a tropical lateritic environment: the upper Niger basin

Jean-Loup Boeglin [a,b,1], Jean-Luc Probst [b,*]

[a] ORSTOM (Institut Français de Recherche Scientifique pour le Développement en Coopération), 213 rue La Fayette,
75480 Paris Cedex 10, France
[b] Centre de Géochimie de la Surface (CNRS / ULP), Ecole et Observatoire des Sciences de la Terre (EOST / ULP),
1 rue Blessig, 67084 Strasbourg Cedex, France

Abstract

The chemical composition of Niger river water measured bimonthly at Bamako (Mali) during the period 1990–1992 provides an estimate of present weathering rates in the upper Niger basin. The dominant weathering process is kaolinite formation (‘monosiallitization’). However, seasonal variations promote gibbsite formation in the rainy season (September) and smectite development in the dry season (May). The results show that lateritic profiles continue to develop even during very dry episodes. The rate of profile development, calculated as the difference between the chemical weathering rate at the base of the soil profile and mechanical erosion rate at the soil surface, is about 1.3 to 3.7 m/Myr. A comparison between 43 river basins of the world shows that, for similar runoff, the CO_2 flux consumed by silicate weathering is about two times lower in lateritic areas than in nonlateritic zones.

Keywords: West Africa; Niger River; Hydrogeochemistry; Laterites; Chemical weathering; Mechanical erosion; Mass balance; CO_2 consumption

---

1. Introduction

The chemical composition of river water in unpolluted areas can be considered to be a good indicator of surface weathering processes (Garrels and Mackenzie, 1971; Drever, 1982; Meybeck, 1984; Tardy, 1986; Berner and Berner, 1987; Probst, 1992). Annual mass balances of dissolved and suspended solids transported by rivers can be used to characterize and quantify the chemical and mechanical erosion in their drainage basin. Different types of chemical alteration can be recognized using major cation and silica contents in river waters, using a weathering index defined by Tardy (1968, 1969, 1971). The amount of suspended sediment is related to

---

[*] Corresponding author.

[1] Present address: Centre ORSTOM de Youndé, BP 1857, Yaoundé, Cameroun.

the physical denudation rate of the soil (Fournier, 1960; Holeman, 1968; Gac, 1980; Pinet and Souriau, 1988; Probst, 1992). The rate of chemical erosion within the soil profile can be calculated from silica mass balance and from the cation budget between bedrock, soil and water (Cleaves et al., 1970; Velbel, 1995; Paces, 1986; Nkounkou and Probst, 1987; Tardy, 1990). The CO_2 flux consumed by mineral dissolution can be modelled from the fluvial transport of dissolved inorganic carbon (mainly HCO_3^-) taking into account the lithology and the drainage intensity (Amiotte-Suchet, 1995; Amiotte-Suchet and Probst, 1993a,b, 1995; Probst et al., 1994a,b, 1997).

The purpose of this study is to assess the present rock weathering rate and the flux of atmospheric/soil CO_2 consumed by the dissolution and hydrolysis of primary minerals in the upper part of the Niger basin. The assessment is based on dissolved major element and total suspended solid concentrations which have been measured twice a month in the Niger at Bamako (Mali) during the period 1990–1992, and which have already enabled the calculation of average river transport of solute and particulate matter (Boeglin and Probst, 1996). A comparison between mechanical and chemical erosion rates will indicate whether the soils of the upper Niger basin are in equilibrium under present-day climatic conditions. If they are not in equilibrium, it is important to know if the thickness of the soil profile is increasing or decreasing. Finally, the values obtained in this study will be compared with results given by different authors for lateritic and nonlateritic river basins.

2. Physical characteristics

The upper Niger basin at the sampling station of Bamako (Mali) covers a drainage area of 117,000 km^2 in a typical tropical zone of West Africa (Fig. 1). The main tributaries of the Niger (river length at Bamako = 800 km) are the Niandan, Milo and Sankarani coming from the south, and the Tinkisso on western side. The river basin is bordered by the Guinean ridge to the south, by the Fouta–Djalon and the Mandingue mountains to the west and northwest; to the east, it is bordered by the drainage basin of the Baoule river which is a tributary of the Niger, joining the Niger downstream of Bamako.

The altitude of the Niger spring, in the northern slope of Guinean ridge, at the boundary of Sierra Leone and Guinea (200 km from the Atlantic Ocean) is about 800 m. Rising as a rapidly flowing stream in a very wet forested zone (precipitation $P > 1750$ mm/year), the Niger progressively reaches a regular flow up to a large flood plain. The characteristics used in this study to differentiate climatic types (see Fig. 1) come from Leroux (1983). The Guinean climate ($P > 1500$ mm/year, mean annual temperature $T = 22–24$°C, mean annual hygrometry $H > 50\%$) with thick forest in the upper part of the basin is replaced by the southern Soudanian climate ($P > 1000$ mm/year, $T > 27$°C, $H > 50\%$) characterized by sparse forests and wooded savannahs, downstream of Kouroussa. The rainy period becomes progressively shorter downstream, from Kouroussa to Siguiri, Bamako and Koulikoro. Between Koulikoro and Segou, the Niger flows over a large plain, affected by a northern Soudanian climate ($500 < P < 1000$ mm/year, $T > 27$°C, $H < 50\%$). In this shrubland savannah zone, high evaporation is responsible for a decrease in the annual mean discharges. Downstream, the ‘central delta’ of the Niger is a very large flood plain where the extent of the surface water area varies considerably between dry and wet seasons; in this part of the Niger basin, the climatic conditions are sahelian ($P < 500$ mm/year, $T > 30$°C, $H < 40\%$), to southern saharian ($P < 200$ mm/year) in the northern part, close to Tombouctou.

Precipitation and river discharge during the study period of 1990–1992 were similar for each year (Table 1); for this period, the mean annual rainfall was 978.6 ± 87.5 mm (DNM, 1990–1992) and the mean annual runoff was 734.6 ± 15.1 m^3/s (i.e. 198 ± 4 mm/year), calculated from discharge measurements at Koulikoro station, about 60 km downstream from Bamako (see 1990, 1991, and 1992 data, DNHE, 1981–1993). However, it is important to note that these data were collected during a very dry period (Fig. 2). Digitization of monthly isohyetal maps for an ‘average typical year’ (Boulvert, 1992) on the upper Niger basin indicates that the long-term average annual rainfall for the Niger Basin is 1568 mm (Fig. 3) at Bamako. The mean annual temperature during the same period has been calculated to be 26.7°C.

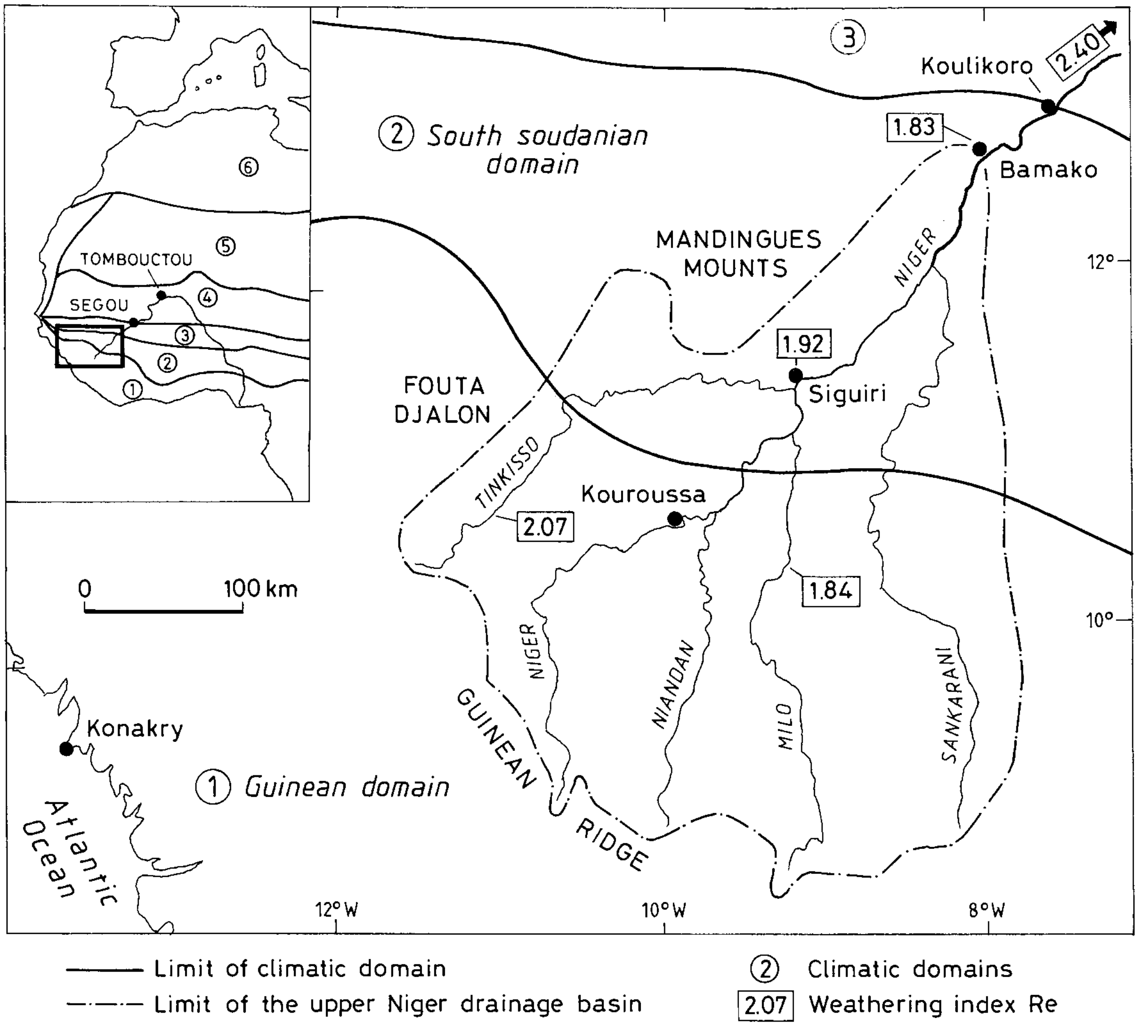

Fig. 1. Location map of the upper Niger basin. Weathering index values Re (see text) calculated for the study area and climatic domains of West Africa (according to Leroux, 1983): (1) Guinean domain, (2) South Soudanian domain, (3) North Soudanian domain, (4) Sahelian domain, (5) tropical Sahara, (6) temperate Sahara.

