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Cenozoic sediment budget of West Africa and the Niger delta

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ABSTRACT

Long-term ($10^{6–7}$ yr) clastic sedimentary fluxes to the ocean provide first-order constraints on the response of continental surfaces to both tectonic and climatic forcing as well as the supply that builds the stratigraphic record. Here, we use the dated and regionally correlated relict lateritic landforms preserved over Sub-Saharan West Africa to map and quantify regional denudation as well as the export of main catchments for three time intervals (45–24, 24–11 and 11–0 Ma). At the scale of West Africa, denudation rates are low (*ca.* 7 m Myr^{-1}) and total clastic export rate represents 18.5×10^3 km^3 Myr^{-1}. Export rate variations among the different drainage groups depend on the drainage area and, more importantly, rock uplift. Denuded volumes and offshore accumulations are of the same magnitude, with a noticeably balanced budget between the Niger River delta and its catchment. This supports the establishment of the modern Niger catchment before 29 Ma, which then provided sufficient clastic material to the Niger delta by mainly collecting the erosion products of the Hoggar hotspot swell. Accumulations on the remaining Equatorial Atlantic margin of Africa suggest an apparent export deficit but the sediment budget is complicated by the low resolution of the offshore data and potential lateral sediment supply from the Niger delta. Further distortion of the depositional record by intracontinental transient storage and lateral input or destabilization of sediments along the margin may be identified in several locations, prompting caution when deducing continental denudation rates from accumulation only.

INTRODUCTION

Clastic sediments fluxes represent the bulk terrigenous supply to oceanic basins derived from the dissection and erosion of continental surfaces (Fig. 1). They build the sedimentary record along continental margins over geological timescale ($10^{5–7}$ yr) and, together with chemical fluxes, contribute to the global biogeochemical cycles. The stratigraphic record may allow retrieving paleoenvironmental information such as the climatic variations, landform evolution and vertical movements on the adjacent continental domains (Burbank, 1992; Molnar, 2004; Clift, 2010), documenting the long-term response of landscapes to external forcing. Comprehensible clastic fluxes are therefore first-order data to geomorphologists, sedimentologists and geodynamicists to decipher sediment production, transfer and deposition in its ultimate basin sinks (Allen, 2008; Fig. 1).

Clastic fluxes are usually obtained from sedimentary basin accumulations (e.g. Rust & Summerfield, 1990; Métivier *et al.*, 1999; Guillocheau *et al.*, 2012). Stratigraphy alone, however, lacks information about catchment evolution (Bishop, 1995) and distribution of erosion within the source region. Furthermore, temporary storage and later erosion of sediments may delay or erase stratigraphic information (Sadler, 1981; Métivier & Gaudemer, 1999; Jerolmack & Paola, 2010). Sediment fluxes predicted from landscape evolution models are calibrated at macro- to mesoscale (m^2 to km^2) and short term ($10^{1–4}$ yr), and may not be representative of large continental surfaces (>10^4 km^2) evolving at geological timescale (Simoes *et al.*, 2010). Sediment budgets comparing source and sink are therefore the most meaningful to

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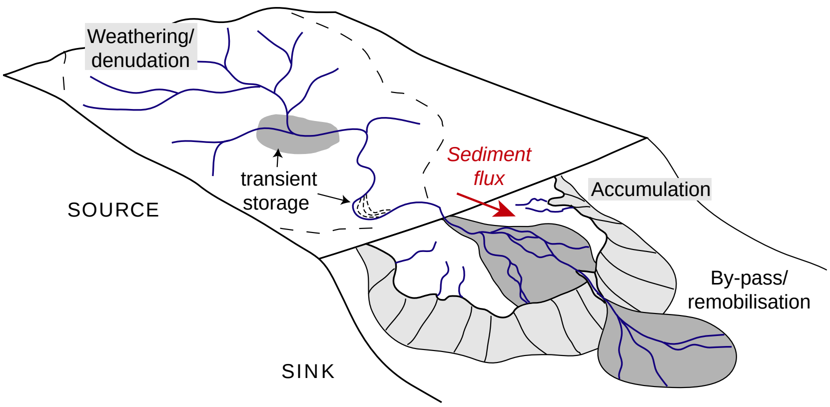

Fig. 1. Schematic representation of a source-to-sink system with the riverine transport of sediment from the continent to the ocean. The figure focuses on the clastic flux and does not represent the solute load.

understand relief dynamics at geological timescales but are limited by the lack of constraints on the source catchments and require making assumptions on their topographic and drainage evolution (e.g. Leturmy *et al.*, 2003; Campanile *et al.*, 2008; Rouby *et al.*, 2009; Macgregor, 2013). Better constraints on continent-scale surface evolution are required to calibrate long-term clastic fluxes and the associated sedimentary basin evolution.

Cratons represent low-lying, slowly eroding domains (Bishop, 2007; Beauvais & Chardon, 2013) but integrate large continental catchments (i.e. 10^6 km^2; Fig. 2). Cratons are the source of major clastic accumulations over long-lasting segments of passive margins in Africa and worldwide, hosting extensive sediment archives as well as hydrocarbon resources (Bradley, 2008). The slow erosion rates of cratons result in the preservation of geomorphic markers as illustrated by the relicts of lateritic landscapes of tropical shields derived from Meso-Cenozoic intense weathering periods associated with warm climate (Tardy & Roquin, 1998; Zachos *et al.*, 2001; Beauvais & Chardon, 2013; Fig. 3). Quantifying erosion using these relict landforms has proven useful to apprehend the denudation rates and landform evolution of cratonic sediment routing systems (Beauvais & Chardon, 2013; Grimaud *et al.*, 2015).

This study presents a comparison between the volumes eroded and exported from the main catchments of Sub-Saharan West Africa and the sediments preserved in the adjoining continental margin basins of the Equatorial Atlantic Ocean during the Cenozoic. We use relict lateritic landforms and recently published paleodrainage maps (Chardon *et al.*, 2016) to constrain continental clastic exports, and a measure of offshore accumulations. We compare accumulation with erosion between the Niger delta and its catchment and between the remaining portion of the Equatorial Atlantic margin of Africa (i.e. without the Niger delta) and its sources. Accumulated and eroded volumes fall within the same range allowing discussion of the influence of rock uplift, catchment evolution and sediment transfers on sediment budgets.

GEOLOGICAL SETTING AND EARLIER WORK

The studied area comprises a 4×10^6 km^2 cratonic surface extending from the Senegal-Mauritania basin to the west and to the Hoggar and Adamaoua massifs to the northeast and southeast respectively (Fig. 2). Major river systems (the Niger, Senegal and Volta rivers) currently collect sediment supplied to the continental margin basins of this domain. The Niger catchment (2.3×10^6 km^2) drains the main topographic massifs: the Guinean rise, the southern Hoggar massif and the Jos plateau and the Adamaoua massif bounding the Benue trough (Fig. 2). At the outlet, the Niger delta surface is 26×10^3 km^2 and its Cenozoic sediment thickness exceeds 9 km (Fig. 2). In contrast, the remaining portion of the Equatorial Atlantic of Africa (i.e. excluding the Niger delta; Fig. 2), fed by rivers such as the Volta, has a larger basin surface (750×10^3 km^2) and a thinner Cenozoic sediment cover (<3 km; Helm, 2009).

The West African bedrock is composed of Archean and Paleoproterozoic basement bounded by mobile belts of Panafrican (*ca.* 800–450 Ma) and Variscan (*ca.* 360–250 Ma) ages (Villeneuve, 2005; Feybesse *et al.*, 2006). It is overlain by Neoproterozoic to Phanerozoic sedimentary series, the main depocenter of which is located in the Taoudeni basin (Villeneuve, 2005; Fig. 2). Cenozoic sedimentary series preserved onshore include Eocene carbonates found in the Senegal-Mauritania, Iullemmeden and Togo-Benin basins overlain by Lutetian to Rupelian (49–29 Ma) continental deposits known as the Continental Terminal (Chardon *et al.*, 2016). Sub-Saharan West Africa is considered as tectonically stable since Late Cretaceous rifting in the Iullemmeden, Chad and Benue basins, and has mostly undergone long-wavelength lithospheric deformation since (Ye *et al.*, 2017 and references therein). The Central Atlantic Ocean opened since the Late Triassic and the Equatorial Atlantic during the Late Early Cretaceous (Brownfield & Charpentier, 2006; Moulin *et al.*, 2010; Labails *et al.*, 2010; Ye *et al.*, 2017; Fig. 2). The offshore Cenozoic stratigraphic record in

