4

Transcontinental Moving and Storage: the Orinoco and Amazon Rivers Transfer the Andes to the Atlantic*

Robert H. Meade

Research Hydrologist Emeritus, US Geological Survey, MS 413, Box 25046, Federal Center, Denver, CO 80225-0046, USA

4.1 INTRODUCTION

Large rivers are massive conveyance systems for moving detrital sediment and dissolved matter across transcontinental distances. As Potter (1978a,b) pointed out a generation ago, the large eastward-flowing rivers of South America transfer sediment over thousands of kilometres, from the leading edge (active margin) to the trailing edge (passive margin) of a drifting continent. Matching these large spatial scales of movement are the temporal scales of alluvial storage, on the order of thousands of years, that retard the conveyance of sediment from original source to ultimate sink. In the post-Pleistocene Orinoco and Amazon River basins, the original sources have been the eastern slopes of the northern half of the Andean mountain ranges. The extensive alluvial plains of the Andean foreland basin and the large tracts of floodplain along the Amazon mainstem and some of its major tributaries are the depositories in which much of the Andean-derived sediment is stored – for periods of centuries, millennia, or longer – during its eastward journey. The ultimate sinks for these sediments ('ultimate' on a multimillennial timescale) are the lowermost floodplains and deltaic regions of the Amazon and Orinoco, and the thousand-and-a-half-kilometre Atlantic coastal zone that separates the mouths of these two great rivers.

All the major parts of the story that follows have been told previously (but mostly separately), especially in the publications by Dunne *et al.* (1998), Eisma *et al*. (1991), Johnsson *et al*. (1991), Meade (1994), Meade *et al.* (1985, 1990), Mertes *et al*. (1996), Nittrouer and DeMaster (1987), Nittrouer and Kuehl (1995), Nordin *et al*. (1994), Stallard (1995), Stallard *et al*. (1990) and Warne *et al.* (2002). This chapter recounts the major components of the story in downstream sequence, from west to east across the northern half of South America.

4.2 ANDEAN SOURCES AND ALLUVIAL STORAGE

The mountainous terranes of the Andes are the principal sources of the fluvial sediment carried by the Orinoco and Amazon Rivers. Alfred Russel Wallace (1853) gave the scientific literature its initial hint of this fact in his discussion of the distinctly different river types in the Amazon basin: 'white-water', 'black-water' and 'blue-water' (changed in later usage to 'clear-water'). Harald Sioli (1957), in a paper published a century after Wallace's book, went on to point out that the large white-water rivers (so-called because of their visibly large concentrations of suspended sediment) of Amazonia had their origins in the Andes or the Andean foothills. Ronald Gibbs reiterated

---

* The US Government has the right to retain a nonexclusive, royalty-free license in and to any copyright covering this chapter. This chapter is CAMREX contribution 125.

Large Rivers: Geomorphology and Management, Edited by A. Gupta

and substantiated this fact a decade later in his doctoral dissertation research (Gibbs, 1965, 1967), for which he travelled thousands of kilometres on local river boats, sampling the suspended-sediment concentrations of the Amazon and its tributaries. He measured the greatest concentrations in the tributaries that drained either the mountains themselves or the tributaries draining the Andean-derived second-generation sedimentary terranes of the foreland basin. Later work in the other major river basins of South America – the Paraná (Ritter, 1977a,b; Drago and Amsler, 1988), Magdalena (NEDECO, 1973; Winkley *et al.*, 1994) and Orinoco (Meade *et al.*, 1990) – have borne out this generality. Subsequent and more detailed work in the Amazon Basin (Meade *et al.*, 1985; Guyot, 1993; Dunne *et al.*, 1998) has shown that, while Gibbs was correct in principle, his numbers might have been too conservative. He estimated that 82% of the sediment carried by the Amazon was derived from the 12% of the drainage area that was underlain by the Andes. Our later measurements and estimates would credit more than 90% to the Andean source. And if we consider the recycled sedimentary deposits in the foreland basins as material of ultimate Andean origin, then we can say that virtually all the modern fluvial sediment in both the Amazon and Orinoco has been derived from the Andes.

The preponderance of fluvial sediment in the world's rivers, great and small, is derived from the regions of greatest tectonism (Milliman and Meade, 1983; Milliman and Syvitski, 1992). Nearly a third of the active fluvial sediment in the world, for example, is being transported seaward by the combination of rivers [Indus, Ganga, Brahmaputra, Irrawaddy, Salween, Mekong, Red (Sông Hóng), Yangtze (Changjiang)] that drain the furrows of the great tectonic collision between the Indian subcontinent and the rest of Asia. Although notable exceptions may be found in the shale outcroppings of the Northern Great Plains of the Mississippi valley and the Loess Plateau of the valley of China's Yellow River, most of the rest of the world's fluvial sediment is being produced in tectonically active regions such as the large islands of the western Pacific and the western edges of North and South America. Although many authors have generalized this correlation by constructing graphs relating sediment yield to topographic relief, it is well to remember that the observed relation is not so much with relief itself as with a numerically less specifiable property which is the degree of tectonism. Perhaps Milliman and Syvitski said it best:

> '. . . that elevation or relief is . . . only a surrogate variable for tectonism. . . . [,and] . . . the strong correlation between sediment and topographic relief may not indicate that the second is the cause of the first, but rather that both are caused by another factor less susceptible to numerical description – namely, tectonism. It is probably the entire tectonic milieu of fractured and brecciated rocks, oversteepened slopes, seismic and volcanic activity, rather than simple elevation/relief, that promotes the large sediment yields from active orogenic belts.'
>
> (Milliman and Syvitski, 1992: pp. 539–540)

The traveller through the Andes is struck by the prevalence of tectonically oversteepened slopes and fractured rocks, massive landslides, and sediment-glutted streams. US Naval Lieutenant Lardner Gibbon, while travelling down an interior Andean valley in Peru in 1851, noted:

> 'Our road lies through a rich valley, often four miles wide, and level as a floor. The mountains on both sides are dry and unproductive, except in the ravines. The half-yearly displacement of earth is very great; during the rainy season the mountain torrents come down from the summit loaded with soil. The Juaja river flows sluggishly and serpent-like through the whole length of the valley, and creeping through the Andes, suddenly rushes off at a rapid rate, as though sensible of its long journey, by the Ucayali and Amazon, to the Atlantic ocean. The bed of the river is half a mile wide, and in the wet season is probably eighteen feet deep.'
>
> (Gibbon, 1854)

Recent examples of catastrophic-scale sediment productions from Andean slopes underlain by tectonically influenced rocks (although neither example is from the Orinoco or Amazon basin proper) are the huge deposits set in motion by the November 1985 eruption of Nevado del Ruiz in the Andes of Colombia and the massive landslides and debris flows that devastated the northern coastal towns of Venezuela in December 1999 (Pierson *et al.*, 1990; Larsen *et al.*, 2001a,b).

As they leave their narrow mountain gorges, the streams coming off the Andes flow onto river beds that are self-made. Massive amounts of sediment brought down from the mountains become the substrates over which and through which the flowing waters, with their accompanying loads of even *more* sediment, must make their ways. Once off the Andean slopes and out of the confinement of mountain-girt channels, the river-borne sediment is likely to endure many episodes of confinement and occupy many rest stops and storage compartments before it reaches its ultimate destination.

During the last century, the scientific community of sedimentologists has shown much less concern for sediment storage than it has for sediment movement. From a temporal point of view, this preponderance of interest in movement over storage is oddly displaced. Any given particle of sediment in an active river system is, at any randomly selected instant, more likely, by factors of thousands or more, to be resting quietly in storage than to be actively in motion. This preponderance of interest likely betrays the preference of most sedimentologists for the physical aspects over the chemical aspects of river sedimentation. Interesting as the physical aspects of sediment movement certainly are, equally interesting are the chemical consequences of prolonged sediment storage. For in tropical river basins, the temporal scales of alluvial sediment storage overlap the temporal scales of soil weathering. As a consequence, many of the chemically less stable minerals and rock fragments that have been hydraulically deposited as solid sediment grains in the flood plains of tropical rivers become weathered *in situ* to the point that they lose their solidity, yield up their substance to the dissolved state, and are easily carried away, ion by ion or molecule by molecule, invisibly into the percolating ground waters and flowing rivers.

4.3 ORINOCO

The Orinoco River today drains most of Venezuela and about one-fifth the area of Colombia. Flowing during earliest Miocene times between the rising Andes to the west and the Guayana Shield to the east, the ancestral Orinoco most likely debouched northward into Caribbean waters near the present site of Lake Maracaibo (Díaz de Gamero, 1996). However, the rising of the easternmost cordillera of the Andes, and its continuation into the east-west-trending ranges along the Caribbean coast during Middle Miocene times, deflected the course of the river to the east and directly into the Atlantic Ocean along the northern edge of the exposed Guayana Shield (Figure 4.1).

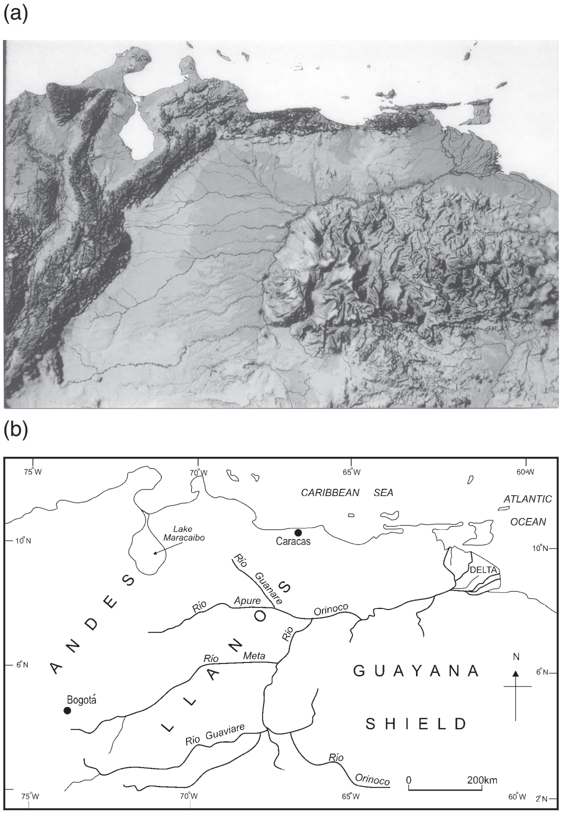

Figure 4.1 (a,b) Orinoco River basin of Venezuela and Colombia. Andes Mountains shown as dark areas along western edge. Lowland llanos (alluvial plains) separate Andes from highlands of Guayana Shield. Orinoco River flows for much of its length along border between llanos and shield. (a) Compiled from satellite imagery by Lisa Mae Olsen and Norman Bliss of US Geological Survey's EROS Data Center

The Orinoco is the most abundantly watered of the large river basins of the world. The fresh-water discharge at the Orinoco's mouth is twice that of the Mississippi, although the Orinoco drains an area only one-third as large. Averaged over their entire river basins, therefore, the landscapes of the Orinoco Basin are six times more abundantly watered than those of the Mississippi. Sediment discharge of the Orinoco, however, is less than half that of the pre-engineered Mississippi (that is, *before* the great dams were built on the Missouri River and other large tributaries; Meade, 1995: p.18). About half the fresh water discharged at its mouth by the Orinoco flows off the Guayana Shield, a terrane of ancient erosion-resistant rocks that yield virtually no sediment. The maps in Figure 4.2 show that, although the Orinoco derives its waters in approximately equal measure from the right-side tributaries that drain the Guayana Shield and the left-side tributaries that drain the Andes, the only significant amounts of sediment are coming off the Andes.

