Channel-floodplain geomorphology along the Solimões-Amazon River, Brazil

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ABSTRACT

Across the cratonic landscape of Brazil the Solimões-Amazon River transports to its delta plain 1240 Mt of suspended sediment derived from Andean erosion and reworks another 3200 Mt of floodplain sediments. Distribution of these sediments has resulted in a variable along-stream pattern of geomorphology. The upstream reaches are characterized by sediment erosion in the main channel and deposition in floodplain channels that are an order of magnitude smaller in discharge than the main channel. Sediment deposition in and migration of the floodplain channels erases oxbow lakes of the main channel and yields an intricate scroll-bar topography that forms the boundaries of hundreds of long, narrow lakes. In contrast, downstream reaches are characterized by channels restricted by stabilizing, long-term, levee building and floodplain construction dominated by overbank deposition. Overbank deposition buries the scroll-bar topography, resulting in a flat floodplain covered by a patchwork of large, more equant, shallow lakes. On the basis of estimated rates of recycling of floodplain sediments, the modern floodplain of the Brazilian Amazon could have been recycled in <5000 yr, and is recycled more rapidly in the upstream than the downstream reaches. The cratonic interior is interrupted by structural arches that bound intracratonic basins. Four of these arches cross the valley of the main river system at intervals of several hundred kilometres and impart a tectonic imprint on the channel-floodplain geomorphology at this spatial scale. Structural arches appear to exert a primary influence by promoting entrenchment of the river as it passes through zones of deformation, thus restricting channel movement. For example, as the river crosses the Purús arch, the valley narrows to <20 km compared to an average of ~45 km, the water-surface gradient decreases, sediment is deposited, and yet the rate of channel migration is negligible. Hence, the effect of the arches is to create a landscape where, on the spatial scale of hundreds of kilometres, the river is confined and entrenched in its valley, is straight, and is relatively immobile. Local valley tilting apparently unrelated to the arch structures also imprints the geomorphology. In particular, a tilted valley in the upstream reaches appears to have caused avulsions which have left behind the only large-scale, oxbow-type features on the Brazilian Amazon River floodplain.

INTRODUCTION

The continental-scale Solimões-Amazon River drains the Andes and crosses a humid cratonic to the Atlantic Ocean (Fig. 1) while traversing structural arches. The structural arches impart a tectonic imprint on the riverine landscape at wavelengths of hundreds of kilometres. Local valley tilting (Tricart, 1977) and apparent fracture patterns (Sternberg and Russell, 1952) also have influenced the development of the channel-floodplain system. Across the craton the river carries 1240 Mt/yr of sediment and reworks 3200 Mt/yr of floodplain sediment (Dunne, Mertes, R. H. Meade, and J. E. Richey, unpub. data). Deposition and erosion of these sediments have resulted in different channel patterns and the construction of a complex floodplain, the várzea, which is a mosaic of deposits (Wolman and Leopold, 1957) from the main channel, anabranches, floodplain channels that have discharges an order of magnitude lower than the main channel (Mertes, 1985, 1990), and nonchannelized overbank flows.

As the Amazon River enters Brazil it is known as the Solimões River until downstream of the Negro River confluence (Fig. 1). The entire system will be referred to as the Amazon River. Over the length of 3000 km of the Amazon River in Brazil we have compiled data on the geomorphic characteristics of the channel and floodplain from remote sensing images and navigation charts. Analysis of navigation charts, aerial photographs, and travel diaries dating to the middle of the nineteenth century indicates that different rates and styles of channel behavior dominate in different reaches of the river. The surface morphology of the floodplain as measured by the geometry and percent cover of scroll bars, overbank deposits, lakes, lake deposits, and floodplain channels also changes in a downstream direction, reflecting variation in the depositional and erosional history of each reach. Interpretation of these geomorphic data in the context of the tectonic setting allows for interpretation of the sediment budget in the context of basinwide hydrology and hydraulics (Dunne, Mertes, R. H. Meade, and J. E. Richey, unpub. data). In addition, we provide here a process-based interpretation of the current development of the channel-floodplain system and a framework for anticipating future patterns of development in the context of global-scale changes in climate, sea level, tectonics, and land use.

BACKGROUND

This study of processes currently active along 3000 km of a continental-scale, tropical alluvial river requires considering basin-wide processes such as tributary effects and interactions between reaches and the long-term effects of climate change, base-level change, and tectonics. For example, Potter (1978) pointed out that continental-scale tectonic deformation controls the physiographic setting of large rivers, in that most large rivers are located in structural lows or continental
rifts, and flow into oceans off trailing edges of continents. In addition, patterns of uplift and subsidence in drainage basins of the Mississippi River watershed (Schumm, 1986; Schumm et al., 1982; Merritts and Hesterberg, 1994), in streams of the Los Angeles basin (Bullard and Lettis, 1993), along the Yangtze River (Lian-yuan, 1982), and along the Rio Grande (Ouchi, 1985) correlate to changes in channel gradient and channel pattern. Data from flume experiments showed that uplift and subsidence cause changes in channel pattern (Ouchi, 1985).

Potter (1978) not only drew attention to the direct influence of plate tectonics on the locations of continental-scale rivers, but suggested that some basinwide impacts could result from climatic and sea-level change. Schumm (1993) concluded that base-level or sea-level changes in a large alluvial river would frequently have only local effects due to the river’s ability to adjust slope, planform, width-depth ratios, or roughness, thus confirming the observations of Leopold and Bull (1979) and Merritts et al. (1994) concerning the limited extent of depositional wedges related to base-level changes in small river systems. Schumm (1993) also suggested that climatic changes or tectonic deformation could affect an entire river system, depending on the scale and trend of the perturbation.

**Amazon River Basin**

**Area of Study.** The scope of this paper is the Brazilian reach of the Amazon River that extends \( \approx 3000 \) km from Vargem Grande near the Peru-Brazil border to the Atlantic Ocean (Fig. 1). At its most downstream gaging station, Óbidos, the Amazon River has a water discharge of \( 180,000 \) m\(^3\)/s (Richey et al., 1989) and a drainage area of \( 4.6 \) million km\(^2\).

The sedimentary deposits of the main-stem Amazon alluvial plain between the Peru-Brazil border and the Atlantic Ocean cover an area of \( \approx 64,400 \) km\(^2\), according to an estimate by Ca-
margo (1954; as described by Irion, 1976a). Sippel et al. (1992) calculated this area to be about 92 400 km², on the basis of a planimetric measurement of the valley area between topographically higher (10–15 m) terraces. The terraces parallel both sides of the river valley and are composed of unconsolidated fluvial and lacustrine deposits and the Tertiary Barreiras Formation, which consists of unconsolidated sands, silts, and clays, with scattered conglomerate lenses and crude stratification (Radambrasil, 1974, 1977, 1978).