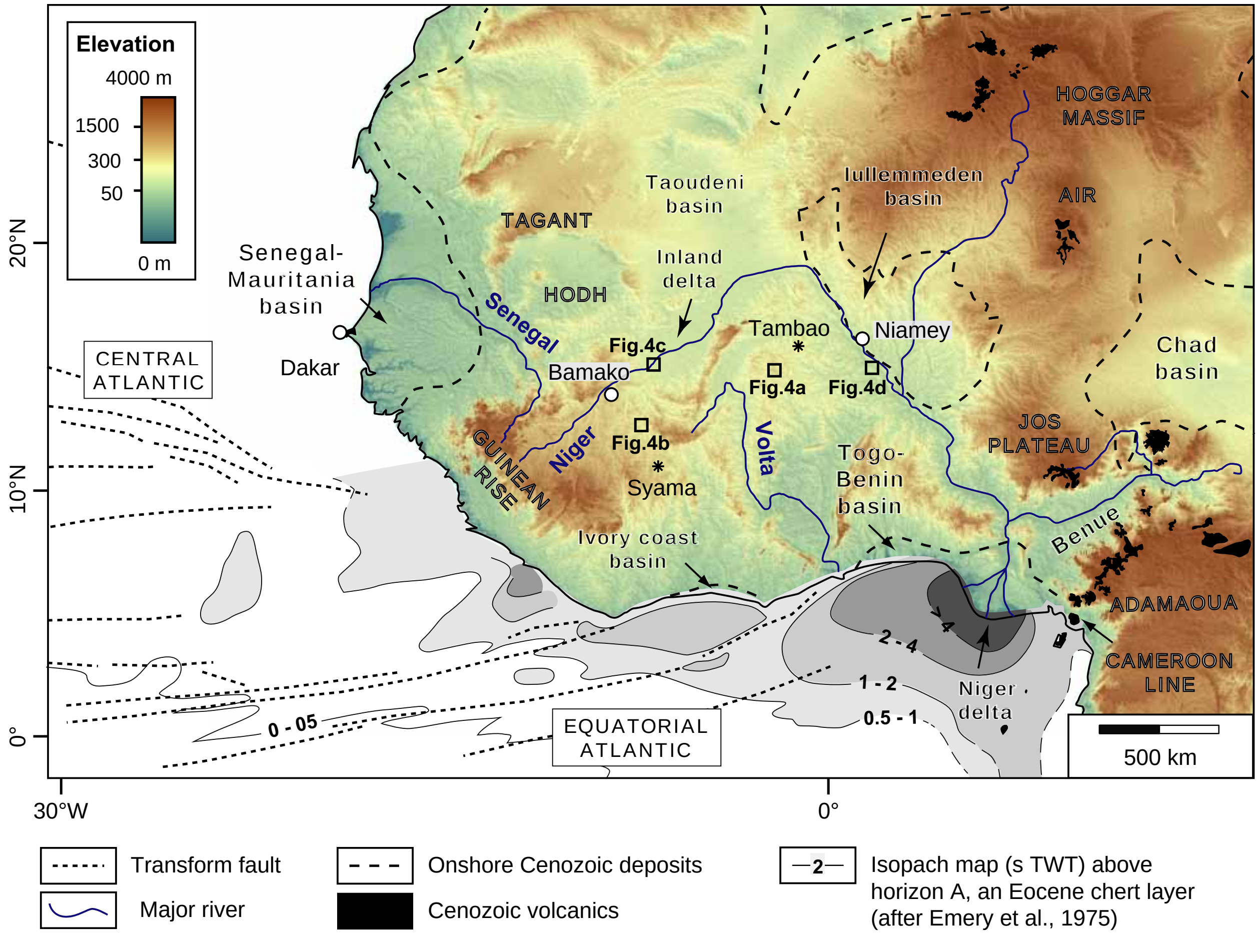

Fig. 2. Map showing the main geologic and morphologic features of Sub-Saharan West Africa modified after Grimaud *et al.* (2014). The offshore accumulation map of Emery *et al.* (1975) does not cover the Central Atlantic margin of Africa (i.e. offshore Senegal-Mauritania basin).

West Africa is characterized by a shift in sedimentation during the Oligocene. The Paleocene-Eocene was a period of relatively high sea level, intense inland weathering and preferential deposition of chemical sediments (i.e. carbonates and phosphates) in the intracratonic and marginal basins (Fig. 3) (Millot, 1970; Valeton, 1991). The Oligo-Miocene period marked the increase in clastic sedimentation in continental basins and adjacent passive margins (Séranne, 1999; Burke *et al.*, 2003). A paleo-Niger delta was likely established in the Benue during the Paleocene (Reijers, 2011), but the main delta progradation started at 34 Ma (Doust & Omatsola, 1990). In the literature, the Oligocene shift in sedimentation has been interpreted as resulting from either the effect of greenhouse to icehouse climatic transition (Séranne, 1999) or to the continental uplift of Africa contemporaneous with the development of its "basin-and-swell" topography driven by the growth of several hotspot swells such as the Hoggar, the Adamaoua or the Jos Plateau (Burke, 1976, 1996; Burke *et al.*, 2003; Fig. 2). Using the reconstructed geometries of dated paleolandscapes, Chardon *et al.* (2016) suggested the establishment of the modern Niger River watershed in, at least, the Late Oligocene (29 Ma) and possibly the Eocene-Oligocene boundary (34 Ma), that is, at the acceleration of the progradation of the Niger delta. The major drainage reorganization and the growth of the Hoggar hot spot swell would explain the increase in clastic fluxes towards the Niger delta (Chardon *et al.*, 2016). Post-Eocene clastic fluxes would also have been increased by uplift-related erosion along a marginal upwarp inherited from Mesozoic rifting that extended from the Jos Plateau to the Guinean rise (Beauvais & Chardon, 2013). The marginal upwarp is a 300–800 km wide strip of relief, running parallel to the coast. It is interpreted as initiating during the rifting and maintained by lithosphere flexure, erosional unloading and associated sediment loading on the adjoining margin (Gilschrist & Summerfield, 1990; Beaumont *et al.*, 2000).

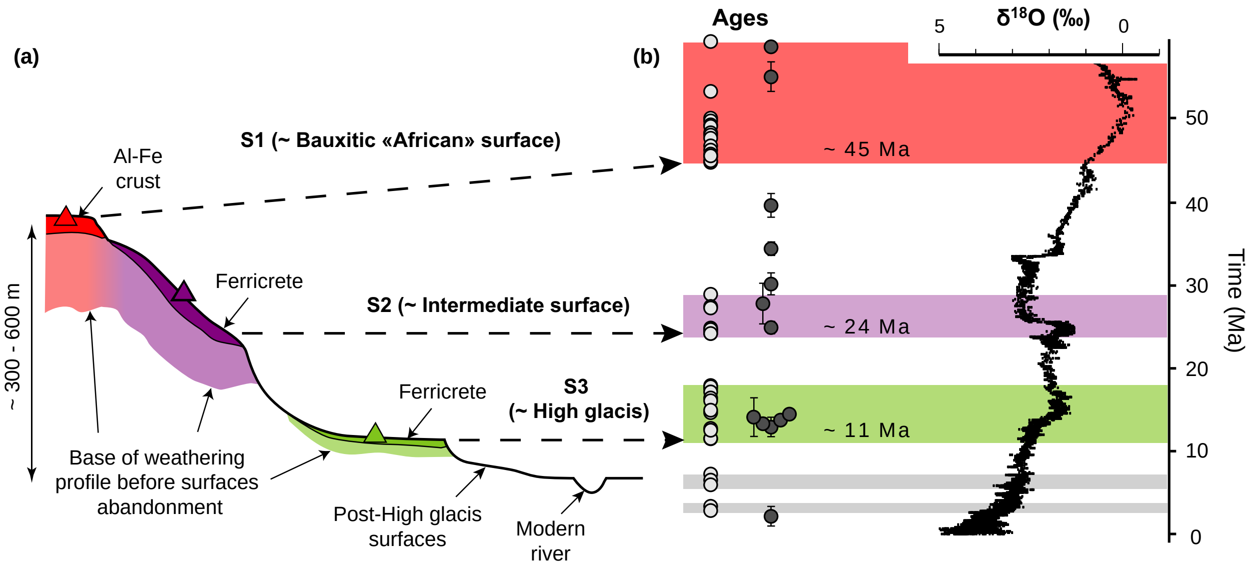

Fig. 3. Denudation chronology of Sub-Saharan West Africa during the Cenozoic. [a] Distribution of lateritic paleolandsurfaces and associated regoliths (weathering mantles and associated duricrusts) in the landscape. [b] Comparison of the ages acquired in the lateritic mantles of Tambao and Syama, (Fig. 2) [after Beauvais *et al.* (2008) (light grey dots) and Vasconcelos *et al.* (1994a) (dark grey dots) respectively] to the oceanic $\delta^{18}O$ variation (‰) on benthic foraminifera tests recording global temperature variations (Zachos *et al.*, 2001). Only the ages with an uncertainty lower than 5 Myr have been reported in Syama (dark grey dots).

DENUDATION CHRONOLOGY

Sub-Saharan West Africa was located within the tropical belt throughout the Cenozoic, allowing several generations of lateritic regoliths to be produced regionally. Rivers removed parts of these regoliths to form a unique geomorphic sequence of stepped paleolandscapes capped by duricrusts (Michel, 1973; Fig. 3a). These landscapes were not subcontinental flat planation surfaces as advocated by King (1962) but composite landscapes, the relief of which increased throughout the Cenozoic (Figs 4 and 5; Beauvais & Chardon, 2013; Grimaud, 2014; Grimaud *et al.*, 2015). Each member of the sequence has a specific morphology and type-regolith that reflect variation in weathering intensity and slope erosion processes (Boulangé *et al.*, 1973; Grandin, 1976; Tardy & Roquin, 1998). This allows for correlations of each type of paleolandscape remnant on a regional scale (e.g. Fig. 4; Beauvais & Chardon, 2013; Grimaud *et al.*, 2014). The regolith formed by lateritic weathering of the bedrock during long (>10^6 yr), warm and humid climatic periods (Fig. 3b). Weathering resulted in leaching of mobile elements and the accumulation of less mobile iron and/or aluminium in the shallow depths of the regolith profiles. Ultimately, the duricrusting of the upper horizons occurred when the weathering profiles became disconnected from the local base levels (i.e. following river incision and/or the return to drier climatic conditions). Hence, the terminal weathering age of a regolith profile capped by a duricrust is considered as marking the abandonment of the associated paleosurface (i.e. Fig. 3).

