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12 The Late-Quaternary Palaeohydrology of Large South American Fluvial Systems

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1 INTRODUCTION

South America has some of the largest rivers in the world in terms of water discharge, including the Amazon River and its tributaries, the Negro and Madeira Rivers, the Orinoco, Paraná, Tocantins and other large rivers such as the São Francisco, the Magdalena and the Uruguay River (Figure 12.1). The rivers listed above drain an area of ~11,800,000 km^2 or approximately 66% of South America. The large South American rivers discharge ca 28% of the total global river water to the oceans. South America has not only the largest rainforest of the earth, the Amazon, but also has the Cerrado savanna and large tropical plains such as the Llanos of Colombia and Venezuela, the Chaco and the Pampa. Despite the enormous potential for the study of fluvial systems, research on hydrology, geomorphology and palaeohydrology of these major basins is comparatively scarce. This chapter focuses on the general geomorphologic and hydrologic background of the main basins of South America and analyzes the impact of global change on the fluvial systems during the Last Glacial and the Holocene. Recent research on fluvial deposits, vertebrate palaeontology, and palynology, together with geomorphological studies, demonstrates that the tropics of South America experienced dramatic climatic and palaeogeographic changes during the Late Quaternary, specifically during the Middle Pleniglacial and Upper Pleniglacial, followed by minor but significant changes during the Holocene.

Nevertheless, almost three quarters of South America is situated between the tropics, making it basically a tropical as well as a fluvial continent, where the responses of the tropical regions and its giant fluvial systems to Quaternary climate changes are not well understood. Little is known about the climatic changes that occurred during the last glaciation, more specifically, since the Middle Pleniglacial, and this chapter considers both existing and new data collected from the large fluvial basins of South America.

2 THE AMAZON BASIN

The Amazon is the largest fluvial basin of the world, with a drainage area of more than 6,000,000 km^2. To the west and to the southwest, it is limited by the Andes mountain chain, and to the north and the south by the Brazilian and the Guyana shields. With an average discharge of more than 209,000 m^3 s^{-1} and a sediment load

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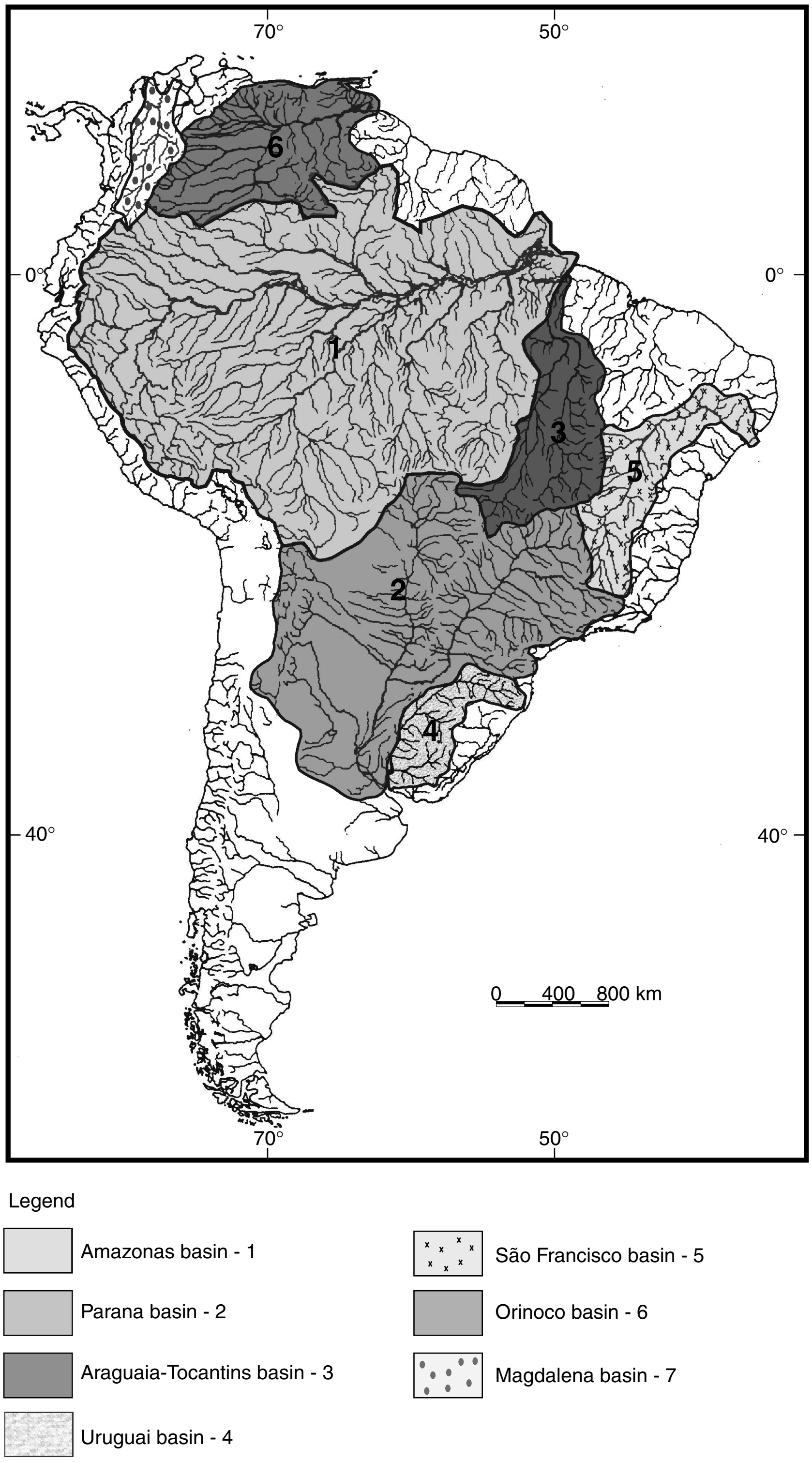
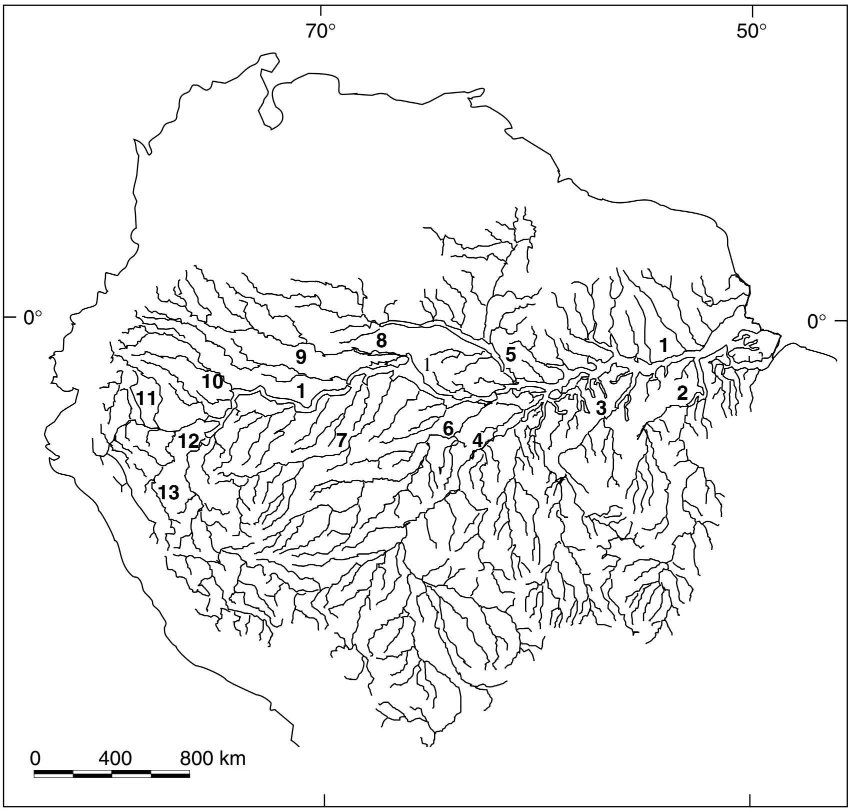