Irion (1976c), Tricart (1977), Iriondo (1982), and Klammer (1984) suggested that the mainstem floods do not inundate the entire alluvial plain. Using Iriondo’s (1982) interpretation of landforms visible on radar images (Radambrasil, 1972) and our estimates from remote sensing data of the distance that sediment-rich main-stem waters travel into the alluvial plain (Mertes et al., 1995), we estimate that between Vargem Grande and Óbidos, ~40 000 km² of floodplain and 4000 km² of islands are inundated by direct flooding from the Amazon River water. The remainder of the alluvial plain between Vargem Grande and Óbidos (~20 000 km²) comprises deposits that may remain dry or are flooded by small tributaries, ground-water seepage, or rainfall.

**Structural Setting.** The pattern of the drainage network of the Amazon Basin has been influenced by structural controls since the origin of the basin (Caputo, 1984; Potter, 1978). On the basis of stratigraphic evidence from deep cores, it has been determined that from west to east in Brazil, the main Amazon valley is a 6000-m-deep sag in the crust between northern and southern crystalline shields (Guiana and Brazil shields, Fig. 1) that leads into a graben in the eastern half of the basin (Caputo, 1984). The structural sag may have first developed in response to Paleozoic rifting (Caputo, 1984) that was reactivated during the Triassic separation of South America and Africa (Potter, 1978). Although the Amazon trough has been present since at least the Paleozoic, significant eastward flow of water may have commenced with the Miocene uplift of the Andes (Caputo, 1984).

This picture of mountains bordering a continental-scale basin is interrupted by structural features that bound intracratonic basins. Räisänen et al. (1987), Dumont et al. (1991), Dumont and Garcia (1991), and Kalliola et al. (1993) reviewed the structural character of the sub-Andean foreland in western Amazonia (Fig. 1) and considered the Peruvian Amazon basin to be an active zone of thin-skinned fold and thrust movement related to Andean tectonics. From near the Peruvian border to the Atlantic Ocean, four structural arches (Fig. 1) lie transverse to the main Amazon trough; these are (from west to east) the Iquitos, Jutai (Carauari), Purús, and Gurupá arches (Fig. 1). Information on the Brazilian arches is scarce and is typically restricted to oil exploration documents that are not published. The presence of the arches in the central Amazon valley has been suggested to explain a discontinuous stratigraphy along the main Amazon trough. The stratigraphy is based on data from sediment cores and seismic surveys and shows that the formations in each basin pinch out as they approach the structural highs (Caputo, 1984, 1991).

From the limited data it appears that the structural arches represent intraplate tectonics (Bigarella, 1973; Caputo, 1984, 1991; Putzer, 1984). For example, Soares et al. (1978) concluded that the Brazilian intercratonic basins passed through a five-stage cycle, and varying rates of uplift and subsidence controlled deposition and erosion. They described the Tertiary sequence as residual deposits preserved in “Quaternary relict basins of slight subsidence” (Soares et al., 1978, p. 190). The stratigraphy of deposits in intervening basins indicates that the Jutai and Purús arches were areas of relief since the Paleozoic (Caputo, 1984), and the Iquitos and Gurupá arches first evolved during the Mesozoic (Putzer, 1984; Dumont et al., 1991). The Iquitos arch seems to mark the cratonic boundary and is probably the result of lithospheric flexure due to the loading of the Andes (Caputo, 1991). Dumont et al. (1991) concurred with this view and also concluded that, after alternate periods of uplift and subsidence, the Iquitos arch has been uplifted since the beginning of the Quaternary, resulting in terraces 30 m above present river floodplains. Caputo (1991) presented evidence for substantial tectonic deformation for the basins between the Iquitos and Purús arches and south of the Jutai arch. Although no detailed analysis was provided, Caputo (1991, p. 249) suggested that the stresses that generated the structures along the Solimões megashear [also generated] other similar structures at distances far to the east in the Amazon basin.”

It is not known whether the Brazilian arches are currently deforming. However, Dunne, Mertes, R. H. Meade, and J. E. Richey (unpub data) found a consistent pattern of steepening channel gradient (Fig. 2B) as the main stem of the Amazon River crosses the approximate positions (Fig. 1 and Table 1) of the three eastern arches. The water-surface gradient decreases as the main stem of the Solimões crosses the approximate positions (Fig. 1 and Table 1) of the three eastern arches. The water-surface gradient decreases as the main stem of the Solimões crosses the arches first evolved during the Mesozoic (Putzer, 1984; Dumont et al., 1991). The Iquitos arch seems to mark the cratonic boundary and is probably the result of lithospheric flexure due to the loading of the Andes (Caputo, 1991). Dumont et al. (1991) concurred with this view and also concluded that, after alternate periods of uplift and subsidence, the Iquitos arch has been uplifted since the beginning of the Quaternary, resulting in terraces 30 m above present river floodplains. Caputo (1991) presented evidence for substantial tectonic deformation for the basins between the Iquitos and Purús arches and south of the Jutai arch. Although no detailed analysis was provided, Caputo (1991, p. 249) suggested that the stresses that generated the structures along the Solimões megashear [also generated] other similar structures at distances far to the east in the Amazon basin.”

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Although not measured, the arches may be undergoing active deformation. For example, the structures may have been active since the Miocene, because the Andean orogeny has altered the structural character of the entire Amazon basin. The impact of this orogenic loading may extend east of the Iquitos arch in the form of reactivation of structural features that originally developed in response to earlier plate movements and attendant stresses. Continental deformation on the scale of 1000 km from subduction zones (Mitrovica et al., 1989) and first flexural nodes of the lithosphere on the scale of hundreds of kilometres from mountain belts (Karner and Watts, 1983) have been predicted from models of subduction and isostatic adjustments to loading. Stratigraphic and structural data for the Sabine uplift, a structural arch in eastern Texas and northern Louisiana, show that it was reactivated several times, resulting in ~0.1 mm/yr of uplift since the mid-Cretaceous (Nunn, 1990). Possible mechanisms for reactivation and therefore continued uplift of cratonic arch structures through changes in the continental lithosphere include thermal rejuvenation, new horizontal stresses, long-term viscous relaxation, or new extensional faulting (Nunn, 1990).

