THE UPPER PARANÁ RIVER (BRAZIL): GEOMORPHOLOGY, SEDIMENTOLOGY AND PALEOClimatology

José C. Stevaux

Universidade Estadual de Maringá, Department of Geography, Núcleo de Pesquisa em Limnologia Ictiologia e Aquicultura (NUPELIA), Grupo de Estudos Multidisciplinares do Ambiente (GEMA), 87020-900 Maringá, PR, Brazil

This study involves the geomorphological, sedimentological and paleoclimatological aspects of the Upper Paraná River at Porto Rico (State of Paraná, Brazil). The alluvial plain is composed of a braided system (main channel) with island and sandy bars, and an anastomosing system (involving secondary channels, tributaries and a complex of swamps, pools and natural levees). River discharge in its upper course varies from 8400 to 13,000 m³/s (minimum of 2550 m³/s and maximum of 33,740 m³/s). Solid discharge reaches 27 × 10⁶ tons/year for suspended sediments and 3 × 10⁶ tons/year for load sediments. Through echohabathymeric survey, bed forms were grouped in ripples, megaripples, dunes and sand waves.

A detailed study of the sedimentology, heavy minerals and facies architecture was applied to the two major geomorphic provinces and their subenvironments: channel province (with sand bar and bed form deposits) and overbank province (with natural levee, flood basin, crevasse and island deposits).

Palynological preliminary studies show that during the Late Pleistocene the area was dominated by grassland and savannas under drier climatic conditions. Since the beginning of the Holocene there has been a generalized transition to a humid phase and the present Broadleaf Forest occupies the area.

Some hypotheses can be formulated for the evolution of the area. (1) The first order architectural element channel (CH) was generated during the Pleistocene associated with climatic changes and tectonism. The alluvial valley was filled up by alluvial colluvial deposits at the end of the Pleistocene (channel deposits present > 40 ka BP). (2) Tectonism and climatic changes (Atlantic Climatic Optimum) generated a new valley bottom (5-8 m below the former level) and a wide meandering plain was built up (4000-4500 BP). (3) A recent fluvial system created a new terrace 3 m above the normal water level.

INTRODUCTION

The Paraná River is the tenth largest river in the world as measured by discharge; the second largest catchment in South America and the principal river of the Rio de La Plata Basin. From its source, at the confluence of the Paranaiba and Grande Rivers, Brazil (lat. 20°S), to its mouth in the Plata Estuary near Buenos Aires, Argentina (lat. 34°S), the Paraná River is about 3780 km long. The Paraná River Basin has an area of 2,800,000 km² and drains all south-central South America, from the borders of the Andes to the Serra do Mar just along the Atlantic Coast (Fig. 1).

The Paraná River’s hydrological basin consists chiefly of sedimentary and volcanic rocks of the Paraná and Chaco Sedimentary Basins, whose borders are constituted by highlands of the eastern flank of the Andes and Precambrian rocks of the Brazilian Shield on the north and east (Petri and Fulfaro, 1983).

The Paraná River alluvial trench is divided into three major parts: an upper course, from its source to the Itaipu Dam near Foz do Iguaçu; a middle course along the Paraguay—Argentina Border; and a lower course from the Paraguay River confluence near Corrientes (Argentina) to the Rio de La Plata Estuary.

The Upper Paraná River, with an extension of 809 km and a basin of 820,000 km², has only 500 km not impounded, and half of that will be modified by the Porto Primavera Reservoir, to be finished in 1995 (Agostinho et al., 1991). The Ilha Grande Hydroelectric Project, whose construction was suspended, would eliminate the last lotic reach of the upper course of the river. From 1972 to 1978, the Upper Paraná River presented, just upstream of Sete Quedas Falls, a total solid discharge between 9.89 × 10⁶ and 30 × 10⁶ tons/year, 9.59 × 10⁷—27 × 10⁷ tons/year for suspended sediments and 0.3 × 10⁶—3 × 10⁴ tons/year for bed load sediments (Itaipu Binacional, 1990).