The first member of the West Africa geomorphic sequence (S1; Fig. 3) is a surface of continental scale, known as the “African Surface”, formed under a humid equatorial climate from the Late Cretaceous to the Eocene (Beauvais & Chardon, 2013; Chardon *et al.*, 2006). Weathering shaped a low-relief landscape and formed bauxites (i.e. Al-Fe crust; Figs 3 and 4). The S1 bauxite was abandoned to form an incised landscape during the development of the next member of the sequence, the so-called “Intermediate” surface (S2; Fig. 3), ultimately capped by a ferricrete. The S2 surface was dissected and abandoned during the development of the S3 erosion surface (“High glacis” in the French literature). S3 is a pediment, that is, a gently sloping concave-upward surface, formed under semi-arid to arid climate during which stable base level and high seasonality favour surface sheetwash during the monsoon (Hadley, 1967; Grandin, 1976). Ferricretes capping S3 formed under more contrasted humid conditions (Fig. 3b). S3 ferricrete often cements a detrital layer that contains clasts of S1 and S2 crusts (Boulangé *et al.*, 1973; Grandin, 1976; Grimaud *et al.*, 2015). Hence, S1, S2 and S3 remnants have first order distinctive landform–regolith associations that allow for regional correlation (Beauvais & Chardon, 2013; Grimaud *et al.*, 2014).

Ages of laterite formation were bracketed by ^{40}Ar–^{39}Ar dating of supergene K-rich Mn oxides such as cryptomelane [K_x $(Mn^{3+})_x$ $(Mn^{4+})_{8-x}$ O_{16}] in Tambao, Burkina Faso (Beauvais *et al.*, 2008) and sulphates as alunite/jarosite in Syama, Mali (Vasconcelos *et al.*, 1994a; Fig. 3b). These minerals formed under weathering and oxidation

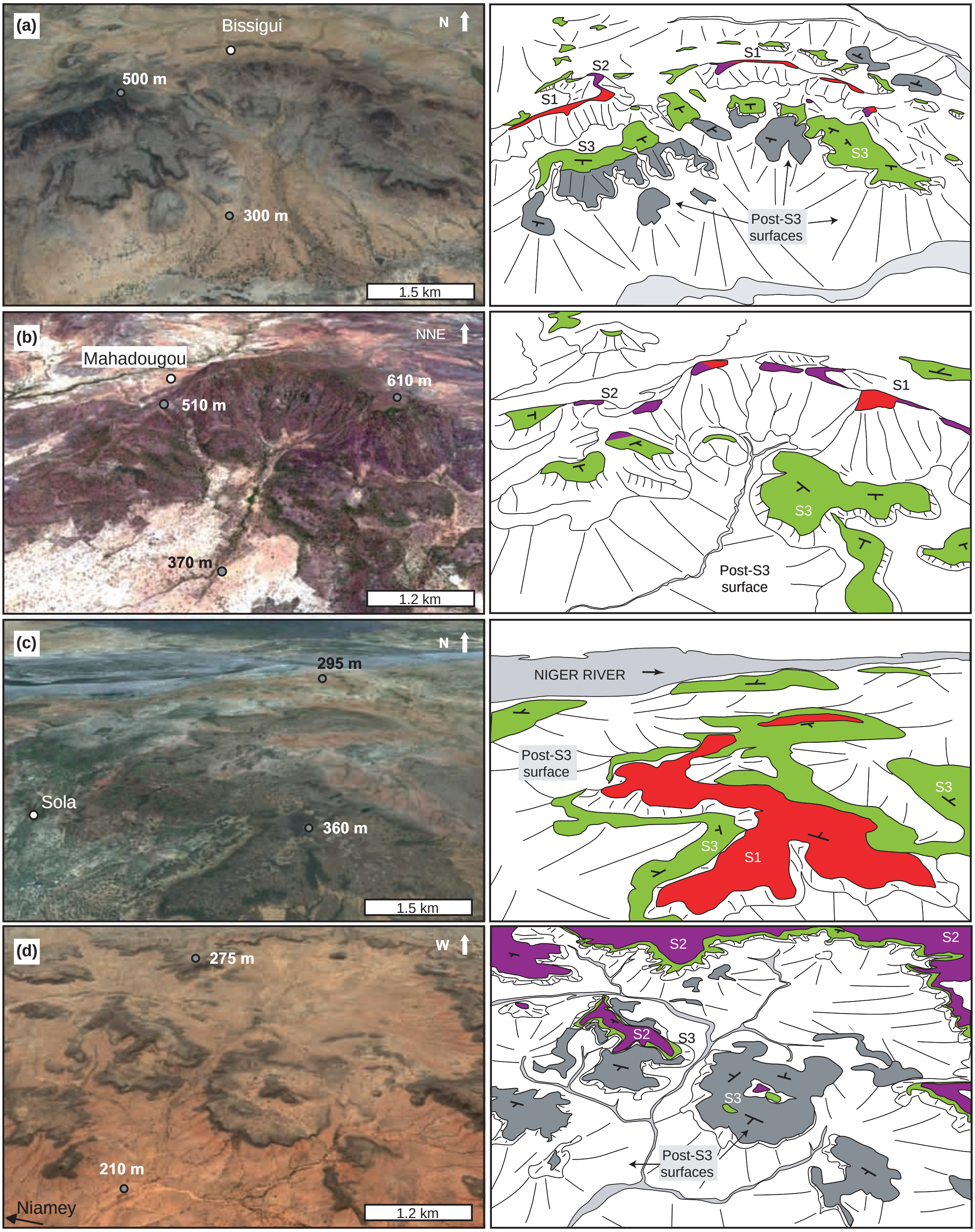

Fig. 4. Interpretation of paleolandsurface distribution after our field work in several type-locations in West Africa (see location on Fig. 2). Google-Earth view and interpretation of paleosurface distribution: [a] over the Precambrian basement, South of Tambao (Burkina Faso); [b] over the Precambrian basement near the Manding Mounts (Mahadougou, Mali); [c] in the Niger inland delta, North of Bamako (Ségou, Mali) where bauxitic remnants are found 60 m above the Niger River; [d] in the Iullemmeden basin (North of Niamey, Niger) where the deposits of the "Continental Terminal", capped with the Intermediate surface, have been incised by the Niger River system. The colour code of relict landforms interpretations is similar to Fig. 3.

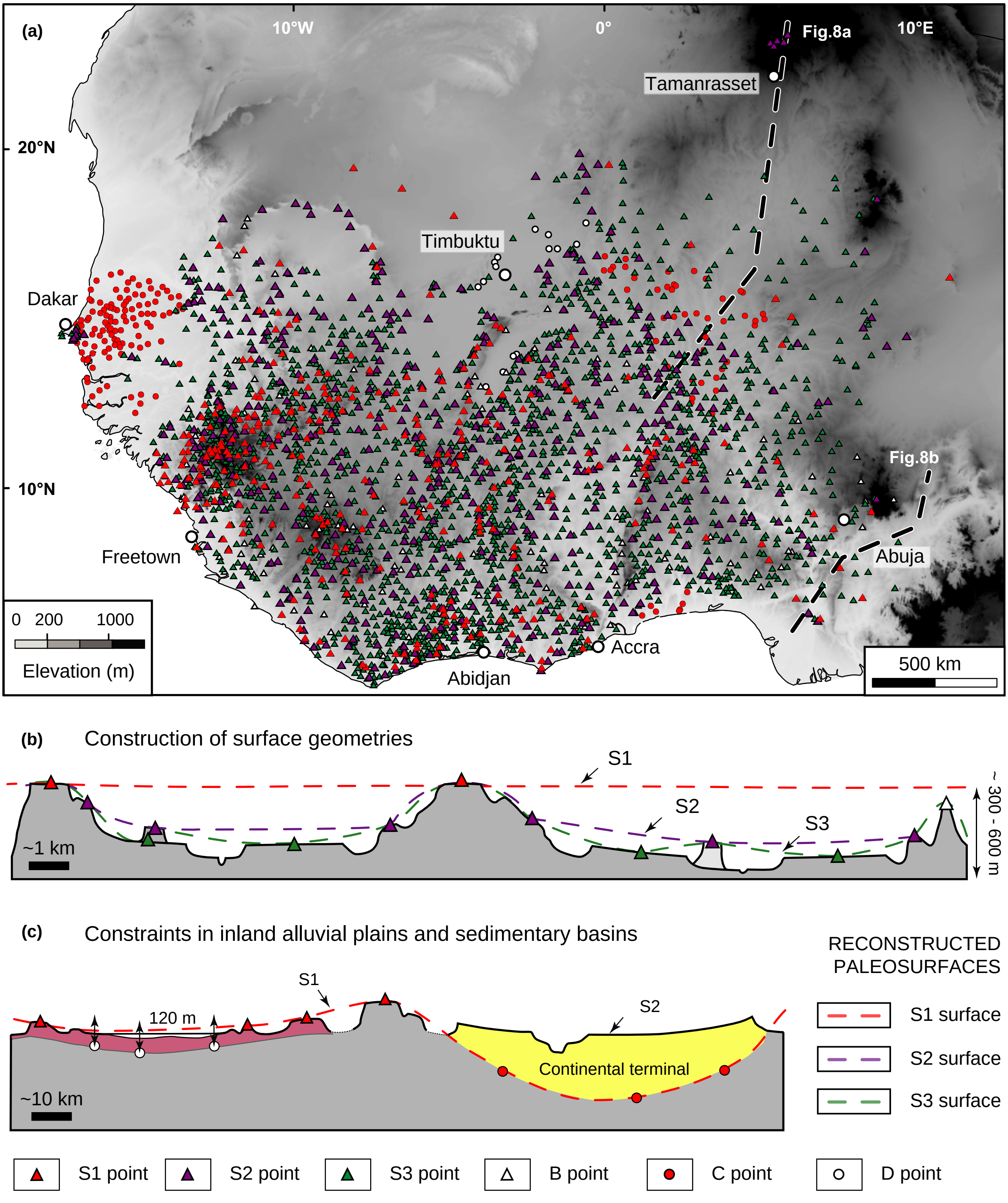

Fig. 5. [a] Map of the *ca.* 2900 data points used to build the 3D surfaces. [b] Schematic distribution of relict landforms and reconstructed surface geometries. [c] Schematic distribution of data points constraining the construction of surface geometries in alluvial plains and sedimentary basins. B points correspond to bedrock massifs summit (referred as "inselbergs"), C points to the top of Early-Mid Eocene carbonates and D points to S1 weathering profile remnants. B points inselbergs are often associated with eroded S1 weathering profiles. B points therefore constrain S1 minimum elevation. C points are time equivalents of S1 bauxite retrieved from well log in sedimentary basins. We used them as depth of S1 below the topography in these basins. D points constrain locally the elevation of S1 paleosurface, which have been eroded, on the basis that a bauxitic weathering profile cannot exceed the maximum depth of 120 m (Bardossy & Aleva, 1990).

