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PII: S0169-555X(15)00203-2
DOI: doi: [10.1016/j.geomorph.2015.04.006](https://doi.org/10.1016/j.geomorph.2015.04.006)
Reference: GEOMOR 5172

To appear in: *Geomorphology*

Received date: 7 November 2014
Revised date: 1 April 2015
Accepted date: 6 April 2015

Please cite this article as: Grimaud, Jean-Louis, Chardon, Dominique, Metelka, Václav, Beauvais, Anicet, Bamba, Ousmane, Neogene cratonic erosion fluxes and landform evolution processes from regional regolith mapping (Burkina Faso, West Africa), *Geomorphology* (2015), doi: [10.1016/j.geomorph.2015.04.006](https://doi.org/10.1016/j.geomorph.2015.04.006)

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**Neogene cratonic erosion fluxes and landform
evolution processes from regional regolith mapping
(Burkina Faso, West Africa)**

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Submitted to **Geomorphology**, 7 November 2014 (MS #5234)

Revised manuscript, submitted 1 April 2015

Abstract

The regionally correlated and dated regolith-paleolandform sequence of Sub-Saharan West Africa offers a unique opportunity to constrain continental-scale regolith dynamics as the key part of the sediment routing system. In this study, a regolith mapping protocol is developed and applied at the scale of Southwestern Burkina Faso. Mapping combines field survey and remote sensing data to reconstruct the topography of the last pediplain that formed over West Africa in the Early and Mid-Miocene (24-11 Ma). The nature and preservation pattern of the pediplain are controlled by the spatial variation of bedrock lithology and are partitioned among large drainage basins. Quantification of pediplain dissection and drainage growth allows definition of a cratonic background denudation rate of 2 m/My and a minimum characteristic timescale of 20 Ma for shield resurfacing. These results may be used to simulate minimum export fluxes of drainage basins of constrained size over geological timescales. Background cratonic denudation results in a clastic export flux of $\sim 4 \text{ t/km}^2/\text{yr}$, which is limited by low denudation efficiency of slope processes and correlatively high regolith storage capacity of tropical shields. These salient characteristics of shields' surface dynamics would tend to smooth the riverine export fluxes of shields through geological time.

Keywords: Regolith; Pediment; Landform evolution processes; Sediment routing system; Source to sink.

1. Introduction

Interactions between landform evolution and regolith production and mobility over shields exert first-order controls on the source, pathways and fluxes of sediments

and solutes over very large emerged surfaces on geological timescales (e.g., Fairbridge and Finkl, 1980; Millot, 1983). Constraining these interactions on continental scales is therefore relevant to quantifying the contribution of shields, as opposed to that of orogens, to global sediment budgets and biogeochemical cycles in the context of long-term Cenozoic climate cooling (Ollier and Pain, 1996a; Molnar, 2004; Willenbring and von Blanckenburg, 2010; Goudie and Viles, 2012; Willenbring et al., 2013; Larsen et al., 2014). Large-scale studies of regolith transfers are also necessary for “source to sink” analyses of coupled drainage areas and sedimentary basins. The present contribution aims to quantify long-term landform evolution, regolith mobility and erosional export fluxes over a large region representative of shields’ sediment routing systems.

Tropical shields are mantled by lateritic regoliths derived from intense rock weathering. Such lateritic covers are subject to remobilization by slope and fluvial processes, and the reworked regoliths are commonly re-weathered after transport (Ollier and Pain, 1996b). Renewed periods of regolith production by weathering and remobilization by pedimentation lead to the formation of composite landscapes consisting in a mosaic of lateritic paleo-landsurface remnants of various generations. Such landscapes are spectacularly preserved throughout Sub-Saharan West Africa, a region of more than 4.5 million km² over which a long-recognized Cenozoic regolith-paleo-landsurface sequence has been dated (Beauvais et al., 2008) and correlated (Beauvais and Chardon, 2013).

Here we develop a field- and remote sensing-based regolith-landform mapping protocol applied over Southwestern Burkina Faso (Fig. 1). The investigated area is large (ca. 300 x 300 km) and exposes the most widespread, type geologic and morphoclimatic configuration of the West African surface (granite-greenstone terrains and flat sandstones in the Guinean and Soudanian climatic zones i.e., between 10 and 13°N; Fig.

1). Given the constrained chronological framework of regolith-landform production over the sub-region, the selected area is therefore suitable for the characterization of landscape and regolith dynamics and the quantification of long-term (10^6 - 10^7 yr) erosion representative of shields surfaces. Regoliths are studied here both as in-situ produced or transported sediments and as paleo-landscape remnants. The obtained regolith-landform map allows evaluation of the nature, distribution and preservation of regolith mantles derived from a pediplain elaborated during the Early and Middle Miocene (ca. 24-11 Ma) over the sub-region. Based on this map, a topographic reconstruction of the pediplain is used to visualize regolith redistribution on slopes during pedimentation and to evaluate landscape and drainage evolution after its abandonment 11 Ma ago. Quantification of post-11 Ma dissection of the pediplain leads to estimation of a type-erosion flux for shields, emphasizing the low capacity of slope and alluvial processes to remove and export regolith mantles.

2. Geomorphological and geological background

2. 1. *The West African geomorphic sequence and its regoliths*

The following summary of the West African sequence of stepped lateritic paleo-landsurfaces (Fig. 2a) is based mostly on the works of Michel (1959, 1973, 1974), Eschenbrenner and Grandin (1970), Boulangé et al. (1973), Grandin (1976), Boulangé and Millot (1988) (see Chardon et al., 2006; Beauvais and Chardon, 2013).

