Organic fluxes of Cameroonian rivers into the Gulf of Guinea : a quantitative approach to bio-degradation in estuary and plume

Cameroon
Guinea Gulf
Organic carbon
Suspended matter
Biodegradation

Cameroun
Golfe de Guinée
Carbone organique
Matière en suspension
Biodégradation

Pierre GIRESSE [a] and Guy CAHET [b]

[a] Laboratoire de Sédimentologie et Géochimie marines, URA CNRS 715, LEA Sciences de la Mer, Université de Perpignan, 66860 Perpignan, France.
[b] Laboratoire Arago, LEA Sciences de la Mer, Université Paris VI, 66650 Banyuls sur Mer, France.

Received 17/06/96, in revised form 20/06/97, accepted 24/06/97.

ABSTRACT

The modern organic carbon flux of the Sanaga River and the rivers around the Bay of Douala is estimated to be 0.62-0.79 × 10^6 t yr^{-1}. In reality, mean Holocene sedimentation of organic carbon, including a presumed low biological production in the euphotic zone, is only 41-52 % of this value. Substantial biodegradation in the salty and brackish turbid waters in the estuaries affects the POC and DOC and corresponds to the highest bacterial densities. Between salinity 6 and 21, the data indicate a non-conservative behaviour of the suspended and dissolved organic matter (POC and DOC). A breakdown of nearly 50 % of organic carbon is observed both in suspended matter of the open sea and in marine muds of near equal grain-size distribution. Incubation experiments show in the first few days the relative stability of POC in fresh water suspensions, where only the DOC is susceptible to degradation. In the fresh water-salt water mixing zones, where there are no autotrophic or heterotrophic developments, experiments indicate a 25-65 % loss of POC + DOC after 96 h. In the clear salt water of the open sea, biodegradation is very low, though DOC becomes more and more concentrated during transport. Off Campo, on the southern boundary of the Cameroonian shelf, a phytoplanktonic bloom was encountered, with a spectacular biodegradation of 45 to 65 % occurring after 24 h.
Such quantitative approaches applied to long-term (10^4 years) processes imply that the present state can be regarded as a representative for the whole Holocene climatic conditions.

RÉSUMÉ

Les flux organiques des rivières du Cameroun dans le Golfe de Guinée: une approche quantitative de la biodégradation dans la zone de mélange eaux douces-eaux salées.

Aujourd'hui, les flux de carbone organique de la Sanaga et des rivières de la Baie de Douala sont estimés de l'ordre de 0,62-0,79 × 10^6 t an^{-1}. Mais la sédimentation moyenne du carbone mesurée pendant l'Holocène bien qu'incluant une présumée faible production planctonique de la zone euphotique, ne représente que 41-52 % de celle calculée sur la base des flux actuels. Une importante biodégradation se développe dans les eaux turbides saumâtres à salées et à forte densité bactérienne et affecte le COP et le COD. Dans les eaux de salinité de 6 à 21, les mesures soulignent le caractère non-conservatif de la matière organique en suspension et en solution (COP and COD). La dégradation d'environ 50 % du carbone organique est observée aussi bien dans les matières en suspension

à la sortie des estuaires que dans les vases marines de granulométries voisines. Des essais d'incubation expérimentale sur des suspensions d'eau douce montrent pendant les premiers jours une relative stabilité du COP alors que le COD est susceptible de se dégrader. Par contre, dans la zone de mélange eaux douces-eaux salées, on mesure (quand il n'y a pas développement autotrophe ou hétérotrophe postérieur) une perte de 25 à 65 % de COP + COD à l'issue de 96 h. Enfin, dans les eaux salées du large, la biodégradation est très limitée et le COD tend à se concentrer mécaniquement pendant le trajet. Au large de Campo, à l'extrême sud du plateau du Cameroun, une floraison phytoplanctonique assez exceptionnelle a permis l'étude par incubation d'une biodégradation très spectaculaire de 45 à 65 % qui se développe en 24 h.
L'application de ces résultats à l'échelle des processus à long terme de 10^4 ans suppose que l'on admette l'état présent comme représentatif de la moyenne des fluctuations climatiques qui ont pu intervenir pendant la durée de l'Holocène.

Oceanologica Acta, 1997, **20**, 6, 837-849.

INTRODUCTION

Several studies on suspended matter in tropical rivers indicate particular organic carbon contents generally close to or higher than 7 % by weight (Eisma *et al.*, 1978; Van Bennekom *et al.*, 1978; Schlesinger and Melack, 1981; Likens *et al.*, 1981; Degens, 1982; Martins, 1982; Meybeck, 1982; Cadée, 1984; Lesack *et al.*, 1984; Meade, 1985; Richey *et al.*, 1990; Hedges *et al.*, 1986; Bongo-Passi *et al.*, 1988). Differences are often linked to difference in grain size (in Hedges *et al.*, 1986).

However, tropical marine muds show organic carbon concentrations which, though higher than in temperate sea deposits, rarely exceed more than 3 or 4 % and exceptionally 5 % (Emerson, 1985; Suess and Muller, 1980). This upper limit has been checked several times in the regional framework of the West-African margin within deposits of near equivalent grain-size as measured in suspended matter (McMaster *et al.*, 1971; Summerhayes *et al.*, 1976; Giresse *et al.*, 1981; Barusseau *et al.*, 1988; Giresse and Barusseau, 1989). It has also been recorded in the temperate North Sea (Eisma and Kalf, 1987).

The processes of oceanic degradation of terrigenous organic matter have been analysed on several occasions, both for the water column as a whole and at the water-sediment interface (Emerson and Hedges, 1988; Reimers and Suess, 1983; Hedges *et al.*, 1986). From these processes, it is possible to quantify the loss in organic matter observed in a large number of deep marine relative to shallow sediments.

However, these mechanisms are preceded by tidal and seasonal cycles of deposition and resuspension that develop within estuarine or coastal waters. As a result of complex processes which affect organic matter, inputs to estuaries are probably not identical to their outputs to the ocean (Cauwet and Martin, 1982). Various processes are observed: estuaries act as filters or traps for particles; and biological and physicochemical reactions may alter organic products (Cadée *et al.*, 1993). Another discussion relates to estuarine phytoplanktonic primary production, which is usually restricted because of the high turbidity (Eisma and Cadée, 1991) although lower-turbidity estuaries can be considered as among the most productive ecosystems in the marine environment (Cadée, 1978; Cadée and Laane, 1983).

The Bay of Douala receives sediments from several rivers (Wouri, Mungo, Dibamba) that flow from the great rainforest; but a large part of the sediments comes from the Sanaga River, originating in a savannah-forest composite basin. The bay is a propitious site both for the observation of initial dissolution or degradation in a fresh water - salt water mixing zone, and for the follow-up of particle accumulation. The present paper addresses the present organic flux of the Cameroonian rivers, as well as the biogeochemical processes in the salty and brackish turbid waters in the estuaries that might help in the identification of organic carbon concentrations in the deposits of the northern Cameroonian shelf. Results from present-day sedimentation have been tested against data relating to Holocene sedimentation.

CLIMATIC AND OCEANIC SETTING, PRESENT INPUT AND MARINE DEPOSITS

Climatic and oceanic setting

The climate in the considered region is equatorial, with precipitation depending on altitude. Rainfall always exceeds 1500 mm yr^{-1}, reaching 2000 mm yr^{-1} in the western uplands and well over 4000 mm yr^{-1} in the coastal belt, with dramatical variability around Mt Cameroon or Bioko Island. For example, the foot of Mt Cameroon, facing west towards the monsoon, receives an average of 10 m yr^{-1}. So the low salinities of the sea water are partly a result of these exceptional rainfalls (Mahé, 1993).

In this inner part of the Gulf of Guinea (Bay of Biafra) and in contrast with other coastal waters of Western Africa, we observed a relatively small annual range of salinity (20 to 24) and no very consequent seasonal physical variation apart from the fact that the temperature of surficial waters is highest in January-March (maximum 30 °C) and lowest in August (about 27 °C). Also the seasonal change does not strongly influence the vertical composition of the water section (Piton and Kartavtseff, 1986).

This Bay of Biafra represents a typically warm and confined sea with low nutrient content and low primary production, and a relatively undersized fish population (Crosnier, 1964). Shrimps, normally plankton-feeders, are locally abundant in some coastal waters away from the river mouths.

On the coast of the Gulf of Guinea (from Cap des Palmes to the mouth of the Congo-Zaïre), the Sanaga, with an annual flow of 65.3 $\times$ 10^9 m^3 yr^{-1}, is the fourth tributary after the Congo-Zaïre, the Niger and the Ogooué. Due to a prevailing south-westerly swell, most of its waters and their loads are oriented northwards where, at the entrance to the Bay of Douala, they meet those of less important rivers: the Mungo (9 $\times$ 10^9 m^3 yr^{-1}), the Wouri (16 $\times$ 10^9 m^3 yr^{-1}) and the Dibamba (4 $\times$ 10^9 m^3 yr^{-1}) (Nouvelot, 1972; Olivry, 1977). Suspended particles in these rivers are buffeted by fairly strong tidal flows in the area, which has one of the highest tidal ranges in Western Africa (2 to 3 m at the equinox). Thus, the Bay of Douala acts as a huge estuarine complex, and it is only in the open sea that the main sedimentation of the pelitic fraction and the organic matter associated with it takes place (Fig. 1). Further north, off Rio del Rey, another estuarine mechanism occurs which regulates the accumulation of particles coming both from the Bay of Douala and from the River Niger deltaic complex (Giresse *et al.*, 1995).

