Late quaternary paleoceanography of the French Guiana continental shelf: clay-mineral evidence

Late Quaternary
French Guiana
Shelf
Clay minerals
ENSO

Quaternaire récent
Guyane Française
Plate-forme continentale
Minéraux argileux
ENOA

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ABSTRACT

Marine muds deposited on the French Guiana coast mostly originate in the Amazon. Recent sediments are composed of (a) illite (33 %) and chlorite (13 %) of Andean mountain origin; and (b) kaolinite (28 %) and smectite (26 %), principally from the Amazonian lowlands but also from the Guiana Shield.

In the coastal mud prism, high-resolution seismic profiles, together with sedimentological, micropaleontological and soil engineering studies, supplemented by ^{14}C dates, permitted a stratigraphic interpretation of eight cores. Three episodes have been determined on the basis of clay-mineral variations related to Amazonian lowland, Andean and Guiana shield sources. The older episodes 3 (3000-1700 y BP) and 2 (1700-1000 y BP) are predominantly characterized by lowland-derived clays (smectite = 43 %, kaolinite = 26 %) from Amazonian and local sources. The most important event is a reduction of the Andean source, due to successive dry phases which occurred in western Amazonia about 2200 and 1200 y BP, confirming that regional decreases in rainfall, water discharge and erosion were associated with climatic fluctuations. It is suggested that these dry phases (within the last 3000 years) are the consequence of several protracted (10-100 years) periods, during which atmospheric conditions mimicked the present-day "El Niño Southern Oscillation" (ENSO) phenomenon. As a result, particulate flux from the ocean decreased, leading to reduced silting of the Guiana coast. In the past 1000 years (episode 1), illite and chlorite have increased, indicating a stronger Andean contribution to the Amazonian continental flux that reaches the ocean. This is the first demonstration that the nature of the coastal marine muds of northern South America reflects climatic changes in the Amazon basin.

RÉSUMÉ

Paléo-océanographie du quaternaire terminal sur la plate-forme continentale de la Guyane française : contribution des minéraux argileux.

Les vases qui se déposent en Guyane française sont pour la plupart d'origine amazonienne. Les dépôts récents sont constitués d'illite (33 %) et de chlorite (13 %) d'origine andine (source montagneuse) et de kaolinite (28 %) et smectite (26 %) issus de llanos (basses terres du bassin amazonien) et du bouclier guyanais.

Dans la vasière littorale, des profils de sismique à haute résolution, des analyses sédimentaires, géotechniques et micropaléontologiques, des datations au ^{14}C permettent de présenter la stratigraphie de huit carottes.

Trois épisodes sont déterminés dans lesquels les minéraux argileux montrent l'origine andine des basses terres amazoniennes et locale des dépôts.

– Les épisodes 3 (3000-1700 ans BP) et 2 (1700-1000 ans BP) sont dominés par des apports issus préférentiellement des basses terres amazoniennes (smectite = 43 %, kaolinite = 26 %) et locale. Dans ces dépôts, la diminution de la source andine est liée à la succession de phases sèches en Amazonie occidentale (2200-1200 ans BP) qui se traduisent par une baisse de la pluviosité, du débit liquide et donc de l'érosion. Ces périodes sèches, témoignage de fluctuations climatiques, pourraient être la conséquence d'une succession de longues périodes (10-100 ans) ou les conditions atmosphériques étaient celles rencontrées de nos jours lors de l'apparition de « El Niño-oscillation australe » (ENOA). Il en résulte une diminution probable du flux particulaire à l'océan et une possible réduction de l'envasement sur les côtes des Guyanes.
– Depuis 1000 ans BP (épisode 1), les teneurs en illite et chlorite augmentent, indiquant une plus forte contribution andine à l'océan.
C'est la première démonstration de la très probable influence des conditions climatiques liées à l'ENOA sur la sédimentation de la vasière marine qui borde tout le littoral nord de l'Amérique du Sud.

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INTRODUCTION

The Amazon river (Fig. 1) currently transports an enormous quantity of suspended matter :1.1 to 1.3 10^9 T year^{-1} (Meade *et al.*, 1985). About half of this (6,3 ± 2 10^8 T year^{-1}) is deposited on the shelf near the river mouth (Kuehl *et al.*, 1986); a significant amount (1.5 10^8 T year^{-1}) is transported towards the northwest by the Guiana Current (Muller-Karger *et al.*, 1988). A small part (1 %) of the total amount is deposited on the inner shelf between the Amazon mouth and the Caribbean Sea (Eisma *et al.*, 1991). Intertidal mudbanks (1 10^8 T year^{-1}) represent another fraction of the Amazonian flux, and migrate in the same northwesterly direction under the action of the Guiana Current, ocean swells and longshore drift (Wells and Coleman, 1981; Froidefond *et al.*, 1988; Pujos and Froidefond, 1995). These muds have built a large coastal sedimentary prism which generally extends to a water depth of 30-40 metres, but locally to greater depths (Pujos and Odin, 1986). In French Guiana, cored sediments consist of homogeneous muds, occasionally with interbedded sands and unconformity surfaces. Clay minerals account for 90 % of these muds (Pujos *et al.*, 1989); they are generally derived from neighbouring continents, and mostly inherited from the soils in river basins (Chamley, 1989; Weaver, 1989). In this study, the most abundant clay minerals are smectite (Sm), illite (I) kaolinite (K) and chlorite (Cl), originating principally in the Amazon basin (Gibbs, 1967) but also in the Guiana Shield (Pujos *et al.*, 1989, 1990) (Fig. 1 and 2). The contribution of erosional material of Andean origin in the Amazon mouth is unknown. However, studies of the basin of one of the major Amazon tributaries, Rio Madeira, show that more than 95 % of suspended matter exported by this river comes from Andean deposits (Guyot, 1992).

