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Dominique Chardon, Jean-Louis Grimaud, Anicet Beauvais, Ousmane Bamba. West African lateritic pediments: Landform-regolith evolution processes and mineral exploration pitfalls. *Earth-Science Reviews*, 2018, 179, pp.124-146. 10.1016/j.earscirev.2018.02.009 . hal-01744579

HAL Id: hal-01744579

<https://hal-amu.archives-ouvertes.fr/hal-01744579>

Submitted on 27 Mar 2018

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West African lateritic pediments: Landform-regolith evolution processes and mineral exploration pitfalls

Dominique Chardon^{a,b,c*}, Jean-Louis Grimaud^{c,d}, Anicet Beauvais^e, Ousmane Bamba^b

^a IRD, 01 BP 182 Ouagadougou 01, Burkina Faso

^b Département des Sciences de la Terre, Université Ouaga I Professeur Joseph Ki-Zerbo,
BP 7021, Ouagadougou, Burkina Faso

^c GET, Université de Toulouse, CNRS, IRD, UPS, France.

^d MINES ParisTech, PSL Research University, Centre de Géosciences,
35 rue St Honoré, 77305 Fontainebleau Cedex, France

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

Submitted to ***Earth-Science Reviews***, 14 September 2017

Revised 28 January 2018

Accepted 09 February 2018

doi:10.1016/j.earscirev.2018.02.009

* Corresponding author

E-mail address: dominique.chardon@ird.fr

26 HIGHLIGHTS

- 27 - Review of the geomorphology, regolith and age of the West African pediment systems
- 28 - Duricrusted and loose transported sediments are dominant on pediments
- 29 - Specific geomorphological exploration guides are required for lateritic pediment terrains
- 30 - Pediments typify slow (<10 m/Ma) denudation regimes and their stepping patterns are not
- 31 gauges of regional uplift

33 Abstract

34 This paper is a contribution to the understanding of surface dynamics of tropical shields over
35 geological timescales. Emphasis is put on the fundamental and applied implications of
36 regolith production and dispersion processes through the formation, dissection and
37 preservation of landforms. It is based on the case study of sub Saharan West Africa, which
38 recorded Neogene stepwise dissection of its topography through the emplacement of three
39 lateritic pediment systems, which still occupy most of its surface. Pediments are erosional /
40 transportation slopes having been weathered and duricrusted. Pediment-regolith
41 associations therefore depend on the parent rock, transport dynamics and preservation of
42 the material having transited on their surface as well as on the intensity of their weathering /
43 duricrusting. Iron oxy-hydroxide-cemented clastic sediments (detrital ferricretes) and
44 unconsolidated clastic sediments are the dominant outcropping material, and as such
45 represent a challenge for mineral exploration that relies on surface geochemical sampling to
46 detect metal concentration in the bedrock. Landform-regolith mapping beyond the scale of
47 modern interfluvies combined with paleolandscape reconstitution are relevant to provide
48 exploration guides for (i) interpreting geochemical anomalies on pediments, (ii) tracing their
49 potential source when they have been “transported” on pediments and (iii) targeting
50 suspected ore bodies concealed beneath pediment(s). Past and present latitudinal climatic

zonation of pedimentation and weathering patterns suggests a gradation of pedimentation process across the intertropical zone and explains why pediments may have been overlooked in equatorial environments, with implications for mineral exploration. Successive pediment systems adapted to uneven, knickzone bearing river networks, producing a spatially consistent and reduced (<80 m) stepping pattern of pediments independent from elevation or position in the drainage. Pediments / pediplains are therefore not proxies of uplift and their preservation over geological timescales typifies regions submitted to less than 10 m/My erosion rates. The identification and study of lateritic pediments bear important implications on shield sediment routing systems and a better access to the bedrock and its resources, which may still be underestimated in the tropics.

keywords: Pediment; Regolith; Landform evolution processes; Mineral exploration; Mega-geomorphology

1. Introduction

Tropical shields of Africa, South America, India and Australia are mantled over large areas by regolith derived from rock weathering. Regolith is a weathered, unconsolidated or secondarily indurated cover that overlies fresh coherent bedrock (Scott and Pain, 2008). If preserved on its parental bedrock, regolith constitutes a weathering profile (Fig. 1), which acts as a filter for the chemical composition of the geological substrate. In this case, weathering concentrates some metals (Fe, Al, Ni, Cu, Au, Mn) in the regolith compared to the bedrock, which can result lateritic ore deposits (Nahon et al., 1992; Valetton, 1994; Freyssinet et al., 2005). Once transported by slope or alluvial processes, regolith may act as a mask for the underlying bedrock. As displaced regolith may undergo weathering after transport (Ollier and Pain, 1996), deciphering regolith production / dispersion scenarios through landscapes