conditions converting the bedrock into lateritic regolith and are therefore useful tracers of major weathering periods and associated formation of duricrusted surfaces. The S1 surface was abandoned after 45 Ma, S2 after 24 Ma and S3 after 11 Ma (Beauvais & Chardon, 2013; see also Grimaud *et al.*, 2015; Figs 3 and 4). The radiometric ages of the West African geomorphic sequence (Fig. 3b) are consistent with other time constraints. The weathering of the bauxitic paleolandsurface is correlated with chemical marine sedimentation in Sub-Saharan West Africa during the Early-Mid Eocene interval (Millot, 1970), while the S2 ferricrete caps the weathering profiles developed upon Late Eocene-Oligocene “Continental Terminal” alluvial deposits (Chardon *et al.*, 2016).

MEASURE OF CONTINENTAL DENUDATION AND SEDIMENT EXPORT

Regional distribution and mapping of lateritic relict landforms

We referenced S1, S2 and S3 relicts over West Africa (Fig. 5) using a combination of fieldwork (in Benin, Burkina Faso, Mali, Niger, Guinea and Senegal), descriptions from existing literature (e.g. Newill & Dowling, 1968; Fölster, 1969; Eschenbrenner & Grandin, 1970; Boulangé & Eschenbrenner, 1971; Boulangé *et al.*, 1973; Michel, 1973, 1977a,b; Grandin & Hayward, 1975; Burke, 1976; Grandin, 1976; Fritsch, 1978; Thomas, 1980, 1994; Rognon *et al.*, 1983; Adegoke *et al.*, 1986; Bowden, 1987; Boulangé & Millot, 1988; Durotoye, 1989; Teeuw, 2002; Chardon *et al.*, 2006) (recent compilations in Beauvais & Chardon, 2013; Grimaud, 2014) and combined analyses of topography and satellite images. Field stations and the full compilation of the references can be found in the Appendix S1. We identified and reported the elevation of S1, S2 and S3 remnants based on their geomorphology and regolith type (see below). In order to further constrain the regional geometries of the surfaces, we also surveyed additional data such as topographic massifs summits (B points), Early-Mid Eocene carbonates (C points) and lower parts of S1 weathering profile remnants (D points) (Chardon *et al.*, 2016). Figure 5 illustrates how these data points were used to reconstruct surface geometries.

S1 relicts dominate West African landscapes in the form of bauxitic mesas capped by a flat duricrust of beige to pink colour reflecting the presence of aluminum (Figs 4a and 5b). In the Guinean rise and eastward (i.e. upwarp domain; Fig. 2), the S1 relicts are preserved 400–600 m above modern rivers (see Beauvais & Chardon, 2013). This local relief decreases towards the coast and the continental interiors, where S1 relicts are <60 m above the Niger River in the Inland Niger delta (Grimaud *et al.*, 2014; Figs 2 and 4c).

S2 ferricretes have red-purple colours on satellite images due to their high iron content and a morphological aspect different from S1 and S3 (Figs 4 and 5b). S2 relicts are usually distributed 50–200 m, and locally up to 400 m, vertically in the landscape below S1 remnants (Grandin, 1976; Beauvais & Chardon, 2013). They are either connected to bauxite relicts, forming convex-upwarp surfaces on the slopes of S1 mesas (Figs 3a and 4a, b), or occur stepped below S1 relicts. It has been shown that the elevation of S2 relicts decreases from the divides to the outlet of West African catchments, following the geometry of the main watersheds and implying that the S2 drainage was similar to the modern one (Beauvais & Chardon, 2013; Grimaud *et al.*, 2014; Chardon *et al.*, 2016; Fig. 4a, b, d).

S3 ferricretes can usually be identified in the field by their embedded conglomerate deposits and their brown to grey colour on satellite images. S3 relicts usually form gently dipping plateaus of several square kilometres in area with concave-up profiles (Figs 3a and 4). S3 plateaus are easily identified when radiating from the piedmont of S1 or S2 mesas (Fig. 4a, b). The downstream parts of S3 relicts are usually 10–100 m above modern rivers and well preserved throughout West Africa, suggesting modest post-11 Ma landscape dissection and denudation (Beauvais & Chardon, 2013; Grimaud *et al.*, 2015; Fig. 4).

Quantification of exported volumes and conversion into sediment fluxes

We estimated denudation volumes and the associated export to offshore basins using regional reconstructions of S1, S2 and S3 surface geometries, and the modern topography. S1, S2 and S3 geometries were reconstructed using the DSI method (Mallet, 1992) that allows building complex geologic surfaces (see Chardon *et al.*, 2016). By subtracting these surfaces, we obtained the S1–S2, S2–S3 and S3–modern elevation differences maps corresponding to incremental denudation maps for the 45–24, 24–11 and 11–0 Ma intervals (Fig. 6) as well as the total denudation map since 45 Ma (i.e. S1–modern map; Fig. 7). S1 and S2 surfaces geometries are those published by Chardon *et al.* (2016) and S3 surface is from this study.

The sediment volumes stored in continental sedimentary basins during the S1–S2 interval (blue colours on Fig. 6b) were subtracted to the eroded volumes to obtain the volumes exported to the continental margin (V_{ex}) (Table 1). These storage volumes were calculated between the S1 and S2 surface geometries. They are actually larger than the volumes currently preserved in the intracratonic sedimentary basins because of erosion after 24 Ma (see Fig. 8 for an illustration in the Iullemmeden basin).

We developed an analysis of uncertainties on the exported volumes estimates. Overall, we found errors values around 10–30% (see Table 1 and Appendix S1). The first uncertainty was estimated for the construction of