Each member in the sequence has a distinct regolith cover and geomorphic character. The first two members of the sequence are the bauxitic and so-called Intermediate surfaces, which bear thick *in-situ* formed regoliths capped by bauxites and ferricretes, respectively. Bauxites are the end-product of a period of enhanced chemical weathering that started in the Late Cretaceous and culminated in the Mid-Eocene.

Bauxites seal a topography called the African Surface, which makes the present-day envelope of the West African relief. The Intermediate surface corresponds to a differentiated landscape carved in the African bauxitic surface. The following three stepped paleo-landsurfaces of the sequence are glacis (French term for pediments) called the High, Middle and Low glacis. Glacis surfaces are commonly covered by a detrital layer issued from degradation of earlier landforms. Each glacis has undergone weathering after pedimentation, indicating repeated transitions from arid or semi-arid pedimentation to seasonally contrasted or wet tropical weathering. Weathering periods generally ended with the formation of a ferricrete cementing the glacis surfaces and their detrital cover. Today, glacis occupy an overwhelming part of the West African landsurface (Beauvais and Chardon, 2013; Grimaud, 2014). The sequence is best preserved in the Sahelian and Soudanian climatic zones. The glacis, having undergone relief inversion, show evidence of degradation further south under the humid climate of the forest zone (Grandin, 1976). Though originally defined in the French-speaking countries, the sequence or elements of the sequence have been formally or implicitly identified and mapped in other countries of the sub-region (e.g., Fölster, 1969; Grandin and Hayward, 1975; Bowden, 1987; Durotoye, 1989; Thomas, 1980, 1994; Teeuw, 2002; see Beauvais and Chardon, 2013; Grimaud, 2014).

The Lower to Mid-Eocene age of peak weathering and abandonment of the bauxitic surface had long been stratigraphically bracketed (e.g., Millot, 1970). In absence of any stratigraphic constraints or radiometric data, the three glacis were thought to reflect Quaternary glacial – interglacial climatic cycles having led to the dissection of the Intermediate landscape of supposedly Latest Pliocene age (Michel, 1959). Absolute age constraints on the paleo-landsurface sequence were provided by radiometric ^{39}Ar - ^{40}Ar dating of supergene cryptomelane ($\text{K}_{1-2}\text{Mn}_8\text{O}_{16}$, $n\text{H}_2\text{O}$) around

Tambao in Northeastern Burkina Faso (Hénocque et al., 1998; Colin et al., 2005; Beauvais et al., 2008; summarized in Beauvais and Chardon, 2013; Fig. 1). Data retrieved from the weathering profiles of each surface relict define five Ar-Ar age groups (ca. 59 - 45, 29 - 24, 18 - 11, 7-6, and 3 Ma; Fig. 2b) bracketing periods of chemical weathering of the paleosurfaces. The lower limit of these age groups corresponds to the abandonment age of each paleosurface, i.e., the stabilization of the weathering front by the end of the weathering period preceding duricrusting and subsequent incision of each paleosurface (Fig. 2b). Abandonment ages are ca. 45 Ma for the African bauxitic surface and 24 Ma for the Intermediate surface. The High glaciais surface developed between ca. 24 and 11 Ma with a predominance of weathering between 18 and 11 Ma. In Syama (Southern Mali; Fig. 1), Ar-Ar ages on supergene alunite and jarosite (Vasconcelos et al., 1994) confirm predominance of weathering conditions during elaboration of the Intermediate surface until the end of the Oligocene and weathering of the High glaciais during the Mid-Miocene (Fig. 2b). Weathering and later abandonment of the Middle and Low glaciais have occurred around 7-6 and 3 Ma, respectively (Fig. 2).

2. 2. Geological context

The study area belongs to the Paleoproterozoic portion of the West African craton exposed South of the Sahara (e.g., Feybesse et al., 2006; Fig. 1). This area comprises Birimian (2.2-2.1 Ga) granite-greenstone terrains over two-thirds of its surface and the Neoproterozoic sandstones of the Taoudeni basin, which were intruded by dolerite sills (Fig. 3). The basement comprises the Banfora, Houndé and Boromo greenstone belts and intervening granitoids (Baratoux et al., 2011; Metelka et al., 2011; Fig. 3b). Greenstones consist mainly of mafic volcanics (basalts and andesites) and

volcanosediments, whereas granitoids comprise TTG (tonalite - trondhjemite – granodiorite) and granitic plutons. The escarpment delimiting the Banfora plateau marks the southeastern boundary of the Taoudeni basin (Fig. 3a). The southern part of the plateau bears the highest summits of the region and the height of the escarpment decreases towards the NE. The study area mostly belongs to the Mouhoun drainage system (the main stream of the Volta drainage system, i.e., the Black Volta) and is fringed by the catchments of the Upper Niger River to the west, the Comoé River to the southwest and the Nazinon River to the east (part of the Nakambé drainage system i.e., the White Volta; Figs. 1, 3).