Figure 12.1 Major fluvial basins of South America

of more than 1.2 billions of tons per year of suspended load (Filizola, 1999; Meade *et al.*, 1983), the Amazon river is the largest and most unique fluvial system of the world in water discharge. The Amazon is the collecting system that receives water and sediments from a large variety of tributaries. Large tributary systems such as the Madeira, Negro, Japurá, Purus and others are ranked among the 20 largest rivers of the planet (Figure 12.2, Table 12.1).

The Amazon Rivers can be classified into three groups:

1. Fluvial systems with headwaters in the Andes chain (Ucayali, Marañón, Madre de Dios, Caquetá-Japurá, Putumayo-Iça, Pastaza).
2. Fluvial systems with headwaters in sedimentary lowlands (Purus Juruá, Javarí).
3. Fluvial systems with headwaters in the cratonic areas (Xingú, Negro, Tapajos, Trombetas).



Legend

1 - Solimoes-Amazonas
2 - Xingú
3 - Tapajos
4 - Madeira
5 - Negro
6 - Purus
7 - Juruá
8 - Caquetá/Japurá
9 - Putumayo-Içá
10 - Napo
11 - Pastaza
12 - Ucayali
13 - Marañón

Figure 12.2 The Amazon basin and the main Amazon tributaries

Table 12.1 Drainage area, average water discharge and sedimentary load for the main fluvial systems of South America

Basin	River	Drainage area (km^2)	Mean annual discharge (m^3 s^{-1})	Sediment load (tons yr^{-1})
Amazonas	Amazon	6,000,000	^{1}209,000	$^{2}1{,}000 \times 10^{6}$
	Madeira	1,360,000	^{1}32,000	$^{3}{\sim}400/500 \times 10^{6}$
	Negro	696,000	^{1}~28,400	$^{3}6 \times 10^{6}$
	Japurá/Caquetá	248,000	^{1}18,620	$^{3}23 \times 10^{6}$
	Purus	370,000	^{1}11,000	$^{3}29 \times 10^{6}$
	Juruá	185,000	^{1}8,440	$^{3}26 \times 10^{6}$
Orinoco	Orinoco	1,100,000	^{2}35,000	$^{2}150 \times 10^{6}$
• Q1 Paraná	Paraná	2,600,000	^{4}18,000•	$^{5}112 \times 10^{6}$
Tocantins	Tocantins	800,000	^{6}~13,000	^{7}
	Araguaia	360,000	^{6}6,400	$^{7}18 \times 10^{6}$
• Q2 Magdalena (1)•	Magdalena	257,438	^{8}7,200	$^{8}144 \times 10^{6}$ (1)
São Francisco (2)	São Francisco	650,000	^{7}3,800	$^{7}16 \times 10^{6}$
Uruguay	Uruguay	365,000	^{9}4,660	$^{10}{\sim}6 \times 10^{6}$

Source: [1]Filizola, 1999; [2]Meade, 1994; [3]Martinelli *et al.*, 1988; [4]Giacosa *et al.*, 2000; [5]Amsler and Prendes, 2000; [6]Data estimated from the Brazilian National Agency of Water-ANA; • Q3 [7]ELETROBRAS, 1992; [8]Restrepo and Kjerfve, 2000; [9]Paoli *et al.*, 2000; [10]Amsler and Prendes, personal communication.•

The Amazon rainforest is the largest tropical rainforest of the world and occupies more than 6 million km^2, spread mostly over the Amazon fluvial basin. Although the rainforest extends into various countries, 60% of the total area is located in Brazil (Capobianco, 2001). In reality, the Amazon region is a complex mosaic of different vegetation types, including closed rainforest, flooded forests, campina forests, savannas, bamboo forests, mangroves, montane and sub-montane forests and liana forests (Murça–Pires, 1984; Nelson and Oliveira, 2001). A humid and tropical climate prevails. Rainfall, averaging 2,000 mm yr^{-1}, increases in the northwest and in some parts of the Sub-Andean zone it can reach more than 4,000 mm yr^{-1}.

2.1 The Pleistocene Fluvial Record

Rivers of the Amazon basin have well-developed alluvial plains and terraces formed by Late Quaternary sediments. In several rivers, the position of the channel and the morphology and size of the alluvial plains have been related to neotectonic activity during the Late Quaternary (Sternberg, 1950; Tricart, 1977; Iriondo and Suguio, 1981; Dumont and Fournier, 1994; Latrubesse and Rancy, 2000; Latrubesse and Franzinelli, 2002). However, this chapter focuses its analysis mainly on the fluvial sedimentary and geomorphologic record as sources of palaeohydrological signals. Sandy and conglomerate sediments were deposited in Middle Pleniglacial times during the Late Pleistocene (ca 65,000–24,000 yr BP) in the Ucayali, Madre de Dios, Caquetá, Purus, Jurua and Negro fluvial systems. In the Peruvian Amazon, coarser sediments were deposited between 32 and >40 kyr BP. Dumont *et al.* (1992) found alluvial gravels that were up to 10 times coarser than the present sandy bed load in the Ucayali River, and coarse sediments in the Madre de Dios River with wood dated around 36 to 38 kyr BP.

Alluvial sedimentation was also recorded in rivers draining the northern Andes such as the Caquetá River, in the Colombian Amazon (named Japurá River in Brazilian territory) and the Pastaza River. In the Caquetá, sandy and gravel deposits with some layers of clay and peaty material are recorded in a lower terrace. Radiocarbon analyzes ranged between 30 kyr BP and infinite age (Van der Hammen *et al*., 1992a). A large fan that extended over an area of approximately 60,000 km^2 was formed by the Pastaza River (Rasanen, 1993; Iriondo, 1994). The age of the sediments estimated by Rasanen (1993) indicates episodes of deposition in the Pastaza fan, occurring at least between 33 kyr BP and 7 kyr BP.