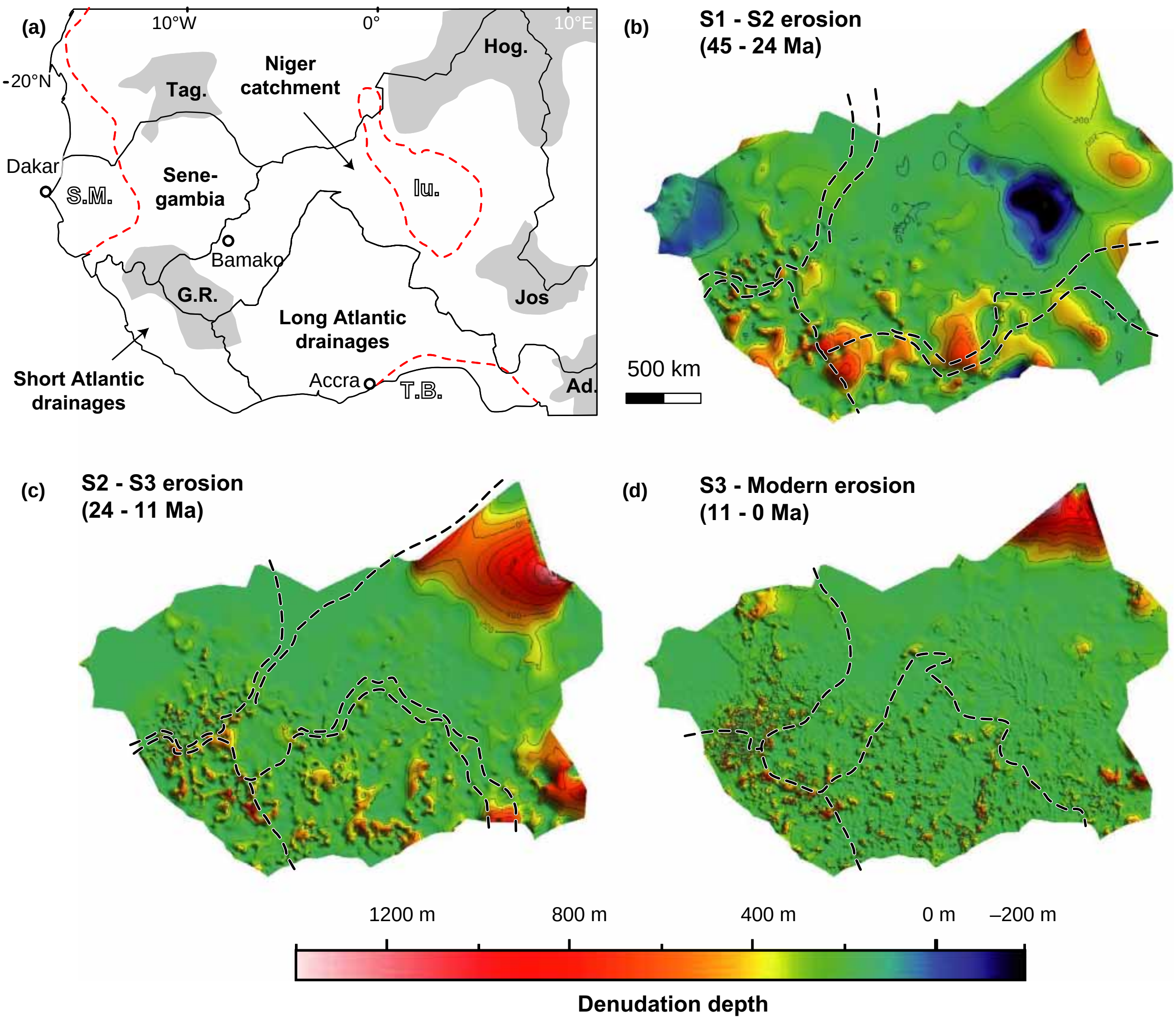

Fig. 6. [a] Simplified map of the four selected drainage groups (bounded by black lines): Senegambia drainage, Short Atlantic drainages, Long Atlantic drainages and the Niger catchment. The modern limits of the Cenozoic onshore sedimentary basins (Senegal-Mauritania [S.M.], Iullemmeden [Iu.] and Togo-Benin [T.B] basins) (red dashed lines) and main topographic massifs (Tagant [Tag.], Hoggar [Hog.], Guinean Rise [G.R.] Jos plateau [Jos] and Adamaoua massif [Ad.]) (grey areas) are also shown. Denudations maps of the 45–24 Ma [b], 24–11 Ma [c] and 11–0 Ma intervals [d]. Successive divides (black dashed lines) are drawn after Chardon *et al.* (2016). Where the position of these divides was less constrained, the uncertainty area is represented between two dashed lines.

surface geometries. For that, we built replicates of the S2 and S3 surfaces, respectively, S'2 and S'3, to measure the variability in their geometries. S'2 and S'3 are less realistic and less elevated than S2 and S3 surfaces (Figs SI2 and SI3) because they were built using only S2 or S3 points, respectively, that is, they were not enforced at the location of the anterior surfaces or forced by the topography. The uncertainties on surface geometries were then measured by the elevation difference between S2 and S'2 and S3 and S'3 (Fig. SI3).

The second uncertainty related to the partitioning of erosion volumes of denudation maps, built at the scale of West Africa, between four drainage groups (Senegambia, Short Atlantic drainages, Long Atlantic drainages and the Niger catchment; Fig. 6a). In this study, we used the paleodrainage maps of Chardon *et al.* (2016), where the drainage divide positions themselves are located within an area of uncertainty (i.e. Fig. 6b, c). We calculated the volume eroded within this uncertainty area to estimate the volume uncertainty associated with the divide location.

The last uncertainty was associated with the type of exported material. Lateritic regolith represents the type-material eroded from the West African continental domain during the Cenozoic (Beauvais & Chardon, 2013). The density and porosity of the eroded lateritic regolith is different from bedrock (e.g. Grimaud *et al.*, 2015). Exported volume (V_{ex}) was corrected for the lateritic regolith porosity, φ, which varies from 10 to 40%

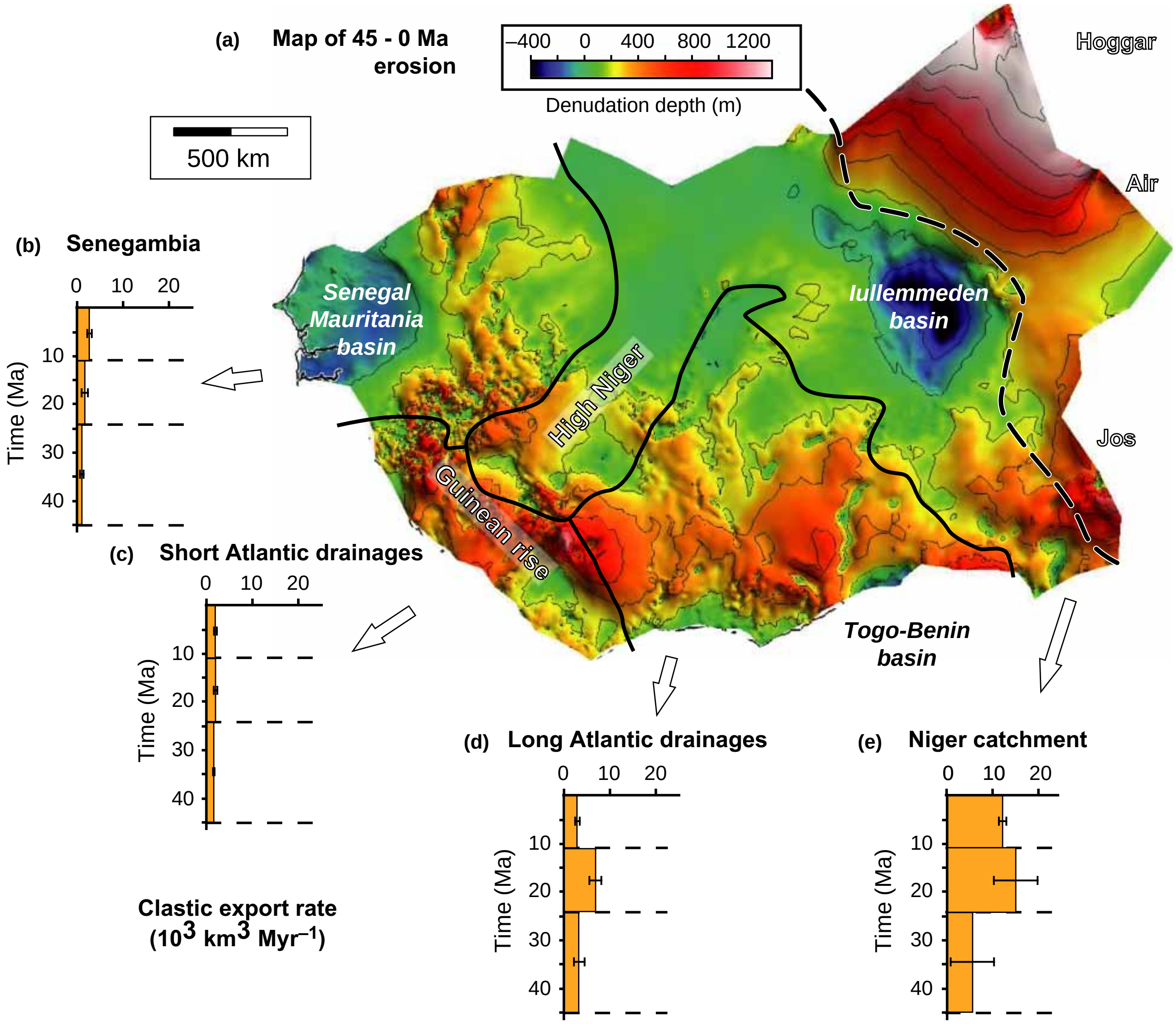

Fig. 7. Cenozoic denudation map and associated exported volumes. [a] Map of total denudation depth at the scale of Sub-Saharan West Africa since the abandonment of S1. Clastic export rates are shown by drainage groups (i.e. Senegambia drainage [b], Short Atlantic drainages [c], Long Atlantic drainages [d] and the Niger catchment [e]). The eastern swells are separated from the rest of the study area by the black dashed line.

(Boulangé, 1984; Valeton, 1991; Beauvais & Colin, 1993; Thomas, 1994). We thus estimated the clastic exported solid volume assuming a 25% mean porosity in the regolith (Table 1). Regolith bulk density is 2,000 kg m^{-3} (Valeton, 1991), which corresponds to a grain density ρ of 2,650 kg m^{-3}. We estimate the clastic yields γ of each drainage group using:

$$\gamma = \frac{V_{ex}.(1-\varphi).\rho}{100.A.\Delta_t} \quad (1)$$

where A and Δ_t are the catchment area and the time interval, respectively, and γ has unit of mass per unit area per time (t km^{-2} yr^{-1}). Calculations of clastic exported solid volumes and clastic yields, therefore, assumed that most eroded material was regolith. Because in West Africa bedrock outcrops are rare, erosion rates are slow and regolith mantles are thick, the assumption seems reasonable (Grimaud *et al.*, 2015). This also implies that a sizeable portion of the denuded volume, which we did not quantify, was exported as solute load. However, in area with fast denudation rates, the eroded material may locally be only moderately weathered. In that case, the actual clastic export was higher than our estimate, which should therefore be considered as minimum.