New observations on late Quaternary marine deposits from the continental shelf of Guyana-Surinam indicate that the clay assemblages have changed since 4000 y BP (Pujos and Pascual, 1992). This is an unexpected finding because the Amazonian flux was considered to have remained more or less constant in the time interval (Pujos and Odin, 1986), and the contribution from the Guiana Shield has always been small compared to that from the Amazon (the Maroni River delivers only 500,000 T year^{-1} of suspended matter; *see* Jouanneau and Pujos, 1988; Pujos *et al.*, 1990). Characteristics of these muds and related clay-mineral assemblages have been compared in this study with those of surficial sediments of coastal and continental catchment areas. Since variations in clay assemblages are dependent on the erosional history of the region, they are ultimately linked to climatic changes. In this context and using the available information on clay minerals in the Andean region (Gibbs, 1967; Guyot, 1992), Amazonian lowlands (Irion, 1991), Amazon fan (Boltenhagen and Marion, 1975; Pujos *et al.*, 1989) global Amazonian hydroclimatology (Tardy *et al.*, 1993) and the northern continental shelf of South America (Gibbs, 1977; Pujos and Odin, 1986; Pujos *et al.*, 1989; Pujos and Pascual, 1992), we studied the clay minerals in the principal catchment areas of the Guiana Shield in comparaison with the clay mineral composition of the muddy sediments along the coast of French Guiana (Fig. 1 and 2; Tab. 1 and 2).

CLAY MINERALS IN ANDEAN SEDIMENTS AND CONTINENTAL SHELF OF THE NORTHERN PART OF SOUTH AMERICA

In the Amazon basin, suspended load varies as a function of geology, relief, vegetation and seasons. Concentrations are much higher on the eastern slopes of the Andes during the wet season (600 *versus* 75 mg/l in the dry season, *see* Gibbs, 1967). A wide range of igneous, metamorphic, and sedimentary rocks is present in the Andean mountains, and the sedimentary mineralogy is highly varied. Clays are derived by mechanical erosion; more than 95 % of the particulate matter in Rio Madeira, a principal tributary of the Amazon, originates in the Andes catchment area (Guyot, 1992). Illite and chlorite are the most abundant minerals (Tab. 1). In marine muds of the Pacific Colombian shelf region where lowlands are reduced, clay minerals are exclusively composed of illite and chlorite as in Andean

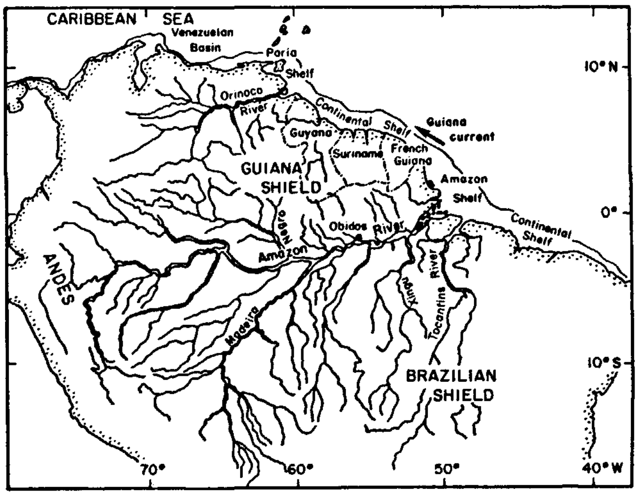

Figure 1

Region influenced by the Amazon dispersal system (Nittrouer et al.*, 1986).*

Système dispersif de l'Amazone (Nittrouer *et al.* 1986).

sediments (Pujos *et al.*, 1995). In the Brazilian shield and the llanos from the Amazonian basin, the Xingu and the Negro are the major rivers (Fig. 1). Both essentially transport kaolinite (Irion, 1991). In the lower Amazon basin, the clay assemblages from some known Andean tributaries (illite and chlorite) and from the lowlands (kaolinite and smectite) accumulate, the latter being due to geochemical weathering in a hot and humid climate, and sometimes to crystallization after diagenesis. However it must be stressed that the Andes is the major contributor of clay minerals to the Amazon (Gibbs, 1967; Guyot, 1992). The resulting clay assemblage, which is dominated by smectite, can be traced from the Amazon mouth to the lesser Antilles, indicating the extent of the Amazon influence (Eisma and Van der Marel, 1971; Boltenhagen and Marion, 1975; Pujos and Odin, 1986) (Tab. 1).

CLAY MINERALS IN FRENCH GUIANA SEDIMENTS

Procedures, sites, and samples

Clays were analysed by X-ray diffraction (Philips diffractometer with Cu Kα radiation and a nickel filter - 35 KV and 25 mA). Sediments were decarbonated (0.1 N HCl) as required and then rinsed thoroughly with deionized water. The clay fraction (< 2 µm) was separated by gravity and centrifuging, and then put on three glass slides for X-ray analysis following the methods described by Holtzapffel (1985). One sample was left untreated; another was saturated with ethylene glycol; and the third was heated to 550°C for one hour. Identification of the clay minerals is based on their typical reaction to these treatments (Brown, 1961; Thorez, 1975). The relative amount of each mineral is calculated from the ethylene glycol-treated samples. Quantitative determinations were performed using peak height of characteristic reflection of each class: 17 Å for smectites, 10 Å for illites, 7,1 Å and 3,57 Å for kaolinites and 7,1 Å and 3,55 Å for chlorites.

French Guiana Shield and coastal sediments

Flooded river bank forests "varzeas" and coastal areas were sampled by hand scoops; river beds and mudbanks were sampled by Ekman and Shipeck grabs; offshore samples were taken with Reineck cores. Studied samples include 150 from the rivers (Maroni, Mahury, Approuague and Oyapock) and tributaries, 10 from swamps (Mana), 40 from the shoreline, and more than 200 from the submarine mud prism. The geographical locations and sedimentological data for all these samples, taken during nine field seasons, are given in Pujos and Odin, 1986; Jouanneau and Pujos, 1987, 1988; Pujos *et al.*, 1988, 1989; Pujos, 1991. The sampling areas are shown in Figure 2.

