the Pliocene (Saadi et al., 2002). Thermoluminiscence (TL) and Optically Stimulated Luminescence (OSL) chronologies accomplished in the sandy sediments of the Araguaia Formation showed that the river avulsion events occurred in Upper Pleistocene from 26.4±3.1 to 17.2±2.3 ka BP and in Middle Pleniglacial from 56.6±5.9 to 34.0±4.6 ka BP. In addition, the fluvial aggradation of the Araguaia Formation sediments was dominant during the Middle and Upper Pleistocene, between 240.0±29.0 and 17.2±2.3 ka BP (Valente and Latrubesse, 2007).

7. CONCLUSIONS

The Araguaia River Basin occupies an area of 384,600 km² on a complex geological environment, reflecting its basement's tectonics and metamorphic polycyclic history. This Precambrian infracrust, with 45% of the Araguaia River Basin, consists of rocks with composition and age very diversified: a) Mesoarchean TTG (tonalite, trondhjemite and, granodiorite) terrains and greenstone belts (Goiás Massif and Rio Maria); b) Paleoproterozoic granitic-gneiss and metavolcano-sedimentary rocks (Porto Nacional-Nova Crixás, Iriri-Xingu, and Rift Basin), and c) widespread Neoproterozoic metamorphic folded belts (Goiás Magmatic arcs, Araguaia and Paraguay belts, and Foreland Basin). The supracrustal domain which covers 55% of the area encompasses the intracratonic sedimentary basins generated during the Paleozoic/Mesozoic (Paraná, Parnaíba and Parecis provinces and Água Bonita Basin) and in the Quaternary (Bananal Basin).

Basement rocks were affected by three tectono-metamorphic events which correspond to Jequié (~2.7 Ga), Transamazonian (~2.0 Ga), and Brasiliano (900-520 Ma) orogenic cycles. The Brasiliano event is the most widespread and consists of three large-scale tectonic episodes: Brasiliano I (900-700 Ma), Brasiliano II (640-610 Ma), and Brasiliano III (600-520 Ma). These Brasiliano systems are characterized by collision-related orogens associated to a displacement of surfaces and thrust faults of low angle (frontal ramps of N-S direction) and an expressive strike-slip fault system with N30-40E trend of high angle, called Transbrasiliano Lineament. The latter is associated to transpressional and transtensional regimes of a ductile-brittle and brittle nature.

These strike-slip fault systems and thrust fault belts involve both the supracrust and the infracrust and are related to important magnetic lineaments in the region. The Transbrasiliano Lineaments have a transgondwanic extension and constitutes the most important dextral strike-slip fault zone of Central Brazil. The Precambrian fault systems are crustal weakness zones that were reactivated during the Phanerozoic with directional, uplift, and subsidence movements, generating expressive taphrogenic events represented by Paleozoic/Mesozoic and Quaternary intracratonic basins. These basins were influenced by the geodynamics of the Gondwana.

The faults of the neotectonic events cut both the Precambrian basement and Quaternary sedimentary rocks. These deformational processes generated a deep imbalance in the hydrologic and fluvial sedimentary systems of the region with the development of innumerable river avulsion points, abandoned channels, and underfit rivers, where radiometric dating (TL and OSL) the sandy fluvial sediments showed that river channel avulsions were more active in the Middle and Upper Pleniglacial.

The Araguaia River Basin contains several tectonic and geological environments with high potentiality for important economic concentrations of gold, copper, emerald, and diamond. The most important gold mine is associated to the Crixás Greenstone Belt (Mine III/New Mine with 65t Au) located within the Goiás Massif. The Goiás Magmatic Arc contains gold-copper and gold deposits originated in diverse tectonothermal activities, such as the Au-Cu deposits from Chapada and Bom Jardim, Au deposits from Posse, Fazenda Nova, and Zacarias. Important emerald "garimpos" of Santa Terezinha de Goiás have been exploited since 1981 with an output estimated at 150 to 200t of emeralds and green beryls, in association with Mara Rosa Magmatic Arc.

Several diamond "garimpos" occur in alluvial deposits along the Caiapó and Pilões rivers as a result of the denudation processes of Paraná Province sediments (Cretaceous Bauru Formation). On the other hand, alluvial gold deposits from rock erosion of greenstone belts (Crixás, Goiás, Guarinos, and Pilar de Goiás) and from metavolcano-sedimentary sequences (Goiás Magmatic Arc) occur along the Crixás and Vermelho rivers, tributaries of the Araguaia River.

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PAPER II

Geology and regional geomorphology of the Araguaia River Basin, Central Brazil: Part II – Geomorphology*

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Geology and regional geomorphology of the Araguaia River Basin, Central Brazil: Part II - Geomorphology

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Abstract

The upper and middle Araguaia River drains an area of about 298,700 km², covered by vegetation of the Brazilian Cerrado (savanna) biome on tropical plateaus and lowlands of Central Brazil. This region is particularly important from the geomorphologic point of view due to the activity of many processes and to the related presence of several landforms from the denudation and aggradation systems. Neotectonic activity (uplift and subsidence) was a main factor that favored the development of the denudation and aggradation systems. Geomorphologic mapping was based on the identification of these landforms and subsequent categories according to their relief features, altitude, erosive stage and depositional characteristics. Three major Regional Planation Surfaces (RPSII, RPSIII, and RPSIV) scheduled between 1000 and 165m altitudes above sea level were mapped. Other secondary geomorphologic units were also mapped. The RPSII represents the most eroded, oldest, and highest surface of the region with an altitude between 1000 and 750m, associated to Paleozoic-Mesozoic sedimentary rocks of the Paraná Province. The RPSIII surface reveals quotas between 850 and 500m, with middle and strong dissection developed on sedimentary rocks from the Paraná Province. The youngest surface is represented by RPSIV that possesses the lowest quotas of the region, between 165 and 550m above sea level. It is dominant by occupying approximately

60% of the study area, exhibiting relief patterns with varied dissection degrees, predominantly low to very low on rocks with different origins, tectonism, and ages that vary from the Neoarchean to Quaternary. Several associations of hills, folded structures, and hogbacks occur with strong structural control, generally associated to intrusive and metamorphic rocks. Karstic relief has little cartographic expression. The aggradation system is characterized by a complex of morphosedimentary units represented mainly by fluvial plains and floodplain belts with abandoned meanders, oxbow lakes, meander cutoffs, and swampy areas that remain flooded during the rainy season (December to March). These units are associated to the Quaternary intracratonic Bananal Basin and Holocene alluvial deposits. Avulsions, abandoned channels, and underfit rivers are geomorphologic registers associated with paleoclimatical and paleohydrological changes and neotectonic reactivation that acted in the region. This study had as its aim the use of new techniques of geomorphologic mapping in tropical areas using remote sensing products, mainly SRTM and ETM images and integration in GIS environment.

Keywords: Geomorphologic Systems; Araguaia River Basin

1. INTRODUCTION

Significant advances in the fluvial geomorphology occurred during the last decades, specifically in the large South America fluvial systems where the knowledge of the great rivers still is enough limited. Therefore, an impressive Quaternary geomorphologic records on large fluvial systems has been focused by several authors in rivers of the Amazon Basin (Latrubesse and Kalicki, 2000; Latrubesse and Franzinelli, 1998, 2005; Latrubesse and Rancy, 1998; Van der Hammen et al, 1992; Dumont et al., 1992, among others) as well as in the Upper Parana River in Brazil and Uruguay River (Iriondo, 1999; Stevaux, 1994; Stevaux and Santos 1998).

In particular, Tocantins-Araguaia Basin constitutes a large Central Brazil fluvial system, with an area close to 800,000 km^2 and a mean annual water discharge ca. 12,000 m^3s-1 (Latrubesse, 2003). The upper and middle Araguaia River Basin, object in this study, drains on bedrock that encompasses the Precambrian granite-gneiss and metasedimentary basements and Paleozoic-Mesozoic sedimentary basin rocks with strong structural control. In the middle Araguaia River occurs a large Quaternary Bananal Basin, occupying approximately 106,000km² where the floodplain is temporarily flooded during the rainy season (December to March) and is made up by a varied and well-developed alluvial and fluvial units.

The dominant vegetal of the study area covering is the Cerrado biome, a savanna-like type of vegetation that shows a diverse range of physiognomies and floristic composition with many species adapted to frequent fires and to the high aluminium contend of the soils. It comprises the second most extensive vegetation type in tropical South America after Amazon rainforest biome.

In the upper and middle Araguaia River Basin the antecedents of geomorphologic mapping are scarce and in large-scale. Presently, the cartographies more utilized are those generated conceptually by Radambrasil Project (Mamede et al., 1981), in the large-scale (1:1:000.000) that constituted practically the single source of available information the regional level since the 1980'. Although these mapping are of great importance and have assisted innumerable research, can be said, that along the time, little has advanced in the geomorphologic mapping in the Brazilian territory.

However, the geomorphologic knowledge of the Quaternary fluvial records of the floodplain belt of the middle Araguaia River has advanced significantly in this last decade through the researches of postgraduate students, such as the works of Bayer (2002), Vieira (2002) and Morais (2006). Recently, Latrubesse and Carvalho (2006) present, in GIS environment, the Geomorphologic Map of the State of Goiás and Federal District, in 1:250.000, 1:500.000, and 1:1.000.000 scales, where the cartographic representation is based on the identification of denudational and aggradational systems and subsequent categories, whose conceptual bases are deeply different of the geomorphologic maps previously accomplished.

This new methodological concepts contribute for the characterization of a better organization of land use and environmental order. An understanding of the use of the land and the management practices within a land use category provides valuable information on the reasons for changes in the condition of our natural resources and environmental management. In the context of environmental management, landforms and geomorphologic processes have great importance, as much by the fact that they constitute the physical substrate on which human activities are developed as by the fact that they often answer aggressively to the changes inflicted by these activities. Thus, the relief cartographic representation becomes an indispensable instrument for an appropriate environmental management. Therefore, the landscape is a unique and valuable resource and it affects and is affected by virtually every economic, social, and environmental activity.

In this way, geomorphology may be considered a basic discipline in environmental studies and has been indicated to use environmental units in a rational and sustainable way. Consequently, the study of the geomorphologic units allows the understanding of the evolution of the landscape and of the action of current morphogenetic processes. For example, the relations between geomorphology and vegetation units (e.g. morphovegetational units), land use patterns, mineral resources, superficial and underground hydric resources, ecology, geotechny, elaboration of plans of territorial order, urban and agricultural planning, among others. Finally, a series of rules has been indicated for the planning of private and public spheres.

However, this paper describes specific methods for the geomorphologic mapping of the Upper and Middle Araguaia River Basin with the aim to define the denudation aggradation systems, e.g. the regional planation surfaces, fluvial plains, and alluvial belts, as well as different relief categories. Their spacialization will allow the subsidy of studies for the formularization and implementation of appropriation strategies of the use of natural resources that will guide management processes and the organization of the territorial space of this important region of rich biodiversity, which still suffers diverse economic, social, and environmental impacts.

2. STUDY AREA

Situated in Central Brazil among the states of Goiás, Tocantins, Mato Grosso, and Pará, in the upper and middle Araguia River Basin, the study area presents an irregular shape of approximately 298,700km² (Fig. 1).

The upper Araguaia region is located on the highlands, with quotas predominating between 1000 and 550m of altitude above sea level, which develops on Paleozoic-Mesozoic sedimentary rocks of the Paraná Province. On another level, the middle Araguaia River drains on lower quotas between 550 and 165m above sea level dominantly associated on Quaternary sediments of the Bananal Basin.

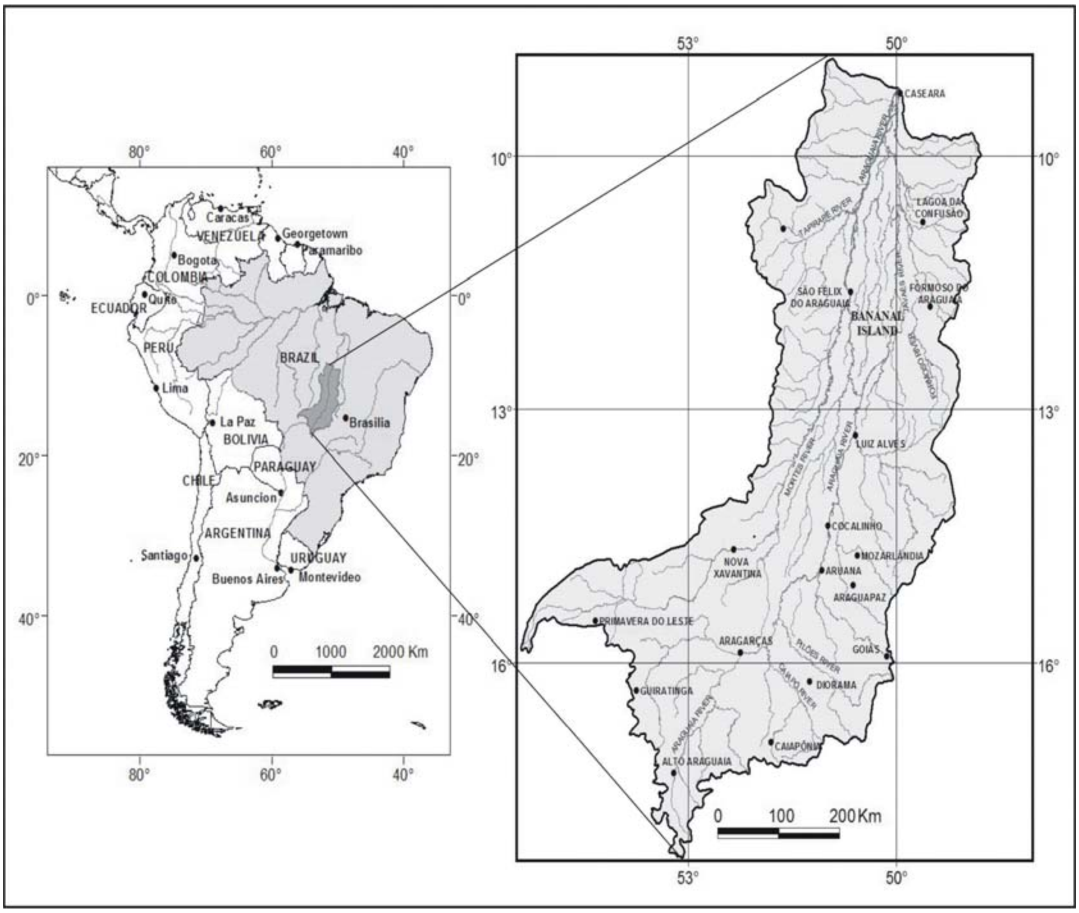

Fig. 1 - Location of the study area.

The typical vegetation landscape within the Cerrado (savanna) biome in the study area is quite varied in form, ranging from dense grassland, usually with a sparse covering of shrubs and small trees, to an almost closed woodland with a canopy height of 12±15m. It is an ancient biome with a rich biodiversity estimated at 160,000 species of plants, fungi, and animals (Ratter et al., 1997) and it was included among the 25 hotspots considered as global priorities for biodiversity conservation by Myers et al. (2000).

The region is affected by a current tropical climate characterized by a dry and a moist season that corresponds to the Aw in Koppen`s Climatic Classification. Annual rainfall varies from 1,400 to 2,200 mm/year. The rainiest season occurs between December and March, while from June to August the rainfall is zero and extends until mid-September. The annual mean temperature increases in the north direction, varying from 22ºC in the upper Araguaia Basin and 26ºC in the middle Basin.

The extensive Bananal Basin plain with 106,000km² and which occupies approximately 27% of the study area is seasonally flooded during the rainy season, a result of both the local rainfall and a saturated water table (Latrubesse, 2003; Valente et al., 2007). The Araguaia River consists of an anabranching system of straight and meandering patterns with low sinuosity.

The geological setting comprises Archean/Paleoproterozoic rocks of the Brazilian Shield (Goiás Massif and Amazon Craton), Neoproterozoic metamorphic rocks (Goiás Magmatic Arc, Paraguay and Araguaia belts), Paleozoic and Mesozoic sedimentary rocks (Paraná and Parecis provinces), Middle and Upper Pleistocene terrigenous deposits (Araguaia Formation), and Holocene alluvial deposits.

3. MATERIALS AND METHODS

For the mapping of the geomorphologic units, state variables (lithology, structure, regional pendent, etc) and transformation processes (erosion, transport, sedimentation, weathering, etc) that modulated geoforms with the geological time are taken into account. In this mapping, the classification (Fig. 2) of the dynamic and genetic type was applied, based on the proposals of Latrubesse and Carvalho (2006) with some modifications by Latrubesse et al. (1998) and Iriondo (1986).

In the development of this study, we used digital data of Interferometric Synthetic Aperture Radar (IFSAR) derived from the Shuttle Radar Topography Mission (SRTM). This radar data permitted the generation of Digital Elevation Model (DEM) by interferometry from the Spaceborn Imaging Radar C-band/X-band Synthetic Aperture Radar sensors (SIR-C/X-SAR). In addition, the Enhanced Thematic Mapper Plus (ETM+) bands of Landsat-7 satellite were used during the period of dry season from July to September 2000. For the mapping of the geomorphologic units we employed interpretation techniques in SRTM and ETM+ images which were integrated in a Geographic Information System (GIS).

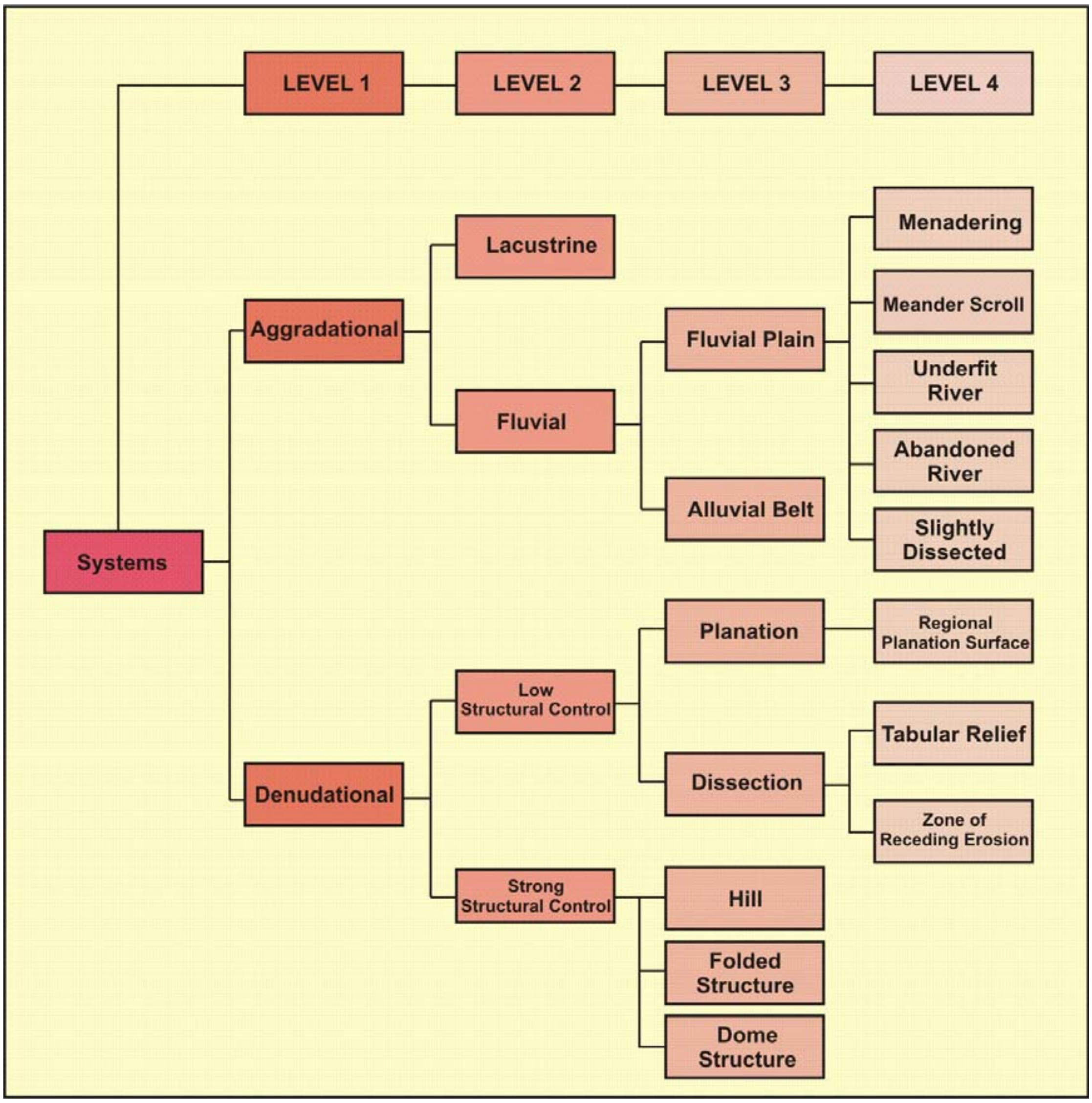

Fig. 2 - Classification system used in the geomorphologic mapping.

The extraction of topographic features of the Aggradational System such as the fluvial plain, alluvial belt, and lacustrine, as well as that of the Denudational System such as the Regional Planation Surface (RPS), Zone of Receding Erosion (ZRE), differentiated patterns of dissection, tabular relief, hill, folded structure, and dome structure were obtained from shaded-relief and shade color images from the SRTM data (Fig. 3). These geomorphologic features form an input into further analysis and can be then applied to discover relationships between multiple features.

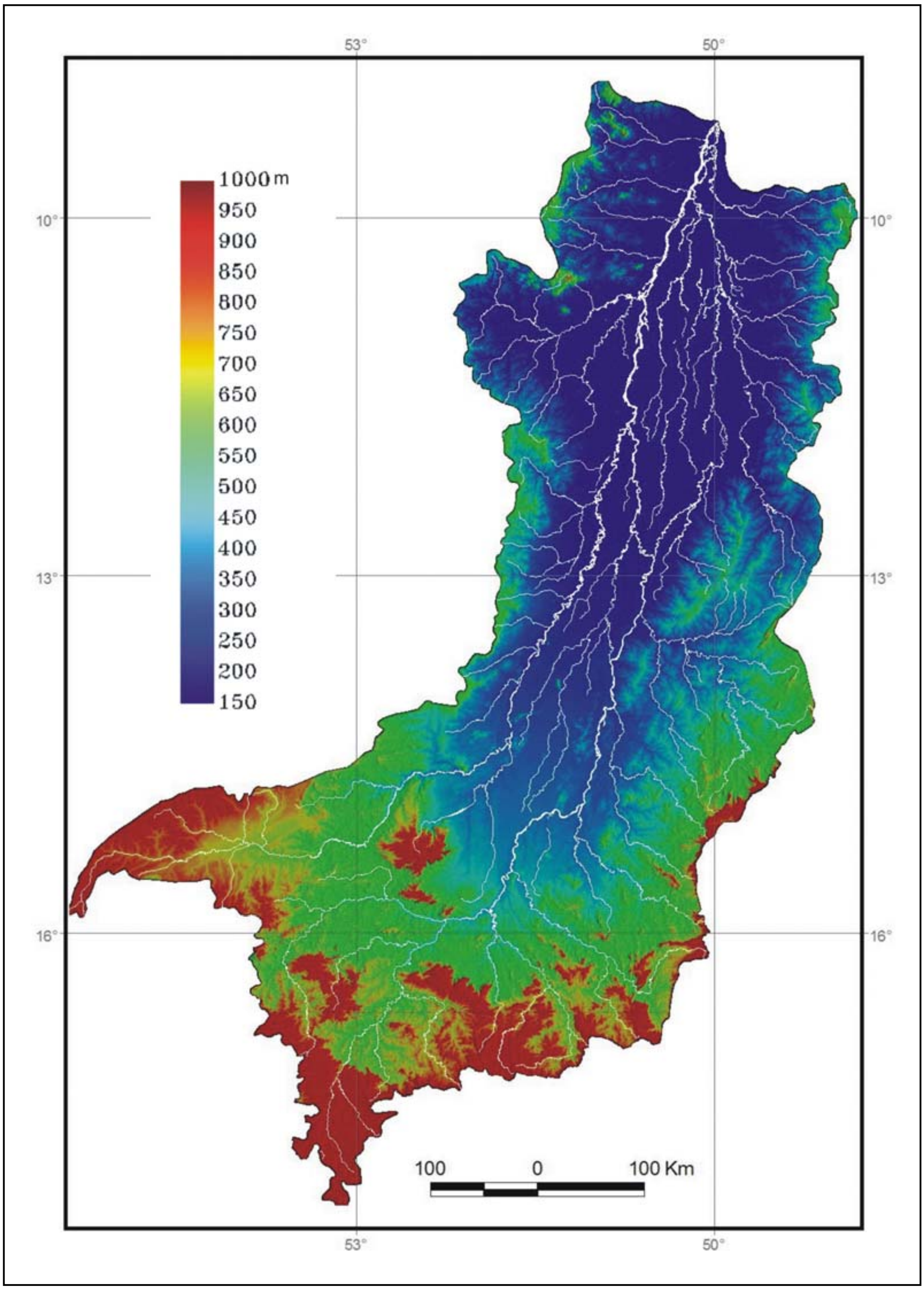

Fig. 3 - Hypsometric features showing altitudes in the Middle and Upper Araguaia River Basin. SRTM shade color class image.

Fieldwork was developed during the dry season, in order to find out and describe characteristics of the morphological features, sediment characteristics, and fracture data, excavation of trenches, drill holes, and profiles in the Araguaia River with the use of a boat. This fieldwork was carried out in two periods, the first from August to September 2005 and the second in August 2006.

4. GEOMORPHOLOGIC CHARACTERISTICS

Aggradational and denudational systems made up of geomorphologic units are characterized by state variables such as lithology, structure, regional pendent, and others. Transformation processes along the geological time modified these variables via erosion, transport, sedimentation, weathering, oscillation of the water table level, etc.

Theses variables were mobilized by external variables from solar heat, winds, rains, etc, causing adjustments in all of the parameters of a system. Therefore, the geomorphologic system is a physical system opened with continuous interchange of mass and energy.

In general, in order to reach the greatest understanding of morphological systems, the grouping of lithologic information and transformation agents is often necessary. The drainage network, as the landscape's modeling agent, allows one to observe the sense and the dissection degree of the relief as well as in which direction the regional planation surface is being eroded. The distribution of landforms as portrayed shows relief patterns that were developed through geological ages under various endogenic and exogenic processes. With the fieldwork and interpretation of the remote sensing products it was possible to identify three Regional Planation Surfaces (Table 1).

In this work the term "Regional Planation Surface (RPS)" was adopted instead of pediplain (King, 1956, 1957), peneplain (Davis, 1954), or etchplain (Budel, 1982) due to the genetic inferences of these terms. According to Latrubesse et al. (2005), there are several questionings in fitting the Planation Surfaces into the evolution models of King, Davis, and Bundel. The RPSs, in the vision of Latrubesse and Carvalho (2006), are geomorphologic systems represented by a set of geoforms which are genetically interconnected by a defined internal structure characterized by state variables (lithology, regional pendent, structures, etc.) and transformation (erosion, transport, weathering/pedogenesis, oscillation of the water level, etc.).

Table 1 - General characteristics of the Regional Planation Surfaces – RPSs.

REGIONAL PLANATION	SUB-UNIT	QUOTAS (m)	DISSECTION DEGREE	GENERAL CHARACTERISTICS ASSOCIATED UNITS
RPSII	B-TR	750-1000	Very low	Tabular relieves generated on horizontal to sub-horizontal rocks of the Paleozoic-Mesozoic Paraná Province
	B	750-1000	Low and strong	Surface generated on sedimentary rocks of the Paleozoic-Mesozoic Paraná Province
RPSIII	A-TR	750-850	Middle and strong	Tabular relieves very flat generated on horizontal rocks of the Paleozoic-Mesozoic Paraná Province basins and Neoproterozoic Arenópolis Magmatic Arc
	B-TR	550-750	Very low and low	Tabular relieves very flat generated on horizontal rocks of the Paleozoic/Mesozoic Paraná Province basins
	B	550-750	Low to very strong	Surface generated on Paleozoic/Mesozoic Paraná Province basins
	C-TR	500-700	Very low	Tabular relieves generated on horizontal rocks of the Paleozoic-Mesozoic Paraná Province basins
	C-H	500-700	Middle	Planation surface developed on sedimentary rocks of the Paleozoic-Mesozoic Paraná Province basins associated with hills
	C	500-700	Low and very low	Surface generated on sedimentary rocks Paleozoic-Mesozoic Paraná Province basins and Neoproterozoic Araguaia Belt
RPSIV	A-TR	400-550	Very low	Tabular relieves generated on horizontal to sub-horizontal rocks of the Paleozoic-Mesozoic Paraná Province basins
	A	400-550	Low to very strong	Developed on Paleozoic-Mesozoic Paraná Province basins and Precambrian basements such as Goiás Massif and Massif and Arenópolis Magmatic Arc
	B	300-550	Middle to very strong	Dominant on Paleozoic-Mesozoic Paraná Province basins and Neoproterozoic Mara Rosa Magmatic Arc
	C1	180-400	Low to strong	Developed on great varieties of rocks dominantly Pre-cambrian (Araguaia and Paraguay belts, Porto Nacional-Nova Crixás, Goiás Massif, Rio Maria Domain, Arenópolis Magmatic Arc, Iriri-Xingu Domain, Foreland Basin) and Quaternary Bananal Basin. Laterite levels occur well developed and hills are frequent associated to metamorphic basements (Araguaia and Paraguay belts, Arenópolis Magmatic Arc)
	C2	165-400	Very low	Lacustrine system associated to the Pleistocene Araguaia Formation and laterite crust, with very flat relieves

The second criterion here adopted considers chemical weathering processes, variation of rock resistance (diversity of lithologic composition), fluvial system, climatic changes, and tectonic activations. The regional interactions of the tectonic events from the opening of the South Atlantic and the Andean orogeny transferred efforts to the crystalline basement rocks and of the Paraná Basin during all the Cenozoic, causing uplift movements that may have been true geomorphologic "triggers" in favor of the generation of different Regional Planation Surfaces.