Large alluvial plains, locally called 'llanos', have formed on the surfaces of the Andean forelands of Venezuela and Colombia. The llanos are built on materials that have been shed from the eastern slopes of the rising Andes since at least early Tertiary times. The alluvial plains slope gently away from the Andes, and halt only where their eastern distal edges abut the opposing slopes of the bedrocked Guayana Shield. Along this broadly clockwise-curving line of contact, the Orinoco River flows as a massive drain. On opposite banks of the great river, one can observe the encroachment of one of the world's

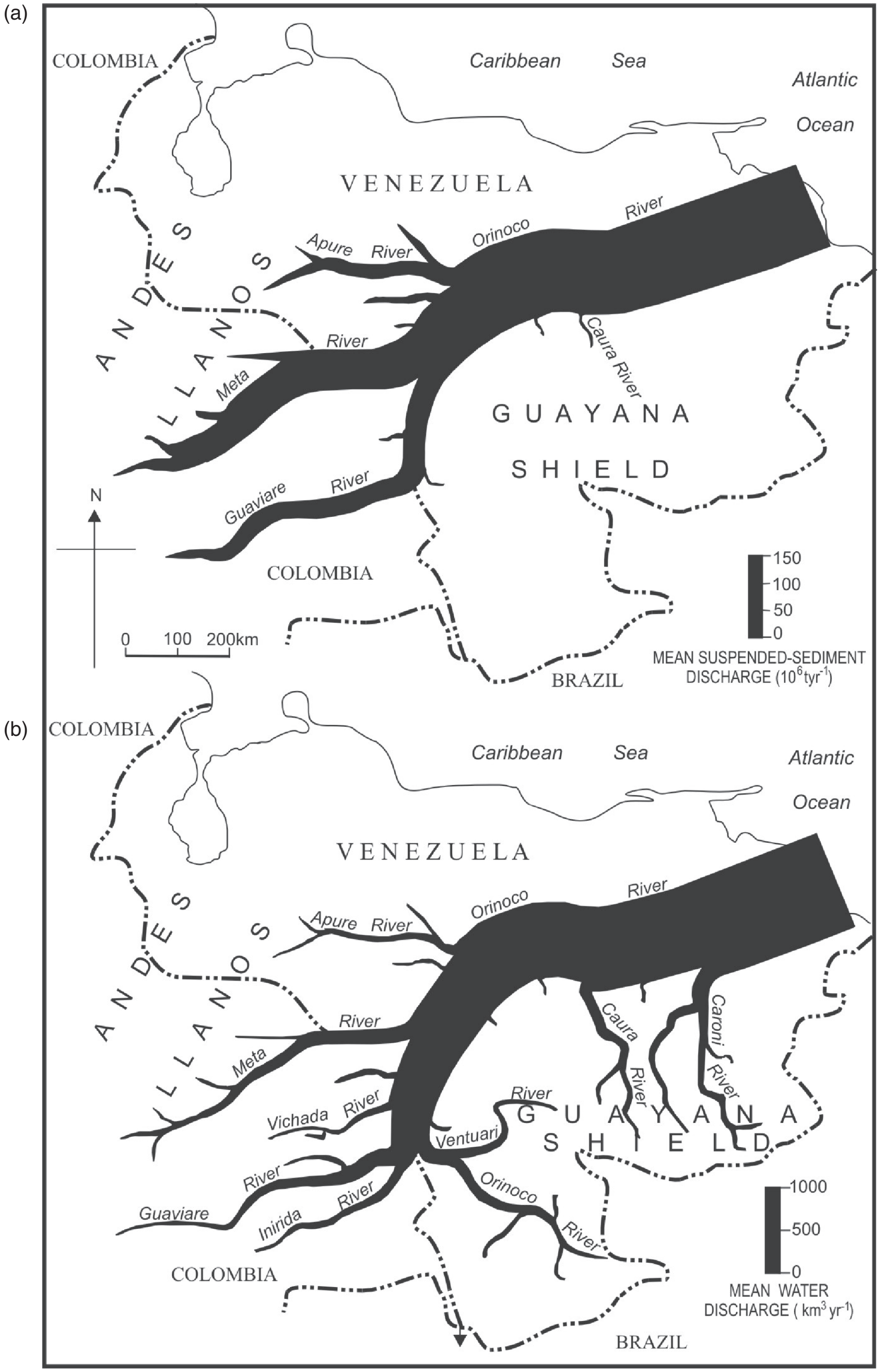

Figure 4.2 Average discharges of suspended sediment (a) and fresh water (b) in Orinoco River and its tributaries. Details of compilation given by Meade *et al.* (1990); for further hydrologic details, see also Nordin *et al*. (1994) and Pérez Hernández and López (1998)

youngest and most active landscapes, the llanos, onto the exposed edge of one of the world's oldest. The ancient landscapes of the Guayana Shield are developed on rocks, which, billions of years ago, formed part of the crystalline core of the supercontinent that we have come to call Gondwanaland.

In the transfer of sediment from the Andes to the Atlantic in the Orinoco River system, the llanos function as an immense storage compartment (Figure 4.3). Although sediment storage times range into the millions of years in the deep underlying sedimentary rocks of the Andean foreland, the processes of storage and remobilization that affect the compositions of sediment exposed on the surface of the llanos today operate mostly at timescales of centuries to millennia. Flowing out of the Andes, the streams shift their courses with great frequency, entraining, in the process, older sediment that had been previously deposited in the alluvial landscape, while leaving behind newer materials that had been brought more recently from the mountains. The effect of these repeated episodes of storage and remobilization can be seen in the mineral compositions of the sediments themselves. With increasing storage times in the alluvial soils of the Venezuelan llanos, the less stable mineral species and rock fragments become more weathered. With each successive episode of transport and intervening period of storage, in stepwise sequence down the gentle slope of the llanos between the Andean front and the mainstem Orinoco River, the sediment becomes more mature in composition. By the time most of the Andean-derived sands have been carried across the llanos, they have lost to solution most of the less stable constituents of their rock fragments, and consist of more than 90% quartz (Stallard *et al*., 1990; Johnsson *et al*., 1991). Andean-derived sands can therefore lose as much as a quarter of their original mass to solution, as their unstable grains are progressively dissolved out during successive episodes of storage and weathering in the alluvial soils of the llanos. Figure 4.4 shows the progressive deterioration of Andean-derived rock fragments and the consequent residual enrichment of quartz in sands being transported down the Guanare and Apure Rivers as they cross the western llanos of Venezuela.

4.4 AMAZON

4.4.1 Setting

The Amazon River today drains large parts of six of the countries (i.e. all but the Guianas) that occupy the northern half of South America. The downstream half of its great length flows from west to east along a lowland between two large cratons, the Guayana and Brazilian Shields (Figure 4.5), that became separated from the Pangaean supercontinent some hundred million years ago to form the ancient bedrock core of what is now South America. Most observers have surmised that, many tens of millions of years ago, the ancestral Amazon River must have flowed westward, in at least part of the same lowland through which it now flows eastward. A supporting supposition is that the rift zone along which South America became separated from Africa (pictured as analogous to the present East African Rift) was a highland from which the ancestral Amazon and other rivers flowed westward down to the sea. The rising of the Andes on the leading edge of the drifting South American continent eventually blocked the westward flow of the Amazon, perhaps (but not certainly) forming a large lake. Blocked from northward and southward flow by topographic obstructions of low but sufficient elevation in the developing Andean forelands, and strengthened by tributary waters from the forelands as well as from the eastern slope of the rising Andes, the Amazon found itself a passage between the shields through which it could flow eastward into the Atlantic Ocean. For a more engaging and stimulating discussion of the geologic history of the drainage of South America, see the paper by Potter (1997). See also the excellent chapter in this volume by Leal Mertes and Thomas Dunne (Chapter 8).

With only a single exception, the hydrographic dimensions and hydrologic parameters of the Amazon far exceed those of all other rivers on the planet. The exception is river length, the record for which is held by the Nile, only a few kilometres longer than the Amazon, according to the latest reliable reckonings (see Goulding *et al*., 2003: pp. 23–24). The total area drained by the Amazon is half again as large as that drained by the second-place Congo, and twice that drained by the third-place Mississippi. The quantity of fresh water discharged by the Amazon at its mouth is five times that of the second-place Congo, six times that of the third-place Orinoco, and twelve times that of the seventh-place Mississippi. (Ranking fourth through sixth in the discharge of fresh water to the coastal oceans are three Asian rivers: respectively, the combined Ganga-Brahmaputra, the Yangtze, and the Yenisey; Meade, 1996.) Two of the Amazon's tributaries, rio Madeira and rio Negro, themselves discharge more fresh water at their mouths than all but the Congo, Orinoco, and Yangtze.