The Brazilian part of the Paraná River Basin has had its hydrological and limnological regime considerably altered in the last decades. At the beginning of the sixties the total dammed area was approximately 1000 km², whereas at present this area is close to 20,000 km² (Fig. 2).

Porto Rico Area

The studied area is situated near the town of Porto Rico (lat. 22°43′S, long. 53°10′W) between the mouths of the Paranapanema River and Ivaí River (Figs 1 and 3). At this point the hydrological basin area is about 670,000 km². Here, the Paraná River has a large, braided channel, 3.4—4.0 km in width, with an extensive alluvial plain in its right margin. This plain is drained by a complex involving the Paraná secondary channels, Ivinheima and Baia Rivers.

There are many lakes, back swamps and secondary streams, forming a typical meandering—anastomosing alluvial plain. The wide area may present fairly recent subsidence — possibly some type of small neorocratic basin — where the Ivinheima River, which comes from the State of Mato Grosso do Sul, is situated.

The annual range of temperature varies from 10.3 (winter) to 33.6°C (summer), with an average of 22°C, and an annual rainfall of 1200 mm (University of Maringa Meteorological
Station), so that the region has a tropical–subtropical climate. In the Fluvial Station of Port S. Jose (Fig. 4), in the Paranapanema River mouth, the Paraná River has a discharge that varies from 8400 m³/s in the dry season of June, July and August to 13,000 m³/s in the wet season from November to March, with the highest discharge registered as 33,740 m³/s (in 1983, with a recurrence of 27 years) and the lowest 2550 m³/s (in 1969). In the study area the gradient of the Paraná River is about 0.096 m/km.

The area belongs to the Highland of Alto Paraná Geomorphological Region (Justus, 1985), which is dominated by very smooth hills gently tilting to the Paraná River. Four major geomorphological units can be found along the alluvial trench (Fig. 5).

**Unit Porto Rico**

This unit consists of the Mesozoic eolic sandstone of the Caiua Formation covered by a 1–8 m autochthonous sandy soil layer associated with colluvial deposits named the Paranavai Formation (Popp and Bigarella, 1975), and forms almost all the high and steep eastern bank of the river. The landscape is constituted of low hills ranging between 250 and 320 m in altitude, with a hydrographical net of rivers not longer than 20 km (except the Paranapanema River), and high gradient (4.2 m/km). They develop rapids in relatively deep and narrow canyons eroded on the Caiua Formation.

**Unit Taquaruçu**

This occurs in the NW and Western portions of the area.

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**FIG. 1.** Studied area in the geological and hydrological contexts (after Iriondo, 1988 and Agostinho et al., 1991).

**FIG. 2.** Upper Paraná River hydrological basin. Impounded area evolution (after Agostinho et al., 1991, Fig. 2).
and 15–45 m above the Paraná normal water level. It consists of a high colluvium terrace where hundreds of small lakes can be found. These lakes probably originated by pseudo-karstic processes during ancient dry periods very similar to the forms described by Popolizio (1975, 1992) in the Paraná–Corrientes River area in Argentina.

**Unit Fazenda Boa Vista**

This unit is a typical alluvial–colluvial terrace rising 8–10 m above the Paraná River water level. It is formed exclusively by sand and irregular lenses of gravel with many levels bearing limonite cement. A great number of paleo channels and levees suggests that this unit was strongly reworked by the ancient Ivinheima River meandering system.

**Unit Rio Paraná**

This unit is the proper Paraná River alluvial plain and consists of high and low flood plains, island, bars and a secondary anastomosing system. Almost all lakes and back swamps in this unit are flooded every year during the wet season.

Two levels of limonite-cement gravel, identified by Fulfaró (1974) and Boggiani et al. (1985) as 'Quartzite and Agate Generations', are possibly the oldest deposits in area related with the geomorphological and sedimentological history of the Upper Paraná River. They occur in the highest altitude of the northwestern portion of the study area (Fig. 5) and paleocurrent analysis show that these deposits have come from the north and northwest. Fullfaró and Suguio (1974) attributed a Neogenic age to these deposits.
FIG. 5. Geomorphological units of the Porto Rico area.
**Fluvial Geomorphology**

The channel pattern in the Paraná River from the Paranapanema mouth to the Sete Quedas Falls canyon (covered by the Itaipu Hydroelectric Dam) is typically braided, with a large number of islands and sandy bars (Fig. 3). However, an accurate analysis shows that this segment has a mixed pattern. The main channel is braided but the secondary channels, in the flood plain on the right margin, are anastomosed according to the concept of Smith (1976).