In this context, erosion processes in the study area had acted on rocks of very distinctive chemical composition, tectonic paleoenvironment, and age. In this geological scenario a great variety of landforms were developed in association with denudational and aggradational systems. The spatial distribution of the major geomorphologic units is illustrated in the geomorphologic map of Fig. 4 and is discussed below (for more details of the categories see Annex I).

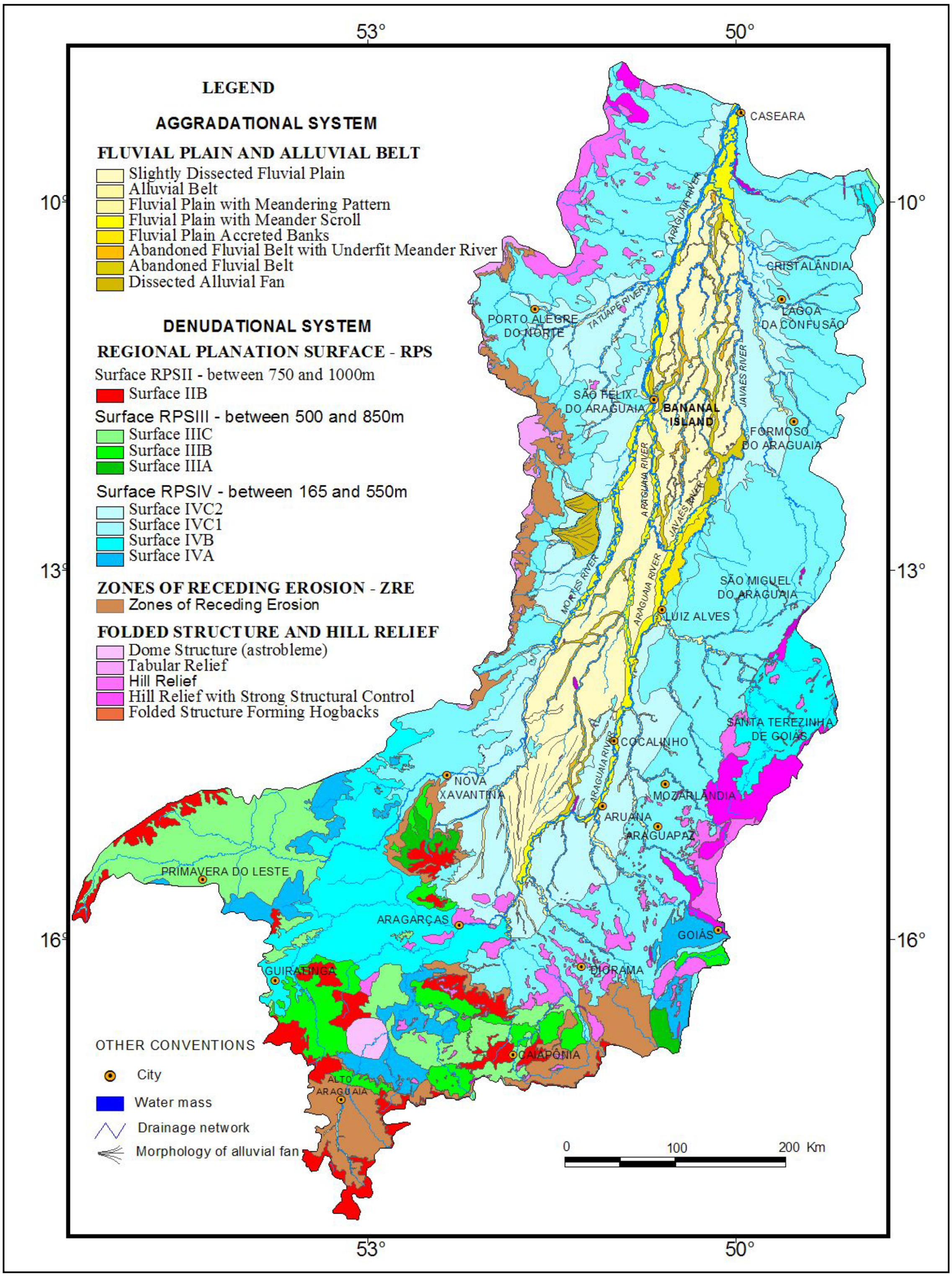

Fig. 4 - Geomorphologic map of the Middle and Upper Araguaia River Basin.

4.1. Denudational system

4.1.1. Regional Planation Surfaces – RPS

The denudational units are generated by erosion and planation of a terrain surface inside a given interval of quotas. The spatial distribution of RPS does not necessarily respect lithologic limits, rock ages, or tectonic styles.

In this form, regional surfaces present a great variety of dissection intensity. The RPS units were generated through topographic differentiation which resulted from the interaction of multiple tectonisms (old and recent) that acted in both Precambrian rocks and Phanerozoic rocks. The differentiation occurs through varied denudational agencies and under various endogenic and exogenic processes.

The morphographic regionalization of surface forms was achieved through recognition of a regional relief pattern into three levels, scheduled in different altitudes, with quotas that vary between 750 and 1000m (RPSII), 550 and 850m (RPSIII), and 165 and 550m (RPSIV). Each surface is capable of containing two or four subdivisions and occupying a total area of approximately 232,000km² or ca. 81% of the study area.

The different levels of each RPS, the Zone of Receding Erosion (ZRE), and differentiated patterns of dissection, tabular relief, hill, folded structure, and dome structure were obtained from the shaded-relief and shade color images from the SRTM data.

4.1.1.1. Regional Planation Surface II – RPSII

This geomorphologic unit is represented by the RPSIIB-TR surface with the most elevated altitudes of the study area, between quotas of 750 and 1000m above sea level. This surface is characterized by Tabular Relief (TR) or plateau which was generated on sediments with horizontal to sub-horizontal bedding, associated to the Paleozoic and Mesozoic sedimentary rocks of the Paraná Structural Province (Furnas, Serra Geral, Aquidauana, and Bauru formations).

The horizontal character of the relief is considered an attribute of this unit and is well represented in the southern region of the study area (upper Araguaia Basin). The dissection pattern is generally very low-to-low with much located occurrence of strong dissection. The relief with very low dissection is developed on Tabular Relief (TR) and mainly occurs northward in/of Primavera do Leste, southward in/of Nova Xavantina and in the Alto Araguaia region. In the Araguainha region, the SRAIIB-TR presents a pattern of low dissection that change to medium in Caiapônia city. Fig. 5 shows the characteristics of the relief patterns of the RPSIIB-BT surface and its relationships with RPSIVC1, RPSIVC2, and ZRE in association with sediments of the Paraná and Bananal basins.

The regional planation surfaces with the most elevated quotas, called RPSI (1.250- 1.600m) and RPSIIA (900-1250m) occur outside the study area, respectively, in Chapada dos Veadeiros and Federal District regions.

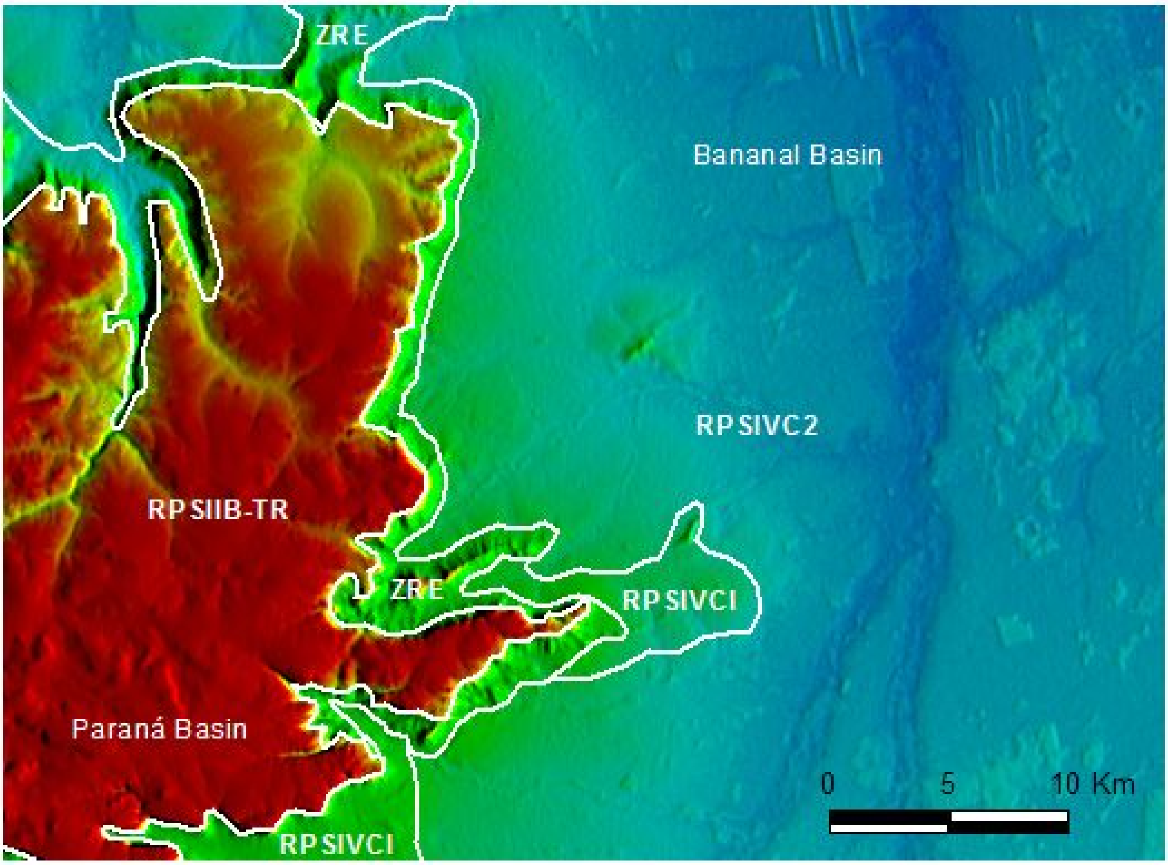

Fig. 5. Relationships between Regional Planation Surfaces (RPSIIB-TR, RPSIVCI, RPSIVC2) and Zone of Receding Erosion (ZRE). SRTM shade color image.

4.1.1.2. Regional Planation Surface III – RPSIII

This planation surface developed between quotas of 500 and 850m above sea level. It occupies a vast area on sedimentary rocks of the Paraná Structural Province (Bauru, Aquidauana, Furnas, and Ponta Grossa formations). The dissection degree is diversified between very strong to very low. The RPSIII surface was subdivided into three geomorphologic units represented by RPSIIIA, RPSIIIB, and RPSIIIC.

The RPSIIIA surface reveals quotas between 750 and 850m, with middle and strong dissection, associated to the Tabular Reliefs (TR) of the Paraná Basin. This surface occurs around 50km to the southeast region of Diorama city. The RPSIIB surface is situated in quotas between 550 and 750m with relief dissection varying from very low to very strong. The RPSIIIC with altitudes between 50 and 700m occurs mainly on a vast area in the Primavera do Oeste region, developed on sedimentary rocks with tabular relief associated to Bauru Formation rocks.

4.1.1.3. Regional Planation Surface IV – RPSIV

The RPSIV surface is dominant, covering more than 170,500 km² and occupying approximately 60% of the study area. This unit was subjected to renewed sculpturing essentially by denudational dynamics resulting in the creation of a younger topography, with the lowest quotas of the region, between 165 and 550m above sea level. In the analysis process, four geomorphologic units were identified: RPSIVA, RPSIVB, RPSIVC1, and RPSIVC2. The relief patterns generated a topography with varied dissection degrees (very low to very strong) developed on rocks with different origins, tectonism, and ages that vary from the Neoarchean to the Quaternary (see Table 1).

The RPSIVA represents the most elevated altitudes between 400 and 550m and exhibits four dissection degrees (low, middle, strong, and very strong). This unit is developed over Paleozoic sedimentary rocks (Aquidauana and Ponta Grossa formations) and Neoproterozoic Goiás Magmatic Arc.

The second level with quotas between 300 and 550m is represented by the

RPSIVB surface with three dissection degrees (middle, strong, and very strong). The main areas of occurrence are situated on the Paraná Basin, predominantly between the Aragarças and Guaratinga regions as well as on the Precambrian rocks in the regions of Santa Terezinha de Goiás and Nova Xavantina.

The RPSIVC1 is widespread and dominant in the study area and is made/formed on the border with the Bananal Plain. This third unit dips softly in the direction of the axis of the Banana Plain with quotas between 180 and 400m. The occurrences of laterite crusts and lateritized fluvial sediments being dismantled in the present climate are common, frequently forming blocks of disseminated fields on this regional planation. The RPSIVC1 surface developed mainly on Precambrian rocks from Goiás Massif, Araguaia and Paraguay belts, Arenópolis Magmatic Arc, Rio Maria and Iriri-Xingu domains. In these Precambrian basement rocks there are diverse associations of hill reliefs and folded structures with hogbacks.

The fourth planation surface is more distal and less dissected. It is represented by the SRAIVC2 that borders on externally and internally, respectively, with the Slightly Dissected Fluvial Plain (SDFP) and the SRAIVC1 surfaces, generally associated with a big quantity of small lakes on the Tertiary-Quaternary laterite crust. According to Vieira (2002), the lacustrine system evolved with the dissolution of laterites controlled by faulting. This unit shows a flat relief with lower quotas lower between 165 and 400m, developed on Pleistocene sedimentary rocks of the Bananal Basin (Araguaia Formation).

4.1.2. Zones of Receding Erosion – ZRE

The Polygenic Planation model is also responsible for the development of the Zones of Receding Erosion (ZRE). The fluvial system, as an antecedent element which is superimposed in the landscape, evolves strongly by receding erosion, expanding while generating rejuvenations of the landscape and the scheduling of old surfaces in more elevated distinct quotas.

In addition, the erosion of saprolites of the original surface which contributes to that fluvial system can be incisive and evolve by receding erosion. During the evolution of the ZRE hill reliefs are developed, all of which are constituted by rocks which are more resistant to erosion, mainly granite and quartzite. The ZREs are characterized by very scarped landform situated between two RPSs (see Fig. 5). This geomorphologic unit occupies an area of ca. 17.000 km² or 6% of the study area and is mainly associated to the Paleozoic-Mesozoic sedimentary rocks of the Paraná Structural Province (Paraná, Serra Geral, and Bauru basins) and Parecis Basin in the Serra do Roncador.

The development degree of the ZREs varies due to the characteristics of the zone that is being eroded (chemical and physical properties of the rocks, structural conditions, and escarpment slope). In general, the relief's main erosive agents are hydrologic conditions and climate, mainly rainfall, high temperature, and winds.

4.1.3. Hills, inselbergs, tors, folded and dome structures

These landforms represent the erosion-resistant basement remnants that cover about 7,4% of the study area. Metamorphic and igneous rocks such as limestone, quartzite, gneiss, and granite constitute these structures. The very strong dissection and strong structural control by faulting and folding are characteristic attributes of these reliefs.

In this context, tectonic reactivations produce new regional declivities that affect the older planation surfaces and, therefore, rejuvenate the structuration and not only the development of the drainage network. This way, while a ZRE evolves, recoil also the front of the escarpment that supports the pre-existing surface with the generation of a complex grouping called Hills, Inselbergs, and Tors. Agents from the chemical and physical weathering that is more characteristic in tropical areas are eroding these reliefs with time.

Thus, hills are a natural elevation of the land surface, rising rather prominently above the surrounding land, usually of limited extent and a well-defined outline. On the other hand, folded structures can be defined as the curving or folding of an area or strata rocks by compressive deformation on a broad scale, and they sometimes have the connotation of large-scale folding. In the hill domain hogbacks and tabular reliefs are sometimes developed. Both hills and folded structures (Fig. 6) in the study region are mainly developed on Precambrian crystalline metamorphic rocks from Tocantins, Central Amazon, and Carajás Provinces, as well as on sedimentary metamorphic rocks from Tocantins Province.

These structures are dominantly associated with the Regional Planation Surfaces, for instance, the RPSIVC1 and RPSIVB surfaces, and subordinately associated in the south portion of the Slightly Dissected Fluvial Plain (SDFP).

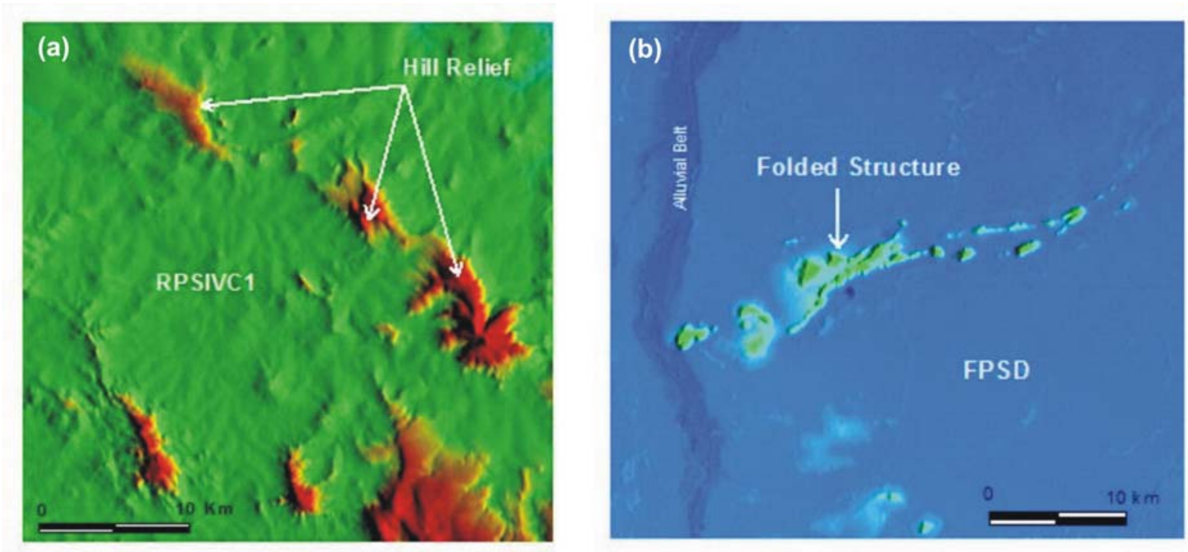

Fig. 6. Main features of the Hill and Folded structures. (a) Hill Relief with structural control in N45ºW trend generated by the Arenópolis Arc associated to the RPSIVC1 surface with middle dissection; (b) Folded Structure with strong structural control forming hogbacks and hills derived from limestone (Cuiabá Group) associated to the FPDS surface with very low dissection. SRTM shadecolor images.

In general, hills, inselbergs, and tors are very frequent morphologies in association with RPSs, mainly those developed on igneous and metamorphic rocks, for example, the RPSIVC1 surface. In the south portion of the Bananal Basin, the western region of Cocalinho, and in Aruanã, these geomorphologic features occur in the form of isolated residual bedrocks of granite and quartzite on the flat plain from Bananal Basin (Fig. 7).

Inselbergs are described as isolated hills that rise abruptly on the surrounding plain constituted of granitic or metamorphic rocks that are resistant to erosion, in plant, circular, elliptical, or complex forms. Tors are frequently spheroidal residual bedrock masses which develop usually on granitic rocks, resulting from subsurface rotting through the action of acidic groundwater penetrating along joint systems, followed by the mechanical stripping of loose material.

Fig. 7 - Quartzite inselberg on the RPSIVC1 surface in the Bananal Plain.

However, the most spectacular structure of the study area is the Araguainha Dome (Fig. 8). This meteorite impact structure is the greatest astrobleme known in South America. It is located at 16°47'S latitude and 52°59'W longitude, in the border of the states of Goiás and Mato Grosso. The Araguainha impact crater covers an area of approximately 1.300km², exhibiting a diameter of 40km mainly inserted in the RPSIVA, PRSIIIB, and RPSIIB surfaces.

This Araguainha Dome presents a circular structure, with scarps and valleys oriented in a succession of hills constituted by sandstones from the Furnas Formation (Paraná Basin). The geology of the uplifted nucleus consists of basement granitic rocks with the presence of shock-metamorphic effects and occurrences of suevite, brecciated material (impactites), and shatter cones (Crósta, 1982; Deutsch et al., 1992; Engelhardt et al., 1992). This astrobleme structure was formed on sedimentary rocks of the Paraná Basin (Furnas and Ponta Grossa formations) and its granitic basement.

Deutsch et al. (1992) estimated the event of the meteorite impact at 243±19 Ma using Rb/Sr dating in a sample of melted material from the crater. Similarly, samples of the melted material were dated by 40Ar/39Ar method and revealed ages varying between 247 and 243 Ma (Engelhardt et al., 1992; Hammerschmidt and Engelhardt, 1995). However, the meteorite impact occurred in the Lower-Middle Triassic.

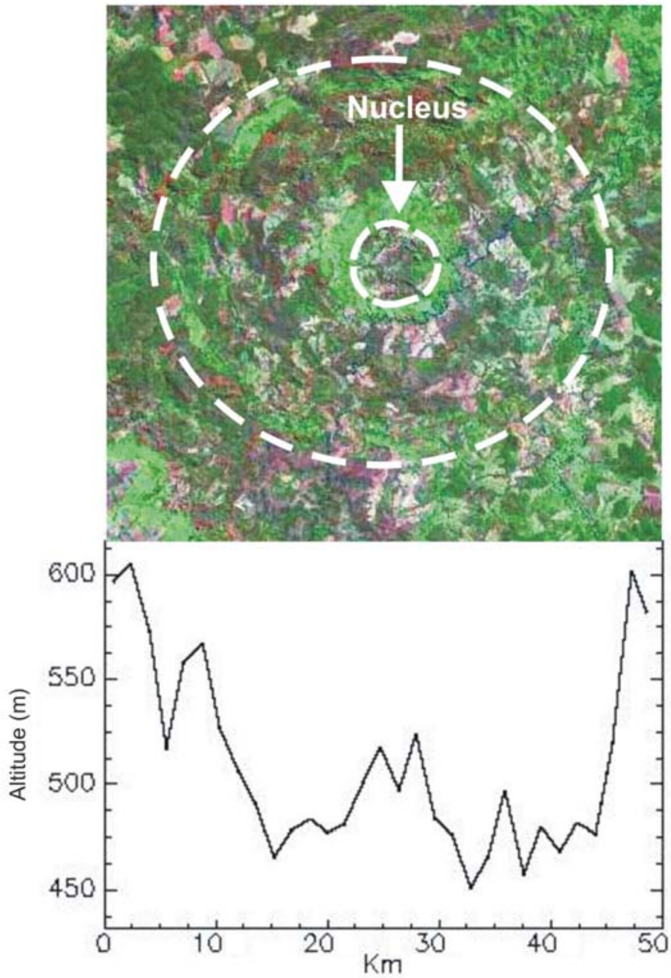

Fig. 8 - Above, circular structure of the Araguainha Dome. Crater with 40Km in diameter originated by meteorite impact during the Triassic period on sedimentary rocks of the Paraná Basin. Below, northwest-southeast profile from the Araguainha Dome obtained in the SRTM image.

4.2. Aggradational system

The Aggradation System occupies an area of 53.300 km² and represents about 18% of the study area. This system encompasses the Bananal Basin and, very subordinately, the Lacustrine System. Moreover, the fluvial Aggradation System is characterized by a flat widespread surface with a low slope along 730km of the longitudinal axis of south-north direction situated in quotas between 300 and 165m above sea level (Fig. 9).

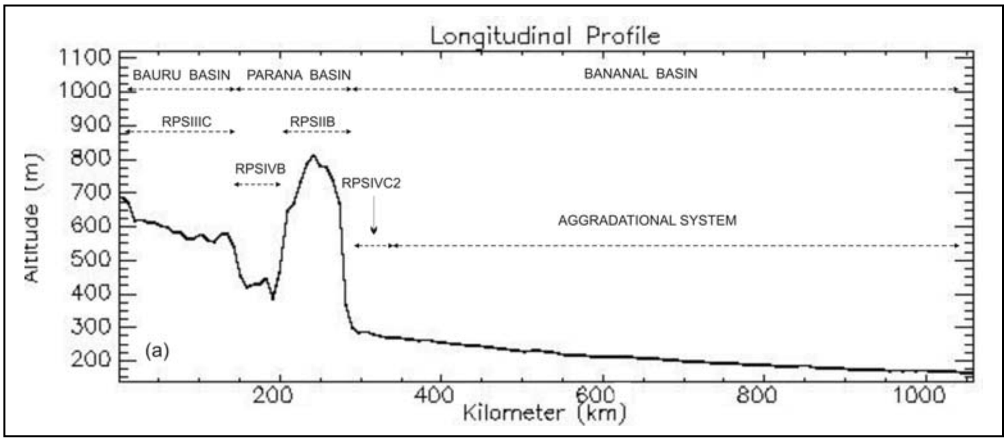

Fig. 9 - Longitudinal profile (south to north) of Upper and Middle Bananal Basin showing relationships between geomorphologic and geological units and altitude. Aggradational System (FP-Fluvial Plain, AB-Alluvial Belt) and Regional Planation Surfaces (RPSIIB, RPSIIIC, RPS IVB, RPSIVC2). Topographic profile generated from SRTM image.

Changes in surface elevation along the longitudinal and the transversal profiles are particularly useful in understanding current and future fluvial behavior. The longitudinal profile (Fig. 9) and transversal profile (Fig. 10) illustrate relationships between the main geomorphologic units from Aggradational and Denudational systems with the geological units and altitudes in the Upper and Middle Araguaia River Basin.

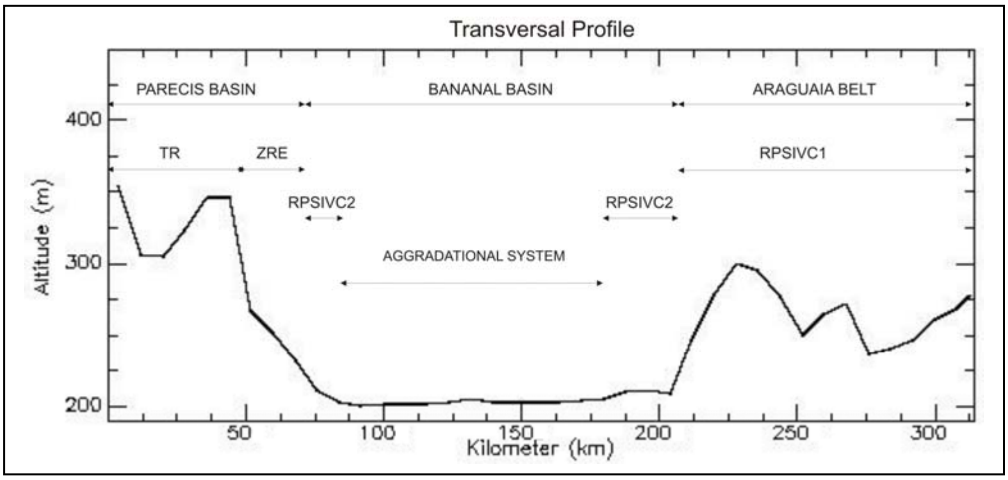

Fig. 10 - Transversal profile (west to east) in the middle part of the Bananal Basin showing relationships between geomorphologic and geological units with altitudes. Aggradational System (FP-Fluvial Plain, AB-Alluvial Belt). Regional Planation Surfaces (RPSIVCI and RPSIVC2), Zone of Receding Erosion (ZRE) and Tabular Relief (TR). Topographic profile obtained from SRTM image.

4.2.1. Fluvial and alluvial plains

The main geomorphologic categories identified in the Aggradational System are the Fluvial Plain, in the broad sense including functional and/or non-functional units, and the Alluvial Plain, related to the floodplain of the Araguaia and Mortes rivers and its main tributaries.

The alluvial plains consist of a complex mosaic of morphosedimentary units (Latrubesse and Stevaux, 2002) formed by sediments of the Holocene and probably of the Upper Pleistocene. In this floodplain six dominant geomorphologic units were recognized: 1) Alluvial Belt (AB) develops along the active channels; 2) Fluvial Plain with Accreted Banks (FPab) where accretion deposits of sandbanks in shallows near the river are dominant; 3) Fluvial Plain with Impeded Floodplain (FPif) constitutes a difficult area for the water flux in the alluvial belt; 4) Fluvial Plain with Meandering Pattern (FPm) represents a river channel having a pattern of successive windings which broadly resembles the trace of a meandering stream; 5) Fluvial Plain with Meander Scrolls (FPms) where meander and paleochannel features are dominant and 6) Abandoned Fluvial Belt with Underfit Meander River (AFBum) is a belt where the water volume of the stream is greatly reduced or whose meanders show a pronounced shrinkage in radius.

On the other hand, the oldest geomorphologic units that are registers of the behavior of the past's fluvial system developed during the Middle and Upper Pleistocene inside the Fluvial Plain which can be divided into three units: Slightly Dissected Fluvial Plain (SDFP), Abandoned Fluvial Belt (AFB), and the Dissected Alluvial Fan (DAF).

The Slightly Dissected Fluvial Plain (SDFP) is the most extensive geomorphologic unit of the aggradational system and represents more than 30.000 km² or around 11% of the study area. It has approximately 730km of length by 70km of average width. This unit is delimited by the Mortes and Araguaia rivers (westward) and by the Araguaia and Javaés rivers (eastward) (see Fig. 4).