Two geological formations underly the upper Niger Basin (Fig. 4).

(1) In the southern part, corresponding approximately to the Guinean zone, the basement Birrimian rocks are of C-Precambrian age and belong to the West-African Craton. The main lithological types resulting from the granitization and the metamorphism of the Eburnean orogeny (about 1800 Myr) are, in order of decreasing outcrop abundance: calc–alkaline granites with gneissic or ultrabasic enclaves, micaschists and greywackes (Bessoles, 1977; Milesi et al., 1986).

(2) In the northern part, sedimentary rocks of Late Proterozoic age (A-Precambrian age, about 600 Myr) comprise the smaller Malian zone and are among the oldest deposits in the Taoudeni basin. These detrital formations are mainly composed of sandstone (Bassot et al., 1981), deeply incised in the Mandingue Plateau area. All these formations are intruded by dolerites, generally of Permian to Triassic in age (Dillon and Sougy, 1974), which resulted from extensional movements associated with the opening of the Atlantic Ocean.

Table 1
Mean annual concentrations and specific fluxes of solute and suspended matter in the Niger river water at Bamako for the period 1990–1992 (after Boeglin and Probst, 1996)

	1990		1991		1992		Mean 1990–1992	
	C	*F*	*C*	*F*	*C*	*F*	*C*	*F*
Na^+	98.4	0.434	99.1	0.454	101.6	0.471	99.7 ± 3.6	0.453 ± 0.024
K^+	32.7	0.245	32.5	0.252	29.6	0.234	31.6 ± 1.4	0.244 ± 0.008
Mg^{2+}	42.3	0.197	40.8	0.198	40.9	0.201	41.3 ± 0.5	0.199 ± 0.006
Ca^{2+}	53.2	0.409	51.1	0.408	58.9	0.476	54.4 ± 3.8	0.431 ± 0.039
HCO_3^-	269.3	3.475	292.1	3.554	310.4	3.820	299.8 ± 11.8	3.619 ± 0.213
Cl^-	10.2	0.070	8.5	0.059	8.1	0.057	8.9 ± 0.7	0.062 ± 0.004
SO_4^{2-}	2.3	0.043	2.1	0.041	1.6	0.031	1.9 ± 0.3	0.039 ± 0.005
SiO_2	237.3	2.743	251.1	3.021	254.6	3.091	247.9 ± 13.8	2.955 ± 0.209
DOC	–	–	–	–	2.25	0.455	–	–
Σ^+	322.1		315.4		330.8		322.7	
Σ^-	284.1		304.8		321.7		312.5	
δ (%)	12.5		3.4		2.8		3.2	
TSS	23.8	4.594	25.4	5.055	24.2	4.944	24.5 ± 1.3	4.868 ± 0.287
TDS	37.9	7.616	40.0	7.988	41.5	8.382	39.8 ± 1.8	8.001 ± 0.470
P (mm/yr)	1101.5		904.7		929.5		978.6	
Q (m^3/s)	713.7		741.2		749.0		734.6	

C are the mean concentrations in $\mu M/l$ calculated from 24 samples/yr and weighted by the discharge except TDS (total dissolved solids), DOC (dissolved organic carbon) and TSS (total suspended solids) in mg/l. *F* are the fluxes in t/km^2 yr; Σ^+ and Σ^- are the cationic and anionic charges in meq/l respectively; δ (%) = $200(\Sigma^+ - \Sigma^-)/(\Sigma^+ + \Sigma^-)$. *P* is the precipitation and *Q* the river discharge.

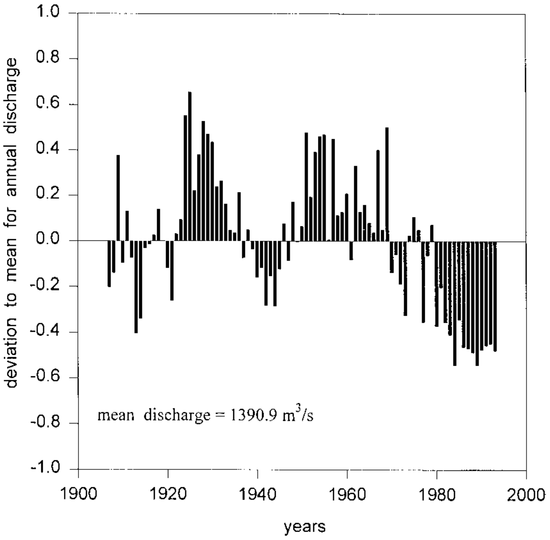

Fig. 2. Deviation from the interannual mean of the annual discharges at Koulikoro station during the period 1907–1993 (according to the data of Brunet-Moret et al., 1986 for the period 1907–1980 and of DNHE, 1981–1993).

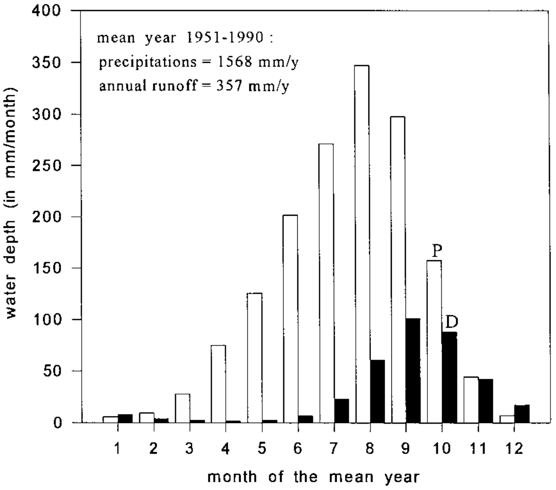

Fig. 3. Variations of the mean monthly precipitation (P) and runoff (R) in the upper Niger basin.

The upper Niger basin is a zone of lateritization. The main widespread superficial formations are ferrallitic soils (upstream of Siguiri) and tropical ferruginous soils (in northern Guinea and southern Mali). The distribution of the different soil types, defined by Pédro (1968) at a global scale according to mineral hydrolysis intensity, indicates that the chemical weathering stage is more advanced in the southern part of the basin, where the runoff is higher. Ferricretes are common at the top of lateritic profiles, as described by Maignien (1958) in Guinea and by Mazaltarim (1989) and Freyssinet (1990) in Mali. Hardened red or white bauxites are also rather common in the study area (Bourdeau, 1991; Tardy et al., 1995). Chronological classifications of bauxitic or ferruginous West African surfaces for the last 200 Myr have been proposed by various authors (Michel, 1973; Tardy, 1993) according to their relative altitudes.

3. Fluvial transport of carbon and minerals by the upper Niger

During the period January 1990–December 1992, two samples per month were collected on the Niger River, 6 km upstream of Bamako. Mean annual concentrations and fluxes calculated for the period 1990–1992 (Boeglin and Probst, 1996) are given in Table 1 for the different major elements; interannual variations of the different parameters (discharge, concentrations of dissolved and suspended elements) during the study period are very low.

The importance of atmospheric input for the chemical composition of the river water has been emphasized, especially by Janda (1971) and Meybeck (1984). No data on rainwater composition are available from the upper Niger basin. Corrections of river water composition for the atmospheric inputs were performed (see Table 2) assuming that all the chloride measured in the river water originates from atmospheric precipitation (Nkounkou and Probst, 1987; Probst et al., 1994a). No evaporite rocks are known from the upper Niger basin. For the other dissolved species (X_i), the ionic ratios $(X_i)/(Cl^-)$ of the precipitation were calculated from the data of Meybeck (1984) for savannah and wet tropical zones (see Table 2). All the following references in this paper to concentrations or fluxes will concern these corrected data (see corrected values in Table 2); however, dissolved silica and bicarbonate contents, as well as the suspended sediment concentrations, will be considered to be completely supplied by chemical and mechanical erosion processes.