Local tilting and fracturing of the valley floor along the Amazon main stem and floodplain in Brazil that are apparently not associated with the
Figure 2. (A) Schematic illustration of observed along-stream pattern of channel-floodplain geomorphology and valley width. Brackets with “tilt” indicate approximate extent of tilting deformation of valley. JA—Jutaí arch, PA—Purús arch, MR—Madeira River confluence, and GA—Gurupá arch. (B) Low-water channel gradient based on Seasat radar altimetric data reported by Guzkowska et al. (1990). Data collected between July 27 and August 9, 1978, with a reported precision of tens of centimetres. The orbit paths for the 15 elevation data with the highest accuracy were replotted on the Radambrasil (1972) images and Operational Navigation charts for Peru. Corrected river distances were combined with the elevation data to compute water-surface gradients (Mertes, unpub. data). The data show the abrupt decrease of the water-surface gradient as the river crosses from the sub-Andean foreland into Brazil and the irregular pattern as it crosses Brazil. (C) Net channel storage of coarse and fine sediment based on sediment budget for channel reaches (Dunne, Mertes, R. H. Meade, and J. E. Richey, unpub. data). Positive values indicate deposition and negative values indicate erosion.
arches also affect the development of the channel-floodplain system. Tricart (1977), Iriondo (1982), and Iriondo and Sugio (1981) interpreted the presence of tilted drainage networks, beheaded streams, and patterns of undated alluvial deposits to be evidence for tectonic activity along the Amazon valley. In particular, Tricart (1977) suggested that the progressive development of terraces between the Japurá River confluences and Itapeua (Fig. 1) has been caused by the southward tilting of the northern valley. The tilting has caused the main stem of the river to lodge against a scarp along the southern edge of the floodplain. Tricart also proposed that the presence of enormous lakes at the mouths of several Amazon tributaries (Negro, Tapajós, Xingu) is in part due to subsidence along major faults. Drainage networks oriented in a northeast and northwest direction may also reflect deep-seated basement fracturing that has continued to disturb the overlying sedimentary rocks (Sternberg and Russell, 1952).

Inferences that structure and tectonic activity are influencing the channel-floodplain systems in the Amazon basin have been based primarily on sparse stratigraphic and geomorphic evidence. Sternberg and Russell (1952) listed the dates of several earthquakes that have been reported in the basin since the seventeenth century. Without precise geodetic or seismic measurements it is not yet possible to prove that there has been recent tectonic movement. However, our interpretation of tectonic influence is consistent with either past or continuing deformation.

Recent Geologic History. The Amazon lowland is dominated by a vast alluvial plain surrounded by Quaternary and Tertiary terraces. The western Amazon basin in Peru was described in detail by Salo et al. (1986), Räsänen et al. (1987, 1990, 1991), Dumont and Garcia (1991), Dumont et al. (1990, 1991), Neller et al. (1992), and Kalliola et al. (1991, 1992, 1993), who discussed the relations among long-term patterns of river migration, floodplain development, tectonics, and forest diversity. For the Brazilian Amazon region, Sternberg (1960, 1975), Sioli (1951), Tricart (1977), Irion et al. (1983), and Johnsson and Meade (1990) described in some detail the construction of the floodplain, island development, floodplain channels, and channel migration.

Several reviews of hypotheses related to the Quaternary evolution of the eastern Amazon basin are those of Sombroek (1966, 1984), Tricart (1977), Putzer (1984), Mertes (1985), Räsänen et al. (1990, 1991), Tuomisto et al. (1992), and Kalliola et al. (1993). In general, the hypotheses concerning the evolution of the landscape range from tectonic control (Iriondo and Sugio, 1981; Iriondo, 1982) to a mix of climatic and tectonic control (Tricart, 1975, 1977, 1985), or to dominance by glacio-eustatic fluctuations during the Tertiary and Quaternary (Sioli, 1957, 1968, 1975a, 1975b, 1984; Irion, 1976a, 1976b, 1976c, 1978, 1979, 1982, 1984; Klammer, 1984; Müller et al., 1995). Most of these hypotheses are based on sparse data measured from the field, maps, and radar images (Radambrasil, 1972), and comparisons with apparently analogous glacio-eustatic effects around the world.

METHODS

Channel width, sinuosity, island area and perimeter, number of islands, and the radii of curvature of main-stem bends, floodplain channel bends, and floodplain scroll bars were measured on radar images (Radambrasil, 1972) for 100-km-long reaches of channel. These images have a 1:250 000 scale, 16 m pixel resolution, and were recorded during low-water periods in the years 1971 and 1972. Channels and islands narrower than 1 mm (250 m) on the images were not included in the measurements. Channel width was computed as the average width of a single channel in reaches where the river has only one channel. Sinuosity was computed as the main channel thalweg length over the valley length. Floodplain width is the average distance across the alluvial surface. The boundary of the alluvial surface was defined as the innermost boundary of either Quaternary or Tertiary terraces designated Apf, t, and Tb on Radambrasil sheets (Radambrasil, 1974, 1977, 1978). The circularity index for islands is the ratio of the measured total island perimeter to the calculated total island perimeter per section if all the islands were circles of the same area.

The radius of curvature of a bend was measured as the radius of the smallest circle containing the arc of the bend. On the modern channel, the arc was measured at the center line of the channel; on the floodplain the arc was measured at the center line of the levee. Data on the lakes were provided by S. Sippel (1994, personal commun.), and the methods for their measurement were described by Sippel et al. (1992).

The low-flow water depth was computed as the average per reach of all of the depths on the most recent editions (1970, 1979, and 1980) of Brazilian Navy navigation charts (Marina do Brasil, 1970–1980). These depths were originally measured at different river stages from 1967 to 1979 and were converted to low-water depths for the charts. The depths are well distributed along the channel length, although in some reaches more measurements were taken in shallow sections, because the intent of the maps is to help pilots avoid shoals during low water.

Figure 3. Example of channel migration on the Amazon River, 1971–1972 to 1980. Migration of this bend was documented from an overlay of 1972 Radambrasil image SA-19-ZB and 1980 Brazilian Navy navigation chart number 4112B (Marina do Brasil, 1974, 1977, 1978). Maximum migration at the apex of this bend for this time period was ≈140 m/yr or 3%/yr of the average channel width.
Because of this sampling bias the computed average depth may underestimate the average low-water depth in some reaches.

Channel changes were measured from two sets of maps (see example in Fig. 3). For the section of the river from Vargem Grande to Manacapurú (Fig. 1), channel and bar margins were traced from radar images recorded in the low-flow season of 1971–1972 (RadaAmBrasil, 1972). The radar images were projected to a scale of 1:100 000 to match the scale of the 1979–1980 edition of 1:100 000 Brazilian Navy navigation charts (Marina do Brasil, 1970–1980). These charts are new editions based on the RadaAmBrasil images and ship surveys and include revisions through 1979 and 1980. These two sets of data were the most accurate available for this reach of the river. For the reaches of the river downstream of Manacapurú, an overlay was constructed of radar images from the RadaAmBrasil project and of revised 1980 editions of 1970 and 1972 navigation charts. The revised 1980 editions of the navigation charts include revisions for channel movements that were current as of 1980. The 1970s editions of the Brazilian Navy navigation charts (Marina do Brasil, 1970–1980) were originally based on aerial photography and ship surveys, but not on radar images. Therefore, measurements of channel change for the sections of the river downstream of Manacapurú are considered less accurate than the data for the reaches upstream of Manacapurú, because there is a greater possibility that the measurements include apparent differences in the channel that actually are due to differences in the mapping techniques. The channel change measurements were computed as the total land area eroded or deposited, divided by the total channel area between the low-water banks of the main river channel in 1971–1972, and divided by the approximately 8 yr during which change occurred. It was not possible to assess errors associated with paper shrinkage and other distortions for both sets of overlays. Therefore, to corroborate the quantitative analysis, a qualitative analysis of overlays of historical maps and more recent remote sensing images was done.