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182
183 76 is key for mineral exploration, which mostly relies on soil geochemical surveys (Butt et al.,
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185 77 2000; Porto, 2016). Throughout the Cenozoic, shield surfaces outside the influence of
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187 78 glaciers have primarily evolved by landscape dissection, the process by which
188
189 79 paleolandscapes become isolated as relics overlooking younger active landforms as a result
190
191 80 of slow and unevenly distributed erosion. Thereby, the relief of shields increases through
192
193 81 geological time (Thomas, 1989; Twidale, 1991), while landscape dissection is instrumental in
194
195 82 exhuming regolith available to re-weathering and transportation. Therefore, the study of
196
197 83 regolith distribution patterns over shield landscapes should not only provide exploration
198
199 84 guides to better access bedrock geology and resources, but also constrain landform
200
201 85 evolution processes and sediment delivery of very large cratonic river systems (Beauvais and
202
203 86 Chardon, 2013; Grimaud et al., 2015, 2018).

206
207 87 Pediments are common landforms that typically form during, and contribute to, the
208
209 88 process of landscape dissection, especially over vast non-orogenic regions of the world (e.g.,
210
211 89 Dohrenwend and Parsons, 2009). In the broadest sense of the term, pediments may be
212
213 90 considered as gently inclined slopes of transportation and/or erosion that truncate bedrock
214
215 91 and/or regolith and connect eroding slopes or scarps to areas of sediment deposition or
216
217 92 alluvial transportation at lower levels (definition adapted from Oberlander, 1997).
218
219 93 Pedimentation involves the physic-chemical processes that concur to form pediments. As
220
221 94 transportation slopes feeding rivers with clastic sediments, pediments are a regulating
222
223 95 element of the sediment routing system. As transit landsurfaces, pediments also carry
224
225 96 transported regolith that masks the geological substrate. They are therefore an obstacle to
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227 97 mineral exploration (Payne, 1969; Pease, 2015) but have not been recognized as such in
228
229 98 lateritic environments by exploration geologists and geochemists. Through the work of King
230
231 99 (1948, 1967), the pediment concept also contributed to landscape evolution theories
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233 100 (Summerfield, 1991, pp. 457-467). However, no general agreement exists on the recognition
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101 criteria, regional correlation and the geomorphic meaning of paleo-pediments. Remaining
102 questions are (i) whether and how pediplains (i.e., regional surfaces of coalescent
103 pediments) can form and be preserved over geological time-scales (10^6 - 10^7 yr) and (ii)
104 whether they may be gauges of continental deformation or whether they have another
105 geological signification (e.g., Tricart *in* Twidale, 1983; Summerfield, 1985, 1996; Thomas and
106 Summerfield, 1987; Twidale and Bourne, 2013; Dauteuil et al., 2015; Guillocheau et al., 2015,
107 2017).

108 Relationships amongst pediment development and preservation and regolith
109 production and remobilization are exceptionally exemplified over sub Saharan West Africa.
110 Pediment systems formed by stepwise dissection of the region West of 10°E and South of
111 20°N (Fig. 2) since the earliest Miocene (ca. 24 Ma) and still occupy an overwhelming part of
112 its surface. They exclusively expose lateritic regolith and are commonly capped by ferricrete
113 (a generic term used here for iron duricrust). The region hosts the southern West African
114 craton, which is an important metallogenic province (Milési et al., 1992; Markwitz et al., 2016)
115 and more specifically the largest Paleoproterozoic gold-producing region (Goldfarb et al.,
116 2017). The ubiquitous lateritic pediments of the region therefore pose an amazing
117 exploration challenge (e.g., Bamba, 2009). Building on decades of geomorphological
118 investigations throughout the sub region, recent progress made at dating, mapping and
119 regionally correlating lateritic pediments and earlier paleolandscape elements left by relief
120 dissection (Beauvais and Chardon, 2013) offered a new perspective for deciphering
121 denudation chronologies and landscape evolution processes on a sub-continental scale.

122 The present contribution is a review of the West African lateritic pediment systems
123 from the landscape to the sub continental scale. It addresses pediment landform-regolith
124 evolution processes to (i) evaluate the factors controlling the production and preservation of
125 pediments over geological timescales and their geological meaning, (ii) call attention to

geochemical exploration pitfalls in lateritic pediment dominated environments and provide adapted geomorphological exploration guides or strategies. The ubiquity of pediment-dominated terrains in West Africa suggests that pediments occupy vast regions of the tropical belt and calls for geomorphic reassessment of shield surfaces from both a fundamental and applied perspective.