2. 3. Earlier works on the study area

The pioneering study of Daveau et al. (1962) around Houndé and Gaoua (Fig. 3) led to the identification of stepped lateritic landsurfaces and to the description of what will be recognized later as the High glacia. Later on, the southern part of the study area and its extension in the Ivory Coast became one of the first regions where the entire West African regolith-landform sequence was thoroughly documented (Eschenbrenner and Grandin, 1970). Boeglin and Mazaltarim (1989) and Boeglin (1990) later focused on an area of ca. 50 x 30 km around Gaoua (Fig. 3), where they mapped the High glacia relicts and performed a detailed geochemical study of their ferricretes. More recently, Bamba (1996) and Bamba et al. (2002) have refined detailed mapping of the three glacia around the Poura mine (left bank of the Mouhoun River, West of Tô; Fig. 3) to study surface remobilization of gold. Lately, Butt and Bristow (2013), reporting on gold prospects of the area, argued for the stepped character of the glacia and the detrital nature of their ferricretes, which had been documented by geomorphologists since the late 1950's (e.g., Michel, 1959; Daveau et al., 1962) but largely ignored since then.

3. Field relationships and regional-scale regolith-landform mapping

3. 1. Rationale

As opposed to the other regolith-landform associations of the lateritic paleo-landsurfaces sequence, High glacia remnants have both distinctive field and remotely-sensed mappable properties at the resolution of the digital data and given the size of the map area (see below). Our work therefore focused on the High glacia regolith-landform associations, which were characterized and mapped for evaluation of the pedimentation and weathering processes controlling the development of the High glacia paleo-landsurface. The topography of this paleo-landsurface was then reconstructed as a datum for the quantification of regional erosion after its abandonment. Higher paleo-landsurface relicts of the sequence (i.e., bauxitic and Intermediate) were already inherited landforms incorporated to the High glacia landscape and are still preserved in the current landscape. As seen below, their duricrusts are also found as reworked elements in the High glacia regoliths. Field characteristics of the higher landsurfaces are therefore described and their occurrences reported in the regolith-landform map. Relicts of the Middle and Low glacia (i.e., lower landsurfaces) occupy lower parts of today's landscape that have been excavated in the High glacia surface. Their field characteristics are briefly described below.

3. 2. Field typology of landforms and associated regoliths

3. 2. 1. Field survey

Our field observations were carried out at stations (Fig. 3b), which consist of areas of several km², where landscape analysis was undertaken by interpreting sceneries using 1/50 000 and 1/200 000 scale topographic maps. Mapping of regolith-landform

units was undertaken at key stations. Landscape interpretations/chronologies and identification of paleo-landsurface relicts were complemented by in-situ examination of the regolith along tracks through the landscape and at road cuts. This work included the identification of the textures of the exposed lateritic weathering profile horizons and the description of the sedimentary facies of the transported regoliths.

3. 2. 2. Higher landsurfaces

Bauxite relicts form mesas on the highest summits. On the basement, those mesas are restricted to mafic substrates and their size is generally limited (i.e., less than 100 m wide) (Fig. 4a). In the Taoudeni basin, bauxitic plateaus are larger and mostly restricted to dolerites (Figs. 4b, 4c). The bauxites have typical pink-whitish pisolithic textures (Fig. 4d) or less evolved, nodular-mottled textures (Fig. 4e). In the Taoudeni basin, particularly on dolerites, the Intermediate ferricrete caps gently dipping convex-concave surfaces forming the downslope extension of the bauxitic plateaus (Figs. 4b, 4c). These ferricretes (Figs. 4f, 4g) show gradational variation in composition and texture with the bauxites. This is interpreted to result from iron leaching that leads to relative aluminum enrichment of the bauxites and net concomitant iron accumulation in the ferricretes (Boulangé, 1986). Intermediate ferricretes on sandstones display typical nodular textures (Fig. 4g). On the basement, the Intermediate ferricrete is rarely found in-situ but rather as pebbles or cobbles reworked in the High glacia ferricrete (see below). Instead, a residual “Intermediate relief” surrounds bauxitic duricrusts and may be locally paved with a cemented scree of bauxite cobbles (Fig. 4a). Bauxites are underlain by weathering profiles that are at least 80 m thick, as estimated on the stripped slopes of mesas, whereas Intermediate weathering profiles exceed 20 m in thickness.

3. 2. 3. High glacia

The best visible High glacia relicts are kilometer-scale plateaus (the largest ones being concave) shallowly dipping away from the topographic massifs made of mafic volcanics, which may carry higher relict paleo-landsurfaces (Fig. 5a). Such High glacia relicts are often separated from the massifs by a peripheral hollow due to incision of their upslope parts (see also Beauvais et al., 1999). This configuration indicates that the High glacia has occupied large piedmonts that have been dissected. Dissection of the High glacia ferricrete has carved 1 to 20 m-high scarps dominating slopes cut into soft regoliths and covered by ferricrete debris (Figs. 5, 6a, 6b).

Most High glacia plateau ferricretes consist of a conglomerate ranging from gravel to cobble, with a predominance of gravels mostly made of ferruginous nodules (Fig. 6). Matrix silts and sands may bear quartz, particularly on volcano-sediments and granitoids. Coarse gravels and cobbles are made of Intermediate-type ferricretes, vein quartz and bauxites (Figs. 6a-6e). Conglomerates are commonly matrix- or block-supported, suggesting emplacement by mudflow or debris flow process. Channels are observed at the base of the ferricrete and decimeter- to meter-scale oblique stratifications are recognized in the downslope parts of some large High glacia relicts (Fig. 6d). The coexistence of mud or debris flow and alluvial facies in the High glacia cover is indicative of interplay of slope and fluvial processes during pedimentation (Dohrenwend and Parsons, 2009).