To characterize bank geometry and the texture of floodplain sediments, field measurements were made at 20 sites along the main channel from Vargem Grande to Óbidos during low water in 1988 and 1991. Banks were classified as one of three types on the basis of the morphometric characteristics of the bank. Steep, nonvegetated, cut banks were considered erosional. Steep, well-vegetated banks were considered stable. Low-gradient banks with grass cover were considered depositional. Elevation measurements were made with a tape and Abney level along a transect perpendicular to the channel, using the water surface of the main channel as the reference elevation. The accuracy of the surveying method was estimated to be ±0.30 cm over 200 m with an elevation change of several metres, based on one resurveyed transect. At most survey points the soil beneath the duff layer was sampled with a 2-cm-diameter soil auger. The sample core was 29 cm long; the top 4 cm and bottom 3 cm were discarded. Samples were air dried and returned to the laboratory for standard particle-size analysis using sieve weights for sand fractions (see Mertes and Meade, 1985, for a detailed description of method) and hydrometer analysis for silt and clay (American Society for Testing and Materials [ASTM], 1984).

Most of the results are shown in figures where the reference distance is kilometres downstream from Iquitos. Many of the data were measured along reaches of ≈100 km in length. We normalized these data by reach length to compare different reaches.

ANALYSIS OF RESULTS

Channel Features

The Amazon River in Brazil is typically an anastomosing river (usage, Knighton and Nanson, 1993). Over a length of 2500 km the average depth at low water increases from 10 to 20 m, and the single-channel width increases from 2200 m to an average of 4500 m; the maximum is 6000 m (Fig. 4). The width-depth ratio (W/D) does not change significantly downstream; the average is 210, and the smallest values for the reaches are between Itapeua and Iquitos (1248–1704 km), and the greatest values for the reaches are between Anori and Manacapurú, ≈1900 m (W/D = 260).

To determine the relationships among river depths, bank heights, and maximum flood heights, we used the height of the river banks from the bank surveys. The surveyed bank heights were adjusted to a low-water surface reference in order to compare the bank heights to each other and to the maximum flood height measured at nearby gaging stations. The maximum flood height was also referenced to the low-water surface. Figure 5 shows the results from these calculations, where typical bank heights are 11 m in the upstream reaches, 10–11 m in the middle reaches, and 7–8 m in the downstream reaches. The maximum flood height decreases from 12 to 13 m in the upstream and middle reaches to 7.5 m at Óbidos (2750 km). Figure 5 also shows the difference in height between the top of the bank and the maximum measured flood. This difference is 1.5 m in the reaches between Tupé and Itapeua (1248–1704 km) and the reaches between São José do Amatari and Parintins (2228–2631 km). In the other reaches the freeboard is <1 m. These data on bank and maximum flood heights indicate that the banks are relatively lower in the reaches between Jutica and Itapeua (1248–1704 km) and between São José do Amatari and Parintins (2228–2631 km). Therefore, in these reaches, the maximum floods top the banks with relatively deeper flows than in other reaches.

The texture of the bank material was found to be more variable along any one transect than along the entire study reach (Mertes, unpub. data). Figure 5 shows the downstream trend in the percent sand of both the erosional and depositional banks, based on averaging data across transects. The percent sand ranges from ≈10% to nearly 20%. As the sand fraction varies, the clay fraction most consistently varies,

![Figure 4. Average depth and width of Amazon River main stem for low water stage. JA—Jutia arch, PA—Purús arch, MR—Madeira River confluence, and GA—Gurupá arch.](image)
and the silt fraction remains relatively constant at 65% for depositional banks and 70% for erosional banks. The most significant trend is an increase in the sand proportion downstream of the Madeira River confluence at 2300 km.

The along-channel consistent width to depth ratio and homogeneous bank texture do not correlate with the variation in sinuosity of the river (Fig. 6). In contrast, based on Student’s t statistic (Zar, 1974) for a linear regression, there is a positive correlation between floodplain width and sinuosity, which has probability $P < 0.001$. The maximum sinuosity of 1.7 at 1400 km was measured in the reach that also has the maximum valley width of nearly 80 km. Both upstream and downstream of these maximum values the sinuosity and valley widths decrease. The river is nearly straight for 350 km from Jutica to Anorí (1528–1885 km), but then increases in sinuosity downstream as the width of the alluvial valley increases downstream from Manacapuru (2031 km). The narrowest reach of the valley, averaging <20 km, is 100 km long in the vicinity of Manacapuru. The asymmetry of the floodplain, that is, the proportion of the floodplain on either side of the river, also changes from upstream to downstream (Fig. 6) without any clear correlation to floodplain width. In the reach between Tupé and Itapeua (1248–1704 km) virtually 100% of the floodplain is north of the river.

Historical Change

Figure 8 shows the magnitude of channel change for the years between 1971–1972 and 1979–1980 for the main channel between Vargem Grande and Óbidos. The values were computed as the total land area eroded and deposited, divided by the total water surface area between the banks of the main river channels, and divided by the 8 yr over which the change occurred. In general, the percentage of erosion recorded is higher than deposition. This pattern does not imply that
Volums of erosion exceed those of deposition, because the mapping of new bar features does not incorporate differences in elevation between new bars and eroding banks or the sediment being deposited on older floodplain surfaces. The total rate of channel change generally decreases from upstream to downstream until it increases again downstream of the Madeira River confluence (2,300 km), only to decrease again in the reaches just upstream of Óbidos. A maximum rate of channel migration of ≈140 m/yr, or ≈3% of the average channel width, was recorded at the apex of the bend shown in Figure 3.

In addition to the along-stream patterns in channel change rate, three distinct types of channel change have been observed. A migrating main channel bend (Fig. 3) is most often found in the upstream reaches. Migration of floodplain channels was also observed throughout the study area for the period between 1971–1972 and 1979–1980 and was previously described by Sternberg (1960). The third type of change that was observed is change in islands. The percentage of total channel change that was due to changes in islands is shown in Figure 8. In most reaches, even reaches with migrating bends such as shown in Figure 3, >50% of the channel change occurred as changes in islands. In the reaches of the river at ≈1,400 km and 1,600 km, changes in islands accounted for >90% of the total change.

In order to verify the 8 yr record of channel change, older maps and records were qualitatively compared for evidence of channel change (Figs. 9, 10, and 11). Only fragments of maps could be pieced together due to inaccuracies in orientation and scale. Figure 9 shows the pattern of long-term channel change between Xibeco (1,051 km) and Tupé (1,248 km). The migration of the bends in this reach follows the scroll-bar floodplain, which probably represents an area of recent channel migration. The rate of erosion of the terrace along the south bank near Fonte Boa can be calculated from historical records. Both Herndon (1853, p. 248) and Bates (1962) reported that Fonte Boa was 2 mi (3.2 km) away from the main Amazon channel, on the banks of a floodplain channel named Cayhiar-hy. To quote Bates (1962, p. 386), “... arrived at Fonte..."
Boa; a wretched, muddy, and dilapidated village, situated two to three miles from . . . the main Amazons. As of 1984 the village church had to be moved before it slid into the water (R. H. Meade, personal observation). The rate of migration of the main channel would therefore have been \( \frac{3000 \text{ m}}{120 \text{ yr}} \), yielding \( 25 \text{ m/yr} \) or 1% of the channel width per year. These long-term rates are within the range of the short-term rates measured in this reach. Recently acquired Landsat images (1988) and U.S. Space Shuttle photographs (various dates, 1988–present) indicate that the observed migration estimated from both the long-term and short-term records is continuing.