4. Present rock weathering type

The present distribution of the various types of lateritic profiles, especially in West Africa, is explained using paleoclimatic variations—mainly using changes in rainfall intensity—induced by migrations of the equator

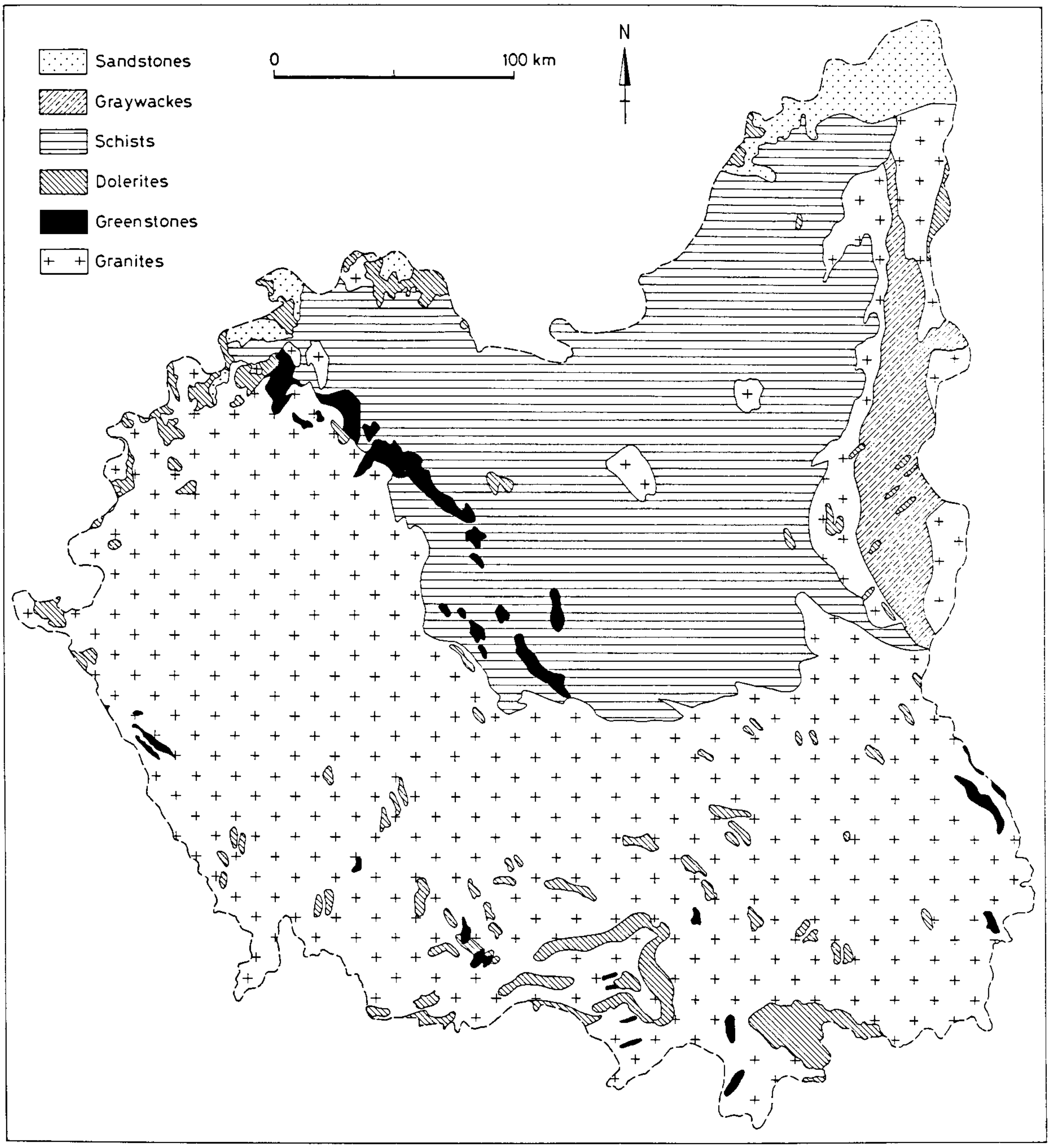

Fig. 4. Lithological map of the upper Niger basin.

Table 2
Correction for atmospheric inputs: mean annual crude and corrected values of concentrations and of specific fluxes in the Niger river waters at Bamako for the period 1990–1992

X_i	Na^+	K^+	Mg^{2+}	Ca^{2+}	HCO_3^-	Cl^-	SO_4^{2-}	SiO_2	TDS	TSS
Precipitations										
Ionic ratios X_i/Cl^- [a]	1.16	0.32	0.28	0.40	0	1	0.49	0	–	0
River waters										
Crude concentrations[b,c]	99.7	31.6	41.3	54.4	299.8	8.9	2.0	247.9	39.8	24.5
Crude fluxes[d]	453	244	199	431	3619	62.4	38.6	2955	8001	4868
Corrected concentrations[b,e]	89.4	28.8	38.8	50.8	299.8	0	0	247.9	35.1	24.5
Corrected fluxes[d]	406	222	187	403	3619	0	0	2955	7792	4868

[a] Ionic ratios estimated in the precipitation of the upper Niger basin are calculated from the average ratios given by Meybeck (1984) for precipitation in Savannah zone and wet tropical areas.
[b] Concentrations in $\mu M/l$ (except for TSS and TDS, in mg/l).
[c] Crude values (see Table 1) after Boeglin and Probst (1996).
[d] Specific fluxes in kg/km^2 yr.
[e] Corrected concentrations (C_i* in river water) for atmospheric inputs are calculated from crude concentrations (Ci) in river water and ionic ratios (X_i/Cl^-) of precipitation as follow: $C_i* = C_i - C_{Cl}\,(X_i/Cl^-)$.

during the last 100 or 150 million years (Savostin et al., 1986; Besse, 1986). At the scale of the upper Niger basin, bauxites and ferricretes have a very large distribution area. According to studies in South Mali (Tardy et al., 1995), it appears that kaolinite is the dominant mineral in the deep saprolite i.e. the youngest part of ferruginous and even of bauxitic profiles. The main problem is to know whether these lateritic soils continue to develop under present-day climatic conditions, or whether they are relics of a past period and are now affected by physical degradation processes. This problem can be solved by analysing the chemical composition of the runoff from these lateritic terrains.

To determine the degree of rock weathering in a given drainage basin, Tardy (1968, 1969, 1971) calculated the molecular ratio Re from the concentrations of different dissolved species measured in the surface waters from granite and gneiss terrains:

$$\mathrm{Re} = \frac{6\mathrm{Na_2O} + 6\mathrm{K_2O} + 2\mathrm{CaO} - \mathrm{SiO_2}}{\mathrm{Na_2O} + \mathrm{K_2O} + \mathrm{CaO}} \qquad (1)$$

which can be also written as follows:

$$\mathrm{Re} = \frac{3(\mathrm{Na^+}) + 3(\mathrm{K^+}) + 2(\mathrm{Ca^{2+}}) - (\mathrm{SiO_2})}{0.5(\mathrm{Na^+}) + 0.5(\mathrm{K^+}) + (\mathrm{Ca^{2+}})} \qquad (2)$$

The different coefficients used in the above formula depend on the major primary minerals of the bedrock and correspond here to an average granitic composition with feldspars and micas. Re is also equivalent to the molecular ratio $(SiO_2)/(Al_2O_3)$ of secondary mineral neoformation within the soil profile (see Tardy, 1971), and so may characterize the weathering process according to the classification of Pédro (1966): if Re = 0, the dominant weathering process is the genesis of gibbsite (called ‘allitization’), if Re = 2, kaolinite is essentially formed (‘monosiallitization’), if Re = 4, the weathering products are mainly smectites (‘bisiallitization’).

Such a weathering index can be calculated for the upper Niger basin, because the geological substratum is mainly composed of granites and micaschists (Fig. 4). But we have modified the initial formula proposed by Tardy (1971) to take into account of Mg-silicate minerals such as amphiboles:

$$\mathrm{Re} = \frac{3(\mathrm{Na}^+) + 3(\mathrm{K}^+) + 1.25(\mathrm{Mg}^{2+}) + 2(\mathrm{Ca}^{2+}) - (\mathrm{SiO}_2)}{0.5(\mathrm{Na}^+) + 0.5(\mathrm{K}^+) + 0.75(\mathrm{Mg}^{2+}) + (\mathrm{Ca}^{2+})} \tag{3}$$

For Mg, the coefficients were determined from a magnesian amphibole $\mathrm{Mg_4Al_6Si_5O_{22}(OH)_2}$ in which the molecular ratios $\mathrm{SiO_2/Mg}$ and $\mathrm{Al_2O_3/Mg}$ are respectively $5/4 = 1.25$ and $3/4 = 0.75$.

The mean annual Re calculated from corrected data (Table 2) for the period 1990–1992 is 1.83 at Bamako; this value, corresponding to monosiallitization, is close to those obtained from the data of Orange (1992) on Guinean tributaries of the Niger: Re = 1.84 for the Milo, Re = 2.07 for the upper Tinkisso, or on the upper Niger at Siguiri, Re = 1.92 (see Table 4). About 350 km downstream of Bamako, upstream of the ‘central delta’, Re is calculated to be 2.40 using the data of Gourcy (1996), indicating that the weathering processes favor more smectite formation. Further downstream, Re values are no longer significant because of elevated evaporation and sedimentation in the Niger ‘central delta’ depression (Gourcy, 1996), and because of the dissolution of carbonates in the vicinity of Niamey (Grove, 1972) and Lokoja (Martins and Probst, 1991). The variations of the Re coefficient show a mineralogical evolution from gibbsite and kaolinite to kaolinite and smectite between the upper part of the Niger basin (Fouta Djalon, Siguiri, Bamako, see map on Fig. 1) and the alluvial plains of Mali (Koulikoro, Segou), upstream of the ‘central delta’. Such an evolution, in relation to decreasing runoff, has already been described at the scale of lateritic toposequences in other tropical areas (Bocquier, 1973; Boulet, 1978; Lévêque, 1979). The well-drained upper parts of the landscape contain significant gibbsite, whereas the poorly drained lower zones, frequently possess smectitic soils. Besides spatial variations, Re shows seasonal variations during the annual water cycle (Fig. 5). The highest values (2.44), indicating smectite formation, correspond to the dry season (January to June) and the lowest values (1.67), characteristic of gibbsitization, occur during the high flow period (July to December). Such Re variations can be related to the alternation of rainy season and dry season, and are observed even in temperate areas (e.g., the Garonne basin in France; Semhi, 1996).

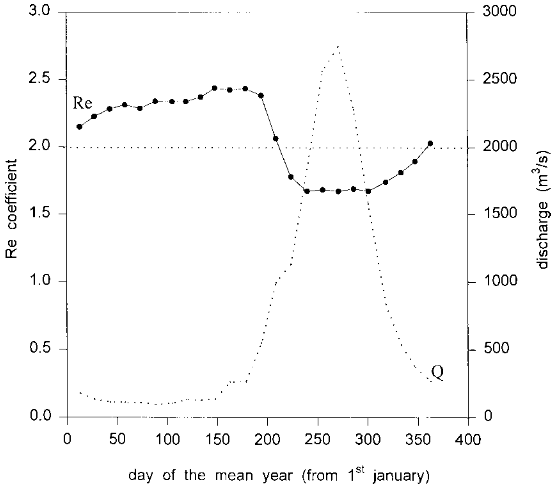

Fig. 5. Seasonal variations of weathering index Re (see text) and river discharge (Q) in the upper Niger basin during the period 1990–1992.