OFFSHORE CLASTIC ACCUMULATION ON THE MARGIN(S)

Offshore accumulations were calculated in term of solid volumes (i.e. corrected for porosity and non-clastic

Table 1. Summary of Cenozoic erosion budgets of Sub-Saharan West Africa

				Average equivalent denudation				Exported volume							
		Eroded volume		Depth		Rate		Total (V_{ex})		Clastic (V_c)		Clastic export rate		Clastic yield	
Location	Interval	(10^3 km^3)		(m)		(m Myr^{-1})		(10^3 km^3)				(10^3 m^3 Myr^{-1})		(t km^{-2} yr^{-1})	
West Africa	45–0 Ma	1149		333		7.4		1112		834		18.5		13	
Senegambia	45–24 Ma	39	5	74	3	3.5	0.1	30	5	22	4	1.1	0.2	4	1
	24–11 Ma	29	12	40	14	3.1	1.1	29	12	22	9	1.7	0.7	6	3
	11–0 Ma	40	5	59	8	5.3	0.7	40	5	30	4	2.7	0.4	11	1
Short Atlantic drainages	45–24 Ma	45	4	154	8	7.3	0.4	45	4	34	3	1.6	0.1	14	1
	24–11 Ma	37	7	119	19	9.2	1.4	37	7	27	5	2.1	0.4	19	4
	11–0 Ma	29	4	104	14	9.5	1.3	29	4	22	3	2.0	0.3	19	3
Long Atlantic drainages	45–24 Ma	99	41	197	17	9.4	0.8	97	40	73	30	3.5	1.4	17	4
	24–11 Ma	86	22	98	18	7.5	1.4	86	22	64	17	5.0	1.3	15	4
	11–0 Ma	44	7	53	8	4.8	0.8	44	7	33	5	3.0	0.5	9	1
Niger	45–24 Ma	196	178	138	31	6.6	1.5	153	136	115	102	5.5	4.8	7	5
	24–11 Ma	260	83	135	40	10.4	3.1	260	83	195	62	15.0	4.8	20	7
	11–0 Ma	177	11	86	5	7.8	0.5	177	11	133	8	12.1	0.7	15	1
Total Niger	45–0 Ma	633	271	359	76	8.2	1.7	591	229	443	172	10.9	3.4	14	4
Benue estimation	45–0 Ma					7.4				187					
Total Niger & Benue	45–0 Ma									630	172				

material such as volcanics and carbonates) following the method of Guillocheau *et al.* (2012), based on regional geological cross-sections (Fig. 9). The calculation technique, non-clastic material and remaining porosity corrections, and uncertainties estimations are presented in the Appendix S1.

In the Niger delta domain, we used the four sections published by Haack *et al.* (2000) that encompass most of the Cenozoic depocenters (Fig. 9a, b). Given the biostratigraphic age constraints available for the sediments, these sections allowed measuring accumulation at higher time resolution (10^{5-6} yr; Fig. 9d; Table 2) than the denudation maps. Hence, we recalculated accumulations for the 45–23, 23–11.6 and 11.6–0 Ma intervals to allow for comparison with the erosion chronology (Fig. 9e; Table 2). In the Equatorial Atlantic, we used six sections (after De Caprona, 1992; Macgregor *et al.*, 2003) that only encompass the proximal parts of the margins. We then used the extrapolation of these cross-sections to the abyssal plain proposed by Helm (2009) (Fig. 9c; Appendix S1) to include volume accumulated across the entire sedimentary wedge and to take into account erosion from, or by-pass of, the continental shelf (Fig. 9f). Volume for the 45–33.9 Ma interval was recalculated using the accumulation rate of the 55.8–33.9 Ma interval (Table 1).

RESULTS

Spatial and temporal denudation patterns

Incremental (45–24, 24–11 and 11–0 Ma) and total (45–0 Ma) denudations are heterogeneous at regional scale (i.e. Figs 6 and 7). Overall, denudation is greater in the eastern swells (i.e. massifs located to the east of the dashed line in Figs 6b, c, d) and along a 300–800 km wide strip running parallel to the coast (i.e. from the Jos Plateau to the Guinean rise and the Tagant) that we interpret as a marginal upwarp following Beauvais & Chardon (2013). Total denudation exceeds 1500 m in the Hoggar massif and ranges between 400 and 1000 m along the marginal upwarp (Figs 7 and 8a). Elsewhere, the total denudation is usually <400 m. Some onshore accumulation (i.e. negative erosion) is observed in the Togo-Benin, Senegal-Mauritania and Iullemmeden basins, where up to 400 m were accumulated during the 45–24 Ma interval (Figs 6b and 8a). Post-24 Ma denudation is low in these basins (<100 m; Fig. 6c, d) with the noticeable exception of the northern Iullemmeden basin where geological sections show that at least half of the "Continental Terminal" deposits were eroded (Fig. 8a).

From 45 Ma to the present, denudation was high in the Hoggar massif with a maximum during the 24–11 Ma interval (up to 1200 m; Fig. 6). During that period,

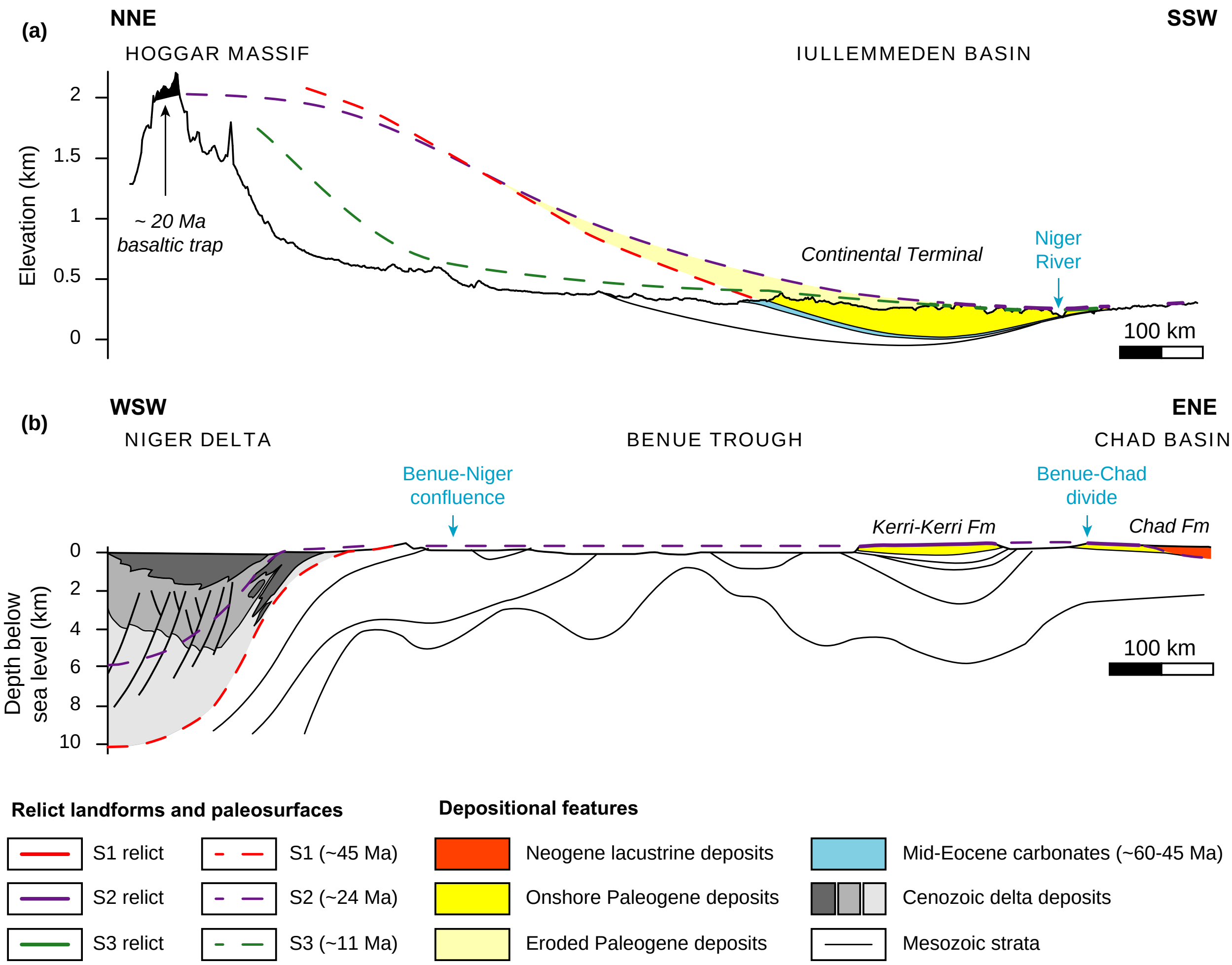

Fig. 8. Regional cross-sections of lateritic relict landforms distribution and contemporary sedimentary deposits (see Fig. 5 for location). [a] Cross section through the Hoggar massif and Iullemmeden basin. [b] Cross section through the Benue trough and onshore Niger delta (geology after Benkhelil, 1989; volcanic accumulation in the Hoggar massif after Rognon *et al.*, 1983). The red, purple and green dashed lines represent large-scale interpolations of the S1, S2 and S3 surfaces respectively.

denudation was more broadly distributed (i.e. it extended towards the North Iullemmeden basin; Fig. 8a) than during the 45–24 and 11–0 Ma intervals. Denudation was more homogenously distributed on the marginal upwarp between 45 and 24 Ma than after 24 Ma. On the Guinean rise (i.e. mostly the Short Atlantic drainages group), relatively high denudation depths were maintained at all times (Fig. 6). Similarly, high denudation depths were recorded from 45 to 11 Ma by the Long Atlantic drainages group in an area that is currently lying low in comparison to the neighbouring Guinean rise (Fig. 2). In the Long Atlantic drainages and Niger catchment groups, denudation depths are overall lower during the 11–0 Ma interval (Fig. 6). In the Senegambia group, denudation increased after 11 Ma in both the Tagant massif and the north-western slope of the Guinean Rise (Beauvais & Chardon, 2013; Figs 2 and 6d). In the Benue trough, the tabular Paleocene Kerri-Kerri Formation is capped by a duricrust comparable to the Intermediate ferricrete (Newill & Dowling, 1968; Adegoke *et al.*, 1986), which allows constraining the incision of these deposits after the abandonment of S2 surface (i.e. 24 Ma; Fig. 3). A geologic section suggests that Benue valley denudation did not exceed 200 m since 24 Ma, corresponding to a maximum denudation rate of 8.4 m Myr^{-1} (Fig. 8b).