2. West African landscape-regolith evolution models for mineral exploration and the recognition/study of pediments

The “landscape geochemistry” approach to tropical geomorphology has prevailed for decades in the exploration and surface geochemistry communities (Butt, 2016). Following Zeegers and Leprun (1979), such an approach led to pedogenetic geochemical dispersion models elaborated for West African base metal deposits and various bedrock lithologies that consider ferricretes as forming the upper residuum of weathering profiles preserved on their parental bedrock (Butt and Zeegers, 1989; Zeegers and Lecomte, 1992; Lecomte and Zeegers, 1992; Freyssinet, 1993; Bowell et al., 1996; Tardy, 1997; Fig 1). Accordingly, ferricretes are inferred to display various degrees of geochemical dependency on the underlying bedrock via the successive horizons of the weathering profile i.e., from bottom to top: saprolite, mottled clays and carapace (Fig. 1). Within such a paradigm, variations in concentration and mode of occurrence of base metals or other elements from the bedrock to the ferricrete result from solute loss, vertical mass transfers and compaction of the residuum as a sole consequence of lateritic weathering, leading to the formation of geochemical dispersion halos (Roquin et al., 1990; Colin and Vieillard, 1991; Freyssinet, 1993; Freyssinet et al., 2005; Fig. 3). West African exploration models consider cases where weathering profiles were truncated by erosion and weathering horizons deeper than the ferricrete are exposed or cases where such truncated profiles are overlain by unconsolidated

colluviums (e.g., *Bowell et al., 1996*). But ferricretes are considered as formed from in-situ regolith. A consequence of such popular landscape evolution models is that both the role of pedimentation-driven relief dissection in redistributing regolith in the landscapes and potential detrital origin of ferricretes have been overlooked for decades of mineral exploration and geochemical investigations. However, among exploration geologists, *Bolster (1999)* suggested that some West African ferricretes were detrital. More recently, former advocates of the in-situ paradigm such as *Butt and Bristow (2013)* claimed that ferricretes were “Fe oxydes-cemented sediments” and that “relief inversion [was] a very widespread and important phenomenon” in West Africa (relief inversion being a case of relief dissection that leads the lower part of an ancient landscape to become the highest part of the new landscape; see *Summerfield, 1991*). Those findings were actually made 60 years ago and documentation on those topics has accumulated since then from investigations by geologists, soil scientists and geomorphologists.

Early geomorphological studies have shown that ferricretes occupying large surfaces of the sub region contained gravels and cobbles of Al-Fe crusts, quartz and bedrock that had no genetic relationships with their underlying saprolite or bedrock (*Dresch, 1952a; Lamotte and Rougerie, 1953, 1962; Pélissier and Rougerie, 1953; Daveau et al., 1962*). In the meantime, following reconnaissance by *Pélissier and Rougerie (1953)*, *Brammer (1955, 1956)*, *Tricart et al. (1957)*, *Michel (1959)* and *Vogt (1959a)* showed that these detrital ferricretes capped generations of glacis - a French term for pediment(s). In his comprehensive geomorphic investigation of the Senegambia drainage basin, *Michel (1959, 1973, 1974)* deciphered and mapped the sequence of lateritic pediments over Central and Northern Guinea, Southwestern Mali and Senegal, (*Fig. 2*). More recently, glacis of Eastern Senegal and their regolith were investigated through combined petrological and near-surface geophysical investigations (electrical resistivity tomography and ground penetrating radar: *Beauvais et*

al., 1999, 2004). The lateritic glacis of Senegal extend in southern and central Mauritania, but they tend to be less iron-rich northward (Michel, 1977) and could even expose even pedogenic calcretes (Nahon et al., 1977).

After Brückner (1955) and especially Hilton (1963) in Ghana (former Gold Coast), De Swardt (1964) led the way for detailed investigations of the extensive lateritic pediment systems of Nigeria that are correlated with the glacis sequence established in Guinea and Senegal (Fölster, 1969a, 1969b; Rohdenburg, 1969; Burke and Durotoye, 1971; Fölster et al., 1971; Fig. 2). Geomorphic description, petrological characterization and mapping of glacis generations were undertaken over Burkina Faso (former Haute-Volta; Fig. 2) by Boulet (1970), Eschenbrenner and Grandin (1970), Grandin (1976), Bamba (1996), Bamba et al. (2002) and Grandin and Joly (2008). Works on glacis were also extended to the neighboring area of the Republic of Niger by Mensching (1966) and Gavaud (1977). More recently, the mapping of the glacis systems in Southwestern Burkina Faso by combinations of field surveys, airborne geophysics and remote sensing was undertaken by Grimaud et al. (2015) and Metelka et al. (2018).

In Côte d'Ivoire, intensive work was undertaken on glacis geomorphology and weathering in the 1970s (e.g., Bonvallot and Boulangé, 1970; Eschenbrenner and Grandin, 1970; Boulangé et al., 1973; Grandin, 1976; Pèltre, 1977; see also Teeuw, 2002), whereas the same glacis systems were reported in Sierra Leone (Fig. 2) by Grandin and Hayward (1975) and studied by Thomas (1980, 1994), Thomas and Thorp (1985), Bowden (1987, 1997) and Teeuw (1987), although the two later authors did not explicitly refer to pediments, but to "footslope laterites (duricrust)" (e.g., Bowden, 1987). Reconnaissance by Dresch (1952b) indicates that the ferricrete-capped pediments of Niger and Burkina Faso extend over Benin (as confirmed by our field observations) as well as in Togo (Fig. 2), where they have been described as such and studied by soil scientists (e.g., Le Cocq, 1986; Meyer, 1992).