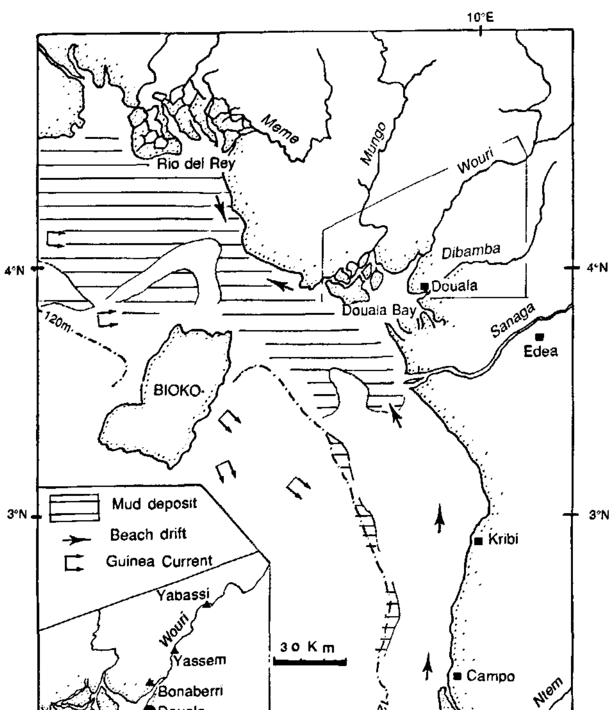

Figure 1

Map illustrating the location of the study area, the distribution of recent pelitic sedimentation according to the main oceanic currents. The planktonic bloom (pb) area off Campo is indicated.

Present inputs

The Sanaga Basin can be subdivided into two main sub-basins. The basin of the Sanaga itself has its farthest limit in the savannah area of the Adamaoua plateau (at about 1000 m), then crosses transition zones of tree-growing savannahs and, finally, semi-deciduous and evergreen tropical forests. The basin of the Mbam, the main affluent of the Sanaga, follows the same succession of flora with an upstream part straddling the Adamaoua plateau and the volcanic dorsal, where sectors of intensive cultivation predominate. The basins of the Mungo, Wouri and Dibamba rivers are mainly covered by tropical forests.

From 1969 to 1971, ORSTOM hydrologists employed a simple methodology to measure the suspended load in two major sub-basins: Sanaga (s.s.) at Nachtigal and Mbam at Goura (Nouvelot, 1972; Olivry, 1977). These two sub-basins account for more than 90 % of the global discharge to the ocean of the Sanaga basin as a whole. The average annual concentrations are 58 g m^{-3} for Sanaga and 160 g m^{-3} for the Mbam. For the Sanaga sub-basin, the transport of suspended sediment to the ocean is near 3.5 $\times$ 10^6 tons each year; for the Mbam sub-basin, this transport is near 2.5 $\times$ 10^6 tons each year. Thus a mean of 6 $\times$ 10^6 tons of suspended matter is transported annually to the ocean. It is obvious that this value is slightly lower than the effective erosion, because sedimentation in the flooded areas and bed-load transport are not taken into account. This bed-load acts generally as 10 % of the total supply to the estuary (Milliman and Meade, 1983) but as in most rivers, however, the larger part of this bed-load does not reach the estuary, being deposited in the lower course of the river. Particulate organic carbon (POC) concentrations in the suspended matters of the Sanaga and Wouri rivers vary seasonally from 7 to 16 % (5 to 15 g m^{-3}). The average POC flux of the Sanaga varies between 0.42 and 0.54 $\times$ 10^6 t yr^{-1}, whereas the other Douala rivers together (Mungo, Wouri, Dibamba) vary from 0.12 to 0.25 $\times$ 10^6 t yr^{-1}. Thus the bulk of annual POC discharge to this part of the Guinea Gulf ranges from 0.62 to 0.79 $\times$ 10^6 t.

Marine deposits

Total organic carbon (TOC) distribution is controlled by sedimentary hydrodynamic factors. In the fairly rough shallow waters (10 to 20 m) off the Bay of Douala and the mouth of the Sanaga, sandy muds are characteristic of intermittent wave-influenced deposition. Usually, these muds contain less than 3 % TOC (Fig. 2*a*). At greater depths, they are less sandy (<3 %) and contain 3 to 4 % total organic carbon (TOC).

Also, in the settling zones off Limbe, sheltered from tidal flows, *i.e.* at the end of an approximately 80 km course, the muds contain more than 4 % TOC. Their highly kaolinitic composition indicates that they come from the Sanaga and the rivers of the Bay of Douala. In contrast, a second settling zone is defined off Rio del Rey, where the abundance of montmorillonite shows the involvement of a Nigerian flux (Giresse *et al.*, 1995).

This relative increase in TOC appears to be related to the differential sedimentation of the suspended matter, as inorganic particles probably settle more rapidly than organic ones (Cadée, 1982). However, the majority of these surficial mud deposits (Fig. 2*b*) contain less than 5 % or even 1 % of sand particles (>50 μm). This feature

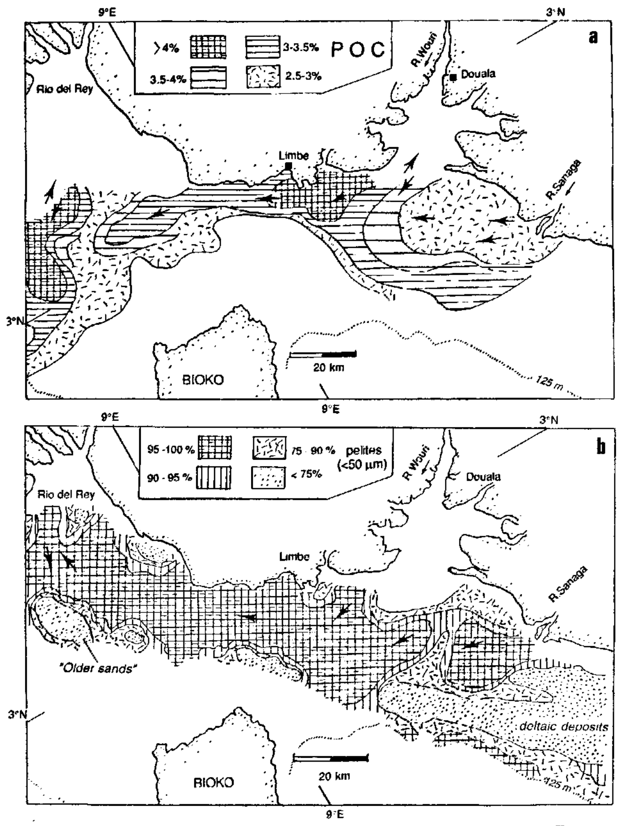

Figure 2

a. Distribution of POC contents in the northern Cameroon shelf deposits;
b. Distribution of the pelitic fraction (< 50 μm) contents in the same area. The arrows indicate the presumed flow direction of the superficial waters. The south-western sandy outcrop is a deltaic accumulation deposited during the last low-stand. 182 grab-samples were analysed and used to draw the isolines of these maps.

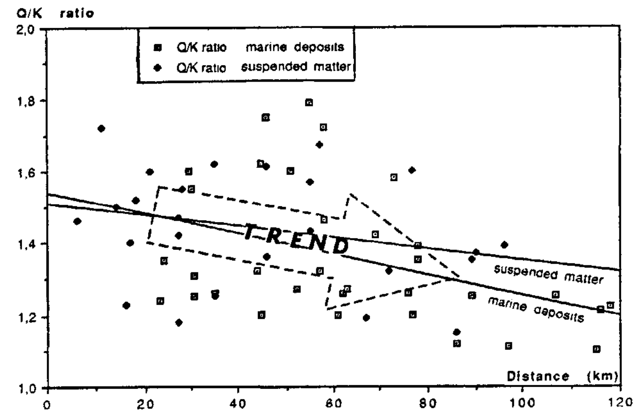

Figure 3

Plots of Q/K ratio of marine deposits and suspended matter versus the length of the transport from the river mouths as indirect grain-size representations.

demonstrates that the larger part of the sediment is derived from suspensions and not from a bed-load transport, an improbable process in this geographical area during this high-stand period. Deltaic sands in the south-western area of the map were deposited during the last low-stand.