In the hinterland, the sediment samples were collected from the major rock types and structural units: granite and gneiss from the central province and schist and quartzite from the northern and southern synclinoria (Choubert, 1974; *see* also Fig. 2). These regions are covered by rainforests, and possess a dense hydrographic network that drains the Guiana Shield from the Amazon basin to the ocean. In the coastal plain, landward of the beach ridges (locally known as cheniers), lowlands are covered with swamps (developing on clayey substrates) and savannahs. The sampled Mana swamps (400 km^2) are located on the east of the Maroni river (Fig. 2).

Cored sediments: Stratigraphic framework

Samples were taken with a Kullenberg corer. The core locations were chosen on the basis of acoustic reflectors recognized in seismic profiles (3.5 kHz). The studied hori-

Table 1

Clay mineralogy of the Amazonian basin, the Amazon fan and the South American northern margin. All the numbers are percentages.

Cortèges argileux du bassin amazonien, du cône de l'Amazone et de la marge nord de l'Amérique du Sud (exprimés en pourcentages).

Clay minerals	Amazonian basin				Ocean				
	Bolivian Andes	Llanos			Amazon Fan		South American Northern margin		
	GUYOT, 92	Madeira GUYOT, 92	Negro Xingu IRION, 91	Amazon IRION, 91	BOLTEN HAGEN *et al.*, 75	PUJOS *et al.*, 89	Southern margin GIBBS, 77	French Guiana PUJOS *et al.*, 86-89	55°W Suriname PUJOS et *et al.*, 92
Sm	3	9		40-50	39	35	27-40	37	34
I	59	53		20-25	23	25	28-18	28	31
K	15	20	> 90	14	35	31	36-32	26	26
Cl	23	18		20		9		9	9

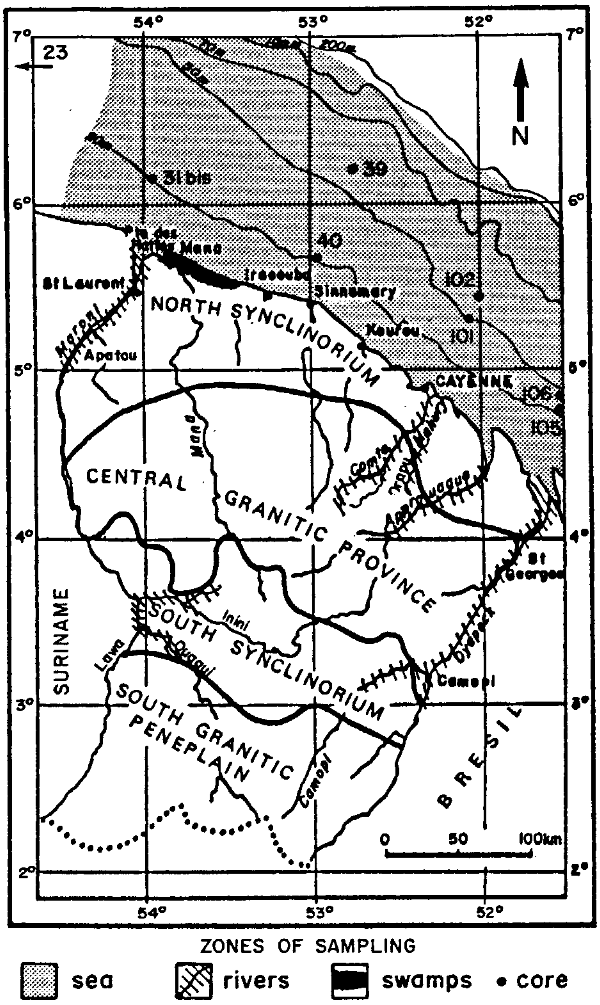

Figure 2

Map with sample locations.

Situation géographique. Localisation des stations.

zons are generally 10-15 cm apart, but this stratigraphic distance is practically halved near the limits of the sedimentary facies.

Twelve seismic profiles accounting for more than 1500 km^2 over a 36000 km^2 area were examined to evaluate the seismic stratigraphic framework. The acoustic reflectors observed in the area and recognized in cores can be attributed to two high sea-level sedimentary prisms C and D (Frappa and Pujos, 1994) (Tab. 3).

The delineations of sedimentary sequences are based on lithology, sedimentary structures (X-ray radiographs), and the components of the coarse and fine grains (microgranulometry by laser diffraction). From analyses of cores it has been possible to identify beige muds rich in wood fragments and pyrite (near the base) and grey muds (at the top) separated by characteristic unconformity, reworked beach rocks and coastal relict cheniers (Pujos *et al.*, in preparation; Tab. 3)

Soil engineering analyses (water content, cohesion and sensibility, which represent the degree of reworking) give information on compaction, especially as a function of burial depth; possible anomalies reflect the evolution of sedimentary deposits (Pujos *et al.*, 1989; Guillaume, 1990). For example, there is a strong difference in compaction between adjacent layers across an erosional surface: compact mud at the base, with overlying soft mud and sand (Tab. 3).

Benthic foraminifera are more or less abundant in the mud samples. Numbers of foraminifera (individuals/g) vary between 0 and > 20,000. The recognized faunal zones are: (a) *Quinqueloculina lamarckiana* (dominant), *Eponides repandus, Cibicides lobatulus, Nonionella atlantica, Hanzawaïa concentrica* (Association A); (b) *Ammonia tepida* (very abundant) and *Nonionella atlantica* (Association B); and (c) Mixed fauna from the two associations (Association C: Tab. 3). These associations provide clues to the environmental conditions of the deposits (Pujos *et al.*, in preparation).

Three radiocarbon dates were obtained (AMS ^{14}C, Laboratoire des Faibles Radioactivités, Gif-sur-Yvette) to establish a firm chronology of the events. The samples analysed (in core Ks 105) consisted of benthic foraminifera: level 325, 3000 ± 80 y BP; level 250, 1860 ± 80 y BP; level 193, 1460 ± 80 y BP. Although we have no radiocarbon date for younger sediment we have used one extrapolated date from the literature (*Atlas de la Guyane*, 1978).

