



Cenozoic sediment budget of West Africa and the Niger delta

Jean-Louis Grimaud, Delphine Rouby, Dominique Chardon, Anicet Beauvais

► To cite this version:

Jean-Louis Grimaud, Delphine Rouby, Dominique Chardon, Anicet Beauvais. Cenozoic sediment budget of West Africa and the Niger delta. Basin Research, 2018, 10.1111/bre.12248 . hal-01567059

HAL Id: hal-01567059

<https://amu.hal.science/hal-01567059>

Submitted on 25 Jul 2017

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Cenozoic sediment budget of West Africa and the Niger delta

Jean-Louis Grimaud^{1,2*}, Delphine Rouby¹, Dominique Chardon^{1,3}, Anicet Beauvais⁴

(1) Géosciences Environnement Toulouse, Université de Toulouse, CNRS, IRD, UPS, CNES, F-31400 Toulouse, France

(2) now at MINES ParisTech, PSL Research University, Centre de Géosciences, 35 rue St Honoré, 77305 Fontainebleau Cedex, France

(3) IRD and Département des Sciences de la Terre, Université Ouaga I Professeur Joseph Ki-Zerbo, 01 PB 182 Ougadougou 01, Burkina Faso

(4) Aix-Marseille Univ, CNRS, IRD, Coll France, CEREGE, BP 80, 13545 Aix-en-Provence, Cedex 4, France

* corresponding author: jean-louis.grimaud@mines-paristech.fr

*Manuscript submitted to **Basin Research**, 25-Nov-2016*

Revised manuscript, submitted 24 April 2017

Accepted, 11 June 2017

DOI: 10.1111/bre.12248

Keywords: Source-to-sink, Cenozoic, sediment flux, Africa, craton, continental margin

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 3 time intervals (45-24, 24-11 and 11-0 Ma). At the scale of West Africa, denudation rates are low (~ 7 m Myr^{-1}) and total clastic export rate represents $18.5 \times 10^3 \text{ km}^3 \text{ Myr}^{-1}$. 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 have been 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 bio-geochemical cycles. The stratigraphic record may allow retrieving paleo-environmental 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 micro- to mesoscale (m^2 to km^2) and short-term (10^{1-4} yr), and may not be representative of large continental surfaces ($> 10^4 \text{ km}^2$) evolving at geological timescale (Simoes et al., 2010). Sediment budgets comparing source and sink are therefore the most meaningful to 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 km²; 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 to 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 paleo-drainage 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 $4 \times 10^6 \text{ km}^2$ 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 ($2.3 \times 10^6 \text{ km}^2$) 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 $26 \times 10^3 \text{ km}^2$ 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 ($750 \times 10^3 \text{ km}^2$) and a thinner Cenozoic sediment cover ($< 3 \text{ km}$; Helm, 2009).

The West African bedrock is composed of Archean and Paleoproterozoic basement bounded by mobile belts of Panafrican ($\sim 800 - 450 \text{ Ma}$) and Variscan ($\sim 360 - 250 \text{ Ma}$) 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 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 of 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) i.e., 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 toward 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 to 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 (Gillschist & Summerfield, 1994; Beaumont et al., 2000).

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 sub-continental 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 of weathering intensity and slope erosion processes (Boulangé et al., 1973; Grandin, 1976; Tardy & Roquin, 1998). This allows for correlations of each type of paleo-landscape 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 aluminum 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 paleo-surface (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). 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 glaxis” in the French literature). S3 is a pediment, i.e., a gently sloping concave-upward surface, formed under semi-arid to arid climate during which stable base level and high seasonality favor 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 $[\text{K}_x(\text{Mn}^{3+})_x(\text{Mn}^{4+})_{8-x}\text{O}_{16}]$ 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 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 paleolandscape is correlated to 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; Michel 1973, 1977a, 1977b; Boulangé et al., 1973; Grandin & Hayward, 1975; Grandin, 1976; Burke, 1976; Fritsch, 1978; Thomas, 1980; Rognon et al., 1983; Adegoke et al., 1986; Bowden, 1987; Boulangé & Millot, 1988; Durotoye, 1989; Teeuw, 2002; Thomas, 1994) (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 Supporting Information. 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 color 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 to 600 m above modern rivers (see Beauvais & Chardon, 2013). This local relief decreases towards the coast and the continental interiors, where S1 relicts are less than 60 m above the Niger River in the Inland Niger delta (Grimaud et al., 2014; Figs. 2 and 4c).

S2 ferricretes have red-purple colors 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-upward surface on the slopes of S1 mesas (Figs. 3a, 4a, 4b and), or occur stepped under 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; Figs. 4a, 4b and 4d).

S3 ferricretes can usually be identified in the field by their embedded conglomerate deposits and their brown to grey color on satellite images. S3 relicts usually form gently dipping plateaus of several square kilometers 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 (Figs. 4a and 4b). 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 to 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 colors on Figure 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 Supporting Information). The first uncertainty was estimated for the construction of surface geometries. For that, we built replicates of the S2 and S3 surfaces, respectively S'2 and S'3, to measure the variability of 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, i.e. 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 paleo-drainage maps of Chardon et al. (2016), where the drainage divide positions themselves are located within an area of uncertainty (i.e. Figs. 6b and 6c). We calculated the volume eroded within this uncertainty area to estimate the volume uncertainty associated to the divide location.

The last uncertainty was associated to the type of exported material. Lateritic regolith represents the type-material eroded from the West African continental domain during the Cenozoic (Beauvais and 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 % (Valeton, 1991; Boulangé, 1984; 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 $2,000 \text{ kg m}^{-3}$ (Valeton, 1991), which corresponds to a grain density ρ of $2,650 \text{ kg m}^{-3}$. We estimate the clastic yields γ of each drainage group using:

$$\gamma = \frac{V_{ex} \cdot (1 - \varphi) \cdot \rho}{1000 \cdot A \cdot \Delta t} \quad (1)$$

where A and Δt are the catchment area and the time-interval, respectively, and γ has unit of mass per unit area per time ($\text{t km}^{-2} \text{ yr}^{-1}$). 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 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 Supporting Information.

In the Niger delta domain, we used the four sections published by Haack et al. (2000) that encompass most of the Cenozoic depocenters (Figs. 9a and 9b). 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 6 sections (after de Caprona, 1996; 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; Supporting Information) 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 Figures 6b, 6c and 6d) and along a 300 to 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 less than 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; Figs. 6c and 6d) 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, denudation was more broadly distributed (i.e. it extended toward the North Iullemmeden basin; Fig. 8a) than during the 45-24 and 11-0 Ma intervals. Denudation was more homogeneously 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 neighboring 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 northwestern 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 sub-continent exported 834 x 10³ km³ of solid clastic sediments to the ocean (Table 1) since 45 Ma. These clastic volumes were distributed between the major drainage groups (Figs. 6 and 7): 74 x 10³ km³ from the Senegambia, 83 x 10³ km³ from the Short Atlantic drainages, 170 x 10³ km³ from the Long Atlantic drainages and 430 x 10³ km³ 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 x 10³ km³) 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. $187 \times 10^3 \text{ km}^3$ assuming that the average West African denudation rate of 7.4 m Myr^{-1} applies to this area ($\sim 0.77 \times 10^6 \text{ km}^2$; 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 neighboring 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 $630 \pm 172 \times 10^3 \text{ km}^3$ 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 (Figs. 7b-7e). 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 (Figs. 7b and 7c). 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 (Figs. 7d and 7e). The highest uncertainties on clastic export rates are estimated for 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; Supporting Information). 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. $5 \text{ to } 10 \times 10^3 \text{ km}^3 \text{ Myr}^{-1}$ between 45 and 16 Ma. After 16 Ma, the accumulation rates increased to more than $20 \times 10^3 \text{ km}^3 \text{ Myr}^{-1}$. A peak in accumulation rate ($40 \times 10^3 \text{ km}^3 \text{ Myr}^{-1}$) 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, re-sampled for long-term intervals, are respectively ca. 5, 12 and $28 \times 10^3 \text{ km}^3 \text{ Myr}^{-1}$ 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 $580 \times 10^3 \text{ km}^3$ (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. $630 \times 10^3 \text{ km}^3$; Table 1).

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 $300 \times 10^3 \text{ km}^3$ during the 45-33, 33-21 and 21-0 Ma intervals, respectively (Fig. 9f). The total accumulated clastic volume since 45 Ma is $450 \pm 120 \times 10^3 \text{ km}^3$. This is 2-4 times higher than our estimate of exported clastic volumes ($151 \times 10^3 \text{ km}^3$) 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 sub-continental 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. $2 \times 10^6 \text{ km}^2$ 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 ($5\text{-}30\text{ m Myr}^{-1}$) at the scale 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 ten meters 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 underestimation 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 and 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 ($\sim 30 \times 10^3\text{ km}^3\text{ Myr}^{-1}$) and the export rate of the Niger catchment ($\sim 12 \times 10^3\text{ km}^3\text{ Myr}^{-1}$) during the 11-0 Ma interval (i.e. Fig. 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 neighboring 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 paleo-sediment 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 (~ 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. $280 \times 10^3 \text{ km}^3$ clastic volume exported to the Niger delta instead of the ca. $450 \times 10^3 \text{ km}^3$ 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, 7c and 7d), resulting in source-to-sink systems that are not monotonous along the marginal upwarp. The variability of 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 of erosion histories along the margin shows (similarly to Pazzaglia & Gardner (1994) along the US Atlantic margin) that modern topography and paleo-

denudation 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; 1994b; 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 ($\sim 7 \text{ m Myr}^{-1}$) 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.