The noticeable absence of a mottled horizon under the glacia conglomerate or exposure of deep portions of weathering profiles right under that cover (Figs. 6a, 6c) indicates that these weathering profiles have been truncated before deposition of the conglomerate. Duricrusting (i.e., iron impregnation or cementation) is mostly restricted

to the conglomerates cover (Figs. 6a, 6b). Still, soft ferricretes, i.e., pedogenic impregnation of a mottled clay lateritic horizon (Tardy, 1997), are common under the cemented conglomerates. This suggests renewed weathering along the upper fringe of the truncated lateritic profiles under the conglomerates. At certain locations, the ferricrete made of cemented debris flows may even be underlain by a type-succession of weathering profile horizons (i.e., soft ferricrete, mottled layer, fine saprolite, coarse saprolite; Figs. 6e, 6f), suggesting the full development of a weathering profile after pedimentation.

On granitoids located away from topographic massifs (e.g., west of Djigoué and south of Bobo Dioulasso, Tô region), the High glacia ferricretes are generally thinner (0.5 - 2 m) and mantle smooth interfluvies (Figs. 5c, 5d). Such ferricretes have vermicular and nodular textures and are devoid of clasts. They appear less ferruginous and less indurated than their plateau counterparts. These ferricretes show gradational contacts with underlying soft ferricretes and are part of in-situ weathering profiles.

3. 2. 4. Lower landsurfaces

The restricted size of higher paleo-landsurfaces remnants is primarily due to the development of the High glacia. But rejuvenation of the slopes of the residual reliefs carrying those remnants and the formation of peripheral hollows (Fig. 5) is attributed to the following periods of glacia formation. The landsurface between High glacia relicts and the modern alluviums is almost exclusively occupied by the Middle and Low glacia. These glacia may be stepped or may combine to form a single polygenic landsurface. The regolith of the Middle and Low glacia is comparable to that of the High glacia, but their ferricrete is generally thinner to absent and may be covered over large areas by loose material made of reworked saprolite, sand and ferruginous gravels.

3. 3. Regional-scale regolith-landform mapping protocol

On basement terrains, High glacia units were manually mapped in GIS on the basis of their airborne gamma ray spectrometry and their photo-interpretation signature (Google Earth), both validated by the field survey / maps (Figs. 3, 7). Airborne gamma ray spectrometry was acquired during the 1998–1999 SYSMIN (System for Mineral Products) project (Metelka et al., 2011). Those data display uranium (U), potassium (K) and thorium (Th) contents of the upper 30 cm of the Earth surface (Dickson and Scott, 1997). The spatial resolution of the data on the basement is 125 m (with an original line spacing of 500 m). Spatial resolution of 250 m (line spacing of 1000 m) over the Taoudeni basin has required resampling to 125 m in the area to obtain a harmonized image. Both the raw and enhanced (Th/K ratio) gamma-ray spectrometry data were used (Fig. 7) during the analysis and combined with the shaded relief maps of the SRTM (Shuttle Radar Topographic Mission) data (90 m spatial resolution). The High glacia ferricretes have a distinctive photo-interpretation texture that spatially matches blue-green colors in raw gamma-ray data. This attests of a strong depletion in potassium, and a relative enrichment in thorium and uranium as a result of weathering processes (Dickson and Scott, 1997; Wilford et al., 1997; Metelka et al., 2011). However, uranium has a complex behavior during weathering and regolith formation (Dickson and Scott, 1997; Wilford et al., 1997; Dequincey et al., 2002). Therefore, the Th/K ratio was preferred to further enhance the signature of the High glacia ferricretes (in yellow-red) and remove any regional gradients in the data (Figs. 7b, 7d).

The spatially homogeneous radiometric signature of the High glacia relicts suggests that their ferricretes have been geochemically homogenized by weathering despite the variability of their substrate. Indeed, trace element concentrations

systematically converge as a function of the Fe_2O_3 content of the ferricrete taken as an index of their geochemical maturity (Boeglin and Mazaltarim, 1989; Boeglin, 1990). Conversely, the ambiguous radiometric signature of the Middle and Low glacis may be interpreted as a lower maturity of their ferricrete and a mixed signature of the material covering their ferricrete.

The strong Th and exceptionally low K signatures of the Taoudeni basin (Figs. 7a, 7b) are explained by the mineralogy of the sandstones that are originally quartz rich and correlatively poor in clays. The larger pixel size (250 m) of the gamma ray spectrometry may have further modified the Th signature of High glacis ferricretes by sampling other surface material with high Th content (e.g., Bauxite and Intermediate duricrusts). Therefore, the high values (red colors) of Th/K ratio image (Fig. 7b) may not only be due to High glacis ferricretes. Hence, regolith-landform mapping over the Taoudeni basin was mainly based on photo-interpretation in Google Earth and field observations.

Bauxite and Intermediate surface relict occurrences were mapped by photo-interpretation, field observations and after Petit (1994). River plain sediments were mapped mainly on the basis of their negligible relief and the characteristic geometries of stream networks in the gamma-ray imagery. Because of the higher mobility of U compared to Th, river plain sediments raw gamma-ray signature may indeed vary i.e., color of the source material (variable content of radioelements), very light to white color (high U / Th / K signal), or very dark color (low U / Th / K signal). It might reflect the composition of the source material, sediment mixing, or strong attenuation by vegetation or water (Fig. 7a).