RESULTS

Rivers, estuaries, swamps and coastal zone

Rivers draining the catchment areas of the High Maroni, Oyapock, Camopi, Approuague, Mahury and tributaries (Tab. 2, Fig. 3) contain fine deposits rich in kaolinite (88 to 100 %), with some smectite (2 to 5 %) and illite (2 to 5 %). In the lower reaches of the rivers, a strong tidal flow carries suspended Amazonian sediments more than 10 km inland. In this estuarian area, four major minerals are found: illite (35 %), kaolinite (26 %), smectite (23 %) and chlorite (17 %). The clay minerals of the Mana swamps are mainly smectite (50 %) with kaolinite (29 %), illite (19 %) and chlorite (2 %). Clay assemblages are similar in the intertidal zone and on submerged banks and interbanks and consist of illite (33 %), kaolinite (28 %), smectite (26 %) and chlorite (13 %). Away from the banks, in the external part of the littoral mud prism, the average clay assemblage is characterized by smectite (37 %), illite (28 %), kaolinite (26 %) and chlorite (9 %).

Thus, four areas are identified in the Guiana Shield and coastal shelf (Fig. 3): (a) lowlands where kaolinite dominates; (b) coastal swamps where smectite is the major clay mineral; (c) estuaries, marine banks and interbanks where illite dominates, but kaolinite and smectite are also common (Tab. 2); and (d) the external part of the littoral mud prism, where smectite and illite dominate but kaolinite is present (Tab. 1).

The variability in clay minerals (French Guiana, Amazon basin, northern coastal part of South America) shows that littoral muds in French Guiana are inherited from two distinct regional sources. First, the mechanical erosion of ferralitic soil (local continental source) produces kaolinite. In the same area, in coastal swamps with poor drainage, erosion of muds (underlying peats) may supply smectite.

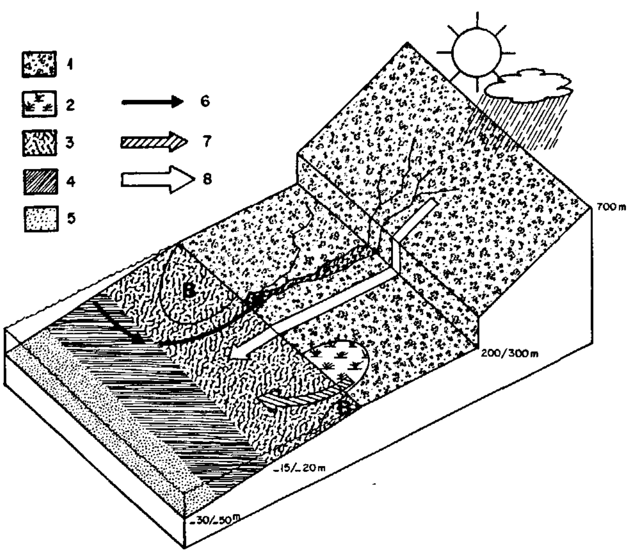

Figure 3

Clay mineral distribution on the French Guiana continental shelf; interprétation of local clay sources.
1. Kaolinite region (rivers).
2. Smectite region (swamps).
3. Illite dominant with accessory kaolinite and smectite (bank zone).
4. Illite dominant with kaolinite (external mud deposits).
5. Sand deposits.
6. Amazonian flux.
7. Local flux (swamps).
8. Local flux (rivers). B = Bank

Distribution des cortèges argileux de la Guyane française.
1. Région à kaolinite (fleuves).
2. Région à smectites (marais).
3. Région à illite dominante avec accessoirement kaolinite et smectite (zone des bancs).
4. Région à illite et kaolinite (vasière littorale externe).
5. Dépôts sableux.
6. Flux amazonien.
7. Flux local (marais).
8. Flux local (fleuves). B = Bank.

Second and much more important is the Amazonian source of suspended matter (1.1 to 1.3 10^9 T year^{-1}, *see* Meade *et al.*, 1985), which is characterized in part by illite and chlorite from Andean environments. Data on particulate matter, discussed in the introduction, show that only 1 % of these muds are deposited on the coasts of the three Guianas (Fig. 1). Since the particulate matter flux from French Guiana rivers is estimated at 1.7 10^6 T year^{-1} (Prost and Lointier, 1988), it is easy to see that the local input of kaolinite and smectite would be much diluted by the Amazonian flux. Thus, the identification of clay-assemblages provides a reasonable framework for interpreting long-term variations in the regional climate.

Cored sediments : Evolution of clay assemblages

Clay mineral variations in the mud prism are consistent with radiocarbon dates and sedimentological and environmental data. Using such diverse information (Tabs. 3, 4), it has been possible to divide the history of the Holocene sedimentary wedge into three episodes (Fig. 4; Fig. 5 which schematically illustrate the facies elements of a synthetic sedimentary sequence).

Episode 3. This is the oldest episode. The sediments consist of beige or grey muds (mean diameter Md = 7 µm) with minimal amounts of sand. The degree of compaction is quite high (water content: W = 25-40 %; non-drained cohesion: Cu pic = 100-190 Kpa; state of reworking of the soil: St = 5). The deposits are rich in wood fragments and pyrite and are derived from the mangrove area of the coast (Van der Hammen, 1974). Seismic profiles indicate the presence of a high-stand prism (formation C of Frappa and Pujos, 1994, *see* Tab. 3) which possesses thin reflectors pinching out towards the top, clearly visible as an unconformity in cores Ks 31 *bis* and Ks 105. Reworked sandy layers (cores Ks 23, Ks 31 *bis* and Ks 105) or beach rocks (core Ks 102) overlie this prism and separate it from the following one. The sediments of episode 3 are occasionally devoid of fossils, but generally contain a scarce marine benthic microfauna. Foraminifers encountered are *Quinqueloculina lamarckiana, Eponides repandus* and *Cibicides lobatulus*; most are damaged and orange-coloured

Table 2

Clay mineralogy of rivers, swamps and the littoral zone (bank zone) from French Guiana. Italics: Total range.
Cortèges argileux des fleuves, marais et zone littorale de la Guyane française (en italiques : valeurs extrêmes).