Alluvial deposits with characteristic Quaternary conglomerates were found in a lower terrace of some southwestern Amazon rivers including the Acre, Jurua, Purus and Madeira rivers (Latrubesse, 2000; Latrubesse and Rancy, 1998; Latrubesse and Kalicki, 2002). The most precise Quaternary data were obtained from the upper Jurua and Purus basins where more than 25 radiocarbon dates of wood and leaves in sediments were obtained. The coarse sediments were deposited during the Middle Pleniglacial and the early stages of the Upper Pleniglacial. In some rivers such as the Jurua and Madeira, the conglomerates have a rich fossiliferous level (Simpson and Paula Couto, 1981; Latrubesse and Rancy, 1998) containing Pleistocene fossil mammals. This "bone-bearing conglomerate" is found in the lower terrace, and facially represents a lag facies or a short period of strong morphogenetic channel activity with the formation of gravel channel bars. Sediments attributable to the Middle Pleniglacial were also found in the Moa River, an affluent of the Juruá River (Latrubesse and Rancy, 2000).

On rivers draining cratonic areas such as the Negro, Xingú, Tapajos and others, the Quaternary alluvial sedimentary record is not yet available in detail. There are some data from the upper Negro River basin (Latrubesse and Franzinelli, 1998). In the Tiquié, Vaupés and Curicuriarí rivers, Late Pleistocene alluvial sandy to coarser sediments frequently form a terrace level of about 14-m thickness produced by sandy to gravel deposits that include plant fragments (stems and leaves), organic matter and impregnation of iron oxide. Radiocarbon dating of trunks and organic matter gives results ranging from 27 kyr to more than 40 kyr BP (infinite age). This episode of sedimentation was provisionally correlated with the Middle Pleniglacial (Latrubesse and Franzinelli, 1998). The palaeohydrological regime of the basin was similar to that of the present producing supermature quartz sands, but the rivers were morphogenetically more active, moving sediments coarser than those of today and aggrading the fluvial system. This indicates more discharge variability and flood energy than at present. In the upper Rio Negro basin, the sedimentological record is similar with palynological results obtained on the watershed between the Caquetá and Negro rivers, where drier and more open vegetation covered a larger area than it does today, but probably with forest-like dominant type of vegetation (Van der Hammen *et al*., 1992a).

Two large fans, occupying an area of thousands of square kilometers, were recorded in the Middle Amazon (Latrubesse, 2002). The fans were formed by two tributaries of the Madeira River: the Jiparana and the Aripuanã rivers, which drain the Brazilian Shield. The Aripuanã system is the larger one and extends over an area of more than 29,000 km^2. Fluvial inactive belts of up to 2.5 km in width and nearly 200 km in length were recognized in this large system. Typically the fluvial belts are relicts
● Q4 and fragmentary and not more than 10 to 20 km in length. TL● dating of 20 ka BP
suggests a Late Pleistocene age, indicating deposition during the Last Glacial Maximum (LGM). Palaeohydrological interpretation of the fans indicates past aridity in the area, replacement of the forest by savanna and avulsion processes in the rivers. Palynological results by Van der Hammen and Absy (1994) obtained at the Catira site in the Rôndonia State (ca 9° S, 63° W) close to the Jiparana River suggest arid

conditions in the area with replacement of forest by savanna during part of the Middle and Upper Pleniglacial, and rainfall estimated to be below 1,000 to 500 mm during the LGM. The generation of the fans agrees with the vegetation and climatic scenario presented by Van der Hammen and Absy (1994) for this part of Amazon.

A younger late Pleistocene phase of sedimentation correlating with the Lateglacial was described in some rivers of the Amazon. In the Peruvian Amazon, Dumont *et al.* (1992) concluded that at 13 kyr BP, the discharge of the Ucayali River was 7 to 10 times smaller than at present. Sedimentation was recorded in the middle Caquetá (Japurá) River (<14 kyr BP) (van der Hammen *et al.*, 1992b) and also in the cratonic basins of the Rio Negro and the tributaries of the Madeira River, on the Jiparana and Aripuanâ fans (Latrubesse and Franzinelli, 1998; Latrubesse, 2002). Holocene data showed that the Amazon suffered the effect of climatic oscillations, which affected the fluvial systems, but to a lesser extent than during the Late Pleistocene. Lower to Middle Holocene deposits are recorded in the Juruá, Purus, Caquetá Rivers, while Upper Holocene sediments younger than 3000 yr BP are also recorded in the Amazon River. Sedimentation during the early-middle Holocene is probably associated with a progressive decrease of precipitation reaching a peak of aridity during the Hypsithermal (7,000–4,500 yr BP).

No important climatic changes have been registered in the Amazon basin during the Late Holocene, although important and drastic changes in river behavior have been registered at that time in some basins including the Negro and Amazon rivers (Latrubesse and Franzinelli, 1998; Latrubesse and Franzinelli, 2002). A major part of the recent alluvial sediments of the Amazon/Solimões (Latrubesse and Franzinelli, 2002) and of the large and abundant islands of the Negro River (Latrubesse and ● Q5 Franzinelli, in prep.●) were deposited in the Late Holocene and were thus more recent than the Middle Holocene climatic change. It is proposed that the Amazon and Negro rivers had a complex and delayed response to variations in the hydrological conditions that were provoked by changes in the Middle Holocene regional climate, approximately during the last 4,000 to 3,500 yr BP. The Negro changed from a river carrying relatively abundant suspended load and with dominant vertical accretion to a river with less suspended load and "black water", while the Amazon River evolved from a river with high rates of vertical accretion to a river with more lateral activity. Late Holocene climate oscillations have been a relatively minor influence on the river channels and on floodplain development, which were affected by continuing autogenic processes (Latrubesse and Franzinelli, 2002).

2.2 Aeolian Sediments in Amazonia

Large fields of aeolian deposits have recently been identified in the Amazon. Sand fields are currently covered by a "campina" vegetational association, composed of low, sparse trees and abundant tall grass. Parabolic dunes with ENE–WSW and NE–SW orientation, probably of the Holocene and the recent age, were identified in the "Pantanal Setentrional". This is the largest area with sandy deposits in the Amazon, and covers nearly 100,000 km^2 between the middle Negro and Branco rivers (Carneiro Filho, 1992; Nelson, 1994; Santos, 1992; Santos *et al.*, 1993). Smaller sand fields between Manaus and the Atlantic coast were described by Iriondo and Latrubesse (1994).

To the north, in the state of Roraima (Brazil) and in western Guyana, aeolian silty and sandy deposits nearly 2 m thick are spread over more than 10,000 km^2 and longitudinal and parabolic dunes with NE–SW orientation are distinguishable to the north of the Tucano range area and in the Cauame area. Silty sediments were deposited peripherally to the west of the aeolian system and also in intramontane valleys. These sediments were interpreted as deposits of an aeolian system during the Late Pleistocene (Latrubesse and Nelson, 2001). A more recent drier period, probably of early-middle Holocene age, is indicated by the existence of pans or blowout hollows. Recently, important results were obtained (Carneiro Filho *et al.*, 2002) on the chronology of the dune fields in the Amazon basin, with TL dating in the palaeodune fields of Catrimani, Aracá, Temedauí, Tucano and Anauã, indicating periods of aeolian activity from the end of the Middle Pleniglacial to the early Holocene (32 ka BP to 8 ka BP). In the area between Manaus and Parintins, in middle Amazonia, silty loams, clayey loams and clayey sands cover the landscape as an irregular mantle, with the upper sections formed by massive loam interpreted to be primarily of aeolian origin (Iriondo and Latrubesse, 1994).