Acknowledgement:

This work was funded by WAXI, the CNRS and the ANR TopoAfrica (ANR-08-BLAN-572 0247–02) and supported by the gOcad consortium. We thank Michel Séranne and the SAFL sediment dynamics group for fruitful discussions and suggestions as well as Damien Huygues and Stéphane Perrouty for support. The manuscript also benefited from constructive reviews by Frank Pazzaglia, Luc Lavier and Peter van der Beek. We acknowledge AMIRA International and the industry sponsors, including AusAid and the ARC Linkage Project LP110100667, for their support of the WAXI project (P934A) as well as the Geological Surveys/Departments of Mines in West Africa as sponsors in kind of WAXI.

REFERENCES

- ADEGOKE, O.S., AGUMANU, A.E., BENKHELIL, M.J. & AJAYI, P.O. (1986) New stratigraphic, sedimentologic and structural data on the kerri-kerri formation, Bauchi and Borno States, Nigeria. *J. Afr. Earth Sci.*, **5**, 249-277.
- ALLEN, P.A. (2008) From landscapes into geological history. *Nature*, **451**, 274-276.
- ANKA, Z., SÉRANNE, M., LOPEZ, M., SCHECK-WENDEROTH, M. & SAVOYE, B. (2009) The long-term evolution of the Congo deep-sea fan: A basin-wide view of the interaction between a giant submarine fan and a mature passive margin (ZaiAngo project). *Tectonophysics*, **470**, 42-56.
- BEAUMONT, C., KOOI, H. & WILLETT, S. (2000) Coupled tectonic-surface process models with applications to rifted margins and collisional orogens. *In: Geomorphology and global tectonics* (Ed. by M. A. Summerfield), 29-55. John Wiley & Sons, Chichester UK
- BEAUVAIS, A., BONNET, N.J., CHARDON, D., ARNAUD, N. & JAYANANDA, M. (2016) Very long-term stability of passive margin escarpment constrained by $^{40}\text{Ar}/^{39}\text{Ar}$ dating of K-Mn oxides. *Geology*, **44**, 299-302.
- BEAUVAIS, A. & COLIN, F. (1993) Formation and transformation processes of iron duricrust systems in tropical humid environment. *Chem. Geol.*, **106**, 77-101.
- BEAUVAIS, A., RUFFET, G., HÉNOQUE, O. & COLIN, F. (2008) Chemical and physical erosion rhythms of the West African Cenozoic morphogenesis: The ^{39}Ar - ^{40}Ar dating of supergene K-Mn oxides. *J. Geophys. Res.*, **113**, F04007.
- BEAUVAIS, A. & CHARDON, D. (2013) Modes, tempo and spatial variability of Cenozoic cratonic denudation: The West African example. *Geochem. Geophys. Geosyst.*, **14**, 1590–1608.

- 533 BENKHELIL, J. (1989) The origin and evolution of the Cretaceous Benue Trough (Nigeria). *J.*
 534 *Afr. Earth Sci.*, **8**, 251-282.
- 535 BISHOP, P. (1995) Drainage rearrangement by river capture, beheading and diversion. *Prog.*
 536 *Phys. Geogr.*, **19**, 449-473.
- 537 BISHOP, P. (2007) Long-term landscape evolution: linking tectonics and surface processes.
 538 *Earth Surf. Proc. Land.*, **32**, 329-365.
- 539 BONNET N.J., BEAUVAIS, A., ARNAUD, N., CHARDON, D. & JAYANANDA, M. (2014)
 540 First $^{40}\text{Ar}/^{39}\text{Ar}$ dating of intense late Palaeogene lateritic weathering in Peninsular India.
 541 *Earth Planet. Sci. Letters*, **386**, 126-137.
- 542 BONNET N.J., BEAUVAIS, A., ARNAUD, N., CHARDON, D. & JAYANANDA, M. (2016)
 543 Cenozoic lateritic weathering and erosion history of Peninsular India from $^{40}\text{Ar}/^{39}\text{Ar}$
 544 dating of supergene K-Mn oxides. *Chem. Geol.*, **446**, 33-53.
- 545 BOULANGÉ, B. & ESCHENBRENNER, V. (1971) Note sur la présence de cuirasses témoins
 546 des niveaux bauxitiques et intermédiaires, plateau de Jos Nigéria. *Bull. Ass. Sénégal.*
 547 *Quatern. Ouest Afr.*, **31**, 83-92.
- 548 BOULANGÉ, B., SIGOLO, J.B. & DELVIGNE, J. (1973) Descriptions morphoscopiques,
 549 géochimiques et minéralogiques des faciès cuirassés des principaux niveaux
 550 géomorphologiques de Côte d'Ivoire. *Cah. ORSTOM, sér. Géol.*, **5**, 59-81.
- 551 BOULANGÉ, B. (1984) *Les formations bauxitiques latéritiques de Côte d'Ivoire; les faciès, leur*
 552 *transformation, leur distribution et l'évolution du modelé*. ORSTOM, Bondy, France.
- 553 BOULANGÉ, B. & MILLOT, G. (1988) La distribution des bauxites sur le craton ouest-africain.
 554 *Sci. Géol. Bull.*, **41**, 113-123.

555 BOWDEN, D.J. (1987) On the composition and fabric of the footslop laterites (duricrusts) of the
556 Sierra Leone, West Africa, and their geomorphological significance. *Z. Geomorphol.*
557 *Suppl.*, **64**, 39–53.

558 BRADLEY, D.C. (2008) Passive margins through earth history. *Earth-Sci. Rev.*, **91**, 1-26.

559 BROWNFIELD, M.E. & CHARPENTIER, R.R. (2006) Geology and total petroleum systems of
560 the Gulf of Guinea Province of West Africa. *U.S. Geol. Surv. Bulletin*, **2207-C**.

561 BURBANK, D.W. (1992) Causes of recent Himalayan uplift deduced from deposited patterns in
562 the Ganges basin. *Nature*, **357**, 680-683.

563 BURKE, K. (1976) The chad basin: An active intra-continental basin. *Tectonophysics*, **36**, 197-
564 206.

565 BURKE, K. (1996) The African Plate. *S. Afr. J. Geol.*, **99**, 339-409.

566 BURKE, K., MACGREGOR, D.S. & CAMERON, N.R. (2003) Africa's petroleum systems; four
567 tectonic 'aces' in the past 600 million years. In: *Petroleum Geology of Africa: New*
568 *Themes and Developing Technologies*. (Ed. by T. J. Arthur, D. S. MacGregor & N. R.
569 Cameron), *Geol. Soc. London Spec. Publ.*, **207**, 21-60.

570 CAMPANILE, D., NAMBIAR, C.G., BISHOP, P., WIDDOWSON, M. & BROWN, R. (2008)
571 Sedimentation record in the Konkan–Kerala Basin: implications for the evolution of the
572 Western Ghats and the Western Indian passive margin. *Basin Res.*, **20**, 3-22.

573 CHARDON, D., ROUBY, D., ROBIN, C., CALVES, G., GRIMAUD, J.L., GUILLOCHEAU,
574 F., BEAUVAIS, A. & BRAUN, J. (2013) Source to sink study of non-cylindrical rifted
575 passive margins: the case of the Gulf of Guinea. *Geophys. Res. Abstr.*, EGU2013-5223-1.

576 CHARDON, D., GRIMAUD, J.-L., Rouby, D., BEAUVAIS, A. & CHRISTOPHOUL, F. (2016)
577 Stabilization of large drainage basins over geological time scales: Cenozoic West Africa,
578 hot spot swell growth, and the Niger River. *Geochem. Geophys. Geosyst.*, **17**, 1164-1181.

579 CLIFT, P.D. (2010) Enhanced global continental erosion and exhumation driven by Oligo-
580 Miocene climate change. *Geophys. Res. Lett.*, **37**, L09402.

581 DE CAPRONA, G.C. (1992) *The continental margin of western Côte d'Ivoire: Structural*
582 *framework inherited from intra-continental shearing*. PhD Thesis. University of
583 Gothenburg. Gothenburg, Sweden.

584 DOUST, H. & OMATSOLA, E. (1990) Niger Delta. In: *Divergent/passive Margin Basins* (Ed.
585 by J. D. Edwards & P. A. Santogrossi), *AAPG Memoir*, **48**, 239-248.