The sediment load of the Amazon, measured at Óbidos near the point of maximum in-channel sediment discharge, averages about 1200 million tonnes per year. Only two other rivers of the world, both in Asia, discharge sediment quantities of this magnitude: the combined Ganga and

Figure 4.3 Oblique aerial photographs of the Venezuelan llanos, showing visual evidences of the distribution and storage of Andean-derived sediment. (a) View up small stream flowing out of Andes (mountains in clouds in distance) and onto llanos, showing meanders and active point bars as evidences of recent shifting of the self-made channel. (b) View up moderate-sized river flowing across central llanos. A more distant view, of a somewhat larger river than the one shown in (a). (c) Abandoned channels in central llanos, showing where rivers formerly flowed and where fluvial sediments are now stored. Approximately same scale as (b). Andes in clouds in far distance. (d) Eastern edge of llanos near the Apure-Orinoco confluence. View south. Middle-ground shows scroll marks developed on edge of llanos. In far distance is Río Orinoco (flowing to left), beyond which (far left) lie the ancient rocks of the Guayana Shield

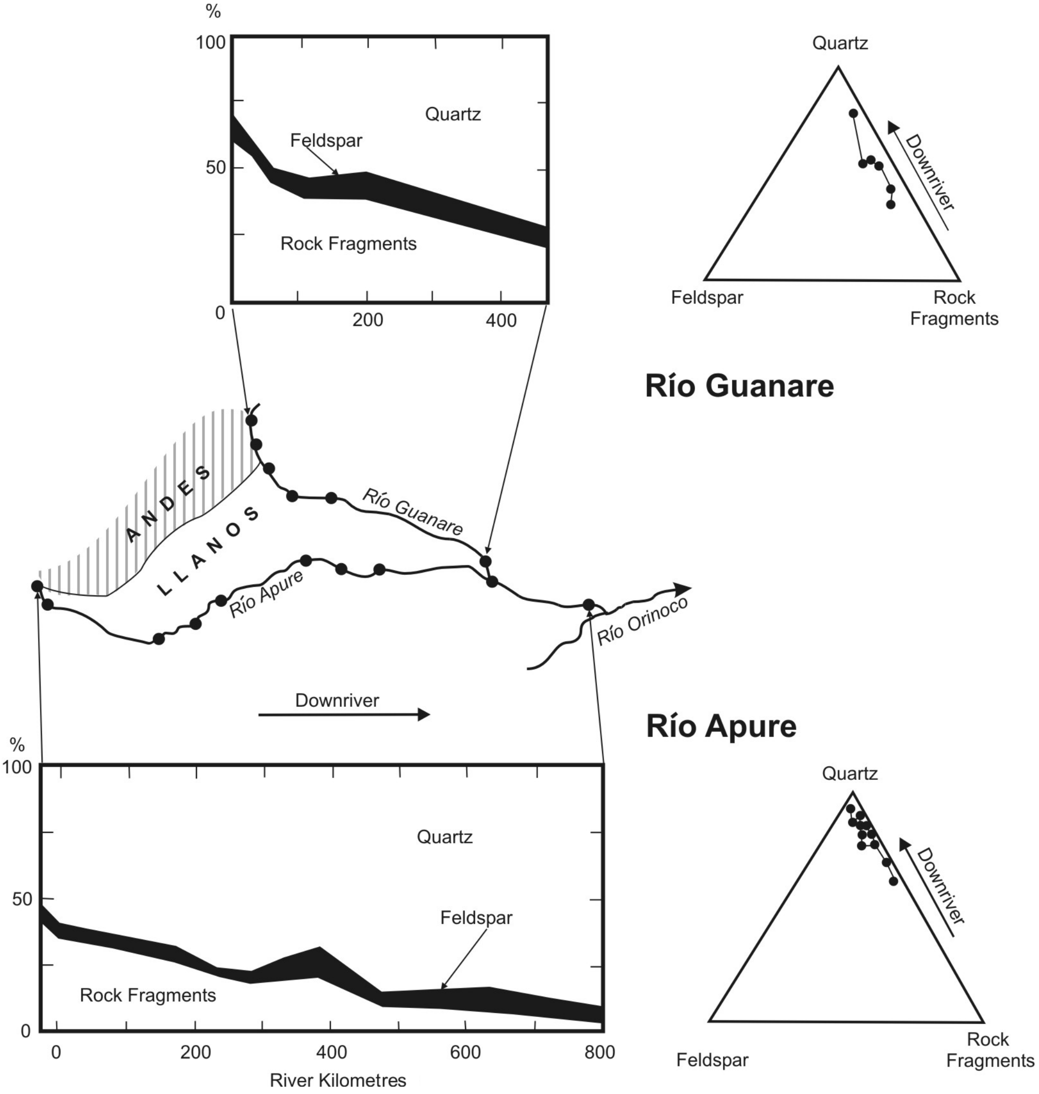

Figure 4.4 Graphs showing the progressive maturation in the mineral compositions of fluvial sands in streams crossing the northwestern llanos of Venezuela. Compiled by Mark Johnsson from supplementary supporting data (Geological Society of America Supplementary Data 91-33) of Johnsson *et al*. (1991)

Brahmaputra, which drain the Himalayas and share a delta in the Bay of Bengal, and the Yellow River (Huanghe) of China, which drains a vast loess plateau that has been subjected to thousands of years of artificially accelerated erosion. Since the completion of large dams at Sanmenxia and Xiaolangdi, however, the Yellow River no longer delivers its enormous sediment loads to its delta (Milliman *et al.*, 1987; Zhao *et al*., 1989; Zhou and Pan, 1994; Shi *et al*., 2002).

Figure 4.6 shows that, while most of the water in the Brazilian mainstem is gathered from the many rainfall-fed tributaries that drain the lowlands, virtually all the suspended sediment is derived from either the Andes of Peru via the Amazon mainstem or the Andes of Bolivia via the Madeira. Quantities portrayed in the figure are averages over the few recent decades of record. Water flows are cumulative and conservative – that is, the total outflow of fresh water at the mouth is the sum of all the tributary

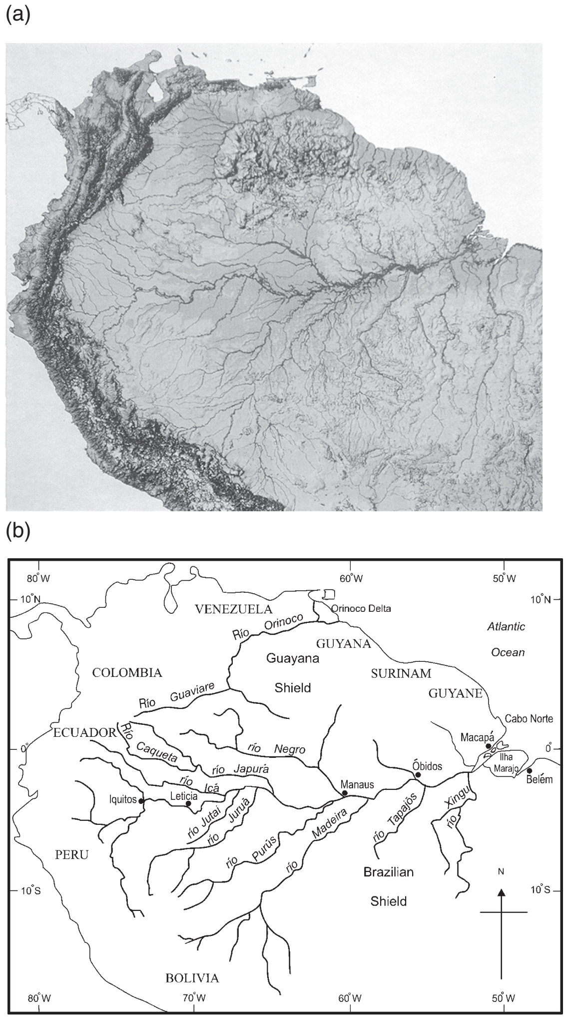

Figure 4.5 Amazon River basin in context of northern South America. Andes Mountains shown as dark area along western margin. Amazon mainstem flows almost due east from Iquitos, Peru, to the Atlantic Ocean. (a) Compiled from satellite imagery by Lisa Mae Olsen and Norman Bliss of US Geological Survey's EROS Data Center. Local usages for 'River' are 'Río' in Spanish-speaking countries and 'rio' in Portuguese-speaking Brazil

inputs. This assumes that the water that leaves the channel to cover the floodplains during the rising-water season is returned to the channel in the same quantities during the following falling-water season (Richey *et al.*, 1989). Suspended-sediment discharges, however, are not shown as conservative. Much of the sediment that leaves the channel in suspension in flood waters during the rising-water season is deposited on the floodplains before the waters are returned to the channel during the falling-water season. In the figure, this is shown especially in the lower Amazon, where large lakes on the floodplains are filling progressively with slowly accumulating sediment.

Similar diagrams constructed by Guyot (1993) for the Amazonian headwaters (Rio Madeira) of Bolivia show similar patterns of conservative water discharges and non-conservative suspended-sediment discharges. Guyot states that almost half the sediment brought down by headwater streams in the Andes of Bolivia is deposited in the foreland basin and on floodplains by the time the waters of rio Madeira flow out of Bolivia and into Brazil. The upper diagram in Figure 4.6, however, tells only part of the story. It does not show seasonal variations in the concentrations and discharges of suspended sediment (Meade, 1985; Meade *et al.*, 1985). Nor does it show the longer timescale exchanges of sediment between the channel and floodplains (Mertes *et al.*, 1996; Dunne *et al.*, 1998)

4.4.2 Storage and Remobilization of Floodplain Sediment

The floodplains of the Amazon retard the seaward progress of Andean sediment, much as do the llanos of the Orinoco. They provide storage compartments where Atlantic-bound sediment can rest for centuries or millennia and can remain sufficiently long for tropical soil-weathering processes to partially transform its mineral composition. The Amazon mainstem in Brazil alone is flanked by nearly 90 000 km^2 of floodplain area (Wolfgang Junk, quoted by Goulding *et al.*, 2003: p. 46). A segment of one of the larger contiguous tracts of floodplain along the middle Amazon is shown in the side-looking-airborne-radar imagery in Figure 4.7. These vast tracts provide the most productive substrates and landscapes of lowland Amazonia: the flooded forests and riparian savannas, and the farms and ranches to which many of them have been converted (Junk, 1997; Junk *et al.*, 2000). The floodplains built of Andean-derived sediment are so distinctive (Sioli, 1951, 1984; Sternberg, 1956, 1975; Irion *et al.*, 1997), especially when contrasted with those of sediment-poor lowland rivers of the Amazon region, that indigenous populations have long given them a special name, *várzea*. Owing to the regularity of the annual rise and fall of the river, the floodplains of the middle Amazon are constructed by slow vertical accretion, particle by particle, layer by layer, year by year, as the overflowing waters spread thin layers of new sediment over wide areas.