3 THE PARANA BASIN

The Parana is the second largest basin of South America considering its drainage area of 2.6 million km^2, and extends into Argentina, Brazil, Paraguay and Bolivia. The Parana River ranks sixth in the world according to water discharge with a mean discharge of ca 17,000 $m^3\,s^{-1}$ and a sedimentary load of approximately 112 million tons a year (Figure 12.1, Table 12.1). The basin drains a variety of geological environments. The Parana sedimentary basin extends over more than 29% of the basin, 29.8% of the Chaco-Pampean region, while the Precambrian Brazilian shield and the Andean chain contribute 7.4% each, approximately. Other units such as the Argentinean Mesopotamia, the Pantanal basin and the Carboniferous sediments of the Upper Parana and other minor units comprise the remaining 26.4% (Paoli *et al.*, 2000). The climate also shows a large variety with a tropical humid climate in the Brazilian region, tropical with a dry season in the Chaco region, temperate in the Pampean region and humid mountainous to semiarid in the Andes. The Chaco tributaries contribute comparatively little water discharge but are the tributaries that are the main sources of suspended sediments. The Bermejo River, a relatively small river draining from the Andes, which crosses the Chaco, introduces just 5% of the water discharge of the Parana but more than 56% of the suspended sediment (more than 50 million tons per year) of the system (Amsler and Prendes, 2000). The water discharge is derived mainly from the Brazilian territory along the upper-Brazilian tributaries and from its main tributary, the Paraguay River. Up to the confluence with the Paraguay, the river has an average discharge of 12,400 $m^3\,s^{-1}$, and the contribution of the Paraguay is more than 3,800 $m^3\,s^{-1}$.

The Quaternary record of the basin is analyzed by differentiating the basin into three main geomorphologic/sedimentary domains: the Parana River, the Pantanal/Paraguay basin and the Chaco system.

3.1 The Parana River

Significant advances have been made on the Quaternary history of the Upper Parana during recent years. Four main climatic events were inferred in the area during the Late Pleistocene and Holocene (Stevaux, 1994; 2000; Stevaux and Santos, 1998). The first event (40–8.5 kyr BP) is characterized by a braided channel with gravelly and sandy deposits. At that time the climate was drier than at present and the savanna vegetation was replaced by subtropical forest. Aeolian activity forming dunes and “pans” was dated by TL with an age of 23,540 ± 2,240 BP (Upper Pleniglacial) (Stevaux, 2000). The second change occurred during the Holocene, around 8.5 ka BP when the climate was wetter and the alluvial plain was excavated. An anastomosing pattern developed, construction of the Holocene floodplain began and a pluvial subtropical forest was installed in the area (Klein, 1975). A shorter drier episode between 3,500 and 2,500 years ago altered the fluvial system. Secondary channels were abandoned and backswamp areas along the alluvial plain were generated. From 2.5 ka to the present, down cutting of the channel occurred into the older units, migration occurred to the left margin, the river continued an anastomosing-braided pattern, and the present pluvial subtropical forest reached its maximum development (Klein, 1975). No significant data about fluvial deposits exist for the middle Parana area.

3.2 The Upper Paraguay/Pantanal Sub-basin

Interesting features are recorded in the Upper Paraguay basin, in the area known as the Pantanal, that is, a large flooded area of more than 100,000 km^2 located on the border of Brazil, Bolivia and Paraguay. The Upper Paraguay is a large sedimentary basin occupied by large coalescing fans formed by the Cuiabá, Taquarí, São Lourenço and other minor rivers draining into the Paraguay River (Tricart *et al.*, 1984). With a semicircular shape and a diameter of approximately 250 km, the Taquari fan is the largest aggradational feature of the Pantanal. The fans were probably formed during the Late Quaternary, although some of them, such as the Taquari, continue to be partially active at present. Aeolian activity formed "pans" or deflation hollows during an arid period of the Holocene (Tricart *et al.*, 1984; Klammer, 1982), probably during the late Holocene (3,500–1,000 years BP). This can be inferred very provisionally from a dating of molluscs in a shallow flooded "pan" of 3,820 ± 70 years BP (Assine *et al.*, 1997).

3.3 The Chaco System

The Chaco is a large plain of approximately 840,000 km^2, which is spread between Bolivia, Paraguay and Argentina. It is situated on both sides of the Tropic of Capricorn, between the Amazon and the Pampa, and borders the Sub-Andean chain and the highlands of the Brazilian Planalto to the west. The climate of the Chaco ranges from semiarid tropical to humid tropical. Annual precipitation varies from west to east from 1,000 to 2,500 mm in the Sub-Andean zone, 400 mm in the Occidental Chaco and 1,200 mm in the Oriental Chaco (Schmieder, 1980). The vegetation is forest, savanna and swamp vegetation (Lopez Gorostiaga, 1984). The fluvial systems of the Chaco are mainly tributaries of the Parana basin such as the Salado, Pilcomayo and Bermejo. During some phases of the late Quaternary, the Parapetí River drained into the Amazon basin and into the Parana basin, whereas at present it flows to the Izozog swamps and connects with the Mamoré River, a tributary of the Amazon basin. The Grande River drains in the direction of the Amazon basin as a tributary of the Mamoré River. The rivers have their headwaters in the Andean and Sub-Andean zones and carry abundant suspended load during peak discharges. There is a scarcity of Quaternary data for the Chaco region although this is one of the more spectacular areas for the study of fluvial sedimentary records, geomorphology and palaeohydrology with the main synthesis of Chaco geomorphology provided by Iriondo (1993).

A conspicuous geomorphologic characteristic of the Chaco is the formation of large Quaternary alluvial fans by the rivers mentioned above. During the Late Pleistocene, they formed complex sedimentary mega-depositional systems, which represent the largest system of coalescing fluvial fans in the world, each mega-fan having special characteristics. In general, they are formed by well-delimited alluvial belts, produced during humid periods of the Late Quaternary, and smaller and lesser stable palaeochannels during dry climates. Swamps and swampy areas are typical and Quaternary paludal deposits and present day swamps cover an area of 125,000 km^2 in the Bermejo and Pilcomayo regions. The fans were affected by two arid episodes in the Late Quaternary (Iriondo, 1993). The first one could have occurred during the LGM and the second during the late Holocene. However, dry episodes with dune reactivation were also recorded during the Middle Holocene in the northernmost fans such as the Parapetí (Kruck, 1996). During the LGM, the fans were formed by small shifting ephemeral channels, spill outs, and experienced contemporaneous aeolian activity that produced the formation of dune fields and loess deposition. TL and OSL● dating by Kruck (1996) for the Pilcomayo fan deposits gave recorded ages that oscillated between 12 ka BP and 9 ka (Lateglacial-early Holocene). During the humid episodes of the Holocene, the fans were characterized by the development of well defined but unstable alluvial belts, which were abandoned by avulsion. TL and OSL dates on sediments of palaeochannels indicate avulsion of fluvial belts between 8 ka BP and approximately 3.5 to 3 ka BP (Kruck, 1996). Aeolian remobilization occurred in the Parapetí fan between approximately 6 ka BP and 3 ka BP.