586 DUROTOYE, B. (1989) Quaternary sediments in Nigeria. In: *Geology of Nigeria, 2nd edition*
587 (Ed. by C. A. Kogbe), 431–444. Rock View International, Paris, France.

588 EMERY, K.O., UCHUPI, E., PHILLIPS, J., BOWIN, C.O., & MASCLE, J. (1975) Continental
589 margin of Western Africa: Angola to Sierra Leone. *Am. Assoc. Pet. Geol. Bull.*, **59**, 2209-
590 2265.

591 ESCHENBRENNER, R. & GRANDIN, G. (1970) La séquence de cuirasses et ses
592 différenciations entre Agnibiléfrou et Diébougou (Haute-Volta). *Cah. ORSTOM, Sér.*
593 *Géol.*, **2**, 205-246.

594 FEYBESSE, J.-L., BILLA, M., GUERROT, C., DUGUEY, E., LESCUYER, J.-L., MILESI, J.-P.
595 & BOUCHOT, V. (2006) The paleoproterozoic Ghanaian province: Geodynamic model
596 and ore controls, including regional stress modeling. *Precambrian Res.*, **149**, 149-196.

597 FÖLSTER, H. (1969) Late Quaternary erosion phases in SW Nigeria. *Bull. Ass. Sénégal. Quatern.*
598 *Ouest Afr.*, **21**, 29–35.

599 FRITSCH, P. (1978) Chronologie relative des formations cuirassées et analyse géographique des
600 facteurs de cuirassement au Cameroun. *Trav. Doc. CEGET*, **33**, 114-132.

601 GILCHRIST, A.R. & SUMMERFIELD, M.A. (1990) Differential denudation and flexural
602 isostasy in formation of rifted-margin upwarps. *Nature*, **346**, 739-742.

603 GRANDIN, G. & HAYWARD, D.F. (1975) Aplanissements cuirassés de la péninsule de
604 Freetown (Sierra-Léone). *Cah. ORSTOM, sér. Géol.*, **7**, 11-16.

605 GRANDIN, G. (1976) *Aplanissements cuirassés et enrichissement des gisements de manganèse*
606 *dans quelques régions d'Afrique de l'Ouest*. ORSTOM, Paris, France.

607 GREIGERT, J. (1966) *Description des formations crétacées et tertiaires du Bassin des*
608 *Iullemmeden (Afrique occidentale)*. Editions BRGM, Paris, France.

609 GRIMAUD, J.-L. (2014) *Dynamique long-terme de l'érosion en contexte cratonique: l'Afrique de*
610 *l'Ouest depuis l'Eocène*. PhD Thesis, Toulouse University, Toulouse, France.

611 GRIMAUD, J.-L., CHARDON, D. & BEAUVAIS, A. (2014) Very long-term incision dynamics
612 of big rivers. *Earth Planet. Sci. Lett.*, **405**, 74-84.

613 GRIMAUD, J.-L., CHARDON, D., METELKA, V., BEAUVAIS, A. & BAMBA, O. (2015)
614 Neogene cratonic erosion fluxes and landform evolution processes from regional regolith
615 mapping (Burkina Faso, West Africa). *Geomorphology*, **241**, 315-330.

616 GUILLOCHEAU, F., ROUBY, D., ROBIN, C., HELM, C., ROLLAND, N., LE CARLIER DE
617 VESLUD, C. & BRAUN, J. (2012) Quantification and causes of the terrigenous
618 sediment budget at the scale of a continental margin: a new method applied to the
619 Namibia–South Africa margin. *Basin Res.*, **24**, 3-30.

620 GUILLOCHEAU, F., CHELALOU, R., LINOL, B., DAUTEUIL, O., ROBIN, C., MVONDO,
621 F., CALLEC, Y. & COLIN, J. P. (2015) Cenozoic landscape evolution in and around the
622 Congo Basin: constraints from sediments and planation surfaces. In: *Geology and*
623 *Resource Potential of the Congo Basin* (Ed. by M. J. de Wit, F. Guillocheau & M. C. J. de
624 Wit), *Regional Geology Reviews*, 271-313. Springer Berlin Heidelberg, Berlin Germany.

625 HAACK, R.C., SUNDARARAMAN, P., DIEDJOMAHOR, J.O., XIAO, H., GANT, N.J.,
 626 MAY, E.D. & KELSCH, K. (2000) Niger Delta petroleum systems, Nigeria. In:
 627 *Petroleum systems of South Atlantic margins* (Ed. by M. R. Mello & B. J. Katz), *AAPG*
 628 *Memoir*, **48**, 213–231.

629 HELM, C. (2009) *Quantification des flux sédimentaires anciens à l'échelle d'un continent : le*
 630 *cas de l'Afrique au Méso-Cénozoïque*. PhD Thesis. Rennes University, Rennes, France.

631 JERMANNAUD, P., ROUBY, D., ROBIN, C., NALPAS, T., GUILLOCHEAU, F. &
 632 RAILLARD, S. (2010) Plio-Pleistocene sequence stratigraphic architecture of the eastern
 633 Niger Delta: A record of eustasy and aridification of Africa. *Mar. Pet. Geol.*, **27**, 810-821.

634 JEROLMACK, D.J. & PAOLA, C. (2010) Shredding of environmental signals by sediment
 635 transport. *Geophys. Res. Lett.*, **37**, L19401.

636 KING, L.C. (1962) *The Morphology of the Earth*. Oliver and Boyd, Edinburgh, UK.

637 LABAILS, C., OLIVET, J.-L., ASLANIAN, D. & ROEST, W.R. (2010) An alternative early
 638 opening scenario for the Central Atlantic Ocean. *Earth Planet. Sci. Lett.*, **297**, 355-368.

639 LAVIER, L.L., STECKLER, M.S. & BRIGAUD, F. (2001) Climatic and tectonic controls on the
 640 Cenozoic evolution of the West African margin. *Mar. Geol.*, **178**, 63-80.

641 LETURMY, P., LUCAZEAU, F., & BRIGAUD, F. (2003) Dynamic interactions between the
 642 gulf of Guinea passive margin and the Congo River drainage basin: 1. Morphology and
 643 mass balance. *J. Geophys. Res.: Solid Earth*, **108**, 2156-2202.

644 LINOL, B., DE WIT, M.J., GUILLOCHEAU, F., DE WIT, M.C.J., ANKA, Z. & COLIN, J.-P.
 645 (2014) Formation and Collapse of the Kalahari Duricrust ['African Surface'] Across the
 646 Congo Basin, with Implications for Changes in Rates of Cenozoic Off-Shore
 647 Sedimentation. In: *Geology and Resource Potential of the Congo Basin* (Ed. by M. J. de

648 Wit, F. Guillocheau & M. C. J. de Wit), *Regional Geology Reviews*, 193-210. Springer
649 Berlin Heidelberg, Berlin Germany.

650 MACGREGOR, D.S., ROBINSON, J. & SPEAR, G. (2003) Play fairways of the Gulf of Guinea
651 transform margin. In: *Petroleum Geology of Africa: New Themes and Developing*
652 *Technologies*. (Ed. by T. J. Arthur, D. S. MacGregor & N. R. Cameron), *Geol. Soc.*
653 *London Spec. Publ.*, **207**, 131-150.

654 MACGREGOR, D.S. (2013) Late Cretaceous–Cenozoic sediment and turbidite reservoir supply
655 to South Atlantic margins. *Spec. Publ. - Geol. Soc. London*, **369**, 109-128.

656 MALLET, J.L. (1992) Discrete smooth interpolation in geometric modelling. *Computer-Aided*
657 *Design*, **24**, 178-191.

658 MÉTIVIER, F. & GAUDEMER, Y. (1999) Stability of output fluxes of large rivers in South and
659 East Asia during the last 2 million years: implications on floodplain processes. *Basin Res.*,
660 **11**, 293-303.

661 MÉTIVIER, F., GAUDEMER, Y., TAPPONNIER, P., & KLEIN, M., (1999) Mass accumulation
662 rates in Asia during the Cenozoic. *Geophys. J. Int.*, **137**, 280-318.

663 MICHEL, P. (1973) *Les bassins des fleuves Sénégal et Gambie : étude géomorphologique*.
664 ORSTOM, Paris, France.

665 MICHEL, P. (1977a) Les modelés et dépôts du Sahara méridional et Sahel et du Sud-Ouest
666 africain. *Rech. Géograph. Strasbourg*, **5**, 5-39.

667 MICHEL, P. (1977b) Recherches sur le Quaternaire en Afrique occidentale. *Supp. Bull. AFEQ*,
668 **50**, 143-153.

669 MILLOT, G. (1970) *Geology of Clays*. Springer Verlag, Berlin, Germany.

670 MOLNAR, P. (2004) Late Cenozoic increase in accumulation rates of terrestrial sediment: How
671 Might Climate Change Have Affected Erosion Rates? *Annu. Rev. Earth Planet. Sci.*, **32**,
672 67-89.