3. 4. Interpretation of the High glacis regolith-landform map

For the purpose of the interpretation, the mapped regolith-landform units were superimposed on the topography in Fig. 8 and on the geological map from Metelka et al. (2011) in Fig. 9. Comparison of these two maps highlights major contrasts in the pattern of High glaciae relicts' distribution on either side of the main watersheds, even on the same geological substrate. This is particularly exemplified on TTG across the southwestern and eastern Mouhoun watersheds (Figs. 8, 9a). Density of High glaciae relicts generally decreases when approaching the main streams (Fig. 8). Relicts are best preserved on TTG and granite (45 and 20% of the total surface of the relicts, respectively). Greenstones underlay less than 25% of the total area of the preserved High glaciae ferricrete (Figs. 3b, 9c). Fifteen percent of the map area of the TTG and more than 20% of the granitoids are covered by High glaciae ferricretes, whereas only 10% of the greenstones are covered (Fig. 9d).

Type-patterns of High glaciae regolith-landforms may be distinguished in the study area (Figs. 5, 9, 10). In high relief volcanic terrains, High glaciae relicts are well preserved on piedmonts (Fig. 10a), equally on greenstones and granitoids. Volcano-sedimentary-granitic terrains of moderate relief (e.g., Djigoué area) display High glaciae relicts that once coated wide N-S trending valleys, which were in turn dissected by second-order narrower E-W oriented valleys (Fig. 10b). Over TTG terrains of the Comoé catchment (e.g., Dandougou-Bobodioulasso area), a very low relief and very low slope High glaciae surface is preserved on sparse residual hills where the ferricrete may be dismembered into boulders resting on the soft ferricrete (Fig. 10c). The resulting landscape is a convexo-concave plain of low amplitude that is gently dipping towards the main stream (Fig. 10c). Equivalent TTG terrains in the Nakambe catchment reveal a better-preserved High glaciae paleo-landsurface (see above), with planar to weakly concave relicts delineating a plain of very low-relief surface envelope (Fig. 10d).

The occurrence of strong and thick plateau ferricretes upon granitoids on the piedmonts of volcanic reliefs contrasts with the weak and thin ferricretes preserved on the same granitoids of the low land (Figs. 5a-5d). This reflects the high iron content and thickness of the piedmont conglomerates made of reworked bauxitic and Intermediate duricrusts that formed on iron-rich mafic rocks. On the contrary, low land ferricretes are solely issued from in-situ weathering of iron poor granitoids. The limited lateritic cover of mafic volcanics massifs further argues for the transfer of upland iron-rich duricrusts as colluviums to the High glacia piedmonts. This transfer has resulted in net iron accumulation on glacia surfaces further down in the landscape (Michel, 1973, 1974; Beauvais et al., 1999).

The above analysis indicates that the High glacia landsurface was a pediplain, defined as a surface of coalescent pediments (Maxson and Anderson, 1935). The spatial distribution of these pediments and their regolith as well as the preservation pattern of the High glacia pediplain are spatially controlled at various scales. A first, local control of this distribution is exerted by the lithology of the bedrock. This sets the relief and therefore the pedimentation process, as well as the weathering mode of the pediplain. On a regional scale, pediplain dissection and erosion mode appear to have been compartmentalized among drainage basins.

4. Reconstruction of the Late Mid-Miocene pediplain and quantification of its erosion

4. 1. Methodology

The high density of High glacia relicts warrants reconstruction of the pediplain they were part of. The reconstructed topography is a triangulated surface interpolated from a set of geo-referenced points generated from the polygons of the High glacia

relicts using the DSI method (Gocad software; Mallet, 1992). Each High glacia polygon was converted to a grid of 500 m-spaced points inside its limits. The elevation of the SRTM digital elevation model, degraded to 500 m resolution, was then sampled for each point to form the High glacia relicts' elevation dataset. The interpolated surface was created from this dataset through a series of iterations. The number of surface's triangles, which reflected the distribution of the dataset for the first incremental surface, was increased at each iteration step, while the High glacia surface was forced to remain above the modern topography. This allowed for the inclusion of the reliefs dominating the pediplain and preserved the composite nature of the High glacia landscape. The resulting topography is shown on Fig. 11. Erosion post-dating the abandonment of the pediplain was obtained by subtracting the modern topography from that of the reconstructed pediplain (Figs. 11a-c). The drainage network and a slope map were then automatically extracted from both the modern and pediplain digital elevation models for comparison (Figs. 11d-h).

4. 2. Late Mid-Miocene topography and landscape dynamics

The pediplain displays the same first-order relief pattern as the current topography. The main divides such as the inselbergs and the main escarpment already existed at the time the pediplain was functional and did not migrate since then (Figs. 11a-b). The main river network was therefore already established since the Late Mid-Miocene with the exception of a few local river rearrangements (Figs. 11d, 11h). Our reconstruction does not allow for testing whether the Upper Mouhoun (flowing on the Taoudeni basin) was connected to the lower Mouhoun at the time of the High glacia (Fig. 11h). This rearrangement (Hubert, 1912; Palausi, 1959) occurred after the upper Mouhoun River, which used to flow northeastward into the Niger River since the

Eocene, formed the Gondo Plain internal delta (Beauvais and Chardon, 2013; Grimaud et al., 2014; Fig. 1).