● Q6

During the late Holocene, a dry period was recorded between ~3,5 and 1 kyr BP and the widespread system of small ephemeral migrating channels was reactivated. Local dune fields, pans and loess-like sediments were deposited. In the Grande River, the last dunes were formed up to approximately 1.4 kyr BP. At present some of the giant fans continue to evolve. The Pilcomayo fan, for example, is the largest active fluvial fan in the world, which since the Late Quaternary has spread over an area of sedimentation of 200,000 km^2.

4 THE URUGUAY BASIN

The Uruguay drains an area of approximately 365,000 km^2 from the Brazilian territory, to the La Plata River (Paoli *et al.*, 2000). The Uruguay and the Parana being the main former rivers of the La Plata basin meet in a large estuary. Its mean annual discharge in the lower course is approximately 4,660 m^3 s^{-1} but a peak discharge of 36,000 m^3 s^{-1} and low flows of 95 m^3 s^{-1} have been recorded (Iriondo, 1999) (Figure 12.1, Table 12.1).

Several units of Quaternary sediments and a good record of fossil mammals are found in the Uruguay fluvial basin. Related to the last glaciation, the fluvial sandy-to-sandy silty sediments of the Arroyo Feliciano Formation were deposited in large palaeochannels during the Middle Pleniglacial (Iriondo, 1999). During the Upper Pleniglacial, colluvial deposits spread in the minor valleys of the basin and loess deposits covered the fluvial landforms in part. A lower terrace is formed by alluvial deposits (conglomerates, sands and fine deposits with carbonate crusts and concretions), attributed to the Sopas Formation in Uruguay (Antón, 1975) and to the Touro Passo Formation in Brazil (Bombim, 1976). The deposits are indicators of semiarid conditions in the basin. Regarding the alluvial sediments of the Sopas Formation that are rich in vertebrates of Lujanean mammal stage, controversies exist about the age of these deposits. Iriondo (1999) suggests an age between 13 and 8 kyr BP and Anton (1975) suggests an age no greater than 30 kyr BP for these rich fossiliferous deposits. However, radiocarbon-dating by Ubilla and Perea (1999) on freshwater mollusc shells and wood, indicates ages of >43 kyr BP and >45 kyr BP respectively, which could indicate that the Sopas formation is older than previously suggested. However, correlation of the Sopas Formation with the last interglacial (120–140 ka BP), as indicated by Ubilla and Perea (1999), is very difficult to accept because the evidence is very weak. This is controversial when we consider that the Palmar Formation, another unit of alluvial deposits rich in palaeomammals, was positioned by Iriondo (1999) in the last Interglacial. That unit was recorded on the Argentinean banks of the rivers and was not recorded in Uruguayan territory, on the right bank. If this is correct, the Sopas Formation can probably be positioned provisionally in the Middle Pleniglacial.

The Dolores Formation is young and composed of alluvial deposits such as silts, clays, sandy to gravelly fine sediments and sands, related to both arid and cold conditions in the basin (Preciozzi *et al.*, 1985). Radiocarbon ages indicate an age of 11 ka BP (Ubilla, 1996). The Holocene record in the Uruguay basin is similar to that of the Parana system, with a warmer and humid climate during the Hypsithermal and a dry period during the Late Holocene (3,5–1,5 kyr BP) (Iriondo, 1999).

5 THE ORINOCO BASIN

The Orinoco River drains an area of about 830,000 km^2 in Venezuela and Colombia with● the average water discharge being about 36,000 $m^3 s^{-1}$ and the suspended-sediment discharge to the delta being more than 200 million tons (Nordin and Perez-Hernández, 1989). The Orinoco is the third largest river of the world and probably the eighth largest in terms of sediment discharge (Meade *et al.*, 1983) (Figure 12.1, Table 12.1). The most important sediment-carrying tributaries are the Guaviare, Meta and Apure rivers, which come from the Andes, cross the Llanos, enter the Orinoco by the left bank, and, like rivers draining the Guyana Shield in the Amazon basin, carry low concentrations of suspended sediment. However, they contribute large discharges and probably have substantial amounts of bed load (Nordin and Perez Hernandez, 1989). The Orinoco is characterized by high bedrock control and rapids at node points between which broad areas of floodplains develop. The Orinoco River floodplain can be divided into fringing floodplain and internal deltas (Hamilton and Lewis, 1990). The fringing floodplain of the Orinoco main channel extends from the Meta River to the delta and covers approximately 7,000 km^2 (Warne *et al.*, 2002). However, in the Apure, Arauca and Meta flooded areas, sediments are stored in an area of 70,000 km^2 (Welcomme, 1979). The tributaries form fanlike features in a swampy area, which is affected by the hydrologic dynamics of the Orinoco. Meade *et al.* (1983) estimated that one half of the amount of sediment transported by the Meta River is temporarily stored in fanlike or internal deltalike deposits.

● Q7

The hydrologic regime is dominated by a tropical wet–dry climate with a high ratio of maximum to minimum discharges so that discharge average variability is about 26 but can oscillate between 54 and 8.1 (Nordin and Perez-Hernandez, 1989). During the low-flow season, deflation affects a large area of fluvial sediment that can be transported upstream by the wind each year.

Despite the enormous potential for palaeohydrological research, the Late Quaternary history of the Orinoco fluvial system is practically unknown although major hydrological changes affecting the Orinoco can be inferred from records of areas in Venezuela and Colombia. During the Late Pleistocene, the Orinoco basin had a climate drier than that at present and in the northwest of the Orinoco delta and in the lower Apure region, large aeolian dune fields were formed (Khobzy, 1981; Carbon and Schubert, 1994;

● Q8

Iriondo, 1997). Inland, between the Meta and Orinoco Rivers, a loess or loess-like formation covered the Colombian Llanos (Gosse, 1971●; Iriondo, 1997). It is inferred that the Orinoco had less discharge than today because at that time the northeast trade winds of the northern hemisphere were more intense and persistent in the area. Dunes were active in the Orinoco Llanos during part of the Middle Pleniglacial and the Upper Pleniglacial, with TL dating (Vaz and Garcia, 1989) indicating dune formation at 36,000 ± 5,000 years BP. Palaeosoils developed under the aeolian sediments dated back to 11,100 ± 450 years BP (Roa, 1979). The pollen record in the Colombian Llanos also agrees with the interpretation of this humid climatic condition during part of the Lateglacial (Behling and Hooghiemstra, 1998).