673 MOULIN, M., ASLANIAN, D. & UNTERNEHR, P. (2010) A new starting point for the South
674 and Equatorial Atlantic Ocean. *Earth-Sci. Rev.*, **98**, 1-37.

675 NEWILL, D. & DOWLING, J.W.F. (1968) Laterites in West Malaysia and Northern Nigeria. *Int.*
676 *Conf. SMFE, Spec. Sess. on Eng. Properties of Lateritic Soils*, **2**, 133-150.

677 PAZZAGLIA, F.J. & GARDNER, T.W. (1994) Late Cenozoic flexural deformation of the
678 middle U.S. Atlantic passive margin. *J. Geophys. Res.: Solid Earth*, **99**, 12143-12157.

679 RADIER, H. (1959) *Contribution à l'étude géologique du Soudan oriental (AOF). 2 Le bassin*
680 *crétacé et tertiaire de Gao le détroit soudanais*. Service de géologie et de prospection
681 minière, Dakar, Sénégal.

682 REIJERS, T. (2011) Stratigraphy and sedimentology of the Niger Delta. *Geologos*, **17**, 133-162.

683 RIFFEL, S. B., VASCONCELOS, P. M., CARMO, I. O. & FARLEY, K. A. (2015) Combined
684 $^{40}\text{Ar}/^{39}\text{Ar}$ and (U–Th)/He geochronological constraints on long-term landscape
685 evolution of the Second Paraná Plateau and its ruiniform surface features, Paraná, Brazil,
686 *Geomorphology*, **233**, 52-63.

687 ROBIN, C., GUILLOCHEAU, F., JEANNE, S., PORCHER, F. & CALVÈS, G. (2011)
688 Cenozoic siliciclastic fluxes evolution around Africa. *Geophys. Res. Abstr.*, **13**,
689 EGU2011-5659.

690 ROGNON, P., GOURINARD, Y., BANDET, Y., KOENIGUER, J.C. & DELTEIL-DESNEUX,
691 F. (1983) Précisions chronologiques sur l'évolution volcanotectonique et

692 géomorphologique de l'Atakor (Hoggar); apports des données radiométriques (K/Ar) et
 693 paléobotaniques (bois fossiles). *Bull. Soc. Géol. Fr.*, **25**, 973-980.

694 ROUBY, D., BONNET, S., GUILLOCHEAU, F., GALLAGHER, K., ROBIN, C.,
 695 BIANCOTTO, F., DAUTEUIL, O. & BRAUN, J. (2009) Sediment supply to the Orange
 696 sedimentary system over the last 150 My: An evaluation from sedimentation/denudation
 697 balance. *Mar. Pet. Geol.*, **26**, 782-794.

698 ROUBY, D., BRAUN, J., ROBIN, C., DAUTEUIL, O. & DESCHAMPS, F. (2013) Long-term
 699 stratigraphic evolution of Atlantic-type passive margins: A numerical approach of
 700 interactions between surface processes, flexural isostasy and 3D thermal subsidence.
 701 *Tectonophysics*, **604**, 83-103.

702 ROUGIER, S., MISSENARD, Y., GAUTHERON, C., BARBARAND, J., ZEYEN, H., PINNA,
 703 R., LIÉGEOIS, J.-P., BONIN, B., OUABADI, A., DERDER, M.E.-M. & DE
 704 LAMOTTE, D.F. (2013) Eocene exhumation of the Tuareg Shield (Sahara Desert,
 705 Africa). *Geology*, **41**, 615-618.

706 SADLER, P.M. (1981) Sediment accumulation rates and the completeness of stratigraphic
 707 sections. *J. Geol.*, **89**, 569–584.

708 SÉRANNE, M. (1999) Early Oligocene stratigraphic turnover on the west Africa continental
 709 margin: a signature of the Tertiary greenhouse-to-icehouse transition? *Terra Nova*, **11**,
 710 135-140.

711 SÉRANNE, M. & NZÉ ABEIGNE, C.-R. (1999) Oligocene to Holocene sediment drifts and
 712 bottom currents on the slope of Gabon continental margin (west Africa): Consequences
 713 for sedimentation and southeast Atlantic upwelling. *Sed. Geol.*, **128**, 179-199.

714 SIMOES, M., BRAUN, J. & BONNET, S. (2010) Continental-scale erosion and transport laws:
 715 A new approach to quantitatively investigate macroscale landscapes and associated

716 sediment fluxes over the geological past. *Geochem. Geophys. Geosyst.*, **11**, Q09001,
 717 doi:10.1029/2010GC003121

718 TARDY, Y. & ROQUIN, C. (1998) *Dérive des continents, paléoclimats et altérations tropicales*.
 719 BRGM, Orléans, France.

720 TEEUW, R.M. (2002) Regolith and diamond deposits around Tortiya, Ivory Coast, West Africa.
 721 *CATENA*, **49**, 111-127.

722 THOMAS, M.F. (1980) *Timescales of landform development on tropical shields; a study from*
 723 *Sierra Leone*. In: *Timescales in Geomorphology* (Ed. by R.A Cullingford, D.A. Davidson
 724 & J. Lewin), 333-354. John Wiley & Sons, Chichester, UK.

725 THOMAS, M.F. (1994) *Geomorphology in the Tropics: A Study of Weathering and Denudation*
 726 *in Low Latitudes*. John Wiley & Sons, New York, US.

727 VALETON, I. (1991) Bauxites and associated terrestrial sediments in Nigeria and their position
 728 in the Bauxite belts of Africa. *J. Afr. Earth Sci.*, **12**, 297-310.

729 VASCONCELOS, P.M. & CONROY, M. (2003) Geochronology of weathering and landscape
 730 evolution, Dugald River valley, NW Queensland, Australia. *Geochim. Cosmochim. Acta*,
 731 **67**, 2913–2930. doi:10.1016/S0016-7037(02)0137

732 VASCONCELOS, P.M., BRIMHALL, G.H., BECKER, T.A. & RENNE, P.R. (1994a) $^{40}\text{Ar}/^{39}\text{Ar}$
 733 analysis of supergene jarosite and alunite: Implications to the paleoweathering history of
 734 the western USA and West Africa. *Geochim. Cosmochim. Acta*, **58**, 401-420.

735 VASCONCELOS, P.M., RENNE, P.R., BRIMHALL, G.H. & BECKER, T.A. (1994b) Direct
 736 dating of weathering phenomena by $^{40}\text{Ar}/^{39}\text{Ar}$ and K-Ar analysis of supergene K-Mn
 737 oxides. *Geochim. Cosmochim. Acta*, **58**, 1635–1665. doi:10.1016/0016-7037(94)9056

- VILLENEUVE, M. (2005), Paleozoic basins in West Africa and the Mauritanide thrust belt. *J. Afr. Earth Sci.*, 43(1-3), 166-195.
- WALFORD, H.L. & WHITE, N.J. (2005) Constraining uplift and denudation of west African continental margin by inversion of stacking velocity data. *J. Geophys. Res.*, **110**, B04403.
- WINDOM, H.L. (1975) Eolian contributions to marine sediments. *J. Sediment. Res.*, **45**, 520-529.
- YE, J., CHARDON, D., ROUBY, D., GUILLOCHEAU, F., DALL'ASTA, M., FERRY, J.N. & BROUCKE, O. (2017) Paleogeographic and structural evolution of northwestern Africa and its Atlantic margins since the Early Mesozoic. *Geosphere*, **13**, in press.
doi:10.1130/GES01426.1
- ZACHOS, J., PAGANI, M., SLOAN, L., THOMAS, E. & BILLUPS, K. (2001) Trends, Rhythms, and Aberrations in Global Climate 65 Ma to Present. *Science*, **292**, 686-693.

FIGURES CAPTIONS

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.

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).

Fig. 3: Denudation chronology of Sub-Saharan West Africa during the Cenozoic. [a] Distribution of lateritic paleo-landsurfaces 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 $\delta^{18}\text{O}$ 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).

Fig. 4: Interpretation of paleo-landscape distribution after our field work in several type-locations in West Africa (see location on Fig. 2). Google-Earth view and interpretation of paleo-surface 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 color code of relict landforms interpretations is similar to Fig. 3.

Fig. 5: [a] Map of the ~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 paleo-surface, which have been eroded, on the basis that a bauxitic weathering profile cannot exceed the maximum depth of 120 m (estimates based on electric profiles; Boulangé et al., 1973).

Fig. 6: [a] Simplified map of the 4 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.

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.

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.

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 Supporting Information). [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 Supporting Information 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.