The strong asymmetry of the alluvial trench geometry (see Fig. 19B, C) shows a possible tectonic control on the fluvial dynamic. There is almost no flood plain along the left margin, so that the river continuously erodes the Mesozoic sandstone of the Caiua Formation. However, in its right margin the Paraná River built up a large flood plain. The multichannel morphology occurring in the main channel can be divided according to its fluvial characteristics (Fig. 6). Along its south side, erosional–depositional dynamics have been intense such that the talweg has totally shifted to the left margin.

**FIG. 7. Upper Paraná at Port São José. Relationship between concentration of suspended material (mg/l) and liquid discharge (Q1). Note the anti-clockwise cycle for the 1988–1989 flood.**

**FIG. 8. Talweg migration in three cross-sections in a braiding of the Upper Paraná. Section Port São José is a node point where the talweg presents high stability (migration velocity 2.7 m/year); section University of Maringá Lab. is in the upstream part of a braid (migration velocity 13.4 m/year) and section Porto Rico is in the middle of a braid (migration velocity 56.6 m/year). Localization on Fig. 9.**
margin. Here the channel is about 13 m deep with a flow velocity of 1.4 m/s. On the opposite side, the fluvial dynamics are reduced, the depth does not exceed 5 m and the flow velocity is less than 0.9 m/s. Thus, the asymmetry of the alluvial deposits suggests tilting of the right block towards the high left margin. Here the channel depth is about 13 m with a flow velocity of 1.4 m/s. On the opposite side the fluvial dynamic is reduced, the depth does not exceed 5 m and the flow velocity is less than 0.9 m/s. Thus, the channel and alluvial deposits’ asymmetry suggests fairly tilted subsidence of the right block against the high one of the left margin.

The anastomosed channels of the external border of the flood plain comprise a complex with the Baia, Curumiba and Ivineima Rivers and secondary channels of the Paraná River. These channels present low to high simuosity (1.2 to 2.1).
The Upper Pararã River (Brazil)

Actually, since 1953, studies from aerial photographs confirm the low activity of these channels, restricted to which is lateral accretion, natural levee build up and mainly avulsion processes that may separate channels many kilometers long. As this complex is controlled by the Paranã and Ivinheima regimes, the water in the secondary channels may flow downstream or ‘upstream’ according to the relative discharge of each.

There are many lakes and swamps associated to the anastomosed branch of the Paranã River, and they are very important environment for local ecosystems (Agostinho et al., 1991).

Water Regime and Suspended Sediments

In spite of two great dams just upstream of the area (Rosana in the Paranapanema and Porto Primavera in the Paranã), the Paranã River section at Port S. José is very important to the local hydrology, because it constitutes a node point controlling the braided reach downstream. The main influence of the dam on the river system dynamic is probably the great decrease of load sediment, especially of coarse material. Suspended solid concentration in the Paranã River at this section varies from 30 to 6 mg/l. Suspended sediment concentration and water discharges during 1988–1989 (Fig. 7). From April to November (dry season) there was an increase in solid concentration, and a decrease from December to January, during the flood period.

During the normal floods the channel water invades the plain by overflowing the natural levee and abandoned channels. The flood is gradual and calm, with no effective unidirectional flow, except locally where levee crevasses may occur. At these points the flow is more intensive, and ephemeral channels with associated splay may occur, or abandoned channels may even become reactivated.

The anastomosed secondary channels are influenced not only by the water of the Paranã River but by the Ivinheima-Baia floods as well. The interrelation between the floods of the Paranã and Ivinheima-Baia systems controls the magnitude of ‘catastrophic floods’. In this case, the water totally invades the alluvial plain, forming a large channel 8 km wide.