Thus are formed the habitats for a remarkable assemblage of plants and animals. Great trees whose roots and lower trunks are tolerant of months of inundation by several metres of flood water, rapidly growing grasses,

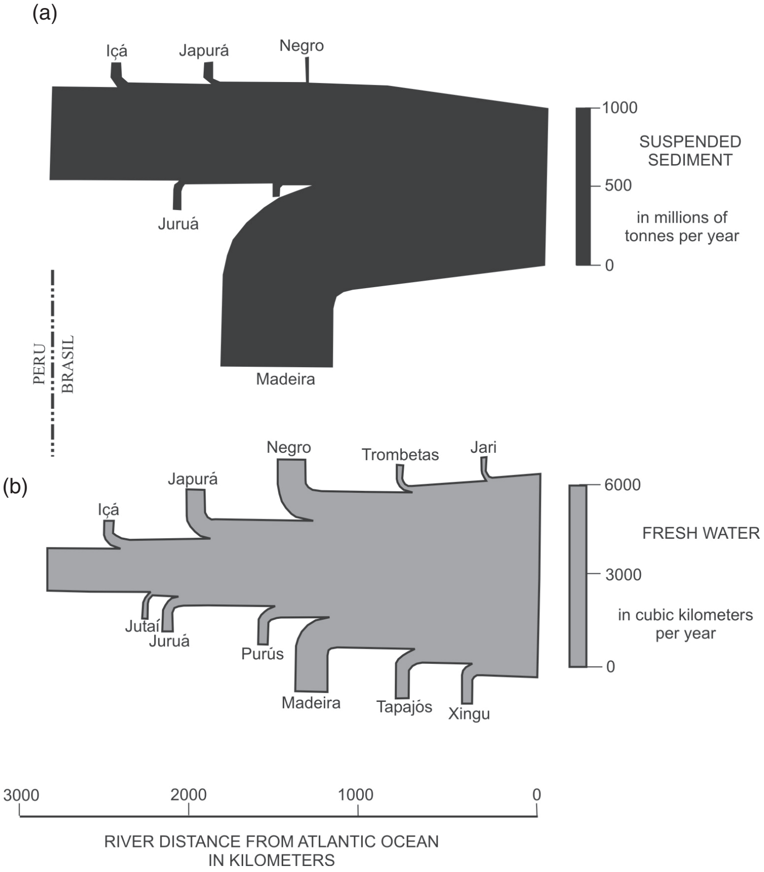

Figure 4.6 Average discharges of suspended sediment (a) and fresh water (b) in the mainstem channel of the Amazon River of Brazil. Suspended-sediment data from Dunne *et al.* (1998); fresh-water data from Carvalho and da Cunha (1998)

Figure 4.7 Side-looking-airborne-radar mosaic of large tract of floodplain between tributary rio Japurá and rio Solimões (local name for Amazon mainstem between Peru-Brazil border and confluence with rio Negro). River flow is from upper left to lower right. From Projeto RADAM (1973). This specific imagery has almost become a poster for large-scale changes in river-channel configuration: it was used, for example, as the dust-jacket picture for the book, *River Channel Changes* (Gregory, 1977). Since the time the imagery was collected (1971), the channel configurations here have continued to change. Within the last few years, for example, the narrow chute channel with the single near-perfect sine-curve meander that crossed the outer part of the neck of the great meander of rio Solimoes (left side of figure) has widened, deepened, and straightened itself sufficiently to become part of the preferred navigation channel used by ocean-going ships to reach the upper-river ports of Leticia, Colombia, and Iquitos, Peru (Jacson Miranda, Amazon river pilot, personal communication, 2001). Other large tracts of stored fluvial sediment on floodplains of the Amazon and Madeira Rivers are described by Latrubesse (2002), Latrubesse and Franzinelli (2002), and by Mertes and Dunne in their chapter in the present volume (Chapter 8)

and herbaceous aquatic species of a spectacular variety – all are adapted not only to the available spatial and nutritional niches of the floodplain, but to the annual transformations from emergent to submerged lands and back again, and, during the months of inundation, to the special rhythms of the flood pulse (Salo *et al.*, 1986; Junk and Piedade, 1997). Among the most interesting animal species that seasonally invade the flooded forests and grasslands along with the rising waters are the turtles and crocodilians, the fish (especially those that gather most of their year's food supply from forest trees during the inundation season), and the mammals (sloths that swim and flexible dolphins that navigate the shallow waters between the tree trunks) (Goulding, 1980; Best, 1984; Goulding *et al*., 1996; Araujo-Lima and Goulding, 1997). The more charismatic residents of the flooded *várzea* habitat, such as the giant water lily *Victoria amazonica* and the freshwater dolphin *Inia geoffrensis*, rank with monkeys and macaws as principal attractants for the local ecotourism industry.

But floodplains do not grow forever. Complementary to the slow upward accretionary growth of floodplains is their destruction and the consequent remobilization of their constituent sediment particles by bank erosion. As the Amazon and its tributaries meander along and across their valley bottoms, their channels are shifted laterally. Meander bends grow larger and larger in radius and circumference, forming longer and longer necks that eventually are cut off to re-shorten, at least momentarily, the overall channel length. All this lengthening, shifting, and re-shortening of channels remobilizes, in the process, considerable quantities of sediment. Thus is the vertical accretion of floodplains counterbalanced by the lateral erosion of their exposed banks.

This constant cycle of the laying down of floodplain sediment and its subsequent remobilization by the shifting river has become a grand metaphor for the chaotic and lacunae-plagued human history of the Amazon region. This metaphor had its most powerful expression in the spectacular prose penned a century ago by Euclides da Cunha, which has been revisited recently and insightfully by Suárez-Araúz (1999) and Slater (2002). Although his prose is notoriously difficult to render into English with simultaneous loyalty to both style and accuracy, a sample translation (mine) from Euclides da Cunha (1909) may perhaps whet the appetite of a more competent reader of Portuguese:

> 'The tumultuous inconstancy of the river manifests itself, moreover, in its interminable meanderings, hopelessly entangled, reading like the indecisive logbook of a lost wanderer, guessing at horizons, directing itself into all its principal courses or throwing itself into unexpected shortcuts. . . . It hurls itself through the drowned narrows of Óbidos in complete disregard of its ancient bed that yet today divines itself in the enormous pestilential floodplain, ganglionic with lakes, of Vila Franca; or goes, at other points, into unexpected "furos", to flow into its large affluents, making itself illogically tributary to its own tributaries, always untidy, disheveled, and fluctuating, destroying and building, reconstructing and devastating, extinguishing in an hour what was built over decades – like . . . a monster artist insatiably applying finishing touches, recomposing and endlessly restarting an indeterminate portrait. Such is the river; such is its history: subversive, unruly, incomplete.'

The quantities of sediment involved each year in the exchanges between channel and floodplain are enormous. In the Amazon Basin as a whole, the quantities of sediment exchanged between channels and floodplains far exceed the quantities of downriver flux shown in the upper diagram of Figure 4.6. In a 1500 km reach of the Amazon mainstem in Brazil (only about one-quarter of the overall mainstem length), the total exchanges – by the overbank accretion of floodplains or the remobilization of sediment by bank erosion – exceed the downriver fluxes of sediment (Figure 4.8). A simple linear extrapolation of this relation to the full length of the Amazon (especially the length fringed by large floodplains) allows us to estimate that annual exchanges of sediment between channels and floodplains must exceed the annual downchannel fluxes of sediment by a factor of at least three.

Residence time of sediment on the Amazon floodplains – the period between the time any given sediment particle may be deposited and the time it is remobilized by bank erosion – is commonly measurable in thousands of years. In their comprehensive assessment of the geomorphology of the Brazilian Amazon, Mertes *et al*. (1996) estimated mean recycling times on the order of 1000–2000 years for the floodplains between the mouths of rios Jutaí and Madeira. Local residence times in specific floodplain tracts will, of course, exceed these mean values, even to periods of time sufficiently long for tropical soil-weathering processes to transform some of the mineral compositions of the sediments. In the central Amazon of Brazil, Johnsson and Meade (1990) described floodplain sediments that had been stored inside a large meander bend (shown on the left side of Figure 4.7) for sufficient time to allow many of the lithic fragments to be weathered out of the sands and some of the less stable clay minerals to be weathered out of the finer fractions.