Location	Interval	Eroded volume (10 ³ km ³)	Average equivalent denudation		Exported volume		Clastic export rate (10 ³ m ³ Myr ⁻¹)	Clastic yield (t km ⁻² yr ⁻¹)
			depth (m)	rate (m Myr ⁻¹)	total (V_{ex}) (10 ³ km ³)	clastic (V_c) (10 ³ km ³)		
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		

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

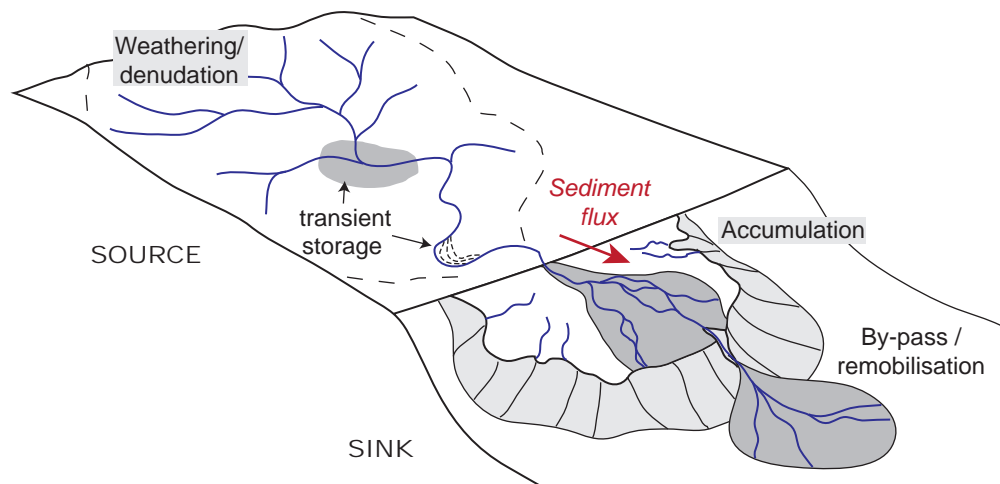
825

	Interval	Accumulated volume
	(Ma)	(10 ³ km ³)
<i>S3 - modern</i>	1.8 - 0	46.8 ± 6.3
	5.3 - 1.8	142.3 ± 19.9
	11.6 - 5.3	127.7 ± 17.8
<i>S2 - S3</i>	16 - 11.5	85.4 ± 11.9
	23 - 11.5	61 ± 8.5
<i>S1 - S2</i>	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