In contrast to Figure 9, Figure 10 shows minimal change between Manacapuru (2031 km) and São José do Amatari (2228 km) over a 20 yr period. This corresponds to our lower, short-term rates, and also to the minimal rates of change estimated by Sternberg (1960). The \(^{14}\text{C}\) dates of levee deposits on Careiro Island suggest that the island has been at its present location for hundreds of years (Sternberg, 1960), and that the only significant change in this area since the early 1900s has been the development of a floodplain channel directly south of Careiro Island at its westernmost tip.

Figure 11 shows that the long-term rate of channel change is slightly greater in the reaches of the river downstream of the Madeira River confluence (2300 km) compared to the rates near Careiro Island. This pattern of increased channel migration in the sections downstream of the Madeira River confluence was also measured from the short-term record.

The high rates of channel change measured for the upstream reaches are comparable to rates reported for other reaches of the Amazon River and for other large, alluvial rivers. Salo et al. (1986) reported rates of 12 m/yr for a 13 yr period on meander bends of the Manu River (a tributary of the Amazon River) in Peru. On the basis of an analysis of Landsat images dating from 1979 to 1983, Kalliola et al. (1992) reported rates of migration as high as 400 m/yr, or 37% of the channel width, for the Amazon River in Peru. Drago (1990) reported rates ranging from <50 m to >200 m per year on sections of the Parana River in Argentina, based on records from the early 1900s to the present. The maximum annual rate of lateral migration measured in our study, 140 m or 3% of the channel width (Fig. 3), compares with the Kesel et al. (1974) report of 40.5 m/yr, or 4% of the channel width, of lateral migration for a bend on the Mississippi River. Our average rates of channel change are even within the range of 0.1%–5%/yr reported by Lewin et al. (1977) for gravel-bedded streams in England.

Figure 8. Channel change in Amazon River during the years between 1971–1972 and 1979–1980. The channel change is reported as the land area reworked per year over 8 yr, that is, eroded, deposited, or total change, expressed as a percent of the total active channel area which was measured as the area between the main channel banks in each reach. Shaded boxes at top of graph show the percentage of the channel change that was due to island movement. JA—Jutaí arch, PA—Purús arch, and MR—Madeira River confluence.

Figure 9. Channel change since 1853 between Xibeco and Fonte Boa. The 1853 map was drawn by Herndon (1853) as he traveled the Amazon River by canoe, and should be regarded as very approximate. Even when standing in his canoe, Herndon would not have been able to perceive the true degree of curvature of the river. His horizon would have allowed him to see only a small segment of any given bend at any time, and his portrayal is likely to have underestimated river curvature. The ca. 1940 map was drawn by a Brazilian Army detachment supposedly in 1934 as part of reconnaissance for the conflict of Leticia, according to the Instituto Brasileiro de Geografia e Estatística (IBGE in Rio de Janeiro), and was supposedly based on trimetrigon aerial photographs. However, in 1942–1943 the U.S. Army Air Corps also took trimetrigon aerial photographs of the Amazon River to draw maps for aerial reconnaissance (Natural Resources Unit, 1966). The 1942–1943 maps were printed by the U.S. Defense Mapping Agency, St. Louis, Missouri, and they are almost exact replicas of the 1934 maps. It may be that both sets of maps were based on the same set of photographs, hence the date ca. 1940 has been applied to these maps. The 1971–1972 map was traced from radar images from Radambrasil (1972).
Floodplain Features

The Amazon floodplain is a complex mosaic of lakes and lake deposits, floodplain channels, scroll bars, and overbank deposits. According to Sippel et al. (1992), 11% of the 92 400 km² of the main-stem floodplain in Brazil is covered by 6510 lakes >100 m across, not including the largest ria lakes (tributary mouthbay; usage of Sioli, 1957). Like islands, lakes become rounder downstream (Figs. 7D and 12C). However, unlike island area, which showed a correlation to increased width of the river, lake area (Fig. 12A) does not show a significant correlation to floodplain width (Fig. 12B), suggesting that the processes of lake formation are decoupled from the processes controlling the floodplain width. In particular, in the upstream reaches (c, 1095 km, and d, 1357 km, in Fig. 12B) where the floodplain is widest, the lakes are small and are confined to narrow swales between scroll bars. In contrast, the larger lakes tend to be in the downstream reaches, regardless of floodplain width, and have less-well-defined boundaries. The largest lakes are just downstream from Óbidos (2750 km) and are as much as 65 km across (Melack, 1984). The along-stream pattern in number of lakes is also irregular. The number of lakes increases between 1000 km and 1700 km (approximately Xibeco to Itapeva), decreases in the downstream direction to São José do Amatari (2228 km), increases again after the Madeira River confluence (2300 km), and then the lakes disappear just downstream from the Tapajós River (2900 km) (Klammer, 1984).

The Amazon floodplain is also covered by a

Figure 10. Channel change since 1952 (map from Sternberg, 1960) to 1971–1972 (Radambrasil, 1972) between Manacapuru and São José do Amatari. Mixed floodplain represents areas covered equally by scroll-bar topography and rounded lakes.

Figure 11. Channel change since 1900 between São José do Amatari and Paurá. The 1900 map was drawn by members of the British Telegraph Agency in association with maintenance of telegraph lines between Manaus and Parintins (map supplied by H. O. Sternberg). The 1971–1972 map was traced from radar images of Radambrasil (1972). Mixed floodplain represents areas covered equally by scroll-bar topography and rounded lakes.
dense network of floodplain channels. In our work we have distinguished floodplain channels from the main channel and its anabranches by defining floodplain channels as channels that have approximately an order of magnitude smaller discharge than the main channel flow and are typically not active during low-water periods. Figure 13 shows the width and depth distributions for 105 of these channels measured on the low-water 1980 navigation charts for reaches of \( \geq 100 \) km. Generally, the width of the largest floodplain channels increases in the downstream direction from 800 to 2000 m, although the smallest floodplain channels (100 m wide) were observed in every reach. Depths were estimated over tabular sills at the entrance to the floodplain channels, on the assumption that these sills control the flow entering the channel. The depth showed no correlation to downstream distance.

As the main channel, anabranches, and floodplain channels migrate, scroll bars are left behind on the floodplain surface. Figure 14 shows typical scroll-bar patterns found in the upstream reaches between Vargem Grande and the Japurá River confluences. The radii of curvature of the scroll bars decrease toward the center of the scroll bar complex (a–d in Fig. 14). In the downstream reaches the scroll bars tend to be longer, farther apart, and straighter than the upstream bars.