Regional typologies and systematics of glacis were defined in the seminal monographs of Michel (1973) and Grandin (1976). Three successive glacis systems have been recognized, namely the High, Middle and Low glacis, stepwise landscape dissection being documented as the key process having allowed the preservation of relict bauxitic, Intermediate and pediment landforms of each generation (e.g., Grandin and Joly, 2008; see also Beaudet and Coque, 1994; Gunnell, 2003). Weathering patterns of the glacis sequence have been treated in the reviews of Tardy (1997) and Tardy and Roquin (1998). The pediment sequence was incorporated by Burke and Gunnell (2008) into their model of the African Surface, which encompasses the entire relief of the continent and would have been generated by deformation and correlative erosion of a initially flat and low lying continent-wide surface since the Cretaceous. Remnants of each West African glacis system have been correlated and mapped regionally by combining regional field surveys, photointerpretation and the available literature (e.g., Beauvais and Chardon, 2013; Grimaud et al., 2014, 2018). The present work stems from the experience gained in the course of those regional correlations and compilations as well as our own field experience in Benin, Burkina Faso, Guinea, Côte d'Ivoire, Mali, Niger and Senegal (Fig. 2). By considering pediments and glacis in the broadest sense of the definition given above, the two terms are used here interchangeably.

3. Pediments in the West African morphoclimatic sequence

The West African landscape is the end product of the stepwise dissection of an old, low relief topography called the African Surface (e.g., King, 1948; Boulangé and Millot, 1988; Chardon et al., 2016). This old landscape is mantled by bauxitic duricrusts resulting from a long period of intense weathering that culminated and ended in the Early and Middle Eocene (Millot, 1970; Valetton, 1991; Colin et al., 2005; Chardon et al., 2006; Beauvais et al., 2008;

226 Beauvais and Chardon, 2013). The African surface is now preserved mostly as bauxite-
 227 capped mesas dominating the current landscape. The High, Middle and Low glacis mark the
 228 last main dissection stages of the African Surface. Remnants of a massive, nodular or
 229 pisolitic ferricrete-capped landscape found below bauxite relics and above the glacis have
 230 been used to define an Intermediate Surface (Michel, 1959, 1973; Vogt, 1959a). Bauxitic
 231 duricrusts of the African Surface and the ferricretes of the Intermediate Surface top thick (>
 232 80 m) weathering profiles that are preserved on their parental bedrock (Grandin, 1976;
 233 Boulangé, 1984, 1986; Boulangé and Millot, 1988; Valetton, 1991).
 234 Each glacis system in the West African sequence shows, in most cases, evidence for
 235 duricrusting (or induration), and lateritic weathering, after its formation. Pediments/glacis
 236 are the most conspicuous and common active landforms of dry or sub-humid regions of the
 237 world (e.g., Dohrenwend and Parsons, 2009). The successive shifts from pedimentation to
 238 lateritic weathering/duricrusting of the three glacis systems are indicative of repeated
 239 transitions from semi-arid to seasonally contrasted wet tropical climate over West Africa
 240 (Tricart et al., 1957; Michel, 1973; Grandin, 1976). Duricrusting took place during climate
 241 shifts toward dryer conditions at the ends of humid weathering periods, before
 242 abandonment and dissection of one glacis system and formation of a new one (Beauvais and
 243 Chardon, 2013). Systematic Ar-Ar geochronology of K-Mn oxides (cryptomelane) from the
 244 Mn-rich duricrust and weathering profile of each member of the West African landform-
 245 regolith sequence allowed constraining their weathering and abandonment ages (Beauvais
 246 et al., 2008; Beauvais and Chardon, 2013; Fig. 4). The African and Intermediate regolith-
 247 landform associations yielded 59-45 and 29-24 Ma age groups, respectively. The High, Middle
 248 and Low glacis weathered before abandonment at 18-11, 7-6 and around 3 Ma, respectively
 249 (Fig. 4). Those age groups would therefore restrain the main pedimentation periods to 24-18,
 250 11-7 and 6-3 Ma for the High, Middle and Low glacis, respectively (Fig. 4). Ages obtained on

251 alunite and jarosite (Vasconcelos et al., 1994), although indicative of lesser weathering
 252 intensities than cryptomelane, are compatible with the period of bauxite formation,
 253 weathering of the Intermediate landscape until the latest Oligocene (24 Ma) and the 18-11
 254 Ma period of High glacia weathering (Fig. 4).
 255