These data show that denudation rates are overall low in West Africa since 45 Ma (mean denudation rate of 7.4 m Myr^{-1}; Table 1). They are higher in the Hoggar massif (i.e. larger than 30 m Myr^{-1}) and the marginal upwarp (up to 10 m Myr^{-1}), where some temporal variations are also observed. Denudation rates remain lower than 5 m Myr^{-1} in the remainder of West Africa.

Export at the scale of major catchments

In total, the West African subcontinent exported 834×10^3 km^3 of solid clastic sediments to the ocean (Table 1) since 45 Ma. These clastic volumes were

Table 2. Summary of Cenozoic clastic volumes accumulated in the Niger delta

	Interval (Ma)	Accumulated volume (10^3 km^3)
S3 – modern	1.8–0	46.8 ± 6.3
	5.3–1.8	142.3 ± 19.9
	11.6–5.3	127.7 ± 17.8
S2 – S3	16–11.5	85.4 ± 11.9
	23–11.5	61 ± 8.5
S1 – S2	33.9–23	69.8 ± 10.4
	45–33.9	44.4 ± 15.7
	55.8–33.9	87.6 ± 30.9
	Total 45–0	577.4 ± 90.5

distributed between the major drainage groups (Figs 6 and 7): 74×10^3 km^3 from the Senegambia, 83×10^3 km^3 from the Short Atlantic drainages, 170×10^3 km^3 from the Long Atlantic drainages and 430×10^3 km^3 from the Niger catchment (Table 1). At first order, exported solid volumes therefore increase with the size of the contributing area. Results also show that the export is modulated by onshore storage of sediments that we subtracted. Hence, 16% (12×10^3 km^3) of the total clastic export from Senegambia is stored onshore in the Senegal–Mauritania basin, whereas only 5% of the total clastic export from the Niger catchment is preserved in the Iullemmeden basin. In the Niger source-to-sink system, we did not measure denudation in the Benue trough and surrounding massifs (Figs 6 and 7) because the rare descriptions of regolith (Fritsch, 1978; Guillocheau *et al.*, 2015) would not allow to rigorously integrating them to the denudation chronology. However, we have estimated and added a Benue trough export to compare the clastic export from the Niger catchment to the accumulations in the Niger delta. We estimated that the Benue contributed a solid clastic volume of *ca.* 187×10^3 km^3 assuming that the average West African denudation rate of 7.4 m Myr^{-1} applies to this area (*ca.* 0.77×10^6 km^2; Table 1). This rate is compatible with observations in the Benue valley (see previous section). Denudation was potentially higher, enhanced by Neogene uplift, in the surrounding massifs (Burke, 1976). However, the preservation of Neogene volcanics and lateritic regoliths in the Jos Plateau and Adamaoua massifs (Boulangé & Eschenbrenner, 1971) suggests that denudation rates were probably much lower there than in the Hoggar area. In parallel, the neighbouring Chad basin has been constantly subsiding and trapping sediment since at least 24 Ma (Burke, 1976), suggesting that no sediment was diverted from the basin into the Benue trough (see Chardon *et al.*, 2016). Using a mean West Africa denudation rate seems therefore reasonable to estimate the erosion in the area of the Benue Trough. In line with these hypotheses, the resulting total clastic export of the Niger-Benue catchment reaches $630 \pm 172 \times 10^3$ km^3 since 45 Ma (Table 1). The Hoggar swell area has contributed *ca.* 66% of this volume.

Temporal variations in clastic export reflect the evolution of denudation rate and drainage. In most drainage groups, clastic export rates were lower during the 45–24 Ma interval than during the 24–11 Ma interval (Fig. 7b–e). Within the Senegambia drainage group, clastic export rate was slightly higher in the 11–0 Ma interval. In contrast, clastic export rate was steady for the Short Atlantic drainages group (Fig. 7b, c). In the Long Atlantic drainages group and the Niger catchment, export rates were lower during the 11–0 Ma interval than during the 24–11 Ma interval (Fig. 7d, e). The highest uncertainties on clastic export rates are estimated in the Long Atlantic drainages group and Niger catchment because of the major drainage reorganization between 45 and 24 Ma (Chardon *et al.*, 2016; Table 1; Appendix S1). Hence, the overall export trends among drainage groups appear regionally consistent in between the 45–24 and 24–11 Ma intervals and more contrasted in between the 24–11 and 11–0 Ma intervals.

Offshore accumulation

Offshore domains differ in their structural and sediment accumulation patterns (Fig. 9a). For the Niger delta, the sections used to estimate accumulation encompass the major part of the Cenozoic sedimentary wedge located along the margin (Fig. SI4). These sections show thick marginal clinoforms that have prograded over 150 km since the Oligocene and that are affected by faulting and folding (Figs 8b and 9b). Along the remaining part of the Equatorial Atlantic margin, 90% of the Cenozoic wedge is spread over the abyssal plain and extends over 300–600 km offshore (Fig. 9c).

Accumulation rates for the Niger delta can be estimated at higher resolution than denudation (Fig. 9d). These rates show a steady increase from *ca.* 5 to 10×10^3 km^3 Myr^{-1} between 45 and 16 Ma. After 16 Ma, the accumulation rates increased to more than 20×10^3 km^3 Myr $^{-1}$. A peak in accumulation rate (40×10^3 km^3 My^{-1}) is recorded between 5.3 and 1.8 Ma, followed by a relative decrease after 1.8 Ma (Jermannaud *et al.*, 2010). Solid accumulation rates, resampled for long-term intervals, are, respectively, *ca.* 5, 12 and 28×10^3 km^3 Myr^{-1} during the 45–23, 23–11 and 11–0 Ma intervals. These data show that a larger volume of Neogene sediments is preserved in the delta compared to Paleogene sediments. The resulting total clastic accumulation since 45 Ma is about 580×10^3 km^3 (Table 2). This number is remarkably consistent with – although slightly lower than – the calculated clastic volume exported by the Niger-Benue catchment since 45 Ma (*ca.* 630×10^3 km^3; Table 1).

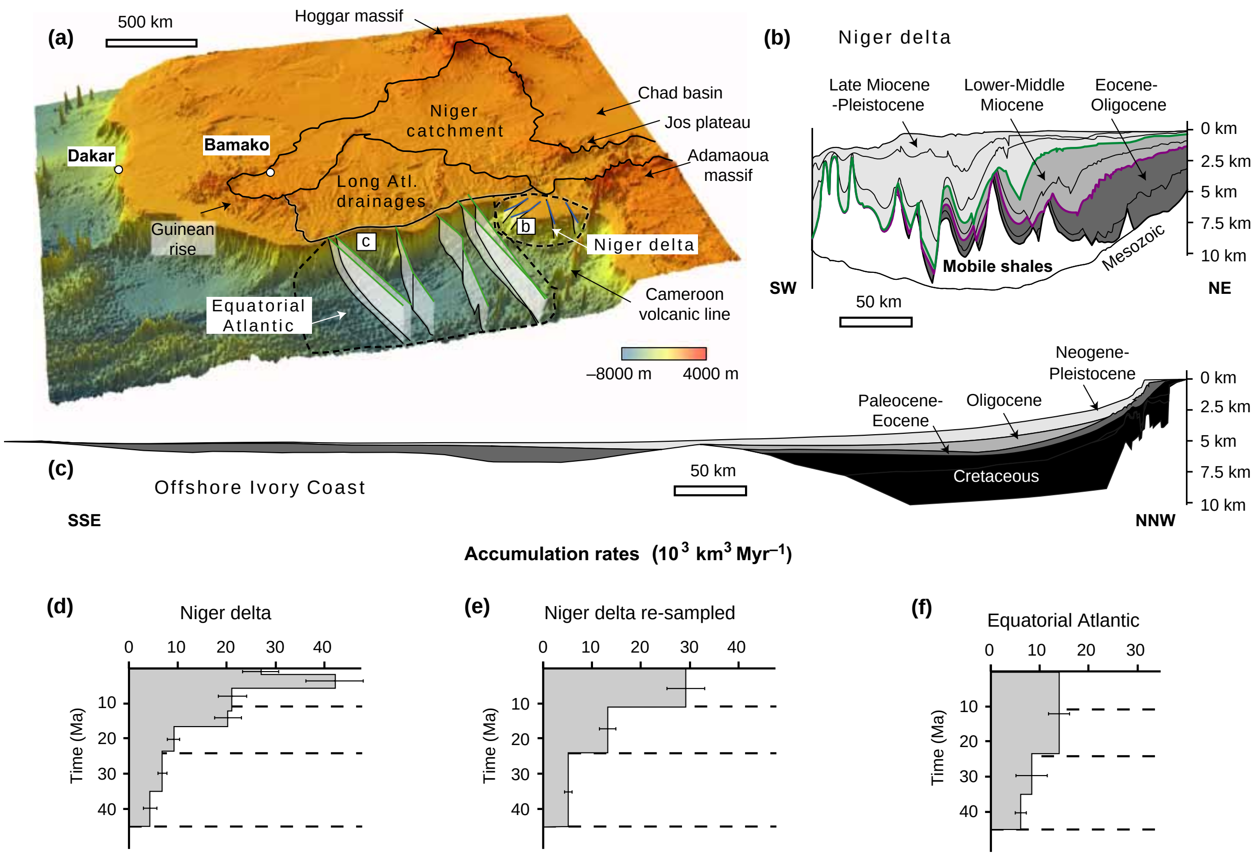

Fig. 9. Offshore accumulation histories. [a] 3D topography and bathymetry showing the location of the cross sections used in the study. [b] Example of cross section for the Niger delta (after Haack *et al.*, 2000). [c] Example of cross section for the sediment accumulation offshore Ivory Coast (after Helm, 2009; see Appendix S1). [d] Evolution of volumetric accumulation rates in the Niger delta (after Haack *et al.*, 2000 and Robin *et al.*, 2011). [e] Evolution of volumetric accumulation rates in the Niger delta after time re-sampling in order to compare to the continental denudation chronology (i.e. 45–23, 23–11.6 and 11.6–0 Ma; see Table 2). [f] Evolution of volumetric accumulation rates on the African margin of the Equatorial Atlantic (modified after Helm, 2009). See methods section and Appendix S1 for details. Error bars include a Monte Carlo estimation of uncertainties related to sections interpolation, as well as non-clastic material (i.e. carbonates and volcanics) and porosity corrections.

