Dynamic interactions between the gulf of Guinea passive margin and the Congo River drainage basin. Part 1 : Morphology and mass balance

Pascale Leturmy, F. Lucazeau, F. Brigaud

Dynamic interactions between the gulf of Guinea passive margin and the Congo River drainage basin: 1. Morphology and mass balance

Pascale Leturmy
Département des Sciences de la Terre, Université de Cergy-Pontoise, Cergy-Pontoise, France

Francis Lucazeau
Laboratoire Géosciences Marines, Institut de Physique du Globe de Paris, Paris, France

Frédéric Brigaud
Total E&P Norge AS, Stavanger, Norway

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[1] A sediment budget between the Congo River drainage basin and the western African margin in the Gulf of Guinea is proposed on the basis of published and unpublished offshore Tertiary isopach maps, and onshore digital elevation analysis. The overall denudation of that area may be as high as 3.5×10^6 km^3 with a maximum of 10% coming from Mesozoic and Cenozoic covers. The southern part of the Congo River basin, related to uplift of the South African and Kalahari shields, appears as the most immature from the morphologic standpoint but provides one third of the present-day sediment production; it represents a maximum denudation of 150,000 km^3. On the easternmost part, East African Rift drainage basins show a more mature relief and a maximum denudation of 270,000 km^3, which can increase to 570,000 km^3 if the Congo drainage basin had extended up to the east branch of the rift. These values are confidently established from the existence of remnant geological surfaces, and can explain the volume of Tertiary sediment in the Gulf of Guinea. During upper Cretaceous, the most important accumulations of sediments correspond to the Ogooe and Kwanza fans, which shows that the organization of continental drainage was different as was potential source of sediments. In the northern part of the present-day Congo River drainage basin, there was a compressional episode during Santonian that may have caused significant relief and erosion along a Benue-Chad axis. *INDEX TERMS:* 8105 Tectonophysics: Continental margins and sedimentary basins (1212); 8110 Tectonophysics: Continental tectonics—general (0905); 8124 Tectonophysics: Earth's interior—composition and state (1212); 8155 Tectonophysics: Plate motions—general; 9305 Information Related to Geographic Region: Africa; *KEYWORDS:* denudation, mass balance, morphology, relief, uplift, Africa

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1. Introduction

[2] The sediment deposits of continental margins are records of Earth surface erosion and drainage processes; sediment budgets between source and deposition areas provide a first-order understanding of the drainage basin dynamics at geological timescales [e.g., *Rust and Summerfield*, 1990; *Métivier et al.*, 1999]. In most cases, high denudation rates as well as large Tertiary fans are related to active tectonics in the major orogenic domains (Himalayas, Andes, Alps, Taiwan, New Zealand), and characteristic of high elevation drainage basins [*Milliman and Syvitski*, 1992]; 80% of the Amazon load comes, for instance, from the active Andean chain that represents 10% only of the drainage area [*Meade et al.*, 1985]. On the other hand, climatic conditions (rainfall, runoff, etc.) do not display a clear correlation with present-day solid loads of large river systems [*Pinet and Souriau*, 1988].

[3] The African margins, especially Gulf of Guinea in offshore Gabon-Angola, have large Tertiary accumulations with regard to the lack of significant tectonic activity since the Pan African orogeny (~600 Ma). The present-day Congo River delivery is also one of the smallest observed for large rivers [*Pinet and Souriau*, 1988; *Milliman and Syvitski*, 1992], but the Congo fan extends up to 1000 km from the coastline [*Savoye et al.*, 2000]. It is therefore important to understand whether or not these large volumes of sediments are compatible with erosion in the Congo drainage basin over a certain period of time. As relics of geological surfaces exist within the Congo River drainage

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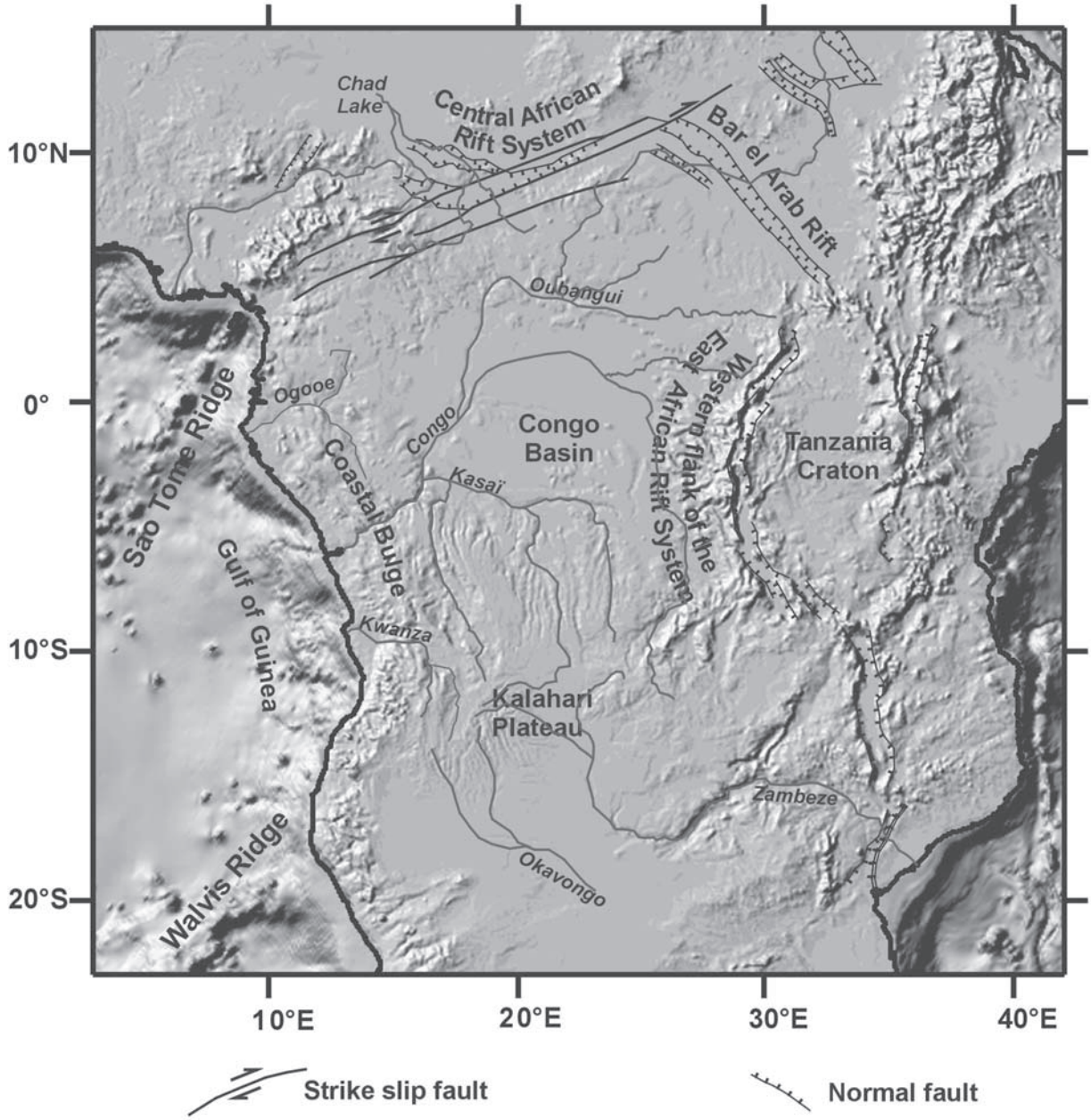

Figure 1. Shaded relief and tectonic provinces in the studied area. The Congo River drainage basin is surrounded by topographic highs which limit the extension of drainage. It is bordered to the north and northwest by Central African Rift System and Bar el Arab Rift of Jurassic age, to the east by East African Rift System of Tertiary age and to the south by Kalahari Plateau. Offshore, gulf of Guinea margin is a domain limited by two topographic ridges (Sao Tome ridge to the north and Walvis Ridge to the south) which protect sediments from dispersion.

basin and as oil exploration research can provide a quantitative view of sediment fluxes, a mass balance analysis is possible. The Gabon to Angola domain is limited by two topographic volcanic ridges, Sao Tome Ridge on the northern part and Walvis Ridge on the southern part; both protect the sediment deposits from important dispersion by submarine currents and relate these deposits to a unique large drainage basin, making the system almost closed (Figure 1).