Bed Form

Bed forms and bars morphology change drastically and talweg tends to drift continuously in the Paranã braided channel. Drago (1990) characterized these movements in two distinctive types: (1) gradual and continuous transverse movements and (2) sudden shifts from one position to another. The magnitude of the movement of the talweg from a stable marker is studied in three different cross-sections (Fig. 8). Cross-section Port S. José shows a talweg shifting about 2.7 m/year. This section is a node point that operates as a zone of bypass of energy in the system. On the other hand, section Porto Rico shows a significant displacement of the talweg, reaching 56.6 m/year. The intermediate section University of Maringa Lab. shows an average shift of 13.4 m/year.

Using the same terminology proposed by Drago (1990), four bed forms can be found in this reach of the Paranã River:

1. Ripples: are forms with wave height from few to 30 cm. Generally, the ripples are superimposed on the upstream face of large bed forms.
2. Megaripples: range from 30 cm to 1.5 m and are
linguoid and lunete in shape. Megaripples are forms with high mobility, like ripples.

3) Dunes: have wave heights ranging from 1.5 to 7.5 m and lengths from 50 to 500 m. They are perhaps the most common forms in the upper course of the Paraná River.

4) Sand waves: are the largest forms with heights reaching 13 m and lengths of 1000 m. Sand waves are probably related to the catastrophic floods and responsible for the bar construction.

An echogram survey was made in three different longitudinal profiles in Paraná River channels (Fig. 9). In the echogram from the main channel, with depth above the crista ranging from 5.5 to 7.5 m and flow velocity near the water surface of about 1.3 m/s (Fig. 9A), the first order forms are

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**FIG. 11.** A, B and C margin types of the Upper Paraná River and their lithologic, topographic and erosional characteristics (after Fernandez, 1990).

**FIG. 12.** Correlation of hydrological conditions, rainfall and erosion rates for three types of margin from July 1988 to August 1989 (after Fernandez, 1990).
dunes 2 to 3 m in height and 200-400 m long. They are not simple forms but incorporate secondary ones as megaripples and ripples. The second echogram (Fig. 9B) made in a secondary channel of braided system with depth less than 3 m (above the crests) and flow velocity 0.9 m/s. The bed forms are essentially megaripples 0.5–1.9 m in height and length ranging from 30 to 150 m. The third echogram (Fig. 9C) was profiled in the unichannel reach of the river near Port S. José (node point). The most spectacular form in this profile is a planar wave gently dipping upstream (1.3 m/1000 m), where only isolated ripples and megaripples appear.

Grain size of the bed load in a transversal section at Porto Rico (Fig. 10) is very homogeneous and well sorted, with the mean between 1 and 2 phi (medium to fine sand) and standard deviation lower than 1.0.

**Bank Line Alteration**

Banks are continuously altered by shifting of erosion and deposition zones. Fernandez (1990) classified the Paraná River margins in three types:

1. **Stable bank:** occurs along almost all of the left margin of the river, constituted by the highly resistant sandstone of the Caiua Formation.

2. **Accretion bank:** this margin is a type of 'lateral bar' that normally develops downstream of islands or pre-existant margin. It has high depositional rates and is generally covered by vegetation.

3. **Erosion bank:** this is the margin that presents continuous recession. It forms steep faced banks with heights ranging from a few centimeters to 3 m above the water level.