Empirical relationships between the width of an alluvial channel and the radii of curvature of bends in that channel have been documented by several authors (see Richards, 1982, for a review). We used the radii of curvature of channels and floodplain features to help identify the places where the floodplain scroll-bar features were deposited. Downstream of the Madeira River confluence the scroll bars are less distinct and tend to be straight along their preserved length, thus yielding infinite radii of curvature; they were not included in this analysis. Figure 15A is a frequency plot of the radii of curvature of all the active main channel bends and bends in floodplain channels upstream of the Madeira River confluence. The mean plus one standard deviation for the main channel is 6.7 + 3.1 km, and for the floodplain channels it is 1.9 + 0.7 km. According to the Mann-Whitney test, a nonparametric statistical ranking test, these two populations are significantly different at a confidence level >99.9%.

The frequency distribution of radii of curvature for a representative sample of outer floodplain scroll bars (i.e., the features labeled “a” in Fig. 14) and inner floodplain scroll bars has been plotted (Fig. 15B). The mean plus one standard deviation for the outer floodplain scroll bars is 6.2 + 2.6 km, close to the values for the main channel bends. The mean value of the radii of curvature of the inner floodplain scroll bars is 3.2 + 2.6 km and appears to incorporate values that scale with both the floodplain and main channels. The outer scroll bars were originally formed by the main channel, but many of the inner scroll bars were deposited in the bends of floodplain channels, which are significantly smaller than the bends of the main Amazon channels.

DISCUSSION

The Amazon River and floodplain in Brazil display an along-stream trend in channel-floodplain geomorphology and channel behavior (Fig. 2A), largely controlled by transfer and storage of sediment from the Andes to the coast. Dunne, Mertes, R. H. Meade, and J. E. Richey (unpub. data) have developed a sediment budget for the Brazilian Amazon River that includes the following inputs: bed load, suspended sediment.
load, sediment from tributaries, and sediment contributed by erosion of bank material. The outputs include bed load, suspended sediment load, loss to floodplain channels, overbank deposition, and sediment lost to new bar or island formation. The summation of all of the input and output terms is presented in Figure 2C as the net storage of sediment per kilometre. In addition, as depicted in Figure 2A, the along-stream change in channel-floodplain geomorphology is not smooth, because the basinwide pattern is overlaid by features produced by intracratonic tectonics, local patterns of deformation, and major tributary inputs.

**General Along-Stream Geomorphic Patterns**

In the upstream reaches (Figs. 2A and 16A), from 863 km to 1528 km (Vargem Grande to Jurua), the water-surface gradient increases slightly (Fig. 2B), promoting erosion of sand (Fig. 2C). The sand erosion also corresponds to high rates of bank and island erosion (Figs. 8 and 9). These high rates probably promote or are the result of the high sinuosity of the river in the upstream reaches (Fig. 6). As a result of rapid channel migration, both lakes and islands are small and streamlined. Lakes tend to be confined to swales between scroll bars as in “meander scroll lakes” (usage, Blake and Ollier, 1971). Islands tend to be shortlived, and therefore rarely attain a large size, due to the rapid change in the channel position.

On the floodplain surface the upstream scroll bars appear fresh, and a large proportion of them are the same size as the bends of floodplain channels rather than the larger main Amazon channel (Fig. 16B). Figure 17 depicts a schematic model for the development of the scroll-bar complexes that cover the upstream floodplain (Fig. 14). As the main channel migrates, bar deposits are left as a series of scroll bars on the scale of the main channel (Fig. 17A). As time passes, the bend migrates farther, and floodplain channels also migrate, reworking the deposits of the large bend and leaving behind smaller-scale scroll bars (Fig. 17B). Eventually the main channel bend is cut off by a more direct channel, and the old channel begins filling with sediment. Subsequent to the cut off, water continues to flow through floodplain channels in the bend area, and they rework the surface deposits (Fig. 17, C and D). If enough time passes, most of the surface features from the larger-scale bend can be erased, and the smaller-scale floodplain channel scroll bars will dominate the morphology of the floodplain (Fig. 17E). The resulting scroll-bar complexes show arcs of two distinct sizes, outer arcs on the scale of the main channel and inner arcs on the scale of the floodplain channels (Figs. 14 and 16A). Scroll topography on the Orinoco floodplain (Colonnello, 1990) also comprises scroll bars at different scales.

In the middle reaches of the river we observe a transition from upstream to downstream features (Fig. 16B). In the reaches from 1528 to 2228 km (Itapeua to São José do Amatari), the river tends to be straighter in a narrower valley, migration rates are slower, scroll bars cover proportionally less of the floodplain, and, on average, islands are slightly larger. Scroll lakes are mixed with rounder, larger lakes. There is fairly consistent deposition of sand (Fig. 2C) through this middle section as the river gradient decreases (Fig. 2B).

In the downstream reaches from São José
do Amatari (2228 km) to the Tapajós River (2850 km) confluence, the Amazon River is fairly straight and migrates slowly compared to the upstream reaches (Fig. 16C). Scroll-bar surfaces are blurred and hundreds of broad, shallow, patchy lakes cover the floodplain. These features suggest that the construction of the floodplain is controlled by overbank deposition of fine material, with the main channel building levees that tend to confine the migration of the main channel and floodplain channels. Occasionally, floodplain channels migrate across lakes creating lake deltas (Fig. 16C) or “sedimentary jetties” (usage of Bird, 1964, as described by Blake and Ollier, 1971). Comparison of the less-well-defined lake boundaries in the downstream reaches to the meander scroll lakes of the upstream reaches indicates that the lake depressions may be due to local subsidence of the floodplain. Any bounding levees are gradually being buried by overbank sedimentation. The blurred appearance of the scroll complexes in these downstream reaches also contrasts with their fresh appearance in upstream reaches.

Blurring of the scroll bars may result from the combined effects of the main channel migrating slowly and floodplain channels being relatively confined, and therefore migrating slowly; hence, fresh new scroll complexes are slowly produced. Over time the old scroll surfaces are buried by sediment decanting from overbank flows.

The delta plain of the river system extends downstream of the Tapajós River confluence to the estuary. The sinuosity is essentially 1.0, and the number and size of islands and lakes decrease dramatically. In contrast to the reaches immediately upstream, in this reach the shallow lakes and floodplain channels have been filled (Klammer, 1984), perhaps by sedimentation from overbank flows, while the main channel has remained straight and locked in position. A sediment budget for this reach suggests that 300–400 Mt/yr of sediment deposition or 0.4 Mt/yr per km (Fig. 2C) could be responsible for the rapid filling of any lakes that may have formed (Mertes, 1985; Mertes and Dunne, 1988, Fig. 3; Dunne, Mertes, R. H. Meade, and J. E. Richey, unpub. data). Recent discovery of fluid muds on the continental shelf (Kineke and Sternberg, 1995) does not substantively alter this budget (Nittrouer et al., 1995) because the fluid muds are typically resuspended material and are not exported at high rates away from the shelf.