Along the rest of the margin, available data have a lower resolution than in the Niger delta, especially in the abyssal plain, and imply larger uncertainties (Fig. 9; see Helm, 2009). Accumulated volumes computed for the three time intervals suggest a long-term pattern of accumulation rate comparable to that of the Niger delta. The volumes are *ca.* 65, 85 and 300 × 10^3 km^3 during the 45–33, 33–21 and 21–0 Ma intervals respectively (Fig. 9f). The total accumulated clastic volume since 45 Ma is 450 ± 120 × 10^3 km^3. This is 2–4 times higher than our estimate of exported clastic volumes (151 × 10^3 km^3) from the source area.

DISCUSSION

Cenozoic sediment budget

Surficial mass transfers from source to sink and the associated (un) loading of the crust are key aspects of the topographic evolution and stratigraphic record of passive margins (Rouby *et al.*, 2013). Our study provides independent volumetric estimations of denudation at a subcontinental scale over the Cenozoic using relict paleolandforms and of accumulation using offshore regional sections. The main insight from our study is the fairly well-balanced sediment budget between the Niger delta and its source area. Such a finding supports the paleodrainage reconstruction of Chardon *et al.* (2016) who suggested the establishment of the modern Niger River watershed since at least the Late Oligocene (29 Ma). The modern-like Niger River catchment since at least 29 Ma collected sediments from a *ca.* 2 × 10^6 km^2 catchment and transferred the large eroded volumes derived from the Hoggar hot spot swell to the ocean. The antiquity of the Niger catchment appears as a prerequisite to the large clastic accumulations in the Niger delta given the low denudation rates (5–30 m Myr $^{-1}$) at the scale of West Africa.

Although our estimations fall within the same order of magnitude, we estimated a deficit on the volume of sediments exported by the Long Atlantic drainages group with respect to the accumulation along the Equatorial Atlantic margin they have fed (Fig. 9f; Table 1). Geometries of the offshore geological sections are, however, not well constrained and were deduced from low-resolution geophysical data with limited age constraints (Emery *et al.*, 1975). Thus, an uncertainty of merely 10 metres thickness on the distal geometry of a stratigraphic horizon may have significant repercussions on volume estimation in a basin as large as the Equatorial Atlantic, leading to under- or overestimation of accumulation. Clastic sediment budgets of the abyssal plains can further be affected by additional aeolian dust input from the Sahara (Windom, 1975), and more importantly by reworking by longitudinal bottom currents (Séranne & Nzé Abeigne, 1999; Anka *et al.*, 2009). Some sediments derived from the Niger catchment may also have by-passed the delta toe and have been deposited on these parts of the Equatorial Atlantic, further complicating the sediment budgets. This is supported by the westward extension of the Niger delta (Fig. 2) and consistent with the fact that, in our estimation, accumulation is slightly lower than denudation in the Niger source-to-sink budget. Future studies constraining westward sediment transfer in the western Niger delta would help to decipher the apparently low export of the Long Atlantic drainages group.

We measured a difference between the volumetric accumulation rate of the Niger delta (*ca.* 30×10^3 km^3 Myr^{-1}) and the export rate of the Niger catchment (*ca.* 12×10^3 km^3 Myr^{-1}) during the 11–0 Ma interval (i.e. Figs 7e and 9e). Assuming that the biostratigraphy used by Haack *et al.* (2000) is accurate, this difference could be explained by post-11 Ma erosion of sediments that were previously stored within the Niger sediment routing system, particularly on the shelf. As an analogy, the widespread erosion of Miocene sediments stored on the continent or the shelf has led to such reworking on the neighbouring South Atlantic margin (e.g. Lavier *et al.*, 2001; Walford & White, 2005; Linol *et al.*, 2014). In the study area, reworking of Cenozoic sediments is supported by the incision of large canyons in the Niger delta (Doust & Omatsola, 1990) and the removal of at least 50% of the former "Continental Terminal" after 24 Ma in the Iullemmeden basin (see geological section in Fig. 8a). Overall, the discrepancy between accumulation and erosion is a point of caution when deducing denudation rates and paleosediment fluxes from the accumulation record only. Indeed, if the 11–0 Ma clastic deposits are partly composed of recycled material, their volume may overestimate continental denudation after 11 Ma, and underestimate denudation before that time.

Erosion dynamics in a non-orogenic domain

Our maps show that denudation is very heterogeneously distributed across West Africa as well as within each drainage group. Regional denudation patterns suggest an influence of long-wavelength rock uplift (>300 km) (Figs 7 and 8; Chardon *et al.*, 2016). Denudation focused on the Hoggar suggests a rock-uplift pattern with >700 km radius (Fig. 7a) related to mantle dynamics (Burke *et al.*, 2003; Chardon *et al.*, 2016). Recently published apatite (U-Th)/He thermochronological data indicate Cenozoic denudation in the Hoggar of 1–2 km between 78 ± 22 Ma and 13 ± 3 Ma (Rougier *et al.*, 2013), which is consistent with our estimation (*ca.* 1.5 km; Fig. 8a). Because we did not find the equivalent of S1 there, it is likely that we have even slightly underestimated the denudation of the Hoggar for the 45–24 Ma interval. Nevertheless, the eroded material derived from the Hoggar swell was instrumental in obtaining the volume accumulated in the Niger delta. As an illustration, applying the mean denudation rate of the other drainage groups (i.e. 6.6 m Myr^{-1}) over the Niger catchment for 45 Ma would have only resulted in only *ca.* 280×10^3 km^3 clastic volume exported to the Niger delta instead of the *ca.* 450×10^3 km^3 we estimated (Table 1). This simple calculation supports that forcing by mantle dynamics is a first-order process for enhancing the sediment export from the African continent (Burke *et al.*, 2003).

West of the dashed line in Fig. 7, maximum denudation depths within the upwarp domain suggest some rock uplift associated with flexure along the passive margin (Beauvais & Chardon, 2013; Grimaud *et al.*, 2014). In detail, denudation histories vary across the different segments along the margin, indicating a complex evolution. For example, erosion rates decreased along major valleys of the Long Atlantic drainages between the 24–11 and 11–0 Ma intervals during the progressive dissection of the upwarp, while they remained high in the Guinean Rise (i.e. Senegambia and Short Atlantic drainages; Fig. 6). These different erosion dynamics resulted in contrasted post-24 Ma evolution of clastic export rates in these drainage groups (Fig. 7b, c, d), resulting in source-to-sink systems that are not monotonous along the marginal upwarp. The variability in erosion rates may tentatively be related to uplift rate variations along the continental margin. Potentially, the stretching of a heterogeneous lithosphere or a non-cylindrical margin during the rifting stage generates potentially complex, laterally variable uplift patterns, which may be maintained long after rifting (Chardon *et al.*, 2013; Rouby *et al.*, 2013), leading to unevenly distributed erosion rates.

Our analysis shows that dated relict lateritic landforms are reliable markers of post-rift denudation of continental passive margins and adjacent cratonic domains with sufficient spatial and temporal resolution. The variability in erosion histories along the margin shows (similarly to Pazzaglia & Gardner (1994) along the US Atlantic margin) that modern topography and paleodenudation rates do not necessarily correlate (Figs 2 and 7) and that independent geomorphic markers are more robust than present-day digital elevation models to constrain surface dynamics over geological timescales. West Africa is a non-orogenic domain where the erosion dynamics may be compared to the adjoining offshore record thanks to a spatially constrained onshore denudation chronology. In the future, new insights on the Cenozoic surface evolution of shields and their bounding margins (e.g. Australia, Brazil, India, South Africa) will arise from the mapping of relict landforms, whose lateritic cover has been dated using supergene minerals (e.g. Vasconcelos *et al.*, 1994a,b; Vasconcelos & Conroy, 2003; Bonnet *et al.*, 2014, 2016; Riffel *et al.*, 2015; Beauvais *et al.*, 2016).

CONCLUSIONS

We have quantified patterns and volumes of Cenozoic denudation and catchment export using dated and regionally correlated relict lateritic landforms of Sub-Saharan West Africa. Overall denudation rates are regionally low in this non-orogenic domain (*ca.* 7 m Myr^{-1}), but may increase significantly locally with rock uplift, whether driven by mantle dynamics or lithosphere deformation and flexure, as, for example, in the Hoggar hotspot swell and along a marginal upwarp. Comparisons with clastic volumes accumulated offshore show a fairly balanced sediment budget between the Niger catchment and its delta since 45 Ma. The Niger catchment was established since at least 29 Ma and allowed transporting sufficient clastic material to the delta; in particular, by collecting the erosion products of the growing Hoggar hotspot swell. Accumulations along the remaining Equatorial Atlantic margin of Africa suggest an apparent export deficit from its source but our estimation is poorly constrained by available offshore data, and complicated by potential sediment input from the Niger delta. Sediment reworking shredding the depositional record is also suggested in several locations, prompting caution when deducing continental denudation rates from accumulation only.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Appendix S1. The method for building the 3D surfaces associated with the relict lateritic landforms, as well as the interpolation technique between offshore regional sections.

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