Fernandez (1990) measured the rates and processes of eroding banks between 1988 and 1989 using a pins and pegs method. Thirty active eroding banks were monitored and grouped in three prominent types: A, B and C (Fig. 11). The morphological and sedimentological bank conditions and the flow characteristic were the basic parameters used in this classification. The mean annual erosion rates for A, B and C types were 4.08, 1.40 and 0.51 m/year, respectively. The correlation between data of hydrological conditions, rainfall amounts and erosion rates for three types of bank are shown in Fig. 12. There are two main erosion processes, corrosion and slumping, that increase activity during the flood period. Rotational sliding occurs secondarily in some high, very cohesive clay-rich banks.
The fluvial channel dynamic is controlled by the river regime, so that intensity, duration and recurrence of flood are responsible for the modeling of the erosional or depositional forms. The area variation of a group of islands was monitored for 37 years (Fig. 4). In 1953 the area was about 2.7 km² and this value increased until 1966, reaching 3.6 km². At this period the increase in area coincided with the increase in the highest and medium annual discharges. Since then, the group of islands has been dominated by the erosional process and presented a reduction of 0.42 km² in area in 1970 (corresponding to 11% of the area in 1966). This reduction coincided with a strong decrease on the maximum and mean annual discharges. From 1970 a new cycle was initiated with an increase of 0.2 km² in the area of the group of islands (about 15,000 m²/year). For the same period the discharge also increased, reaching a peak of 34,000 m³/s in the historical flood of 1983.

SEDIMENTOLOGY, FACIOLOGY AND MORPHOGENESIS

Fluvial sediments were described using the lithofacies classification of Miall (1977, 1985), with two additional specific facies observed in these deposits. Lithofacies, with their respective sedimentary structures and interpretation, are shown in Table 1. Six major deposits were identified for the alluvial and associated sediments, and could be grouped into three geomorphic provinces (Table 2).

Channel Province

Sand bar deposits

Paraná River sand bars were characterized by Santos et al. (1989) and Santos (1991) as central and lateral bars according to faciology and channel position (Fig. 13).

Central bars are elongated sandy bodies deposited in the middle of main channels with a length of 200–1000 m and length/width ratio of 3 : 1. The sand varies from very fine to very coarse (Fig. 14), with prominent granulometric alternation among the sets. Subordinately thin levels of mud may occur without expressive lateral continuity. The deposits are composed essentially of quartz (>95%) and mica (5%); the main heavy minerals are opaque (magnetite), amphibole, pyroxene, staurolite, kyanite and sillimanite (Table 3).

Two faciological associations related to the genetical phase of the central bars are found in a typical vertical profile (Fig. 15A). The initial phase, denominated protobar (Santos, 1991), is constituted essentially of Sp facies at the bottom and St facies at the top. These facies were deposited as dunes and megaripples during the sub-aquatic phase of bar construction. In the second phase, the bar was reworked by shallow water processes relating to flood reflux and by wind action. The faciological association of this phase is composed by facies Sr and So originated by ripple bed forms, facies S1 (eolic) and facies Fm (suspension).

During the floods, small 'natural levees' are deposited at the bar’s upstream face (Fig. 13), forming protected shallow pools in the inner part of the bar. In these places, primary herbaceous vegetation may develop, contributing to bar stabilization. These deposits can migrate hundreds of meters or even totally disappear in the intensive floods (Santos, 1991).

Lateral bars develop beside the margins and island due to shadow zones originated by topographical particularities (Fig. 16). In these zones the flow velocity falls below 0.9
m/s, creating a location with high depositional rate. These bars are formed by quartzose fine sand with high sorting (Fig. 14), with important layers of mud intercalated. Heavy minerals are less than 2%, prevalently opaques, amphibole and kyanite (Table 3). The occurrence of unstable minerals (amphibole and pyroxene) associated with metastable material (kyanite, sillimanite, staurolite) suggests a source area composed of metamorphic aluminum-rich rocks, probably originated from the Brazilian Shield, with recent deposition in the fluvial system (Santos and Fernandez, 1992).

These deposits present an alternation of muddy facies Fm and F1 with sandy facies Sp, Sr and So (Fig. 15B). Occurrence of drape and flaser structures indicates fall-out and a tractive process. Frequent leaf banks are associated with the shallow pools in the inner portion of the bar.

The evolution of a lateral bar in the Porto Rico area was observed over the last 36 years (Fig. 17). In 1953, the process began with a shadow zone formation created in the right margin of the main channel. By 1970, with the intensive sedimentation, the protobar attached to the margin and the bar surface was covered by herbaceous vegetation. In 1980,
as the hydrological and morphological characteristics remained the same, a new protobar began to be deposited and the latter herbaceous vegetation was replaced by arboreous. By 1989, the last protobar became a lateral bar covered by herbaceous vegetation and a new bar began to be deposited (1989).