**Influence of Structural Arches**

The cratonic interior of the Amazon basin is interrupted approximately every 1000 km by structural arches (600–1300 km between arches;
Table 1 and Fig. 1) that traverse the main axis of
the river system and form the boundaries of ap-
parently subsiding basins. The river hydraulics in
the form of the low-water surface slope appear to
be responding to the presence of the three arches
in Brazil; these are low water-surface gradients
upstream of the arches, increasing water-surface
gradients as the river crosses the apex of the arch,
and then a rapidly decreasing water-surface gra-
dient on the downstream limb of the arch. Simi-
lar patterns have been described for other alluvial
and bedrock channels, where high uplift rates
have been estimated (Merritts and Vincent, 1989;
Bullard and Lettis, 1993) or more resistant lithol-
ogy (Hack, 1973) occurs.

Assuming that the water-surface slope is pro-
portional to the boundary shear stress responsi-
ble for transport of sediment, one can predict
erosion in zones of increasing surface slope and
deposition in zones of decreasing surface slope.
In a downstream direction, the river erodes
course material as the slope increases in the
reaches between Vargem Grande and Jutica
(863–1248 km). Between Jutica and Itapeua the
slope decreases and both coarse and fine sedi-
ment are deposited (see next section regarding
local deformation). The slope increases again as
the river crosses the Purús arch (2000 km), and
there is a corresponding increase in coarse sedi-
ment erosion. As the river crosses the arch, the
slope decreases, and deposition of coarse and
fine material occurs.

As the river approaches the Gurupá arch in
the delta plain, the surface slope again increases
slightly. The estimated deposition rates of
0.4 Mt/yr per km (Fig. 2C) could result from de-
creasing surface slopes on the downstream limb
of the Gurupá arch. This reach of the river is ap-
proximately at sea level. The effect of the Holoc-
enne rise in sea level could have been to en-
hance the influence of the arch and graben,
because the increased base level would initially
further reduce water-surface slopes.

In addition to influencing the patterns of hy-
draulics and sediment transport, the arches are
associated with narrowing of the alluvial valley.
The valley width is <30 km near the Jutai arch,
<20 km near the Purús arch, and <40 km ap-
proaching the Gurupá arch. As described herein,
a correlation exists between the narrowest sec-
tions of the alluvial valley and the lowest chan-
nel sinuosity. Aside from its upstream reaches,
the river is also unusually straight along most of
its length, according to empirical relationships
between width and bend amplitude for other al-
luvial rivers as reported by Lewin and Brindle
(1977) and Leopold and Wolman (1957). From
these empirical relationships based on channel
width, predicted Amazon bend amplitudes
should range from 20 km upstream to 60 km
downstream. Only two modern bends have am-
plitudes >20 km. They are both upstream in the
widest part of the valley. Hence, the river is ap-
parently freely meandering only in the upstream
reaches and elsewhere is confined. Whether the
arches are restricting the migration of the chan-
nel through influence on the valley width, or the
valley is narrower because of reduced channel
migration, is not clear. In either case, a combina-
tion of reduced vertical incision or lateral migra-
tion relative to activity upstream and down-
stream could produce the geomorphic patterns
spatially associated with the arches.

Influence of Local Deformation

The clearest example of the influence of local
deformation not associated with the arches is
in the reach between Jutica and Itapeua

Figure 16. (A) Typical scroll-bar floodplain along upstream reaches of Amazon River near
Xibeco (1051 km). (B) Typical transitional floodplain in middle reaches of Amazon River near
Itapeua (1704 km).
(1528–1704 km, Fig. 2A), where the water-surface slope is high and then abruptly decreases (Fig. 2B). Nearly 100% of the floodplain is north of the main channel (Fig. 6), and the river runs nearly straight as it carves a path at the base of the terraces forming the south bank. Tricart (1977), Iriondo (1982), and Iriondo and Sugio (1981) described this as a southerly tilted basin extending at least as far north as the Japurá River. The impact of the tilted valley on channel behavior and geomorphology is significant: the river is straighter, deeper, and narrower, and the water-surface slope is high. These patterns are observed in part because flow is being forced to the south edge of the valley and the river cannot erode the terraces rapidly enough to form bends or even to widen the channel. As the river leaves this tilted section downstream of Itapeua, the water-surface slope decreases. As the river has carved its new position on the south bank, it also has cut across several blocked valley lakes (Fig. 16B) and has changed the position of the confluences of the southern tributaries.

In this tilted reach there is also evidence that channel migration has been achieved partially through avulsions of the main channel. Figure 17 shows the proposed development of typical scroll complexes on the Amazon floodplain. As the scroll complexes develop through reworking of the surface deposits by floodplain channels, it is unlikely that oxbow lakes on the scale of the main channel would remain, in contrast to many river systems where oxbow lakes are an important floodplain feature (e.g., the Mississippi River; Fisk, 1944). However, if the channel were to avulse to a distant location, then the floodplain channels would no longer receive flood waters, and it would be possible for an oxbow to remain on the floodplain surface. The only large-scale, oxbow-type features on the Brazilian Amazon floodplain are located north of Xibeco (1051 km) and north of Itapeua (1704 km). The oxbow lake north of Xibeco (Fig. 18A) lies along an old channel belt (Tricart, 1977; Iriondo, 1982; Iriondo and Sugio, 1981) and is the same size as the main channel bends. Between the northern channel belt containing the oxbow lake and the present channel, the floodplain surface is smooth, suggesting that recent channel migration was not continuous across its surface. Both the relatively smooth intervening floodplain surface and the presence of the oxbow lake suggest that the channel avulsed ~40 km to its present location. Figure 18B shows that the river has cut across the blocked valley lake near Itapeua as it carved a tortuous bend south around older terrace deposits. North of the terrace deposits are signs of older channel deposits and some remnant oxbow-like lakes. All of this evidence suggests that the river may have avulsed to its southern position, perhaps captured by the former drainage of the blocked tributary. Without the south-tilting deformation, which may be the cause of these avulsions, the oxbow-type lakes may not have been preserved on this upstream part of the floodplain. This evidence also suggests that the tilted reach extends from Xibeco to Itapeua (1051–1704 km).

**Influence of Major Tributaries**

Local variability in channel behavior and floodplain geomorphology could also be the result of input from the major tributaries, as has been suggested for much of the Orinoco River and floodplain (Hamilton and Lewis, 1990). However, unlike tributaries of the Orinoco, most of the tributaries of the Amazon have much smaller flows and sediment loads than the main channel. Therefore, their individual influence on the main channel behavior and floodplain morphology is difficult to assess, aside from the overall effect of downstream dilution of the sediment load and the dramatic appearance of their large mouthbays. However, we can discern the inde-
rapid rates of channel migration. These characteristics indicate that the Madeira and the number of islands (Fig. 7A) increase. The Japurá River confluence is in the middle of the tilted reach, and the location of the confluence may be controlled by the deformation. In turn, as the Japurá migrates to the south and builds its floodplain, it may be contributing to the overall tendency for the main Amazon to impinge along the southern edge of its alluvial plain.