The SDFP developed on the Pleistocene Araguaia Formation that usually consists of superficial beds of indurated clayey sediments with very variable thickness, ranging from 1 to 7m where observed. Under this clayey package there are centimetric to metric intercalations between sand and clay which exhibits parallel laminations and cross-bedding structures (Fig. 11).

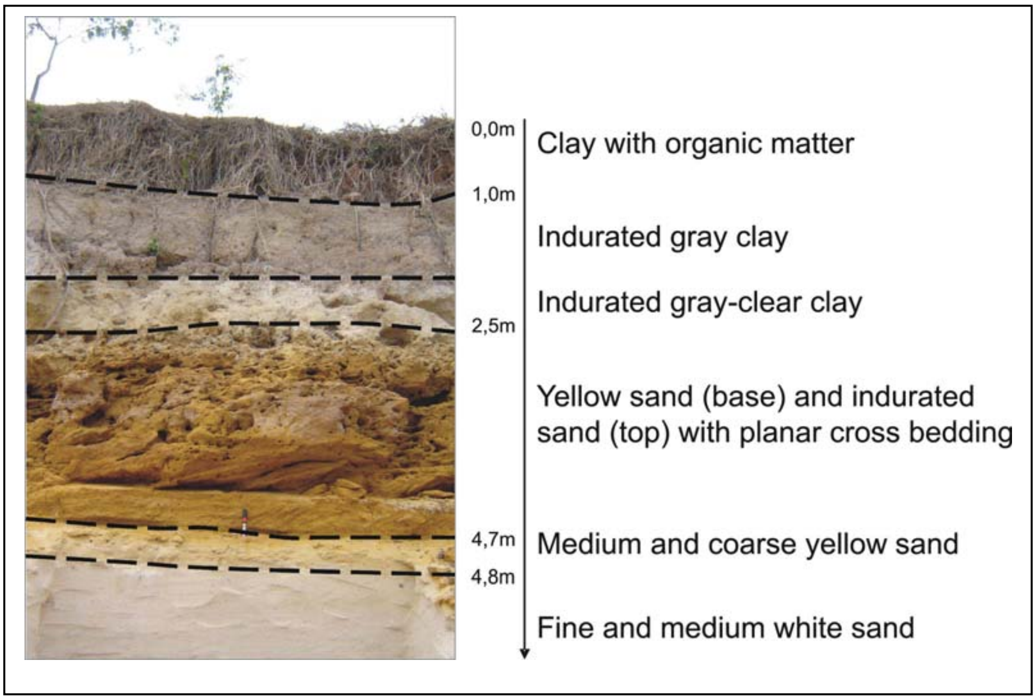

Fig. 11 - Representative stratigraphic structuration of the fluvial deposits from Slightly Dissected Fluvial Plain in the Araguaia River bank.

By and large, when the yellow sand beds are cemented with iron oxide they reveal an appearance of ferricrust. The SDFP is constituted by waterproof clayey soils that is periodically waterlogged as a result of the high rainfall during the rainiest season between January and March, whose flooding remains until May (Fig. 12). This surface is low structural that functions like a floodplain of water accumulation on the surface and underground.

The Abandoned Fluvial Belt (AFB) represents areas of abandoned channels originated through avulsions and river migrations. Avulsion is defined by Makaske (2001) as the diversion of flow from an existing channel onto the floodplain, eventually resulting in a new channel belt. In other words, avulsion is an abrupt change in the course of a stream, by a stream breaking through a meander or by a sudden change of current whereby the stream deserts its old channel for a new one. Avulsions may occur as a direct response to an individual tectonic event or in response to a gradual, tectonically-induced change in floodplain topography. It also occurs due to climatic changes or authigenic adjustments of the system itself. In these conditions, the river channel can be incised or it may abandon old alluviums and develop a new alluvial plain to lower levels. Therefore, the old alluvial deposits constitute the paleochannels or abandoned channel (Fig. 13).

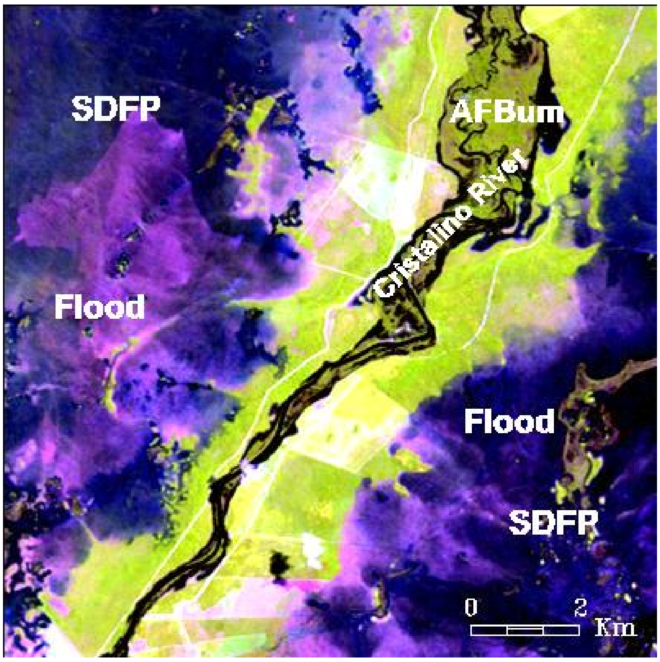

Fig. 12 - Flooding on the Slightly Dissected Fluvial Plain (SDFP) in ETM image, bands 543-RGB from May 23, 2000. See the levee features that separate the Abandoned Fluvial Belt with Underfit Meander River (AFBum) from the SDFP surface.

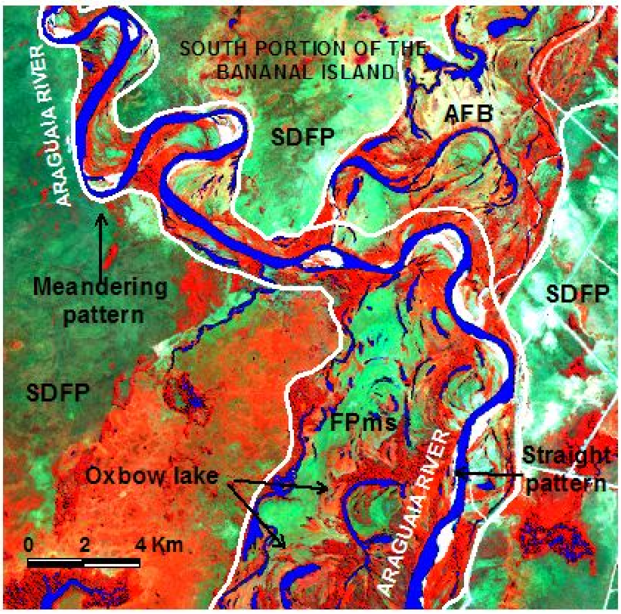

Fig. 13 - Characteristics of the Abandoned Fluvial Belt (AFB) generated by avulsion of the floodplain from the Araguaia River (FPms).

The geometry and distribution of channel incisions in the Bananal Basin suggest that avulsion processes were controlled by neotectonic events. These events are associated to the Goiás-Tocantins Seismogenic Zone that occurred mainly in the Quaternary, more specifically in the Middle Pleniglacial between 56.6±5.9 and 34.0±4.6 ka BP and during the Upper Pleniglacial between 26.4±3.1 and 17.2±2.3 ka BP (Valente and Latrubesse, 2007).

Abandoned Fluvial Belt with Underfit Meander River (AFBum) is characterized by an ancient floodplain with continuous or discontinuous channels, asymmetric and non-harmonic meanders that are generally associated to the oxbow lakes. The geometry and meander wavelength indicates that the modern underfit river is either too large or too small for the valley in which it flows. In the study area the AFBum unit is represented by small rivers that drain the Bananal Basin, for instance, the Jaburu and Riozinho rivers in the Bananal Island and Corixão, Corixinho, and Cristalino rivers situated westward of Cocalinho city. This fluvial system generated in the past a complex pattern of underfit and abandoned rivers by avulsion and abandonment that today work as intermittent drainage.

Fluvial Plain with Meander Scroll (FPms) is associated to the active fluvial plain, with width varying between 2 and 8km, located along the actual floodplains of the main rivers that drain the Bananal Basin (Araguaia, Mortes, and Javaés rivers). This unit is characterized by meander plains where a variety of landforms is identified, such as abandoned meanders, oxbow lakes, meander cutoffs, and swampy areas. Fig. 14 obtained in the Araguaia River illustrates the internal features of the FPms unit.

Fieldwork and analysis of seasonal ETM and MODIS images doubtlessly reveal that the overbank floodings of the Araguaia, Mortes, Javaés, and Cristalino rivers do not affect the Bananal plain. Therefore, the waterlogged surface of the SDFP is independent from the overbank flood of these rivers, as can be observed in the hydric control between the flooding in the Abandoned Fluvial Belt with Underfit Meander River (AFBum) from the Cristalino River and the flooding on the SDFP surface.

The Dissected Alluvial Fans (DAF) are alluvial deposits that occur westward of Aruanã city, between Araguaia River and Grande Stream, as well as in base of the Serra do Roncador, on the left margin of Mortes River (Fig. 15).

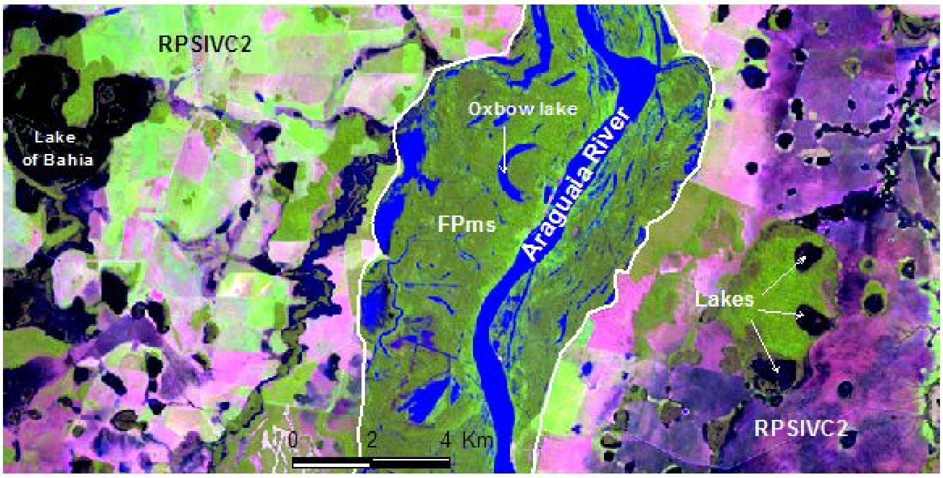

Fig. 14 - Geomorphic features of the floodplain from the FPms. Meander lakes and oxbow lake occur associated to the floodplain from Araguaia River, northward of Arauanã city. See the Lacustrine System with rounded lakes generated on the RPSIVC2 surface. ETM image, bands 543-RGB from May 23, 2000.

The alluvial fans developed a large number of ephemeral and small channels and simultaneously suffered active deflation on the oldest alluvial belts. The geometry of the fans possesses a triangular shape characterized by thick proximal sedimentation with associated water currents and flows of detritus that generate gradational bedding. The debris flow is deposited in foothills of the horizontal sediments of the Furnas Formation (Paraná Basin). Its implantation in the region was initiated by fault scarps, for crustal uplift through neotectonic events during the Quaternary.

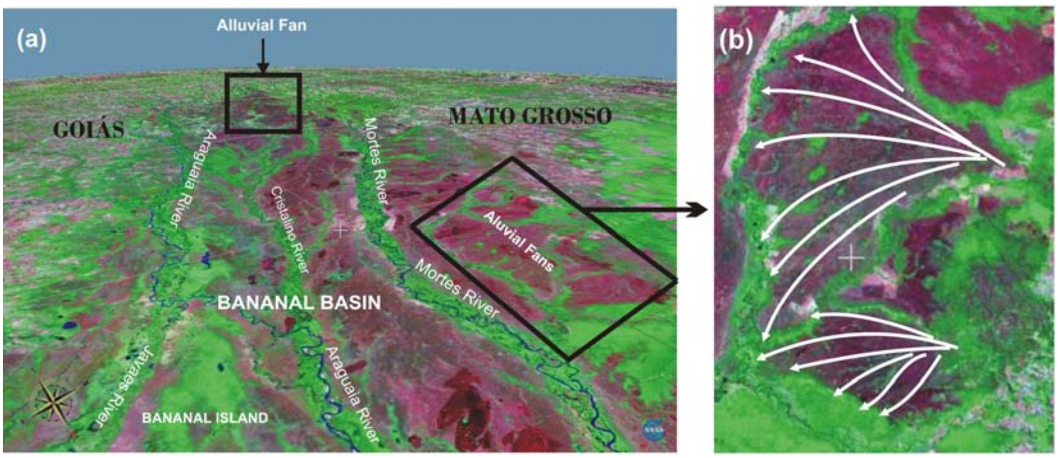

Fig. 15 - Dissected Alluvial Fans in the Bananal Basin. (a) Panoramic view of part of the Bananal Basin with location of fan areas. (b) Detail of the morphology of alluvial fans with indication of the sediment flows deposited in the foothill of the Roncador Mountain, in State of Mato Grosso. Geocover images obtained from NASA (worldwind.arc.asa.gov).

The Lacustrine System possesses a relatively restricted spatial distribution and occurs in association with the RPSIVC1, RPSIVC2, and very subordinately with the DSFP. The majority of these lakes is small, whose diameter is generally lower than 1000m. They have a rounded form that can evolve to bigger lakes through the coalescing of lakes with elongated forms in the direction of the regional subsurface hydrological gradient, for instance, the Lake of Bahia with approximately 7km of length along the N80W direction (see Fig. 14). The genesis of the lakes is related to the dissolution processes of laterite crust in association with fracture systems with NE-SW and NW-SE trends (Vieira, 2002, Latrubesse and Carvalho, 2006).

On another level, the lakes of the karstic system occur locally in the Lagoa da Confusão and in the Serra Dourada and developed, respectively, on limestone from Cuiabá Group and Couto Magalhães Formation. This karstic type is characterized by lakes in dolines and underground drainage (Fig. 16).

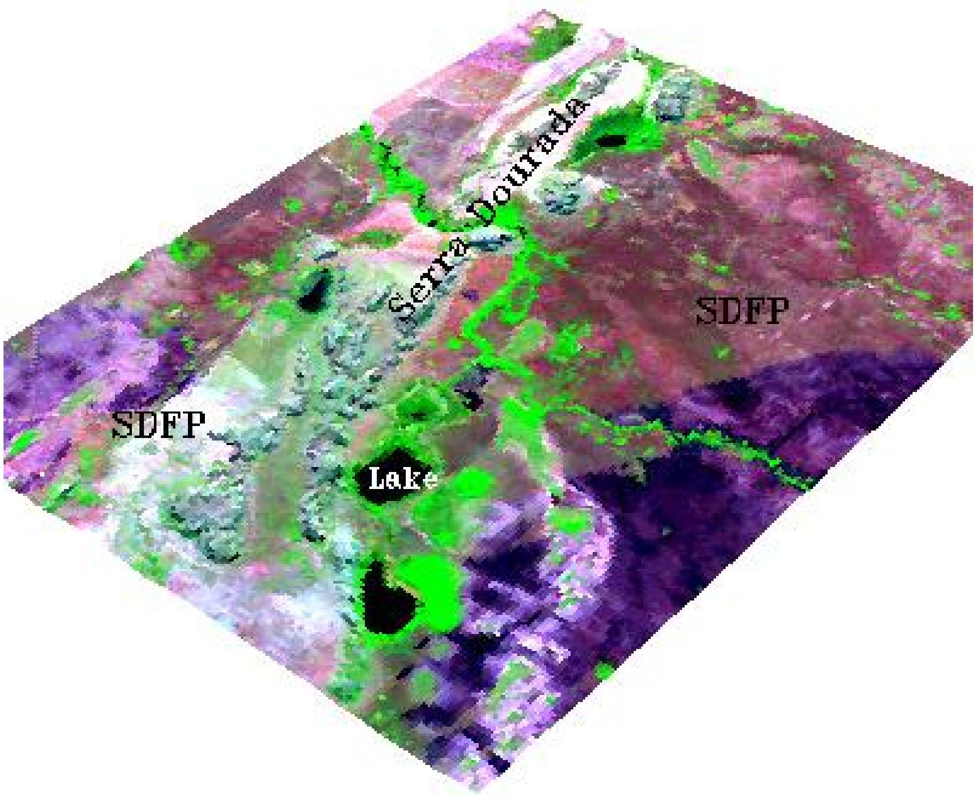

Fig. 16 - Lakes associated to the karstic system in folded structure forming hogbacks at the Serra Dourada. Neoproterozoic basement limestone of the Cuiabá Group into the Slightly Dissected Fluvial Plain (SDFP) from the Pleistocene Bananal Basin. 3D surface view in ETM image, bands 345-RGB.

The karstic relief of Serra Dourada and Lagoa da Confusão is constituted by Neoproterozoic limestone from calcareous-dolomitic facies. The limestone has a complex polygenic relief associating dried fluviatile erosion forms that were disorganized by water infiltration in fractures due to dissolution (karst). The karstic relief itself is remarkable for its high degree of evolution which shows residual interfluves and a series of dolines forming lakes with up to 2,60km in diameter (Lagoa da Confusão) and up to 1,70km in diameter (Serra Dourada). The calcareous-dolomitic outcrops are explored economically as limestone powder for soil correction in irrigated agriculture (soy, rice, corn, and watermelon) in Tocantins, Goiás, and Mato Grosso regions.

5. CONCLUSIONS

This study has demonstrated how SRTM data integrated with optical remote sensing and fieldwork data can be used to support geomorphologic mapping in a tropical area like the Araguaia River Basin.

Tectonic reactivations by uplift and subsidence movements that occurred during the Cenozoic may have been true geomorphologic triggers favoring the erosion process with generation of three different Regional Planation Surfaces (RPSII, RPSIII, and RPSIV). These surfaces of the denudation system are scheduled and separated by Zones of Receding Erosion (ZRE) in the following quotas: RPSII surface presents the highest altitudes between 1000 and 750m; RPSIII with intermediate altitudes of 750 to 550m; and the RPSIV surface encompasses the flat reliefs with the lowest quotas between 550 and 165m altitude above sea level. Each one of these landforms has two to four subsequent categories.

The RPSII and RPSIII are the oldest remaining surfaces with a predominance of strong dissection associated to the rough and hilly reliefs, covering an area, respectively, of approximately 9,300km² and 32,200km², associated to occurrences of Paleozoic-Mesozoic sedimentary rocks of the Paraná Province. On another level, the youngest and most widespread geomorphologic unit of the denudation system is the RPSIV surface with approximately 170,500km² or ca. 60% of the study area, developed dominantly on Precambrian basement metamorphic rocks.

As a result of erosive processes one of the biggest and most important Quaternary intracratonic basins of Central Brazil was generated: the Bananal Basin. Internally, the aggradational system of the Bananal Plain contains several morphosedimentary units formed by sediments of the Pleistocene and Holocene, covering an area of 52,300km² and occupying approximately 18% of the study area. The most representative geomorphologic units of this system is made up of Fluvial Plain Slightly Dissected, Fluvial Plain with Meander Scrolls, Fluvial Plain with Meandering Pattern, Abandoned Fluvial Belt, and Abandoned Fluvial Belt with Underfit Meander River. The oldest and most extensive unit with ca. 11% of the area is the Slightly Dissected Fluvial Plain generated on fluvial sediments from the Pleistocene Araguaia Formation.

The lacustrine system consists of innumerable lakes with rounded forms developed on Tertiary-Quaternary lateritic crusts in association with RPSIVC2 and RPSIVC1.On the other hand, the lakes associated to karstic relief have occurrences in the Serra Dourada and Lagoa da Confusão regions.

Avulsions, abandoned channels, underfit rivers, and channel pattern changes in the Bananal Basin are direct consequences of neotectonic movements that can be associated to the seismic activity from the Goiás-Tocantins Seismogenic Zone. Finally, sedimentologic, tectonic, and seismic studies and radiometric dating could make significant advances in the understanding of paleohydrological and paleoenvironmental reconstructions in the tropical system from the Bananal Basin.

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PAPER III

Paleohydrological characteristics and river channel avulsions during Middle and Upper Pleniglacial in Bananal Basin, Brazil*

* Submitted to the Quaternary Science Reviews

Paleohydrological characteristics and river channel avulsions during Middle and Upper Pleniglacial in Bananal Basin, Brazil

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Abstract

The Bananal Basin is one of the most important intracratonic Quaternary sedimentary basins of South America and preserves a good record of the paleohydrological conditions of Central Brazil where the Cerrado-Amazon ecotone currently develops. This area acts as a huge tropical plain, seasonally flooded by rainfall and water table saturation which can be classified as seasonal wetland. The Quaternary sedimentation of the Araguaia Formation is spread out on ~106,000km^2 of the Bananal Basin. The main driver filling the basin was the Araguaia fluvial. Significant paleohydrological and paleoclimatic data were recorded in the Bananal Basin, during the Middle and Upper Pleistocene. Geological and geomorphologic studies associated with TL and OSL dating was used to reconstruct the Pleistocene environmental and tectonic history of the region. The older alluvial deposits were recorded at 240 and 167 ka BP. This is the first record for this age of fluvial deposits belonging to a large alluvial system in Brazil. TL and OSL chronologies of the Araguaia Formation also provided evidence of the major fluvial aggradation phases and drainage avulsions in the region during the Upper Pleistocene. Aggradation and avulsion processes were important in the Middle Pleniglacial between 56.6±5.9 and 34.0±4.6 ka BP and in the Upper Pleniglacial between 24.5±3.1 and 17.2±2.3 ka BP. River avulsions were more intense in the low Bananal Basin (Bananal Island region).

We did not record dating between 17 and 10 ka BP. The age attributed to the older sediments is preliminary because more data is needed to generate a more detailed scenario of that time. However, dating is important because this is the first of these ages described in a large alluvial tropical system in Brazilian territory. The alluvial system was dominated by avulsion of fluvial belts which were re-occupied along the time by underfit rivers. Although avulsion seems to have been more active in the past, the abandonment by the Araguaia of a large fluvial belt where the Javaés River develops today indicates that the avulsion process is still active and can probably also be related to an active neotectonic activity in the basin, as demonstrated by present-day seismic activity. The record of the Bananal plain sheds new light on the paleohydrological conditions of Central Brazil and provides information between the transitional areas of Cerrado-Amazon. In general terms the record is in agreement with the fluvial record described in large Brazilian fluvial systems such as the Amazon and Paraná basins. However, the Bananal plain is unique because of its particular style of sedimentation and geomorphologic processes in which avulsion was the main mechanism along the time, generating such a mega-scale anabranching pattern of active channels, paleochannels, and underfit streams.

Keywords: Paleohydrology; Channel Avulsion; TL and OSL Dating, Bananal Basin

1. INTRODUCTION

The Bananal and the Pantanal Basins (Brazil), the Llanos de Moxos (Bolivia), and the Llanos del Orinoco (Venezuela and Colombia) are the most spectacular examples of tropical savanna plains affected by seasonal floods of South America (Fig. 1). The Bananal Basin is the main Quaternary sedimentary basin of Central Brazil spreading on approximately 106,000km² in the Cerrado-Amazon ecotone region. The extensive Bananal plain, formed by quaternary alluvial deposits of the Araguaia Formation, is temporarily flooded during the rainy season by both local rainfall waters and a saturated water table. With a drainage area of 384,600km² the Araguaia River is the main fluvial system draining the Bananal Basin.

The Bananal plain is crossed by the Araguaia River and is lightly dissected by several of Araguaia's tributaries. Many inactive alluvial paleochannels and other fluvial and swampy/lacustrine features occur on the Bananal plain, including a number of underfit rivers occupying paleo-alluvial belts and an underdeveloped drainage system. In the northern portion of this fluvial basin the Bananal Island can be found, a seasonal wetland with 20,000km², considered by some researchers as the largest fluvial island in the world. The Bananal Island is an area of environmental conservation that contains Araguaia's National Park and some aboriginal reserves.

Fig. 1 - Map of the main fluvial plains seasonally flooded of South America (according to Hamilton et al., 2002).

In this region, the vegetation cover is the Cerrado, a neotropical savanna constituted mainly of grassland, shrubs, and sparse trees with 1,5% of endemic plants, which is considered one of the world's 25 hotspots for biodiversity conservation (Mittermeier et al., 1998; Myers et al., 2000).

Although research on the Quaternary fluvial record of tropical South America has been growing substantially during the present decade, paleohydrological study and radiometric dating are non-existent in the Bananal Basin. In this context, the present study has as its objectives: (*i*) to define the morphosedimentary units of the Bananal Basin; (*ii*) to characterize the paleohydrological environment and the processes that controlled river channel style, dating the events by using absolute dating techniques, and (*iii*) to insert the Bananal area in tropical South America's paleoenvironmental context.

This study was developed using interpretation techniques of geomorphologic mapping from the SRTM and ETM+ images with fieldwork support, according to the methodological proposal by Latrubesse and Carvalho (2006). Sediment samples obtained from drill holes and riverbanks were dated through the Optically Stimulated Luminescence (OSL), Thermoluminesce (TL), and Radiocarbon (^{14}C) methods.

The antecedents of geomorphologic mapping and Quaternary studies in the Bananal Basin are scarce and in large-scale. Presently, the most frequently used cartographies are those generated conceptually by Radambrasil Project (Mamede et al., 1981), in large-scale (1:1:000.000) that has practically constituted the single source of available information at regional level since the 1980s. However, studies of fluvial geomorphology have concentrated in specific areas of the Bananal Basin, mainly along the floodplain of the Araguaia River (Bayer, 2002; Vieira, 2002; Latrubesse and Stevaux, 2002; Morais, 2006).

Recently, Latrubesse and Carvalho (2006) presented the Geomorphologic Map of the State of Goiás and Federal District, whose cartographic representation is based on the identification of denudational and aggradational systems and subsequent categories, and whose conceptual bases are deeply different from previously accomplished geomorphologic maps.

2. CHARACTERISTICS OF THE STUDY AREA

The Bananal plain is located in the Middle Araguaia River basin in Central Brazil, spreading on approximately 106,000km² (Fig. 2). The area encloses part of the states of Goiás, Tocantins, and Mato Grosso.

The plain is drained northward by the Araguaia River and its tributary, the Mortes River. The main tributaries of the Araguaia in this region are the Javaés, Peixe, Vermelho, and Crixás-Açu rivers entering from the right margin and the Mortes, Tatuapé, and Cristalino rivers from the left side.

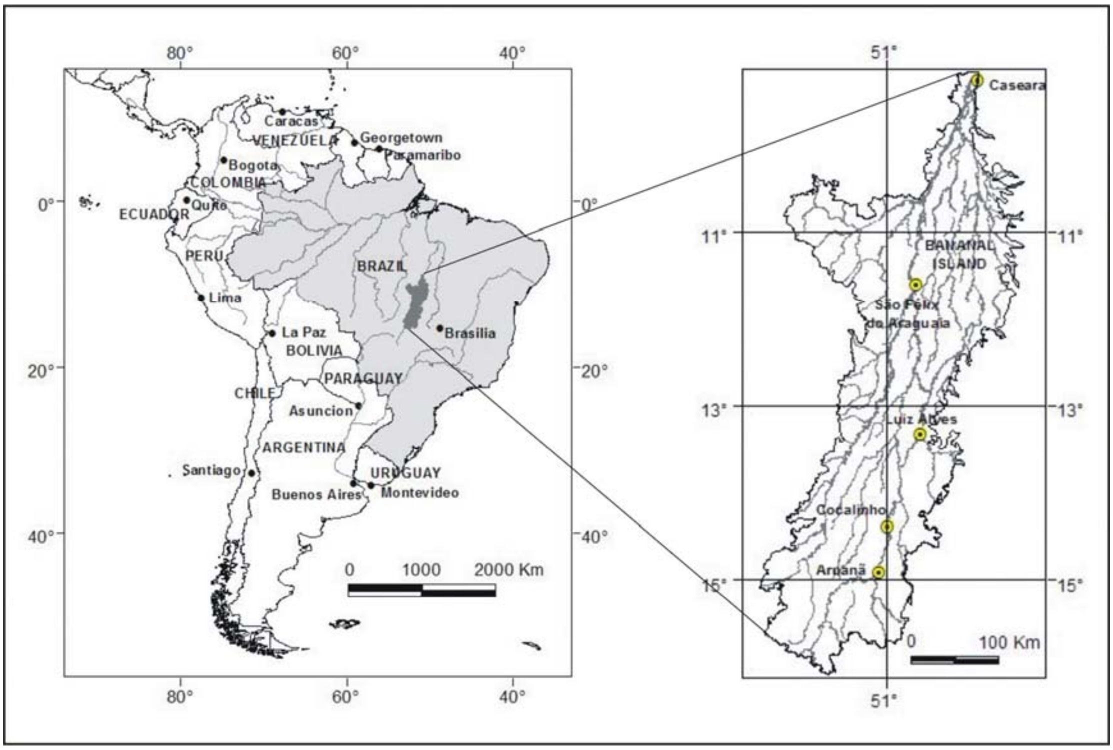


Fig. 2 - Location of the Bananal Basin in the South America setting.

The Bananal Basin is composed of Quaternary fluvial sediments of the Araguaia Formation (Barbosa et al., 1966) and Holocene alluvial deposits. The basement outcrops found mainly in the surrounding areas consist of Archean-Paleoproterozoic terrains (Goiás Massif, Rio Maria and Iriri-Xingu domains), Neoproterozoic metamorphic rocks (Arenópolis Magmatic Arc, Araguaia and Paraguay belts), Paleozoic sedimentary rocks (Paraná Basin Province), and Cretaceous ultramafic rocks (Alkaline Complexes).