When a new lateral bar is formed, a narrow channel ('ressaco') develops between the bar and the ancient margin. With the continuity of the process, each new channel being formed beside the last one generates a very typical pattern in aerial photography (Fig. 18).

**Bed form deposits**

This reach of the river presents a sandy mobile bottom, except in some places with limonite cemented gravel, sandstone or basalt. Ripples, megaripples and dunes are very common in this area; on the other hand, sand waves are restricted to catastrophic floods.

A very significant outcrop could be studied in Porto Primavera Dam, just upstream of Port S. José where, in a continuous trench of 13 km, all alluvial deposits are totally exposed. Thus, it is possible to apply the Architectural Elements concepts of Miall (1985). Figure 19 reunites the Architectural Elements identified in that exposition. Figure 19B presents the CH element (channel) in regional scale, where it is about 11 km wide—this is one of the largest expositions of this element in the world. In Fig. 19C it is possible to distinguish the spatial distribution of the present Paraná River, where the element SG and, secondarily, GB (respectively 'sediment gravity flow' and 'gravelly bars and bedforms') occur in the basal portion of the sequence. Architectural elements FM, LS ('forset macro form' and 'laminated sand') and GB are present in the middle of the sequence and LA ('lateral accretion') in a thin layer on the top.

The three vertical profiles in Fig. 19A present different characteristics of this sedimentary environment. In profile 1,
the prevailing Gms facies indicates debris flow as the main sedimentary process. However, the relative sorting and roundness of the clasts suggest that these deposits had various cycles of transport and sedimentation.

Profile 2 presents facies Sp and St with few Gt interbedded. This profile is very similar to the Plate and Donjek Rivers described by Smith (1971, 1972), Williams and Rust (1969) and Rust (1972). The faciology is typical of the FM architectural element, whose generator bed forms are sandwaves, dunes and megaripples (Allen, 1983; Kirk, 1983; Cant and Walker, 1978; Haszeldine, 1983a, b). This profile is the more representative on Paraná River deposits, suggesting that the element FM is in adjustment to the present river pattern (Stevaux, 1993).

Gravel facies (Gm, Gms, Gt and Br) interbedded with sandy facies (Sp, St and Sh) are found in profile 3. Br facies shows reactivating phases and instability, with erosion and remobilization of pre-deposited sediments. Blocks of pebbly sand and sandy gravel suggest that sediments suffered some extensive diagenesis. In outcrops it is possible to identify gravity flow, slump and fluidization. However, the intensive actuation of traction flow reorganized the blocks and

FIG. 19. Architectural elements and faciology of Paraná River channel deposits at Porto Primavera dam. (A) Faciological profiles in the channel deposits; (B) CH element (present and ancient); and (C) spatial distribution of the architectural elements of the channel deposits (after Stevaux, 1993).
corresponds to overbank environments involving a large number of sub-environments that may or may not be in connection with the Paraná main channel, depending upon flood magnitude. It is interesting to emphasize the importance of overbank deposits, traditionally neglected by fluvial sedimentologists in favor of channel belt studies (Farrel, 1987). The overbank deposits give a more complete sedimentary history than the fragmentary channel records. Information about paleoclimate, paleocology, palinology, macro fossil, paleopedology and absolute dating are preferentially found in these deposits rather than in channel sequences.

Natural levee deposits

Natural levees in the Porto Rico area do not exceed 3 m in height and occur in the main channel as well as in secondary ones. The natural levee faciology can be divided into three major faciological units (Fig. 20): (1) a basal unit, constituted by sandy facies Sp and St from the bar phase; (2) a middle unit, muddy borrowed facies deposited in the flood plain phase and (3) an upper unit, a thickening and coarsening upward sequence corresponding to the levee deposits, ubiquitous in almost all right margins of the Paraná River. Figure 21 shows the evolution and idealized profile of a typical ‘erosive margin levee’. Each growth phase (T₁, T₂, etc.) advances toward the flood plain, resulting in the characteristic coarsening-thickening upward sequence (Stevaux, 1993).