The Madeira River, with its confluence at 2300 km, can carry half of the sediment load of the main Amazon channel (Meade, 1985, 1994; Meade et al., 1985; Dunne, Meade, and J. E. Richey, unpub. data). Downstream of the Madeira River confluence the banks of the Amazon tend to have a higher proportion of sand (Fig. 5), and the number of islands (Fig. 7A) increase. These characteristics indicate that the Madeira River may be imparting an “upstream” character to the system as it provides a coarser sediment load from the Andes that is available for more rapid rates of channel migration.

**Floodplain Aggradation, Erosion, and Recycling Time**

In considering the evolution of the Brazilian Amazon alluvial landscape it is instructive to estimate long-term rates of floodplain aggradation, erosion, and recycling based on the prevailing patterns of sediment transport along the main channel. This discussion does not include the transport and deposition rates estimated for floodplain channels, which were shown (Figs. 13, 14, and 15) to represent a distinct population of channels at least an order of magnitude smaller than the main channel. In developing the sediment budget for the Brazilian Amazon River, Dunne, Meade, and J. E. Richey (unpub. data) found that the rates of main channel erosion essentially equaled the rates of overbank deposition plus the rates of deposition of new bar or island formation along the main channel. Over the entire study reach, the annual rates of exchange (erosion or deposition) between the main channel and floodplain each summed to ≈1600 Mt, for a total of ≈3200 Mt of reworked floodplain sediment. The exchange rates slightly exceed the rate of suspended sediment transport at Óbidos, which averages 1240 Mt/yr (Dunne, Meade, and J. E. Richey, unpub. data). Accounting for the local recycling of old sediments, we estimate that a large proportion of the suspended sediment passing Óbidos has passed through floodplain storage and is not freshly eroded sediment from the Andes or sub-Andean foreland. The likelihood that a high proportion of the sediment spends time in floodplain storage and is in turn weathered was confirmed by Johnsson and Meade (1990), who reported that sediments in point-bar deposits near Xibeco (1051 km) show morphological and chemical characteristics that are likely the result of several thousands of years of in situ weathering. Hence, it is reasonable to estimate that an individual particle may take thousands of years to travel the 3000 km length of the Brazilian Amazon.

As the river exchanges material with its floodplain, it is continuously recycling the sediments of the alluvial plain. Given the virtual balance between the rate of destruction (erosion) and construction (overbank deposition and new bar formation) of the floodplain, it is reasonable to use the rates of bank erosion to calculate the order of magnitude of time required to recycle the sediments of the floodplain and alluvial plain. Figure 19 shows the area of erosion calculated from the overlay of radar images and navigation charts grouped into reaches that correspond to the general pattern of along-stream variation in channel migration rates. We divided the area of the alluvial plain by the area of erosion per year to predict the time period for recycling in years. The number of years required to recycle the alluvial plain generally increases from 1000 yr in the upstream reaches to 2000 yr in the downstream reaches, with an increase to >4000 yr in the downstream reaches near Óbidos (2750 km). We do not have channel change data for the reaches downstream of Óbidos, but the geomorphic data suggest that the channel is relatively immobile, hence we predict that the recycling time in the delta plain is also >4000 yr.

For this calculation we did not include sediment transport associated with floodplain channels. As suggested by Figure 17, the floodplain channels rework the surface deposits of the floodplain and produce landforms at a smaller spatial scale than the main channel. The floodplain channels do not penetrate deeply into the alluvium, and therefore reworking would account for only a small proportion of the total recycling of floodplain sediments. In addition, for the calculation we included the entire area of the alluvial plain, and not just the modern, regularly inundated floodplain. By including the entire alluvial plain we are not accounting for the fact that in some

![Figure 17. Schematic model for development of scroll-bar complexes. See text for a complete description of the pattern development over the five stages. Compare to Figures 14 and 16A.](Image)
reaches channel migration and river-water incursion (Mertes et al., 1995) are restricted to narrow bands of the floodplain. The more distal reaches of the alluvial plain may not have been reworked within the calculated time periods. For example, although we predict a turnover time for the alluvial plain near Xibeco of \( \approx 1000 \) yr, which matches radiocarbon dates of buried wood fragments showing ages of 1180 yr (L. Pessenda and P. Camargo, unpub. data), the channel belt on the northern part of the alluvial plain that contains the large oxbow lake (Fig. 18A) probably has not been recently reworked and may be older than 1000 yr.

SUMMARY

The Solimões-Amazon River annually carries 1240 Mt of suspended sediment as it crosses the cratonic landscape of Brazil, which has been punctuated by tectonic deformation in the form of structural arches and basin tilting. Variations in river slope and transport of sediment across this landscape result in upstream reaches characterized by erosion of sand in the main channel and deposition of sediment in floodplain channels, producing an intricate scroll-bar topography forming the boundaries of hundreds of long, narrow lakes. In contrast, downstream reaches are characterized by channels restricted by stabilizing levee building, and floodplain construction dominated by overbank deposition that gradually buries scroll topography, resulting in a flat floodplain characterized by a patchwork of large, more equant, shallow lakes.

Imprinted on this along-stream geomorphic trend is the influence of basin structure and deformation. Structural arches appear to exert a primary influence on the channel-floodplain system by promoting entrenchment of the river as it passes through zones of deformation in Brazil, thus restricting channel movement. This pattern is similar to observations made by Dumont et al. (1990) for the western, Peruvian Amazon basin. Our schematic model for the eastern Amazon (Fig. 2) illustrates the spatial correlation between the narrowing of the alluvial valley as the river crosses the arches and the gradual widening of the valley on the downstream limb of the arches. This impact is clearest as the river crosses the Purús arch, where the valley narrows to \( \approx 20 \) km, the water surface gradient decreases dramatically, large amounts of suspended sediment are deposited, and yet the rate of channel migration is negligible. Hence, the overall effect of intracratonic tectonic deformation on the continental-scale Solimões-Amazon River is to create a landscape where, on the spatial scale of hundreds of kilometres, the river is confined and entrenched in its valley, is straight, and is relatively immobile.

On the basis of estimated rates of recycling of floodplain sediments due to activity by the main channel, the modern floodplain of the Brazilian Amazon could have been recycled in \(<5000\) yr, and is recycled more rapidly in the upstream than the downstream reaches. These results suggest that during the Holocene, fluvial transport in the Amazon River in Brazil has reestablished a channel-floodplain system that disposes of its sediment load in a manner controlled by tectonic features and the modern hydrology and hydraulics of the main channel, anabranches, and floodplain channels. By contrast, the more distal alluvial plain appears to be a remnant feature.
that cannot be entirely explained by modern processes. In particular, the tremendous expan-
sions of open water in the downstream flood-
plain invite questions regarding the long-term processes active in the system. For example, it is
not yet known whether this open alluvial plain is
due to evacuation of sediment during lower sea
level (e.g., Müller et al., 1995) or the result of
continuing subsidence.

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