The Bananal plain is a complex mosaic of morphosedimentary units formed by continental sediments attributed to the Quaternary which suffer seasonal flooding during the southern hemisphere's summer and is covered mainly by Cerrado grassland, shrub Cerrado, wooded Cerrado, Cerrado woodland, and gallery alluvial forest along fluvial belts.

The Bananal Island wetland, located in the northern part of the Bananal Basin, has an extension of 800km in north-south direction and 150km of mean width in east-west direction, with approximately 20,000km². The Bananal wetlands are not permanently flooded and have been identified as periodically flooded savanna wetlands based on analysis of fieldwork and ETM and MODIS data. However, high rainfall and its seasonal distribution cause periodic flooding during the summer, mainly between December and February.

The climate is wet-dry tropical with two well-defined seasons: a dry season and a wet season that correspond to the Aw in Koppen's Climatic Classification. The annual mean rainfall varies from 1,400 to 2,200mm/yr. Rain is predominant in the summer, therefore more than 70% of the total rainfall occurs between November and March. The annual mean temperature increases in the northern direction, varying from 22ºC to 26ºC and reaching a maximum of 38ºC in August and September. However, during the winter, mainly in June, there is a temperature reduction of about 15ºC.

3. MATERIALS AND METHODS

Thematic maps (tectonic, geological, and geomorphologic) were elaborated from visual interpretation techniques of the image spatial attributes of Landsat ETM+ from the dry season (July and September 2000). This interpretation was complemented with the digital processing of images (ENVI) and the integration of data through a Geographic Information System (ArcMAP). In addition, interferometric data from SRTM (Shuttle Radar Topography Mission) was also used for the topographical analysis of the relief features such as shaded-relief, density slice, topographic profile, and geomorphologic units.

Fieldwork was carried out in the Araguaia Basin and several reaches of the Araguaia River and Bananal plain since 1998 by car and boat. Trenches, drill holes, riverbank profiles, facies description, and fractures of the basement rocks were accomplished, as well as sediment sampling for sedimentary analysis by TL, OSL, and ^{14}C methods.

Fifteen sedimentary samples of river-abandoned channels from the Bananal Plain were dated by Thermoluminescence (TL) and Optically Stimulated Luminescence (OSL) methods and were processed in the Laboratory of Glass and Dating of the School of Technology of the University of São Paulo.

Three radiocarbon age determinations of wood samples from banks of the Araguaia River floodplain were carried out in the Radiocarbon Dating Laboratory of the University of Waikato, Hamilton, New Zealand.

4. THE BANANAL BASIN AND THE ARAGUAIA FORMATION

The Bananal plain is the main geomorphologic expression of the Bananal sedimentary basin. The Bananal plain is a flat lowland area which extends from 160 to 400m above sea level and is crossed by two large rivers (Araguaia and Mortes) which flow through a Quaternary sedimentary basin formed dominantly by the Araguaia Formation.

Based on magnetic and seismic anomalies, Hales (1981) interpreted that in the deepest part of the Bananal Basin, between Luiz Alves and the southern part of the Bananal Island, Paleozoic sediments could exist under Pleistocene sedimentary beds of the Araguaia Formation and the total thickness of the sedimentary cover could reach around 2,000m.

Furthermore, the Brazil-Canada Geophysical Project data demonstrated that the Bananal Island is the deepest region of the Bananal Basin where the magnetic basement has a minimum depth ranging from 5,000 to 5,500m (Hales, 1981). In addition, the map of gravimetric anomaly of Fig. 3 shows slow gravimetrics in the Bananal Island region that reveals a great thickness of sediments in relation to other parts of the Bananal Basin. According to this author, the Island presents economic potentialities in relation to fossil fuels.

However, according to Araújo and Carneiro (1977), based on seismic studies, the largest thickness of the Quaternary deposit probably varies between 170 and 320m.

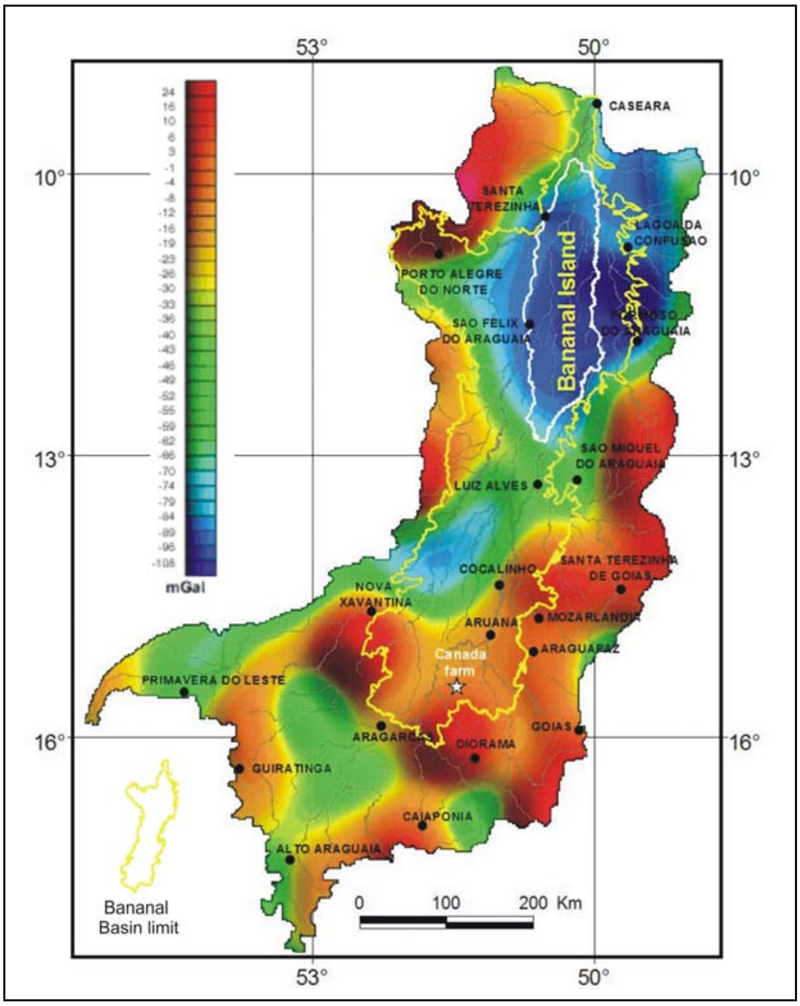


Fig. 3 - Map of gravimetric anomaly of the Upper and Middle Araguaia River Basin with location at the Bananal Island in the northern part of the Bananal Basin. See the low gravimetrics (blue color) in the Bananal Island region in relation to other areas of the Bananal Basin.

The Bananal Plain is developed on the fluvial deposits of the Araguaia Formation which were first described by Barbosa et al. (1966). According to these authors, the Araguaia Formation consists of Pleistocene continental sediments represented by a basal conglomerate covered by silts and sands that are yellowish to brownish ferruginous, unconsolidated to consolidated, and have varied texture and color. Pena et al. (1975) worked in the Goiás II project of the Geological Survey of Brazil and defined the Araguaia Formation as a succession of sandy silt to sandy sediments of a yellowish color, sometimes with sandy conglomerates. In that project a drill hole was performed on an aeromagnetic anomaly in the southern area of the Upper Bananal Basin in a locality named Canada farm (Fig. 4).

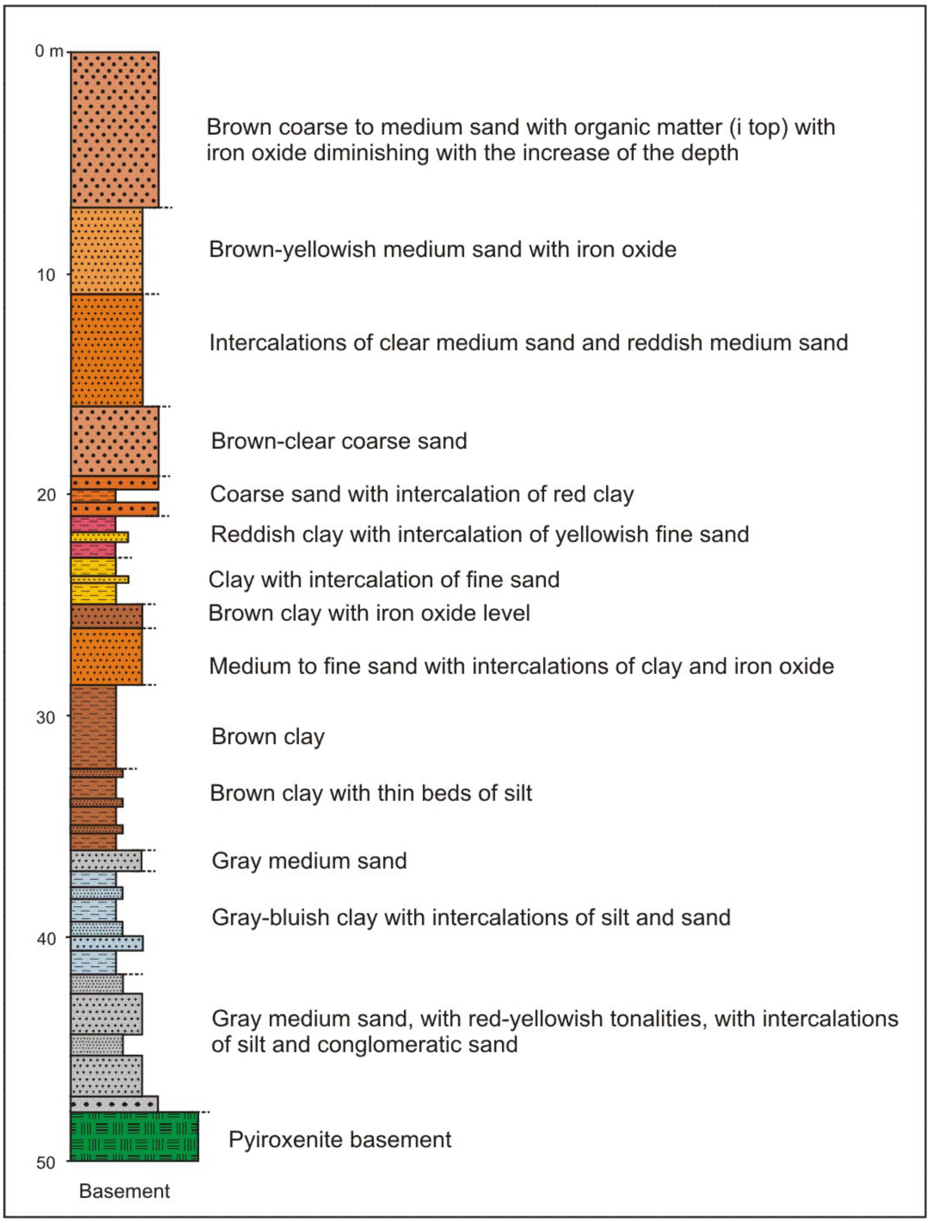


Fig. 4 - Stratigraphic profile of the Araguaia Formation drill hole carried out in magnetic anomaly in the Canada farm (adapted from Pena et al., 1975). The Canada farm is located in Figure 3.

In a broad sense, the Araguaia Formation is characterized by a succession of Neogene fluvial sediments constituted by a predominance of sandy sediments of variable textures with intercalations of clayey sediments. In some sectors, a clay layer that is generally indurated up to 6m of thickness can cover the top of the formation.

4.1. Geomorphologic setting

The geomorphologic mapping was based on the proposals of Latrubesse and Carvalho (2006) which was applied to the official governmental map of Goiás State, Brazil. Through fieldwork and interpretation of remote sensing products (SRTM and ETM) it was possible to identify and classify the regional geoforms in two main groups: Denudational and Aggradational Systems. Obviously, each system may involve many processes and landforms, but the criterion of classification is determined by the dominant landforms (active or inactive, erosional or aggradational) that can be identified in the mapping. The classification is based on the genetic type and organized in several levels of hierarchy. The spatial distribution of the geomorphologic units is shown in Fig. 5.

The fluvial units are characterized by a complex pattern of fluvial belts containing mainly underfit rivers or flooded areas with intermittent drainage. The fluvial belts were generated in the past by avulsion and channel abandonment. This system of paleochannels and underfit streams is spread along an area of ca. 700km of length and, in average, ~80 km width. The alluvial geomorphologic units were classified in six categories due to the internal complexity as: Slightly Dissected Fluvial Plain, Alluvial Belt, Abandoned Fluvial Belt, Fluvial Plain generated by Accreted Banks, Fluvial Plain formed by Meander Scrolls, and Abandoned Fluvial Belt with Underfit Meander River.

The Slightly Dissected Fluvial Plain is the most representative geomorphologic unit of the aggradational system and occupies an area of approximately 51,600km^2. This unit is characterized by a flat surface between 165 and 300m above sea level with low slope and very low dissection, spreading along a south-north longitudinal axis. Two large fan-like features of different ages were interpreted to the west of Aruanã city and at the piedmont area of the Serra do Roncador, on the left margin of the Mortes River (Fig. 5). These fan systems are generally fragmented relicts of abandoned channels, which ran northward and eastward in the past, respectively.

The Denudation System consists of two Regional Planation Surfaces (RPSIVC2 and RPSIVC1) and hilly reliefs related to folded structures which articulate laterally with the aggradational surface of the Bananal Plain. The RPS is a unit generated by the planation of a land surface, cutting a variety of lithologic and structural units.

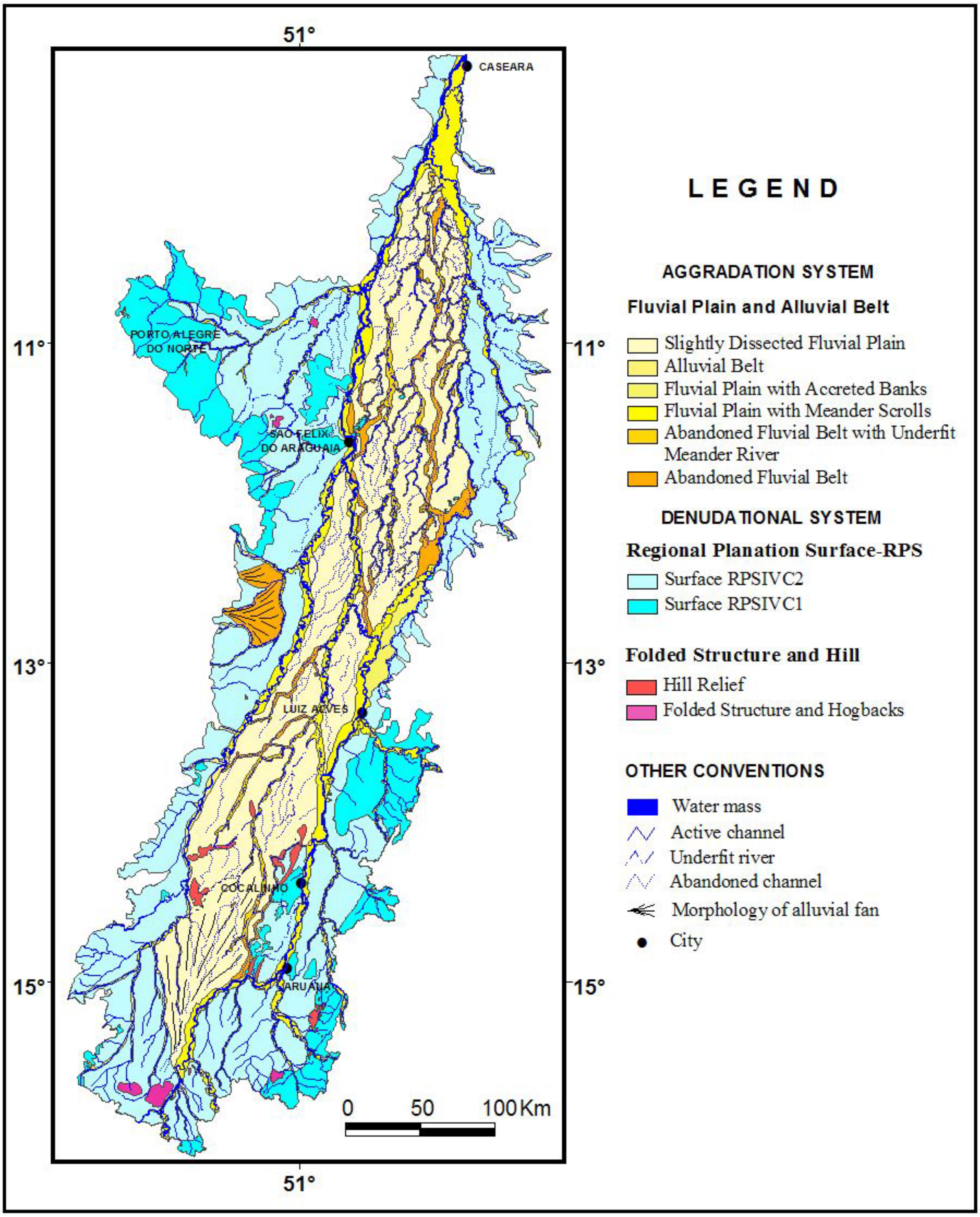


Fig. 5 - Map of main geomorphologic units of the Bananal Basin.

Regionally the RPSIVC2 is characterized by a flat surface with low dissection, innumerable lakes, and a low northward slope oscillating between 180 and 400m above sea level. The RPSIVC1 surface occurs in the northwest and southeast regions of the Bananal Basin. The dissection ranges from low to middle and altitudes vary between 180 and 400m above sea level.

The Bananal plain contains inselbergs and groups of hills formed by Neoproterozoic metamorphic rocks that are attributed to the Araguaia and Paraguay belts and the Arenópolis Magmatic Arc. The outcrops of the basements occur in the forms of folded structure forming hogbacks associated to hills, generally with very strong dissection and strong structural control in the NE-SW trend, for example, at Serra Dourada, Serra Branca, and Morro dos Índios. All of these basements are located in the Upper Bananal Basin region.

4.2. Tectonic interpretation

The alluvial belt of the Bananal Plain shows strong structural control. Evidence of neotectonism in the region has been reported in a broad sense by several authors. However, the most specific work is that by Hales (1981) who, by interpreting seismic and magnetometric data, defines, in Luiz Alves region, a horst and graben system. The Bananal Plain is located in the active seismogenic zone called Goiás-Tocantins Seismogenic Zone (GTSZ). In this zone there are frequent occurrences of seismic activity with a magnitude that varies from 2,9 to 4,1 (Richter scales) along lineaments with a NE-SE trend (Veloso, 1997).

According to Oswald and Wesnousky (2002) and Goodbred Jr. et al. (2003), tectonically active areas have a straight relation between natural seismicity and neotectonism. The GTSZ is associated with the main structural feature of Central Brazil named Trasbrasiliano Lineament with a N20-30E trend, and it is visible in remote sensing products (Fig. 6) and aerogeophysical data (magnetometry and gamma-ray spectrometry). In the Bananal Basin, the lineaments represent lines of crustal weakness that were reactivated from Precambrian geological faults along the geologic time up to the present.

During the fieldwork structural measurements (including faults, shear zones, and joints) were obtained directly from outcrops of the Neoproterozoic basement (Fig. 7). The basements occur into the Bananal Plain as hills which can be developed on folded structures. The basement is constituted by granite (Neoproterozoic Arenópolis Magmatic Arc), sandstone and limestone (Neoproterozoic Araguaia and Paraguay belts), and pyroxenite/dunite (Cretaceous ultramafic rocks).

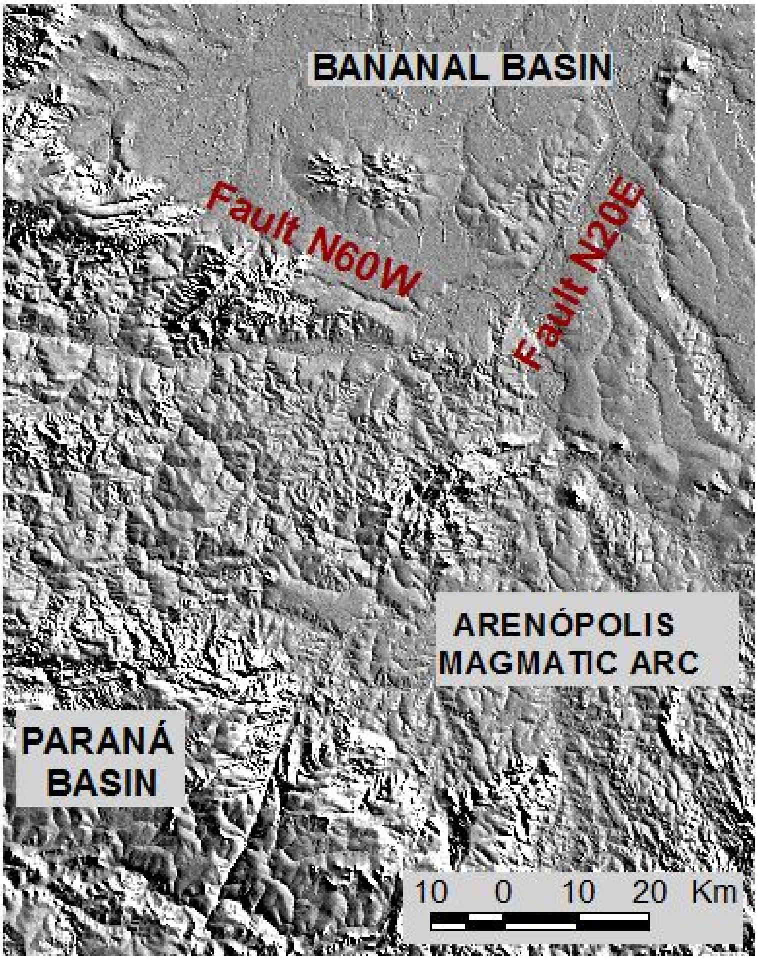


Fig. 6 - Neotectonic faulting evidences reactivated from Precambrian geosutures. See fault systems with N20E and N60W trends cutting the Furnas Formation of the Paraná Basin (Devonian), Arenópolis Magmatic Arc (Neoproterozoic), and Bananal Basin (Pleistocene). SRTM 3D shaded relief.

These structural data were plotted in a rose diagram. Fracture systems showed that variations of orientations are grouped in classes, according to the frequency of determined trends. Five trends were identified: two main groups with N20-30E and N60-65W trends and three secondary groups constituted by E-W, N-S and N20W trends (see rose diagram of Fig. 7f). The system of the first group is more developed and represents orthogonal extensional fractures with a high angle which is generally vertical to sub vertical (Figs. 7a, b).

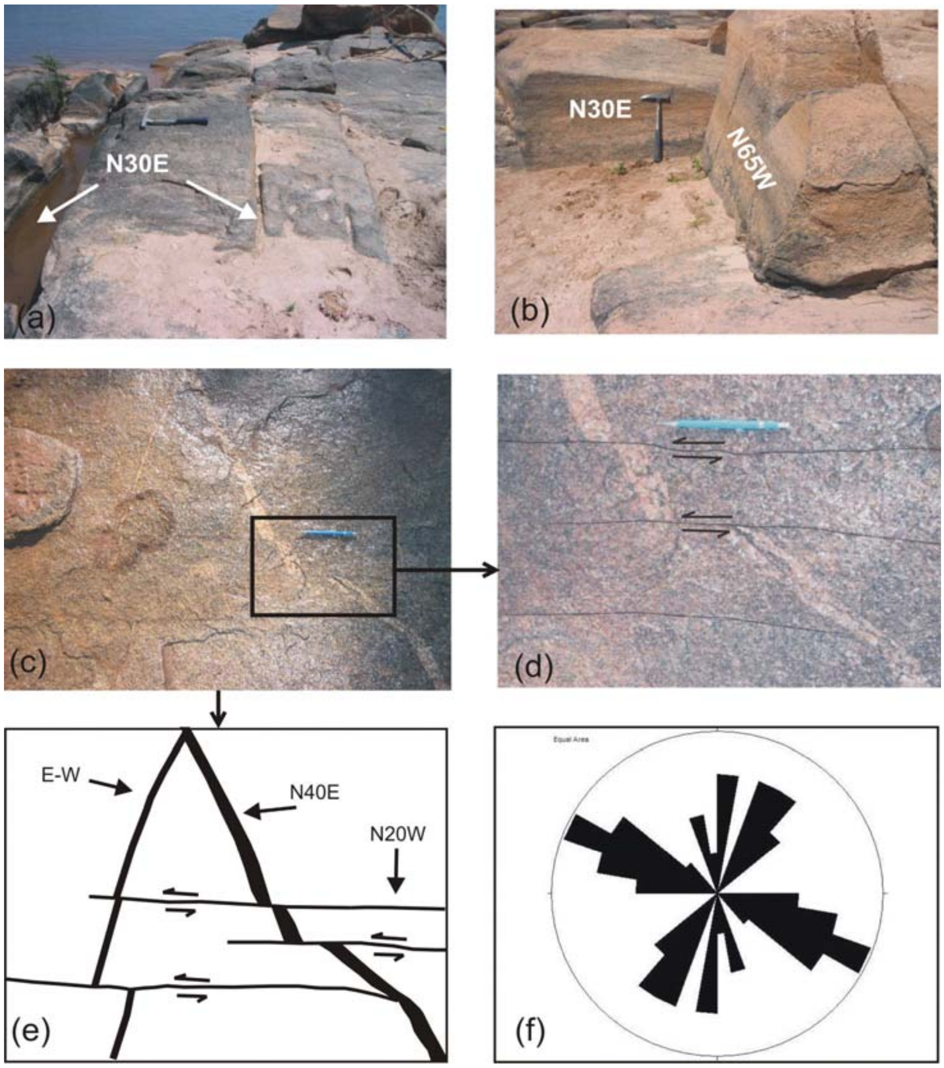


Fig. 7 - Fracture systems of the Neoproterozoic basement of the Bananal Plain. (a) Dominant fractures with N30E trend related to the regional Transbrasiliano Lineaments; (b) Two main systems of orthogonal extensional fractures with N30E and N65W directions; (c) Vein quartz with N40E trend dislocated by sinistral fractures of N20W direction; (d) Detail of the previous outcrop; (e) Illustration of the kinematics of the fracture systems of Fig. c: (f) Main directions of fractures in rose diagram obtained on outcrops of the basement of the Bananal Plain. The outcrops of the cited illustrations are constituted by garnet-biotite granite that occurs in the bed of the Araguaia River in the quarry of Itacaiú (Figs. 7a, b) and Aruanã city (Figs. 7c, d).

The N20-30E trend belongs to the Transbrasiliano Lineament and shows an impressive linearity of continental expression which is visible in satellite images. The other group is represented by extensional faults with N40E and E-W trends that are generally filled by quartz veins (Fig. 7c).

The sinistral fault system with N20W trend is younger and dislocates the N20-30E, N40E and E-W faults (Fig. 7e). On the other hand, the E-W system dislocates the N20-30E and N40E trends with a dextral movement. In the intersection between the N20-30E and N60-65W faults there are generally intrusions of granite and ultramafic rocks in the north part of the Upper Bananal Plain.

The neotectonic reactivation mechanism of these fault systems is the one that controls the Cretaceous magmatism and the Quaternary sediment deposition for the formation of the Bananal basin, and the one that influenced the development of the present landform patterns, drainage systems, and river avulsion into the Bananal Basin. The criteria of lineament interpretation in remote sensing images were the expressions of the linear elements of drainage and relief (drainage channel linearity, crest segment lines, rectilinear lake, vegetation belts, and linear variation of soil tonality).

4.3. River avulsions

Field data in the Bananal Basin showed that river avulsion processes have great influence in alluvial architecture because they determine the location, pattern, density, and interconnection of channels. This way, these processes produced hydro-geomorphologic conditions that created the avulsive aggradational systems such as the Abandoned Fluvial Belt and Abandoned Fluvial Belt with Underfit Meander River units. In addition, the influence of neotectonic activity on avulsions and framework of the deposits in fluvial systems are demonstrated by Alexander and Leeder (1987) and Oswald and Wesnousky (2002).

In the Bananal Basin the avulsions were interpreted and classified in conformity with the dimension of the width of the generated paleochannel as: (a) large - between 4 and 10km; (b) medium - between 3 and 1km, and (c) small - lower than 1km. We identified 69 avulsion points in the Bananal Plain but the greatest concentration occurs inside the Bananal Island. The location of channel avulsion points (or nodes) as mentioned in the text are indicated in Fig. 8.

Six large avulsion points or nodes, with magnitudes that vary from 4 to 10km in width, are related to the Araguaia River channel. Two of these avulsions happened in the Upper Bananal Basin and four in the Lower Bananal Basin (considering the 13º parallel as a limit between the upper and low basin, as can be seen in Fig. 8).