Flood basin deposits

Six major units were identified in these deposits (Fig. 22).

Sandy mud with iron nodules unit. Light olive-gray sandy mud with nodular and root traces with iron oxide coating; SEM and X-ray diffraction analyses show kaolinite and smectite as clay minerals. Fe-oxide precipitant suggests that the environment was well drained, allowing for Fe²⁺ mobilization and subsequent precipitation as Fe³⁺. Centimetre to decimetre layers of rooted sand can be

pebbles, building up gravelly sand facies (Gp and Sp), common in the GB architectural element.

On the top of profile 3 (Fig. 19A) there is a sandy faciological association belonging to the LA element. This element is often referred to point bar deposits (Miall, 1985), where the sigmoidal foresets transversely shift the channel, generating a sequence of ‘off lap’. However, this reach of the Paraná River is straight, suggesting that lateral accretion was induced by talweg migration.

Overbank Province

About 70% of the Porto Rico alluvial plain area
The environment of this unit is the same as the previous one, but in a more proximal splay position.

**Sand grading to clay unit.** This is one of the most common facies on the flood basin deposits in the area. Its granulometry varies from medium/fine cross-bedded sand with clay clasts in the base to medium gray borrowed organic-rich mud. This faciologic is interpreted as small abandoned channels from Paraná secondary anastomosing channels or local tributaries.

**Clay clasts unit.** This unit is constituted of thin levels of clay clasts in a sandy matrix and is interpreted as the product of sub-aerial exposure of the swamp bottom (mud cracks formation) and re-sedimentation in the next flood. This unit is very important in paleoregime studies, because it may identify periods of complete dessication of the flood basin.

**Peat and clay unit.** A 0.5–2.0 m layer of peat interfingered with organic-rich clay, with leaves and logs fragments; lamination is partially obliterated by bioturbation. This unit was deposited in back swamp or shallow pool environments.

**Massive sand unit.** This facies is derived from colluvial-alluvial processes on the sandy geomorphological units (Porto Rico and Fazenda Boa Vista) and it can be randomly associated with other units. When sand is deposited in thick layers interfingered with peat or organic-rich clay in a well drained part of the alluvial plain, the high pH of subsurface water can mobilize the Fe-oxide coatings of the grains, and the sand becomes very clean.

**Crevasse deposits**

The Paraná River's natural levees are not continuous, so that water floods often enter the plain before the levee overflows. This diminishes the channel water stress on levee walls, avoiding crevassing. The complex of channels originated by the lateral bar accretion process (Fig. 18) distributes the flood water, diminishing the stress. Thus, when the bankfull level is reached, all of the plain is already inundated, and in strong floods, the plain, as a whole, operates as a great channel. In this case the bed load passes over the plain, generating bed forms like those found in the main channel. The predominance of Sp facies indicates that the 'crevasse' deposits in the Paraná River display the same faciologic as the channel.

**Island deposits**

In spite of the islands' occurrence in the channel, their sedimentary processes are closely related to overbank environments. These forms are originated from channel bars followed by aggradation produced by flood process. Island morphology develops from depositional and erosional processes whose equilibrium defines its permanence or disappearance from the system.

A representative profile obtained from vibro corer and elucidates the island formation (Fig. 23). The first phase bar deposition, and the second involves vertical accretion originated by the flood process. The island sequence is
FIG. 23. Faciological vertical profile, depositional environment and shifting margin curve ('G' curve) in a channel island of the Upper Paraná River, near Porto Rico. 'G' curve is the distance between the margin and the profile. (1) channel deposits — 'G' curve in O; (2) stable bar condition — 'G' curve goes far from O; (3) aggradation processes — 'G' curve continues far from O; (4) levee in erosional margin condition — 'G' curve tends to O; (5) flood basin condition — 'G' curve stable far from O; and (6) erosional margin levee (present situation) — 'G' curve back to O (after Stevaux, 1993).

composed of bar deposits followed by natural levee deposits (depth 2.1–4.0 m.). About 2.5 m of muddy sediments were deposited in the flood plain environment. Finally, a natural levee sequence ends the island depositional history (depth 0.0–2.1 m.).