256 **4. Glacia landforms and landscape chronologies**

257 *4. 1. Type-landforms and their spatial arrangements*

258 The three generations of West African glacia remnants are best distinguished on the
 259 piedmonts of topographic massifs, which form up to hundreds of meters' high residual
 260 reliefs that had not been leveled by pedimentation (Figs. 5 and 6a). Those massifs are
 261 typically made of greenstone belt material (andesite, basalt, gabbro, volcano sedimentary
 262 rocks) or early Mesozoic dolerite sills hosted by tabular sandstones and preserved from
 263 erosion thanks to their capping bauxites and/or Intermediate duricrusts. Glacia are graded
 264 upward-concave surfaces sloping away from the massifs (e.g., Grandin, 1976). The stepping
 265 of successive glacia relics attests to the polycyclic nature of the landscapes due to renewed
 266 periods of pedimentation (Fig. 6a). The uppermost portion of an early glacia (e.g., the High
 267 glacia) is commonly eroded in such a way that a peripheral hollow separates the glacia
 268 remnant from its upslope relict landscape (Fig. 6a and 7a; e.g., Beauvais et al., 1999). A later
 269 glacia (e.g., the Middle glacia) may shape the inner slopes of the peripheral hollow so that it
 270 can reach a higher elevation than the relics of the earlier glacia (Fig. 6a). Relative elevation
 271 alone is therefore not a reliable criterion to decipher glacia generations given their slopes
 272 and their dissection patterns. Careful investigation of the relative geomorphic position,
 273 lateral extension and age of landscape elements should therefore be preferred to establish a
 274 glacia landscape chronology.

Massifs to which piedmont glacis are connected may be eroded by headward river erosion so that only an inselberg (i.e., a rocky topographic massif stripped from its regolith) remains as a relic of the former bauxitic / Intermediate topography. Such an inselberg may have a lower elevation than the piedmont glacis relicts (Fig. 7) and in many instances erosion may even totally erase the massif to which glacis were connected. Likewise, glacis relict surfaces carrying cobbles or boulders of bauxites are commonly preserved in areas where no bauxite massifs remain (Bamba, 1996; Fig 7). River valleys connected upstream to peripheral hollows generally have a lower slope gradient than the early (High) glacis (Fig. 7b). Later (Middle or Low) glacis settle on their valley sides (Fig. 7b) that dip at a high angle to the earlier glacis slope direction. This implies that slope direction – and therefore surface material transport direction on the pediment – not only varies spatially for a given glacis generation (for instance for the High glacis radiating around a residual topographic massif) - it varies also from one glacis generation to the next.

Over vast granitoid or tabular sandstone / siltstone terrains, the landsurface is a multi-convexo-concave plain that is occupied by undulating glacis encompassing the entire relief i.e., from the top of smooth convex interfluves to the lower part of their concave slopes (Fig. 6b). Following Rohdenburg (1969) in his review of Southern Nigerian pediment systems, the term of rolling pediplain is used here to describe such glacis landscape regions (see also Fölster, 1969a). They have 2 to 20 km wavelength and modest (< 30 m) amplitude and may preserve a relict - and often dismantled - ferricrete inherited from a former glacis surface on their interfluves (called, in this case, residual hills) (Fig. 6b). Rolling pediplains are by far the most common regional landform associations in today's West Africa and are locally studded with relict glacis plateaus of limited extent that were not reduced to residual hills. They are mostly inherited from past glacis landscape stages. Middle glacis pediplains (Fig. 6b) are the best preserved in today's landforms although the downslope portions of such

300 paleolandscapes are generally re-cut by the Low glacia (e.g., Fig. 6b). Regional correlations of
 301 glacia systems chronology may be deciphered along 10-100 km long transects going from
 302 piedmont contexts - where the pediment stepping pattern is well defined - to rolling
 303 pediplain contexts. Field investigations restricted to the scale of an interfluv or a few
 304 interfluves are indeed not sufficient to elaborate a landscape chronology given the lateral
 305 variability of the paleolandforms preservation patterns (see section 6.2).

307 4. 2. *Relief dissection patterns*

308 Repeated relief dissection favored the stepping of successive glacia in piedmont
 309 contexts (Figs. 8a and 8b). The relative elevation between successive glacia does not
 310 systematically decrease downslope i.e. away from the residual massif (Fig. 8a) contrary to
 311 the common slope evolution models (e.g., Summerfield, 1991, pp. 457-467). It may increase
 312 downslope toward the main drainage axes (Grandin and Joly, 2008; Fig. 8b). The dissection
 313 of rolling pediplains leads to more complex stepping patterns owing to whether erosion
 314 focused on residual hills or valleys from one glacia landscape stage to the next (Figs. 8c to 8e).
 315 Inselbergs are locally preserved on granitoid terrains. They seem to have formed by a
 316 combination of geological factors among which rock structural control, the original relief of
 317 an old and thick weathering profile and the polycyclic denudation history are the most
 318 important (Thomas, 1978, 1994).