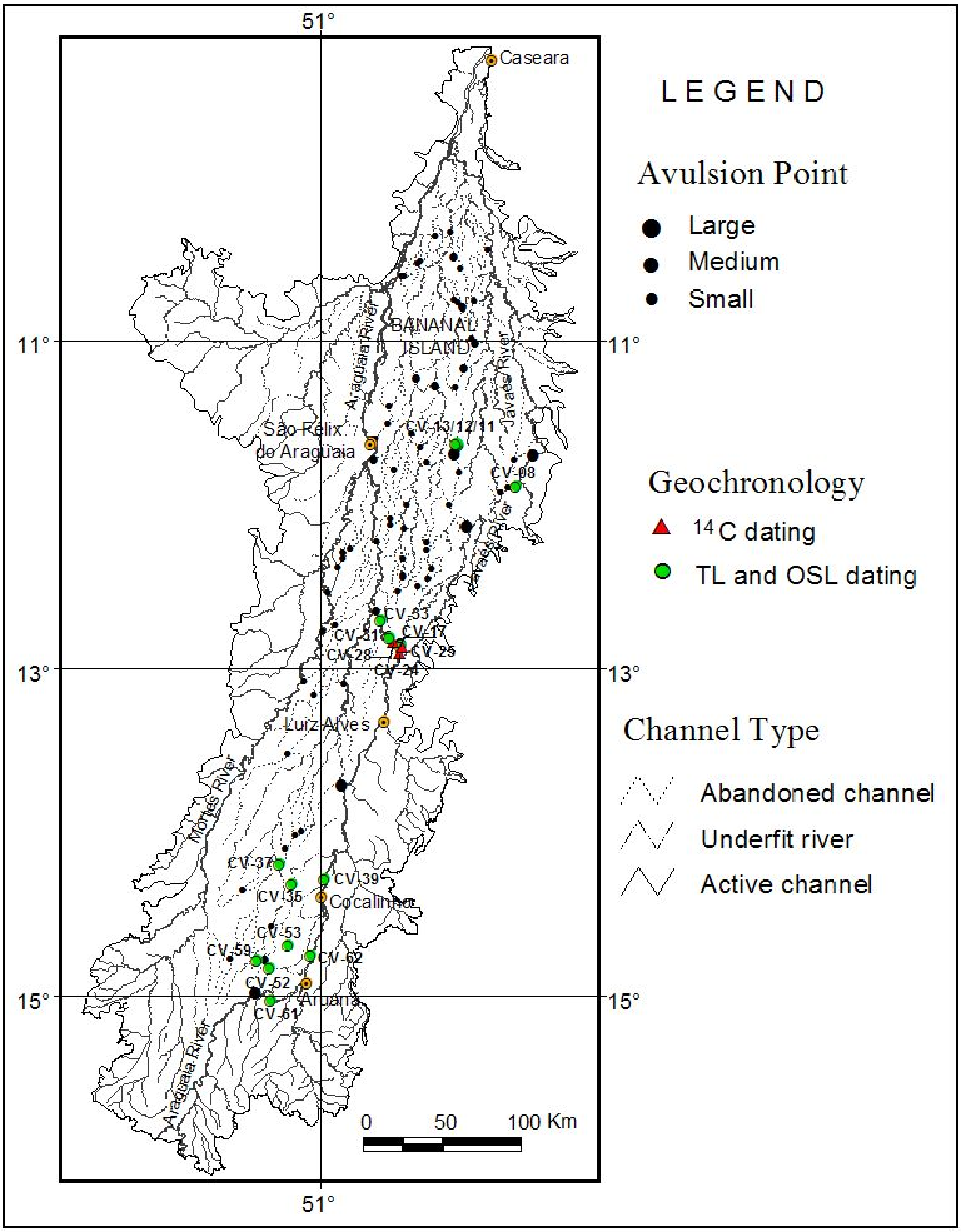
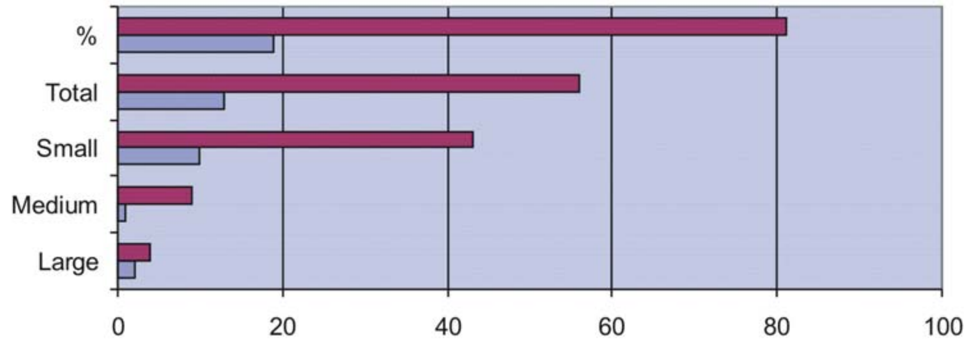


Fig. 8 - Map of drainage and paleodrainage features with location of avulsion points and radiometric dating (OSL and TL) in the Bananal Basin.

In this context, around 81% of the total of avulsion points are founded in the Lower Bananal Basin and distributed between Araguaia/Mortes and Javaés Rivers in the Bananal Island region. The statistical data of the avulsions in the Bananal Basin are illustrated in Fig. 9.



	Large	Medium	Small	Total	%
Low Bananal Basin	4	9	43	56	81
Upper Bananal Basin	2	1	10	13	19

Fig. 9 - Classification of magnitude of avulsion points in the Bananal Basin.

The abandoned fluvial belts show different characteristics and were classified in several categories as previously mentioned. For example, the Abandoned Fluvial Belt is a very characteristic and widespread geomorphologic unit in the plain. It represents paleochannels originated through river avulsions that shows the abandonment of the Araguaia River channel of its floodplain by avulsion, and bypasses the new channel towards the floodplain from Cristalino River (Fig. 10).

The abandoned fluvial belt shows several stages of evolution and the paleoplain may still contain remnants of paleochannel activity and styles such as oxbow lakes and other meandering lakes (scroll lakes), and in a more advanced stage avulsion is only possible in the identification of meandering features. In general, the abandoned fluvial belt consists predominantly of sandy and clayey sediments with oxbow features of different sizes.

The underfit river system is represented by small rivers, mainly the Jaburu and Riozinho, which are located inland of the Bananal Island plain as well as the Corixão, Corixinho, and Cristalino rivers located to the west of Cocalinho city. Nevertheless, in the upper reach of the Javaés River, close to the Araguaia River, the Javaés developed an underfit channel on the older floodplain of the Araguaia (Fig. 11). In this reach, the Javaés River channel is inactive (entirely dry) during the winter. The channels of the underfit rivers are narrow and continuous or discontinuous, with asymmetric and non-harmonic meanders. They are temporarily active only during the rainy season in the summer and have a lower proportion of suspended sediment in relation to bed load.

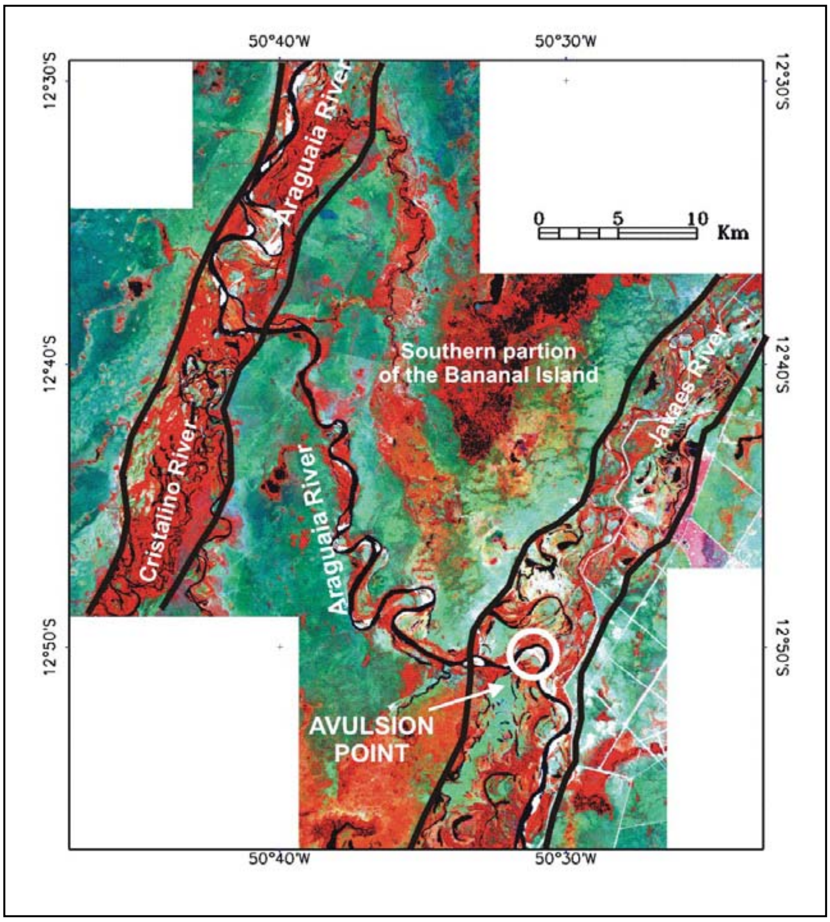


Fig. 10 - Spectacular avulsion of the Araguaia River. The Javaés River follows along the abandoned fluvial belt of the Araguaia. Note that the Araguaia is generating a new fluvial belt trough the increase of sinuosity and is cutting the older sediments of the Araguaia Formation on the southern border of the Bananal Island.

Fig. 11 shows the incompatibility between the dimension and geometry of the channels of the underfit Javaés River and the floodplain size. The floodplain with abandoned channels and oxbow lakes is interpreted as the fluvial paleoplain of the Araguaia River, abandoned as a consequence of avulsion. The natural vegetal cover in the abandoned belts and underfit rivers is gallery forest which can be partially or entirely replaced by shrub Cerrado and Cerrado grassland. In this case, the gallery forest is very fragmented because of a natural process of vegetational succession which creates a patchy mosaic.

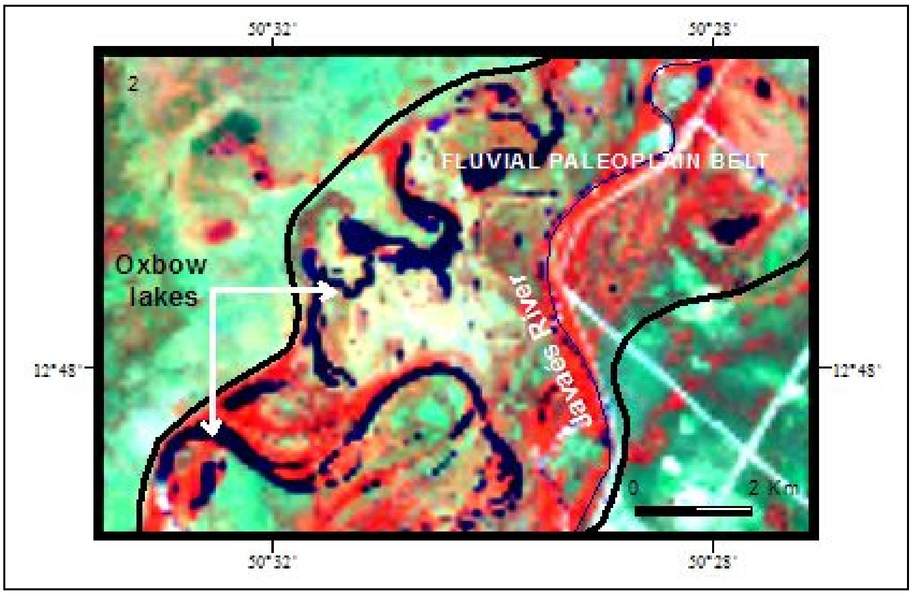


Fig. 11 - Characteristics of the abandoned fluvial belt with underfit meander river. The underfit Javaés River flowing on an ancient floodplain with oxbow lakes in the southern portion of the Bananal Island.

5. RADIOMETRIC CHRONOLOGY OF THE FLUVIAL DEPOSITS

An understanding of how fluvial deposits are distributed in space requires a study of the water flow, sediment transport, bed geometry during erosion and deposition, and the pattern of channel migration. In addition, the control of alluvial architecture in which a channel moves around the floodplain may be independent of processes within the sedimentary basin (allocyclic), for example, tectonism, climate, eustasy, or intrabasinal factors (autocyclic) when the controls are those related to factors such as seasonal floods, progradation of levees, and channel avulsions. Therefore, there are complicated interactions among these controls, and it is commonly difficult to isolate the cause for a particular sedimentological change (Ethridge et al., 1998).

Therefore, the study of sedimentary basins requires detailed knowledge of these controls that surpasses the aims of this research. However, the interpretation of the characteristics of sedimentation of the Bananal Basin was based on field observations and radiometric chronology of the deposits of the Quaternary Araguaia Formation and Holocene deposits.

The best exposures of the Araguaia Formation sediments occur in Araguaia River banks with a height that varies from 2 to 14m above water level in the dry season (Fig. 12). The sediments of these profiles are composed by a combination of sandy and clayey sediments. The sandy facies is formed by trough cross bedding sets but planar cross-bedding and planar stratification can also be found. The prevailing colors range from yellow to red-brown, due to the enrichment of iron oxides. Sometimes the sediment appears indurated, like a ferralitic crust (Fig. 13). Levels with more iron oxides are more frequent in the Low Bananal Basin region. These sediments represent channel-dominated environments.

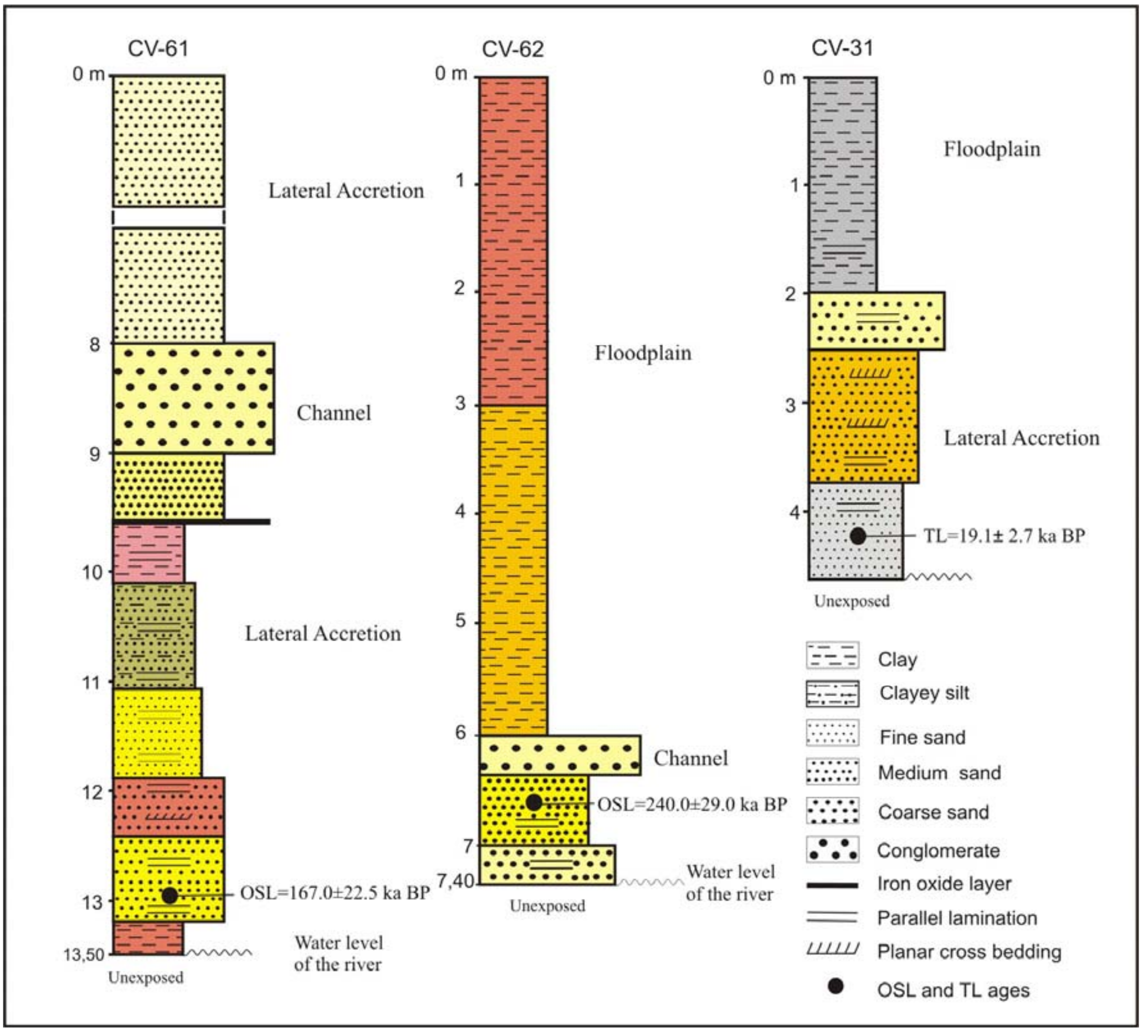


Fig. 12 – Characteristics of the main stratigraphic profiles in Araguaia River banks with OSL and TL ages. For location, see map in Fig. 8.

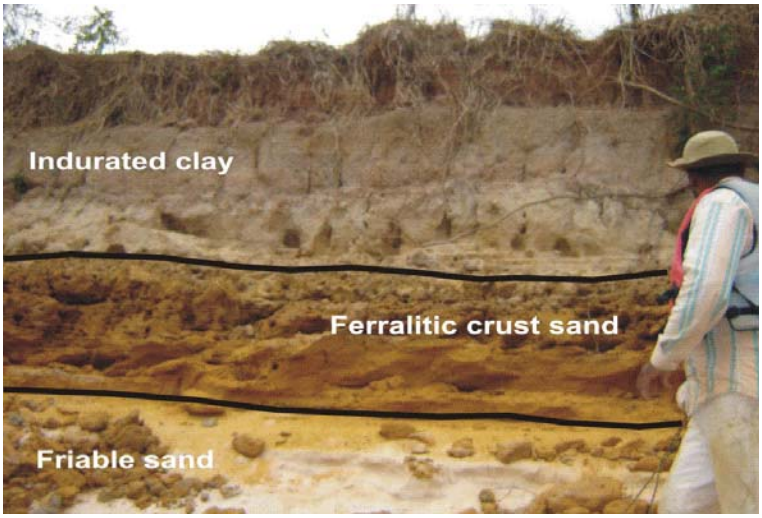


Figure 13 – Riverbank in Low Bananal Basin that shows a bed of oxidized sand like a ferralitic crust (1,70m) intercalated in white friable medium sand (base) and indurated clayey sediments (2,00m) in the top. The outcrop is located in the reach of the Araguaia River between the Cristalino River and the southern part of the Bananal Island.

The texture of sandy facies generally varies from fine to medium but coarse textures may also appear. Sandy conglomeratic facies outcrop is very restricted as beds in a general sandy sequence. The uppermost fine sediments consist generally of indurated clay and silts with colors ranging from gray-clear, yellow, to red-brown. The thickness ranges from 1 to 6m and represents a floodplain environment of sedimentation.

In Itacaiú region, fluvial sediments occur over the Neoproterozoic basement of granitic rocks. In this locality (Fig. 14 and profile CV-61 from Fig. 12), the Araguaia River incised the sediments of the Araguaia Formation where the riverbank exhibits 13,50m in height in relation to the low river water level. From the water level to 4,5m the sediments are well preserved by the uppermost level, which had suffered intense chemical weathering, pedogenic activity, and whose part of the internal structures was lost. Vegetation covers are common in the overbank deposits and are generally bioturbated by animals and plant roots.

Fig. 14 – Araguaia River bank in the Upper Bananal Basin (Itacaiú region) showing the fluvial deposits of the Araguaia Formation with 13,50m in height. This picture is illustrated in profile CV-61 of Fig. 12.

Some stratigraphic sections in abandoned channels and in the Bananal Plain which were obtained from boreholes by mechanic auger are shown in Fig. 15. In a broad sense, the Quaternary sediments from the abandoned fluvial belts consist of sandy, silty, clay, and clayey-sandy sediments. The texture varies from fine to coarse prevailing light-gray- to gray-medium and yellow to red-brown colors, due to the precipitation of iron oxides. Occasionally some indurated sedimentary layers, enriched in iron oxides, can be found mainly in the Low Bananal Basin. Sedimentary structures such as parallel lamination and planar cross beddings are frequent.

In addition, in the paleochannel of "Impuca de Macaúba", an ancient abandoned paleoplain of the Araguaia River, located in the inner part of the Bananal Island, three drill holes were carried out, whose profiles consist of white fine sand and clayey silty sediments. A bed of unconsolidated clay covers these fine deposits with a thickness of up to 3,2m. TL ages of the samples of fine sand near the base of the sections were 56.6±5.9 ka BP, 24.5±3.1 ka BP, and 17.2±2.3 ka BP, related respectively with the samples of the profiles CV-13, CV-12, and CV-11 (Fig. 16). The decrease of TL ages from west to east into the floodplain can be explained by two hypotheses: (i) Successive events of erosion by reworking of old fluvial deposit and adjacent eastward sedimentation in a manner of stacked ribbon sequences, or (ii) through lateral eastward migration of the river channel into the floodplain by regional tilting movements.

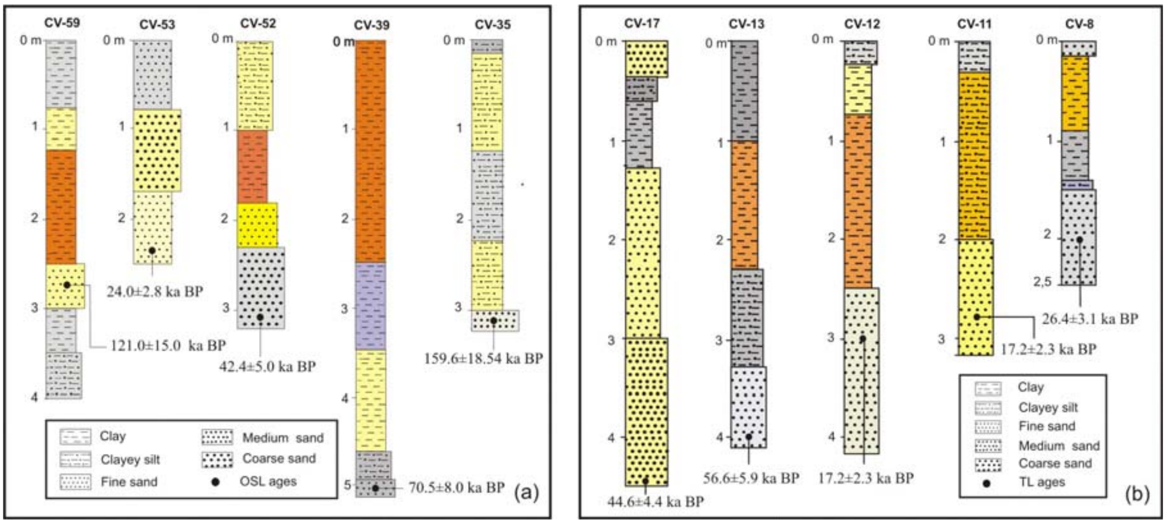


Fig. 15 - Stratigraphy and OSL and TL chronologies of various sections of abandoned channels from Bananal Basin. (a) Upper Bananal Basin showing the TL ages; (b) Low Bananal Basin with OSL ages. For location, see map in Fig. 8.

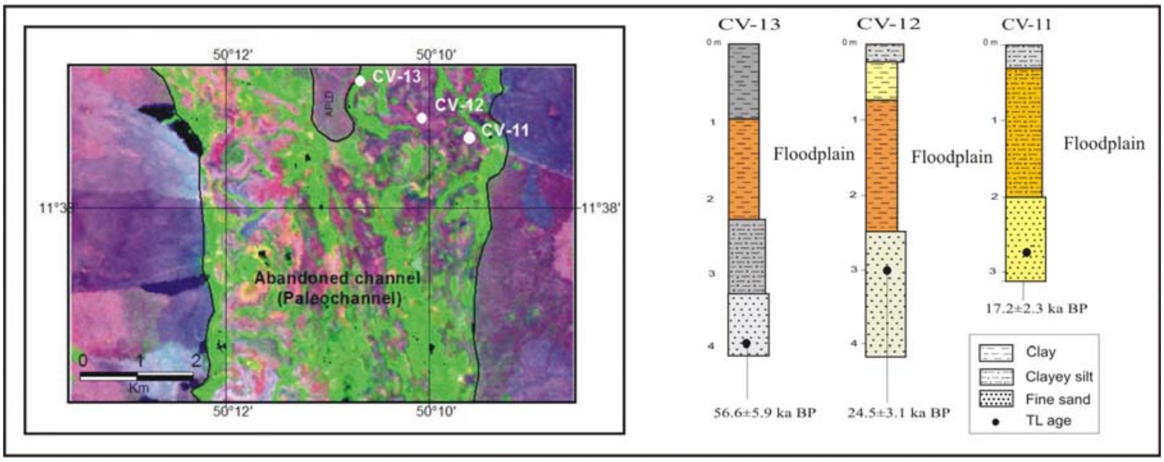


Fig. 16 - Location, stratigraphy, and thermoluminescence ages of profiles of the abandoned channel of “Impuca de Macaúba”.

Absolute ages of sand samples from abandoned channels and riverbanks were determined by Optically Stimulated Luminescence (OSL) and Thermoluminescence (TL) methods (Table 1). TL ages were obtained in the Low Bananal Basin which gave ages ranging between 56.6±5.9 and 17.2±2.3 ka BP (Upper Pleistocene). On the other hand, analyses of ages in the Upper Bananal Basin revealed old ages ranging between

240±29 and 24,0±2.8 ka BP (Middle and Upper Pleistocene) that showed a predominant deposition in the Middle Pleistocene related to the basal part of the Araguaia Formation (Fig. 17).

The OSL and TL age data of sands support the interpretation that river avulsions in the Bananal Basin were intensive in two stages of the Pleniglacial period. The older ages between 56.6±5.9 and 34.0±4.6 ka BP correspond to the Middle Pleniglacial, while the youngest ages between 26.4±3.1 and 17.2±2.3 ka BP are correlated with the Upper Pleniglacial when the basin's paleohydrological regime was morphogenetically more active than that of the present.

Table 1 - Results of TL and OSL dating for sand samples of the Bananal Basin.

Lab No	Sample No	Location	Depth (m)	Annual Dose (µGy/year)	P (Gy) TL	P (Gy) OSL	Age (year) BP
1461	CV-08	11°52' 56.6"S 49°48'21.2"W	2.00	776±53	20,51		26.400±3.100
1462	CV-11	11°37'18.1"S 50°09'32.8"W	2.70	1.424±117	24,51		17.200±2.300
1463	CV-12	11°37'05.3"S 50°10'02.1"W	3.00	1.062±81	26,04		24.500±3.100
1464	CV-13	11°36'43.1"S 50°10'38.0"W	4.00	536±29	30,3		56.600±5.900
1465	CV-17	12°51'25.1"S 50°30'21.2"W	4.50	475±23	21,21		44.600±4.400
1466	CV-31	12°48'22.35"S 50°34'47.54"W	4.20	2.774±252	52,93		19.100±2.700
1467	CV-33	13°14'32.77"S 50°37'42.10"W	5.90	1.597±135	54,23		34.000±4.600
1694	CV-35	14°18' 9.92"S 51°10'32.49"W	3.10	740±50		118	159.600±18.542
1695	CV-37	14°11'15.38"S 51°14'57.21"W	1.80	715±45		7	9.800±1.100
1696	CV- 39	14°16'48.80"S 50°58'21.24"W	5.00	715±45		47	70.500±8.00
1697	CV-52	14°49'29.96"S 51°18'52.21"W	3.30	800±55		34	42.400±5.000
1698	CV-53	14°41'21.38"S 51°11'50.83"W	2.40	730±50		17,4	24.000±2.800
1699	CV-59	14°46'35.57"S 51°23'5.89"W	2.70	995±75		120	121.000±15.000
1700	CV-61	15°1'19.13"S 51°17'59.83"W	13.00	995±75		265	167.000±22.500
1701	CV-62	14°44'59.09"S 51°3'31.15"W	6.50	900±65		215	240.000±29.000

The Araguaia alluvial plain develops mainly along the Middle Araguaia from Registro do Araguaia to Conceição do Araguaia, downstream of the Bananal Island. A general description considers the Araguaia alluvial plain as formed by three main units: a hindered drainage plain, a unit with abandoned meanders, and a more recent unit formed mainly by accreted bars, islands, and scroll features in the most occasional sinuous reaches (Latrubesse and Stevaux, 2002).

The alluvial sediments of the Araguaia in the southern part of the Bananal Island are associated to a fluvial plain with meander scrolls because of the sinuosity in this reach. These sediments represent the youngest geomorphologic unit attributed to the Holocene age. The fluvial plain with meander scrolls occurs in association to the active floodplain along the Araguaia and Javaés rivers and its tributaries.

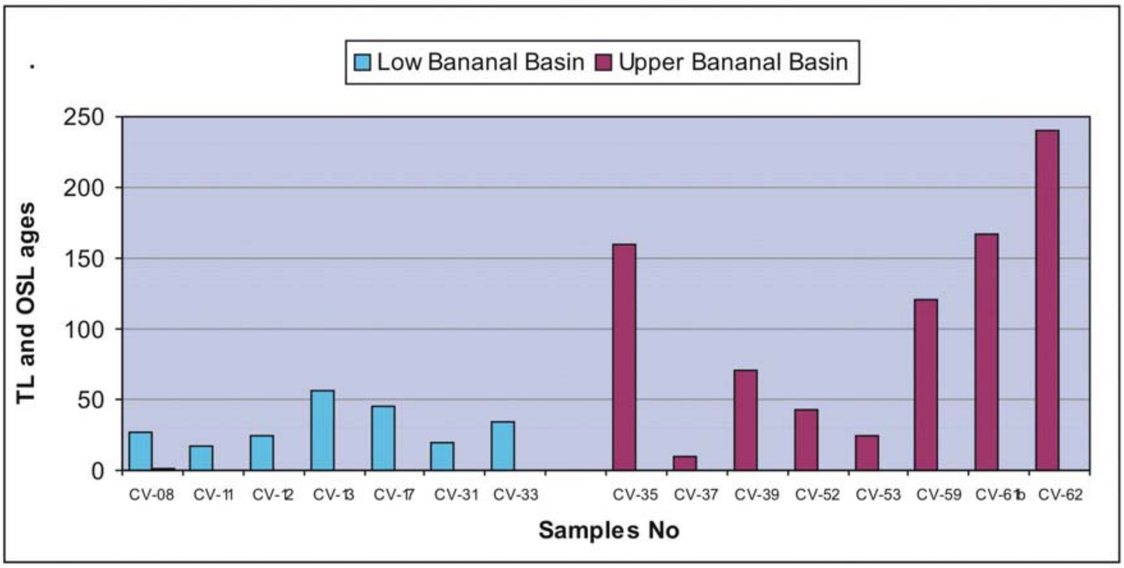


Fig. 17 - Comparison between TL (Low Bananal Basin) and OSL (Upper Bananal Basin) ages.