5. Present erosion rate

The alteration processes at the earth's surface fundamentally include chemical weathering, predominant within a soil profile, and mechanical erosion, predominant at the top of the soil. The difference between the rates of chemical weathering and physical erosion indicates wether the soil thickness is increasing or decreasing, or if it is in dynamic equilibrium.

5.1. Chemical erosion rate

For lateritic areas, when the chemical composition of bedrock, soils and runoff waters are not precisely known, one can estimate like Tardy (1990) the chemical erosion rate from silica river fluxes. If one supposes that an amount of silica $S_L = 10^6$ g/m^3 is leached during the weathering of a granitic rock (76% SiO_2, density 2.7) into a kaolinite soil profile (67% SiO_2, density 1.65), that the runoff R corresponds to 1000 mm/y (1000 l/m^2 yr), and that the dissolved silica content in the river waters C_{SiO_2} is 10 mg/l, the chemical weathering rate WR_{ch}, calculated for 1 m^3 rock, can be estimated as follows:

$$WR_{ch} = 10^6 \times C_{SiO_2} \times R/S_L = 10\,\mathrm{m/Myr}$$

If $C_{SiO_2} = 6$ mg/l, which corresponds to the value of silica content for quartz saturation at 25°C (according to Helgeson, 1969), the weathering rate will be 6 m/Myr. In such an approach, the weathering processes are assumed to be isovolumetric (after Millot and Bonifas, 1955).

If we want to calculate a precise budget for the chemical weathering rate, we need to know the chemical composition (1) of the parent rock, (2) of the saprolite (this is the name given to the alteration facies found at the base of lateritic profiles, mainly composed of neoformed kaolinite and residual quartz) and (3) of the runoff water.

A lithological map of the upper Niger basin has been compiled (Fig. 4) from geological or pedological maps from Guinea (BRGM, 1960), Mali (Bassot et al., 1981) and Ivory Coast (Dabin et al., 1960). Six major bedrock types are found in the upper Niger basin: granites and gneisses occupy 58.0% of the total area, schists 29.7%, doleritic rocks 4.4%, greywackes 3.6%, sandstones 2.3% and greenstones 1.9% of the total drainage basin area. These percentages, calculated for the Niger basin at Bamako (117,000 km^2) are rather close to those estimated by Orange (1992) at Siguiri (67,000 km^2). The average chemical composition of the bedrock has been estimated for the Niger basin at Bamako (Table 3) from data given by Blanchot (1958), Pion (1979) and Freyssinet (1990); as silica content averages 68.3% (including quartz content = 29%) and density 2.60, the volumetric amount of silica in the unweathered mean parent rock will be $S_0 = 1776$ kg/m^3. It is important to note that the magmatic and metamorphic acid rocks constitute about 88% of the total geological substratum; granite and gneiss are predominant in the upper part, whereas schists are almost exclusively located in the lower part of the basin.

The specific flux of dissolved silica F_{SiO2} exported by the Niger, given in Table 1, is estimated at 2955 kg/km^2 yr. In the absence of mean saprolite composition in the upper Niger basin, data relating to a lateritic profile developed on a granitic substratum in the Ivory Coast (Tardy, 1969) are used in this study. The characteristics given for that typical lateritic facies are: SiO_2 content = 67.3% (including quartz content = 42.4%), density = 1.65, so that the amount of silica in the saprolite is $S_S = 1110$ kg/m^3. As in the previous case, the chemical weathering rate WR_{ch} will be the ratio between the amount of silica to be removed S_L (kg/m^3) to transform 1 m^3 of granite into 1 m^3 of kaolinite and the flux F_{SiO_2} of dissolved silica (kg/km^2 yr) measured in the Niger river; as $S_L = S_0 - S_S$, we have:

$$WR_{ch} = F_{SiO_2}/(S_0 - S_S) = 2955/(1776 - 1110) = 4.44\,\mathrm{m/Myr} \tag{5}$$

This mean value obtained for the upstream part of the Niger at Bamako during the period 1990–1992 is rather close to the rate of 4.12 m/Myr calculated by the same method for the Niger basin at Siguiri (see Table 4) using the data given by Orange (1992) for the year 1987 ($S_0 = 1734$ kg/m^3, $F_{SiO_2} = 2570$ kg/km^2 yr).

Table 3
Composition of the mean bedrock in the upper Niger basin

	Granites	Schists	Dolerites	Greywackes	Sandstones	Greenstones	Mean
Outcrop (%)	58.0	29.7	4.4	3.6	2.3	1.9	
SiO_2	71.0	65.0	51.1	69.0	94.4	49.5	68.3
Al_2O_3	15.0	15.0	15.1	12.5	2.8	14.2	14.6
Fe_2O_3	2.0	6.0	12.2	5.5	0.7	13.0	3.9
Na_2O	4.5	3.0	2.2	3.4	0.1	2.6	3.8
K_2O	3.0	2.0	1.0	1.5	0.1	0.4	2.4
MgO	0.9	2.5	5.4	2.1	0.1	6.1	1.7
CaO	2.2	2.0	9.2	2.4	0.2	9.1	2.5
TiO_2	0.3	0.7	1.4	0.6	0.1	0.9	0.5
LOI	0.4	3.3	1.9	2.7	1.3	2.2	1.5
Total	99.3	99.5	99.5	99.7	99.8	98.0	99.3
Quartz	28	32	3	30	91	1	29

Compositions (in %) after data from Blanchot (1958), Pion (1979) and Freyssinet (1990).
LOI, loss of ignition.

For a given bedrock composition and a given dissolved silica river flux in a drainage basin, the weathering rate that can be calculated depends mainly on the saprolite composition, particularly on the relative abundance of neoformed kaolinite and residual quartz. During rock weathering, part of the silica derived from the hydrolysis of primary minerals is consumed in kaolinite formation. The quartz solubility is lower than that of the other minerals, so the total rock weathering rate will be slower when the amount of quartz leached during the weathering of the bedrock into saprolite is more important. This means that if quartz is not dissolved, all the silica comes from other silicate mineral hydrolysis and so the weathering rate increases.

In the upper Niger basin, the deepening rate of the saprolitization front can be modeled from the bedrock composition ($S_0 = 1776$ kg/m^3, including quartz content $Q_0 = 754$ kg/m^3), and using variable proportions between kaolinite ($P_{SiO_2} = 46.5\%$, $P_{Al_2O_3} = 39.5\%$, $P_{H_2O} = 14.0\%$, apparent density $d_k = 1.45$) and residual quartz (density $d_q = 2.65$). As before, if we consider the weathering of 1 m^3 bedrock, we can write:

$$\mathrm{WR}_{ch} = F_{SiO_2}/S_L \tag{6}$$

with WR_{ch} in m/Myr, S_L in kg/m^3, F_{SiO_2} in kg/km^2 yr; $S_L = S_0 - (S_q + S_k)$, where S_q and S_k are the silica amounts present in residual quartz and in neoformed kaolinite respectively per cubic meter of saprolite. These two parameters S_q and S_k are related to the weight percentage of residual quartz content in saprolite (P_q in%), to the density of quartz (d_q) and kaolinite (apparent density d_k), and to the silica content in quartz (100%) and in kaolinite (P_{SiO_2}), as follows:

$$S_q = 1000 P_q \left(\frac{P_q}{d_q} + \frac{100 - P_q}{d_k} \right), \ \text{in kg/m}^3 \tag{7}$$

$$S_k = 10 P_{SiO_2} (100 - P_q) \left(\frac{P_q}{d_q} + \frac{100 - P_q}{d_k} \right), \ \text{in kg/m}^3 \tag{8}$$

So, WR_{ch} (m/Myr) can be expressed as a function of P_Q (%) as follows:

$$WR_{ch} = \frac{F_{SiO_2}\left[P_q(d_k - d_q) + 100 d_q \right]}{S_0\left[P_q(d_k - d_q) + 100 d_q \right] - 10 d_k d_q \left[(100 - P_{SiO_2}) P_q + 100 P_{SiO_2} \right]} \tag{9}$$

Table 4

Comparison of weathering index (Re) values and weathering rates calculated for different stations in the upper Niger basin

River basin	Station	Drainage area (10^3 km^2)	Runoff (mm/yr)	Study period	Re	WR_{ph} (m/Myr)	WR_{ch} (m/Myr)						D (m/Myr)
							SiO_2	Na	K	Ca	Mg	Mean	
Niger	Siguiri	67.6	261	1987	1.92	6.0	4.12	4.91	4.07	7.36	10.92	6.13	0 to −2
	Bamako	117	198	1990–1992	1.83	2.4–3.4	4.44	5.54	4.29	8.66	6.98	6.06	+1 to +3.6
	Ke Macina	243	100	1992–1993	2.43	2.15	2.54	–	–	–	–	–	+0.4
Milo	Kankan	9.6	437	1987	1.84	10.6	9.05	–	–	–	–	–	−1.5
Tinkisso	Dabola	6.4	246	1987	2.07	4.0	5.33	–	–			–	+1.3

WR_{ph}, physical weathering rate; WR_{ch}, chemical weathering rate. Mean: mean of WR_{ch} calculated for cations; $D = WR_{ch} - WR_{ph}$. Re, WR_{ph} and WR_{ch} are calculated from the data of Orange (1992) for the Niger at Siguiri, the Milo and the Tinkisso and from the data of Gourcy (1996) for the Niger at Ke Macina (see Boeglin and Probst, 1996 for the basis data).