[4] In this paper, we develop a quantitative analysis of the sediment budget and erosion process for the Congo River drainage basin/Gulf of Guinea margin. Offshore volumetric estimates are derived from published and unpublished isopach maps and corrected for dissolved loads, whereas onshore volumetric estimates and chronology of erosion are obtained from the analysis of the GTOPO30 topographic database and geological map of Africa.

2. Regional Context

2.1. Offshore

[5] The studied area includes the Gulf of Guinea, between Gabon and Angola, and the drainage basins delivering

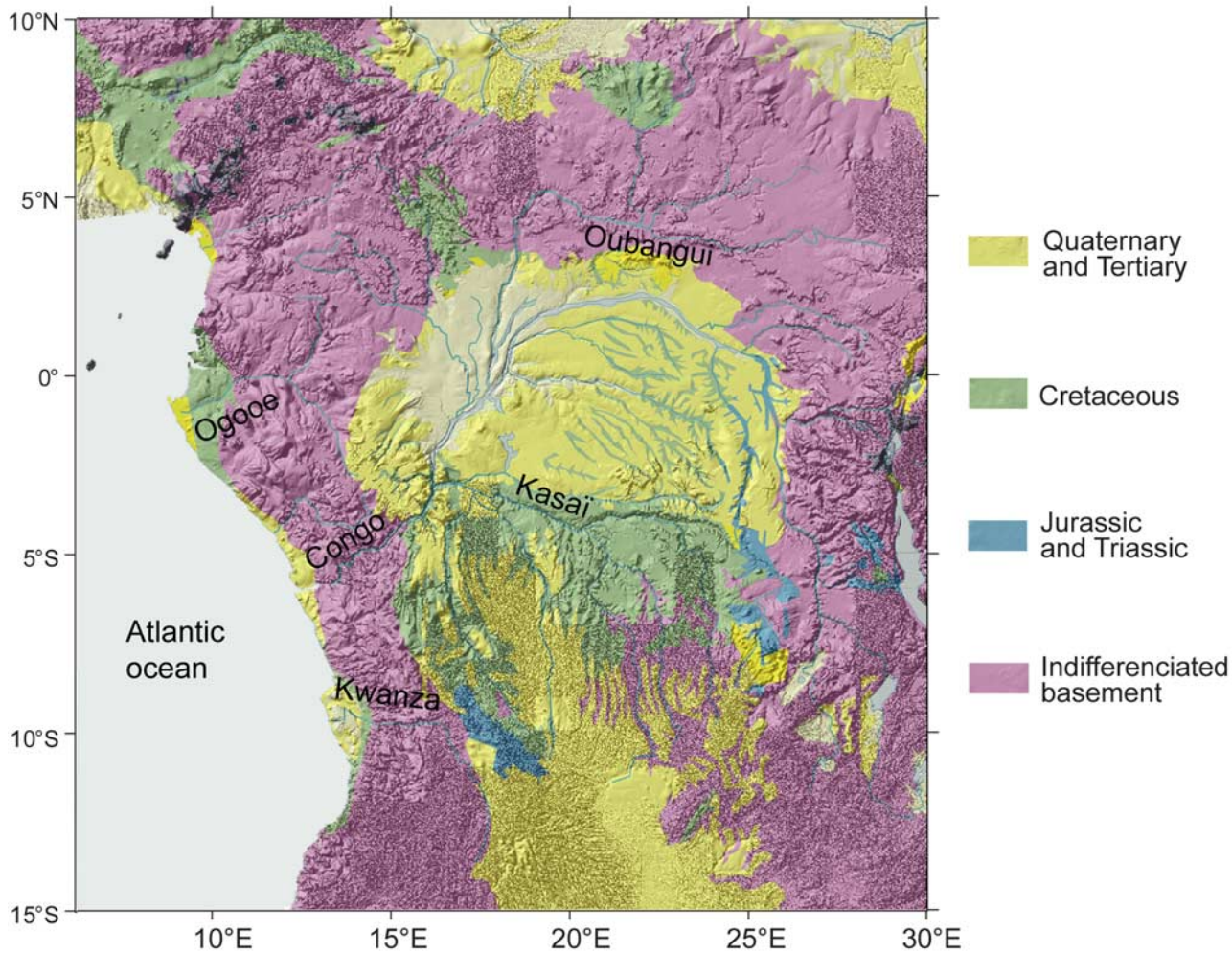

Figure 2. Regional geology projected on GTOPO30 digital elevation model. Major topographic highs surrounding the Congo River drainage basin are mainly basement rocks, whereas central Congo basin is a subsiding sedimentary zone.

sediments to that part of the margin. It covers 5×10^6 km^2 onshore and 2×10^6 km^2 offshore.

[6] Breakup of Gondwana during Early Cretaceous has separated this area from Brazil. Rifting propagates from south to north, beginning at 126.5 Ma south of the Walvis ridge and at 118.7 Ma in the Benue Trough [*Nürnberg and Mueller*, 1991]. It ends up in late Aptian with a marine transgression which generates salt deposit along all the Gabon-Angola margin.

[7] South of this domain (Congo-Angola), postrift sedimentation begins with the development of a shallow water carbonate platform during Albian. Carbonates are progressively replaced by more detritic sediments as the margin subsides. At the Eocene-Oligocene transition, submarine erosion affects the upper slope and the shelf break of the West African margin and may have removed up to 1000 m of sediments [*Lavier et al.*, 2001]. In the north (Gabon), a late Cretaceous sedimentary succession of estuarine-deltaic mud and sands are followed by a carbonate sedimentation [*Séranne et al.*, 1992; *Rasmussen*, 1996].

[8] Postrift sediments are characterized in that part of the African margin by raft tectonics related to salt decollements [*Burollet*, 1975; *Ludin*, 1992; *Mauduit and Brun*, 1998; *Valle et al.*, 2001]. *Valle et al.* [2001] recognize three main periods for this deformation (Aptian; late Eocene-late Oligocene and late Miocene-recent).

2.2. Onshore

[9] The Congo basin is a spread drainage basin (3.5×10^6 of km^2) that takes place above a circular Paleozoic sedimentary basin; it remained almost continuously subsiding before Tertiary and has been filled with lacustrine, marine and continental sediments through time [*Lawrence and Makazu*, 1988]. The central part of the basin is flat: a preserved surface at 610 m covers up to 330,000 km^2. Divides of the Congo River drainage basin are related to various geological structures. On the western part of the Congo River drainage basin, Precambrian igneous and metamorphic outcrops [*Brognon*, 1971] are exposed within a 500–800 m high topographic bulge (Figure 2). As the Mesozoic and Cenozoic covers are tilted seaward on the proximal margin and affected by several erosion unconformities [*Emery et al.*, 1975], it is likely that the origin of the bulge is recent. In the northern part of the Congo basin, the Central African Rift System is active from late Jurassic to Early Cretaceous [*Genik*, 1992; *Guiraud and Bosworth*,