319 In case where a glacia is not strictly stepped into an older glacia, mostly as a
 320 consequence of limited base-level fall (i.e., river down-cutting) during its development, a
 321 composite (i.e., polygenic) landsurface forms. Slight oblique leveling of the early glacia up to
 322 a certain elevation by the younger glacia may lead to a more or less expressed change of
 323 slope in that landsurface (Fig. 6). Polygenic development is also mostly expressed in the
 324 downslope parts of two successive glacia that merge into a single graded (and often

functional) surface, whereas they are stepped higher up in the landscape (e.g., Fig. 6a).

Polygenic High/Middle glacis are observed but the most common cases of polygenic developments are between the Middle and Low glacis, particularly in dry regions (Boulet, 1970; Eschenbrenner and Grandin, 1970). In the Sahelian zone (Fig. 2) where base-level fall has been limited between the Intermediate Surface and the High glacis approaching the Niger River (e.g. Grimaud et al., 2014), polygenic glacis development is common between these two landscape systems (see also Fig. 5).

Relief dissection and denudation did not allow a good preservation of High glacis stage rolling pediplains of significant regional extent with the exception of specific areas of flat sandstones. Those rolling pediplains generally have longer (>10 km) wavelength than those of the Middle glacis. Low glacis pedimentation did not produce rolling pediplains. From the Soudanian zone southward (Fig. 2), Low glacis systems mostly contributed to re-cut or straighten downslope portions of Middle glacis landscapes (often producing a polygenic surface). Further north, the Low glacis system largely developed and is still functional (see below).

4. 3. Sequential landscape development

The High glacis pedimentation period has produced a multi-concave pediplain over granite-greenstone terrains or dolerite sills provinces. The pediplain was studded with relictual reliefs inherited from the bauxitic and/or the Intermediate landscape stages (Grimaud et al., 2015; Figs. 7 and 9). In other geological provinces, the High glacis landscape consisted in a rolling pediplain of long (>10 km) wavelength (e.g., Fig. 8c). Middle and Low glacis pedimentation cycles generally formed narrower valleys than those of the High glacis landscape (e.g., Figs. 8d and 8e), especially within and south of the Soudanian zone (Fig. 2). Figure 10 summarizes the sequential development of a type West African landscape. Each of

the successive landscape stages incorporates relict landforms of various earlier generations. It is a composite landsurface comprising inselbergs (not shown on the Figure), relicts of the bauxitic and/or Intermediate landscapes and former glacis (Fig. 10). The Middle and Low glacis landscape stages therefore integrate increasing complexity compared to earlier landscapes. This is explained by a decreasing pedimentation efficiency manifested by generally narrower glacis widths and would be consistent with the decreasing duration of pedimentation periods through time i.e., 6, 4 and 1 My for the High, Middle and Low glacis, respectively (Beauvais and Chardon, 2013). Relics of the entire West African paleolandscape sequence are not always preserved on a 10-100 km scale (Fig. 10). Besides an evolving drainage density, landscape stages succession implies slope direction changes or reversals (Fig. 10), with implication for material transit patterns on glacis slopes through time (section 7.2).

Multi-concave pediplains are mostly restricted to granite-greenstone terrains or areas of mafic substrate owing to iron-rich lithologies, which are more alterable than felsic rocks. They tend therefore to produce thick and massive duricrusts, which have a protective effect once the landscape they cap is submitted to dissection. The development of piedmont glacis is favored below scarp-bounded relict paleolandscapes, the scarp being armored by the ferricrete. In such contexts, glacis are also prone to dissection because their capping ferricretes are mostly cemented debris of Al-Fe crusts inherited from the older, inverted landsurfaces and are therefore iron-rich and resistant even though they are not underlain by mafic rocks (see section 5). Over iron-poor lithologies and away from mafic sources, both the lower iron content and thickness of the duricrusts reduce their strength. Pedimentation is therefore more efficient at leveling interfluvies to produce rolling pediplains and no strict relief inversion takes place.

4. 4. Summary

Notwithstanding the regional spatial variability of the glacis stepping patterns described above, each glacis system has type-geomorphic characteristics that may be summarized as follows (Grandin and Joly, 2008). Relics of the High glacis are abandoned as plateaus or residual hills that rarely occupy more than 20 % of the current landsurface over 100 x 100 km areas. They can attain heights of more than 100 m above the local base level for the upslope portion of very large relics and not more than 30 m for their lowermost portions along the main drainage axes. Middle glacis are generally eroded downslope and are still connected to their upslope reliefs. They are preserved as low plateaus or relictual hills in dry regions (Fig. 2), where the Low glacis developed at their expense. Large Middle glacis remnants may still be functional i.e., currently subjected to runoff and sediment transport. Low glacis occupy a large part of the landsurface and are still functional in dry climatic zones, where they are connected to the local base level. Elsewhere, river alluviums usually mask the incision of Low glacis of a few meters.