As can be seen in Fig. 6, the chemical weathering rate (WR_{ch}) increases when the residual quartz content in saprolite (P_q) increases or, when the original quartz dissolution ratio, called D_R, decreases (which is equivalent); as $D_R = 100\ (Q_O - S_q)/Q_O$, we have:

$$D_R = 100 - \left(d_k d_q P_q \times 10^5\right) / \left[Q_o\left(P_q d_k - P_q d_q + 100 d_q\right)\right], \text{ in\%} \quad (10)$$

$$\text{or } P_q = 100 d_q Q_0 (100 - D_R) / \left[d_k d_q \times 10^5 + Q_0 (100 - D_R)(d_q - d_k)\right], \text{ in\%} \quad (11)$$

Taking a quartz dissolution ratio of 100%, the weathering rate of the upper Niger basin upstream of Bamako (for a considered $d_K = 1.45$) is determined to be 2.68 m/Myr, whereas if the bedrock quartz is fully preserved ($D_R = 0$, corresponding to $P_Q = 42.1\%$) during saprolitization, the chemical erosion rate is calculated to be 5.48 m/Myr. Lelong (1969) and Tardy (1969) proposed a 15% dissolution ratio of initial quartz in their respective studied saprolites in French Guyana, and in the Ivory Coast. On the basis of $D_R = 15\%$, corresponding to $P_Q = 36.8\%$ (calculated from Eq. (11)) in the upper Niger basin, the weathering rate WR_{ch} would be 4.73 m/Myr.

The validity of the results obtained by this method of calculation is limited by the following conditions.

(1) Bedrock weathering into saprolite is isovolumetric. In natural cases, the quartz dissolution ratio is generally low ($D_R = 15\%$ by weight is here equivalent to 8.8% by volume); even in the theoretical case where $D_R = 100\%$, corresponding to a 28.5% volumetric rate for the upper Niger basin, the volume is considered to remain constant between bedrock and saprolite.

(2) All primary minerals, except quartz, are fully transformed into kaolinite (if not, the weathering rates will be higher than those calculated here, except for gibbsite and Al–Fe oxy–hydroxyde formation).

(3) All the silica exported by the draining waters comes from the silicate mineral hydrolysis, occuring mainly at the bottom of the lateritic profile.

(4) The flux of silica transported by the river is conservative, i.e., it is not affected by any biogeochemical process (precipitation of silica by diatoms, for example).

Another way for calculating the weathering rate, based on similar hypotheses, is to take into account the leaching of cations (Na^+, K^+, Mg^{2+}, Ca^{2+}) during the saprolitization process. The quasi-complete removal of

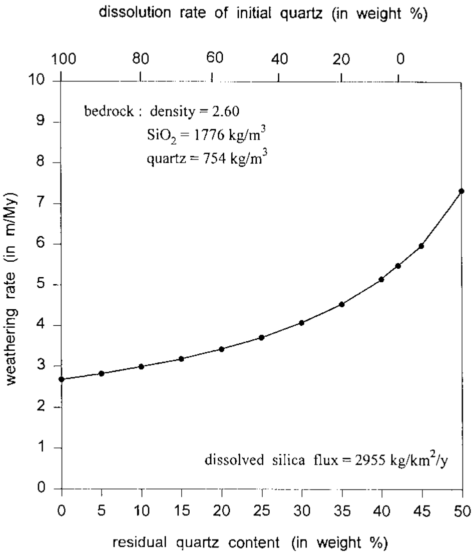

Fig. 6. Relationship between chemical weathering rate WR_{ch} and residual quartz content P_Q (P_Q is related to the initial quartz dissolution ratio D_R by Eq. (11) (see text)) in the saprolite.

cations, resulting from an intense hydrolysis of the bedrock silicate minerals at the bottom of lateritic profiles, has often been described (Bonifas, 1959; Tardy, 1969). From the mean bedrock cation composition (Table 3) and the cation fluxes transported by the upper Niger after correction of atmospheric inputs (Table 2), the weathering rate could be determined in the same way as for silica to be 5.54 m/Myr for sodium, 4.29 m/Myr for potassium, 6.98 m/Myr for magnesium, 8.66 m/Myr for calcium. In these simulations, the quartz dissolution has not been considered. The average of these different estimations, weighted by the molar proportions of the different cations in the mean bedrock, is 6.06 m/Myr. For comparison, the weathering rates obtained for the Niger basin at Siguiri, using the data of Orange (1992), are similar (see Table 4). At Bamako, as at Siguiri, the differences between the weathering rates calculated using silica and the different cations reflect the alterability order of the primary minerals (after Goldich, 1938): lower values were determined for sodium and potassium which originate from alkali feldspars. These last minerals are more resistant to weathering than plagioclases and ferromagnesian silicate minerals (and calcite or dolomite, if present), which are responsible for the higher weathering rate values calculated using magnesium and calcium. Upstream of Siguiri, the chemical weathering rates calculated for two tributaries of the upper Niger, the Milo at Kankan and the Tinkisso at Dabola, from the data of Orange (1992) are higher (see Table 4) than in the lower part of the Niger basin because the amount of precipitation and the runoff are higher in the Fouta Djalon and the Guinean Rift than in the lower part of the Niger basin.

5.2. Mechanical erosion rate

The average mechanical erosion rate can easily be calculated from the suspended sediment transported by the Niger and the mean density of surficial lateritic horizons. The mean TSS (total suspended solid) has been calculated as 4868 kg/km^2 yr (Table 1) by Boeglin and Probst (1996) on the basis of two samples per month during the period 1990–1992. However, it is well known that for some hydroclimatic regimes, most physical erosion occurs not by ‘normal’ erosion but during low frequency but high magnitude erosional events. If much physical erosion occurs episodically in the Niger basin, particularly during time intervals not sampled by our regular bimonthly sediment-load sampling schedule, the mean TSS calculated in this study could be an underestimate. Olivry et al. (1995) have calculated mean annual TSS of 6.3 t/km^2 yr in 1992 and 7.4 t/km^2 yr in 1991 for the Niger at Koulikoro (drainage basin area: 120,000 km^2), near Bamako, on the basis of daily sampling which takes into account low-frequency erosional events. These results show that our bimonthly sediment sampling probably underestimates the TSS by about 30–40%.

The average density for gravel soils, more or less porous bauxites and ferricretes was estimated to be 2.0 in the upper Niger basin so that this TSS corresponds to a mean denudation rate $\mathrm{WR}_{\mathrm{ph}}$ of 2.40 to 3.40 m/Myr. For comparison, the mechanical erosion rates obtained for other stations of the Niger basin from data compiled by Boeglin and Probst (1996) are 6.0 m/Myr at Siguiri, 3.7 m/Myr at Banankoro (calculated from the data of Olivry et al., 1995), 2.15 m/Myr at Ke–Macina and Douna (upstream of the ‘central delta’) and 1.2 m/Myr at Diré (downstream of the ‘central delta’) where sediment deposition is important, 2.6 m/Myr at Niamey and 5.0 m/Myr at Lokoja (Nigeria). The Niger tributaries coming from the Fouta Djalon or from the Guinean ridge reveal physical erosion rates higher than the Niger at Bamako: 4.0 m/Myr for the Tinkisso river, 10.6 m/Myr for the Milo river (see Table 4).

5.3. Physical vs. chemical weathering mass balance

The lateritic profile is in permanent dynamic evolution: each facies (saprolite, mottled clays, ferricretes...) is developed from the previous one. So, at the bottom of the soil profile, the saprolite is constantly renewed by the bedrock chemical weathering ($\mathrm{WR}_{\mathrm{ch}}$), whereas at the top, the ferricrete is progressively destroyed and removed by physical erosion ($\mathrm{WR}_{\mathrm{ph}}$). The result of these two processes is a gradual deepening of the lateritic cover (Nahon and Millot, 1977). The difference $D = \mathrm{WR}_{\mathrm{ch}} - \mathrm{WR}_{\mathrm{ph}}$ between the rates of the two competiting processes can be used to quantify if the lateritic profile thickness is increasing (if $D > \mathrm{O}$) or decreasing (if

$D < O$). In the study area, it appears that the mean thickening rate of lateritic cover is between 1.0–2.0 and 2.7–3.7 m/Myr, the values calculated for WR_{ch} ranging from 4.4 to 6.1 m/Myr according to the method of calculation (silica and various cations) and the estimations for WR_{ph} ranging from 2.4 (data of this study) to 3.4 (calculated from the data of Olivry et al., 1995). These results allow us to conclude that laterites continue on average to develop ($D > O$ in all cases) in the upper Niger basin, upstream of Bamako, under the present-day climatic conditions. Nevertheless laterites can not be considered as a one-dimensional system. If we could look in detail at the spatial distribution of chemical and physical weathering rates of these lateritic covers (see Tardy, 1993), we could probably see that the difference between WR_{ch} and WR_{ph} is greatly variable from the plateau to the alluvial plain, and can even be negative. Within the upper Niger basin, it appears that in the southern part, upstream of Siguiri, where the precipitation and runoff are higher, the difference ($D = WR_{ch} - WR_{ph}$) is zero or even negative as for the Milo at Kankan (weathering rates calculated from the data of Orange (1992) (see Table 4). These results mean that in the Fouta Djalon and in the Guinean Rift, the lateritic profiles are in dynamic equilibrium as previously shown by Orange (1992), but in the most humid part of the upper Niger basin (as in the Milo basin where the annual runoff is 437 mm) where the relief is also the most important, the soil equilibrium is broken down and then the thickness of the lateritic profile is decreasing ($D = -1.5$ m/Myr in the Milo basin, see Table 4).