The spatial variability of the pediplain relief on the basement is representative of the type-landscapes shown in Fig. 10 (comparisons with Figs. 9a, 12). One distinguishes (i) an inselberg-studded pediplain around volcanic terrains, (ii) almost flat lands over TTG, and (iii) a mix of the first two landscape types over volcano-sediments and associated granite plutons. In the Taoudeni basin, the pediplain consists of wide and shallowly dipping piedmonts connecting sandstone or higher landsurfaces plateaus to the main streams.

4. 3. Interpretation of the pediplain dissection pattern

The pediplain has a low drainage density compared to that of the modern landscape, with typical pediment widths of 10-20 km (up to 30 km over the sandstones; Figs. 11, 12). Dissection of the High glacia landscape accompanied an increase in the drainage density. The modern valley sides rarely exceed 5 km in width (Figs. 3, 8). Dissection of the pediplain also resulted in an increase in slopes (Fig. 11g), which is in agreement with the evolution from a pediplain towards narrower / deeper valleys. In other words, the Middle and Low glacia, which contributed to the dissection of the pediplain, never attained the width of the High glacia.

Post-11 Ma dissection of the pediplain is non-uniformly distributed, with denudation depths ranging from 0 to 100 m and corresponding denudation from 0 to 10 m/my (Fig. 11c). Extreme denudations (> 60 m, > 5 m/My) over basement terrains are concentrated on the steep slopes of residual reliefs (Figs. 6, 10, 11). Along the two main streams, denudation is moderate to high (30 - 60 m; 2.5 - 5 m/My). The denudation is rather uniformly distributed in the Comoé drainage, meanders being delineated by

denudation patterns in the vicinity of the Mouhoun River (Fig. 11c). The lowest erosion range (< 10 m, < 1 m/My) is recorded east of Tô, southeast of Bobo-Dioulasso and around Gaoua and Djigoué (Fig. 11c), in agreement with the high degree of preservation of the pediplain relicts (Fig. 8). The volume eroded from the pediplain over the map area represents a spatially averaged denudation of ca. 20 m, corresponding to a denudation rate of about 2 m/My.

Dissection of the Late Miocene pediplain affected the whole region and did not propagate upstream by scarp or knickzone retreat as advocated by King (1962) and as implicitly included in river profile inversion works based on stream power incision models (e.g., Paul et al., 2014). As an illustration, the bounding escarpment of the Taoudeni basin is stable since at least 11 Ma (Fig. 11) and most probably 45 Ma (see Grimaud et al., 2014). Higher erosion rates coincide with the main drains outside the High Mouhoun, suggesting a control of the stream power (e.g., Whipple and Tucker, 1999) on pediplain dissection. Moderate stream power in the rest of the river network would have preserved the pediplain from complete stripping. Scarps bounding High glaciais relicts often coincide with second-order divides of the modern topography, indicating a component of slope retreat in the dissection of the pediplain. Meandering patterns of the Mouhoun River (Figs. 8, 11c) further suggest that channel migrations may have contributed to slope retreat. The typical retreat distance of the High glaciais relicts' edges over the study area (1-10 km) suggests a retreat rate of 100-1000 m/My. Therefore, under the erosion dynamics at play since ca. 10 Ma and assuming an initial valley side width of 20 km (Fig. 12), a minimum of 20 My would be required to entirely resurface the High glaciais pediplain.

5. Discussion

Our results complement denudation and incision rates estimated from differential elevation of sparse High glaciais remnants and local base levels that have mean values of 5-7 m/My but non-uniform distributions over the sub region from 2 to 15 m/My (Beauvais and Chardon, 2013; Grimaud et al., 2014). This suggests a partitioning of erosion among geomorphic provinces, with implications on the spatial variability of the sediment routing system. This variability may be a function of the regional topographic relief and/or positive epeirogeny, which seem to focus higher denudation (Beauvais and Chardon, 2013; Grimaud et al., 2014). Importantly, this variability is also and primarily due to contrasted river network evolution among sub-drainage basins separated by stationary knickzones (Grimaud et al., 2014; this work).

Our approach has consisted in regional scale, volumetric quantification of denudation from a dated paleo-landscape datum, which enhances accuracy of denudation measurement over a West African province of lowest Neogene erosion. The obtained averaged denudation rate of 2 m/My is close to the lower limit of Cenozoic cratonic denudation rates measured worldwide (Beauvais and Chardon, 2013). Given the relevance of the size and morpho-geological context of the study area, we propose that this rate determines the background denudation ‘noise’ of shields. The Late Neogene increase in clastic sedimentation documented worldwide and particularly in African deltas such as that of the Niger (Séranne, 1999; Jermannaud et al., 2010; Fig. 1) should however be somehow included in the 2 m/My of background denudation averaged since the Early Late Miocene. This issue constitutes a sizable research challenge.

The material derived from dissection of the pediplain and removed since the Late Mid-Miocene was made of regolith, i.e. the High glaciais cover and its underlying laterites. Indeed, no outcrop of significant surface / height has been exhumed since the

abandonment of the pediplain. The fact that only the main stream channels locally flow atop the bedrock and that an averaged denudation of less than 20 m since abandonment of the pediplain is estimated further argues for denudation being restricted to the regolith. Denudation is however not strictly weathering-limited because if glacis typically cut preexisting and potentially old regoliths (i.e., Late Cretaceous to Eocene and Oligocene for the bauxitic and Intermediate weathering episodes, respectively, Figure 2), they rarely attained the bedrock. Therefore, although weathering is instrumental in producing regolith mantles available to future stripping (Fairbridge and Finkl, 1980), low abrasion power of the pedimentation process combined with a probably limited transport capacity of the river network should be regarded as the limiting factor of tropical shields denudation.