The purpose of this paper being to estimate the transport of organic matter, we rely heavily on concentrations of particulate carbon in relation to grain-size. Concentrations of both POC and DOC are likely to be higher in finer fractions. In a large part of the water samples, suspended matter was too low to permit sedimentometric measurements. We tried another approach using diffractometric measurements of the main peaks of quartz (Q) and kaolinite (K) in both marine muds and suspended matter. We used the Q/K ratio as a function of sandy and silty fractions *versus* the clayey fraction (Fig. 3). Although the ratios were rather scattered, one can observe: (i) a very slight decrease in the ratio of both deposits and suspended matter to the length of the transfer, and a slight trapping of quartz particles after 50-60 km of transport; and (ii) in the mass, the ratio Q/K appears rather constant during this 120 km transfer; in both cases, suspended and deposited matters are present in a nearly similar size area of the spectrum. Such relative homogeneity may be due to a combination of factors, but sea water with a particular low planktonic production (Crosnier, 1964) allows a comparative observation of organic contents in these two steps of the sedimentation process.

METHODS

Most of the sediments and water samples analysed were taken on board the research vessel *André Nizery* of ORSTOM. Surface sediments were collected by a Shipek grab sampler, frozen and stored and later freeze-dried. River sediments were collected from the bank with a dredge or a shovel and subjected to the same procedures. A classical set of sedimentological measurements previously performed, as well as and fine-grain size-analyses and X-ray diffractometry (cobalt anticathode) were useful in this study.

The organic material from sediments and alluvia was analysed for its organic carbon content (LECO induction furnace) and hydrogen index (Rock-Eval pyrolysis).

Water samples were collected during the March 1992 and March 1993 cruises, at the beginning of the rainy season. The samples were analysed for "particulate" and "dissolved" matter, which were differentiated by filtration over 0.6 μm GFF Whatman filters. The filters were dried and weighed before and after the operation in order to measure the total quantity of particles. Then they were subjected to combustion at 950 °C to estimate C, H, N with a Perkin-Elmer 2450 (using pure helium as the driving gas). The reproducibility of each value was ± 3 % and exceptionally ± 5 %.

"Dissolved" organic matter corresponds, by convention, to the organic material passing through a 0.6 or 0.45 μm mesh. Dissolved organic carbon (DOC) was estimated with a TOC 5000 SHIMADZU after fixation of the samples with $HgCl_2$, then decarbonatation and oxidation at 700 °C. Reproducibility of duplicate measurements was much better than ± 5 %. It should be pointed out that this DOC includes all the organic phases of carbon, whether truly dissolved or in the macromolecular, colloidal or microparticulate states (Johnson and Kepkay, 1992; Koike *et al.* 1990; Tranvik, 1994; Wells and Goldberg, 1991). In order to study the biodegradability of this complex material, we operated on samples filtered over GFF (pore size 0.6 μm) to remove bacterial predators (Kirchman *et al.*, 1991; Servais *et al.*, 1989). These samples were left in darkness at atmosphere temperature (25-30 °C) in order to follow the disappearance or stability of the DOC and the evolution of the bacterial flora. After fixation with $HgCl_2$ (final 5 ppm), the bacteria were coloured with DAPI and counted by UV fluorescence (Hobbie *et al.*, 1977). However, in the case of some waters of the Wouri river, it was not possible fully to respect the experimental conditions of darkness.

GENERAL CHARACTERISTICS OF THE RIVERINE ORGANIC MATTER

Alluvial deposits

The particular organic carbon (POC) content of muddy alluvial deposits collected close to the banks was irregular (from 3 to 10 %), due to variation in grain size. Contents close to 3 % were recorded in some sandy alluvial deposits of the Sanaga.

The analysis of the organic matter isotopic composition ($\delta^{13}C$) carried out on the Sanaga deposits showed a progressive decrease of $\delta^{13}C$ in the direction of flow (Bird *et al.*, 1994). In the upstream savannah areas, the $\delta^{13}C$ were of the order of –22 °/₀₀. Then, in forest areas, they fell as low as –25 °/₀₀, reflecting a mixture of C4-dominant plant matter upstream and C3-dominant matter downstream. The Wouri and Mungo rivers, also in the forest domain, present $\delta^{13}C$ of the order of –27 to –28 °/₀₀. In the marine muds off the river-mouths, values of –25 °/₀₀ can be found, characteristic of the Sanaga's main flux, so the passage of the fresh water-salt water interface does not seem to have altered the isotopic composition of particulate carbon.

This conservation of the isotopic signature is all the more remarkable in that the successive effects of pedogenesis and the alluvial course have led to fairly substantial degradation, as shown by pyrolytic analysis (Table 1). This is especially true in the savannah zones of the basin where the hydrogen index (HI), which should reach values characteristic of herbaceous components (*i.e.* over 500), usually remains below 150, or even 100. In these paroxysmal oxidation cases, the action of large bush fires can be envisaged. Downstream, in forest or littoral areas, the degradation should be more moderate: the HI usually varies between 150 and 200, whereas the reference HIs of lignocellulosic tissues vary between 200 and 500. The "conservative" characteristics of ligneous matter are always stronger than those of herbaceous matter (Talbot and Livingstone, 1989) and can explain, somewhat paradoxically, a higher HI on forest slopes than on savannah slopes.

Table 1

Hydrogen Index (HI) and particular organic carbon (POC) contents of estuarine deposits from the main rivers and of fluvial-deposited sediments from the various vegetal covers (forest/savannah) of the Sanaga basin.

Estuaries	% POC	HI
Rio del Rey	5.85	132
"	10.58	185
Mungo	2.45	174
"	1.19	151
"	1.16	174
Wouri	3.46	116
"	5.64	111
"	4.56	138
Sanaga	1.96	149
"	2.69	149
"	0.68	225
"	3.41	130
"	1.58	109
Sanaga River		
Savannah	3.65	110
"	6.03	197
"	1.56	124
"	3.42	137
"	1.05	141
"	1.35	578
"	0.17	753
"	10.41	208
"	1.93	98
"	0.87	111
"	3.31	95
"	1.41	111
"	2.26	75
Forests	2.84	97
"	3.68	202
"	3.79	132
"	2.90	117
"	2.95	81
"	0.71	108
"	2.96	72
"	4.48	154
"	1.44	94

Riverine suspensions

Despite variations which are also linked to grain size, suspended matter upstream of the estuarine sector generally shows a high POC content. This varies from 7 to 16 %, *i.e.* similar to that found in several areas of the neighbouring Congo-Zaïre great basin (Bongo-Passi *et al.*, 1988; Mariotti *et al.*, 1991) or in other Southwest African rivers (Cadée, 1984), such as the Niger (5.8 %), the Benué (28.5 %), the Ogooué (6.1-6.6 %) and the Dibamba (12.2 %), but with the exception of the Sanaga (2.3 %).The C/N ratios of between 6.7 and 8.9 indicate that degradation is still moderate in the suspensions of both the Wouri and the Sanaga. Dissolved carbon contents (DOC) are between 4.8 and 8.3 mg l^{-1}, *i.e.* comparable to the POC concentrations (5 to 12.5 mg l^{-1}).

CHARACTERISTICS OF ORGANIC SUSPENDED MATTER IN SEA WATER

General distribution of POC and DOC in sea water

On the large scale of the western shelf, there is an inverse relationship between POC content and the concentrations of suspended matter which support it (Fig. 4*a*). In the

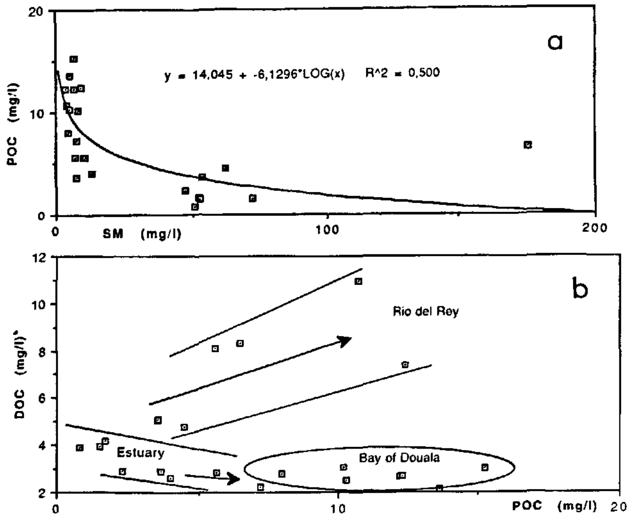

Figure 4

Plots of (a) Particulate organic carbon (POC) contents versus suspended matters (SM) and (b) of particulate organic carbon (POC) versus "dissolved" organic carbon (DOC); in this last case, we note the distinct opposition between the proximal points of the estuaries and of the Douala Bay and the distal points of the Rio del Rey offshore.