Excavation of the Bauxitic African Surface varies from ca. 500 m in central Côte d'Ivoire to less than 30 m near the Niger River in Central Mali, with a mean value around 300 m (Beauvais and Chardon, 2013; Grimaud et al., 2014; Fig. 2). Incision of the High glacis is typically of 50-80 m, whereas the High glacis pedimentation period contributed to 40-130 m of incision of the Intermediate landscape (Grimaud et al., 2018). The three pedimentation cycles therefore contributed as much excavation of the African bauxitic Surface (90-210 m) as the Intermediate period of erosion (75-200 m; Grimaud et al., 2018) over comparable time spans of 22-24 My (Fig. 2), leading to a long-term denudation rate of 3-9 m/My. Pedimentation efficiency decreased over the Neogene in West Africa. Given the glacis widths and ages in the Guinean and Soudanian zones (Grimaud et al., 2015; Fig. 2), lateral growth rate ranges of glacis would typically be of 0.75-3 km/My and 0.15-1 km/My for the High and

Middle glacis system, respectively. Given its restricted development in the same climatic zones (e.g., Fig. 7), the Low glacis system grew at lower rates (0.03-0.75 km/My), which are those of the Plio-Quaternary Southwestern United States' pediments (0.03-0.36 km/My; Dohrenwend and Parsons, 2009).

5. Glacis regolith and weathering patterns

Similarly to pedimentation efficiency, the intensity of weathering and duricrusting of the glacis decreases generally from the High to the Low glacis (Boulangé et al., 1973; Grandin, 1976; Tardy and Roquin, 1998). This decrease is consistent with long-term Neogene climate cooling and the progressively shorter duration of humid periods required for the weathering of the glacis material (Beauvais et al., 2008; Beauvais and Chardon, 2013; Fig. 4). The spatial and temporal variability in the nature of glacis surfaces and regolith (Fig. 11) is further controlled by the interplay of three main factors, which are (i) the nature of the substrate cut by pedimentation, (ii) the nature, transport dynamics and degree of preservation of clastic sedimentary material that has been transiting on the glacis and (iii) the nature and intensity of weathering and duricrusting undergone by the glacis after their formation. Figures 12 to 14 illustrate field examples of the main types of glacis regolith / ferricretes and Figure 15 represents various types of regolith associations on glacis. A synthetic model of the relations between pedimentation and weathering is provided in Figure 16.

5. 1. Conglomeratic regolith, ferricrete and slope processes

Remarkable and common glacis ferricretes derive from cementation of conglomeratic material transiting on the glacis surface. The most spectacular ones are matrix- or block supported debris flows. Depending on the landscape having been stripped off and the pedimentation regime, conglomerates' elements range from gravel to boulder

425 and consist of bauxite, Intermediate ferricrete, earlier glacia ferricrete, iron oxy-hydroxide
 426 nodules and/or quartz debris (Figs. 12b to 12e). Conglomerates' matrixes comprise reworked
 427 weathering profile materials ranging from clays to sands (former saprolite) and gravels made
 428 of ferruginous nodules and quartz debris. Apart from quartz, the occurrence of fresh bedrock
 429 clasts in debris flows is extremely rare, indicating that mostly regolith was stripped-off
 430 and/or submitted to landsliding to produce debris flows. When present in glacia transported
 431 regolith, bedrock clasts are almost always highly ferruginized to the point of being a massive
 432 ferricrete preserving bedrock structures such as schistosity. Such ferricretes are typical of
 433 the Intermediate weathering profile (Fig. 12d).

434 Lower-slope alluvial sedimentary facies are also common, especially in the
 435 downslope parts of glacia, even though ferruginization contributed to alter sedimentary
 436 structures in glacia alluviums such as parallel and oblique stratifications and cross beds. The
 437 occurrence of rounded quartz pebbles in the most distal parts of glacia near river drains
 438 indicates that glacia pass downslope to alluvial terraces (the "glacia-terrace" concept of
 439 Michel (1959, 1973) and Vogt (1959a)). Erosional unconformities and disconformities at the
 440 base or within the glacia sedimentary cover are consistent features of truncation and
 441 deposition by channelized to sheet flow down the glacia slopes. The most obvious (and best
 442 preserved) alluvial features are channels identifiable along the basal erosional surface of the
 443 glacia sedimentary layer (Fig. 12f). Beddings are also observed as separating successive
 444 debris flows or within sedimentary units.