Only the erosion rates at the bottom and at the top of the lateritic profiles have been previously considered; however, the front of ferricrete formation progresses downwards at a rate which is not necessarily the same as that of the saprolitization front. The rate of ‘ferricretization’ is very difficult to estimate from the chemical

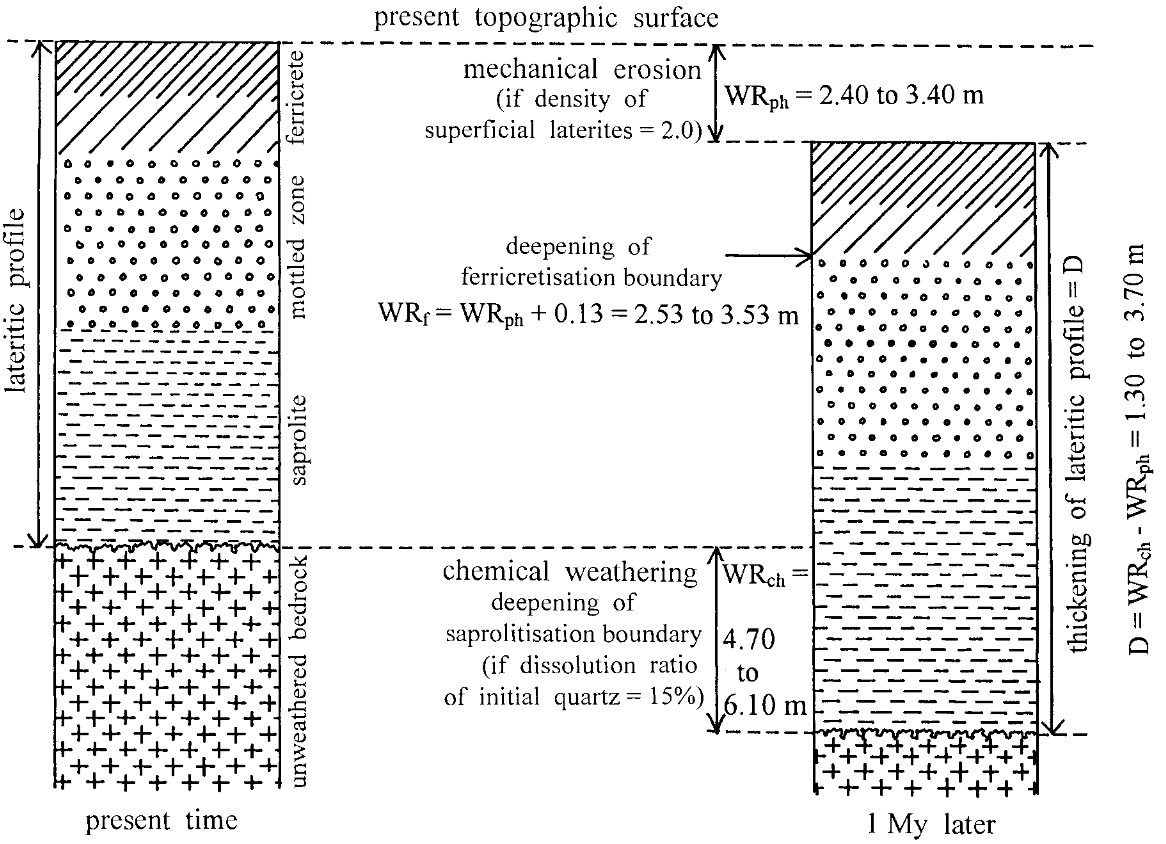

Fig. 7. Physical and chemical weathering rates and lateritic profile formation in the upper Niger basin.

composition of the draining waters because the dissolved concentrations of meteoric waters at the boundary between mottled clay and ferricrete are not known; moreover, the weathering processes at this level of the profile can no longer be considered as isovolumetric. An estimation of the ferricretization rate could nevertheless be attempted by another method, on the basis of some assumptions.

(1) If the mean thickness of lateritic cover is 40 m (in the southern Mali area, Delaître (1994) showed from surficial resistivity measurements that the thickness is often greater than 50 m), the age of profile is $40/D$, i.e., 16 Myr for a mean soil thickening rate D of 2.5 m/Myr assuming constant weathering during that period.

(2) If the mean thickness of ferricretes—or bauxites—is assumed to be 2.0 m over the whole basin area (the hardened formation being often missing), and if we consider that the age of the profile is 16 Myr (see above), the average rate of ferricrete—or bauxite—thickening is $\mathrm{WR}_f = 2.0$ m/16 Myr = 0.125 m/Myr. To obtain the total ferricrete formation, we have to add the ferricrete depth which has been eroded at the top of the soil profile (2.40 to 3.40 m/Myr from mechanical erosion calculation). The total ferricrete—or bauxite—deepening rate will be $F = \mathrm{WR}_f + \mathrm{WR}_{ph} = 2.50$ to 3.50 m/Myr.

Fig. 7 summarizes the present dynamics of the mean lateritic profile in the upper part of the niger basin taking into account the chemical weathering rate and the mechanical erosion rate.

6. CO_2 consumption during weathering

Chemical weathering processes require CO_2: the hydrolysis reactions of albite (12) or the dissolution of calcite (13), for example, can be written as follows (Garrels and Mackenzie, 1971):

$$\underset{\text{albite}}{2\,\mathrm{NaAlSi_3O_8}} + 3\mathrm{H_2O} + 2\mathrm{CO_2} = 2\mathrm{Na^+} + 2\mathrm{HCO_3^-} + \underset{\text{kaolinite}}{\mathrm{Al_2Si_2O_5(OH)_4}} + 4\mathrm{SiO_2} \tag{12}$$

$$\underset{\text{calcite}}{\mathrm{CaCO_3}} + \mathrm{H_2O} + \mathrm{CO_2} = \mathrm{Ca^{2+}} + 2\mathrm{HCO_3^-} \tag{13}$$

In these equations, the CO_2, provided by soil organic matter oxidation, originates from the atmosphere. In the case of silicate weathering (kaolinization), all the bicarbonate originates from the atmospheric/soil CO_2,

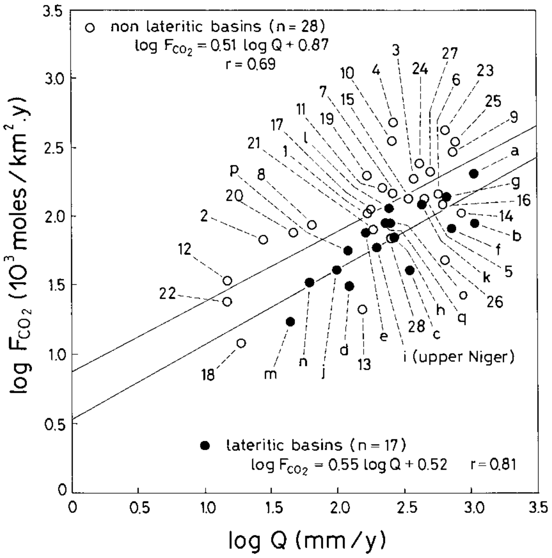

Fig. 8. Relationship between CO_2 flux consumed by silicate weathering and annual runoff for some river basins in lateritic (black circles) and nonlateritic (white circles) areas. The numbers 1 to 28 and the letters a to q refer respectively to nonlateritic and lateritic basins which are listed in Table 4.

Table 5
Fluxes of atmospheric/soil CO_2 consumed by silicate rock weathering (F_{CO2} sil) and river fluxes of alkalinity (total = F_{HCO3} total and derived only from carbonate dissolution = F_{CaCO3}) in nonlateritic and lateritic river basins

References in Fig. 8	River basin (station)	Area (10^3 km^2)	Runoff (mm/yr)	F_{CO2} sil	F_{CaCO3}	F^-_{HCO3} total
				$\times 10^3$ mol/km^2 yr		
Nonlateritic[a]						
1	Amur	1920	169	104	7	118
2	Colorado	710	28	67	0	67
3	Columbia	670	375	187	159	505
4	Danube	780	265	477	174	825
5	Fraser	250	453	134	156	446
6	Ganges–Brahm	1670	582	146	371	888
7	Godavari	320	261	147	125	397
8	Huanghe	810	65	87	62	211
9	Hungo	160	745	293	353	999
10	Indus	920	260	355	147	649
11	Lena	2440	219	162	38	238
12	Limpopo	340	15	35	0	35
13	Mackenzie	1620	154	22	123	268
14	Magdalena	280	859	106	294	694
15	Mehandi	190	344	135	105	345
16	Mekong	850	624	123	235	593
17	Mississippi	3260	178	112	127	366
18	Murray	1140	19	12	9	30
19	Negro	180	169	196	0	196
20	Nile	1900	47	77	22	121
21	Ob	2250	186	80	79	238
22	Orange	730	15	25	1	27
23	Po	70	657	427	746	1 919
24	Severnaia Dvina	260	416	242	295	832
25	Susitna	50	784	355	219	793
26	Xi Jiang	460	651	48	686	1 420
27	Yangtze	1830	508	207	356	919
28	Yukon	830	252	69	199	467
Lateritic[b]						
a	Amazon	5910	1 066	204	129	462
b	Orinoco	1020	1 078	89	65	219
c	Zaire	3700	352	39	19	77
d	Niger	1550	124	31	19	69
e	Parana	2870	164	77	13	103
f	Jamari	30.4	729	82	0	82
g	Jiparana	60.3	676	139	0	139
h	Niger (Siguiri)	67.6	261	70	0	70
i	Niger (Bamako)	117	198	59	0	59
j	Niger (Ke–Macina)	243	100	40	0	40
k	Milo (Kankan)	9.6	437	122	0	122
l	Tinkisso (Dabola)	6.4	246	114	0	114
m	Senegal (Dagana)	218	44.6	17	0	17
n	Faleme (Kidira)	28.9	62.2	33	0	33
o	Gambia (Kedougou)	7.5	249	89	0	89
p	Chari–Logone	330	121	56	0	56
q	Ouham (Batangafo)	44.7	230	89	0	89

[a] Data from Amiotte-Suchet (1995), Amiotte-Suchet and Probst (1996), Probst et al. (1994a, 1997).