PALEOClimATOLOgy

Palynological studies in the area are very scarce and restricted to only a few samples collected in the main Upper Paraná River hydrographic sub-basins in the State of Paraná.

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<td>Typha</td>
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<td></td>
<td>Urticaceae</td>
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<td></td>
<td>Araceae</td>
<td>Araceae</td>
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</tbody>
</table>

I, Tibagi River (S 25°10'50"/W 50°38'00"); II, Piquirivai River (S 24°07'50"/W 52°14'00"); III, Umuarama (S 23°30'00"/W 53°30'00"); IV, Porto Rico (S 22°00'10"/W 53°06'00").

(Jabur, 1993). Table 4 presents an expeditious correlation between the palinology of these sub-basins and samples from the Paraná River alluvial plain in the Porto Rico area. During the late Pleistocene (between 25 and 10 ka BP), the area was dominated by grassland and savannas under drier climatic conditions, as suggested by the low frequency of pollen (Fig. 24). Since the beginning of the Holocene there was a generalized transition to a humid phase, reaching a climatic 'optimum' at about 5 ka BP identified by Jabur (1993) as the 'Optimum Atlantica'. It is very suggestive that this event corresponds to the highest sea level in the SE Coast of Brazil according to the relative sea level variation curve presented by Suguio et al. (1985).

In this last humid phase, the Paraná Basin was occupied by the present Broadleaf Forest (Klein, 1975). Nevertheless, a significant fall in the relative sea level curve between 3500 and 2000 BP seems to be correlated with an interval of low frequency of pollen (drier climatic conditions?) in the profile of Fig. 24.

QUATERNARY EVOLUTION

Unfortunately, the greater part of the Upper Paraná River and associated deposits are flooded by hydroelectric dams, hence the importance of the Porto Rico area as the last resort for the study of its Quaternary history. Based on analysis of

FIG. 24. Pollen frequency, climate and vegetation during the Quaternary in the Upper Paraná River hydrological basin (Source: Klein, 1975 and Jabur, 1993).
geomorphology, sedimentology and lithofacies associations, together with palynology, ^14C and TL dating (Stevaux, 1993), several hypothesis can be put forward as to the Quaternary evolution of the Upper Paraná River:

— Two different levels of conglomerate identified as the ‘Quartzite and Agate Generations’ (Fulfaro, 1974; Boggiani et al., 1985) can be correlated with tectonic events that raised the western watershed between Paraná and Paraguay hydrologic basins during the Neogene.

— Many authors attribute to the excavation of the first order architectural element channel (CH) an age about at the limit of the Pliocene/Pléistocene (King, 1959; Bigarella and Ab’Saber, 1964; Braun, 1971; Berthelussen, 1961; Fulfaro and Suguió, 1974; Suguió et al., 1984; Stevaux, 1993). Several recent ^14C age determinations in samples from the channel deposits of the Paraná River in Porto Rico and Porto Primavera dam and from geomorphologic unit Taquarupu show an age superior to 40 ka BP. This emphasizes the hypothesis that during the Pleistocene, under predominant dry climate, the valley was filled with typical braided system and colluvium.

— Wet climatic conditions (Atlantic Climatic Optimum) probably associated with tectonic reactivation changed the river channel pattern and a new valley bottom was generated (corresponding to the surface of the high flood plain and major islands). A fluvial meandering system with large flood plain was formed at this time (6000–4000 BP). The sandy deposits of the ancient braided system were covered by the muddy meandering deposits.

— The present fluvial system was reactivated probably by tectonic movements, creating a new terrace 3 m above the present active flood plain. This terrace is flooded only during major floods that occur cyclically every 7 years. The present flood plain is 1 to 2 m above the normal water level and is flooded every year. This last recivation exposed part of the ancient braided system and thus liberatetd a great amount of sand

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