An arid phase towards the end of the Lateglacial and early Holocene (11,600 ± 1,600 years BP) produced reactivation of aeolian activity and dune formation (Vaz and Garcia, 1989), although that dry period was less intense than that of the LGM. The pollen record in the Colombian Llanos indicates drier conditions between ca 10,000 and 5,000 yr BP (Behling and Hooghiemstra, 1998).

6 THE MAGDALENA RIVER

With an average discharge of 7,200 m^3 s^{-1} and a drainage area of 257,438 km^2 the Magdalena River is the main system draining the Andes of Colombia to the Caribbean Sea (Restrepo and Kjerfve, 2000) (Figure 12.1, Table 12.1), with headwaters at an elevation of more than 3,000 m, and the Cauca, Sogamoso, San Jorge and Cesar Rivers as the main tributaries. The mean rainfall for the drainage basin is 2,050 mm yr^{-1} but some areas receive more than 3,000 mm yr^{-1}. Despite having relatively small catchments, the Magdalena carries more sediment to the ocean than the Orinoco or the Parana, which have the largest basins and the highest water discharges. Milliman and Meade (1983) estimated an annual sediment load of 220×10^6 t yr^{-1} while Restrepo and Kjerfve (2000) estimated a mean sediment load of 144×10^6 t yr^{-1}. From a geomorphic and sedimentary point of view, the Magdalena was considered an anastomosing river situated in a tectonically active foreland basin with wetlands, which maintained an anastomosing pattern, with average rates of vertical accretion of 3.8 mm yr^{-1} in response to the subsiding basin, at least during the last 8,000 yr BP (Smith, 1986). Van der Hammen (1986) proposed the existence of fluctuations in the flood stage of the Magdalena during the Holocene. On the basis of an analysis of borehole evidence, he proposed dry periods in ca 7,000 yr BP, 5,500 yr BP, 4,700 yr BP, 4,000 yr BP, 2,500 to 2,100 yr BP, 1,400 yr BP and 700 yr BP, although, as the method used does not include morpho-sedimentary analysis with a detailed study of facies, the results need to be considered with caution. Anastomosing rivers in a subsiding basin tend to develop changes in the areas flooded, swamps, channel-crevasse splays and channel avulsion. As both facies and sedimentary environments change along the alluvial plain, different types of sediments and differential rates of accumulation occur in the fluvial record, even without the direct influence of change in the hydrological regime.

7 CENTRAL BRAZIL: THE TOCANTINS AND THE SÃO FRANCISCO BASINS

Two main basins drain Central Brazil: the Tocantins–Araguaia River and the São Francisco River. There is little information about palaeohydrology and palaeoclimates of these basins.

The Tocantins–Araguaia basin is practically ignored in international literature on large rivers. With an area close to 800,000 km^2, the Tocantins ranks in the twentieth or twenty-first position among world rivers, with drainage basin sizes close to that of the Mekong and Danube, although, only having a mean annual water discharge ca 12,000 m^3 s^{-1}. The Araguaia–Tocantins River could be ranked tenth or eleventh according to water discharge. The Tocantins basin is located on the central highlands of Brazil at altitudes lower than 1,000 m, the geological setting comprises Precambrian rocks of the Brazilian Shield, Palaeozoic and Mesozoic rocks of the Paraná basin, the tertiary terrigenous sequence and widespread Quaternary deposits. The area is covered mainly by the Brazilian savannas ("Cerrado"), and by the Amazon rainforest in the lower course of the Tocantins. Annual rainfall varies between 1,200 mm in the upper basin and more than 2,000 mm in the lower basin. Two mistakes are frequently made in the fluvial literature concerning the Araguaia–Tocantins River. The first is that, although considered a tributary of the Amazon Basin, the water of the Araguaia–Tocantins River goes to the Atlantic Ocean, along the Para River, a channel situated to the south of the Marajo Island, while the Amazon discharge is diverted to the north of the Marajo island. The second mistake concerns the denomination of this river because, although the name Tocantins is traditionally used, the Araguaia is, from a geomorphological and hydrological point of view, the main drainage system. These rivers have few developed alluvial plains because they flow on bedrock with structural control by the Precambrian Shield rocks and faults. However, a large Quaternary sedimentary basin, the Bananal plain, is found in the middle Araguaia River covering more than 90,000 km^2 and occupying approximately 12% of the fluvial basin. The Quaternary sediments that reach more than 100 km in width and extend more or less continuously in the north-south direction for about 700 km are almost unknown. Many inactive alluvial palaeochannels and other fluvial and swampy/lacustrine features occur in the Bananal plain including a number of underfit rivers that occupy the palaeoalluvial belts, and a drainage system on the Araguaia formation that is underdeveloped. This extensive plain is temporarily flooded during the rainy season as a result of both the local rainfall and a saturated water table. The Araguaia River has a well-developed alluvial belt in the middle course and stretches for more than 1,100 km. The middle Araguaia alluvial plain is a complex mosaic of Quaternary morpho-sedimentary units (Latrubesse and Stevaux, 2002) with Late Quaternary and Holocene sediments forming the floodplain. The older sediments (Late Pleistocene?) are composed of ferruginous coarse sands to conglomeratic sands indurated by iron oxides.

In the Holocene alluvial plain, three main units can be identified: a plain of accreted bars/islands and scrolls in the more sinuous reaches accompanying the channel; a palaeomeander-dominated unit; and an impeded floodplain, both of them situated marginally in relation to the channel. The impeded floodplain, formed by a discontinuous backswamp, is relatively the oldest unit of the floodplain. The palaeomeander-dominated unit is characterized by the presence of large oxbow lakes and scroll features. In general, this unit occupies an intermediate position between the accreted bar/islands unit and the impeded floodplain and it is assumed that this unit was formed earlier than the plain of accreted banks/islands. The accreted bars/islands unit is being generated by the channel activity at present and forms an irregular belt along both sides of the channel. Although the age of the units was not calibrated by absolute dating (very recent radiocarbon ages were obtained in the accreted bars/islands units), the existence of palaeomeanders and the impeded floodplain indicate hydrological changes in the system that occurred during the Holocene.

The São Francisco River is the main fluvial system draining the Brazilian semiarid northeastern region, with a drainage area of 650,000 km^2, and drains mainly the Precambrian rocks of Central Brazil from the south to the north through the Cerrado and the Caatinga vegetation realms. Its mean water discharge is 3,800 m^3 s^{-1} and the sediment discharge 6 $\times 10^6$ t yr^{-1}.

As in other South American rivers, information about the Quaternary fluvial record of the Araguaia and São Francisco rivers is almost nonexistent. Nevertheless there are some inferences, albeit controversial, about climatic changes affecting the Cerrado (savannas to dry forest) of Central Brazil. During the end of the Middle Pleniglacial and the LGM, arid and cooler conditions with grassland expansion and reduction of montane and cloud forests in south and southeast Brazil (Behling, 2002) were recorded. However, a relatively humid and warm climate between >32,400 to ca 32,000 yr BP and a cold and humid climate between 30,000 and 26,000 yr BP has also been reported (Salgado-Labouriau *et al*., 1998). For the LGM, both approaches agree with cold and dry conditions in Central Brazil extending up to the early Holocene. The interpretation of the middle-late Holocene is also controversial among palynologists for Central Brazil. While some suggest arid conditions from the Late Pleistocene to the late Holocene (Behling, 2002), others suggest better climatic conditions in the Holocene since 6,500 yr BP.