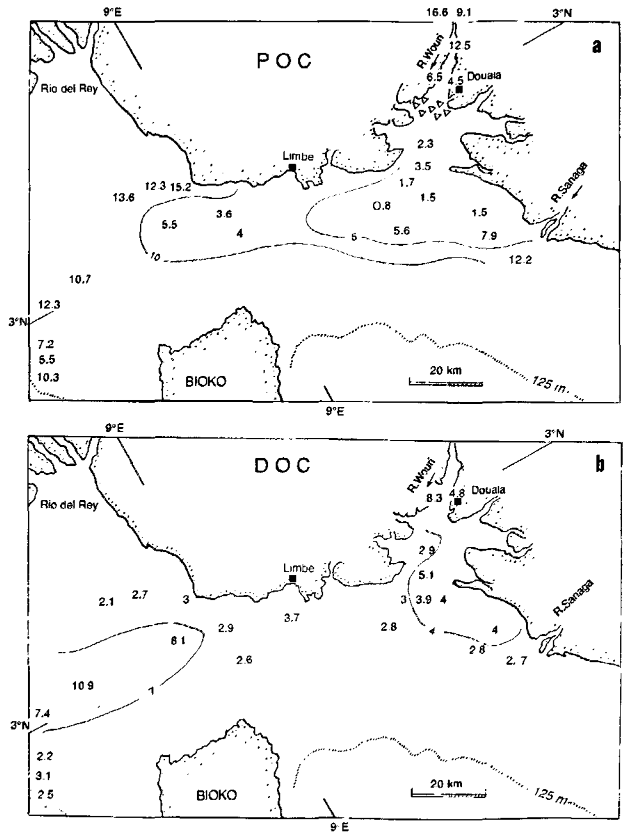

Figure 5

Distribution maps of (a) POC contents (mg/l) and (b) DOC contents (mg/l) from suspended matters. In the POC map, triangles indicate the fresh water-saline waters mixing zone.

Wouri estuary, maximum turbidity reaches 50 to 200 mg l^{-1}; it is close to 50 mg l^{-1} off the Bay of Douala and the mouth of the Sanaga and remains at 5 to 10 mg l^{-1} in the offshore waters including those of Rio del Rey. The POC contents are inversely distributed. They are highest within the least concentrated turbidity area which is the furthest from the source: 1.5-2 % off the Bay of Douala, then 3-5 % between the Isle of Bioko and the continent and lastly, 5-13 % in the western sector (Fig. 5*a*). This hydrodynamic process is well known also in the Dutch Wadden Sea: POC settles less easily than inorganic suspended matter as POC is highest during slack tide when suspended matter is at its lowest (Cadée, 1982). Here, the suspensions most distant from the sources are the best sorted and the richest in fine and organic particles.

The distribution of "dissolved" carbon is fairly closely to that of POC (Fig. 6*b*), with a decrease from above the Wouri estuary to the open sea (from 8.3 to 4.8 mg l^{-1} to 2.8-2.6 mg l^{-1}), and a few local concentrations off Rio del Rey (7.4-10.9 mg l^{-1}). The POC/DOC graph (Fig. 6*b*) presents two groups of points. One starts at the estuary and shows a gradual upstream-downstream decrease. The other (Rio del Rey), where the positive POC-DOC correlation is clear, concerns the most western stations whose low turbidities have been observed. Both DOC and POC concentrate in the least abundant suspensions most distant from their source. The effect of the DOC hydrodynamic selection is longer in making itself felt: it is only recorded at a few western stations in Rio del Rey where the suspended matter has mostly reached the microparticulate state.

Longitudinal distribution of POC and DOC in the Wouri estuary and the Bay of Douala

In order to present estuarine processes regulating organic carbon content in estuaries, one useful method is to plot POC and DOC against salinity (Cadée, 1982; Cadée and Laane, 1983; Cadée, 1984; Cadée *et al.*, 1993). Normally, riverine values are high and the marine end-member values are low. If all values in intermediate salinities are on a straight line connecting river and ocean values, then mixing is conservative and the values indicate simple dilution in the open ocean. If values are above this line, production takes place in the estuary; if they are below the line, losses will occur (Liss, 1976). From these graphs (Fig. 7*a*), mixing appears non-conservative at salinities between 0 and 21 for POC values and, possibly, at salinities between 0 and 21 for DOC values. Estimation of such losses will be far more difficult as we have to add eventually the POC and DOC bioproduction (Cadée, 1984). Specific data for phytoplankton were not collected in this study, but during evaluation of bacterial density, cell numbers of diatoms and flagellates were estimated below 10^4 ml^{-1} in all of the mixing zone; diatoms occurred mostly in the river waters. C/N ratios were also plotted against distance from the source and indicate a downstream increase (Fig. 7*b*). River ratios were about 6-8 and riverine phytoplankton is suggested as a cause for such a low ratio; higher ratios for the mixing zone may be attributed to the decomposition of this halophobic plankton, but are probably also due to the terrestrial POC. However, some low ratios were found in this mixing zone and were thought to be related to local bloomings before the open sea. But it seems that these possible bloomings were too weak to induce any consequent plasmolytic release of DOC from dying plankton.

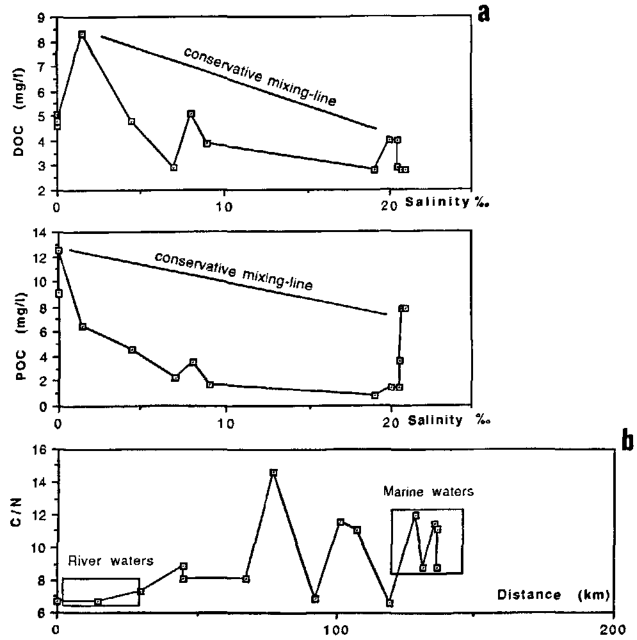

Figure 6

a. Distribution of particulate organic carbon (POC) and dissolved organic carbon (DOC) relating to salinity (March 1993). Large parts of estuarine POC and DOC are below the conservative mixing line of POC and DOC of river and sea water.
b. Longitudinal distributions of C/N andC/H, in these estuarine waters, no C/N ratio decrease by phytoplanktonic production was observed for this cruise.

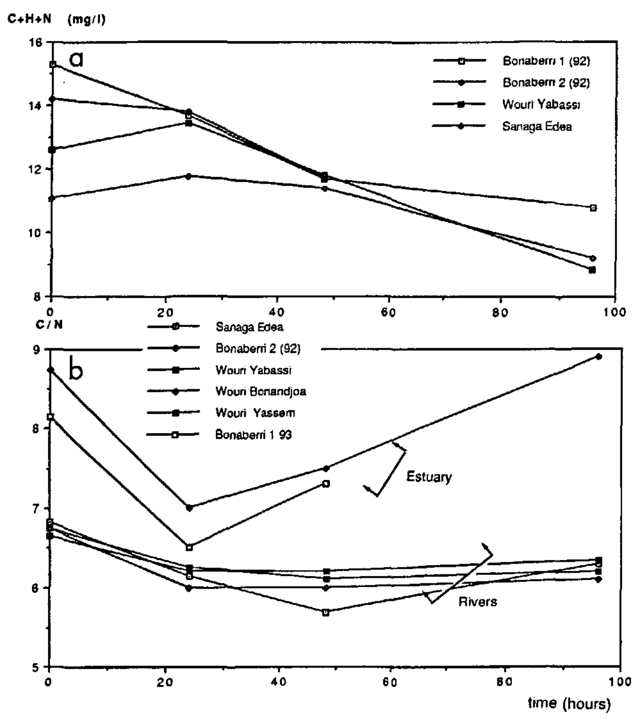

Figure 7

Plots versus time during experimental bacterial degradation of suspended matters from fresh and brackish waters: (a) total mass C + H + N; (b) C/N ratio; (c) the C/H ratio.

Lastly, the variation of C-isotope composition (Bird *et al.*, 1994) from various river sediment in the Sanaga and Wouri basins to the shelf exhibits a progressive downstream decrease that is very consistent with the progressive change from organic matter of mixed C3/C4 origin from the savannah and montane regions to C3 forest-derived organic matter. The possibility that algal-derived C is a significant source of C within the rivers cannot be rigorously addressed, although the values encountered suggest that this source does not exert a large influence on the δ^{13}C budgets of rivers and marine sediments.

The non-conservative behaviour of organic carbon is most probably produced by consumption of the organic matter caused by bacteria.

EVOLUTION OF EXPERIMENTALLY INCUBATED SUSPENDED ORGANIC MATTER (24 to 120 h)

River water experiments

Suspended matter concentrations in the Wouri (Yassem, Yabassi and Bonaberri, at low tide) and in the Sanaga (Edea) are relatively low (30 to 50 mg l^{-1}). The total C + H + N content varies from 11 to 15 mg l^{-1}. After 96 h of incubation, this mass remains more or less stable, although in several cases (Bonaberri 1 and 2, Yabassi, Edea), a weight loss varying from 10 to 17 % can be measured (Fig. 7*a*). Two stations of the Wouri were unique in that there was a gain of matter, possibly due to photosynthesis because of insufficient darkness. The C/N ratios, varying from 6 to 7, remained remarkably stable after 96 h, whereas the estuary waters of the Bonaberri show, at low tide, the beginning of a degradation (C/N from 7 to 9) (Fig. 7*b*).