The floodplain exhibits a variety of landforms such as oxbows lakes, sand bars, islands, levees, active meanders, and swampy areas. The most common depositional forms are the sandy point bars colonized by a vegetation succession that stabilizes them. These recent deposits are mainly constituted by gravel, conglomeratic sand, sand beds with planar cross bedding and secondarily trough cross bedding, silt, clay, and organic matter intercalations represented by wood and leaf detritus (Fig. 18).

Radiocarbon dating of organic beds (logs and leaves) from Araguaia River (Table 2) showed that sedimentary deposits are very recent and was deposited between 115 and 220 ^{14}C BP.

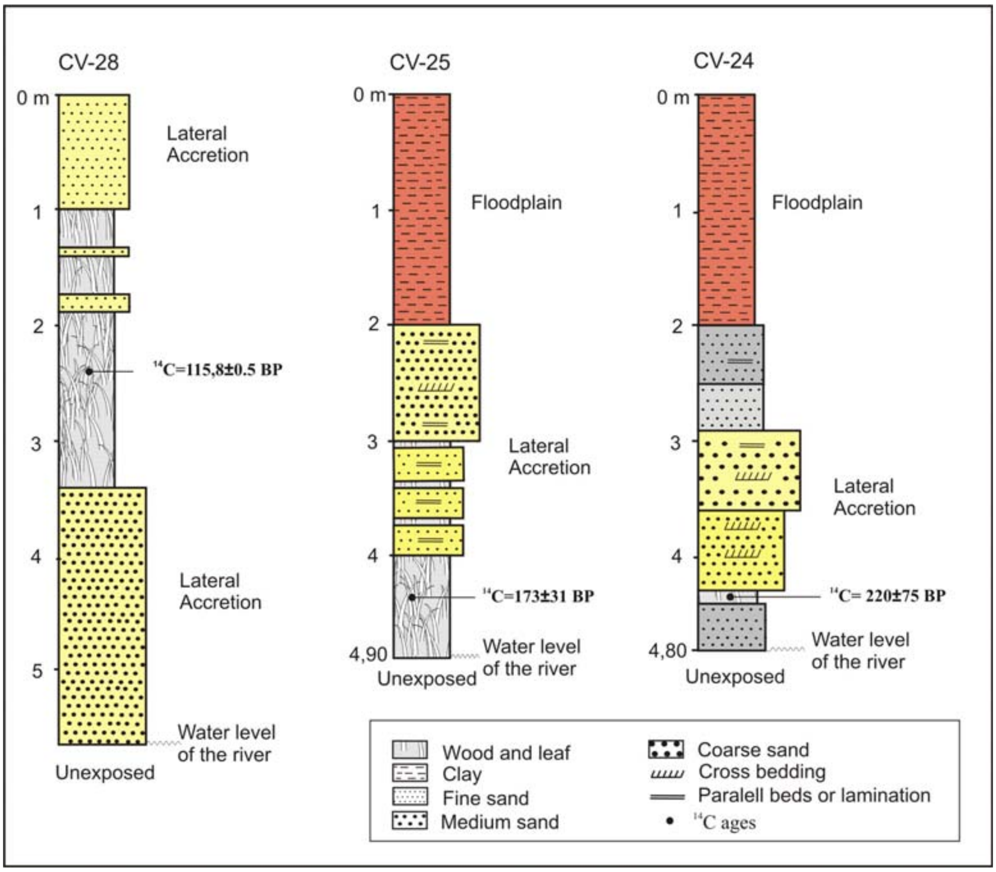


Fig. 18 - Profiles in Holocene fluvial sediments of the Araguaia River (Fluvial Plain with Meander Scroll). Radiocarbon dating was obtained from wood and leaf samples. These profiles are located in the map of Fig. 8.

Table 2 - Radiocarbon dating in organic beds from Holocene deposits of the Araguaia River

Lab No	Sample No	Location	Depth (m)	dC13	% Modern	Age (year)
18042	CV-24	12°54`27.98`` 50°30`40.17``	4.30	-29.4±0.2	97.3± 0.9	220±75 BP
8043	CV-25b	12°52`03.75`` 50°29`54.66``	3.70	-27.4±0.2	97.9±0.4	173±31 BP
18044	CV-28a	12°50`13.15`` 50°33`05.60``	2.50	-29.7±0.2	15.8±0.5	115.8±0.5 %M

6. DISCUSSION

The interpretation of the geomorphologic units described above and the fluvial sedimentary records of the Araguaia Formation can be used as indicators of climatic and paleohydrological changes during the Pleistocene. The TL/OSL ages suggest a long interval of Quaternary sedimentation in the Bananal Basin from 240±29 to 17.2±2.3 ka BP, that is to say, from the Middle Pleistocene to the Last Glacial Maximum of the Upper Pleistocene (Table 1).

The TL results of all the samples of the Low Bananal Basin (CV-08 to CV-33 in Table 1) gave ages attributed to the Upper Pleistocene and related to Upper and Middle Pleniglacial, while the older OSL Middle Pleistocene ages occur in the Upper Bananal Basin (CV-35 to CV-62) where the basal part of the Araguaia Formation outcrop is located (Fig. 14).

Therefore, the older data are scarce and located in the upper part of the basin. They represent an old unit of deposition of the Araguaia Formation that built the general architecture of the Bananal Plain, in a regional sense, during part of the Last Interglacial (Isotope stages 7 and 6). Clearly, the data presented here is scarce but we consider it important because they represent the first alluvial deposits of these ages recorded in large alluvial systems of South American tropics.

The second set of data is concentrated in the Middle-Upper Pleniglacial time (isotope stages 4, 3 and 2). The fluvial system was very active and the river suffered intensive avulsion on the Bananal plain during the Middle Pleniglacial, between 70.5±8.0 and 34.0±4.6 ka BP, but fluvial sedimentation was still active during the Upper Pleniglacial as indicated by several datings between 26.4±3.10 and 17.2±2.3 ka BP.

The Middle Pleniglacial in South American tropics (isotope stages 3 and early stage 2) presented lower mean annual temperatures and an increase in rainfall concentration or seasonality, but in general terms it was more arid than in the present (Latrubesse, 2003). An impressive fluvial record indicating an alluvial sedimentation was recorded by several authors in rivers of the Amazon basin (Van der Hammen et al., 1992a, 1992b; Dumont et al., 1992; Latrubesse and Rancy, 1998, 2000; Latrubesse and Kalicki, 2000; Latrubesse and Franzinelli, 1998, 2005, among others) as well as in the Upper Paraná River in Brazil and in the Uruguay River (Stevaux and Santos 1998; Ubilla and Perea, 1999; Iriondo, 1999; Stevaux 1994, 2000; Latrubesse et al., 2005).

The chronologic data as well as the geomorphologic and sedimentological styles of the Araguaia fluvial system are in agreement with the general conditions described above, which means a more strongly seasonal climate with a tendency towards aggradation and active avulsion processes on the Bananal Plain; mean while there are abandoned belts still to be occupied by underfit streams. We interpret that neotectonics is also still active, favoring slight subsidence, avulsion mechanism, and accumulation at least since the last interglacial.

In a continuous functioning of the fluvial system, the changing conditions toward a more arid regime produced the decrease in water discharge, and the reutilization of previous abandoned fluvial belts by minor channels that are still active as demonstrated by several datings related to the Upper Pleniglacial sediments in a manner of stacked ribbon sequences (56.6±5.9, 24.5±3.1, and 17.2±2.3 ka BP), as shown in Fig. 16. Probably at this time, savanna vegetation reached its maximum extension when a considerable part of the forest was replaced by Cerrado physiognomies in the Amazon region (Van der Hammen and Hoogiemstra, 2000; Latrubesse, 2000, 2003).

Unfortunately we did not have a palinologic record inside the drainage area of the Araguaia River, but data from several Cerrado localities in Goiás such as Lagoa Bonita (DF) and Águas Emendadas (Salgado Laboriau, 1997; Salgado Laboriau et al., 1997; Barberi et al., 2000; Barberi, 2001) which are located on an old planation surface to the east of the Araguaia basin and in Cromínia (Salgado Laboriau et al., 1997), indicate that cold and relatively wet conditions should exist around 26-22 ka BP; however, the climate became drier and colder from 22 ka to 13 ka BP and lakes dried between 21 ka and 19 ka BP.

Curiously, we do not yet possess a good record from the Lateglacial and good part of the Holocene. The only data we have is an age at the Pleistocene-Holocene limit (9.8±1.1 ka BP) in an underfit river of the plain (sample CV-37 of Table 1). Probably a good part of the Holocene sequences is in general overlapped by younger sediments in the Araguaia Alluvial plain and the alluvial plains of other major tributaries. It is clear that after the Upper Pleniglacial the river incised and generated the modern floodplain that, in the Araguaia River, is in average ~4 to 6km in width along ~1100km. However, geomorphologic features suggest that avulsion processes have still acted in recent times in the basin.

The area where the Araguaia turns to the NE at the southern margin of the Bananal Island where the Javaés River is generated can be considered a good example. The Araguaia along the southern border of the Bananal Island does not show a well-developed alluvial plain and the sinuosity increases, acquiring a meandering pattern which dissects older sediments of the Araguaia Formation up to the confluence with the Mortes River (Fig. 10). Considering that in this particular reach the Araguaia takes this new channel as a consequence of avulsion, there was not enough time to develop a complex and broad Holocene alluvial plain as founded upstream and downstream of this reach. Additionally, the river encased exposed older sediments and increased its sinuosity. Considering that the Bananal plain still has seismic activity it is possible to suggest that neotectonic activity has played a role in favoring avulsion in recent times. The radiocarbon datings which we obtained were very modern.

7. CONCLUSIONS

The Bananal Basin is the most important intracratonic Quaternary sedimentary basin of South America and preserves a good record of the paleohydrological conditions of Central Brazil where the Cerrado-Amazon ecotones develop today. This area acts as a huge tropical plain, seasonally flooded by rainfall and water table saturation which can be classified as seasonal wetland.

The Quaternary sedimentation of the Araguaia Formation is spread out on ~106,000km² of the Bananal Basin. The main driver filling the basin was the Araguaia fluvial systems as interpreted from a dominant NNE-SSW and N-S Quaternary drainage, which is in agreement with the present-day Araguaia-Mortes rivers' flow. The age of the sediments of the Araguaia Formation range from ~240 to 9 ka BP, indicating a long-term record of alluvial deposits in the basin extending from the Interglacial to the Holocene-Pleistocene limit.

The most active period recorded on the uppermost sediments seems to have happened during the Middle Pleniglacial and part of the Upper Pleniglacial (isotope stages 3 and 2). We did not record dating between 17 and 10 ka BP. The age attributed to the older sediments is preliminary because more data is needed in order to generate a more detailed scenario of that time. However, datings are important because they represent the first of these ages described in a large alluvial tropical system in Brazilian territory.

The alluvial system was dominated by avulsion of fluvial belts which were re-occupied along the time by underfit rivers. Although avulsion seems to have been more active in the past, the abandonment by the Araguaia of a large fluvial belt where the Javaés River currently develops indicates that the avulsion process is still active and can probably also be related to an active neotectonic activity in the basin as demonstrated by present day-seismic activity.

The record of the Bananal plain sheds new light on the paleohydrological conditions of Central Brazil and provides information between the transitional areas of the Cerrado and Amazon biomes. In general terms, the record is in agreement with the fluvial record described in large Brazilian fluvial systems such as Amazon and Paraná basins. However, the Bananal Plain is unique because of its particular style of sedimentation and geomorphologic processes, in which avulsion was a main mechanism along the in time, generating such a mega-scale anabranching pattern of active channels, paleochannels, and underfit streams.

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PAPER IV

Relationships among vegetation, geomorphology and hydrology in the tropical wetland savanna region of Central Brazil: the Bananal Island*

* Submitted to the River Research and Applications

Relationships among vegetation, geomorphology and hydrology in the tropical wetland savanna region of Central Brazil: the Bananal Island

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Abstract

The present work is a contribution to the knowledge of the physical and vegetational characteristics of the environment of the Bananal Island. The study area is a flat surface characterized by a fluvial anabranching system, the Araguaia River, which crosses the Bananal plain. In the past, the system generated a complex pattern of abandoned fluvial belts by avulsion and abandonment that today work as intermittent drainage channels that can be identified on the Bananal Island surface. The climate's current annual oscillation is characterized by a dry and a wet season. In the rainy period, the Bananal Island floodplain is subjected to seasonal flooding between January and March. A temporal series of MODIS-VI and Landsat ETM+ images was digitally processed, interpreted, and compared with climate and fieldwork data to allow discrimination of Cerrado phytophysiognomies. Geomorphologic map and field surveys together with descriptions and mapping of vegetation allowed us to obtain a map of morpho-vegetation units. The objective of the study was to define the relationships between state variables that control the spatial distribution of the physiognomy types of the Cerrado biome. The results showed that the Bananal Island region consists of a complex mosaic of geomorphologic units interrelated with a

morphovegetational unit variety with influences from rainfall, prolonged annual flooding, and neotectonic events during the evolution of the Quaternary landscape.

Keywords: Cerrado Biome; Bananal Island; Morpho-vegetational units

1. INTRODUCTION

The Araguaia Basin, with an area close to 384,600km² and a mean annual discharge of 6,420 m^3s^{-1}, is part of the Tocantins-Araguaia hydrographic basin which is considered a fluvial system of great importance that drains the Cerrado.

The Brazilian Cerrado takes its name from the specific vegetation common to the area: cerrado, a savanna-like type of vegetation. The Cerrado region, with 1,5% of endemic plants, was included in the top 25 world biodiversity hotspots (Myers et al., 2000). In that sense, the areas of Cerrado that extend to the middle Araguaia system are the last remnants of the ecosystem. The alluvial plain vegetation and its lake system are some of the last refuges for the Cerrado biome fauna, and have a rich biodiversity.

The Cerrado is located in Brazil's Central Plateaus, originally with about 208 million hectares of continuous area. It comprises the second most extensive vegetation type in tropical South America after the tropical humid forests. A vegetation of neotropical savanna is constituted mainly of grassland and dispersed shrubs and trees that originate a great variety of physiognomic types.

The Bananal Island, the area of this study, situated within the Brazilian Cerrado biome, consists of a complex system of floodplain that encloses numerous smaller lakes formed by migrations of river channels and significant alterations in the distribution of vegetation physiognomies in the Bananal Island floodplain. The natural vegetation tends to be mainly of the denser physiognomic types such as the wooded layer in areas that are not subject to seasonal floodings, along the less dense dominant herbaceous layer. This floodplain lies between the Araguaia and Javaés rivers with very low longitudinal slopes.

The complex floodplains of many large rivers are a remarkable example of the influence of geomorphology on hydrology and, consequently, on ecosystem biodiversity (Hamilton et al., 2005). Much of this influence can be attributed to spatially variable patterns in the frequency and duration of soil saturation and surface flooding (Winter, 2001; Hamilton, 2002).

Within this context, climate changes in the drainage basin could potentially affect avulsion by changing the discharge regimes and sediment supply to the rivers. In fact, this is what occurs during a flood period that affects the vegetation cover types. In that sense, the active tectonics is seen to be the underlying cause of avulsion and migration of the river channels in sedimentary basins (Alexander and Leeder, 1987; Allen and Densmore, 2000; Schumm el al., 2000; Latrubesse and Rancy, 2000; Latrubesse and Kalicki, 2002; Bridge, 2003).

Research related to the phenologic dynamics of the vegetation, based on seasonal series, have been directed to the global modeling, monitoring and climatic changes, assisting in the study of elements of the landscape and in the classification of vegetation physiognomies in local or regional scale (Zhang et al., 2003). In this direction, MODIS EVI images (Enhanced Vegetation Index) have been widely used for monitoring, analyzing, and mapping the seasonal and spatial distributions of physiological and biophysical characteristics of the vegetation. In this way, the use of multi-temporal satellite imagery (e.g. EVI data) approaches the experimental study of Kaurivi et al. (2003) regarding the influence of temperature and rainfall in the phenologic variation of the vegetation.

The advances of the remote sensing technology and analysis of spatial data supply the opportunity for the systematic analysis of large floodplain regions based in feature ecosystems observed from space (Mertes, 2000; Alsdorf and Lettenmaier, 2003). Thus, the spatial and temporal complexity of ecosystems presents important components of regional biodiversity (Puhakka et al., 1992; Lewis et al., 2000).

Indeed, remote sensing products have often been used for assessing the vegetation dynamics of the Brazilian Cerrado (Huete et al., 2002; Ferreira et al., 2003) and its physiognomy distribution patterns (Mesquita Jr., 2003; Ferreira et al., 2005).

Nevertheless, to a certain extent**,** the Bananal Island region is not well-known regarding the fluvial sedimentation processes and geomorphologic, geological, and climatic controls in the distribution of the vegetation of the Cerrado biome. The pioneering works in the region are in large-scale (1:1.000.000) such as those by Barbosa et al. (1966) and the Radambrasil Project (Mamede et al., 1981).

With this respect, the main goal of this study is focused on understanding and defining the interactions of the physical processes (geomorphology, geology, and climate) that control the changes and distribution of the Cerrado biome vegetation in the tropical wetland region of the Bananal Island floodplain.

2. STUDY AREA

The Bananal Island is a savanna region of approximately 2 million hectares with approximately 320km of length by 80km of average width, located in the Middle Araguaia River in Central Brazil region (Fig. 1), comprised among 49º40' and 51º00' of west longitude and 9º30' and 13º00' of south latitude.

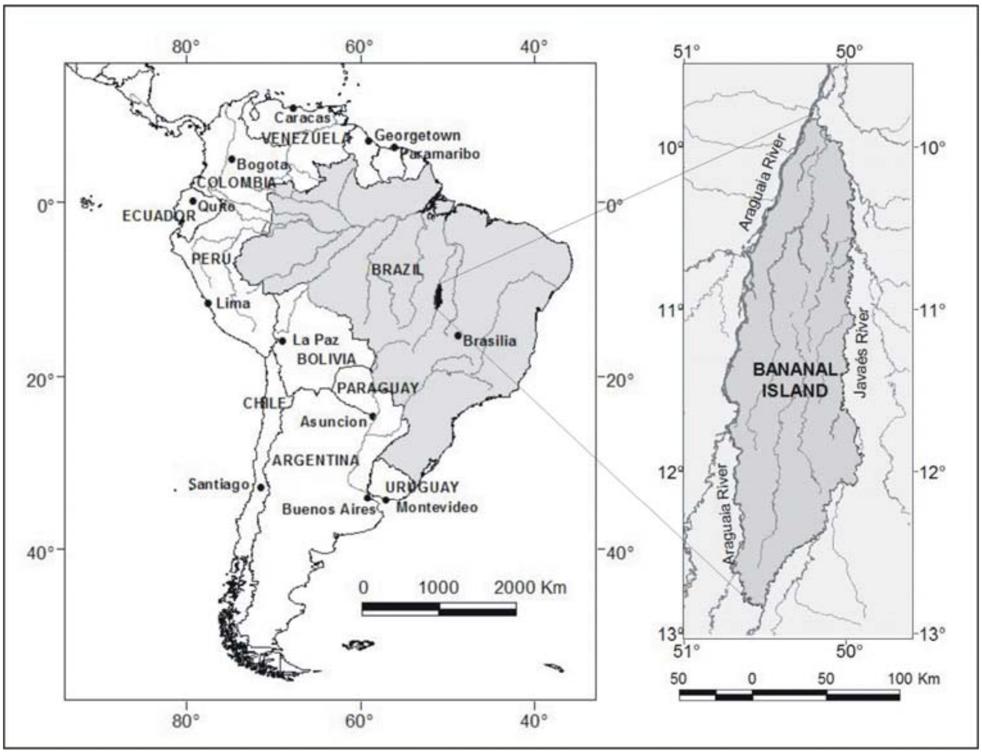


Fig. 1 - Location of the study area.

This region is drained by Araguaia and Javaés rivers and their tributary streams in the center of the Island, mainly the Jaburu and Riozinho rivers. River channels within the floodplain tend to be anabranching and much water flows outside the main channels during flooding.

According to Hamilton et al. (2002), the maximum area subject to flooding in the Bananal wetland, including permanent open water or river channels and lakes, is 58,550km². Based on inundation records from several decades, the long-term mean inundation area including rivers and lakes was 13,110km².

In the middle Araguaia region, the flood occurs from January to April, between 18 and 51 days per year for a historic period of 1970-1999, with possibility of recurrence every 1.5 years, equivalent to a discharge of $3,200 m^3.s^{-1}$ or approximately 5.7m in quota of overflow (Aquino, 2002). In this sense, some humid climate systems show prolonged annual flooding. Means of 45 days for the Columbia (Locking, 1983), 50 days for the Magdalena (Smith, 1986), and even 100 days for the Solimões River (Mertes, 1994) floodplains have been recorded.

Cerrado's major characteristics is the distinct seasonality in its phenological cycle, which is a direct response to the dominant tropical rainy/dry climate. The overall climate of the Cerrado region is Tropical Monsoonal with dry winters and rainy summers, which corresponds to the Aw in Koppen's Climatic Classification. It is characterized by two well-defined seasons: six months of wet condition, from November to March, and six months of dry condition, from April to September. In the rainy season, more than 83% of the rainfall occurs from October to April.

The annual mean temperature increases in the north direction, varying between 22ºC and 26ºC, with the maximum (38º) occurring in August and September and the minimum (22ºC) in June. The annual mean rainfall varies from 1,400 to 2,200 $mm.year^{-1}$.

The native vegetation covers of the region are characterized by a vegetation of Cerrado biome, consisting of formations from the dominant herbaceous stratum such as Cerrado grassland and shrub Cerrado. Wooded Cerrado, Cerrado woodland, and gallery forest occur along the current alluvial plains.

From the geological point of view the study area is represented by Quaternary sedimentary units, as follows: 1) Middle and Upper Pleistocene Araguaia Formation that has covered about 90% of the study area, which is composed of clay, silt, sand, and conglomeratic sediments; 2) The Holocene alluvial belt consists of intercalations of sandy, silty, clayey, and organic sediments with gravel along the Araguaia River and its tributaries.

Up to the present, Quaternary alluvial sedimentation processes and flooding patterns in the Bananal basin (the largest fluvial island of South America) are little known. The Bananal Island is a conservation unit divided into its northern portion by Araguaia's National Park and in the southern portion by aboriginal reserves (Xavantes and Javaés tribes).

3. MATERIALS AND METHODS

The availability of Moderate Resolution Imaging Spectroradiometer (MODIS) data, specifically MOD13 Vegetation Index (VI) products, is designed to provide consistent spatial-temporal measures of photosynthetically active vegetation, and comprises two VIs: the NDVI (Normalized Difference Vegetation Index) and the EVI (Enhanced Vegetation Index). The EVI consist of a new index designed to be resistant to residual atmospheric noise and canopy background effects (Liu and Huete, 1995; Huete et al., 2002). The MODIS VI products are available in a variety of spatial and temporal resolutions and algorithms and operate on a pixel basis, taking into account multiple observations within a 16-day period.

The temporal series of MODIS-VI images were acquired from the MOD13Q1 (250m), tile h13v10, obtained from EDC-DAAC, through ftpPull, during the period from March to October 2003. The original data (sinusoidal projection in HDF format) was converted into the UTM projection and GeoTiff format through the MODIS Reprojection Tool. The EVI images were screened for clouds, aerosols, and shadows, based on the accompanying quality assurance layers (QA), and then recomposited into bi-monthly datasets (in order to minimize the occurrence of cloudy contaminated pixels as much as possible) according to Ferreira et al. (2006).

This study was also conducted based on the visual photointerpretation of the spatial attributes observed in the Landsat ETM+ imagery (WRS-2, path 223, rows 067, 068, and 069) from the dry season period (July and September, 2000). This interpretation, complemented with image processing techniques and integration through a Geographic Information System (GIS), resulted in the map of geomorphologic units for the Bananal Island plain. Concerning the mapping of the main Cerrado biome's physiognomic types, this was based on the Parallelepiped classification algorithm applied to the MODIS EVI images.

All phases of digital image processing proceeded by the rectification for the geographic projection system, with datum WGS-84 (World Geodetic System 1984).

The Geological Survey of Brazil supplied the rainfall and discharge data from Araguaia River of the historic period from 1994 to 2003 of the São Félix do Araguaia station.

Fieldwork was carried out in the Bananal Island and in the Araguaia River from August to September 2005. Several profiles of roads were considered in the Bananal Island region during 16 days and studies in the Araguaia River were carried out with the use of a boat during 10 days. The main activities counted of drill holes, excavation of trenches and geological, geomorphologic, and vegetational surveys.

4. HYDROLOGY

The Tocantins-Araguaia basin with an area of 757,000 km² and an annual mean discharge of $12{,}000 m^3 s^{-1}$ is practically ignored in the international literature on large rivers (Latrubesse and Stevaux, 2002). For these authors the river systems of this basin correspond to the world's eleventh drainage in outflow; however, recent research of geomorphology and hydrology are concentrated in the Upper and Middle Araguaia reaches from Bananal Plain (Prado and Latrubesse, 2000; Bayer, 2002; Aquino, 2002). The hydrologic approach in this study is the Araguaia River and the Bananal Plain, more specifically the Bananal Island region.

4.1. The Araguaia River and the Bananal Plain

According to the hydrologic conditions and river regimes, the Araguaia River is usually divided into three main parts: the Upper, Middle, and Lower Araguaia. The object of our study is the Middle Araguaia in the Bananal Island region. The Middle Araguaia is mainly a low sinuosity river with islands and anabranches which tend to be braided.

This region is characterized by a plain that presents seasonal flooding with six dry months and six rainy months. The dry and rainy seasons control the variations of discharge in the Araguaia. The hydrogram of Fig. 2 shows the discharge and rainfall of a historic series of 10 years from 1994 to 2003 obtained from São Miguel do Araguaia station.

For the period, the annual mean discharge was 2,644m^3s^{-1} and the mean flood discharge was 6,654m^3s^{-1}. The Araguaia River discharge starts to increase in November and extends until April with maximal discharge in March and April 1997 with anomalous values nearing 8,680m^3s^{-1}. The discharge then gradually decreases until June, however; the lowest flow level was registered on September 20, 2001 with a minimum value of 550m^3s^{-1}.

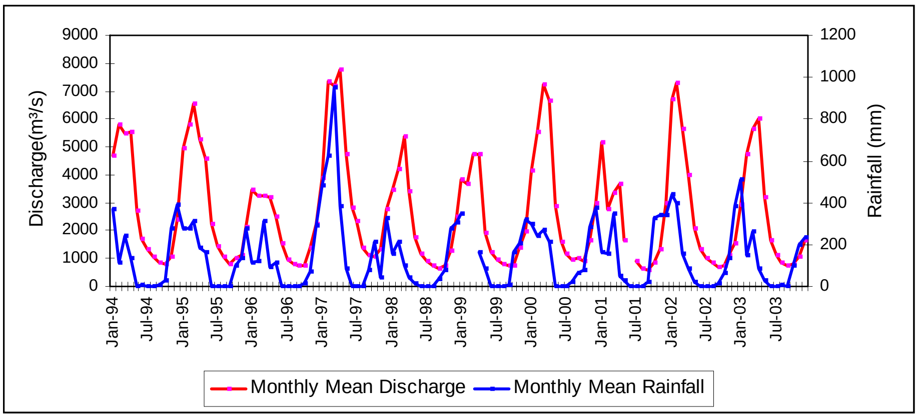


Fig. 2 – Hydrograms of mean discharge and mean rainfall at São Miguel do Araguaia station for the period between 1994 and 2003.

In a broad sense, the hydrograms above enable one to visualize that the curve of the discharge is in phase with the rainfall. However, one observes that the phase curves of the minimum values between these two variables are not coincident. The phase variation of the minimum discharge is delayed about one to two months.

The Araguaia River has peak discharges during the rainy season. The four major peaks of full bank occurred in 1995, 1997, 2000, and 2002. This overflow is responsible for the feedback of the abandoned channels, meander lakes, swampy areas, and flood of the alluvial belt. On the other hand, during the dry season, the flow is much lower and there is an abandonment of the river channels; for instance, the Javaés River, an abandoned belt of the Araguaia, reveals a channel filled with sand (Fig. 3). Such channel becomes active only during floods. The large seasonal variability is reflected in the water discharge varying from 10 to 14 times.

Fig. 3 – Abandoned channel of the Javaés River with 130m in width. This channel is only active during the overflow of the Araguaia River

Mainly local rainfall waters and consequently water table saturation produce the seasonal floodings in the Bananal Island plain. The overbank floodings of the Araguaia River that flood the recent alluvial plain do not affect the Bananal Island plain. In this way, the waterlogged surface of the Bananal Island plain is independent from the overbank flood of the Araguaia River.

In the rainy season, rainfall occurs from December to March, while from June to August the precipitation is zero and extends until mid-September. Fig. 4 exemplifies the floods on February 2, 2002 and shows the extensive waterlogged surface in the Bananal Island region.

The Bananal Island plain contained in the Bananal plain is a complex mosaic of morphosedimentary units formed by fluvial sediments attributed to the Middle and Upper Pleistocene Araguaia Formation. These units are crossed by the Holocene alluvial plain characterized by scrolls features, oxbow lakes, swampy areas, and active and abandoned paleochannels.