	Rivers					Estuaries				Swamps	Littoral (bank-zone)			
	Lawa Ouaqui Inini (Maroni)	Comté Orapu (Mahury)	Oyapock Camopi	Approuague	Mean	Maroni	Mahury	Oyapock	Mean	Mean	tidal zone	infralittoral zone	Between mud banks	Mean
Sm	5			5	2	27	20	24	23	50	24	27	26	26
						22-28	*15-28*	*16-28*		*48-52*	*20-30*	*25-29*	*24-28*	
I	5	2	tr	6	3	31	36	36	35	19	36	32	30	33
						29-38	*25-40*	*33-42*		*18-20*	*32-41*	*29-35*	*30-31*	
K	90	98	100	88	95	26	29	22	26	29	27	28	28	28
						23-28	*25-40*			*22-33*	*22-30*	*27-30*	*24-32*	
Cl						16	15	18	17	2	13	13	16	13
						13-19	*13-18*	*17-20*		*0-10*	*11-15*	*12-15*	*14-18*	

Table 3

Sedimentary properties and radiocarbon dates of cored intervals. Granulometry (μm), water content (w %), non-drained cohesion (Cu pic in Kpa), sensibility (St), radiocarbon dates (AMS ^{14}C), uncorformity (U).

Caractéristiques sédimentologiques et datations au radiocarbone dans les carottes. Granulométrie (μm), teneur en eau (W %), cohésion non drainée (Cu pic en Kpa), sensibilité (St), datations au radiocarbone (AMS ^{14}C), uncorformity (U).

Episodes		**1**	**2**	**3**
Geophysical units		**D2**	**D1**	**C**
Lithology sediment, structure		beige and grey muds sands	grey muds sands	U grey muds, wood fragments, and pyrite
Granulometry		6 (muds) 100 (sands)	7 (muds) 100 (sands)	7 (muds)
Soil engineering	W Cupic St	110 20 2	90 54 4	25/40 100/190 5
Radiocarbon dates			1460 ± 80 BP	1860 ± 80 BP 3000 ± 80 BP
Benthic foraminifera		Abundant fauna Assoc. A sands B muds	Rare fauna Assoc A-C (sands and muds)	very rare fauna Assoc. A (displaced fauna)

and bear signs of transportation. The substrate, rich in locally derived organic matter (from the mangroves) and very poor in oxygen (with presence of pyrite), is generally unsuitable for the development of shelled microfauna. The radiocarbon dates were obtained from episode 3 sediments of core Ks 105: 3000 ± 80 y BP (at 325 cm) and 1860 ± 80 y BP (at 250 cm). Smectite (40 %) and kaolinite (29 %) are the dominant clay minerals (Tab. 4).

Episode 2. The sediments are generally grey muds with the same granulometry as the previous interval. Sands and grey muddy sands are also present. Muds are not well-compacted (W = 90 %; Cu pic = 50 Kpa; St = 4). Wood fragments and pyrite are common at the base. The sedimentary prism of episode 2 can be identified on the basis of its seismic transparency, although some fine stratifications can sometimes be detected (Frappa and Pujos, 1994:

Table 4

Clay mineralogy of cored sediments.

Cortèges argileux des dépôts carottés.

					FRENCH GUIANA - SURINAM					
Units	**Cores**	**KS23**	**KS31Bis**	**KS39**	**KS40**	**KS101**	**KS102**	**KS105**	**KS106**	**Mean**
	Sm	31	37	36	40	36		29	37	**35**
	I	38	30	31	28	30		37	29	**32**
	K	20	22	21	21	21		20	23	**21**
1	Cl	11	11	12	11	13		14	11	**12**
	S/I	0.8	1.2	1.2	1.4	1.2		0.8	1.3	**1.1**
	K/I	0.5	0.7	0.7	0.75	0.7		0.5	0.8	**0.7**
	K/I + Cl	0.4	0.5	0.5	0.5	0.5		0.4	0.6	**0.5**
	Sm	46		49	37	46	46		51	**46**
	I	27		17	28	25	22		17	**23**
	K	19		26	27	22	22		23	**23**
2	Cl	8		8	8	7	10		9	**8**
	S/I	1.6		2.9	1.3	1.8	2.1		3	**2.1**
	K/I	0.7		1.5	1	0.9	1		1.35	**1.1**
	K/I + Cl	0.5		1	0.75	0.7	0.7		0.9	**0.8**
	Sm	45	39	40	37		44	37	43	**40**
	I	27	28	18	18		23	25	22	**23**
	K	20	23	39	38		28	29	27	**29**
3	Cl	8	10	3	7		5	9	8	**8**
	S/I	1.6	1.4	2.2	2.1		1.8	1.5	1.95	**1.8**
	K/I	0.7	0.8	2,2	2.1		1.2	1.2	1.2	**1.4**
	K/I + Cl	0.5	0.6	1.85	1.5		1	0.85	0.8	**1**