In contrast, there appears to be a progressive degradation of DOC. Most of the waters showed a decrease in concentration of 25 to 60 % (Fig. 9). The process is therefore more active at the microparticulate than at the macroparticulate scale. The highest decrease (60 %) was observed in the Sanaga waters, downstream from Edea, an area of high human population with discharge.

The two stations of the Wouri where there is a gain of C + H + N matter (Bonaberri 8 and Bonandjoa) present a regular decrease in DOC concentration (Fig. 8). Such low values for DOC at the end of the experiment do not indicate a phytoplanktonic production or a consequent plasmolitic release. If photosynthesis is not responsible for the C + H + N increase, an alternative explanation would be related to the mycelial development observed in the DAPI preparation.

Bacterial densities in the rivers were moderate and fairly constant. In the Sanaga, they vary between 25 and 30 × 10^4 ml^{-1}, with the exception of the city of Edea, where urban pollution contributes to the figure of 59 × 10^4 ml^{-1}. In the Wouri (Fig. 9), dynamic tide upstream, densities were moderate (15 to 20 × 10^4 ml^{-1}) but particle-bound bacteria were often observed. In most cases, no significant change occurred during the 96 h of the experiment, thus confirming the generally low rate of degradation.

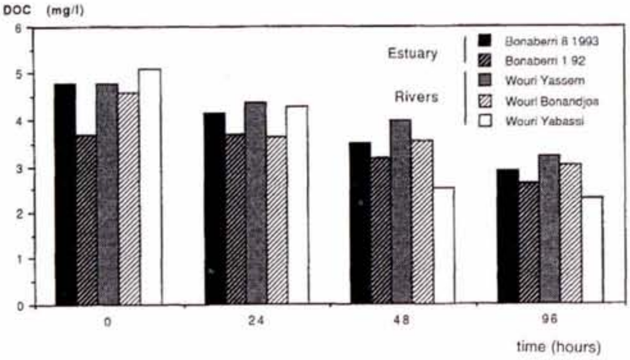

Figure 8

Dissolved organic carbon (DOC) biodegradation illustrated by two examples from estuarine saline waters and by three examples from Wouri River fresh waters.

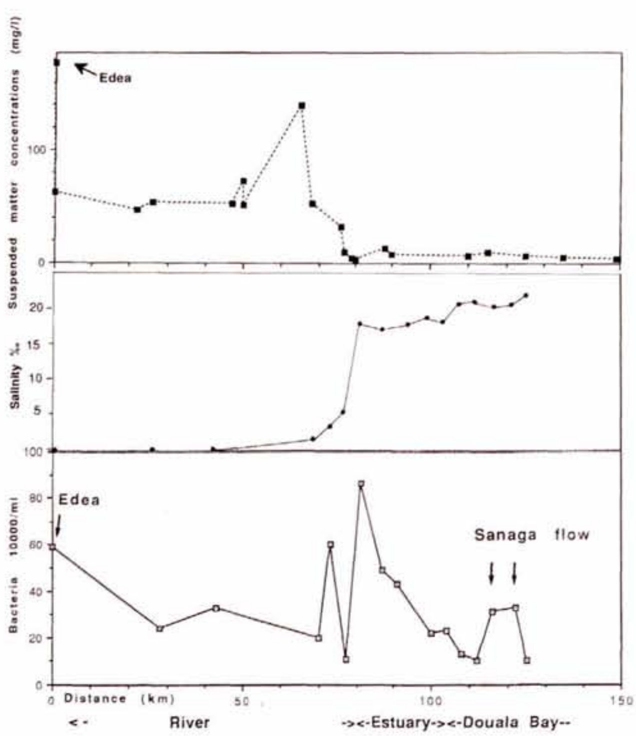

Figure 9

Bacterial abundance in the surficial suspended matter from upstream to downstream of the Wouri River, from its estuary and from Douala Bay. Two arrows correspond to the Sanaga flow; note the pollution by the Edea urban community.

Waters of the estuary and the Bay of Douala experiments

Bacterial density is generally linked to the concentration of matter in suspension, *i.e.* to the nutrient matter in the water. The richest waters will therefore be those agitated by tides in the estuary and the Bay of Douala, with densities varying from 42.2 to 86.3 $\times$ 10^4 ml^{-1}. It is also in these waters that the highest proportion of particle-bound bacteria was found. Further offshore (Fig. 9), the density falls and the bacteria are all free- living. However, two stations off the Sanaga mouth indicate the course of this river's effluent plume by their bacterial densities.

Since the suspended matter concentrations were high (up to 200 mg l^{-1}), the total concentration C + H + N reached 35 to 40 mg l^{-1}. Because of this high charge, it was difficult to collect the same mass of matter at each stage in the experiment. However, in five out of seven analyses, a substantial decrease was measured at the end of the incubation, varying from 10.9 to 29.4 % in the most turbid waters and from 7.8 to 40 % in the clearer waters of the Bay of Douala. In each case, it is the saltiest waters of the flow that seem most susceptible to this degradation (Fig. 10 *a*, *b*). The two examples where organic mass seems to be preserved are either upstream from the saline estuary (Bonaberri 8) or in the open sea of the Bay of Douala. In most cases, the C/N ratio showed an important increase (Fig. 10 *c*), rising from 8-14 to 11-20 (a factor of 1.5-3.5). Thus, biodegradation is much more significant here than for fresh-water organic matter. It is fairly general, with the C/N ratio liable to increase even in the case of seemingly stable suspensions in terms of C + H + N. But it decreases very sharply in the offshore marine waters.

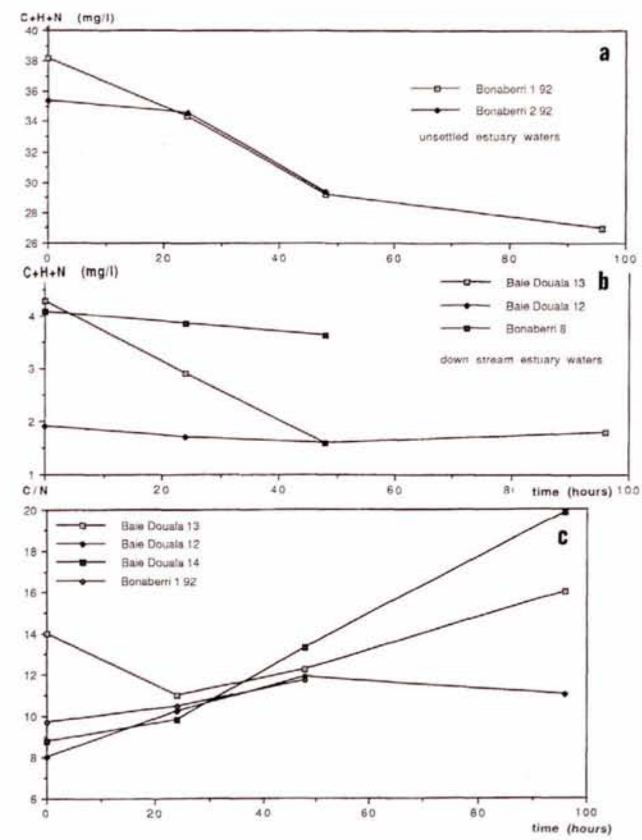

Figure 10

Plots versus *time of C + H + N of organic matter from saline waters of estuaries during incubation:*
a. unsettled estuary waters;
b. downstream estuary waters;
c. biodegradation plot versus time from organic matter from saline waters of Douala Bay and Wouri estuary (C/N ratio).

The evolution of DOC over time (Fig. 8) also indicated substantial biodegradation, with two examples in Bonaberri giving losses of 25 to 30 %.

In the Wouri estuary's "maximum turbidity" suspensions, bacteria were abundant at the start (1200×10^4 ml^{-1}), then decreased very rapidly (160×10^4 ml^{-1}) as soon as feeding was done. In the meantime they degraded an average of 20 % of the organic matter. On the other hand, three marine waters just a little farther away from the Bay of Douala present fairly low bacterial densities (4 to 12×10^4 ml^{-1}). During incubation, the amplitude of fluctuations remained fairly low, with the negative sometimes leading to an almost total disappearance after the third day.

Planktonic bloom off Campo experiment

This planktonic bloom occurred in February 1992, off Campo, namely on the extreme southern boundary of the Cameroonian shelf (some 150 km from the Bay of Douala). It seems to have been related to a comparatively rare northern extent of the equatorial upwelling belt and provided a good opportunity to analyse planktonic mass biodegradation in these fairly unproductive sea waters.

Two samples were collected and subjected to the same incubation protocol. The first, at the beginning of the bloom, showed a suspension with a still slightly low organic load, but composed of living plankton. After 120 h, the POC content dropped from 5.7 to 1.9 mg l^{-1}, *i.e.* a 76 % loss. The second sample, at the end of the bloom, contained an almost opaque green layer composed of dead phytoflagellates. The decrease in this case only reached 40 %. In both cases, the C/N ratio remained stable at around 6, and the C/H ratios did not change significantly; however, the live plankton ratio was 1.7 whereas dead degraded plankton ratio rose to 3.7.