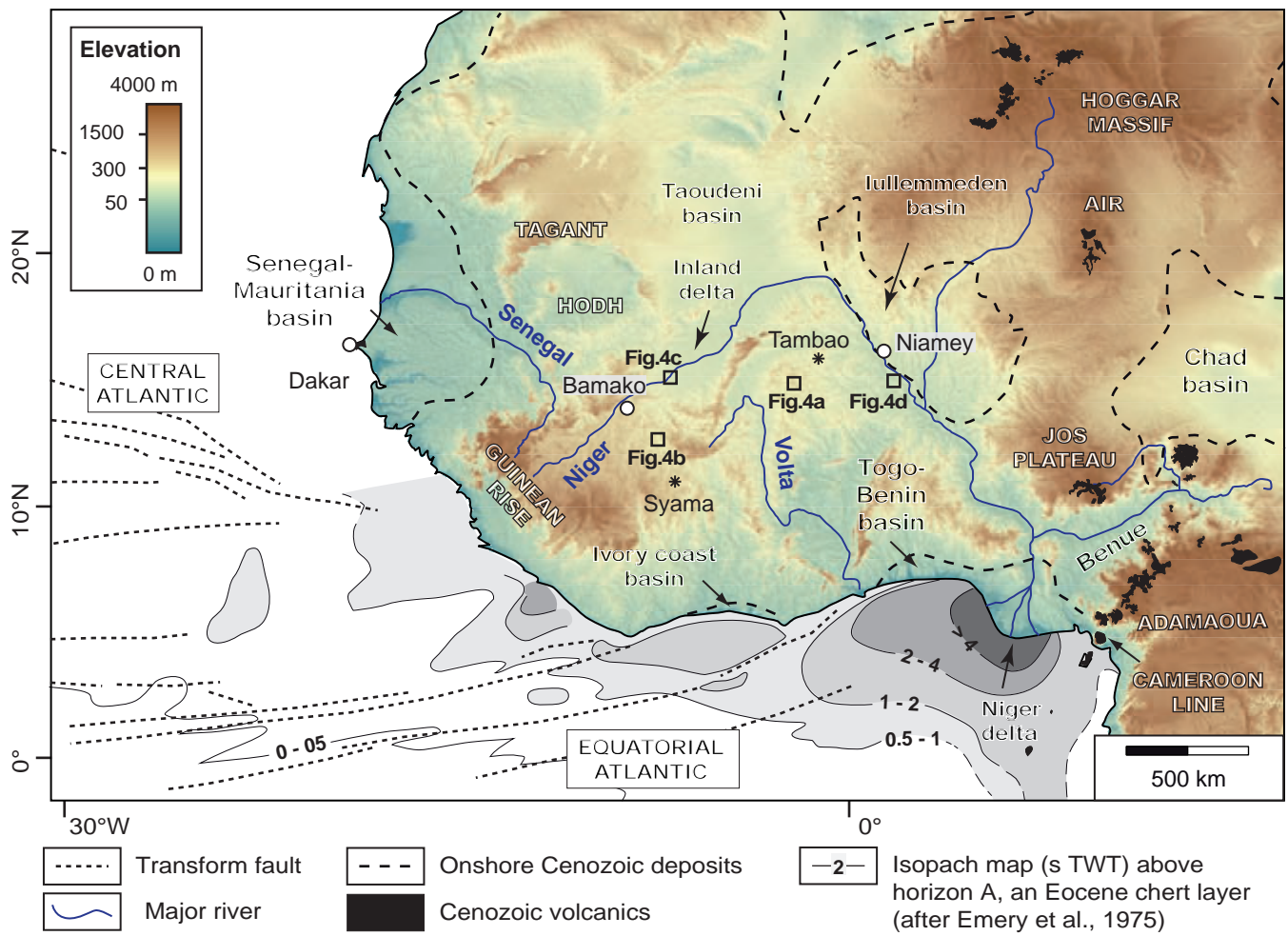
826

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

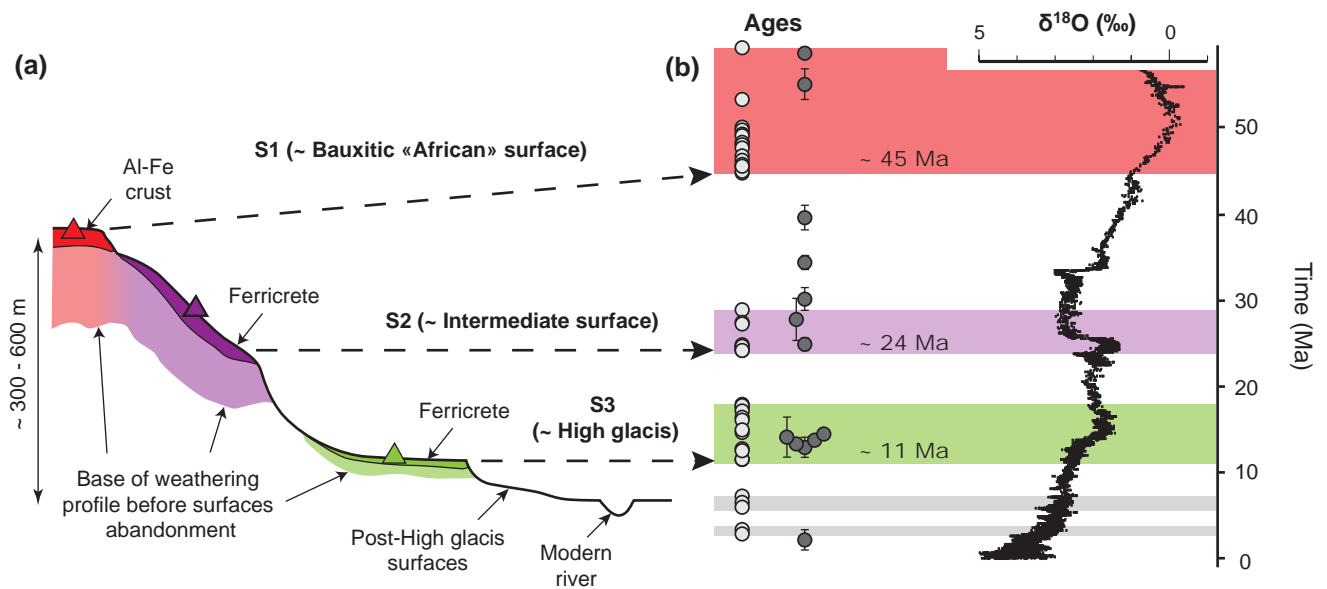
828



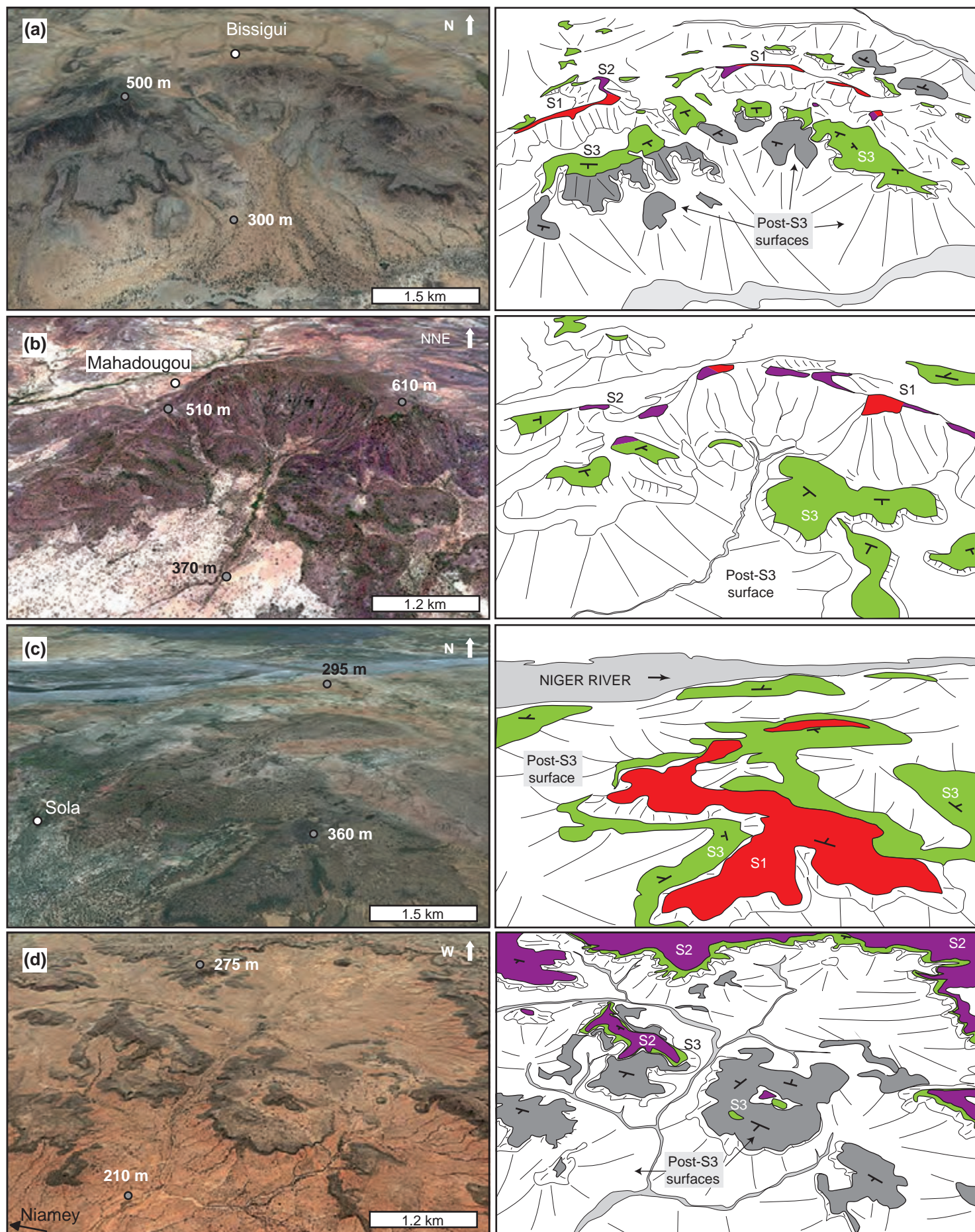
Grimaud et al., Fig. 1



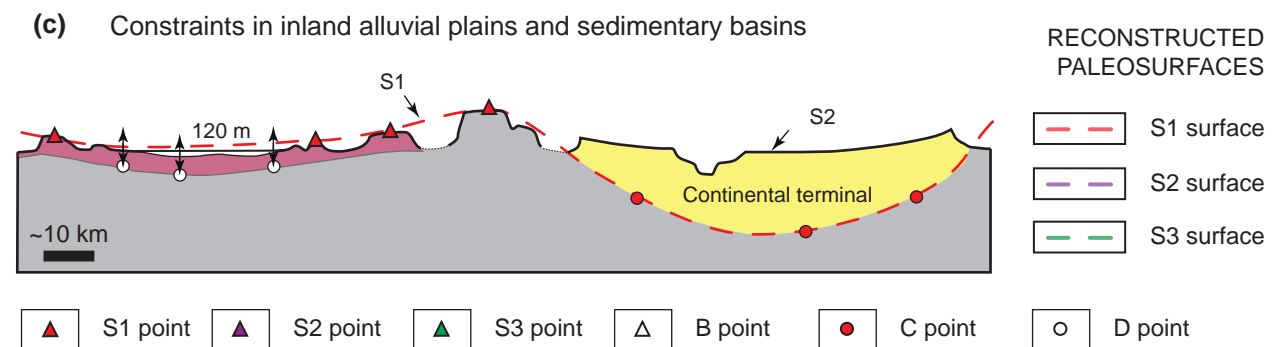
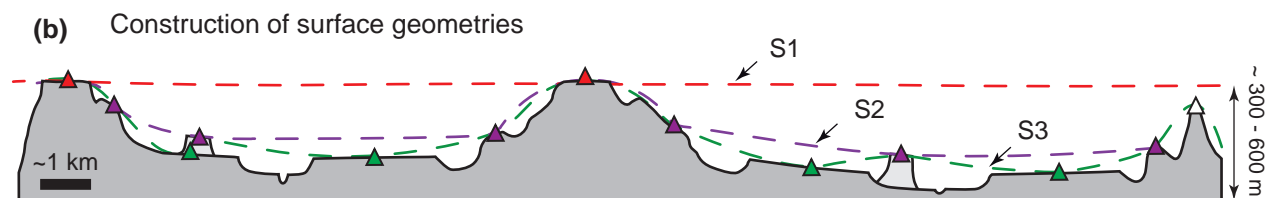
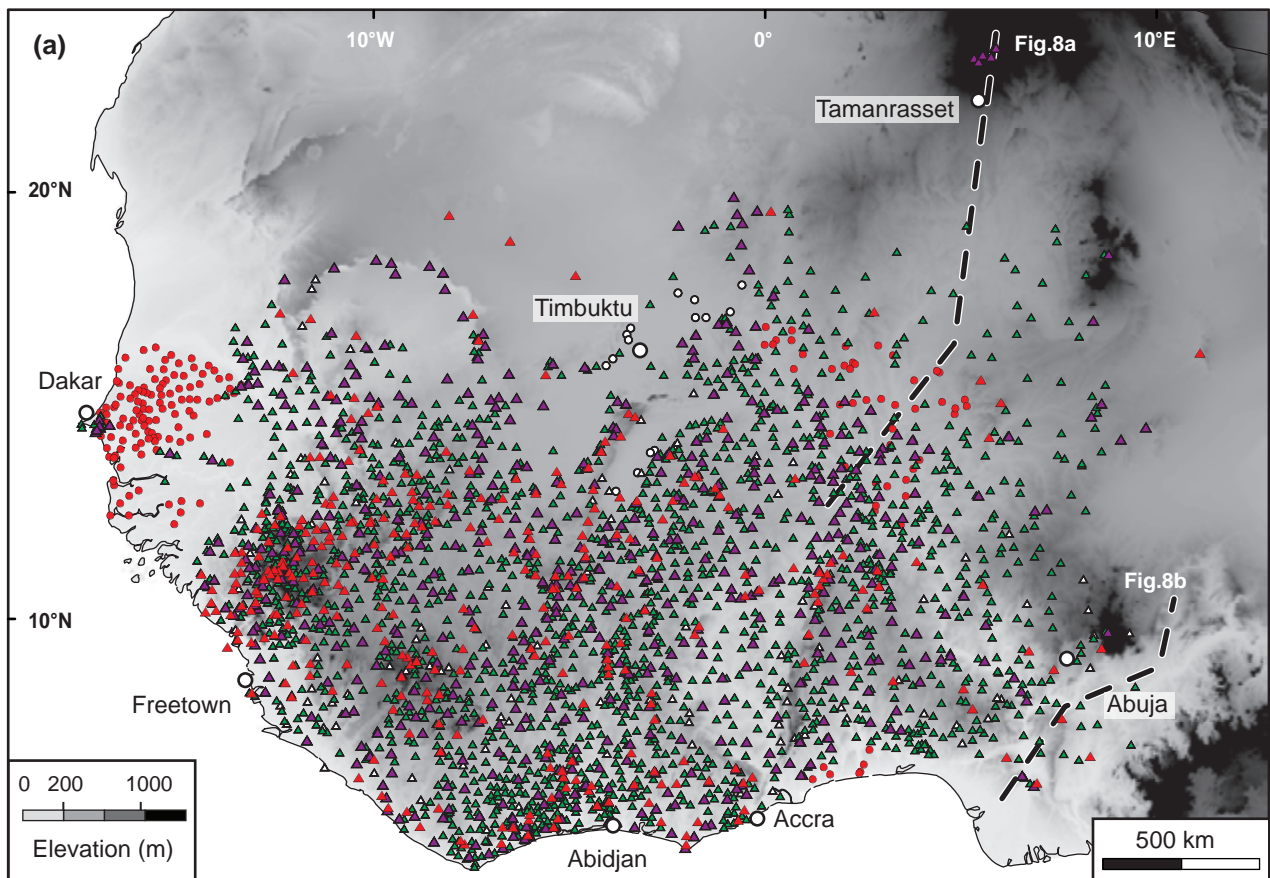
Grimaud et al., Fig. 2