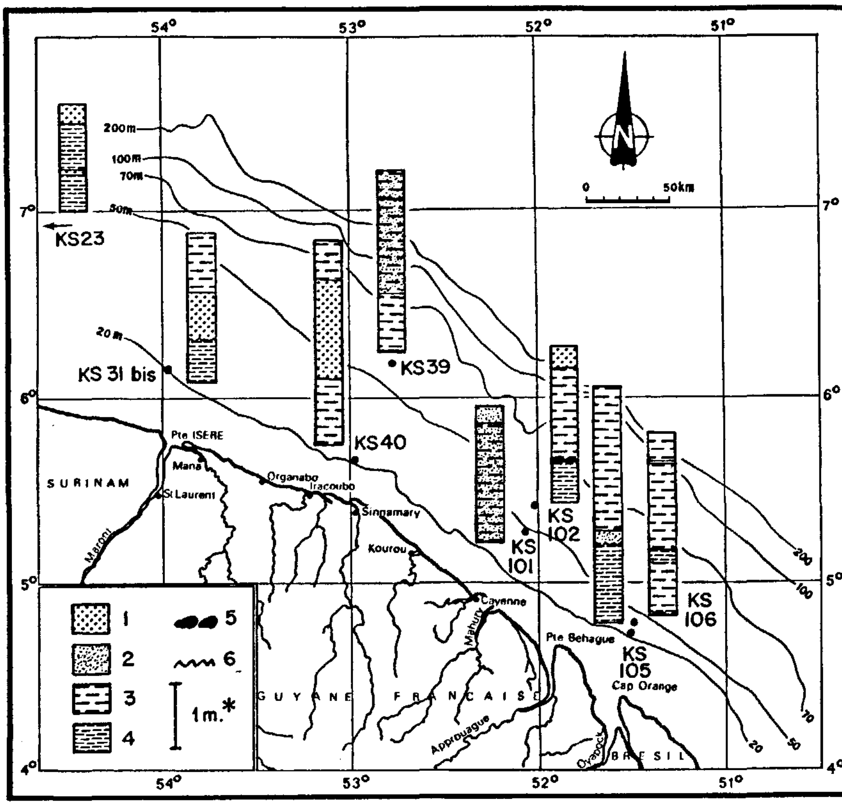

Figure 4

Distribution of sedimentary facies based on seismic, sedimentological and paleontological data and on soil physical properties taken from Frappa and Pujos (1994) and Pujos et al. *(submitted).*
*1. Coarse sand ; 2. Fine sand ; 3. Grey mud ; 4. Beige mud ; 5. Beach rok ; 6. Unconformity (erosional surface). *Core scale.*

Distribution des faciès sédimentaires.
1. Sables grossiers ; 2. Sables fins ; 3. Vases grises ; 4. Vases beiges ; 5. Dépôts de plage indurés ; 6. Surface d'érosion. *Échelle des carottes (en mètres).

Formation D1). Benthic foraminifera are scarce but present. They consist of species such as *Quinqueloculina lamarckiana, Hanzawaia concentrica* (Association A) and mixed fauna with *Ammonia tepida* (Association C), indicating the initial development of a coastal marine biotope. A radiocarbon date from the lower part of the episode 2 sedimentary prism yielded an age of 1460 ± 80 y BP. Since the uppermost part of the episode 3 prism dates close to 1860 ± 80 y BP, we suggest 1700 ± 100 y BP as the date for the boundary of these two episodes. The clay-mineral assemblage is characterized by the high dominance of smectite (46 %). Kaolinite (23 %) and illite (23 %) are also present (Tab. 4).

Episode 1. The most recent episode is represented by two sedimentary facies (a) fine to coarse sands (Md = 100 µm); and (b) grey muds (Md = 6-10 µm). The muds have a high water content (W = 110 %) and a flow cohesion (Cu pic = 20 Kpa; St = 2). Abundant plant remains and pyrite may be present (Ks 40 and Ks 106). The sedimentary package

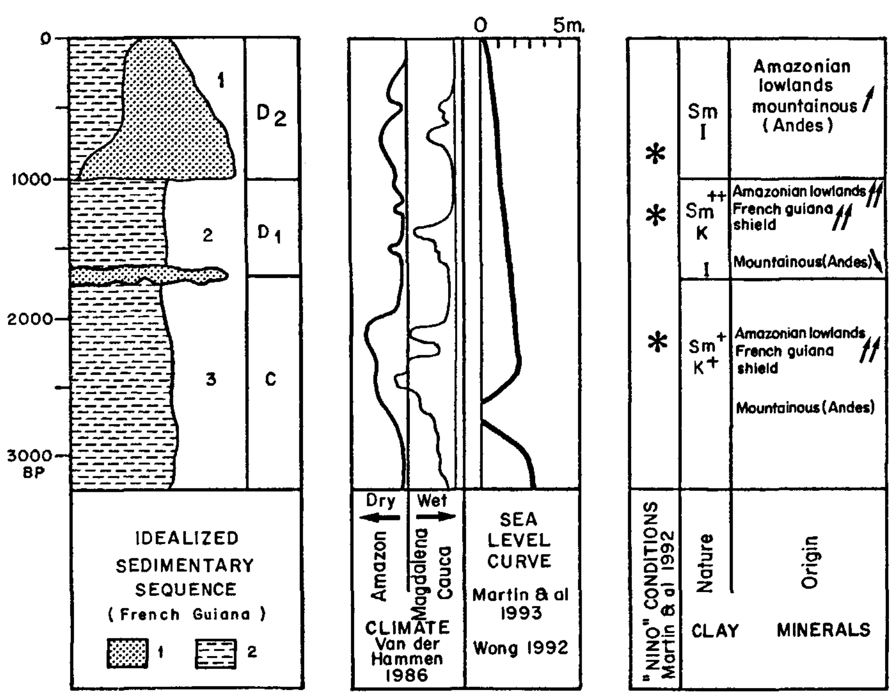

Figure 5

Synthetic sedimentary sequence based on 8 cores analysed by Pujos et al. *(submitted).*
1. Sands ; 2. Muds.