The minimum characteristic timescale of 20 My for shield resurfacing indicated by post-Mid-Miocene drainage growth reinforces the view that shields are non-equilibrium landscapes, which increase their relief through geological time by preserving old landforms (Thomas, 1989; Twidale, 1991; Bishop, 2007; Beauvais and Chardon, 2013). A long resurfacing timescale also implies the high sediment retention capacity of shields as those sediments stem from weathering mantles dating back from at least the Early Paleogene and have been slowly recycled through the landscape since then. This suggests that weathering and slope processes play a major role, comparable to or greater than sediment transport by rivers (Métivier and Gaudemer, 1999; Jerolmack and Paola, 2010) in “shredding” and particularly smoothing or buffering climatic signals in the sedimentary record. Still, the ubiquitous character of the West African lateritic paleo-landsurfaces sequence and its chronology would suggest that Cenozoic landscape rejuvenation and sediment fluxes were punctuated by major climatic periods. Subdued clastic exports are indeed expected for time intervals of

enhanced weathering during the Lower and Mid-Eocene, Late Oligocene, Mid Miocene, Latest Miocene and Latest Pliocene (e.g., Fig. 2b).

The background denudation rate of 2 m/My may be converted into a volumetric export rate of $2 \times 10^{-3} \text{ km}^3/\text{km}^2/\text{My}$ and a clastic yield of $4 \text{ t}/\text{km}^2/\text{yr}$, considering an effective grain density of $2,500 \text{ kg}/\text{m}^3$ (estimated from a bulk density of $2,000 \text{ kg}/\text{m}^3$ and a 20 % porosity) for the stripped regolith. This value corresponds to the lower limit of modern West African solid river loads ($3.5 - 300 \text{ t}/\text{km}^2/\text{yr}$) and to the $4 \text{ t}/\text{km}^2/\text{yr}$ measured at the outlet of the Volta catchment (Milliman and Farnsworth, 2013). Therefore, cratonic erosion fluxes derived from a 2 m/My denudation rate appear to be realistic for low-capacity shield drainage systems on geological timescale. Conversely, this could suggest that the lower limit of large tropical shields catchments yields is governed by a cratonic background denudation noise. Importantly, background cratonic denudation of 2 m/My may be used to simulate the minimum export fluxes of drainage basins of constrained size over geological timescales.

9. Conclusions

Regional regolith-landform mapping allows characterizing surface dynamics, weathering patterns, paleotopography and dissection mechanisms of the last pediplain formed over West Africa from Early to Mid-Miocene. The nature and preservation / dissection patterns of the pediplain are controlled by the spatial distribution of bedrock lithologies and are partitioned between large drainage basins. Quantification of the post Mid-Miocene dissection of the pediplain determines a cratonic background denudation noise of 2 m/My and a minimum shield resurfacing characteristic timescale of 20 My. The minimum clastic yield of the major African catchments seems to be currently dominated by such a cratonic noise. Our results, once combined with landscape /

weathering chronologies, point to the shields' high storage capacity of sediments, consisting exclusively of regoliths that have been mainly recycled in the landscapes since the Late Cretaceous. Such a slow regolith turnover is due to the low efficiency of slope denudation processes by pedimentation and would tend to smooth riverine export fluxes of shields over geological timescales.

Acknowledgments

This work was funded by WAXI, the CNRS and the ANR TopoAfrica (ANR-08-BLAN-572 0247-02). The manuscript benefited from the comments of R. Teeuw and an anonymous referee as well as from editorial suggestions by A. Plater. We thank M. Jessell, D. Rouby, L. Baratoux and D. Huyghe for discussions and support and A. Fofana for participation in the fieldwork. 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.

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Figures Captions

Figure 1: Simplified geology of sub-Saharan West Africa. The study area is shown by a red frame (map modified from Feybesse et al., 2006).

Figure 2: (a) Lateritic paleo-landsurface sequence and incision chronology of West Africa (compiled after Michel, 1973; Beauvais et al., 2008; Beauvais and Chardon, 2013 and modified after Grimaud et al., 2014). (b) Synthesis of Ar-Ar age data obtained on supergene Mn oxides. Colored time slices represent the main periods of weathering correlated with the successive paleolandsurfaces, based on dating of cryptomelane in Tambao (after Beauvais et al., 2008; Beauvais and Chardon, 2013). Ages reported from Syama were obtained on alunite and jarosite (after Vasconcelos et al., 1994). Note that only alunite and jarosite ages with error of less than 5 Ma are reported. Terminology of the paleo-landsurfaces: Bx – Bauxite; Int – Intermediate; HG – High glacia; MG – Middle glacia; LG – Low glacia. Syama and Tambao are located on Fig. 1.

Figure 3: Topography and simplified geology of the study area (see Fig. 1 for location). Shaded topography (a) based on SRTM digital elevation model smoothed to 500 m resolution. Simplified geology (b) is adapted from Baratoux et al. (2011). Field stations are shown by yellow dots.

Figure 4: Illustrations of field characteristics of the higher lateritic paleo-landsurfaces in Southwestern Burkina Faso. (a) Bauxite-capped greenstone massif, 15 km SE of Iridiaka (location on Fig. 3; see also Fig. 9b). The bauxitic plateau is ca. 300 m long. (b) – (c) South-looking Google Earth view and interpretation of a dolerite topographic massif near Kokoro, Taoudeni basin (location on Figure 3; Vertical exaggeration x3).