After 120 h, the DOC decrease was high: 45 % in the case of live plankton, and 65 % in the case of dead plankton.

Bacteria pullulate exuberantly in planktonic suspensions (Fig. 11). Unquantifiable densities are expressed by the high abundance of attached bacteria on phytoflagellates whose core is released. But, from the second day of observation, the densities start to decrease.

This biodegradation emphasizes the specifically non-conservative behaviour of this phytoplanktonic suspension.

DISCUSSION

Application to the sedimentary budget

The purpose of recent work carried out (Giresse and Maley, in press) was to estimate organic carbon fluxes as a varying

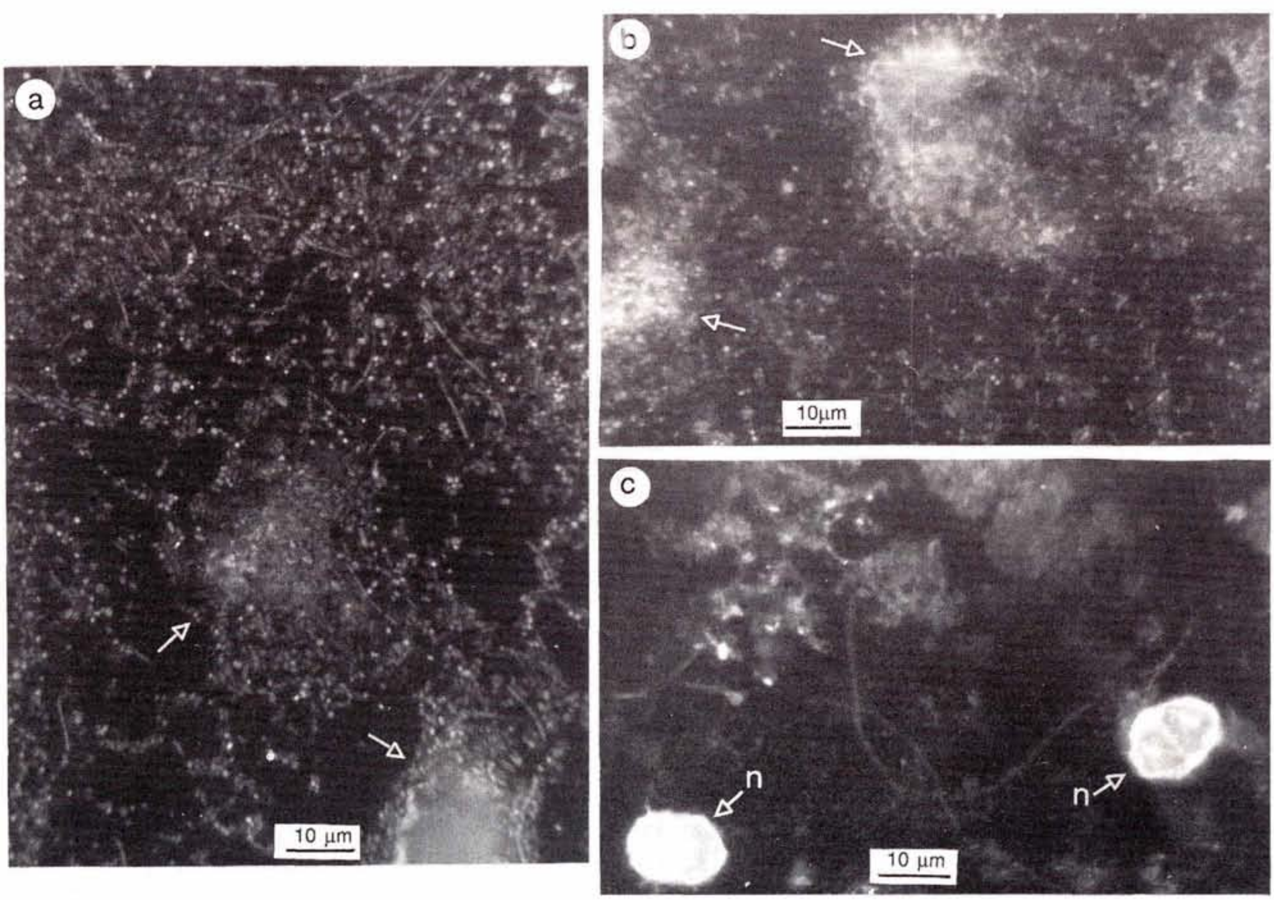

Figure 11

Bacterial abundance of plankton-derived matter off Campo after DAPI coloration:
a. after 24 h: high bacterial growth and particularly of particle-bound cells (arrows);
b. after 36 h: decrease of density with together a concentration of particle-bound bacteria (arrows);
c. after 36 h: release of Phytoflagellates nucleus *(arrow) and near- disappearance of bacteria, we can detect mycelial filaments.*

Table 2

Summary of the Holocene sedimentation rates and budgets of organic carbon on the various deposition zones of the Cameroon margin.

	High System Tract	Slope (200-2000 m)	Total
Holocene deposit volume (10^6 m^3)	56.712 ± 4.125	7.79	
org. C sedimentation rate ($g/cm^2/10^3$ y)	0.5 (outer shelf) 9 (nearshore)	5 (upper slope) 0.5 (lower slope)	
Org. C Holocene deposit (10^9 t 10^4 y)	3.271 ± 0.237	0.319	3.4

carbon sink on a glacial-interglacial time scale in marine and lake basins of Cameroon. The direct measurements and the indirect calculations on which the conclusions were based have been summarized here and applied to the Holocene period (Table 2).

Through settling of the terrigenous particles, only a small part reaches the outer shelf where Older Sands formation (Allen, 1965) crop out. Therefore, the Sanaga river and Douala Bay river sedimentation follow a well-delimited area of distribution reaching 3,140 km^2. High-resolution seismic reflection surveys permitted the definition of the Holocene High System Tract (HST) where the muds reach a thickness of 20 to 40 m close from the shore, but are reduced to a 10 m veneer 40 km offshore. This HST overlaps the first sandy deposit of the Holocene transgression where these sediments, which are very poor in organic matter, will not be taken into account in this budget. The Holocene deposit corresponds to a prism of 56.712 ± 4.125 × 10^6 m^3. This prism was sampled by corings: TOC contents closely approximates the surface values and radiocarbon datings ($\approx$60) show a gradual decrease in total sedimentation rates from the shore (9 × 10^{-3} g cm^{-2} yr^{-1}) to the prism wedge (0.5 × 10^{-3} g cm^{-2} yr^{-1}). This rate therefore permits us to estimate that 3.271 × 10^9 tons TOC are trapped during 10^4 years. This trapping includes a northern mixing area where the clay mineral analysis enables us to define a hybrid deposit of near 50 % of Nigerian particles (this allochthonous origin is emphasized by relatively high smectite contents, *e.g.* 20 to 40 %). The mean thickness of upper-slope sediments is estimated by core-data and radiocarbon dating as amounting to about 5 m. Toward 2000 m, the average thickness is 0.5 m and the deeper slope will not be considered here due to a very low sedimentation rate (Giresse and Barusseau, 1989). It can be estimated that 0.279 × 10^9 tons Holocene TOC are trapped on the slope. But it can be assumed, on the basis of the mineralogical study, that only half originates from the Cameroonian rivers because only a part of their suspended matter is actually able to bypass the outer shelf. So, it was assumed that the organic storage on this slope is about twenty times less than on the shelf.

The average annual flux of particulate organic carbon was estimated to be 0.62-0.79 × 10^6 t yr^{-1}. During Holocene time, the TOC contribution of the Sanaga river and of the other rivers of this coast would be 6.2-7.9 × 10^5 t yr^{-1}, if we assume that its nearly the same as at present. But taking into account the cumulated organic carbon values of the deposit on the margin, the total mass of TOC was found to be 3.271 × 10^5 t yr^{-1}, *i.e.* only 41-52 % of the supply. This apparent loss could be regarded as a minimal evaluation if we admit a presumed weak but existing plankton production. Thus, $\delta^{13}C$ values from the marine muds off the Sanaga River mouth are very near (– 25 ‰) those from the estuary (Bird *et al.*, 1994) supporting the weakness of the plankton input.