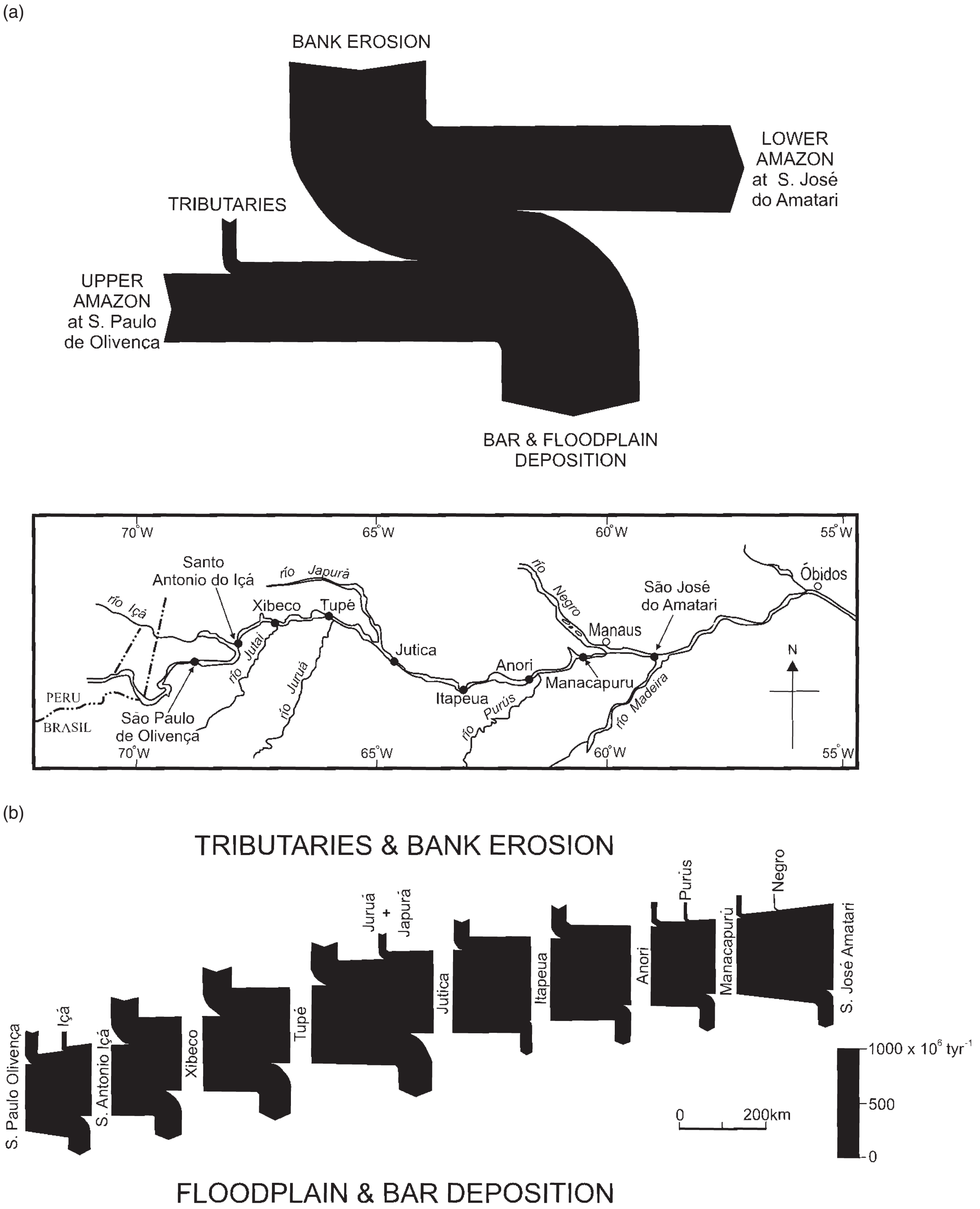

Figure 4.8 Diagrams showing average annual fluxes and exchanges of sediment between channels and floodplains of a 1500 km segment of the Amazon mainstem of Brazil, between the Peru-Brazil border and the confluence with rio Madeira. (a) Generalized diagram that shows schematically the averaged values for the entire 1500 km reach. Quantities of sediment exchanged through the erosion of banks and through deposition on point bars and floodplains significantly exceed the flux of sediment from upriver (including tributary inputs) or the flux continuing downriver. (b) An exploded version of (a), showing the individual sediment budgets for each of eight consecutive reaches of the mainstem Amazon between São Paulo de Olivença and São José do Amatarí. The upper left corners show the quantities of sediment contributed to the eight segments from bank erosion. The lower right corners show the quantities removed from the channel by overbank deposition onto floodplains and pointbars. Details of the calculations and compilations are given by Dunne *et al.* (1998)

A detailed look at the storage and remobilization of Amazonian floodplain materials, given in the context of average annual fluxes of sediment in the mainstem channel, is provided by the exploded lower diagram of Figure 4.8. The 'explosion' was made possible by a series of repeated measurements made at nine mainstem cross-sections and in five principal tributaries during the early 1980s (Meade, 1985; Richey *et al.*, 1986), giving us sufficiently accurate averages that we were able to break the diagram into eight segments. Within each segment – about 200 km of river length, defined between the regularly measured cross-sections – Dunne *et al.* (1998) were able to estimate the mean annual quantity of new sediment added to the floodplain and the mean annual quantity of sediment remobilized by bank erosion. By sweeping the eye more or less horizontally from left to right across the exploded diagram, the reader might gain the impression (or at least the supposition) that any given sediment particle moving downstream past São Paulo de Olivença (especially during high-water season when much sediment-laden water is flowing onto the floodplain) is likely to be carried out of the channel and be deposited on the floodplain before the thread of the water flow reaches São José do Amatari. Conversely, by looking upstream from the section at São José do Amatari, the reader might just as easily visualize the likelihood that any sediment particle passing through this cross-section (especially during falling-water season when river-bank collapse is maximal for the year) had come out of one of those eroding banks, rather than having been swept this year off an Andean slope somewhere in Peru or Ecuador.

In the Amazon system, we are able to look closely at such processes because of the general lack of engineering works along the river and the complete freedom this great river is still allowed in the making of its floodplains and the destruction of its banks. Most rivers in highly developed parts of the world (the Mississippi, for example) have been engineered to prevent or at least retard these processes: levees to prevent flooding, revetments to prevent bank erosion. In the Amazon, these natural processes are still visible, and their visibility is useful in understanding such issues as the fates of sediment-transported contaminants. Many of the contaminants in the world's river systems are transported as materials adsorbed onto sediment particles. Trace metals, many radionuclides and insecticides, for example, show a marked preference – by factors of thousands or more – for piggyback transport in the adsorbed state on sediment particles rather than as dissolved ions or molecules in true solution in the water. The fate of the sediment particles, therefore, determines the fates of many contaminants. This is sufficiently true that the contaminants in many polluted rivers can be used as tracers to follow the pathways and find the eventual resting places of the sediment particles.

Let us return to the exploded lower diagram of Figure 4.8 and consider some of its implications for the fates of sediment-transported contaminants in large rivers. We consider two scenarios, both of which are hypothetical and not based on any known or even suspected occurrence to date. Suppose that, somewhere along the Peruvian Amazon, a large quantity of polychlorinated biphenyls (PCBs) is spilled into the sediment-laden waters of the flowing mainstem river during, say, the rising-water season. The PCBs, as usual, are preferentially adsorbed onto the particles of suspended sediment. This being high-water season, the bulk of the sediment particles to which the PCBs are adsorbed will settle out of the overflowing waters and onto the floodplains before they reach the middle of the Brazilian Amazon. The sediment particles and their adsorbed PCBs will remain on the floodplains until they are remobilized by bank erosion or some other process. Because the disintegration time of PCBs (only 100–200 years) is so much shorter than the likely residence time of the sediment (millennia), the floodplains will have acted as 'decontamination depositories' for the PCBs. By the time the sediment is remobilized into the flowing waters of the river, the PCBs will have long since 'disappeared' by having been degraded into daughter compounds and carried away mostly in solution.

Let us now consider another, longer-lived, contaminant that is preferentially adsorbed onto sediment particles. Instead of PCBs, let us consider the highly toxic radionuclide, plutonium, which has a half-life in excess of 20 000 years. This hypothetical example postulates, as in the previous example of PCBs, a plutonium spill somewhere in the Peruvian Amazon, the complete adsorption of the plutonium onto sediment particles in the flowing river, and the complete removal from the flowing river of the plutonium-carrying particles by overbank deposition onto the floodplains of the middle Amazon. Because the bulk of the spilled plutonium is likely to have been adsorbed by the finest particles in suspension, and because their fineness will have allowed them to be transported long distances onto the floodplain before being deposited as overbank sediment, the plutonium-contaminated particles are likely to be remobilized by lateral bank erosion only after some decades, perhaps centuries, of storage. Some hundreds, perhaps thousands, of years after the original plutonium spill, these same sediment particles will be remobilized as the banks of the floodplains are eroded, and the City Fathers of Manaus will have no way of determining the source of (or being able to do anything about) the by-then-mysterious presence of plutonium in the river.

4.4.3 Sediment Storage in the Lowermost Amazon Valley

The lowermost Amazon River is herein defined as the reach between the farthest downstream river gauge on the mainstem at Óbidos and the estuarine embayment south of Macapá. In this 600 km reach, much river sediment apparently is being deposited on floodplains, especially in floodplain lakes. As the upper diagram in Figure 4.6 indicates, new sediment is being deposited on the lowermost floodplain at a significantly greater rate than the older deposits are being remobilized by bank erosion. This lowermost segment may be considered an upstream extension of the Amazon Delta – an area in which much sediment is being deposited in places where it is unlikely to be re-eroded under present-day conditions.

The lowermost reaches of most large rivers are difficult places in which to measure the fluxes of sediment. River hydrologists traditionally locate their farthest downstream gauges somewhere upriver of the influence of daily fluctuations in oceanic tides. In the Amazon this location is at Óbidos, some 700 km landward of the transition from fresh water to salt water. Even here, diurnal tidal fluctuations of a few centimetres may be observed during some weeks of lowest river stage (Oltman, 1968). Because hydrologists generally monitor day-to-day river discharges by continuously measuring river stages, any fluctuations (tidal or otherwise) in river level that are unrelated to fresh-water discharge will introduce errors.

Sediment fluxes are even more difficult to measure, and therefore subject to even greater errors. Sediment transport is sensitively determined by water velocity and by the slope of the river surface. In reaches affected by oceanic tides, river slope and velocity may change markedly from one hour to the next. In the estuary proper, water flows may even reverse directions. Appropriate measurements of sediment discharges in tidally affected river reaches therefore require a complex scheme of temporally frequent and spatially dense sampling (see, for example, Meade, 1969, 1972; Milliman *et al*., 1985; Kineke and Sternberg, 1995). Sediment fluxes in the lowermost Amazon, as shown in Figure 4.6, are estimated, partly by difference between measurements made both landward and seaward of this lowest reach. The farthest downstream measurements of sediment flux of any reliability are those at Óbidos. These measurements are derived from repeated discharge-weighted samples that were collected and composited through the full depth and across the full width of the Amazon River (Meade, 1985; Richey *et al.*, 1986). From a total of a dozen such measurements made at Óbidos at different seasons of the year and related to the typically simple sinusoidal hydrograph of river discharge there, Dunne *et al.* (1998) reported a mean annual sediment discharge of 1240 (±130) million tonnes.

This figure for the suspended-sediment discharge at Óbidos is certainly more correct than the estimate of 600 million tonnes per year reported recently by Naziano Filizola and his colleagues (Filizola, 1999; Seyler and Boaventura, 2001). Filizola computed this 'more recent' estimate from archived data on a set of about 20 samples collected at Óbidos during 1979–1983, and he apparently was unaware that these samples had been collected only a few tens of centimetres below the river surface. Such surficial sampling, in river waters 40–60 m deep, as they are at Óbidos (Figure 4.9), will not detect the greater concentrations of suspended sediment that are typical of deeper flowing waters. Consequently, the 'more recent' estimate of 600 million tonnes per year is too small by a factor of two.

4.5 THE AMAZON GOES TO SEA

Many photographs and satellite images show the areal distribution of turbid waters offshore of the mouth of the Amazon as the river debouches into the Atlantic Ocean. Vertical satellite images are presented by Curtin and Legeckis (1986), Geyer *et al.* (1996), and Kineke and Sternberg (1995), and an especially dramatic astronaut photograph has been published in the book by Apt *et al*. (1996: p. 152) and on the cover of the November 1996 issue of *National Geographic* magazine (Apt, 1996).