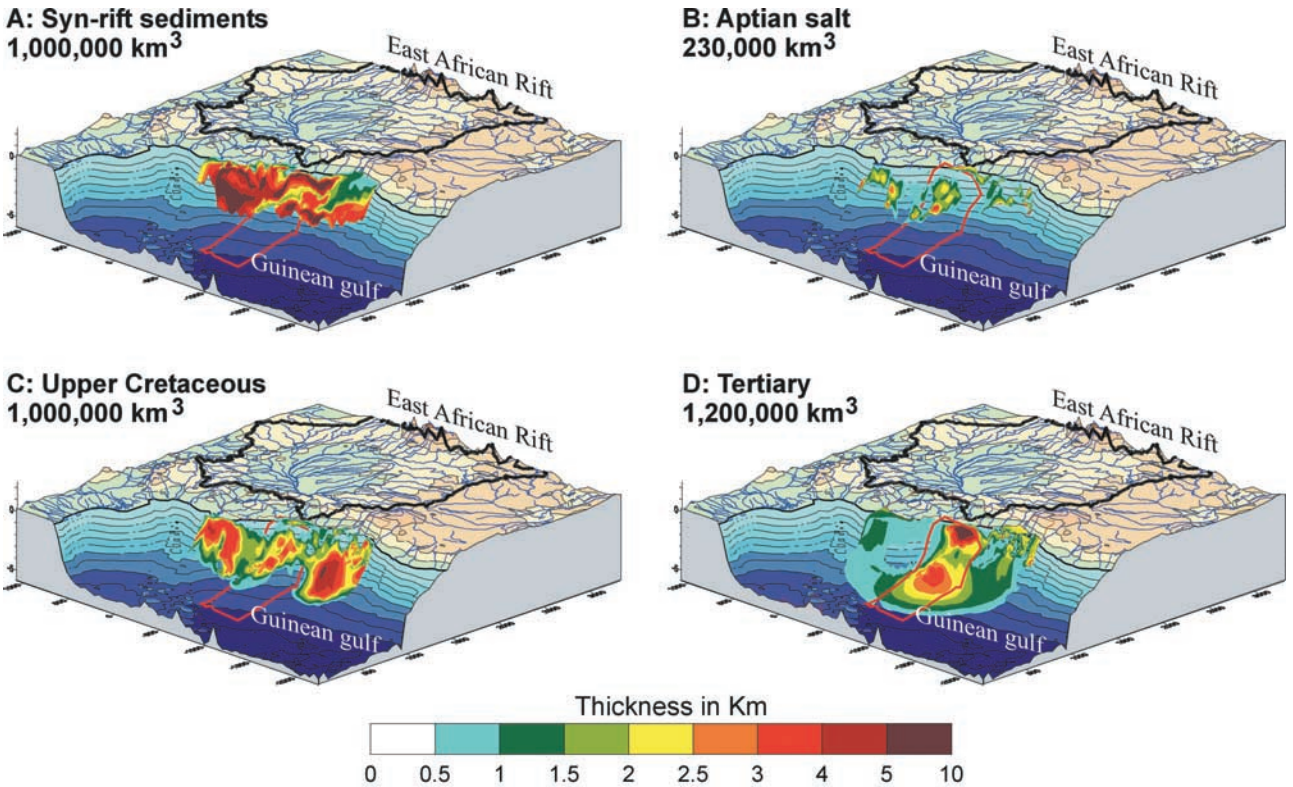

Figure 3. Evolution of sediment accumulation along the West African margin since break up of Gondwanaland. Red rectangle corresponds to the area investigated by Zaiango experiment [*Savoye et al.*, 2000], and heavy black line inland corresponds to the limit of the Congo River drainage basin. (a) Synrift sedimentation and (b) Aptian salt represent approximately one third of the total amount of sedimentation. (c) During upper Cretaceous, two main depot centers are individualized offshore and correspond to the present-day Ogooe River outlet in the north and Kwanza River outlet in the south. (d) During Tertiary, one third of the total amount of sediments is deposited in the Congo River fan. Migration of depot centers from Upper Cretaceous to Tertiary is supposed to be related to a major change in drainage organization inland.

1997] and has been inverted later on during Santonian as were all extensional basins in Africa [*Guiraud and Bosworth*, 1997]. The Central African Rift still appears as a 900 m maximum elevation relief and the presence of Lower Cretaceous deposits on its southern flank (Figure 2) suggests that it has never been as high as the East African Rift. On the eastern part of the Congo basin, East African Rift is a morphological barrier since Middle Miocene at least, presently as high as 3400 m. On the southern part of the Congo basin, the Kalahari plateau appears as a relatively flat area with a mean elevation of 1000 m, but the age of this topography has not clearly been established. Large-scale vertical motions [*Sahagian*, 1988; *Nyblade and Robinson*, 1994] and seismic tomography [*Lithgow-Bertelloni and Silver*, 1998] suggest that this topography could be supported dynamically in the deep mantle.

[10] Drainage system as it appears now is obviously a recent feature that develops during Tertiary, as a consequence of the progressive uplift of the present divides.

3. Estimation of Tertiary Denudation From Sediment Accumulation

[11] Large-scale studies of the Atlantic margins [*Emery et al.*, 1975] have shown the deep offshore extension of the Congo fan and Tertiary deposits in the Gulf of Guinea, but had low stratigraphic and spatial resolutions. Oil exploration studies have substantially increased the knowledge of sediment distribution in the deep offshore of the Gulf of Guinea by 2D and 3D seismic investigations. It has resulted in new geological and geophysical interpretations on the continental margin and the transition to the oceanic domain [e.g., *Marton et al.*, 2000; *Uenzelmann-Neben*, 1998; *Lavier et al.*, 2001]. However, the exploration domain investigated by commercial seismic studies ends up in the vicinity of ocean-continent boundary, where more or less 3000–4000 m of sediment still exist. A remaining uncertainty on the total amount of Tertiary comes therefore from estimates of the sediment wedge on the oceanic crust, only constrained by a limited number of long enough profiles [*Emery et al.*, 1975; *Savoye et al.*, 2000]. Our global estimate of postrift sediment, including the distal sedimentary wedge, is $3.5 \pm 1 \times 10^6$ km^3.

[12] The compilation of sedimentation data is presented as a set of time sliced isopach maps (Figure 3) that show the displacement of depot centers with time and as sedimentation rates across the Congo fan (Figure 4) that provide a detailed time evolution. Synrift sediments and Aptian salt (Figures 3a and 3b) represent one third of the total amount of sediments (1,000,000 km^3 and 270,000 km^3, respectively); a north-south gradient appears in the synrift

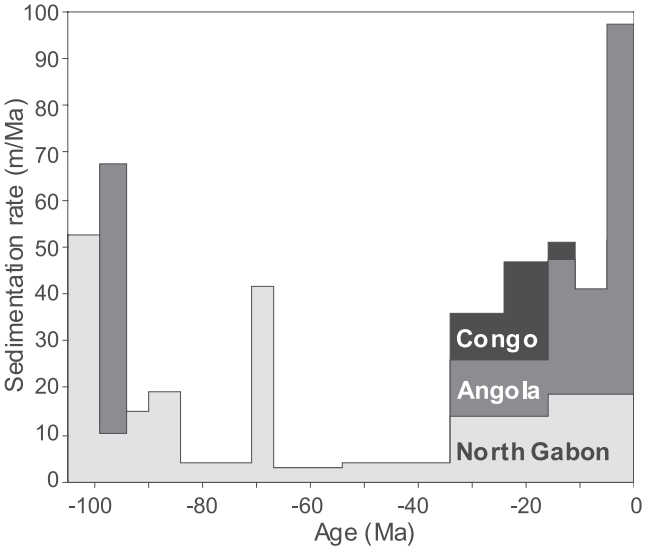

Figure 4. Average sedimentation rates across three sections in gulf of Guinea. All curves show a similar trend: rifting and uplift of flanks causes synrift erosion and sedimentation (140–90 Ma). This period is followed by slow sedimentation rates during upper Cretaceous and lower Tertiary (locally higher in Ogooe and Kwanza vicinity). From 34 Ma to present-day, sedimentation rates progressively increase up to values as high as 100 m/Myr in Congo fan.

sedimentation but may be partly related to some imaging problem. During Upper Cretaceous (Figure 3c), the volume estimate of sediment is 1×10^6 km^3. Two major depot centers as thick as 5 km are individualized and correspond to the present-day Ogooe River in the north and Kwanza River in the south. On the other hand, the present-day Congo River has a smaller contribution, which probably reflect a smaller drainage basin at that time. During Tertiary, the total amount of accumulation is 1.2 km^3 (Figure 3d), but the depot center is now restricted to the Congo fan where thickness reaches 6 km in the proximal part of the fan and 4 km in the distal part. This indicates that a complete change in drainage system happened at that time. A detailed analysis of the sediment rate evolution with time (Figure 4) clearly shows that the sedimentation rates before Oligocene have been low or reduced by erosion in the proximal part of the margin [*Séranne et al.*, 1992; *McGinnis et al.*, 1993; *Lavier et al.*, 2001]. When the modern drainage of Congo River takes place at about 34 Ma, the sedimentation rate increases almost continuously with time (Figure 4), in connection with either an elevation of the continent or the effect of the switch from greenhouse to icehouse conditions [*Séranne*, 1999]. This point will be discussed later on and in our companion paper [*Lucazeau et al.*, 2003].