[b] Data from Mortatti et al. (1992), Probst et al. (1994b), Boeglin and Probst (1996).

whereas in the case of carbonate dissolution, bicarbonate ions released in the draining waters come half from the atmospheric/soil CO_2 and half from the carbonate mineral dissolution. In the upper Niger basin, carbonate outcrops are considered as insignificant (see lithological map, Fig. 4). Thus, the total bicarbonate river flux measured at Bamako can be directly related to the atmospheric/soil CO_2 and to the silicate weathering intensity in the upper Niger basin. In this case, the CO_2 flux can be estimated for the upper Niger to 59.10^3 mol/km^2 yr from the mean annual flux of bicarbonate (3619 kg/km^2 yr, see Table 1).

In Fig. 8 the CO_2 fluxes consumed by silicate weathering vs. the annual runoff for some lateritic and nonlateritic river basins (see characteristics in Table 5) are plotted. The CO_2 fluxes have been calculated from the river fluxes of HCO_3^-, after correction for possible carbonate rock dissolution using a geochemical model (MEGA) based on the stoichiometry of the chemical reactions which control the dissolution and hydrolysis of the different minerals and on ionic ratios in streamwater draining the major rock types (see Amiotte-Suchet, 1995; Amiotte-Suchet and Probst, 1996; Probst et al., 1994a, 1997). Nevertheless, corrections for $CaCO_3$ can introduce some errors. Moreover, a very small proportion of $CaCO_3$ (e.g., traces of calcite in silicate rocks) can contribute a large proportion of the alkalinity in river water (see Drever and Hurcomb, 1986). The specific CO_2 fluxes for 17 lateritic, or partly lateritic, basins, could be calculated using the data given by Mortatti et al. (1992) or compiled by Probst et al. (1994b) and by Boeglin and Probst (1996). As can be seen in Fig. 8, there are good linear relationships between CO_2 fluxes and runoff. As previously shown by different authors, climate (e.g., precipitation, temperature and runoff) is one of the main factors controlling continental rock weathering and fluxes of atmospheric/soil CO_2 consumption (Amiotte-Suchet and Probst, 1993a; Velbel, 1993; White and Blum, 1995). Nevertheless, a comparison with the 28 nonlateritic basins compiled by Amiotte-Suchet (1995) clearly shows that, for similar runoff, the CO_2 flux consumed by silicate weathering (i.e., corrected from carbonate dissolution) is lower in lateritic areas than in nonlateritic areas. But this comparison also shows that the slopes of the relationships are very similar. According to our regression equations, it appears that, for a mean runoff of 250 mm/yr, the chemical weathering of silicate in nonlateritic basins consumes a specific CO_2 flux about 1.8 times higher than in lateritic basins. However, the fact that CO_2 flux consumed by the chemical erosion of silicate rocks appears lower in lateritic zones cannot necessarily be attributed largely to a lower weathering intensity in these regions, but also to other parameters, such as relief, mineralogical weathering stage or thickness of soil profiles, which play an important role in these tropical lateritic regions.

7. Conclusion

Weathering processes in the upper niger basin could be characterized and quantified from the chemical composition of its runoff waters, as well as from data concerning climate, hydrology, lithology and pedology.

The 72 river-water samples, collected twice a month at the station of Bamako (Mali) from January 1990 to December 1992 (corresponding to a very dry period) show that water composition changed little during 3 years. The substratum is mainly composed of acid rocks (granites, gneiss, micaschists); there are no carbonate or evaporite rock outcrops.

This study leads to the following conclusions.

(1) The weathering type, characterized from the geochemical ratio Re between dissolved cations and silica in the Niger waters, corresponds to monosiallitization associated predominantly with the formation of kaolinite (mean annual $Re = 1.83$). However, Re presents seasonal variations; during the rainy season ($Re = 1.67$), the weathering favors gibbsite formation indicating a trend to bauxite, whereas during the dry season ($Re = 2.44$) the weathering corresponds to the genesis of smectites indicating a tendency to form vertisols.

(2) The lateritic profiles continue on average to develop in the upper Niger basin, even in the present-day dry conditions. The physical erosion rate (WR_{ph}), at the top of the soil profile, has been calculated to be 2.4 to 3.4 m/Myr from the total river suspended sediment transport. The chemical weathering rate (WR_{ch}), at the bottom of the profile, can be estimated from the silica budget to be 4.7 m/Myr (for a 15% weight dissolution of quartz

between bedrock and saprolite), and from the cation budget to be 6.1 m/Myr (for the average from Na^+, K^+, Mg^{2+}, Ca^{2+}). The difference between WR_{ch} and WR_{ph} is positive, indicating that the soil profile thickness is mostly increasing in the whole basin, even if in the most humid and elevated areas of the upper Niger basin, the laterite thickness appears to be constant (landscape in dynamic equilibrium) or even on the decrease.

(3) It is important to consider the residual quartz in the lateritic profile when calculating the weathering rate. If the quartz dissolution ratio is taken into account, the weathering rate calculated from silica budget could be much lower than for total preservation of quartz between bedrock and saprolite.

(4) The CO_2 fluxes consumed by silicate rock weathering are partially controlled by weathering type. A comparison between 43 river basins of the world shows that the CO_2 fluxes consumed by silicate weathering are about two times lower in lateritic areas than in nonlateritic zones, for similar runoff.

All the results obtained in this study correspond to a dry period. It would be important now to determine the weathering mass balance of the upper Niger basin during a humid period.

Acknowledgements

We thank Y. Hartmeier, G. Krempp and D. Million for the chemical analysis of the Niger river water. We are very grateful to R.A. Berner, J.I. Drever, D. Nahon, M.A. Velbel and R.F. Yuretich for their review of the manuscript. Their valuable comments and careful corrections have greatly contributed to improve the first version of our manuscript. Many thanks to Graham Shields for the English corrections on the last version of the manuscript and to Claude Hammel for the figure drawing.

References

Amiotte-Suchet, P., 1995. Cycle du carbone, érosion chimique des continents et transferts vers les océans. Sci. Géol. Mém. (Strasbourg) 97, 156.

Amiotte-Suchet, P., Probst, J.L., 1993a. Modelling of atmospheric CO_2 consumption by chemical weathering of rocks: application to the Garonne Congo and Amazon basins. Chem. Geol. 107, 205–210.

Amiotte-Suchet, P., Probst, J.L., 1993b. Flux de CO_2 consommé par altération chimique continentale: influences du drainage et de la lithologie. C.R. Acad. Sci., Ser. II (Paris) 317, 615–622.

Amiotte-Suchet, P., Probst, J.L., 1995. A global model for present-day atmospheric/soil CO_2 consumption by chemical erosion of continental rocks (GEM-CO_2). Tellus 47B (1/2), 273–280.

Amiotte-Suchet, P., Probst, J.L., 1996. Origines du carbone inorganique dissous dans les eaux de la Garonne. Variations saisonnières et interannuelles. Sci. Géol. Bull., Strasbourg 49, 101–126.

Bassot, J.P., Meloux, J., Traore, H., 1981. Carte géologique au 1,500,000ème de la République du Mali (notice, 137 pp.). Dir. Nat. Géologie et Mines, Bamako.

Berner, E.K., Berner, R.A., 1987. The Global Water Cycle. Geochemistry and Environment. Prentice Hall, Engelwood Cliffs, NJ.

Besse, J., 1986. Cinématique des plaques et dérive des pôles magnétiques. Thèse Sciences, Univ. Paris 7, 380 pp.

Bessoles, B., 1977. Géologie de l'Afrique. Le craton ouest-africain. Mém. BRGM, Vol. 88, 402 pp.

Blanchot, A., 1958. Bull. Serv. Géol. Prosp. Min. Dakar, Vol. 27, 280 pp.

Bocquier, G., 1973. Genèse et évolution de deux toposéquences de sols tropicaux du Tchad. Interprétation biogéodynamique. Mém. ORSTOM, Paris, Vol. 62, 350 pp.

Boeglin, J.L., Probst, J.L., 1996. Transports fluviaux de matières dissoutes et particulaires sur un bassin versant en région tropicale: le bassin amont du Niger au cours de la période 1990–1993. Sci. Géol. Bull., Strasbourg 49, 7–23.

Bonifas, M., 1959. Contribution à l'étude géochimique de l'altération latéritique. Mém. Serv. Carte Géol. Als. Lorr., Strasbourg, Vol. 17, 159 pp.

Boulet, R., 1978. Toposéquences de sols tropicaux en Haute–Volta. Equilibre et déséquilibre pédobioclimatique. Mém. ORSTOM, Paris, Vol. 85, 272 pp.

Boulvert, Y., 1992. Eléments d'atlas climatologique de la région guinéenne et péri-guinéenne. Rapport ORSTOM, Bondy, 16 pp.

Bourdeau, A., 1991. Les bauxites du Mali. Géochimie et minéralogie. Thèse Doc., Univ. Louis Pasteur, Strasbourg, 336 pp. + annexes.

BRGM, 1960. Guinea geological map (scale: 1/1,000,000). Doc. BRGM interne.

Brunet-Moret, Y., Chaperon, P., Lamagnat, J.P., Molinier, M., 1986. Monographie hydrologique du fleuve Niger. Tome I: Niger supérieur. Monographies Hydrologiques ORSTOM, No. 8, ORSTOM Editions, Paris, 396 pp.

Cleaves, E.T., Godfrey, A.E., Bricker, O.P., 1970. Geochemical balance of a small watershed and its geomorphic implications. Geol. Soc. Am. Bull. 81, 3015–3032.

Dabin, B., Leneuf, N., Riou, G., 1960. Carte pédologique de la Côte d'Ivoire au 1/2,000,000. Notice explicative, ORSTOM, Abidjan, 30 pp.

Delaître, E., 1994. Etude des latérites du Sud–Mali par la méthode du sondage électrique. Thèse Doc., Univ. Louis Pasteur, Strasbourg, 193 pp.