HG - High glaciis. (d) Close-packed pisolithic texture of the Iridiaka bauxite shown in (a). (e) Nodular - mottled texture of the Kokoro bauxite shown in (b) and (c). (f) Massive nodular facies of the Intermediate ferricrete shown in (b) - (c). (g) Iron nodulation at the root of the Intermediate ferricrete over sandstones, Taoudeni basin north of Banfora (location on Fig. 3).

Figure 5: Illustrations of the High glaciis relict landforms. (a) - (b) Google Earth view and interpretation of the eastern piedmont of a volcanic inselberg near Dano (Fig. 3). (c) - (d) Google Earth view and interpretation of parse High glaciis relict hills resulting from dissection by a dendritic river network on granitic substrate, Dandougou area (Fig. 3). High glaciis relicts are shown in green. Dip symbols indicate High glaciis paleolandsurface direction and sense of slope. (e) Gently west-dipping plateau bounded by a 10-15 m high scarp (5 km West of Gaoua, view looking SW). (f) Closer view of the plateau edge shown in (e). (g) Scarp carved in >10 m thick ferricrete cementing glaciis cover material (in between Djigoué and Gaoua).

Figure 6: Illustrations of High glaciis regoliths. (a) Base of a High glaciis ferricrete truncating a granitic weathering profile (Djigoué area). Light-colored cobbles in the ferricrete are quartz clasts. (b) Details of a High glaciis ferricrete showing cobbles of Intermediate ferricrete and quartz in a finer grained conglomerate, base of the cliff shown in Fig. 5g. (c) Cemented debris flow on dolerites near Kokoro (site of Fig. 4b, 4c). Light-colored debris consists of bauxite clasts. The flow rests upon a truncated weathering profile developed from dolerites that remain as core stones in the saprolite. (d) Alluvial channel at the base of High glaciis ferricrete carved into weathered sandstones of the Taoudeni basin (South of Bobo-Dioulasso). (e) Cobble of

Intermediate ferricrete cemented in a High glacia ferricrete. (f) Weathering profile underlying that same ferricrete (northeast of Dédougou). See Fig. 3 for locations.

Figure 7: Ternary image of the airborne gamma-ray spectrometry survey (a) and the enhanced Th/K ratio image of the survey (b) over the study area. (c) - (f) Details of the datasets that were combined for the identification and mapping of High glacia relicts on the example of the Djigoué area. (c) Airborne gamma-ray spectrometry 100-250 m (resampled to 100 m) resolution ternary image. The area corresponding to the High glacia ferricrete has a strong thorium signature in green and a medium uranium signature in blue. In this area, the substrate has a strong potassium signature in red. (d) Ratio image of thorium over potassium (100 m resampled resolution). The High glacia ferricrete, enriched in thorium and depleted in potassium, is highlighted in white to red colors. (e) 15-m resolution LANDSAT image. (f) Mapping by construction of the polygons (crossed frame) corresponding to the High glacia ferricrete, superimposed on the SRTM topography. Field stations are shown as yellow dots. Rivers are shown in white.

Figure 8: Regolith-landform map superimposed on the STRM digital elevation model (90 m resolution). Black boxes correspond to the frame of the maps shown in Fig. 10.

Figure 9: (a) Regolith-landform map superimposed on the geology that is simplified from Metelka et al. (2011). (b) Synthetic regional cross-section of the study area. The line of section is located in (a). Trace of the HG surface is shown in dark green (dashed where eroded). (c) Histogram of the High glacia ferricrete total area partitioned on each substrate. (d) Proportion of the High glacia surface on each lithology covered by

ferricrete. For the whole Birimian basement, this percentage is of about 11 %. Dolerites and sandstones were not distinguished in the Taoudeni basin.

Figure 10: Maps and cross-sections of type-landscapes on basement terrains. Frames of the maps are located on Fig. 8. Dip symbols represent the direction and sense of slope of the High glacia relicts (in green). Dashed lines on the maps are lithological boundaries (see Fig. 9a).

Figure 11: (a) Modern topography based on SRTM digital elevation model smoothed to 500 m resolution. (b) Reconstructed topography of the High glacia pediplain. (c) Denudation map obtained by subtracting present-day topography from that of the High glacia stage. (d) River network automatically extracted from the digital elevation model of the High glacia pediplain in Fig. 11b. Red arrows represent drainage rearrangements in between the High glacia stage (d) and the present-day landscape (a). (e) Slope map of the current topography derived from (a). (f) Slope map of the High glacia pediplain derived from (b). (g) Comparative slope distribution for the High glacia and modern topographies. (h) River network automatically extracted from the present-day topography in Fig. 11a.

Figure 12: Geomorphological map of the High glacia pediplain before its abandonment in the Earliest Late-Miocene (ca. 11 Ma). The thick black dashed line represents the boundary of the Mouhoun catchment.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 9bis

Figure 10

Figure 11

Figure 12

Graphical abstract

Highlights

- Regolith-landform mapping allows reconstruction of the West African Miocene pediplain
- Pediplain dissection defines shield background denudation/yield (2 m/My; 4 t/km²/yr)
- Landscape evolution reveals very high regolith storage capacity of shields
- Very slow regolith turnover on shields should smooth river erosion exports