Conservative or non-conservative behaviour of the total organic carbon during transfer to the ocean

The fresh water-salt water passage is not conservative between salinity 2 and 20, as many POC and DOC values lie below the mixing zone. Phytoplanktonic production in the Bay of Douala cannot be addressed but decomposition is of greater magnitude than production suggested by the non-conservative behaviour. The negative relation between POC-DOC and salinities ranging from 0 to 22 indicates that terrigenous input is the primary source of organic carbon in the Gulf of Guinea. Such relatively low phytoplanktonic production, particularly in the upstream part of Bay of Douala, expresses a relative nutrient scareness which is well known in this part of the Guinea Gulf. There is no maximum level of primary productivity found for some distance at the mouth of the rivers as in the Congo-Zaïre estuary. The dual and near-coincident decomposition of POC and DOC indicates that mineralization of POC may result mostly in CO_2 formation. Here, mass mortality of halophobic fresh-water phytoplankton is not related to a release of DOC (Van Es and Laane, 1982; Cadée, 1987). Compared to the Congo-Zaïre plume, the nutrient discharge of the rivers is rapidly diluted and the salinity is never higher than 20-21. In the same Congo-Zaire plume, a peak of phytoplankton biomass was only found at a salinity above 20, *e.g.* when the nitrate-phosphate ratio corresponded to the normal assimilation ratio (Van Bennekom *et al.*, 1978; Cadée, 1984) and to salinities below 30. Also in Indonesia, studies in the Porong estuary showed that high chlorophyll values were only present for salinities above 24 (Cadée *et al.*, 1993): a slight increase of chlorophyll at a salinity of $\approx$ 30 indicated growth of estuarine phytoplankton related to river-induced eutrophication.

In their recent review, Eisma and Cadée (1991) stressed the low organic content of estuarine as compared to riverine suspended matter, indicating that 50 % to more than 90 % of the particulate matter supplied by the river is lost in the Ems and Gironde estuaries and in the Amazon mouth. In the Bay of Douala, if observation of the loss is widely verified, quantitative estimation will be far more difficult with the data available and with the presumed DOC production and release in the mixing zone, but this loss is most probably not inferior to 50 %. This corresponds to the results obtained from the other approach. But despite this degradation, the isotopic composition of the carbon remained unchanged (Bird *et al.*, 1994).

Accumulation

Marine sediment total organic carbon (TOC) contents vary according to the grain size of the deposit. They usually contain less than 3 % of TOC, and the zones where concentrations exceed 4 and even 5 % are fairly limited. In comparison with the contents of river suspensions of very equivalent grain- size distribution, the apparent loss is often higher than 50 %. But this first estimation does not take into account the whole of the DOC, sedimentation of which is slow and distant as shown by measurements off Rio del Rey.

Organic matter degradation in the fresh water-salt water mixing zone

Suspensions lose a large part of their particulate organic matter during transfer from the upstream part of the saline estuary to the open sea. POC concentrations only reach 2.3-6.5 % in the estuary and 0.8-1.7 % in the Bay of Douala. Concurrently, the C/N ratio, which is less than 8 in rivers, varies between 10 and 20 in the open sea; the C/H ratio, though less than 2 in rivers, reaches 3 to 5 in the ocean. However, hydrodynamic selection of the finest particles means that the organic matter content of the low- concentration suspensions off Rio del Rey rise again. Thus the DOC, which reaches 4.8 to 8.3 mg l^{-1} at the entrance to the estuary, decreases to 2.8 to 2.6 mg l^{-1} off Douala, but increases off Rio del Rey (7.4-10.9 mg l^{-1}). Due to the same hydrosedimentary process, DOC and POC appear to be associated in the finest sediments. Though the sedimentary effect of a distant POC transfer is limited, more than 100 km from Douala, due to the low charge of the waters, the importance of the DOC flux must be emphasized.

Results of experimental biodegradation

The *in vitro* protocols show differences between the river and sea domains:

– in rivers, the POC contents were fairly stable after 96 or 120 h though, in four cases, a slight decrease (10 to 17 %) was observed. This relative stability is confirmed by the constancy of the C/N ratio. On the other hand, under the same conditions, DOC decreased considerably (25 to 60 %).

– in the salt water of estuaries, a very clear POC decrease was observed in five out of seven cases. Salinity seems to encourage this degradation: the loss is between 10.9 and 29.4 % in the upstream part of the estuary and between 7.8 and 40 % further seawards. Concurrently, C/N increases from 8-14 to 11-20 and C/H from 1.2-3 to 3.35-4.8. The concentrations remain stable in the open sea. As in fresh water, DOC degrades more rapidly (30 %) due rather, it would seem, to its very divided, probably colloidal state than to salinity.

It is not easy to quantify the loss of POC during these estuarine processes, since the DOC includes microparticulate and truly dissolved states. Irrespective of the riverine or estuarine origin of this organic carbon of a POC/DOC ratio $\sim$ 1, the loss would be between 25 and 65 % after 96 h, namely near a magnitude intended from the lines connecting river and ocean values.

The information obtained from the observation of bacterial populations matches previous measurements. Concentrated suspensions from the estuarine area of maximum turbidity present the densest populations of often attached bacteria (42.2-86.3 $\times$ 10^4 ml^{-1}). The density was lower in river waters (25-30 $\times$ 10^4 ml^{-1}), where bacteria are usually free. It was still lower in the clear offshore marine waters where fixed bacteria disappear and degradation is very low. Observation over a period of time indicates a maximum proliferation during the first one or two days. This intensification of bacterial action upon entering the estuary results from the concentration of suspensions and also probably from the pH increase in the mixing zone; another cause could be a thermal rise of waters trapped by the tide (30-31 °C against 27-28 °C). Finally, an exceptional bacterial pullulation occurred in the plankton rich waters off Campo; here too, the density decreases significantly after the second day of observation.

CONCLUSIONS

It is difficult to quantify the sedimentary result of these processes, since an unknown part of the DOC is in the microparticulate state and since estuarine and marine planktonic production – albeit very weak – is not negligible. But if we assume a very slight temporal variability in organic sources, the various approaches of this study suggest in most cases a net loss of organic matter, irrespective of the relative amounts of riverine and planktonic materials in the samples:

– without significant sorting during transport, namely with nearly the same grain-size distribution, values between 3 and 4 % organic carbon were found in marine muds, while values of more than 7 % were usually observed in the riverine suspended matter. In the temperate North Sea, the organic content of the bottom sediment is much lower than that of the suspended matter, even in winter when there is no primary production (Eisma and Kalf, 1987), a probable cause being consumption by bacteria.

– both POC and DOC values show a broad depression at salinity between 6 and 21; they may indicate a non-conservative behaviour and brackish flowing estuarine waters seems unfavourable to phytoplankton development. The data available seem to indicate a breakdown of nearly 50 % of the organic matter in this fashion.

– experimental biodegradations indicate a 25-65 % loss of POC + DOC after 96 h in various cases without autotrophic or heterotrophic postdevelopments.

Even if our estimates of Holocene trapped organic matter on the margin can be slightly informative, on the basis of present flux, our budget suggests that about 50 % were biodegraded during the estuarine transfer. Such direct use of almost instantaneous data to explain long-term Holocene processes implies that this margin has not been subject to drastic climatic changes (Maley, 1992), and suggests that the present state could be regarded as representative of the mean Holocene fluctuations. In addition, it confirms that marine plankton-induced production did not have a prominent role during Holocene times.

Acknowledgements

The authors thank the crew of the RV *André Nizery* (ORSTOM) and Jean Maley for helpful assistance in sampling. This research was funded through the French Ministry of Cooperation "Campus Program" and the project CHRIS (Elf-Aquitaine). It was supported in part by the ECOFIT project of ORSTOM-CNRS. Helpful comments and critical review of this manuscript by G.C. Cadée and two anonymous reviewers are also acknowledged.

REFERENCES

Allen J.R.L. (1965). The Nigerian continental margin: bottom sediments, submarine morphology and geological evolution. *Mar. Geol.* **1**, 289-332.

Barusseau J.P., P. Giresse, H. Faure, A.M. Lézine, J.P. Masse (1988). Marine sedimentary environments on some parts of the tropical and equatorial margins of Africa during the Late Quaternary. *Cont. Shelf Res.* **8**, 1, 1-21.

Bird M.I., P. Giresse, A.R. Chivas (1994). Effect of forest and savannah vegetation on the carbon-isotope composition of sediments from the Sanaga River, Cameroon. *Limnol. Oceanogr.* **39**, 8, 1845-1854.

Bongo-Passi G., F. Gadel, P. Giresse, Kinga-Mouzeo, G. Moguedet (1988). Séquences géochimiques et minéralogiques dans l'éventail détritique profond quaternaire du fleuve Congo à 2000 et 4000 m de fond: sédimentogenèse et diagenèse. *Bull. Soc. Géol. France*, **8**, IV, 3, 452-497.

Cadée G.C. (1978). Primary production and chlorophyll a in the Zaïre River, estuary and plume. *Neth. J. Sea Res.* **12**, 368-381.

Cadée G.C. (1982). Tidal and seasonal variation in particulate and dissolved organic carbon in the Western Dutch Wadden Sea and Marsdiep tidal inlet. *Neth. J. Sea Res.* **15**, 228-249.

Cadée G.C. (1984). Particulate and dissolved organic carbon and chlorophyll a in the Zaïre River, estuary and plume. *Neth. J. Sea Res.* **17**, 2-4, 426-440.

Cadée G.C. (1987). Organic carbon in the Ems River and estuary: a comparison of summer and winter conditions. *Mitt. Geol.-PalSont. Inst.*, Univ. Hamburg, SCOPE/UNEP Sonderb., **64**, 359-374.

Cadée G.C., R.W.P.M. Laane (1983). Behaviour of POC, DOC and florescence in the freshwater tidal compartment of the River Ems. *In: Transport of carbon and Minerals in Major World, Pt 2. Mitt. Geol-PalSont. Inst.*, Univ. Hamburg, SCOPE/UNEP Sonderb. **55**, 331-342.