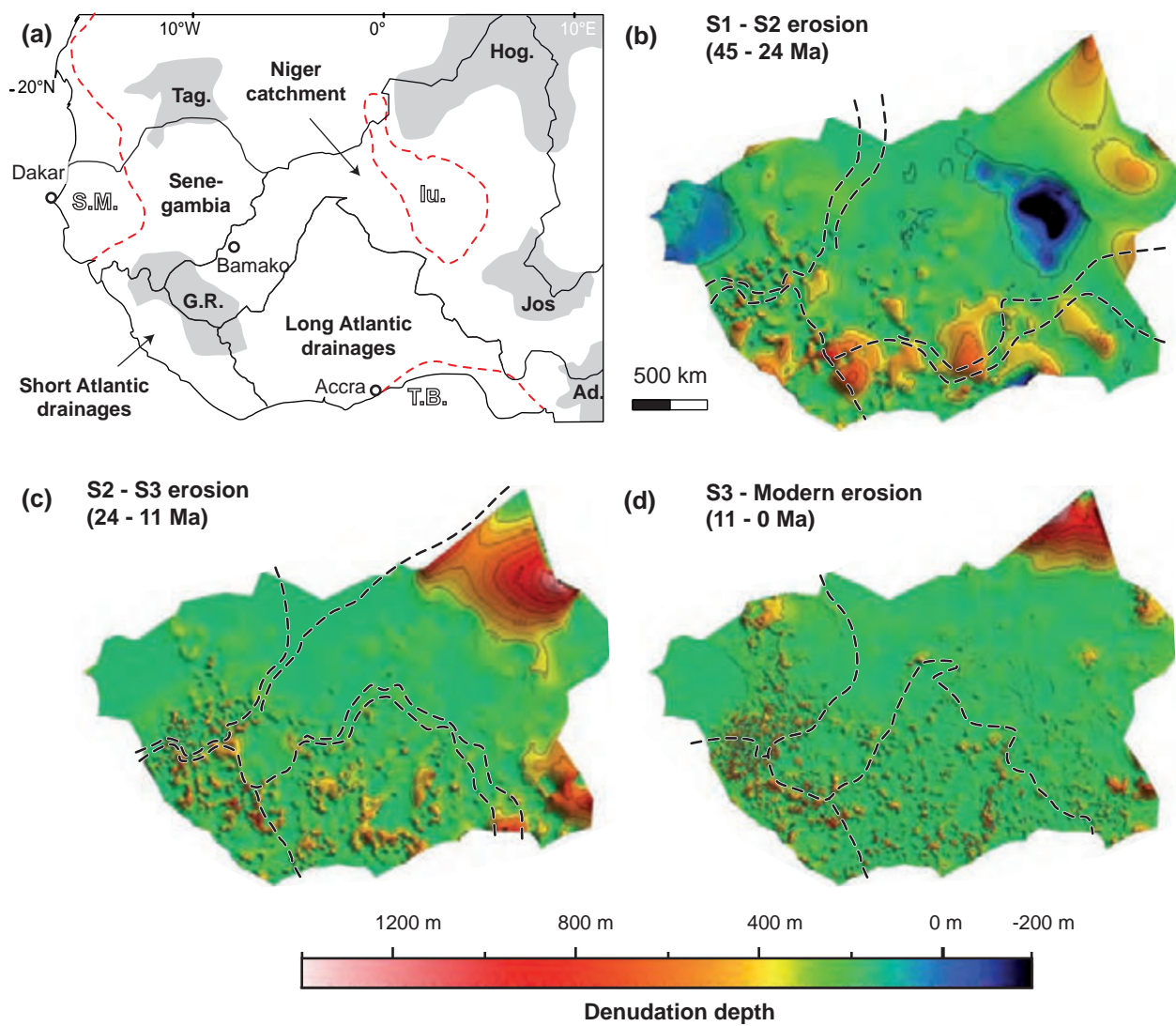
Grimaud et al., Fig. 3



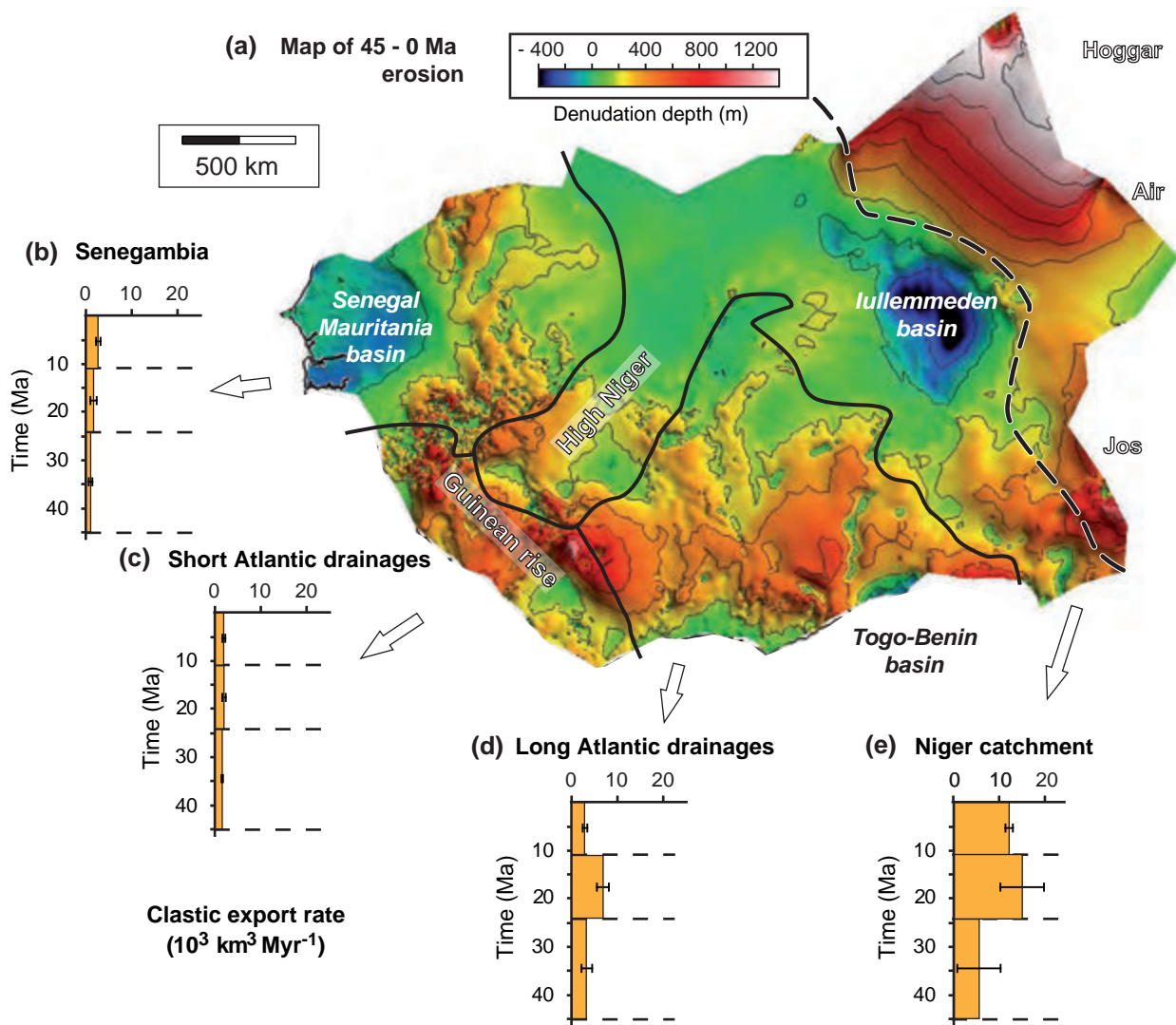
Grimaud et al., Fig. 4



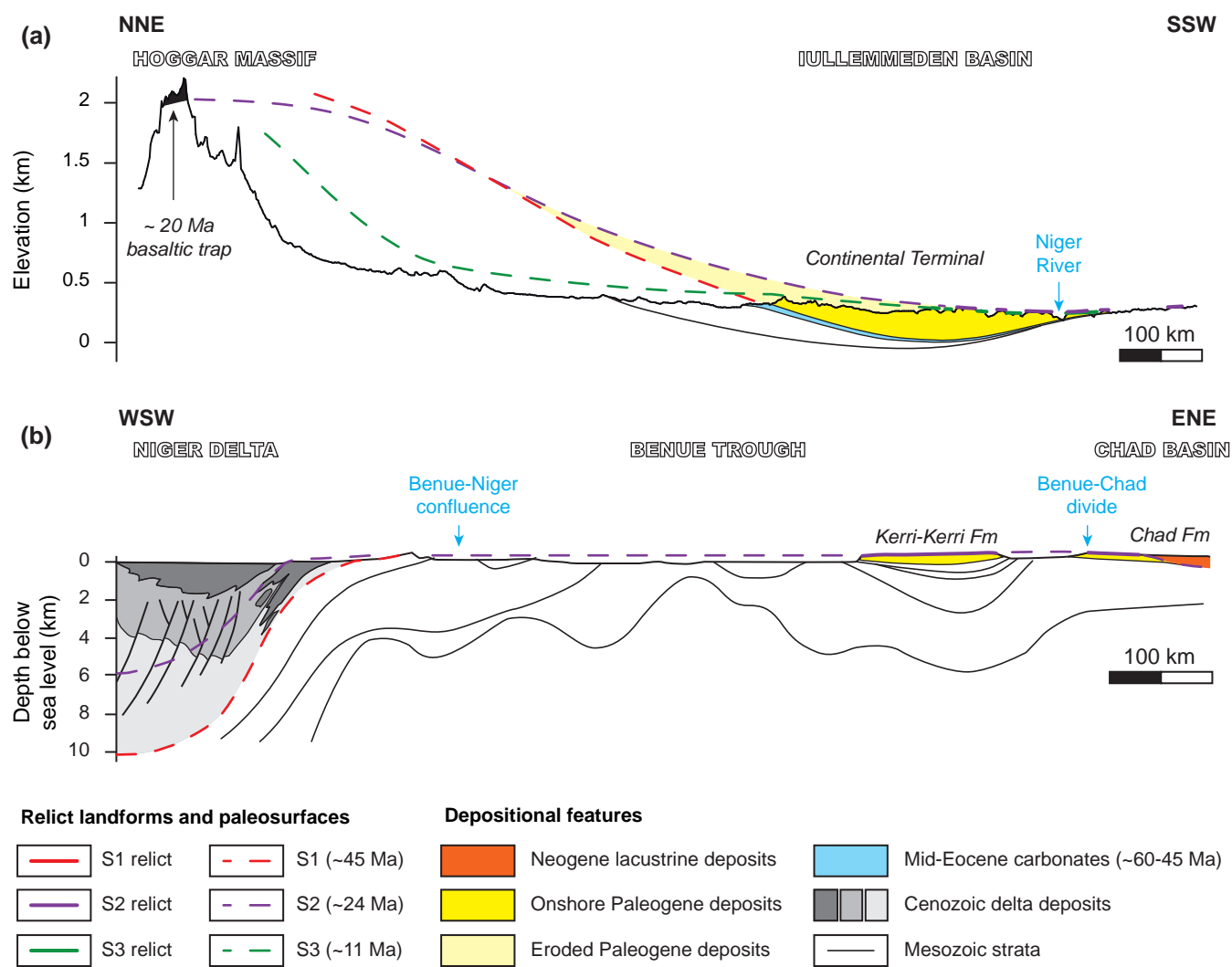
Grimaud et al., Fig. 5



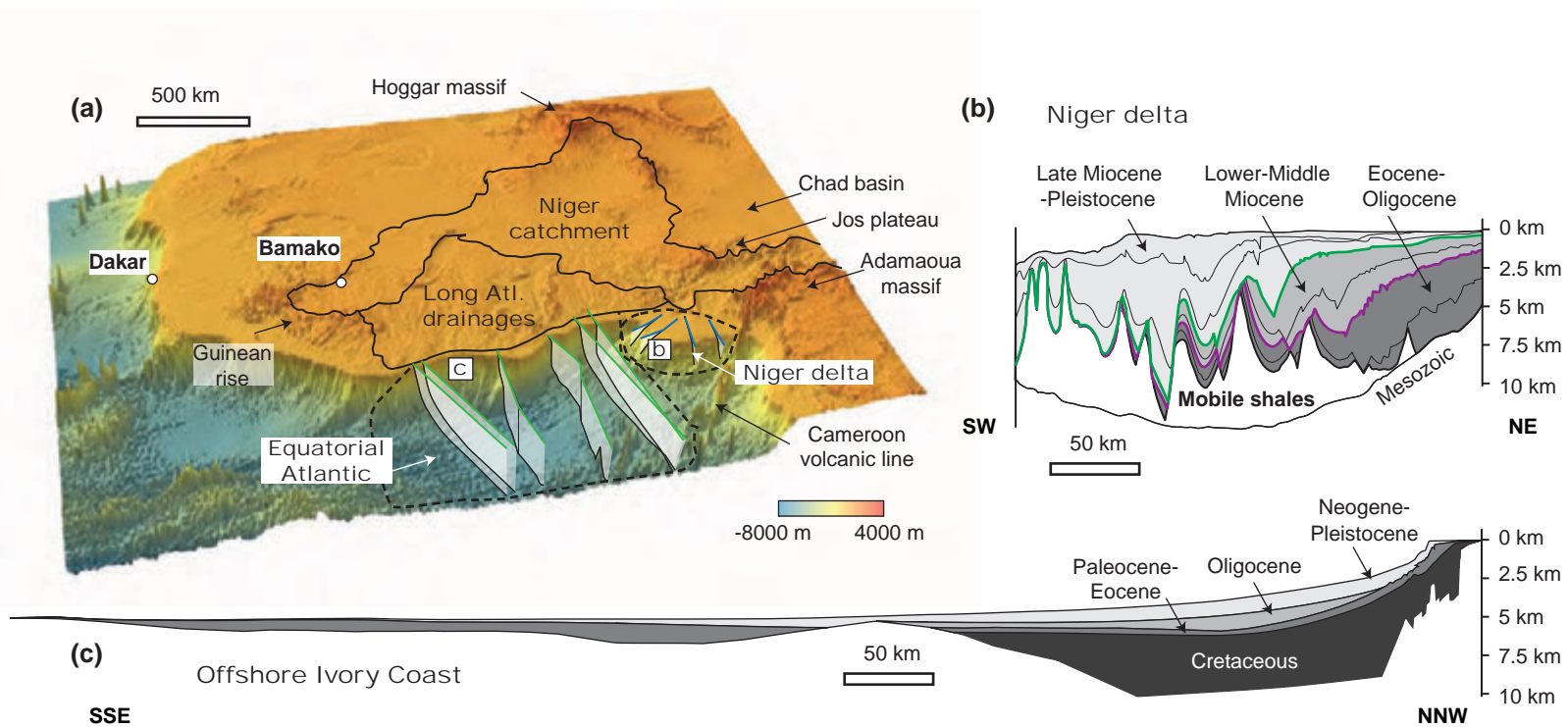