[13] In addition to the offshore sediment volume, the alluvial plain of Congo River stores a significant Mesozoic/Tertiary cover that may reach up to 1 s two-way travel time [*Lawrence and Makazu*, 1988]. Expanding a corresponding average thickness of 500 m over the alluvial plain area (1×10^6 km^2) may lead to an additional 0.5×10^6 km^3. On the other hand, present-day dissolved load of the Congo River can represent from 60% of the solid load [*Gaillardet et al.*, 1995] to 100% [*Pinet and Souriau*, 1988]. The proportion of dissolved material that has not been precipitated in the Gulf of Guinea and returned to the global ocean is difficult to estimate, and this can also lead to an underestimation of the volume of erosion. The total volume of erosion material provided to the Gulf of Guinea may be therefore of the order of 5×10^6 km^3 after the breakup of Gondwana, and up to 1.5×10^6 km^3 during Tertiary.

4. Estimation of Tertiary Denudation From Relic Surfaces

[14] Previous estimates of denudation have been obtained along the East African Rift and in Namibia by restorations of the cooling history inferred from Apatite Fission Track Analysis (AFTA). *Van der Beek et al.* [1998] observed three cooling events along the Malawi and Rukwa Rift flank at 250 Ma, around 150 Ma, and after 40–50 Ma with less than 1 km of denudation associated with this last event. *Foster and Gleadow* [1996] proposed similar results for the Kenya rift, with three stages of denudation at 220 Ma, 140–120 Ma and 60–70 Ma with 2.5 km denudation for the latest stage. In Tanzania, *Noble et al.* [1997] proposed two stages of cooling at 110 and 65 Ma. Conversely, *van den Haute* [1984] results suggest a slower and more continuous cooling since 300–400 Ma in Rwanda and Burundi, with a mean denudation rate between 2 and 10 m/Myr. In Namibia, most of denudation follows the Atlantic breakup (120 Ma) on the coastal domain, and increases inland during Tertiary [*Gallagher and Brown*, 1999]. All of these results indicate that a stage of denudation has been driven by the South Atlantic rifting, and another one started from early Tertiary (around 50 Ma). In the central rift of Kenya, *Roessner and Strecker* [1997] reconstructed a paleosurface from relics of 3.4 Ma basalts to infer the volume that has been eroded between this surface and the present-day topography. They obtain a denudation rate in the range of 11–14 m/Myr. At a different timescale and a different space scale, other estimates of denudation can be derived from geochemical budget [*Gaillardet et al.*, 1995]; an average denudation rate of 6 m/Myr is obtained for the overall Congo basin, with a greater contribution from Eastern and Southern tributaries.

[15] In order to estimate the regional variation of denudation in the Congo River basin, we have generalized the technique of paleosurface reconstructions similar to that developed by *Roessner and Strecker* [1997]. Topography is obtained from the GTOPO30 database [*U.S. Geological Survey*, *Earth Resources Data Center* (*USGS-EDC*), 1996], relics surfaces are respectively defined by the envelope of topographic ridges, base of Tertiary/Quaternary, base of Cretaceous, base of Triassic/Jurassic (Figure 5); these three geological limits are picked up on the 1/1,000,000 geological map draped over GTOPO30 topography (Figure 2). Subtraction of the present topography from those envelopes can give a first-order estimate of the eroded volume of rocks. Where geological relics are missing, extrapolation of the average thickness for a given geological unit has been used to maximize estimation of denudation. For instance, Cretaceous unit is well constrained along the western part of the Kasai subbasin, where the mean thickness is 130 m. This thickness value is used where Cretaceous has not been preserved along the coast and along the northwest flank of the rift.

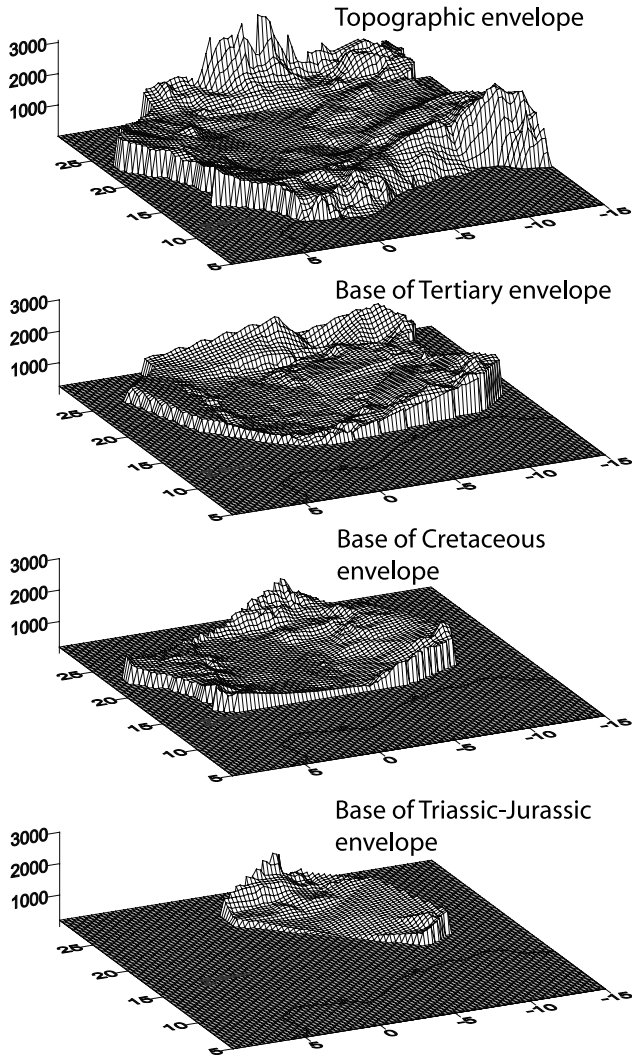

Figure 5. Relic surfaces reconstructed from GTOPO30 DEM and geological map. Topographic envelope is a smooth surface matching a selection of highest elevation pixels. Base of Tertiary, base of Cretaceous and base of Triassic-Jurassic envelopes are surfaces constructed with preserved outcrops picked up on geological map. Volumes between these different surfaces have been used to estimate erosion linked to the Congo River drainage basin.

[16] Accordingly, denudation below the envelope of topographic ridges ranges between 725,000 km^3 to 1,000,000 km^3 whether or not this extrapolation of the average thickness has been used. This represents 300,000 to 400,000 km^3 of Cenozoic, 75,000 to 275,000 km^3 of Mesozoic and 350,000 km^3 of basement (Figure 6). The principal sources of sediments are the East African Rift (200,000–270,000 km^3 in volume or 230–320 m average denudation) and the Kasai domain (140,000–150,000 km^3 or 160–175 m average denudation). Coastal drainage basins deliver large denudation as well: Ogooe drainage basin in the northwest corresponds to 45,000–85,000 km^3 (190–385 m average denudation) whereas Kwanza drainage basin in southwest to 36,000–50,000 km^3 (210–300 m average denudation).