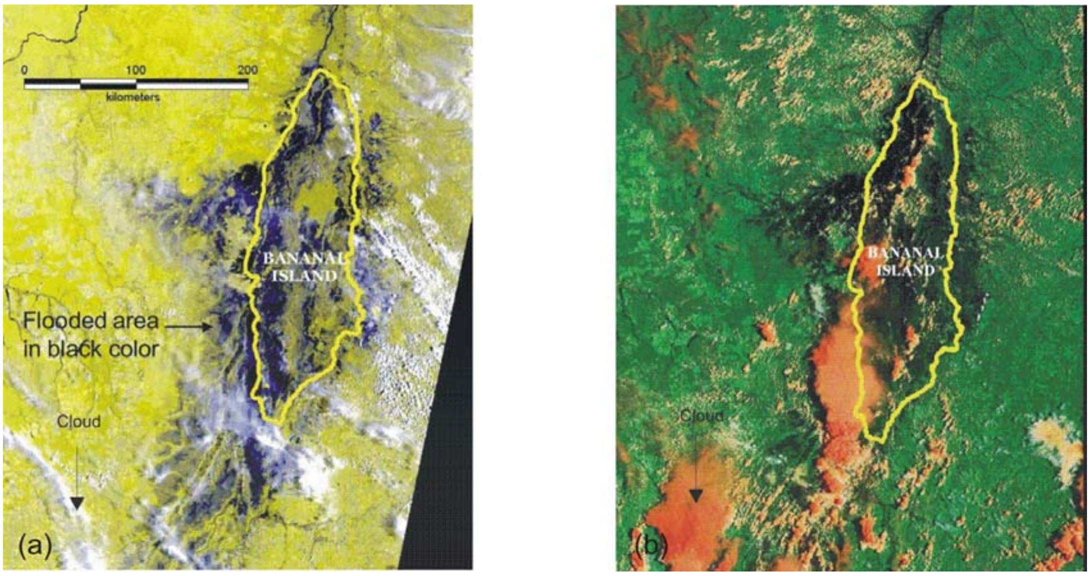


Fig. 4 - Floodplain of the Bananal Island region as seen in the MODIS 250 images. (a) Flooding from February 2, 2002; (b) Flooding from February 18, 2002. Images acquired from E. Anderson at Dartmouth Flood Observatory.

5. GEOMORPHOLOGIC UNITS

The study area consists of a complex mosaic of morphosedimentary units constituted by a group or association of active or inactive geoforms which are characterized by state variables and transformation genetically related and subject to mapping.

Through fieldwork and interpretation of the remote sensing products it was possible to identify five geomorphologic units in the Bananal Island Plain: 1) Slightly Dissected Fluvial Plain; 2) Slightly Dissected Fluvial Plain with Laterite; 3) Abandoned Fluvial Belt; 4) Abandoned Fluvial Belt with Underfit Meander River; 5)

Fluvial Belt with Meander Scroll. The spatial distribution and relationships among these units are presented below in Fig. 5.

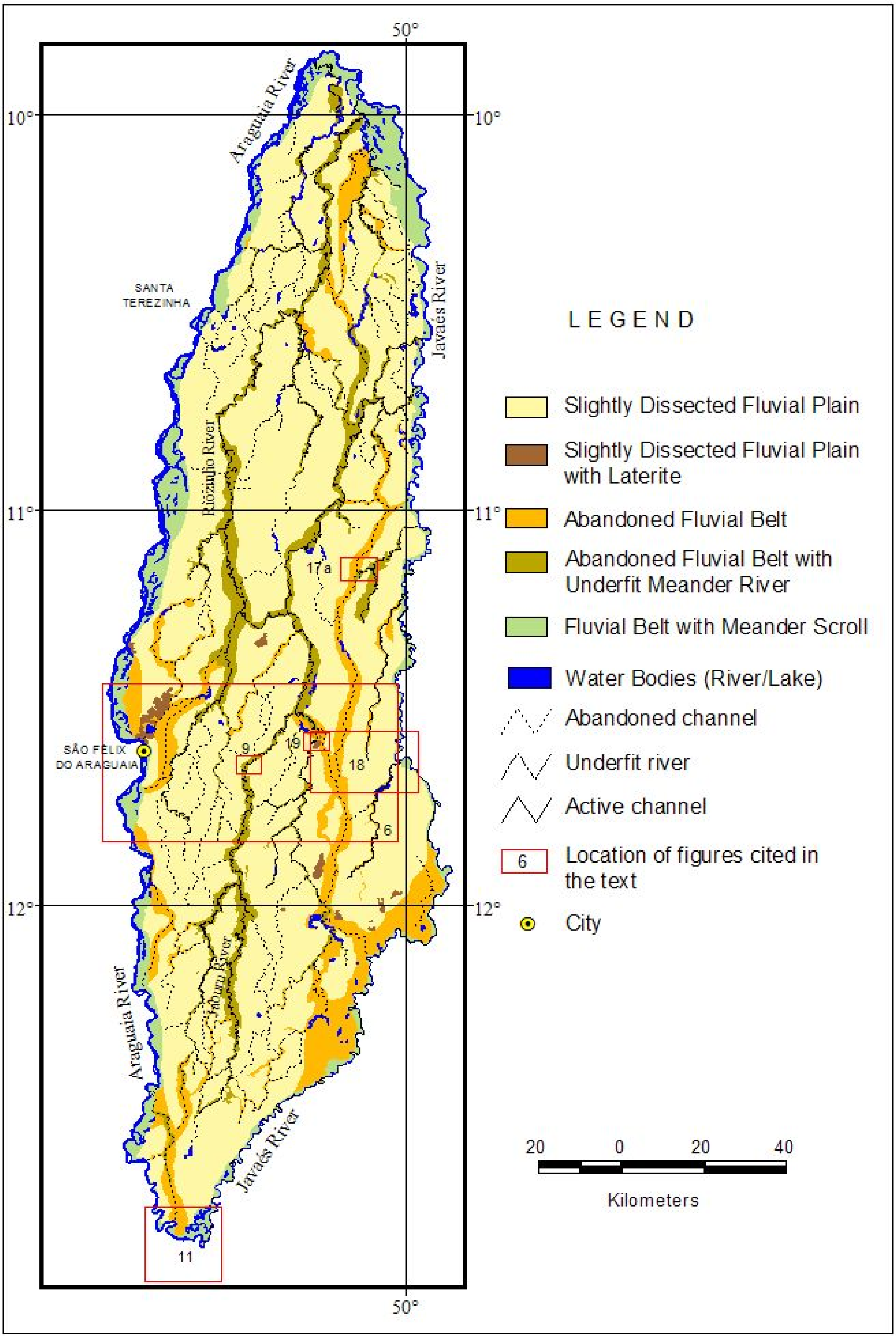


Fig. 5 – Main geomorphologic units of the Bananal Island. The rectangles with numbers are the locations of the Figures cited in the text.

5.1. Slightly Dissected Fluvial Plain

The Slightly Dissected Fluvial Plain (SDFP) constitutes the oldest geomorphologic unit in the study area, associated with fluvial sediments from the Middle and Upper Pleistocene Araguaia Formation. It is seen as a flat widespread surface of low slope with an area close to 14.500 km² or about 70% of the surface in the Bananal Island floodplain. It forms the substrate of all the geomorphologic units in the region (Figs. 5 and 6). Clayey and sandy sediments compose this geological formation which many times the sand layers are rich in iron oxide. We did not find the basal conglomerate, according to definition proposed by Barbosa et al. (1966).

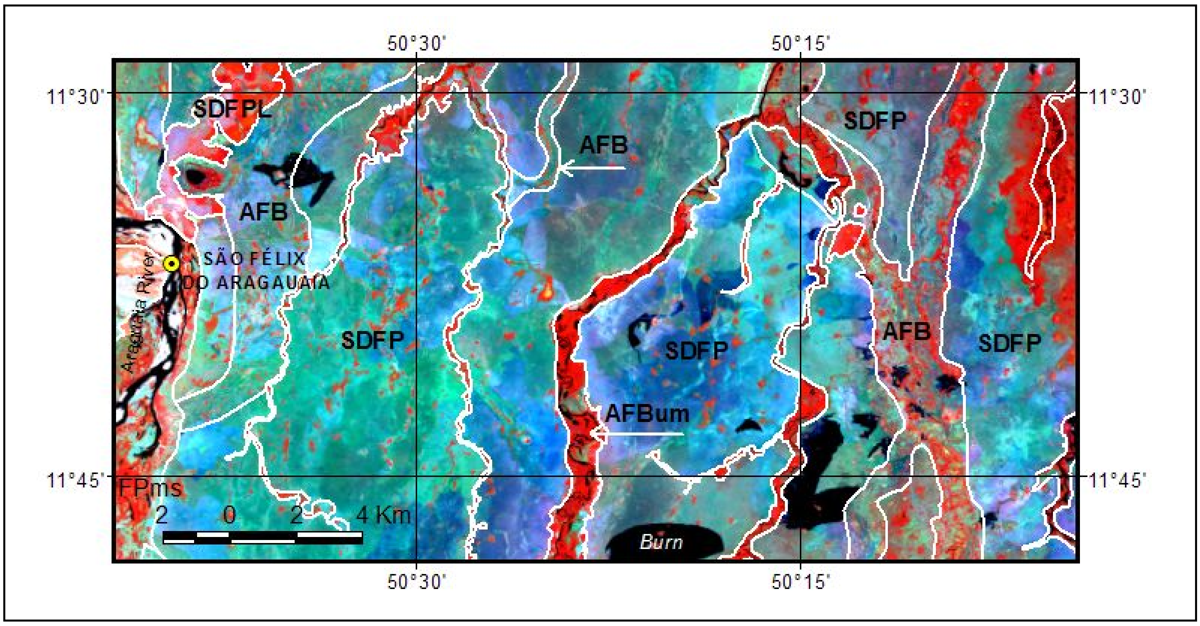


Fig. 6 - Relationships among the Slightly Dissected Fluvial Plain landscape with other geomorphologic units in the central part of the Bananal Island. SDFP (Slightly Dissected Fluvial Plain); SDFPL (Slightly Dissected Fluvial Plain with Laterite); AFB (Abandoned Fluvial Belt); AFBum (Abandoned Fluvial Belt with Underfit Meander River); FBms (Fluvial Belt with Meander Scroll). Landsat ETM image bands 4,3,5 in R,G,B.

In the SDFP profiles for boat were carried out in the Araguaia River bank, between Javaés and Cristalino rivers. Fig. 7a illustrates the fluvial sediments of the river bank (base to top): friable white sand with fine to medium texture; medium to coarse yellow sand with 10cm in thickness; indurated yellow sand layer with iron oxide and planar cross bedding (2,10m); indurated gray-clear clay (1,50m), and clay with organic matter on the surface (l,0m).

In the other localities there are organic matter layers, mainly leaf and wood subfossils, intercalated in clayey and sandy sediments. Several outcrops of redness-indurated sand of great expression that is rich in iron oxide are common in the bed and bank of the Araguaia River. In the interior of the Bananal Island a 3,24m deep trench was excavated, which is constituted exclusively by gray and yellow clays (Fig. 7b).

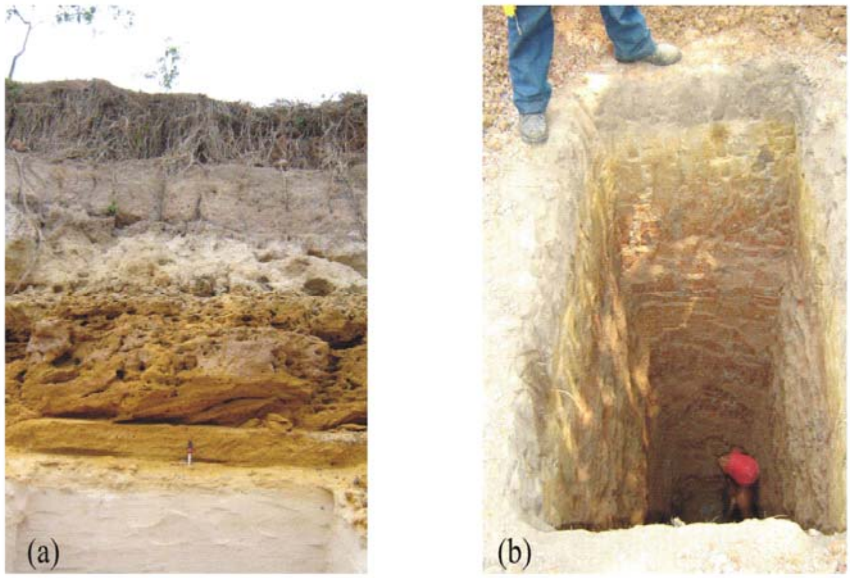


Fig. 7 – Profiles of the fluvial sedimentation of the Slightly Dissected Fluvial Plain. (a) Araguaia River bank strata; (b) trench (3.24m deep) of indurated clayey sediments in the inner Bananal Island plain.

5.2. Slightly Dissected Fluvial Plain with Laterite

The Slightly Dissected Fluvial Plain with Laterite (SDFPL) has the smallest area in the Bananal Island (around 100km²). This geomorphologic unit is sparsely distributed in the more elevated areas or on the interfluves of the main rivers as remnants of flat plateau landscape in several localities. Field mapping shows occurrence of lateritic crusts with rich concretions in Fe-Al oxides and with diverse textural characteristics according to the nature of the source rock. The laterite formation within the regolith is thus central to some fundamental questions of interest in the geochemistry in the last decades. As such, laterites area is essentially viewed as fossil residual in nature.

The laterite is a product of intense weathering made up of mineral assemblages that may include iron or aluminium oxides, oxyhydroxides or hydroxides, kaolinite, and quartz. These processes are favored by a high rainfall index in tropical regions and by high temperatures; the development speed of these mantles decreases with depth. According to the economic potential of laterites may be named, for example, diamondiferous laterites from Diamantina (Chaves and Benitez, 2004), nickeliferous laterites from Niquelândia (Melfi et al., 1988), and bauxitic laterites from Paragominas (Kronberg et al., 1982).

5.3. Abandoned Fluvial Belt

The Abandoned Fluvial Belt (AFB) constitutes the second most extensive unit around 2.000 km², corresponding to 10% of the total area. The AFB represents areas of paleochannels originated through migrations and river avulsions. Avulsion may occur as a direct response to an individual tectonic event or in response to a gradual, tectonically induced change in floodplain topography. Thus, avulsion is defined as the diversion of flow from an existing channel onto the floodplain, eventually resulting in a new channel belt (Makaske, 2001).

In this tectonic context, the study area is located in the Goiás-Tocantins Seismogenic Zone associated with significant a seismotectonic generator in Central Brazil (Veloso, 1997). This neotectonic belt is a product of basement fault reactivations (Precambrian) with dimensions of approximately 700km in length and 200km in mean width, distributed along the NE-SW trend, named Transbrasiliano Lineaments. The fault system of NE-SW, N-S, and NW-SE trends controls the drainage installation of the Bananal Basin.

In the “Impuca da Macaúba” paleoplain drillings were carried out with a mechanic auger and the results showed the existence of fluvial deposits represented by a clay layer with about 2,50 to 3,20m of thickness overlapped with a fluvial sandy deposit constituted by fine white sand (Fig. 8). This paleoplain with 4,3km in width correlates well with the abandoned meander lines identified in remote sensing products.

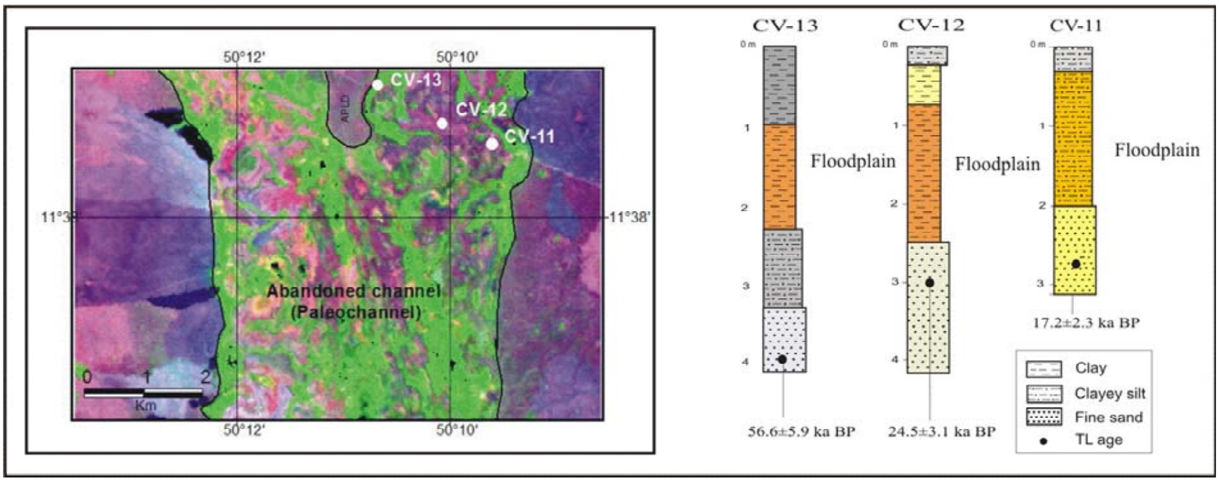


Fig. 8 – Profiles of the abandoned channel in the "Impuca da Macaúba" paleoplain (ancient Araguaia River floodplain). See location of the drillings with a mechanic auger in the abandoned channel on the ETM+ image.

5.4. Abandoned Fluvial Belt with Underfit Meander River

The Abandoned Fluvial Belt with Underfit Meander River (AFBum) is associated with inner river floodplains of the Bananal Island and constitutes a variety of the AFB distributed along the alluvial plain, represented mainly by the Jaburu and Riozinho rivers. It forms a complex fluvial system that is temporarily flooded during the rainy season from December to March. This geomorphologic unit consists of narrow alluvial plains that can rise up to 3km in width and which were affected by neotectonic activities (mainly uplift and subsidence).

Typically, in this system, river channels are relict and discontinuous and are characterized by rounded and irregular lakes and swampy areas, abandoned narrow channels and meandering and actives only during the flooding period (Fig. 9). Sandy, silty, and clayey sediments represent the sedimentary facies associated to AFBum.

The most common case is the underfit river, whose valley morphology indicates a larger ancient river. Such rivers are those for which some practical measure of size, most often the meander wavelength, indicates that the modern river is either too large or too small for the valley in which it flows.

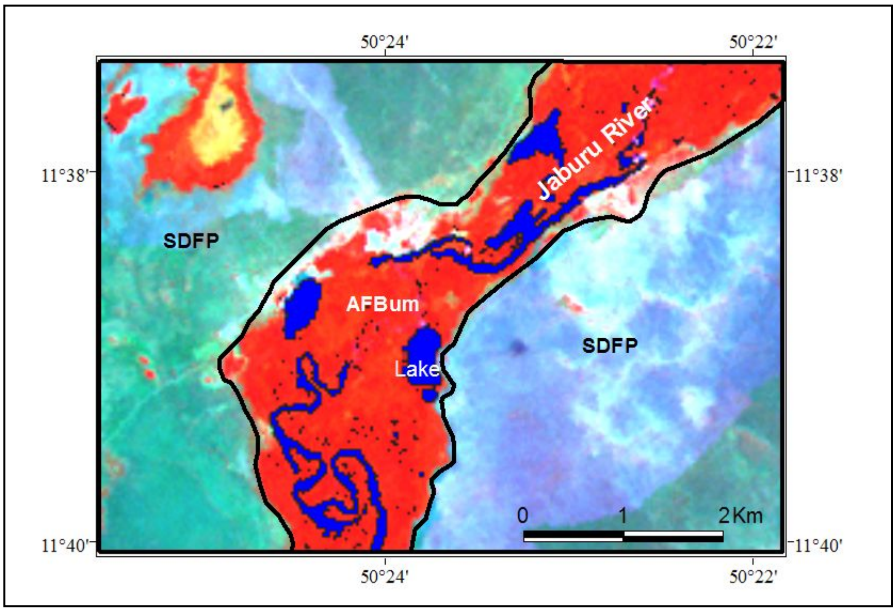


Fig. 9 - Features of the AFBum (Abandoned Fluvial Belt with Underfit Meander River) with lakes and discontinuous channel in the Jaburu River floodplain. ETM image bands 4,3,5 in R,G,B.

5.5. Fluvial Belt with Meander Scroll

Fluvial Belt with Meander Scroll (FBms) is the youngest geomorphologic unit attributed to the Holocene age. It is associated with the active plain located in the floodplain along the Araguaia and Javaés Rivers and its width varies between 2 and 8km.

Meanders of several generations of the oxbow type can be identified. This unit exhibits a variety of landforms, such as sand bars, islands, levees, meander cutoffs, and swampy areas. Some small tributaries are partially blocked by sedimentation in the main system, forming blocked valley lakes. The FBms are predominantly composed of gravel, conglomeratic sand, sand beds with dominant planar cross bedding (Fig. 10a) and secondary trough cross-bedding, silt, clay, and organic matter intercalations with semi-fossils represented by wood and leaf detritus (Fig. 10b).

The Araguaia main river in this geomorphologic unit is characterized by a low-sinuosity river with a mean of 1,24 with islands and anabranches. However, some reaches show a tendency to have single, channel-forming meanders, with height value of 2.18, between the Javaés and Cristalino rivers (Fig. 12). In this region, the most spectacular avulsion occurred with the diversion of the Araguaia River that abandoned its old channel (Javaés River plain) in the southern extremity of the Bananal Island and migrated in the northwest direction to the Cristalino River.

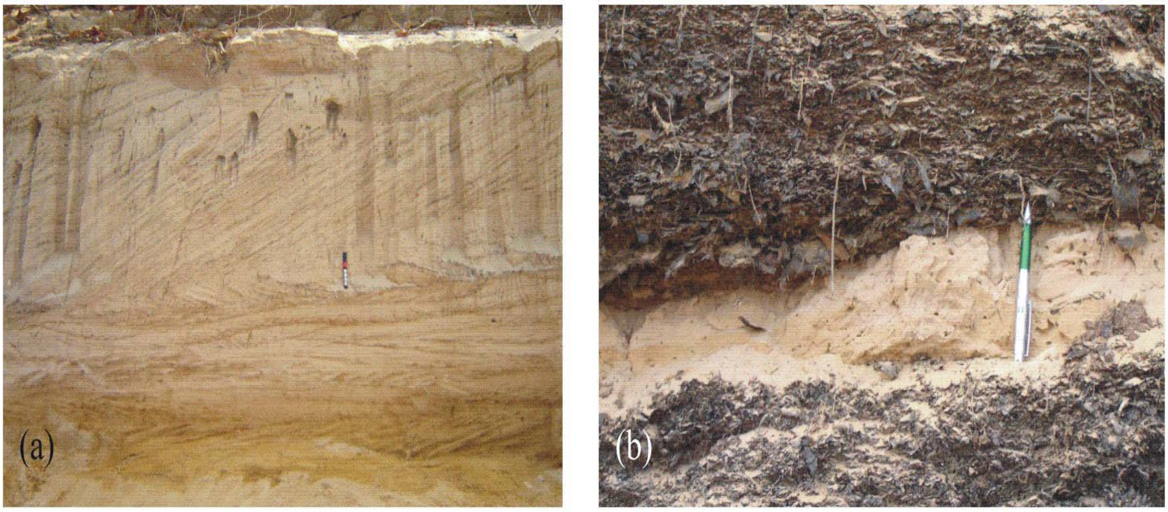


Fig. 10 - Characteristics of the fluvial sediments of the Fluvial Belt with Meander Scroll. (a) Araguaia River sand bank with planar cross strata covered by clayey sediments; (b) Sand stratum (15cm) intercalated in beds of semi-fossils (leaf and wood).

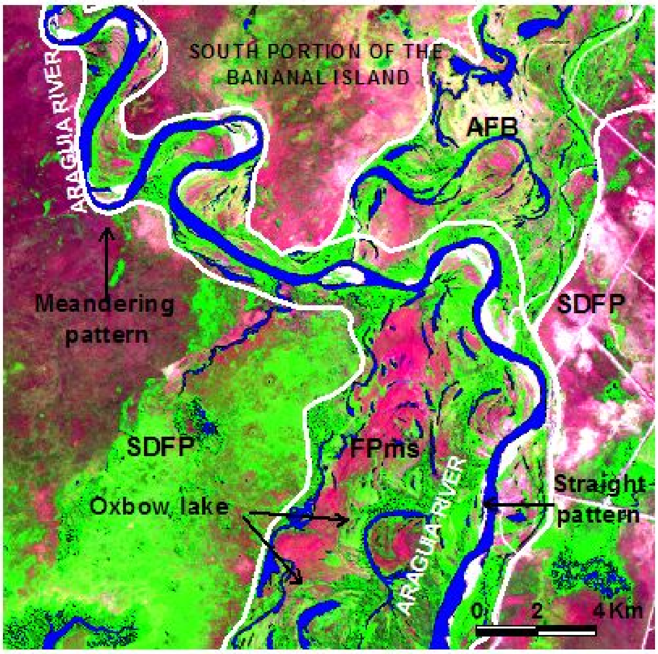


Fig. 11 – Characteristics of the floodplains (FBms and AFB) from Araguaia and Javaés rivers. See width and channel pattern changes in the floodplain before and after the avulsion. ETM image bands 3,4,5 in RGB.

6. VEGETATION UNITS

The vegetation in the Bananal Island is one of the few remaining large and intact areas in Central Brazil without any anthropic interference. Each phytogeographic area is characterized by prevailing topography, dominant vegetation groups, floristic affinities, and species distribution patterns.

The Cerrado biome, considered here in its *lato sensu*, does not have only one physiognomy in all of its extension, as demonstrated by Ratter and Daigie (1992) and Ratter et al. (1996). It physiognomy is quite diversified, revealing from well open grassland forms to relatively dense forest forms.

In this study, in order to find out the distribution of the phytophysiognomic types of the Bananal Island region, we used the EVI images (Fig. 12). These images enhance the seasonal variation in landscape vegetation dynamics from March to November 2003. The visual comparison between the EVI_{dry} and EVI_{wet} images shows significant seasonal variations in the vegetation activities from the Bananal Island. Nevertheless, the bi-monthly images of October/November presented a great quantity of clouds.

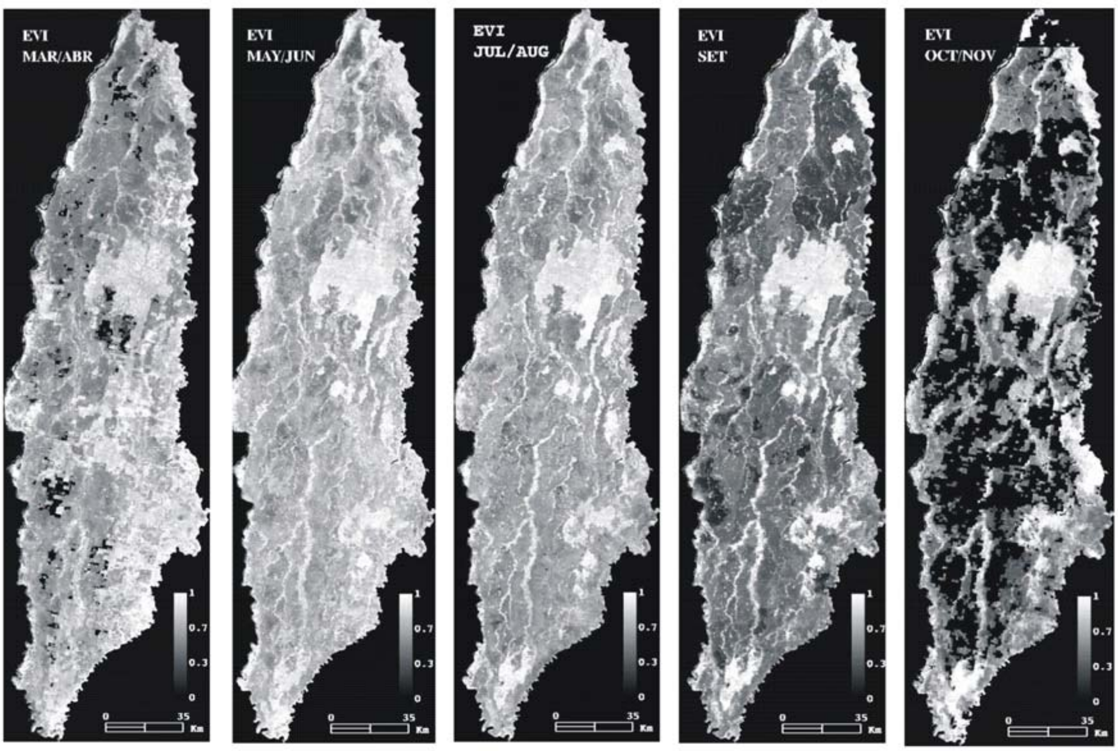


Fig. 12 - Comparison among bi-monthly EVI images (re-composites) of the Bananal Island. Seasonal image from MODIS 250 meter in 2003.

These seasonal series of VI images indicate high photosynthetic activity and high green biomass accumulation during the wet season (e.g. March/April) and a significant soil water deficit and low levels of green biomass in the dry season (e.g. September).

Therefore, in order to map the physiognomic types of Bananal Island's vegetation the algorithm of classification by Parallelepiped in EVI images was applied from September 2003, dry season (Fig. 13a).