Grimaud et al., Fig. 6



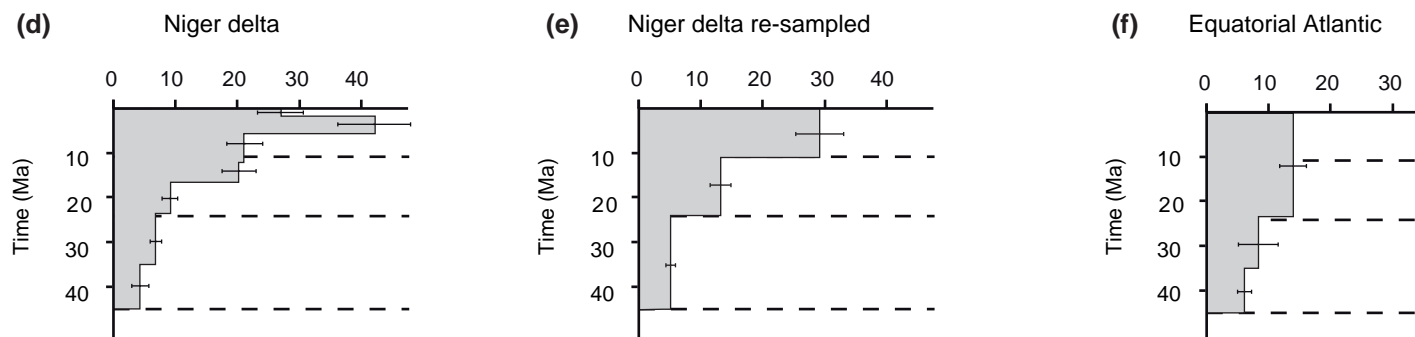
Grimaud et al., Fig. 7



Grimaud et al., Fig. 8



Accumulation rates ($10^3 \text{ km}^3 \text{ Myr}^{-1}$)



Grimaud et al., Fig. 9