The astronaut photograph, taken during August 1985, is an oblique view that includes the curvature of the earth in the far distance. In the nearer distance, multiple plumes of lighter-coloured water show the ebb-tide extents of successive surges of sediment-laden Amazon River waters making their entries into the ocean. The diurnal range of oceanic tide is large here, usually on the order of 3 m (Geyer *et al.*, 1996). The 'fronts' of river water therefore surge considerably as they enter the Atlantic. The most prominent plume in the picture probably represents the ebbing river flow on the day of the photograph. More ragged-looking plume edges that float seaward of the latest plume most likely represent the remnants of previous ebb-tide pulses of seaward-flowing river waters. As the river waters are slowed by their entry into the ocean and their flow is reversed by the rising tides, most of their sediment particles gradually settle towards the sea floor. Kuehl *et al*. (1986) report that approximately half the quantity of sediment that passes Óbidos settles onto the sea bed of the continental shelf off the mouth of the Amazon River.

But this is not the end of the story. All the Andean sediment that the Amazon brings to the Atlantic does not end its journey here on the continental shelf of Brazil.

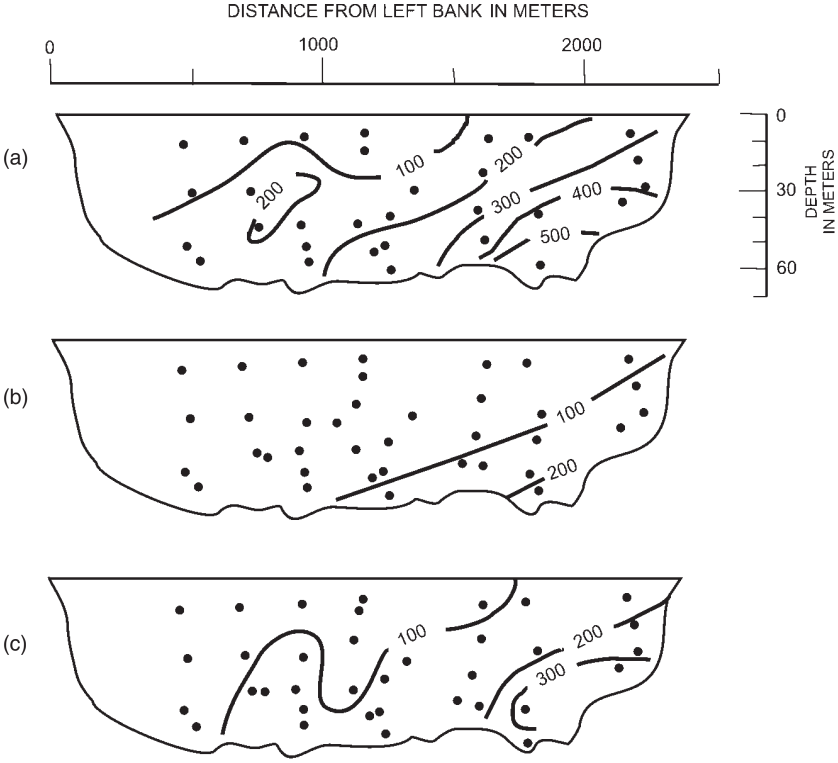

Figure 4.9 Cross-sections of rio Amazonas at Óbidos, 15 June 1976, showing vertical and lateral heterogeneity of suspended-sediment concentrations. Based on individual point-sample data. Viewer is facing downstream. Vertical distance scale is exaggerated 10 times relative to horizontal. (a) Total suspended sediment, in mg l^{-1}. (b) Suspended sand (>63 μm), in mg l^{-1}. (c) Suspended silt and clay (<63 μm), in mg l^{-1}. Data from Meade *et al.* (1979a); cross sections previously published by Eisma (1993, p. 33) and Meade (1994). Clearly shown is the increase in sediment concentration with increasing water depth, from which one may easily infer the unsuitability of surface-only sampling for accurate measurement of the total sediment discharge at Óbidos. Illustrations of similar differences in sediment concentration between surface waters and deeper waters in other Amazonian river cross sections have been published by Curtis *et al.* (1979) and Meade *et al.* (1979b)

Each of the images cited in the first paragraph of this section shows a band of turbid water along the coastline to the northwest of the large open mouth of the Amazon. A substantial proportion of the sediment that is discharged by the Amazon to the sea (perhaps as much as a fifth, or even a quarter, of the quantity that was transported past Óbidos) is being carried to the northwest around Cabo Norte, the promontory that marks the northern corner of the Amazon's estuarine embayment, and is being transported longshore and nearshore, under the influence of the North Brazil Current, along the northeastern coast of South America (Eisma *et al.*, 1991).

The entrainment of the Amazon's sediment alongshore to the northwest is an episodic process. Timescales of alternating transport and storage range from diurnal (tidal) to at least centennial. During their slow progression to the northwest, the sediment-laden coastal waters are washed into and out of mangrove swamps and mudflats as the tides rise and fall. Along the Brazilian coast north and northwest of the Amazon mouth, century-scale episodes of shore erosion alternate with equivalent-scale episodes of coastal accretion. Farther downcurrent, hundreds of kilometres from the Amazon mouth, along the coasts of Guyane (French Guiana), Surinam, and Guyana, great mudbanks shift their ways gradually northwestward (Allison *et al.*, 1995a,b, 2000).

Just how much Amazonian sediment is dispersed northwestward along the northeast coast of South America, and how far does it eventually travel? Perhaps an average as great as 200–250 million tonnes per year is carried around Cabo Norte. Along the first thousand kilometres alongshore downcurrent of Cabo Norte, much of the river-derived sediment is carried into coastal wetlands and estuarine embayments, probably to reside there more or less permanently on a centuries-to-millennia timescale. Perhaps a quantity on the order of 100 million tonnes per year – half what is carried around Cabo Norte at the beginning of the northwestward trajectory, but still in excess of the sediment loads of all but a dozen of the world's largest rivers – reaches the outer coastline of the Orinoco Delta, some 1600 km downcurrent from the mouth of the Amazon.

Whatever the absolute quantity of Amazonian sediment that reaches the outer delta of the Orinoco, that quantity is greater than the amount supplied by the Orinoco River itself. By comparing the mineral compositions of recently deposited fine-grained sediments submerged on the outer Orinoco Delta with the distinctively different compositions of like-sized sediments from the two rivers, Eisma *et al.* (1978) were able to conclude that the outer-delta deposits were more Amazonian than Orinocoan. At its point of maximum sediment transport near the inner edge of its delta, the Orinoco River carries seaward an average of about 150 million tonnes per year. Most of this quantity is deposited in the inner and middle regions of the delta (Warne *et al.*, 2002). The quantity of Orinocoan sediment deposited on the outermost delta of the Orinoco therefore is apparently less than that of the more extensively traveled Amazonian materials deposited there.

In the astronaut photograph of the Orinoco delta region in Figure 4.10, the incoming Amazonian sediment may be seen as the turbid coastal water in the right third of the picture. It is attractive to speculate, in the light of the earlier discussions in this chapter, on the histories of the individual particles that cloud the waters of this incoming plume. Among the billions of particles suspended in this plume may well be a few that were detached recently from an Andean slope somewhere in Bolivia or Peru and, within less time than the span of a single year, were carried virtually nonstop for a distance of 5000 or 6000 km, down the Amazon River and along the Guiana coast to the Orinoco Delta. Much more likely, however, is that the particles now suspended in the plume shown in the eastern third of the picture have spent hundreds to thousands of years making their journeys from their Andean sources to this eventual sink. They are likely to have spent days or weeks in active river transport, centuries or millennia in storage after having been deposited on floodplains, before being remobilized, by bank erosion or channel shifting, into flowing water for another few days or weeks of riverine transport. This cycle of transport, deposition, remobilization, and re-deposition likely was repeated in the river multiple times until the particles passed out the Amazon mouth, around Cabo Norte, to continue their journey, through many more episodes of successive deposition and remobilization, northwestward along the South American coastline. All in all, the histories of most of these particles have comprised many long periods of storage in floodplains, coastal wetlands and mudbanks, punctuated by short bursts of downstream transport.

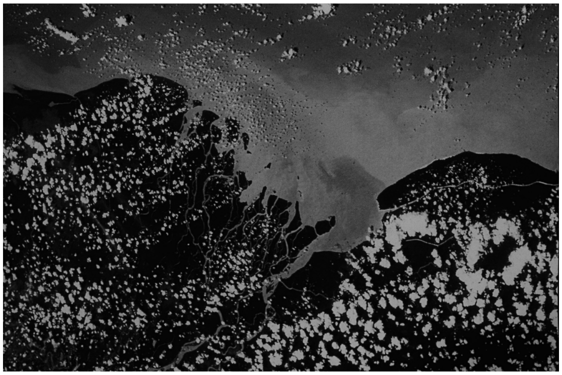

Figure 4.10 Astronaut photograph of Orinoco delta region. NASA photograph 51D-32-004, selected and generously supplied by Michael Helfert. Vertical or near-vertical view. Long dimension of photograph is 200 km. Main mouth of Orinoco River is in bottom centre. Land area in left half of photograph is Orinoco Delta. Coastal waters in right side of picture are made turbid by sediment carried alongshore from the mouth of the Amazon

4.6 CODA

In the eastern cordillera of the Andes of Colombia, about 3° latitude north of the Equator and nearly 75° longitude west of the Greenwich meridian, is a narrow divide between the headwaters of the Orinoco and those of the Amazon. From one side of the divide, water carries sediment into a small tributary of Río Guaviare, through which it eventually enters the Orinoco. From the other side of the divide, water carries sediment into and through a series of tributaries of Río Caquetá, which, as it flows out of Colombia and into Brazil, becomes rio Japurá, a principal tributary of the mainstem Amazon.

Now consider two soil particles that lay, some thousands of years ago, less than a metre apart – one on the Orinoco side of the divide and the other on the Amazon side – and began, during a heavy rainfall, their separate journeys downstream. What is the likelihood that these same two particles, after their diverging and circuitous journeys down their separate great rivers, now lie again within a few metres of each other, here on the floor of the continental shelf on the seaward edge of the delta of the

Orinoco? Such an outcome may be improbable – but not highly so. It is certainly not impossible. And a full consideration, beginning with their separation and concluding in their reunion, of the spatial and temporal trajectories of these two particles – in some aspects similar to each other and in others quite different – across thousands of kilometres of transport and during thousands of years of storage, amounts to no less than a grand mental excursion through the sedimentary processes by which the earth's surface recycles itself.