5. Digital Elevation Analysis

[17] Previous analysis provides volumetric estimates of denudation in the different geological structures of the Congo drainage basin, but no real information on the

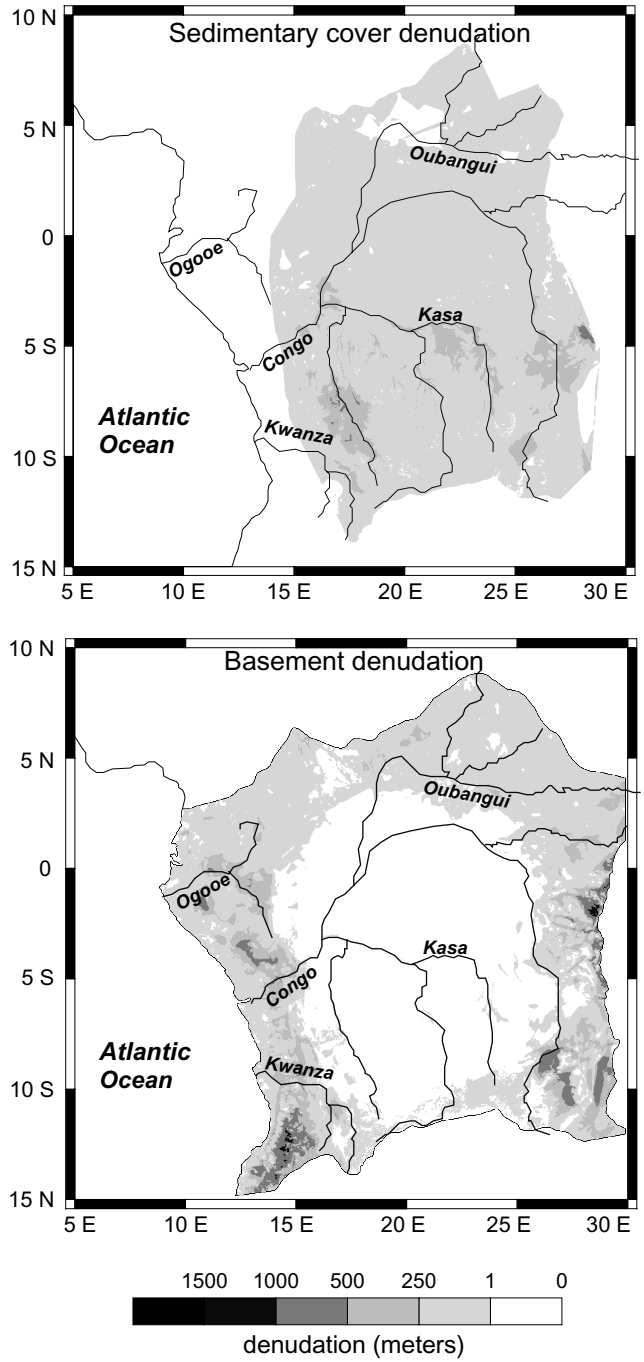

Figure 6. Distribution of estimated erosion thickness. (a) The overall sediment cover denudation represents 375,000 to 675,000 km^3, including 300,000–400,000 km^3 of Tertiary, 75,000–275,000 km^3 of Cretaceous and 14,000 km^3 of Trias-Jurassic. (b) The minimum denudation of basement represents 350,000 km^3. Total amount of denudation in this area ranges between 725,000 km^3 and 1,000,000 km^3, only one third of the total volume of sediments deposited offshore.

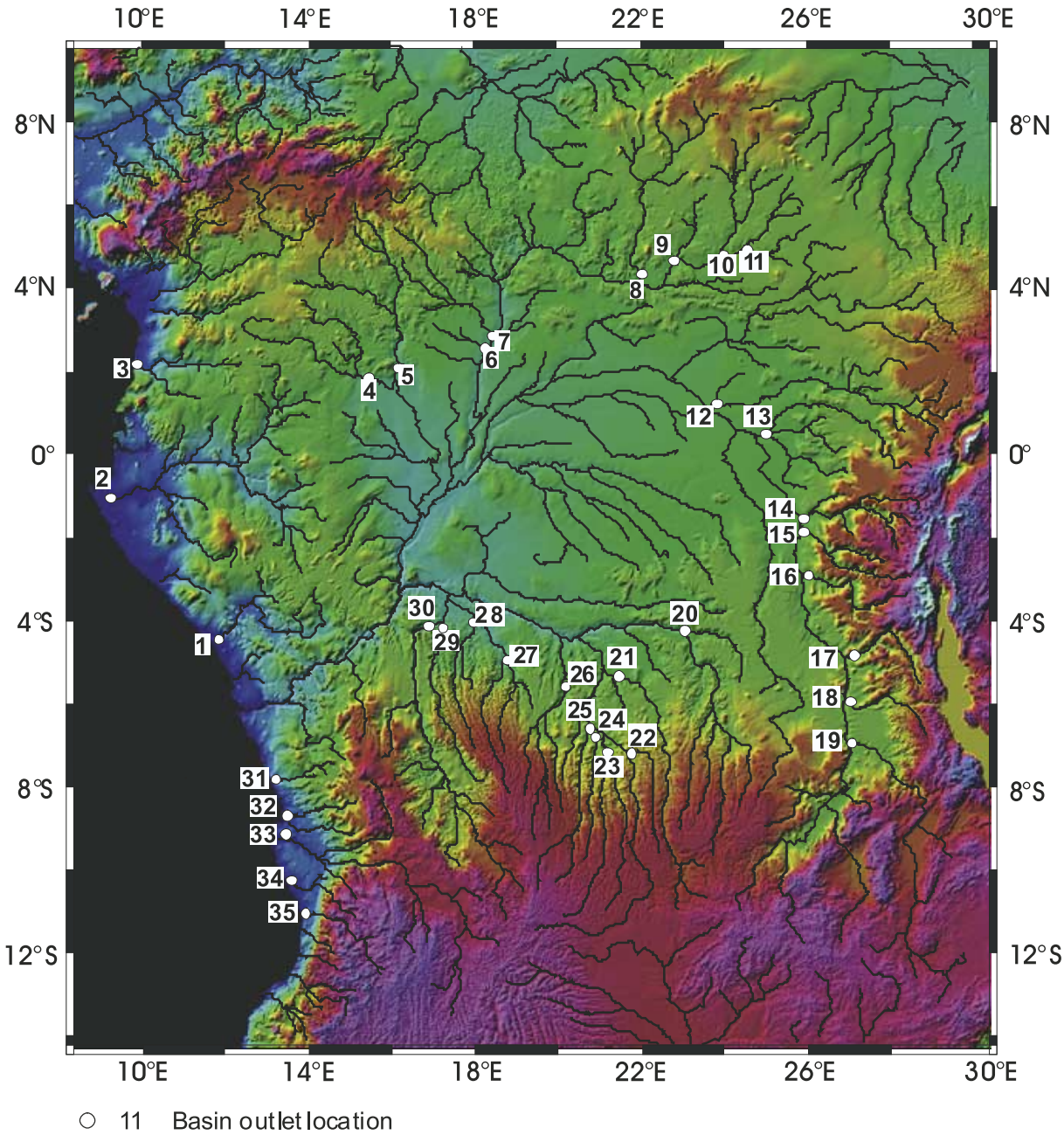

Figure 7. Location of studied drainage basin outlets in hypsometric and relief length scale analysis. Numbers refer to Table 1.

chronology of denudation. We examine here if some morphologic features can provide such information.

5.1. Characteristics of Drainage Basins

[18] We used the GTOPO30 database [*USGS-EDC*, 1996] at the resolution of 30 arc sec. Several morphologic analyses have used large-scale databases to characterize morphologic properties of topography [*Weissel et al.*, 1994; *van der Beek and Braun*, 1998; *Lucazeau and Hurtrez*, 1997; *Vörösmarty et al.*, 2001]. We have selected 35 drainage basins related to the Gulf of Guinea (Figure 7 and Table 1), including 27 tributaries of the Congo River and 8 coastal rivers located between 3°N and 12°S. The 27 tributaries have been taken in the upstream parts of the Congo River and their outlets chosen in similar conditions of channel slope; their cumulated drainage area represents 60% of the Congo drainage basin while the 40% remaining corresponds mostly to the inner part where sediment storage occurs. Drainage basins areas range from 12,000 km^2 to 220,000 km^2. The morphometric analysis may be influenced by the differences of upstream drainage areas [*Ohmori*, 1993; *Lifton and Chase*, 1992; *Hurtrez et al.*, 1999b], but the choice of outlets in comparable positions with respect to the Congo sedimentary basin seems to have minimized this effect; elevation of the outlets ranges from 515 m for the easternmost drainage basins and 265 m for the westernmost drainage basins.