Archétype de séquence sédimentaire des huit coupes étudiées. Cortège argileux. Conditions climatiques (phases sèches et humides, récurrences de l'ENOA).
1. Sables ; 2. Vases.

constitutes the formation D2 recognized in seismic profiles which can be distinguished from the older D1 either by a higher density of reflectors or by greater transparency (Frappa and Pujos, 1994). Benthic foraminifers are more diverse than those found in older sediments. The mud mostly contains *Ammonia tepida* (Association B). In the sands, *Quinqueloculina lamarckiana* dominates and *Eponides repandus, Hanzawaia concentrica, Cibicides lobatulus* and *Nonionella atlantica* are present (Association A). These are now common on sandy substrates on continental shelves. These deposits are probably synchronous with the green marine muds that constitute the uppermost sedimentary unit ("Comowine" Formation) described from the coastal plain of the Guianas (*Atlas de la Guyane*, 1978). The development of this formation is known to have begun around 1000 y BP, which we consider as the age of the boundary between episodes 2 and 1. The clay-mineral assemblage is composed of smectite (35 %), illite (32 %), kaolinite (21 %) and chlorite (12 %; Tab. 4).

Clay-mineral assemblages from episodes 3 and 2 are characterized by the higher smectite and kaolinite content. Kaolinite is more abundant in the beige muds of episode 3 (K = 29 %, K/I+Cl = 1); it decreases towards the top of the sections (K = 23 % and K/I+Cl = 0.8; K = 21 % and K/I+Cl = 0.5 for episode 1). Smectite is the main mineral in the grey muds of episode 2 (Sm = 46 % and Sm/I = 2; Sm = 35 % and Sm/I = 1.1 for episode 1). The abundance of kaolinite indicates an Amazonian lowland source (Gibbs, 1967). In these sediments, smectite is always abundant and frequently dominant (episode 2), reflecting the clay mineral composition of the soil formed under humid climatic conditions. The result of higher smectite-kaolinite content between 3000 and 1000 y BP could be attributed to an increased Amazonian lowland source but also to a reduction of the Andean source.

The clay assemblage of episode 1 resembles that of the French Guiana surface sediment (Tab. 1); it is characterized by predominant smectite (35 %), illite (32 %) and kaolinite (21 %). The ratio K/I+Cl is low, about 0.5 (Tab. 4). Since 1000 y BP, the increase in illite (32 % against 23 % in episode 2) and chlorite (12 % against 8 % in episode 2) reflects an increased Andean flux (mountain source).

DISCUSSION

Earlier research on late Quaternary deposits from northern South America has indicated the existence of successive dry and wet climatic phases. Mean water levels in the lower part of valleys and in lakes from the Amazonian basin (Absy, 1979; Van der Hammen, 1986) and the Andes (Mourguiart and Roux, 1990) can fall drastically during dry periods (*e.g.* several tens of metres in Lake Titicaca; *see* Mourguiart and Roux, 1990). Today, the South American inter-tropical region is a zone of conspicuous climatic variability, particularly with regard to wind and rain (Kousky *et al.*, 1984). Research conducted in the past decade has led to an understanding of many of the mechanisms responsible for the atmospheric and oceanic variability associated with El Niño/Southern Oscillation (ENSO; Graham and White, 1988). During the very characteristic ENSO event of the 1982-83 winter, the position of Walker cells (related to atmospheric currents) was modified. Consequently, ascending currents (generating rainfall) and descending currents (generating dry periods) were displaced (Besleaga, 1992). The ENSO event was directly reflected in temperature and rainfall changes, and as argued later, in longshore drift anomalies.

An ENSO event (*e.g.* 1982-83) is characterized by anomalously dry conditions in some parts of the Amazon basin and northeastern Brazil (Nobre and De Oliveira, 1986; Kayano *et al.*, 1988; Besleaga, 1992; Marengo *et al.*, 1993). ENSO events are also registered by major reductions (30 %) in precipitation as reconstructed from the thickness of the annual layers in the Quelccaya ice cap (southern Peruvian Andes, *see* Thompson *et al.*, 1984).

By studying the geometry along the South Brazilian coast (at 13°S), Martin *et al.* (1992) were able to identify reversals of the longshore drift during the last 5000 years, each lasting 10-100 years. They suggested that many long-term climatic events happened during the Holocene, with effects resembling those of ENSO events. However, because of the much longer durations of the former (10-100 years, as opposed to a few months for a Niño), these cannot be considered as "paleo-Niños". These longshore drift reversals have never been identified on the Guiana coasts. In the sedimentary record of the last 3000 years (age of the most ancient deposit dated in the French Guiana mud patch) three episodes of such El Niño-type conditions have been detected. The first two events occured at 2250 ± 150 y BP and 1300 ± 150 y BP; the date of the third event has not been established.

Hydrological data in the Amazon basin at Obidos in 1983 (Tardy *et al.*, 1993; Tab. 5) show a decrease in rainfall (25 %), water discharge (17 %) and mechanical erosion (53 %). These observations reflect the Niño event of late 1982 which effectively influenced the hydrology of the Amazon basin in the following year. As a result the particulate flux from the Andes, which today accounts for an important part of the Amazonian input, especially during the wet season (Gibbs, 1967; Guyot, 1992), decreases notably.

The accumulation of shell middens below river-level (– 4 m. in Rio Xingu, *see* Fig. 1) suggest three episodes of human occupation (during low-river levels): 2200 ± 60 y

Table 5

Rainfall (P), total discharge (D_t) and mechanical erosion in the Amazon, at Obidos, for the years 1982-1984. ME_m and ME_o are respectively the mineral (m) and the organic (o) mechanical erosion (ME) (Modified from Tardy et al., *1993).*

Pluie (P), décharge totale (Dt), érosion mécanique dans l'Amazone à Obidos (1982-1984). Me.m et Me.o sont respectivement l'érosion (Me) minérale (m) et organique (o). Modifié de Tardy *et al.*, 1993.

Year	P ($mm\ yr^{-1}$)	D_t ($mm\ yr^{-1}$)	ME_m ($km^{-2}\ yr^{-1}$)	ME_0 ($tkm^{-2}\ yr^{-1}$)
1982	2,487	1,144	247	2,48
1983	1,834	937	114	1,14
1984	2,377	1,109	225	2,25
Mean	2,233	1,063	195	1,96

BP, 1200 ± 80 y BP and 850 ± 60 y BP. This is another record of three dry periods (El Niño-type conditions) in the Amazon basin, each lasting 10 to 100 years (Martin *et al.*, 1992).