ACKNOWLEDGEMENTS

A thoughtful and energetic company of colleagues and coworkers has unfolded and told the story that is recounted in this chapter, and the most relevant names may be found among the authors and acknowledgees of the papers listed in the introductory paragraphs. Chief among those who consistently kept my sights highest during two decades of joyous potamologic pursuits on the Amazon and Orinoco were Tom Dunne, John Edmond, Georg Irion, Abel Mejía, Leal Mertes, Carl Nordin, David Pérez Hernández, Jeff Richey, and Bob Stallard.

REFERENCES

Allison, M.A., Nittrouer, C.A., and Kineke, G.C., (1995a) Seasonal sediment storage on mudflats adjacent to the Amazon River, In: *Geological significance of sediment transport and accumulation on the Amazon continental shelf*: *Marine Geology* (special issue) (C.A. Nittrouer and S.A. Kuehl, Eds.), v.125, nos 3 and 4, pp. 303–328.

Allison, M.A., Nittrouer, C.A., and Faria, L.E.C., Jr, (1995b) Rates and mechanisms of shoreface progradation and retreat downdrift of the Amazon River mouth, In: *Geological significance of sediment transport and accumulation on the Amazon continental shelf*: *Marine Geology* (special issue) (C.A. Nittrouer and S.A. Kuehl, Eds.), v. 125, nos 3 and 4, pp. 373–392.

Allison, M.A., Lee, M.T., Ogston, A.S., and Aller, R.C., (2000) Origin of Amazon mudbanks along northeastern coast of South America. *Marine Geology*, 163, 241–256.

Apt, J., (1996) Orbit – the astronauts' view of home: *National Geographic*. v.190, no. 5, pp. 2–27.

Apt, J., Helfert, M., and Wilkinson, J., (1996) *Orbit – NASA astronauts photograph the earth*. National Geographic Society, Washington, DC, 224 p.

Araujo-Lima, C., and Goulding, M., (1997) *So fruitful a fish: ecology, conservation and aquaculture of the Amazon's tambaqui*. Columbia University Press, New York, 191 p. (Also published in Portuguese: 1998, *Os frutos do tambaqui: Ecologia, conservação e cultivo na Amazônia*. Sociedade Civil Mamirauá, Tefé, 186 p.)

Best, R.C., (1984) The aquatic reptiles and mammals of the Amazon, In: *The Amazon: limnology and landscape ecology of a mighty tropical river and its basin* (H. Sioli, Ed.). Dr W. Junk, Dordrecht, pp. 371–412.

Carvalho, N.O., and da Cunha, S.B., (1998) Estimativa da carga sólida do rio Amazonas e seus principais tributários para a foz e oceano: uma retrospectiva. *A Água em Revista*, v. 6, no. 10, pp. 44–58.

Curtin, T.B., and Legeckis, R.V., (1986) Physical observations in the plume region of the Amazon River during peak discharge – I. Surface variability. *Continental Shelf Research*, v. 6, pp. 31–51. (Reprinted 1987 *in* Nittrouer, C.A., and DeMaster, D.J., Eds. *Sedimentary processes on the Amazon continental shelf*. Pergamon Press, Oxford, pp. 31–51.)

Curtis, W.F., Meade, R.H., Nordin, C.F., Jr, Price, N.B., and Sholkovitz, E.R., (1979) Non-uniform vertical distribution of fine sediment in the Amazon River. *Nature*, v. 280, pp. 381–383. (Portuguese translation published 1982, Distribuição vertical não uniforme de sedimento fino no rio Amazonas: *Acta Amazonica*, v. 12, pp. 697–700.)

da Cunha, E., (1909) *A margem da história*: Aillaud & Lellos, Lisbon. (Many subsequent reprints; e.g. 1999, Livraria Martins Fontes, São Paulo, 209 p. English translation by R. Sousa, (2006) *The Amazon*: *land without history*. Oxford University Press, Oxford, 96 p.)

Díaz de Gamero, M.L., (1996) The changing course of the Orinoco River during the Neogene: a review. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 123, 385–402.

Drago, E.C., and Amsler, M.L., (1988) Suspended sediment at a cross section of the Middle Parana River: concentration, granulometry and influence of the main tributaries, In: *Sediment budgets* (M.P. Bordas and D.E. Walling, Eds.). *International Association of Hydrological Sciences Publication* 174, pp. 381–396.

Dunne, T., Mertes, L.A.K., Meade, R.H., Richey, J.E., and Forsberg, B.R., (1998) Exchanges of sediment between the flood plain and channel of the Amazon River in Brazil. *Geological Society of America Bulletin*, 110, 450–467.

Eisma, D., (1993) *Suspended matter in the aquatic environment*. Springer, Berlin, 315 p.

Eisma, D., van der Gaast, S.J., Martin, J.M., and Thomas, A.J., (1978) Suspended matter and bottom deposits of the Orinoco delta: turbidity, mineralogy and elementary composition. *Netherlands Journal of Sea Research*, 12, 224–251.

Eisma, D., Augustinus, P.G.E.F., and Alexander, C., (1991) Recent and subrecent changes in the dispersal of Amazon mud. *Netherlands Journal of Sea Research*, 28, 181–192.

Filizola, N.P., Jr, (1999) *O fluxo de sedimentos em suspensão nos rios da bacia Amazônica Brasileira*. Agencia Nacional de Energia Elétrica, Brasilia, 63 p.

Geyer, W.R., Beardsley, R.C., Lentz, S.J., Candela, J., Limeburner, R., Johns, W.E., Castro, B.M., and Soares, I.D., (1996) Physical oceanography of the Amazon shelf, In: *Oceanography of the Amazon continental shelf*: *Continental Shelf Research* (special issue) (C.A. Nittrouer and D.J. DeMaster, Eds.), v. 16, nos 5 and 6, pp. 575–616.

Gibbon, Lt L., (1854) *Exploration of the valley of the Amazon, made under the direction of the Navy Department, by Wm. Lewis Herndon and Lardner Gibbon, Part II*: U.S. House of

Representatives, 33d Congress, 1st Session, Executive no. 53, 339 p.

Gibbs, R.J., (1965) *The geochemistry of the Amazon River Basin*. University of California, San Diego, PhD dissertation, 96 p.

Gibbs, R.J., (1967) The geochemistry of the Amazon River system: Part I. The factors that control the salinity and the composition and concentration of the suspended solids. *Geological Society of America Bulletin*, 78, 1203–1232.

Goulding, M., (1980) *The fishes and the forest: explorations in Amazonian natural history*. University of California Press, Berkeley, 280 p.

Goulding, M., Smith, N.J.H., and Mahar, D.J., (1996) *Floods of fortune: ecology and economy along the Amazon*. Columbia University Press, New York, 193 p.

Goulding, M., Barthem, R., and Ferreira, E., (2003) *The Smithsonian atlas of the Amazon*. Smithsonian Institution, Washington, 255 p.

Gregory, K.J., Ed., (1977) *River channel changes*. John Wiley & Sons, Ltd, Chichester, 448 p.

Guyot, J.L., (1993) *Hydrogéochimie des fleuves de l'Amazonie bolivienne*. ORSTOM Editions, Paris, 261 p.

Irion, G., Junk, W.J., and de Mello, J.A.S.N., (1997) The large central Amazonian river floodplains near Manaus. Geological, climatological, hydrological and geomorphological aspects, In: *The central Amazon floodplain: ecology of a pulsing system* (W.J. Junk, Ed.). Springer, Berlin, pp. 23–46.

Johnsson, M.J., and Meade, R.H., (1990) Chemical weathering of fluvial sediments during alluvial storage: the Macuapanim Island point bar, Solimões River, Brazil. *Journal of Sedimentary Petrology*, 60, 827–842.

Johnsson, M.J., Stallard, R.F., and Lundberg, N., (1991) Controls on the composition of fluvial sands from a tropical weathering environment: sands of the Orinoco River drainage basin, Venezuela and Colombia. *Geological Society of America Bulletin*, 103, 1622–1647.

Junk, W.J., Ed., (1997) *The central Amazon floodplain: ecology of a pulsing system*. Springer, Berlin, 525 p.

Junk, W.J., and Piedade, M.T.F., (1997) Plant life in the floodplain with special reference to herbaceous plants, In: *The central Amazon floodplain: ecology of a pulsing system* (W.J. Junk, Ed.). Springer, Berlin, pp. 147–185.

Junk, W.J., Ohly, J.J., Piedade, M.T.F., and Soares, M.G.M., editors, (2000) *The central Amazon floodplain: actual use and options for sustainable management*. Backhuys, Leiden, 584 p.

Kineke, G.C., and Sternberg, R.W., (1995) Distribution of fluid muds on the Amazon continental shelf, In: *Geological significance of sediment transport and accumulation on the Amazon continental shelf*: *Marine Geology* (special issue) (C.A. Nittrouer and S.A. Kuehl, Eds.). v. 125, nos 3 and 4, pp. 193–233.

Kuehl, S.A., DeMaster, D.J., and Nittrouer, C.A., (1986) Nature of sediment accumulation on the Amazon continental shelf. *Continental Shelf Research*, 6, 209–225. (Reprinted 1987 *in* Nittrouer, C.A., and DeMaster, D.J., editors, *Sedimentary processes on the Amazon continental shelf*: Pergamon Press, Oxford, pp. 209–225.)

Larsen, M.C., Vásquez Conde, M.T., and Clark, R.A., (2001a) Flash-flood related hazards: landslides, with examples from the December 1999 disaster in Venezuela, In: *Coping with flash floods* (E. Gruntfest and J. Handmer, Eds.). Kluwer, Dordrecht, pp. 259–275.

Larsen, M.C., Wieczorek, G.F., Eaton, L.S., Morgan, B.A., and Torres-Sierra, H., (2001b) Venezuela debris-flow and flash-flood disaster of 1999 studied. *EOS*, *American Geophysical Union Transactions*, 82, 572–573.

Latrubesse, E.M., (2002) Evidence of Quaternary palaeohydrologic changes in middle Amazonia: the Aripuana-Roosevelt and Jiparaná 'fans'. *Zeitschrift für Geomorphologie*, Suppl., 129, 61–72.

Latrubesse, E.M., and Franzinelli, E., (2002) The Holocene alluvial plain of the middle Amazon River, Brazil. *Geomorphology*, 44, 241–257.

Meade, R.H., (1969) Landward transport of bottom sediments in estuaries of the Atlantic Coastal Plain. *Journal of Sedimentary Petrology*, 39, 222–234.

Meade, R.H., (1972) Transport and deposition of sediments in estuaries, In: *Environmental framework of coastal-plain estuaries* (B.W. Nelson, Ed.). *Geological Society of America Memoir* 133, pp. 91–120.