[19] Channel networks and drainage basins have been extracted with MAD software [*Moussa*, 1991; *Moussa et*

Table 1. Morphometric Properties of the 35 Drainage Basins of the Studied Area

No.[a]	River	Drainage Area, km^2	Hypsometric Integral	Hurst Exponent
1	Kouilou	62,500	0.49	0.65
2	Ogooe	139,400	0.43	0.67
3	NTem	39,900	0.54	0.68
4	Sangha Dja	70,100	0.26	0.55
5	Sangha Kadei	83,500	0.39	0.59
6	Ibenga	30,200	0.45	0.58
7	Lobaye	25,200	0.33	1.08
8	Kotto	46,600	0.42	0.5
9	M'Bari	79,200	0.54	0.49
10	Chinko	24,800	0.38	0.6
11	Ouara	53,300	0.64	0.34
12	Aruwimi	111,900	0.27	0.67
13	Lindi	88,200	0.14	0.73
14	Lowa	52,250	0.22	0.62
15	Ulindi	28,900	0.21	0.71
16	Elila	27,000	0.23	0.61
17	Luama	25,000	0.21	0.59
18	Lukuga	21,400	0.28	0.38
19	Luvua	38,900	0.27	0.45
20	Sankuru	116,200	0.51	0.37
21	Lulua	70,300	0.52	0.23
22	Kasaï	60,000	0.51	0.40
23	Luembe	41,900	0.50	0.20
24	Luachimo	19,700	0.54	0.27
25	Chicapa	21,000	0.45	0.30
26	Lowange	53,700	0.47	0.40
27	Kwenge	20,600	0.47	0.31
28	Inzia	22,200	0.39	0.20
29	Wamba	33,600	0.39	0.29
30	Kwango	139,000	0.44	0.40
31	M'Bridge	77,300	0.48	0.61
32	Dange	26,800	0.57	0.68
33	Kwanza	220,750	0.46	0.47
34	Longa	19,500	0.40	not available
35	Queve	21,400	0.47	0.39

[a]Numbers refer to Figure 7.

al., 1999], based on the standard methods described by *Band* [1986]. It determines the downward steepest slope for each cell to attribute them a flowing direction, and then fills hollows to assure the continuity of drainage. The drainage basin is defined as the set of cells flowing toward a given outlet.

5.2. Morphometric Parameters

[20] We retained three morphometric parameters: (1) river longitudinal profile, (2) hypsometry, and (3) relief.

5.2.1. Longitudinal Profile

[21] Defined as the longest channel for a given drainage basin, a selection of them is represented in Figure 8. River profile in declining relief has a characteristic concave shape (e.g., Figure 8c). Abrupt local change can be attributed to a tributary junction [*Sklar and Dietrich*, 1998], a lithologic change or a local tectonic displacement. Rivers are generally very sensitive to vertical tectonic displacements, and they adjust surface warping by deflection, avulsion, erosion and aggradation along the profile or changes in channel pattern [*Goodrich*, 1898; *Howard*, 1967; *Ouchi*, 1985; *Merrits et al.*, 1994; *Holbrook and Schumm*, 1999]. However, the time response to change in river slope remains difficult to estimate as it depends on rock strength, stream power and magnitude of tectonic movements [*Whipple and Tucker*, 1999]. Regional studies can provide information on the time response of rivers to tectonic uplift [*Hurtrez et al.*, 1999a], but those results can not be extrapolated to other contexts.

[22] Some characteristic features are observed in the Congo River drainage basin in connection with the local geologic context, whatever the lithology or drainage area considered. Along the East African Rift flank (Figures 8c and 8d), rivers show a typical equilibrium profile in the upstream part, and river slope changes are weak and can be related easily to river junctions or lithologic properties. In the northeastern part of the Congo River drainage basin, rivers show variable patterns: some of them have a typical equilibrium profile (Figure 8e) while others have a flat upstream shape as the Ouara river related to a 610 m plateau previously described (Figure 8f). In the southern (Figures 8a and 8b) and northwestern (Figure 8g) parts of the Congo River drainage basin, rivers have generally convex profiles with low gradients upstream, typical of retrogressive erosion; in the north, all rivers crossing the coastal bulge are concerned; south of latitude 4°S, 73% of coastal rivers and all tributaries of Congo River flowing from the Kalahari plateau show this convex profile.

5.2.2. Hypsometry

[23] It represents the proportion of basin area below a given elevation [*Strahler*, 1952]. Hypsometric curve (Figure 9) represents therefore the complete statistics of hypsometry from the divide to the outlet and can be associated with a hypsometric integral value HI. Maturity of drainage basins can be related to shape of hypsometric curves or value of HI; immaturity is characterized by convex curves and high HI value ($\geq$0.65) whereas maturity is characterized by S-shaped or concave curves and low HI values ($\leq$0.35). Recent studies have pointed out several factors influencing hypsometry: *Ohmori* [1993] and *Masek et al.* [1994] proposed that hypsometry is mainly representative of erosional processes; *Lifton and Chase* [1992] found an influence of tectonics on hypsometric integrals for drainage basins larger than 1000 km^2 and a lithologic control on smaller basin hypsometry; *Hurtrez and Lucazeau* [1999] found similar conclusions.

[24] In the Congo River drainage basin (Figure 9), mature basins are located mostly along the East African Rift flank while immature basins correspond to drainage basins located to the south (Kasaï river, southern coastal rivers) and some basins in the north related to the 610 m plateau. However, sigmoid to linear curves with various HI (0.26–0.64) are observed in northern drainage basins.

5.2.3. Relief

[25] Relief is basically defined as the elevation difference for a given length scale [*Anhert*, 1970] and has been determined in this study at all scale domains by the technique of structure functions [*Weissel et al.*, 1994; *Lucazeau and Hurtrez*, 1997]: $R(l) = \langle |h(x + l) - h(x)| \rangle$, where h is the elevation, x the horizontal position, l the window length scale and angle brackets refer to the average of all elevation differences in the length scale window l. A power law relationship $R(l) = R_0 l^H$ can describe how relief R(l) increases with length scale l. R_0 is relief at a reference scale (l = 10 km for instance) and H is the Hurst exponent related to the fractal dimension of topography; Because R(l) is an average value of all couples in the length scale range l,