Dillon, W.P., Sougy, J.M.A., 1974. Geology of West Africa and Canary and Cape Verdeislands. In: The Ocean Basins and Margins, New York. Vol. 2, pp. 315-390.

DNHE, 1981–1993. Annuaires hydrologiques du Mali. Dir. Nat. Hydraulique et Energie, Bamako.

DNM, 1990–1992. Annuaires climatologiques du Mali. Dir. Nat. Météorologie, Bamako.

Drever, J.I., 1982. The Geochemistry of Natural Waters. Prentice Hall, 388 pp.

Drever, J.I., Hurcomb, D.R., 1986. Neutralization of atmospheric acidity by chemical weathering in an alpine drainage basin in the North Cascade Mountains. Geology 14, 221–224.

Fournier, F., 1960. Climat et érosion. Presses Universitaires de France, Paris, 220 pp.

Freyssinet, P., 1990. Géochimie et minéralogie des latérites du Sud Mali. Evolution des paysages et prospection géochimique de l'or. Thèse Doc., Univ. Louis Pasteur, Strasbourg, 269 pp.

Gac, J.Y., 1980. Géochimie du bassin du lac Tchad. Bilan de l'altération, de l'érosion et de la sédimentation. Trav. Doc. ORSTOM, Paris, Vol. 123, 251 pp.

Garrels, R.M., Mackenzie, F.T., 1971. Evolution of Sedimentary Rocks. W.W. Nortonand, New York, 397 pp.

Goldich, S.S., 1938. A study in rock-weathering. J. Geol. 46, 17–58.

Gourcy, L., 1996. Le delta central du Niger agit-il comme un piège à éléments dissous et particulaires? Sci. Géol., Strasbourg, in press.

Grove, A.T., 1972. The dissolved and solid load carried by some west African rivers: Senegal Niger, Benue and Chari. J. Hydrol. 16 (4), 277–300.

Helgeson, H.C., 1969. Thermodynamics of hydrothermal systems at elevated temperatures and pressures. Amer. J. Sci. 267, 729–804.

Holeman, J.N., 1968. The sediment yield of major rivers in the world. Water Resour. Res. 4 (4), 737–747.

Janda, R.J., 1971. An evaluation of procedures used in computing chemical denudation rates. Geol. Soc. Amer. Bull. 8 (21), 67–80.

Lelong, F., 1969. Nature et genèse des produits d'altération de roches cristallines sous climat tropical humide (Guyane française). Mém. Sci. Terre, Nancy, 14, 188 pp.

Leroux, M., 1983. The climate of Tropical Africa. Champion, Paris, 633 pp. and Atlas, 24 pp. and 250 maps.

Lévêque, A., 1979. Pédogenèses sur le socle granito–gneissique du Togo. Différenciation des sols et remaniements superficiels. Trav. Doc. ORSTOM, Paris, 108, 224 pp.

Maignien, R., 1958. Le cuirassement des sols en Guinée (Afrique occidentale). Mém. Serv. Carte géol. Als. Lor. Strasbourg, 16, 239 pp.

Martins, O., Probst, J.L., 1991. Biogeochemistry of Major African Rivers: Carbon and Mineral Transports. In: Degens, E.T., Kempe, S., Richey, J.E. (Eds.), Biogeochem. of Major World Rivers, SCOPE, Chap. 6. Wiley, pp. 129–157.

Mazaltarim, D., 1989. Géochimie des cuirasses ferrugineuses et bauxitiques de l'Afrique occidentale et centrale. Thèse Doc., Univ. Louis Pasteur, Strasbourg, 263 pp. + annexes.

Meybeck, M., 1984. Les fleuves et le cycle géochimique des éléments. Thèse Sci., Univ. Paris, 6, 558 pp.

Michel, P., 1973. Les bassins des fleuves Sénégal et Gambie. Etude géomorphologique. Mém. ORSTOM, Paris, 63, (1,2,3), 752 pp.

Milesi, J.P., Diallo, M., Feybesse, J.L., Keyta, F., Ledru, P., Vinchon, C., Dommanget, A., 1986. Caractérisation lithostructurale de deux ensembles successifs dans les séries birrimiennes de la boutonnière de Kédougou (Mali–Sénégal) et du Niandan (Guinée). Implications gîtologiques, CIFEG Publi. occasionnelle, 10, pp. 113-181.

Millot, G., Bonifas, M., 1955. Transformations isovolumétriques dans les phénomènes de latérisation et bauxitisation. Bull. Serv. Carte Géol. Als. Lor. 8, 3–10.

Mortatti, J., Probst, J.L., Ferreira, J.R., 1992. Hydrological and geochemical characteristics of the Jamari and Jiparana river basins (Rondonia, Brazil). GeoJournal 26 (3), 287–296.

Nahon, D., Millot, G., 1977. Géochimie de la surface et formes du relief: 5. Enfoncement géochimique des cuirasses ferrugineuses par épigénie du manteau d'altération des roches mères gréseuses. Influence sur le paysage. Sci. Géol. Bull., Strasbourg 30, 275–282.

Nkounkou, R.R., Probst, J.L., 1987. Hydrology and geochemistry of the Congo river system. Mitt. Geol–Paläont. Inst. Univ. Hamburg, SCOPE/UNEP, 64, pp. 483-508.

Olivry, J.C., Gourcy, L., Toure, M., 1995. Premiers résultats sur la mesure des flux de matières dissoutes et particulaires dans les apports du Niger au Sahel. Actes du Colloque PEGI/Grands Bassins Fluviaux Périatlantiques. In: Olivry, J.C., Boulegue, J. (Eds.), Congo, Niger, Amazone, 22–24 Novembre 1993, Paris, ORSTOM Editions, Collections Colloques et Séminaires, Paris, pp. 281–292.

Orange, D., 1992. Hydroclimatologie du Fouta Djalon et dynamique actuelle d'un vieux paysage latéritique (Afrique de l'Ouest). Sci. Géol. Mém. Strasbourg, 93, 206 pp.

Paces, T., 1986. Weathering and mass balance in small drainage basins: environmental applications in the Bohemian Massif Central Europe. Sci. Géologiques Bull. 392, 131–150, Strasbourg.

Pédro, G., 1966. Essai sur la caractérisation géochimique des différents processus zonaux résultant de l'altération superficielle. C.R. Acad. Sci. Paris 262, 1828–1831.

Pédro, G., 1968. Intérêt géochimique et signification minéralogique du paramètre moléculaire $K_i = SiO_2/Al_2O_3$ dans l'étude des latérites et des bauxites. Bull. Gr. Fr. Argiles 18, 19–31.

Pinet, Souriau, 1988. Continental erosion and large scale relief. Tectonics 7 (3), 563–582.

Pion, J.C., 1979. L'altération des massifs cristallins basiques en zone tropicale sèche. Etude de quelques toposéquences en Haute–Volta. Sci. Géol. Mém. Strasbourg, 57, 220 pp.

Probst, J.L., 1992. Géochimie de l'érosion continentale: mécanismes, bilan global, actuel et fluctuations au cours des 500 derniers millions d'années. Sci. Géol. Mém. Strasbourg, 94, 161 pp.

Probst, J.L., Amiotte-Suchet, P., Ludwig, W., 1994a. Continental erosion and river transports of carbon to oceans. Trends Hydrol. 1, 453–468.

Probst, J.L., Mortatti, J., Tardy, Y., 1994b. Carbon river fluxes and global weathering CO_2 consumption in the Congo and Amazon river basins. Applied Geochem. 9, 1–13.

Probst, J.L., Amiotte-Suchet, P., Ludwig, W., 1997. A global modelling of CO_2 uptake by continental erosion and carbon river transports to the oceans. Sci. Géol. Bull., Strasbourg, 50.

Savostin, L.A., Sibuet, J.C., Zoneshain Lev, P., Le Pichon, X., Roulet, M.J., 1986. Kinematic evolution of the Tethys belt from the Atlantic Ocean to the Pamirs since the Triassic. Tectonophysics 123, 1–35.

Semhi, K., 1996. Erosion et transferts de matières sur le bassin versant de la Garonne. Influence de la sécheresse. Thèse Doc., Univ. Louis Pasteur, Strasbourg, 203 pp.

Tardy, Y., 1968. Une méthode de détermination des types d'altération actuels par l'étude des eaux en pays granitiques et gneissiques. C.R. Acad. Sci. Paris 267, 579–582.

Tardy, Y., 1969. Géochimie des altérations. Etude des arènes et des eaux de quelques massifs cristallins d'Europe et d'Afrique. Mém. Serv. Carte géol. Als. Lor., 31, 199 pp.

Tardy, Y., 1971. Characterization of the principal weathering types by the geochemistry of waters from some European and African crystalline massifs. Chem. Geol. 7, 253–271.

Tardy, Y., 1986. Le Cycle de l'Eau. Climats, Paléoclimats et Géochimie globale. Masson, Paris, 338 pp.

Tardy, Y., 1990. L'érosion. Encyclopedia Universalis, Vol. 8, pp. 615-627.

Tardy, Y., 1993. Pétrologie des Latérites et des Sols Tropicaux. Masson, Paris, 459 pp.

Tardy, Y., Boeglin, J.L., Novikoff, A., Roquin, C., 1995. Petrological and geochemical classification of laterites. In: G.J. Churchman, R.W. Fitzpatrick, R.A. Eggleton (Eds.), Clays Controlling the Environment, CSIRO, Melbourne, pp. 481–186.

Velbel, M.A., 1993. Temperature dependence of silicate weathering in nature: how strong of a negative feed back on long term accumulation of atmospheric CO_2 and global greenhouse warning?. Geology 21, 1059–1062.

Velbel, M.A., 1995. Geochemical mass balaces and weathering rates in forested watersheds of the Southern blue Ridge. Am. J. Sci. 285, 904–930.

White, A.F., Blum, A.E., 1995. Effects of climate on chemical weathering in watersheds. Geochim. Cosmochim. Acta 59 (9), 1729–1747.