Meade, R.H., (1985) Suspended sediment in the Amazon River and its tributaries in Brazil during 1982–84. *US Geological Survey Open-File Report* 85-492, 39 p.

Meade, R.H., (1994) Suspended sediments of the modern Amazon and Orinoco Rivers, In: *Quaternary of South America* (M. Iriondo, Ed.). *Quaternary International*, v. 21, pp. 29–39.

Meade, R.H., (1995) Setting: geology, hydrology, sediments, and engineering of the Mississippi River, In: *Contaminants in the Mississippi River, 1987–92* (R.H. Meade, Ed.). *US Geological Survey Circular* 1133, pp. 13–28.

Meade, R.H., (1996) River-sediment inputs to major deltas, In: *Sea-level rise and coastal subsidence* (J.D. Milliman and B.U. Haq, Eds.). Kluwer, Dordrecht, pp. 63–85.

Meade, R.H., Nordin, C.F., Jr, Curtis, W.F., Mahoney, H.A., and Delaney, B.M., (1979a) Suspended-sediment and velocity data, Amazon River and its tributaries, June–July 1976 and May–June 1977. *US Geological Survey Open-File Report* 79-515, 40 p.

Meade, R.H., Nordin. C.F., Jr., and Curtis, W.F., (1979b) Sediment in rio Amazonas and some of its tributaries during the high-water seasons of 1976 and 1977. *Simpósio Brasileiro de Hidrologia, 3d, Anais*, v. 2, pp. 472–485.

Meade, R.H., Dunne, T., Richey, J.E., Santos, U. de M., and Salati, E., (1985) Storage and remobilization of suspended sediment in the lower Amazon River of Brazil. *Science*, 228, 488–490.

Meade, R.H., Weibezahn, F.H., Lewis, W.M., Jr, and Pérez Hernández, D., (1990) Suspended sediment budget for the Orinoco River, In: *El Río Orinoco como ecosistema/ The Orinoco River as an ecosystem* (F.H. Weibezahn, H. Alvarez and W.M. Lewis, Jr, Eds.). Impresos Rubel, Caracas, pp. 55–79.

Mertes, L.A.K., Dunne, T., and Martinelli, L.A., (1996) Channel-floodplain geomorphology along the Solimões-Amazon River, Brazil. *Geological Society of America Bulletin*, v. 108, pp. 1089–1107.

Milliman, J.D., and Meade, R.H., (1983) World-wide delivery of river sediment to the oceans. *Journal of Geology*, 91, 1–21.

Milliman, J.D., and Syvitski, J.P.M., (1992) Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers. *Journal of Geology*, 100, 525–544.

Milliman, J.D., Shen, H.-T., Yang, Z.-S., and Meade, R.H., (1985) Transport and deposition of river sediment in the Changjiang estuary and adjacent continental shelf. *Continental Shelf Research*, 4, 37–45.

Milliman, J.D., Qin, Y.S., Ren, M.E., and Saito, Y., (1987) Man's influence on the erosion and transport of sediment by Asian rivers: The Yellow River (Huanghe) example. *Journal of Geology*, 95, 751–762.

NEDECO, (1973) *Río Magdalena and Canal del Dique Survey Project*. Netherlands Engineering Consultants, The Hague, 397 p.

Nittrouer, C.A., and DeMaster, D.J., Eds., (1987) *Sedimentary processes on the Amazon continental shelf*. Pergamon, Oxford, 379 p.

Nittrouer, C.A., and Kuehl, S.A., Eds., (1995) *Geological significance of sediment transport and accumulation on the Amazon continental shelf*: *Marine Geology* (special issue), v. 125, nos 3 and 4, pp.175–399.

Nordin, C.F., Mejía, A., and Delgado, C., (1994) Sediment studies of the Orinoco River, Venezuela, In: *The variability of large alluvial rivers* (S.A. Schumm and B.R. Winkley, Eds.). American Society of Civil Engineers, New York, pp. 243–265.

Oltman, R.E., (1968) Reconnaissance investigations of the discharge and water quality of the Amazon River. *US Geological Survey Circular* 552, 16 p.

Pérez Hernández, D. and López, J.L., (1998) Algunos aspectos relevantes de la hidrología del Río Orinoco, In: *El Río Orinoco – Aprovechamiento sustentable* (J.L. López Sánchez, I.I. Saavedra Cuadra and M. Dubois Martínez, Eds.). Universidad Central de Venezuela, Caracas, pp. 88–98.

Pierson, T.C., Janda, R.J., Thouret, J.-C., and Borrero, C.A., (1990) Perturbation and melting of snow and ice by the 13 November 1985 eruption of Nevado del Ruiz, Colombia, and consequent mobilization, flow, and deposition of lahars. *Journal of Volcanology and Geothermal Research*, 41, 17–66.

Potter, P.E., (1978a) Significance and origin of big rivers. *Journal of Geology*, 86, 13–33.

Potter, P.E., (1978b) Petrology and chemistry of modern big river sands. *Journal of Geology*, 86, 423–449.

Potter, P.E., (1997) The Mesozoic and Cenozoic paleodrainage of South America: a natural history. *Journal of South American Earth Sciences*, 10, 331–344.

Projeto RADAM, (1973) Mosaico semi-controlado de radar SA-20-Y-A: 1 sheet, scale 1: 250 000.

Richey, J.E., Meade, R.H., Salati, E., Devol, A.H., Nordin, C.F., Jr, and dos Santos, U., (1986) Water discharge and suspended sediment concentrations in the Amazon River: 1982–1984. *Water Resources Research*, 22, 756–764.

Richey, J.E., Mertes, L.A.K., Victoria, R.L., Forsberg, B.R., Dunne, T., Oliveira, E., and Tancredi, A., (1989) Sources and routing of the Amazon River floodwave. *Global Biogeochemical Cycles*, 3, 191–204.

Ritter, J.R., 1977a, Reconnaissance of sediment transport and channel morphology in the lower Río Bermejo basin, Argentina, with a section on reconnaissance of the lower Río Pilcomayo basin, Argentina and Paraguay. *US Geological Survey Open-File Report* 76-564, 41 p.

Ritter, J.R., 1977b, Reconnaissance of sedimentation in the Río Pilcomayo basin, May 1975, Argentina, Bolivia, and Paraguay. *US Geological Survey Open-File Report* 77-327, 34 p.

Salo, J., Kalliola, R., Häkkinen, I., Mäkinen, Y., Niemelä, P., Puhakka, M., and Coley, P.D., (1986) River dynamics and the diversity of Amazon lowland forest. *Nature*, 322, 254–258.

Seyler, P.T., and Boaventura, G.R., (2001) Trace elements in the mainstem Amazon River, In: *The biogeochemistry of the Amazon Basin* (McClain, M.E., Victoria, R.L., and Richey, J.E., Eds.). Oxford University Press, Oxford, pp. 307–327.

Shi, C.-X., Dian, Z., and You, L.-Y., (2002) Changes in sediment yield of the Yellow River basin of China during the Holocene. *Geomorphology*, 46, 267–283.

Sioli, H., (1951) Sobre a sedimentação na várzea do baixo Amazonas. *Instituto Agronómico do Norte Boletim Técnico* no. 24, pp. 45–65.

Sioli, H., (1957) Sedimentation in Amazonasgebiet. *Geologische Rundschau*, 45, 608–633.

Sioli, H., (1984) The Amazon and its main affluents: Hydrography, morphology of the river courses, and river types, In: *The Amazon – limnology and landscape ecology of a mighty tropical river and its basin* (H. Sioli, Ed.). Dr W. Junk, Dordrecht, pp. 127–165.

Slater, C., (2002) *Entangled Edens: visions of the Amazon*. University of California Press, Berkeley, 332 p.

Stallard, R.F., (1995) Tectonic, environmental, and human aspects of weathering and erosion: a global review using a steady-state perspective. *Annual Review of Earth and Planetary Science*, 23, 11–39.

Stallard, R.F., Koehnken, L., and Johnsson, M.J., (1990) Weathering processes and the composition of inorganic material transported through the Orinoco River system, Venezuela and Colombia, In: *El Río Orinoco como ecosistema/ The Orinoco River as an ecosystem* (F.H. Weibezahn, H. Alvarez and W.M. Lewis, Jr, Eds.). Impresos Rubel, Caracas, pp. 81–119. (Reprinted in 1991 in *Geoderma*, 51, 133–165.)

Sternberg, H.O., (1956) *A Água e o Homem na Várzea do Careiro*. Universidade do Brasil, Rio de Janeiro. (Second edition: 1998, published by Museu Paraense Emilio Goeldi, Belém, v. 1, 248 p. + Appendix; v. 2, 17 maps.)

Sternberg, H.O., (1975) *The Amazon River of Brazil*. Geographische Zeitschrift Beihefte, 40, 74 p.

Suárez-Araúz, N., (1999) Amazonian literature: a fountain of memory and amnesia. *Amazonian Literary Review*, issue 2, pp. v–xx.

Wallace, A.R., (1853) *A narrative of travels on the Amazon and Rio Negro, with an account of the native tribes, and observations on the climate, geology, and natural history of the Amazon Valley*. Reeve & Co., London. (The 2nd edition of 1889: Ward, Lock and Co., London, 363 p., has been reprinted numerous times, e.g., (1972) Dover Publications, New York.)

Warne, A.G., Meade, R.H., White, W.A., Guevara, E.H., Gibeaut, J., Smyth, R.C., Aslan, A., and Tremblay, T., (2002) Regional controls on geomorphology, hydrology, and ecosystem integrity in the Orinoco Delta, Venezuela. *Geomorphology*, 44, 273–307.

Winkley, B.R., Ordonez, J.I., Saenz, J.E., and Duque, R., (1994) The Magdalena River, Colombia, In: *The variability of large alluvial rivers* (S.A. Schumm and B.R. Winkley, Eds.). American Society of Civil Engineers, New York, pp. 139–160.

Zhao, Y.A, Pan, X.D., Fan, Z.Y., and Han, S.F., (1989) Sedimentation in the lower reaches of the Yellow River and its basic laws, In: *Taming the Yellow River: silts and floods* (L.M. Brush, M.G. Wolman and B.W. Huang, Eds.). Kluwer, Dordrecht, pp. 477–516.

Zhou, Z., and Pan, X.-D., (1994) Lower Yellow River, In: *The variability of large alluvial rivers* (S.A. Schumm and B.R. Winkley, Eds.). American Society of Civil Engineers, New York, pp. 363–393.