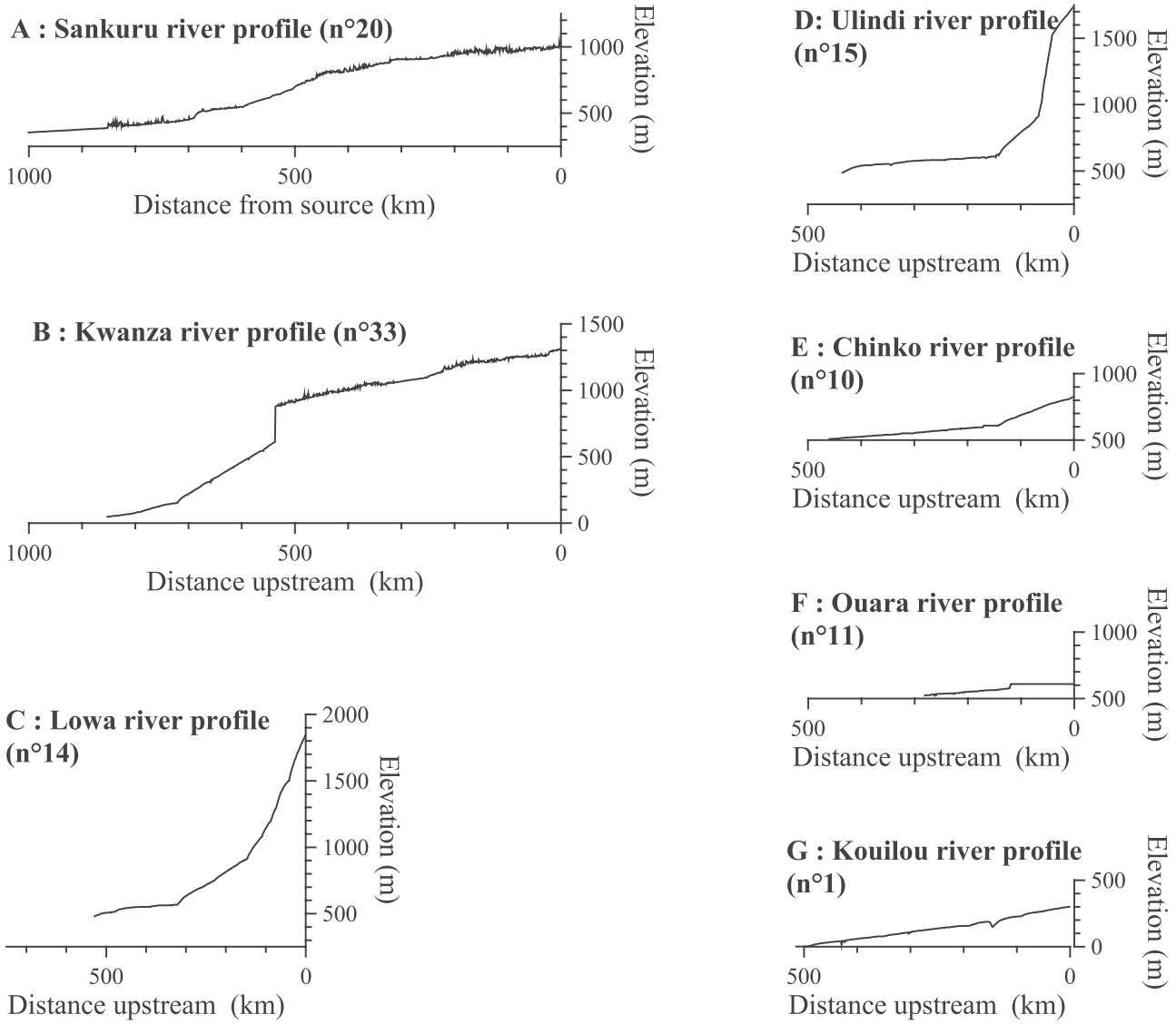

Figure 8. Characteristic river profiles in the studied area. (a and b) Rivers across Kalahari plateau have convex profiles typical of retrogressive erosion. (c and d) River profiles of the Western flank of the East African Rift and (e) of the northern part of the Congo drainage basin have typical equilibrium profiles. (f) Ouara River profile to the north shows an anomalous flat segment upstream linked to a preserved surface (610 m) in central Congo basin. (g) Rivers crossing coastal bulge have convex profiles.

H tends to 1 for a smooth topography and H tends to 0 for a rough topography. Several studies [*Weissel et al.*, 1994; *Lucazeau and Hurtrez*, 1997; *van der Beek and Braun*, 1998], proposed that several domains of scales may be identified according to the processes that create topography: diffusive hillslope processes at small scale, river incision at mesoscale and tectonics or geodynamics at large scale. Resolution of GTOPO30 is not good enough to access the small-scale processes and the smooth trend observed at the lower scales in this study (Figure 10) is mostly caused by the interpolation of the DEM. We have considered therefore the mesoscale domain only, as it corresponds to the domain where the amplitude and scaling exponent can provide information on the tectonic and erosion interactions [*Lifton and Chase*, 1992; *Weissel et al.*, 1995; *Hurtrez et al.*, 1999a].

[26] High Hurst exponents are found in East African Rift (0.38–0.71) and the northern part (0.5–1.0) with the exception of Ouara basin (0.34). On the other hand, low Hurst exponents are found in the Kasaï (0.39–0.47) and the southern coastal (0.23–0.40) domains. Relief at the scale of 10 km is generally more important for the East African rift (R_0 = 100–120 m) than for the Kasai and coastal bulge (R_0 = 70–90 m), or the northern part of the Congo drainage basin (R_0 = 50–60 m).

5.2.4. Summary

[27] The three retained morphometric parameters allow identification of four regional trends in the Congo River drainage basins: (1) mature drainage basins in the Eastern part (concave longitudinal profiles, concave hypsometric curves, and smooth relief); (2) poorly mature basins in the northwestern part (convex longitudinal profiles, convex

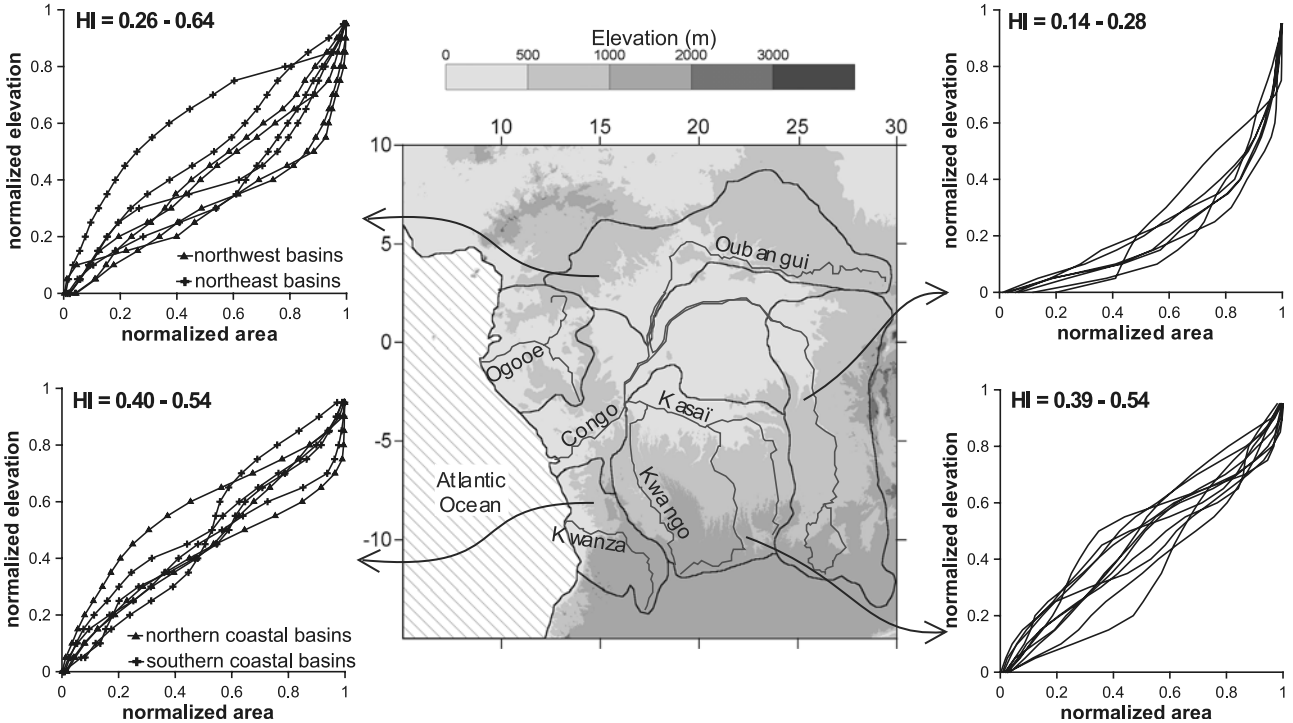

Figure 9. Hypsometric analysis of selected subbasins (hypsometric curves and hypsometric integrals HI). Hypsometric parameters show a regional distribution with both mature drainage basins (low HI and concave curves) along the East African Rift flank and immature drainage basins (high HI and convex curves) to the south. To the north, hypsometric parameters also show both immature drainage basins (linked with the presence of a 610 m plateau located in the central part of the Congo basin) and mature drainage basins.