In Central Amazonia, Quaternary deposits from Lake Dos Carajas also record low detrital fluxes during dry phases (Sifeddine, 1991; Absy *et al.*, 1991). In the ocean, several workers have shown that, from the Amazon mouth to the Caribbean Sea, erosion-sedimentation cycles depend on the importance of the particulate input from the Andes (Augustinus *et al.*, 1989; Eisma *et al.*, 1991; Allison, 1993).

The dry phases (Fig. 5) suggested by Amazonian pollen data (Absy *et al.*, 1991) correlate well with: (a) river-level fluctuations (Van der Hammen, 1986); and (b) El Niño-type conditions proposed by Martin *et al.* (1992 and 1993).

In French Guiana, episodes 3 and 2 (3000-1000 y BP) are characterized by a high amount of kaolinite and smectite as a result of the decrease in the Andean input (*i.e.* illite and chlorite) and by the hot and humid climate that created smectite-rich lowland soils. These episodes correspond to changes in the Amazonian flux, possibly linked to periods of El Niño-type conditions. Around 1000 y BP (within episode 1), the clay minerals were mainly transported by the Amazon from lowland and Andean sources (Fig. 5). Pollen data for western Amazonia suggest a moister episode from 1300 to 800 y BP, caused by an increase in precipitation on the eastern slopes of the Andes; the effect would have been felt throughout the Amazon drainage basin (Colinveaux *et al.*, 1985, 1988). Hansen *et al.* (1994), working on late Quaternary vegetational change in the central Peruvian Andes, set the beginning of this more humid episode at 1000 y BP. This renewal of the Andean erosion at about 1000 y BP is recorded in the marine sediments of the French Guiana coast.

Within episode 1, El Niño-type conditions reappeared at about 850 ± 60 y BP (Martin *et al.*, 1992) but did not affect the clay-mineral assemblage, which is probably the product of an active erosional phase which affects the Andean mountains locally (lands lides, mudflows).

Local coastal instability in the Holocene of the French Guiana is shown by a wide recent chenier plain along a progradational shoreline (*Atlas de la Guyane,* 1978). Required conditions for the development of the cheniers of French Guiana are as follows: (a) sand supply from local rivers (Pujos *et al.*, 1989) and migration by longshore drift, developing a local beach ridge on the western part of estuaries from submerged (bars) to well exposed (cheniers, *see* Prost, 1992); (b) a time interval when the mud accretion is interrupted (Augustinus, 1989). During the Holocene (since 3000 y BP) the sea level varied (+ 3 to + 4 m) between Brazil (Martin *et al.*, 1992) and Surinam coast (Wong, 1992). Figure 5 schematically illustrates these variations and highlights the lowering at about 2700 y BP. During this event, recorded in the cored sediments (– 3 to – 4 m), rivers would have eroded and discharged more sands on the coast (Pujos and Odin, 1986). Concomitantly, the Andean and total Amazon fluxes would be reduced on the French Guiana coast (this study). These are the reasons for the chenier formation. Sedimentary characters (reworked shelly sands, beach rocks) and the presence of an unconformity suggest that the coast was eroded at about 1700 y BP (episode 3-2 boundary). Cheniers and swamps (rich in smectites, *see* Fig. 3 and Tab. 2) were destroyed, this occurrence accounting for the higher smectite content of episode 2 sediments.

CONCLUSIONS

Two recent clay assemblages are present in the Guiana Shield. Rivers transport kaolinite (the major assemblage), whereas coastal swamps are rich in smectite. These two assemblages are derived from the local tropical source, and mingle with a huge Amazonian flux in the ocean. The Amazonian flux is composed of four minerals: illite, chlorite, kaolinite and smectite. On the basis of recent data collected in the upper part of the Amazonian basin – notably in Rio Madeira and the Bolivian tributaries – illite and chlorite would appear to originate mainly in the Andean environment. Conversely, kaolinite and smectite originate in the Amazonian lowlands (Rio Negro, Rio Xingu).

In the coastal mud prism, three episodes are identified for the Holocene (since 3000 y BP) on the basis of seismic profiles, sedimentary facies and structures, microfaunal zones and radiocarbon chronology. Clay-mineral data reveal the following significant variations:

(a) 3000 to 1000 y BP (episodes 3 and 2). Kaolinite and smectite show an increased contribution from the Amazonian basin and the French Guiana Shield, associated with a decreased Andean flux. Two long dry phases (10-100 years each; 2200 ± 60 y BP, 1200 ± 80 y BP) with effects resembling those of modern ENSO events, *i.e.* decreases in rainfall, water discharge and mechanical erosion, affect a large part of the Amazonian basin. The consequent reduction in the Amazonian input to the ocean reduces sedimentation on the Guiana coast.

(b) 1000 y BP to the present. Illite and chlorite content increases, apparently indicating a high Andean contribution to the Amazonian supply that reaches the ocean. The most likely cause of this is a return to a normal (moister) climate in Western Amazonia, with increased precipitation, water discharge, mechanical erosion and supply of particulate matter. The effect on the French Guiana coast is seen in a high flux of Amazonian muds and rapid accretion of the sedimentary prism.

The sea level dropped at about 2700 y BP, leading to a higher sand supply from local rivers. At the same time, a dry climate led to a reduced input of Amazonian muds. As a result, a series of cheniers was built. Judging from interbedded relict chenier sands, beach rocks, and an unconformity, the coast was eroded and the chenier and swamps destroyed at about 1700 y BP. The addition of smectite from the swamps to that of the Amazonian basin explain the higher content of this mineral in episode 2 sediments.

Our results illustrate the importance of the clay-mineral content of marine sediments in reconstructing past Amazonian climates. For the first time, we demonstrate that dry periods controlled by ENSO - type conditions have influenced sedimentation on the northern atlantic shelf of South America.

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