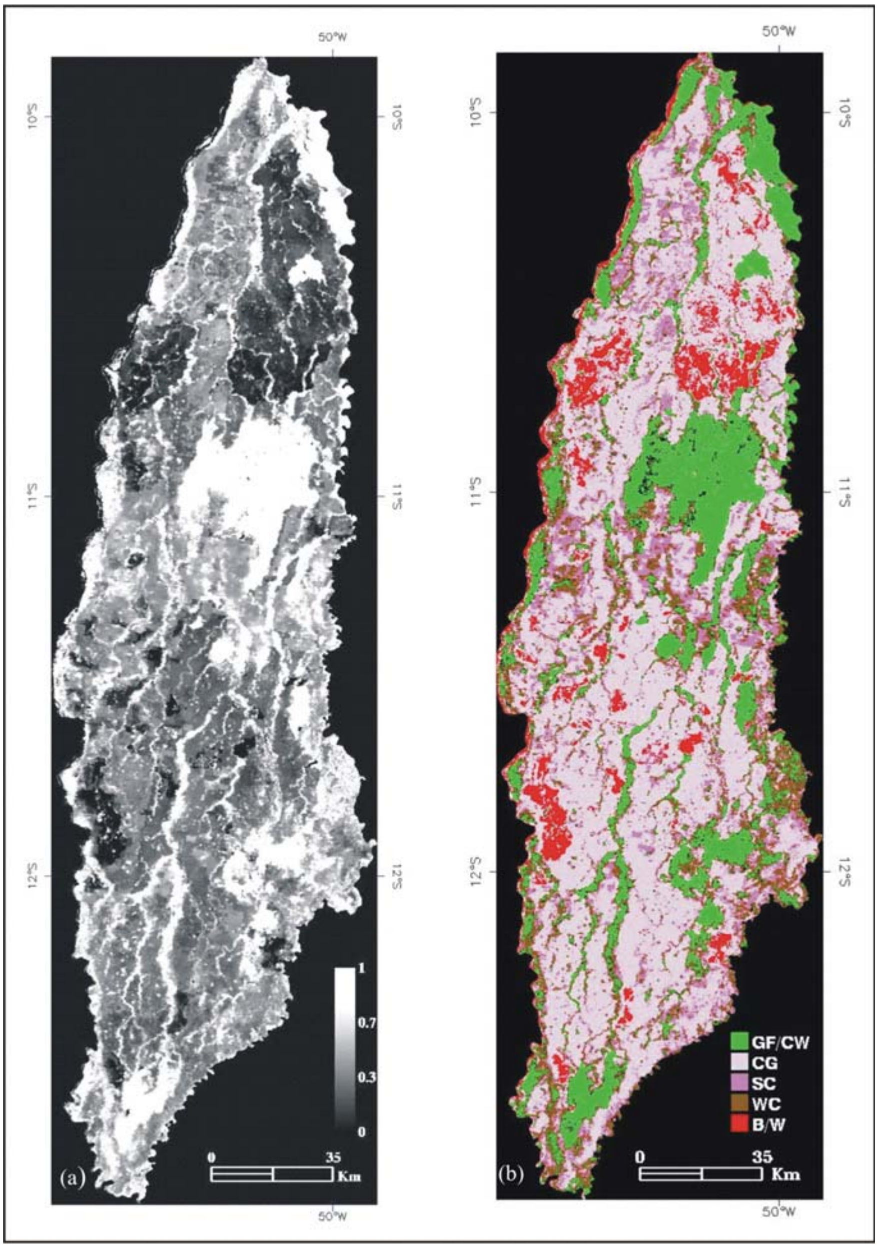


Fig. 13 - Features of the Cerrado land cover types in Bananal Island. (a) Vegetation Index of MODIS EVI image, dry season (September 2003); (b) Digital classification of cover types. GF/CW: Gallery Forest/Cerrado Woodland; WC: Wooded Cerrado; SC: Shrub Cerrado; CG: Cerrado Grassland; B/W: Burn/Water.

As a result of the classification the following vegetation physiognomies were identified (Fig. 13b): 1) Cerrado grassland; 2) shrub Cerrado; 3) wooded Cerrado; 4) Cerrado woodland/gallery forest. Specifically for the classification of the Cerrado land cover types we found the following intervals in the vegetation index (EVI): gallery forest (0.700 to 0.385), shrub Cerrado (0.384 to 0.280), Cerrado grassland (0.279 to 0.160).

The complexity of the Cerrado biome physiognomies and their seasonal variations are responsible for many misclassifications, not only in the field but also when remotely sensed satellite used to classify them (Mesquita Jr. et al., 2004). However, when the vegetation undergoes seasonal variation of its green biomass, it greatly increases the chances of misclassification.

A similar situation occurred in the classification of Bananal Island's vegetation where the physiognomies with more biomass (e.g. gallery forest and Cerrado woodland) as well as the cover types with lower vegetation index (e.g. burn, water, and bare soil) presented misclassification between these physiognomies. The main reason for the difficulty to discriminate Cerrado types was their similar seasoned behavior. Thus, the gallery forest and Cerrado woodland physiognomies were considered in a single class as well as burn and water (rivers and lakes).

6.1. Cerrado grassland

The physiognomy type with dominant herbaceous layer, rare bushes, and complete absence of trees (Fig. 14) represents 44% of the area or about 9.000km².

This vegetation type occurs on clayey and sandy soils, generally with saturated water in lower areas subjected to a flooding long associated with the Slightly Dissected Fluvial Plain unit. This physiognomy is more tolerant than denser forms to soil water logging by long flooding periods.

In the dry season between May to August the vegetation index corresponds to the senescence annual cycle of the phenology of the vegetation when the photosynthetic activity quickly begins to decrease with the decrease of the moisture soil. For example, a pixel of the Cerrado grassland referents the bi-monthly MODIS-EVI images the value of the vegetation index decrease, respectively of 0,396 (May-Jun) to 0,3467 (Jul-Aug) and to 0,1926 (Sep) (Fig. 12). However, in September it has a low vegetation index and represents the dormancy when photosynthetic activity is almost zero, as shown by vegetation index EVI image in Fig. 13a.

Fig. 14 - Cerrado grassland with predominance of grassy and rare shrubs.

6.2. Shrub Cerrado

It is generally an exclusively herbaceous-arbustive vegetation, with bushes and trees scattering in a dense gramineous cover upon clayey and sandy soils, associated with lower altitude areas subject to seasonal floodings (Fig. 15). Shrub Cerrado is distributed in the transition zone between Cerrado grassland and wooded Cerrado physiognomies. It also occurs in areas of Abandoned Fluvial Belt associated with gallery forests, for example in the “Impuca da Macaúba” region. Shrub Cerrado physiognomy in the EVI image (September 2003) presents a medium gray tonality with vegetation index between 0.384 and 0.280.

The example of nature selection in the shrub Cerrado environment is depicted in Fig. 15a, which shows trees constituted by the unique vegetal species (*Tabebuia carayba*) scattered on denser grass strata. In other localities, the bush is the *Byrsonima sp*. It is characterized by a mixture of grasses and shrubs, less than 10% of tree cover, around 3m tall, well-scattered, exceptionally reaching 10m tall and 2,5% of land cover.

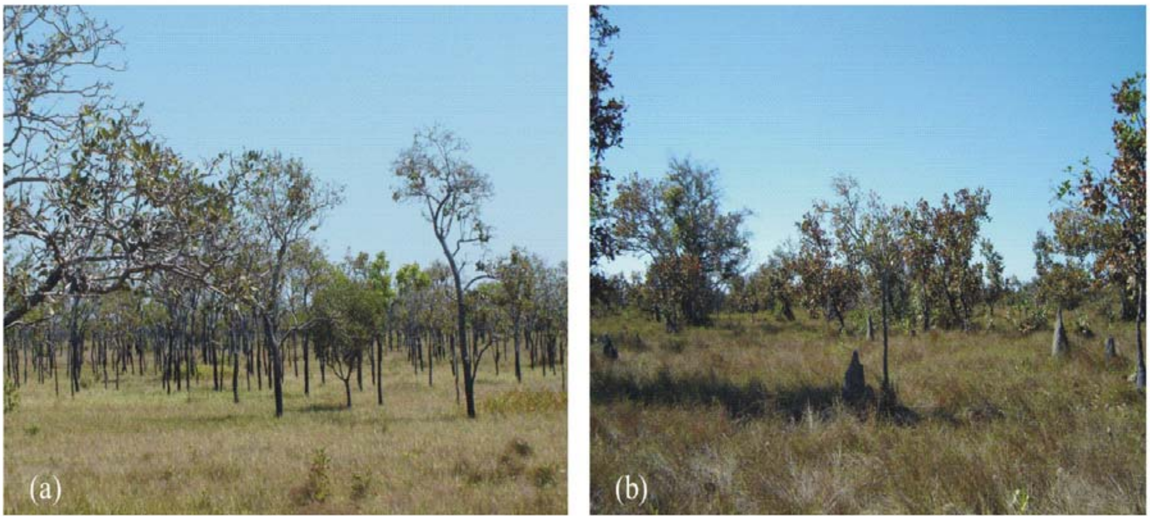


Fig. 15 - Aspects of occurrence of the shrub Cerrado. (a) Unique species (*Tabebuia carayba)* distributed over a gramineous stratum; (b) trees and arbustives (*Curatella americana*) grouping on termite mounds.

The shrub Cerrado also occurs in groups of trees on termite mounds re-covered by the vegetation of the Cerrado trees, with predominance of the *Curatella Americana* species dispersed in graminous stratum. Fig. 15b shows the relation between the wooded Cerrado with termite mounds re-covered by the vegetation of the Cerrado trees, while the soil remains saturated with gramineous strata between termite mounds ("murunduns").

6.3. Wooded Cerrado

The wooded Cerrado (cerrado *stricto sensu* or savanna), with about 9% of area cover, occurs predominantly in relatively more elevated areas where the surface remains apart from the flooding or by short flooding period. In these conditions, this physiognomy occurs mainly in the eastern part of the study area, generally with gradation for Cerrado Woodland. This form also develops at the riverside of the Bananal Island.

It is characterized by a community of trees and large shrubs, usually of up to 3-5m in height and producing 10-60% cover, scattered about well-developed grassy ground layers (Fig. 16).

Fig. 16 – Physiognomic aspect of the Wooded Cerrado with trees and herbaceous strata.

The trees are of characteristic savanna form, typically with sufficiently diversified herbaceous-arbustive strata. Such trees are generally inclined and crooked, with irregular and twisted ramifications. Leaves are rigid in general and trunks possess rind with cleft or furrowed thick cork. These features present an adaptation aspect of dry climate and fire. However, the species do not suffer hydric restriction during the dry season, at least those that possess deep roots, and some are evergreen while others are deciduous for variable periods of the dry season.

6.4. Cerrado Woodland

Cerrado woodland, also named xenomorphic forest, is a vegetation type that occurs more frequently as an "island" scattered on the plain and in the east portion of the Bananal Island. It is a formation constituted by an expressive quantity of species of Cerrado mixed with a number of forest species. Its structure and physiognomy are those of a forest, with closed canopy due to the elevated density of trees (20-50% of tree cover). However, it is a formation of forest with trees around 15meters and some reaching up to 18-20m in height.

The conditions of brightness enable the occurrence of arbustive and herbaceous strata that are distributed in scattered tuffs, interspersed by puny woody plants. The floristic aspect stands out and is distinct from the vegetation forms of the Cerrado *lato sensu*. The general physiognomy of the Cerrado woodland is evergreen biomass, even though some species, such as *Qualea grandiflora* Mart. and *Caryocar brasiliense* Camb., will present arboreal deciduous in non-coincidental in short periods during the dry season.

6.5. Gallery Forest

The gallery forest is a riparian-like vegetation domain that consists of the evergreen forest that is formed alongside Araguaia and Javaés rivers and their tributaries, mainly Jaburu and Riozinho rivers. This physiognomy presents significant landscape features in many parts of the region (Fig. 17). In the majority of cases, the contact with the Cerrado grassland is brusque. In other localities it occurs as forest fragments on abandoned floodplains associated with shrub Cerrado. They are a tall formation with trees reaching up to 20-30m in height and with canopy coverage of 80 to 100%, and contain several endemic species.

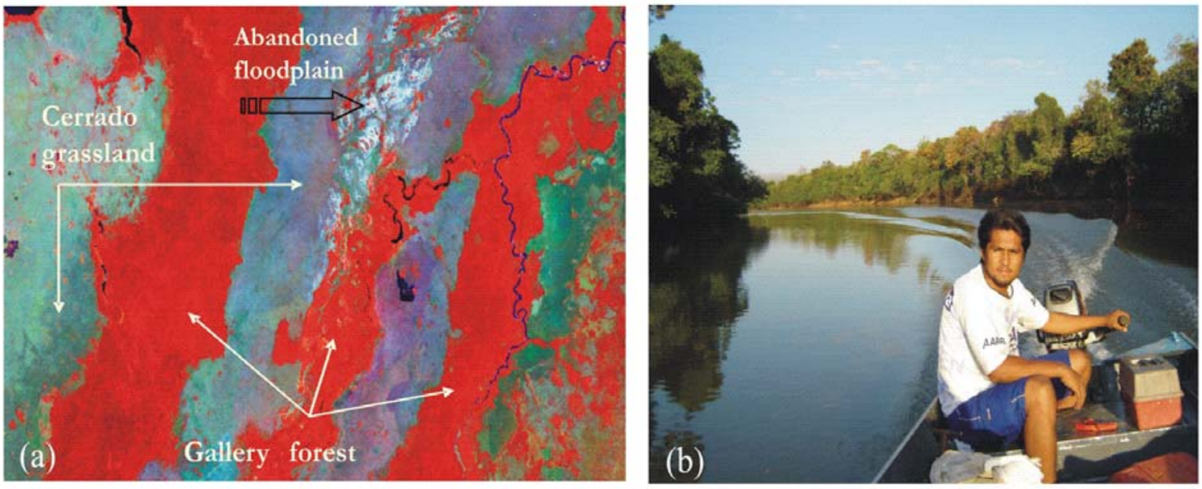


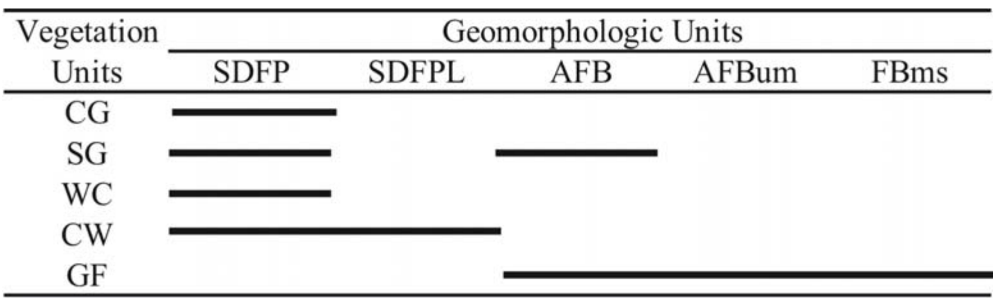
Fig. 17 - Occurrence features of the gallery forest. (a) Relationship between gallery forest and Cerrado grassland in inner rivers of the Bananal Island plain (ETM+ color composite 4,3,5 in RGB) ; (b) Gallery forest along the Riozinho River.

Despite occurrences in narrow belts along streams and rivers and despite being surrounded by the extensive Cerrado grassland formations, the diversity of gallery forests is elevated. According to Felfiti (1995), the total tree flora consists of 93 species, 81 genera and 44 families. The *Leguminosae*, *Myrtaceae*, and *Rubiaceae* were the richest families in number of species.

7. MORPHOVEGETATIONAL UNITS

They represent areas of vegetation that occupy a given position in a geomorphologic unit of the fluvial plain. Its distribution is configured as an environmental mosaic that differs in the floristic, soil, and topographical composition, which is also regulated by state variables and hydro-geomorphologic transformations. In the Bananal Island plain, in large-scale, five main morphovegetational units were identified (Table 1).

Table 1 – Relationship between vegetation and geomorphologic units.



7.1. Slightly Dissected Fluvial Plain (SDFP) in association with Cerrado Grassland (CG), Shrub Cerrado (SC), Wooded Cerrado (WC), and Cerrado Woodland (CW)

The Slightly Dissected Fluvial Plain (SDFP) unit relates with the main physiognomies of the Cerrado biome that can be collected in two groupings: (i) grassland with well open such as Cerrado Grassland (CG) and Shrub Cerrado (SC); (ii) relatively dense forest forms like Wooded Cerrado (WC) and Cerrado Woodland (CW) according to Table 1. In the EVI image of September 2003 the grassland physiognomies present dark gray tonality for Cerrado Grassland and medium gray for

Shrub Cerrado, while a white color with high photosynthetic activity is shown for the two forest forms, e.g. Cerrado woodland and gallery forest (see Fig. 13).

According to the argument already presented in this paper, the SDFP remains waterlogged for a long period during the rainy season between December and March. Despite the fact that the rainy period ends in March, the soil remains drenched until June. In this period, the water accumulation in SDFP acts as a limiting factor for the growth of the forest forms of the Cerrado by the restriction of root respiration and by acting as a disturbance that selectively eliminates woody plant species. In this context, the Cerrado woodland and wooded Cerrado grow in more restricted areas, with relatively more elevated topography, well-drained soils; they also occur under spot forms, located in the region to the east of the Bananal Island (Fig. 18a) and subordinately upon the levee of the Jaburu River.

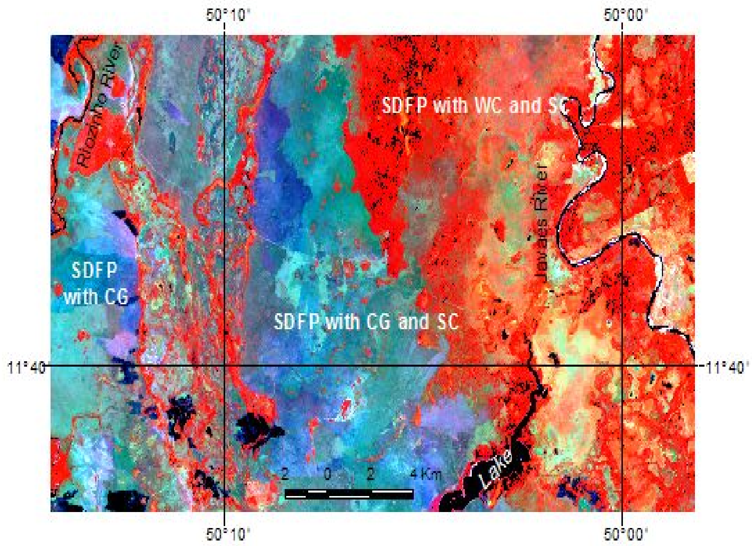


Fig. 18 – Relationship between the Slightly Dissected Fluvial Plain **(**SDFP) with the Cerrado grassland (CG), Shrub Cerrado (SC), and wooded Cerrado (WC) physiognomies. ETM image bands 4,3,5 in RGB.

Unlike the environment with poorly-drained and waterproof soils in lower areas, the plain with water persists for a longer time, favoring the development of more flooded-tolerant vegetation such as herbaceous types, represented in the area by Cerrado grassland (Fig. 18b) and shrub Cerrado that together correspond to close to 58% of the cover area. In the dry season, mainly in September, when the dryness of the soil and grassland is more intense, there are generally occurrences of fire in the Bananal Island Plain.

7.2. Slightly Dissected Fluvial Plain with Laterite (SDFPL) in association with Cerrado Woodland (CW)

As already discussed in the previous item, soaked soils inhibit the growth of the Cerrado Woodland. Thus, the Cerrado Woodland develops on Slightly Dissected Fluvial Plain with Laterite (SDFPL) on higher and isolated areas such as lateritic plateaus distributed in the Bananal plain (Fig. 19). Generally, this form grows upon surface better-drained compounds by latosol, lateritic soil, and laterite.

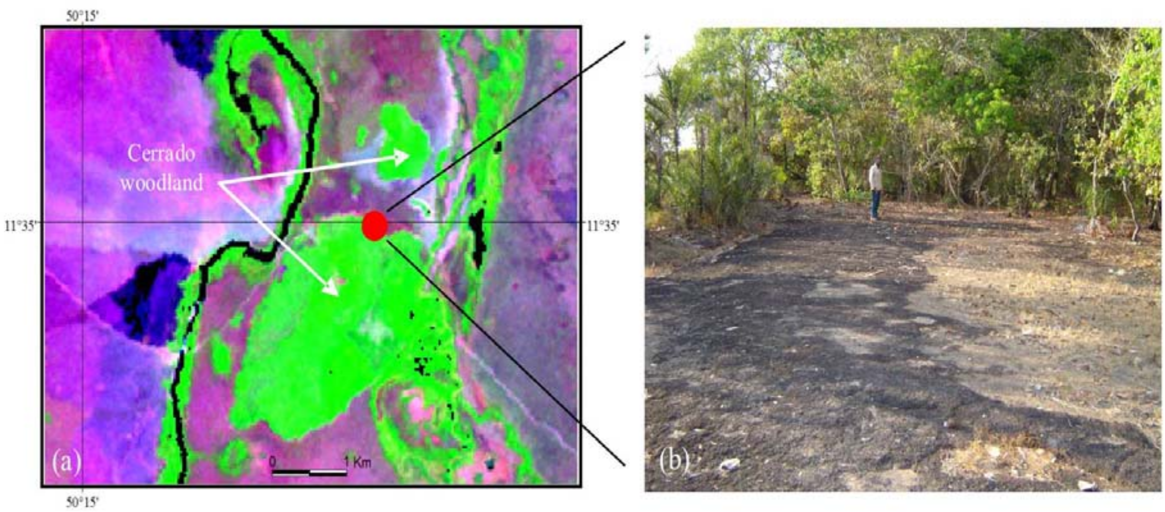


Fig. 19 - Geomorphologic features of the Slightly Dissected Fluvial Plain with Laterite (SDFPL). (a) Laterite plateau on interfluves with Cerrado woodland in ETM image bands 3,4,5, in RGB; (b) detail of the outcrop of lateritic crust with Cerrado woodland.

7.3. Abandoned Fluvial Belt (AFB) in association with gallery forest (GF) and shrub Cerrado (SC)

On the Abandoned Fluvial Belt (AFB) the shrub Cerrado and gallery forest physiognomies are developed. The gallery forest that occurs along the AFB paleoplain is characterized by isolated stains of forest fragments scattered on an open vegetation of shrub Cerrado. One striking feature in this geomorphologic unit is the vegetational succession where the gallery forest is replaced by shrub Cerrado by channel avulsions in the inner Bananal Island plain through neotectonic activity. Recent tectonics in fluvial environments is subject of hydro-geomorphologic disturbances through dynamic process variations of sedimentation and erosion that regulate the generation and renewal of successions of some phytophysiognomies.

The vegetational units inside a single area present specific adaptations to the environment and their own characteristics frequently do not verify outside that area. For instance, the successional process in the AFB environment is depicted in Fig. 20, where the gallery forest is replaced by shrub Cerrado (Fig. 20c). By and large, in similar situations, the gallery forest was entirely replaced by grass. The substrate consists of fluvial sediments composed by clay and sand (for more details see item 5.3).

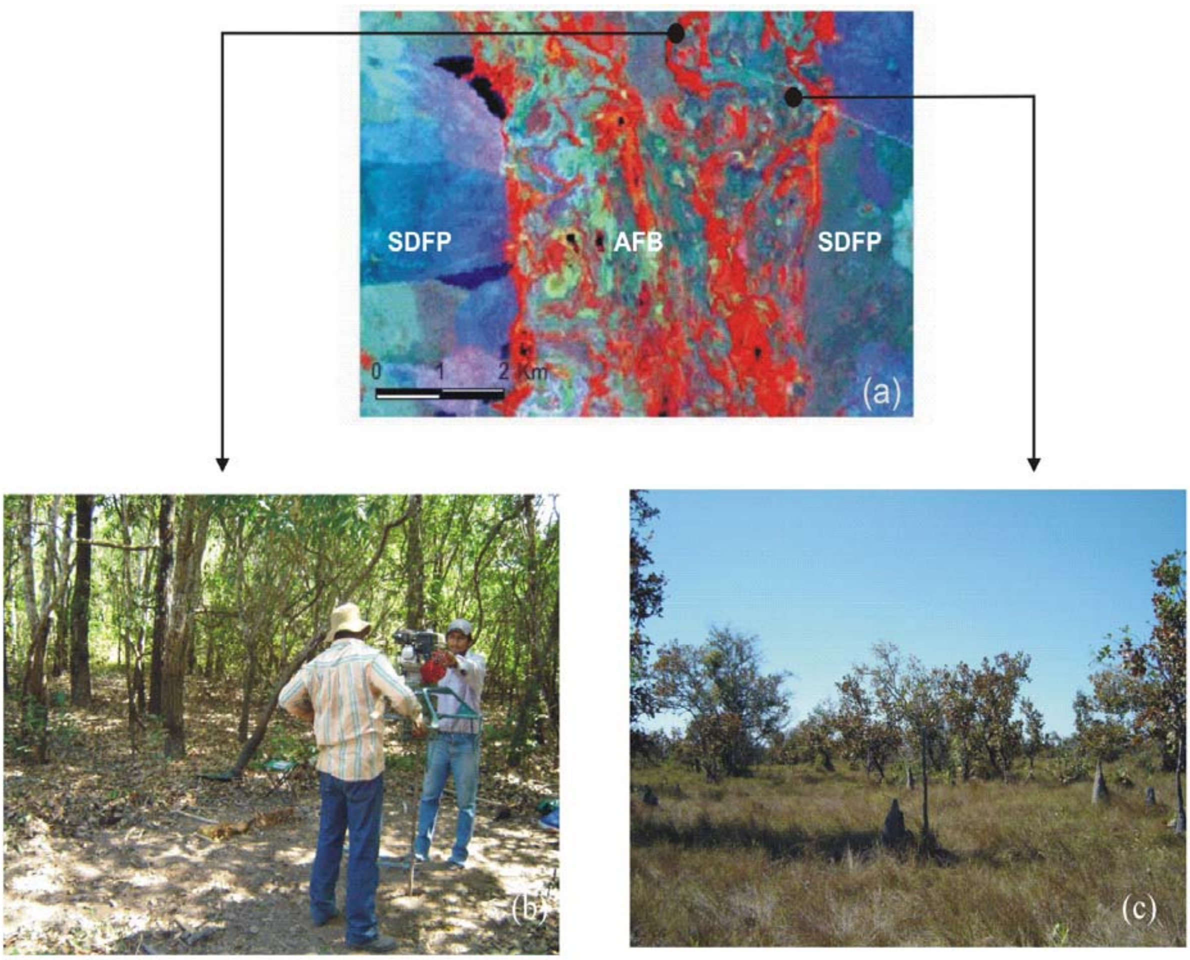


Fig. 20 - Abandoned Fluvial Belt with gallery forest (fragments) and shrub Cerrado. (a) View the Abandoned Fluvial Belt of "Impuca da Macaúba" paleoplain with 4km in width. ETM image bands 4,3,5 in RGB; (b) gallery forest on abandoned channel; (c) Shrub Cerrado on abandoned paleoplain with shrubs and some trees scattered at grassy stratum with termite mounds.

7.4. Fluvial Belt with Meander Scroll (FBms) and Abandoned Fluvial Belt with Underfit Meander River (AFBum) in association with gallery forests (GF)

The FBms and AFBum are geomorphologic units of alluvial floodplain that are intimately associated with gallery forests. The alluvial forest of the FBms is the most developed and occupies the extensive floodplains of the Araguaia and Javaés rivers. On the other hand, gallery forests associated with the AFBum unit are of smaller dimensions and occur along the inner rivers of the Bananal Island, with detach for alluvial plain forest of the Jaburu and Riozinho rivers (see Fig. 17).

The fluvial plains these rivers remain floods for a long time. The hydric availability during the rainy season and the high concentration of nutrients associated with the internal range of the landforms enabled the development of a predominant vegetation of the gallery forest.

The gallery forest greatly contributes to overall floristic diversity because both the composition and physiognomy changes not only between regions but also locally as a function of small changes in topography and of the flooding regime variations. The alluvial plain forest and its lake system are some of the last refuges for the Cerrado fauna and have a rich biodiversity (Latrubesse and Stevaux, 2002).

8. CONCLUSIONS

Visual interpretation from Landsat ETM+ image and digital processing from MODIS EVI data allied with field verification allowed the distinction of five major geomorphologic and phytophysiognomic units in the Bananal Island. In general, the physiognomies analyzed are in equilibrium with the different biological and physical parameters of the study area. However, the gallery forest physiognomy associated with Abandoned Fluvial Belt is in disequilibrium because it shows a vegetational succession via the substitution of the gallery forest by Shrub Cerrado.

Periodic flooding that persists for a long time inhibits to the growth of woody plants. The surface of the Slightly Dissected Fluvial Plain unit, that is poorly-drained and soaked, remains flooded for a longer period favoring the development of more flood-tolerant herbaceous vegetation that corresponds to close to 58% of the cover area.

The great annual floods are only confined to the actual floodplain of the Araguaia River and its main tributaries associated to the Fluvial Belt with Meander Scroll and Abandoned Fluvial Belt with Underfit Meander River. The great-waterlogged area of the Bananal Island plain (e.g. Slightly Dissected Fluvial Plain) is independent from the overbank flood of the Araguaia River. The floodings of the Island plain are provided mainly by local rainfall and by water table saturation.

The waterlogged area of the Bananal Island plain is a result of three factors, which are: (1) high rainfall during the rainy season between January and March; (2) low waterproof soils with predominance of clayey sediments; (3) the Plain is a low-structural with flat-relief that functions like an extensive floodplain of water accumulation on the surface and underground.

By and large, the growth of the spatial distribution of the phytophysiognomies of the Cerrado biome in the Bananal Island plain are controlled mainly by the variation of the geomorphologic forms, with influence from the seasonal floods and secondly from tectonic events. Neotectonic activities were the main causes of river channel avulsions, underfit rivers, incisions, and channel pattern changes that were more active in the Middle and Upper Pleistocene.

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