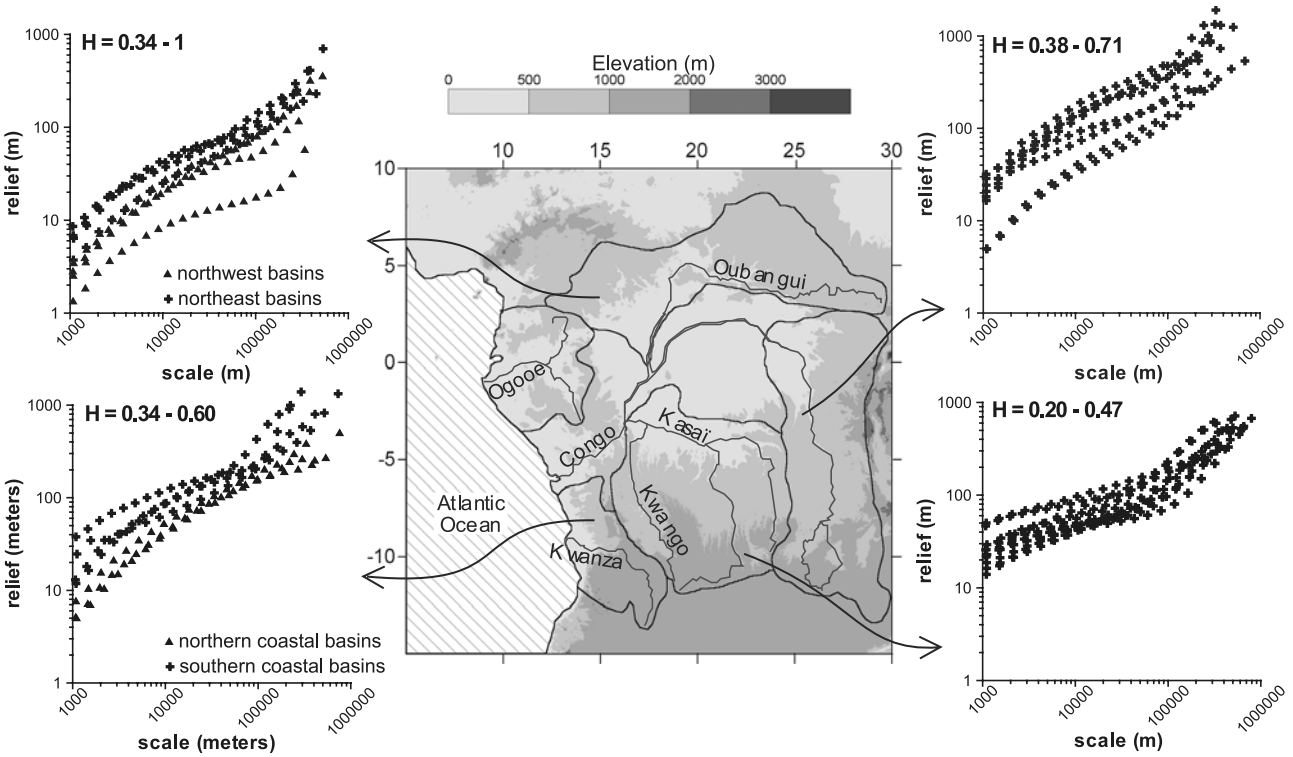

Figure 10. Length scale analysis of relief properties of selected subbasins (H, Hurst exponent). Relief properties show a similar regional trend as hypsometric parameters. Low Hurst exponents are found to the south (Kasaï area and southern coastal domain), and high Hurst exponents are found in the north and along the East African Rift flank.

hypsometric curves); (3) highly immature drainage basins in the Southern part and along the coastal bulge (S shape longitudinal profiles, convex hypsometric curves and rough relief); and (4) immature basins (sigmoid hypsometric curves, variable Hurst exponents) related to the presence of the 610 m high plateau. A large domain of the Congo basin is therefore immature, showing that uplift has been recent or erosion weak.

6. Discussion

[28] The present-day sediment discharge of the Congo River is consistent with our total denudation estimate of 725,000 to 1×10^6 km^3: extrapolation from Oligocene (35 Ma) of the *Gaillardet et al.* [1995] results (6 m/Myr or 2.1×10^4 km^3/Myr) leads to an average denudation of 210 m and a total volume of 735,000 km^3. In addition, both methods attribute to the East African Rift and the Kasaï domains the most important role for the Congo River solid load.

[29] The total denudation may have been underestimated by some changes of the drainage basin limits or significant erosion of the divides in domains where no remnant surface exists. It is unlikely that more denudation came from the Kasai domain, because of the highly immature character of basins. This excludes the possibility that a spreader drainage has ever extended to the south (Namibia) where *Gallagher and Brown* [1999] have noticed local Tertiary denudation. In the East, evolution of the African rift in two branches may have decreased the drainage area during Tertiary: *Zeyen et al.* [1997] proposed a model of the East African Rift in which the Tanzanian Craton is tilted to the west by a rising plume in the Early Oligocene. A consequence of this model is that the Congo drainage area increases by 1×10^6 km^2 (area between the two rift branches) until the development of the western branch of the rift around 12 Ma. This scenario allows adding 230,000–300,000 km^3 to the total denudation within the present Congo River drainage basin, assuming the same average denudation as that of the western flank (230–310 m) and better explains the onset of high sedimentation rates during early Oligocene in the Gulf of Guinea. Contribution of coastal rivers may have been neglected as extrapolation of remnant surface is difficult and that Oligocene and Miocene erosion stages are identified on proximal margin: thermochronological data on the Angola platform suggest denudation thickness as high as 2 km [*Walgenwitz et al.*, 1990].

[30] The volume of sediment deposited in the Gulf of Guinea on the other hand is 1.2 to 1.5×10^6 km^3. This is the order of magnitude of the erosion in the Congo River drainage basin with the addition of coastal rivers' contribution. A progressive increase of sediment flux is however observed in the Congo fan showing an acceleration of denudation with time.

[31] During late Cretaceous and Paleocene, the location of depot centers is different and corresponds essentially to the Ogooe and Kwanza fans. Another million cubic kilometers has been eroded at that time, but it is unlikely that an important proportion comes from the present Congo drainage basin because of the presence of remnant surfaces. However, the more likely place for Cretaceous denudation may be the Central African Rift System (CARS), in the northern part of the Congo River drainage basin. *Genik* [1992] and *Guiraud and Bosworth* [1997] have shown that the northern border of the Congo drainage basin was inverted during late Santonian. Remnant surfaces are not present in this region, showing that former fold and thrust belt topography has possibly been eroded. An older connection between Oubangui River and Ogooe River may have existed providing the necessary material to feed the upper Cretaceous fan in Gabon margin. A similar source of sediment is necessary for the Kwanza fan, and one should assume that the paleo-Kwanza basin was more developed with possible connections with Zambeze or Okavongo drainage.

[32] Morphometric analysis of the large-scale topography in the Congo River drainage basin can provide a relative timescale of erosion processes. The Western branch of the East African Rift that starts around 12–13 Ma [*Ebinger*, 1989] has the highest elevation but the smoothest relief and the more mature hypsometry. The northern part of the Kalahari plateau, probably related to an African superswell supported dynamically [*Nyblade and Robinson*, 1994; *Lithgow-Bertelloni and Silver*, 1998], has been eroded by a system of very immature drainage basins (Kasaï tributaries). Assuming that all other factors do not affect the erosion pattern all around the Congo River drainage basin, the comparison with the maturity of the East African Rift basins suggest that uplift of the Kalahari plateau is not older than 10 Ma. A similar argument can be used for the development of the 610 m plateau all around the Congo basin. Basins that develop on this plateau are very immature, mostly on the Eastern part. A relationship with a necessary uplift of 500 m on the proximal margin of the Gulf of Guinea [*Lavier et al.*, 2001] is likely [*Lucazeau et al.*, 2003].

[33] On the basis of sediment rates calculated along two profiles across the Congo fan, *Lavier et al.* [2001] proposed that the change in sediment supply correlates with a global cooling of climatic conditions in the southern hemisphere characterized by ice accumulation in Antarctica [*Barron et al.*, 1991; *Wise et al.*, 1992] and increase in continent/ocean temperature contrasts [*Séranne*, 1999]. Therefore they suggest that the onset of high sedimentation rates on the margin is linked with this climatic event. On the other hand, on the southwestern margin of Africa (i.e., south of the Walvis Ridge), *Rust and Summerfield* [1990] found that sediment accumulation decreases by half at the transition Eocene/Oligocene. Similarly, Ogooe and Kwanza sedimentation decreases at the same time. The Mozambique margin evolves the same way [*Davies et al.*, 1995; *Salman and Abdula*, 1995]. Our interpretation is that sediment discharge following the Atlantic breakup has been more controlled by the reorganization of drainage in connection with the different vertical movements rather than global climatic changes. The youth of morphology and the increase of sediment flux in the Congo fan suggest a recent development of surrection.

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F. Brigaud, FinnestadVeien 44, Dusavik, P.O. Box 168, N-4001 Stavanger, Norway. (frederic.brigaud@ep.total.no)

P. Leturmy, Département des Sciences de la Terre, Univ. é de Cergy-Pontoise, F-95031 Cergy-Pontoise Cedex, France. (Pascale.Leturmy@geol.u-cergy.fr)

F. Lucazeau, Laboratoire Géosciences Marines, Institut de Physique du Globe, 4, place Jussieu, F-75252 Paris cedex 05, France. (lucazeau@ipgp.jussieu.fr)