The main palaeoclimatic indicators in the basins may be due to the existence of large dune fields in the middle São Francisco River where Tricart (1974) described large longitudinal dune fields produced by deflation of E to ESE winds. The dunes formed during arid conditions of the LGM were stabilized during the Lateglacial. Humid climatic conditions were suggested in the area during ca 11,000 to 10,000 yr BP (Oliveira *et al*., 1999), with progressive warming and high humid levels between ca 10,000 and 6,500 yr BP. The return to “Caatinga/Cerrado” arid conditions could have started at 6,500 yr BP with increasing aridity from ca 4,500 yr BP until today.

8 DISCUSSION

As observed throughout this chapter, the palaeohydrological record of the large fluvial basins of South America is scarce and, in some basins, very fragmentary. Some basins are relatively well studied, whereas others have no systematic fluvial studies. The best information that we have about Pleistocene chronology, palaeoecology and geology is related to the period before 24 kyr BP, possibly corresponding to the Middle Pleniglacial (ca 65–24 kyr BP) (Figure 12.3). In the Amazon basin, sedimentation in the fluvial belts occurred during this period in rivers with their headwaters in the Andes and also in the lowlands of the southwestern Amazon (Dumont *et al*., 1992; Latrubesse and Franzinelli, 1998; Latrubesse and Ramonell, 1994; Rasanen *et al*., 1990; 1992; van der Hammen *et al*., 1992a). For some authors (Dumont *et al*., 1992; van der Hammen *et al*., 1992a), the alluvial sedimentation could have been directly associated with glacial advances and strong rains in the central and northern Andes where the rivers deposited sand and gravel. However, the rivers with headwaters in the lowlands of the southwestern Amazon (Purus and Jurua basins, for example) and those with headwaters in cratonic areas such as the Negro River also carried abundant sediment loads. In the lowlands, the occurrence of coarse sand and pebbles and fossil mammals found in the conglomerate deposits, clearly indicate the magnitude of hydrological changes. The Middle Pleniglacial would have been characterized by high precipitation in the Andes and a continuing change towards dry conditions in the

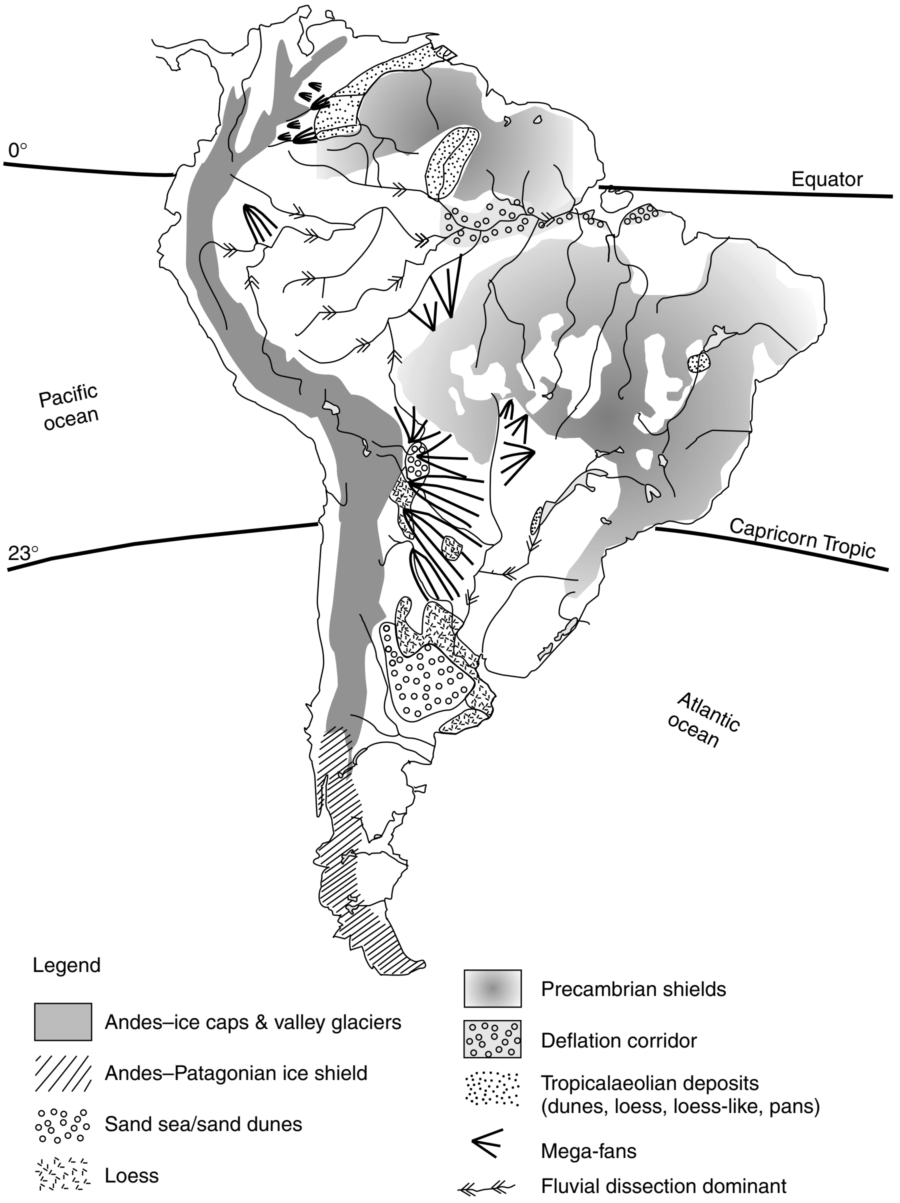


Figure 12.3 The palaeohydrological and palaeoenvironmental situation of South America at the end of the Middle Pleniglacial and the Last Glacial Maximum (LGM). Dissection (as indicated on the map) was dominant in the fluvial systems during the LGM, however, the end of the Middle Pleniglacial was characterized by sedimentation in the fluvial belts

lowlands, including the cratonic areas (Latrubesse, 2000). Recent results on dune-field chronologies (Carneiro Filho *et al*., 2002), confirmed the claim of Latrubesse (2000) that the aridity in the lowlands of Amazonia began during the Middle Pleniglacial or early stages of the Upper Pleniglacial.

The Middle Pleniglacial–early Upper Pleniglacial episode of fluvial sedimentation is also well recorded in the Upper Parana basin. Coarse sediments were deposited at this time for the Parana River indicating a more arid period than at present (Stevaux, 1994; 2000; Stevaux and Santos, 1998).