Cadée G.C., Sudarmadji Rusmiputro, J. Hegeman (1993). Conservative and non-conservative mixing of DOC in some Indonesian estuaries. *Mitt. Geol.-PalSont. Inst.*, Univ. Hamburg, SCOPE/UNEP Sonderb., **74**, 227-239.

Cauwet G., J.M. Martin (1982). Organic carbon transported by French rivers, in: *Marine organic chemistry*, E. Duursma, K.R. Dawson, ed. Elsevier Oceanography Series 31, Elsevier, Amsterdam, 71-89.

Crosnier A. (1964). Fonds de pêche le long des côtes de la République Fédérale du Cameroun. Cah. ORSTOM, Paris, 132 p.

Degens E.T. (1982).Transport of carbon and minerals in major world rivers, part 1. *Mitt. Geol.-Paläont. Inst.*, Univ. Hamburg. SCOPE-UNEP Sonderb., **52**, 1-12.

Eisma D., J. Kalf, Van der Gaast (1978). Suspended matter in the Zaire River, estuary and plume. *Neth. J. Sea Res.* **12**, 382-406.

Eisma D., J. Kalf (1987). Distribution, organic content and particle size of suspended matter in the North Sea. *Neth. J. Sea Res.* **21**, 265-285.

Eisma D., G.C. Cadée (1991). Particulate matter processes in estuaries, in: *Biogeochemistry of major world rivers*, E.T. Degens *et al.*, eds. SCOPE, John Wiley and sons, London, **13**, 283-296.

Emerson S. (1985). Organic carbon preservation in marine sediments. In: *The carbon cycle and atmospheric CO_2: Natural variations from Archean to Present*, E.T. Sundquist, W.S. Broecker, eds. Geophys. Monogr.32 Am. Geophys. Union, 78-87.

Emerson S., J.I. Hedges (1988). Processes controlling the organic carbon content of open ocean sediment. *Palaeoceanography* **3**, 5, 621-634.

Giresse P., F. Jansen, G. Kouyoumontzakis, G. Moguedet (1981). Les fonds de la plateforme congolaise, le delta sous-marin du fleuve Congo. Bilan de huit ans de recherches sédimentologiques, paléontologiques, géochimiques et géophysiques. *Trav. Doc. ORSTOM*, Paris, **138**, 13-45.

Giresse P., J.P. Barusseau (1989). Quaternary accumulation rates by hemipelagic and gravity current sedimentation on the atlantic margin of Africa; control factors of advective and vertical flows. *Mar. Geol.* **89**, 279-287.

Giresse P., J.C. Aloisi, M. Kuete, J. Monteillet, G. Ngueutchoua (1995). Quaternary sedimentary deposits on the Cameroon shelf; characterization of facies and of Late Quaternary shorelines. *Quatern. Intern.* **29/30**, 75-87.

Giresse P., J. Maley (1996). The dynamic of organic carbon in South-Cameroon: Present day and Late Quaternary budget, application to oceanic and lacustrine palaeoenvironments. *Global and Planetary Change*, in press.

Hedges J.I, W.A. Clark, P.D. Quay, J.E. Richey, A.H. Devol, U. de M. Santos (1986). Compositions of particulate material in the Amazon River. *Limnol. Oceanogr.* **31**, 4, 1137-1152.

Hobbie J., R. Daley, R. Jasper (1977). Use of nucleopores filters for counting bacteria by fluorescence microscopy. *Appl. Environ. Microbiol.* **33**, 1225-1228.

Johnson B.D., P.E. Kepkay (1992). Colloid transport and bacterial utilisation of oceanic DOC. *Deep-Sea Res.* **39**, 855-869.

Kirchman D.L., Y. Suzuki, C. Garside, H.W. Ducklow (1991). High turnover rates of dissolved organic carbon during a spring phytoplankton bloom. *Nature* **352**, 612-614.

Koike I., H. Shigemitsu, K. Terauchi, K. Kogure (1990). Role of sub- micrometre particles in the ocean. *Nature* **345**, 242-245.

Lesack L.F.W., R.E. Hecky, J.M. Melack (1984). Transport of carbon, nitrogen, phosphorus and major solutes in the Gambia River, West Africa. *Limnol. Oceanogr.* **29**, 4, 816-830.

Likens G.E.F., F.T. Mackenzie, J.E. Richey, J.R. Sedell, K.K. Turekian (1981). Flux of organic carbon by rivers to the ocean. Conf. 80009140 DOE Office Energy Res., Washington, D.C.

Liss P.S. (1976). Conservative and non-conservative behaviour of dissolved constituents during estuarine mixing. In: *Estuarine chemistry,* J.D. Brown, P.S. Liss, eds. Academic Press, London, 93-127.

Mahé G. (1993). Les écoulements fluviaux sur la façade atlantique de l'Afrique. Etude des éléments du bilan hydrique et variabilité interannuelle, analyse de situations hydroclimatiques moyennes et extrêmes, ORSTOM, Paris, Coll. Etudes et Thèses, 438 p.

Maley J. (1992). Mise en évidence d'une péjoration climatique entre ca. 2500 et 2000 ans BP en Afrique tropicale humide. *Bull. Soc. Géol. France* **163**, 363-365.

Mariotti A., F. Gadel, P. Giresse, Kinga-Mouzeo (1991). Carbon isotope composition and geochemistry of particulate organic matter in the Congo River (Central Africa): application to the study of Quaternary sediments off the mouth of the river. *Chem. Geol.*, Isotope Geosc. section, **86**, 345-357.

Martins O. (1982). Geochemistry of the Niger River. In: *Transport of carbon and minerals in major world rivers*: Part I. SCOPE/UNEP Sonderband, Hamburg, 397-418.

Mc Master R.L., J.D. Milliman, A. Ashraf (1971). Continental shelf and upper slope sediments off Portuguese Guinea, Guinea and Sierra Leone, West Africa. *Journ. Sedim. Petrol.* **41**, 1, 150-158.

Meade R.H. (1985). Suspended sediments in the Amazon River and its tributaries in Brazil during 1982-1984. *U.S. Geol. Surv. Open-File Report* 85-492, 39 p.

Meybeck M. (1982). Carbon, nitrogen and phosphorus transport by world rivers. *Am. J. Sci.* **282**, 401-450.

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

Nouvelot. J.F. (1972). Le régime des transports solides en suspension dans divers cours d'eau du Cameroun de 1969 à 1971. *Cah. ORSTOM, sér. Hydrol.*, IX, **1**, 47-73.

Olivry J.C. (1977). Transports solides en suspension au Cameroun. *Int. Ass. Hydro. Sc. Publ.* **122**, 134-141.

Piton B., A. Kartavtseff (1986). Utilisation des bouées dérivantes à positionnement par satellite pour une meilleure connaissance de l'hydrologie de surface du Golfe de Guinée. *Doc. ORSTOM*, Brest, 34, 41 p.

Reimers C.E., E. Suess (1983). The partitioning of organic carbon fluxes and sedimentary organic matter decomposition rates in the ocean. *Mar. Chem.* **13**, 141-168.

Richey J.E., J.I. Hedges, A.H. Devol, P.D. Quay, R. Victoria, L. Martinelli, B.R. Forsberg (1990). Biogeochemistry of carbon in the Amazon River. *Limnol. Oceanogr.* **35**, 352-371.

Schlesinger W.H., J.M. Melack (1981). Transport of organic carbon in the world's rivers. *Tellus* **33**, 172-187.

Servais P., A. Anzil, C. Ventresque (1989). Samples methods for determination of biodegradable dissolved organic carbon in water. *Appl. Environ. Microbiol.* **55**, 10, 2732-2734.

Suess E., P.J. Muller (1980). Productivity, sedimentation rate and sedimentary organic matter in the oceans. 2. Elemental fractionation. *Colloq. Int. CNRS*, Paris, **293**, 17-26.

Summerhayes C.P., J.D. Milliman, S.R. Briggs, A.G. Bee, C. Hogan (1976). Northwest African shelf sediment. influence of climate and sedimentary processes. *J. Geol.* **84**, 277-300.

Talbot M.R., D.A. Livingstone (1989). Hydrogen index and carbon isotopes of lacustrine organic matter as lake level indicators. *Palaeogeogr., Palaeoclim. Palaeoecol.* **70**, 121-137.

Tranvik L. (1994). Colloidal and dissolved organic matter excreted by a mixotrophic flagellate during bacterivory and autotrophy. *Appl. environm. microbiol.* **60**, 6, 1884-1888.

Van Bennekom A.J., G.W. Berger, W. Helder, R.T.P. De Vries (1978). Nutrients distribution in the Zaïre estuary. *Neth. J. Sea Res.* **12**, 3/4, 296-323.

Van Es F.B., R.W.P.M. Laane (1982). The utility of organic matter in the Ems- Dollart estuary. *Neth. J. Sea Res.* **16**, 300-314.

Wells M.L., E.D. Goldberg (1991). Occurence of small colloids in sea water. *Nature* **35**, 342-344.