The aridity in South America reaches its climax during the Upper Pleniglacial, when the aeolian sedimentation extended along the Venezuelan and Colombian Llanos and over parts of central and northern Amazonia. At that time, savanna vegetation reached its maximum extension in the Amazon, the Llanos had an arid climate and aeolian remobilization reached the core of the Amazon region. The Upper Pleniglacial was also a time of extensive aeolian activity as a response to increasing aridity also in Central Brazil, Chaco and Pampa. During the LGM, a large sand sea with large dunes was formed in the Pampean region (Argentina) and a mantle of loessic sediments was deposited in the Chaco–Pampean plain. At this time the Parana had a smaller discharge than it does today and dune fields formed on the older terraces of the Upper Parana River and deposition occurred in the Uruguay system during the Lateglacial. The Chaco mega-fans developed a large number of ephemeral and small channels and simultaneously suffered active deflation of the oldest alluvial belts. Dune fields formed in the Grande and Parapetí fans, and loessic sediments were deposited in the Chaco along the Sub-Andean foothills (Iriondo, 1993). The large basins of Central Brazil, such as the São Francisco and Tocantins–Araguaia, have also experienced climatic deterioration since the Middle Pleniglacial. During the LGM, the sand dunes of the Middle São Francisco River were active and the fluvial sediments suffered deflation.

Wind-circulation models were proposed for the Amazon and the Llanos area for times close to the late Pleistocene (ca 40–14 ky BP), (Iriondo, 1997; Iriondo and Latrubesse, 1994; Latrubesse and Ramonell, 1994; Latrubesse, 2000). In the middle Amazon region, second-order changes in regional climate dynamics would have been sufficient to instigate a dry climate phase (Iriondo and Latrubesse, 1994). Trade winds would have been stronger and drier than at present, producing extensive deflation corridors and aeolian sedimentation. Northeastern trade winds were dominant approximately north of 0°, removing sand and silt in the Llanos, "Pantanal Setentrional" and in Roraima. Southeastern trade winds that originated in the anticyclonic circulation of the southern hemisphere would have dominated south of 0° reaching as far as the western Chaco along the Sub-Andean foot-slopes, forming dunes and loess deposits. Considering the data mentioned, the palynological record in Carajas and Rondonia, the palaeomammals and the palaeohydrologic record of the southwestern Amazon show that it was characterized by a dominant savanna environment during the Upper Pleniglacial, with a dry season that was more pronounced and prolonged than that of the present. Aridity was also widespread in central and northeast Brazil producing the formation of sand dunes in the middle São Francisco.

Cold air masses of the South Pacific Anticyclonic (SPA) circulation were dominant in the Argentinean Pampas and part of the Eastern Chaco where the climate was dry and cold (Iriondo and García, 1993; Ramonell and Latrubesse, 1991), penetrating up to the Upper Parana and upper Araguaia basin and moving into the south and southwestern Amazon, causing clear falls in winter temperatures (Latrubesse and Ramonell, 1994). The SPA winds were strengthened by katabatic winds coming from the ice field of the Patagonian Andes (Iriondo and García, 1993). After 14 kyr BP, sedimentation in the fluvial belts occurred in response to climatic changes associated with the last deglaciation, the gradual recuperation of the rainforest occurred, and this sedimentation phase probably culminated with the marine transgression of the Middle Holocene.

In the early to middle Holocene, the plains of northern South America were dry. A climate drier than that of the present was also suggested for the Amazon basin during the Hypsithermal (Martin *et al*., 1993). The Hypsithermal was characterized by humid and temperate conditions in the Chaco and Pampa plain as well as in the upper Parana and Uruguay basins (Iriondo and García, 1993; Stevaux and Santos, 1998) and dry conditions dominated that large region between 3,5 and 1 kyr BP.

The Late Holocene, mainly the last 1,000 years, seems to be a period of rapid recuperation of the fluvial systems accompanied by high rates of sedimentation. Many radiocarbon dates for the Amazon floodplain and some tributaries are very young (Late Holocene, <3,000 yr BP) and many of them indicate ages of less than 1,000 years (Absy, 1979; Latrubesse and Franzinelli, 2002; Sternberg, 1960; Vital and Stattegger, 2000).

9 CONCLUDING REMARKS

Knowledge of the Quaternary fluvial record of large South American rivers has advanced significantly in recent years. However, the richness, complexity and size of these rivers mean that the results reviewed in this chapter must be regarded as incipient and pioneering. Discovery of extensive and widespread aeolian fields in the Amazon is an advance that opens a new horizon in Quaternary research of tropical South America. As expressed by Latrubesse (2000), aeolian sediments and landforms can be the future key to the reconstruction of wind patterns and for the determination of different times of maximum aridity in the Amazon and, more generally, for the whole of tropical South America. Palaeogeographic reconstructions and estimates of temperature variability based exclusively on palynological studies should be made with caution, especially when they are not correlated with a regional scenario that considers well-documented sedimentologic and geomorphologic records and mapping.

When compared with the reality of other large fluvial basins of the world, which were or are being affected directly by intensive human use, the large South American rivers have particular potential for the study of the Quaternary palaeohydrology and for comparison of the palaeohydrological record with present-day hydrology and fluvial morpho-dynamics. Large parts of the Amazon fluvial system remain untouched by direct human intervention along the channels, while others, such as the Chaco's rivers, offer a large potential for understanding palaeohydrological river adjustment to climatic changes, metamorphosis (Baker, 1978) or understanding autogenic processes during the Late Quaternary, together with one of the more spectacular environments of alluvial sedimentation of the planet, the large and complex mega-fan features. As expressed by Baker (2000): *discoveries from field work in South America afford a spectacular opportunity to develop a synthesized understanding of realized hydrological change. This understanding can only be achieved by interpreting the indicators (signs) of past hydrological processes, that is, via... paleohydrology.*

Understanding past hydrology has become a necessary investigation in South America for at least two fundamental reasons. First, considering the global influence of tropical South America on the interaction of the water movement from the land surface to the atmosphere and hence the importance of South America in the global hydrologic and palaeohydrologic context (Baker, 2000); secondly, as a scientific priority tool reconciling environmental and political decisions about the role of large rivers for the future development of South American countries, in the light of the contrasting policies of use and conservation that are currently being proposed for these large basins.

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Please clarify the following queries:

Q1 The amount for annual mean discharge for the Parana Basin in Table 12.1 is shown as 18,000 $m^3\ s^{-1}$ as against 17,000 $m^3\ s^{-1}$ in the text. Please clarify.
Q2 Please clarify what these numbers in brackets indicate.
Q3 These author's names are not provided in the reference list. Please provide the complete details.
Q4 Please clarify if the expanded form is 'Thermoluminescence'.
Q5 The given authors' names have not been cited in the reference list. Please clarify.
Q6 Please spell out this abbreviation at the first instance.
Q7 This sentence has been rephrased. Please clarify if it retains the intended meaning.
Q8 Please clarify if Gosse, 1971 should be Gossen, 1971; because the latter has been provided in the bibliography.
Q9 Please provide the place of publication for this reference.
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