445 Sedimentary patterns vary spatially from coarse flows to braided channels at the
 446 scale of single large glacia relics. This indicates space-time interplay of debris flows and
 447 sheet floods comparable to those observed on Quaternary or functional alluvial fans and
 448 pediments of arid or semi-arid regions of the world (Bull, 1977; Oberlander, 1997;
 449 Dohrenwend and Parsons, 2009). Besides, functional glacia in the Soudanian and Sahelian

zones (Fig. 2) provide an actualistic perspective onto the sedimentary patterns and alluvial/colluvial processes having operated on the past West African glaxis before duricrusting (Grandin and Joly, 2008). Water and sediment transport modes on glaxis precluded the maintenance of ramified river networks but instead favored dense and unstable channel networks that were active only during rainy episodes. Rivers maintained their courses only at the downslope junctions of converging glaxis, where alluvial sedimentary facies can be found (e.g., Figs. 8, 9 and 10).

Glaxis conglomeratic ferricretes are usually underlain by a carapace and/or a mottled clays horizon (Fig. 15a), implying that duricrusting is confined to the conglomeratic layer. In other cases, thick conglomeratic covers are duricrusted only superficially, meaning that part of their thickness became a carapace. Glaxis conglomeratic overburdens are not necessarily cemented (Fig. 12a), allowing to access original sedimentary textures that have not been obscured by iron segregation and cementation. The conglomerates and their matrixes consist almost exclusively of reworked Al-Fe duricrusts, carapace, mottled clays and saprolite, which are all rich in iron oxy-hydroxides. Large quantities of iron are therefore available in the conglomerates. Remobilization of that iron should favor cementation of the glaxis sedimentary overburden by oxy-hydroxides to form ferricretes. Such cementation scenarios are attested to by the common examples of glaxis ferricretes directly overlying fresh bedrock. This shows that ferricretes do not result from the sole relative accumulation of iron in a horizon of the weathering profile having successively gone through bedrock, saprolite, mottled clays and carapace stages. In other words, lateritic weathering is not a necessary condition for duricrusting (Grandin, 2008).

5. 2. Non-conglomeratic ferricretes, relationships with the underlying regolith

Some glacia ferricretes are composite, comprising an upper conglomeratic layer and a lower layer that results from iron aggradation/segregation and induration of the underlying carapace (Figs. 13 and 15b). In this case, duricrusting appears to have taken place beyond the base of the sedimentary overburden and the relative contributions of in-situ iron accumulation (from segregation within the carapace) and absolute iron input from the clastic sediments would be difficult to assess. Conglomeratic ferricretes are also seen to rest directly atop a saprolite or a saprock (i.e., basal core stone-bearing saprolite; e.g., Figs. 12b, 12f and 15c) or even the bedrock. This indicates that pedimentation truncated a weathering profile by removing its mottled clays, carapace or part or the entire thickness of its saprolite. Those truncations are currently seen in the field and have been also imaged by geophysics (e.g., Beauvais et al., 2003). The formation of iron nodules and/or iron segregation may be observed immediately under the conglomerate in the truncated weathering profile, indicating that ferruginization was not restrained to the transported sedimentary layer and that iron originated from the conglomeratic cover. Whether the weathering horizons underlying a conglomeratic ferricrete developed onto a preexisting saprolite or from pristine weathering of bedrock exhumed by pedimentation would be difficult to assess in the field.

Glacia ferricretes developed from fine-grained material (clay, silt, sand or a mix of those) have vermicular to nodular structures (Fig. 14) typically resulting from the maturation of mottled clays by iron concretion/segregation (Tardy, 1997; Fig. 15d). Those ferricretes are preferentially found on the distal parts of wide glacia and are ubiquitous in rolling pediplain contexts i.e., on lower-gradient slopes than the debris flows, which are mostly restricted to piedmont contexts. In conglomeratic ferricretes, matrixes are vermicular, as is the duricrusted material underlying conglomeratic layers of composite ferricretes (e.g., Fig. 13). If a comprehensive succession of weathering horizons exists under the vermiform/nodular ferricrete down to the bedrock, the glacia surface could be considered as erosional, and the

ferricrete as genetically linked to the underlying bedrock (e.g., Fig. 15d). But weathering of a composite section made of bedrock and/or saprolite topped by a fine-grained glacis overburden would end up producing a comparable profile (Fig. 15e). Fine-grained overburdens being mostly reworked saprolite, it would be difficult to locate the boundary between the in-situ and transported portions of the section, which would have been further obscured by weathering after pedimentation, unless a major break in lithology or granulometry be identified (Fig. 15e). The very large areas of functional glacis exposing alluviums composed of clays, silts and sands suggest analog fine-grained overburdens for past glacis systems. Weathering/duricrusting of such overburdens should end up forming a typical vermicular / nodular ferricrete that may top weathering horizons mimicking those produced on bedrock (e.g., Fig. 13). Most weathering profiles of West African ferricrete-capped glacis weathering profiles may therefore be composed of fine-grained transported material instead of resulting from weathering of bedrock even though the ferricrete is not conglomeratic.

There is commonly a spatial variability in the nature of the surface at the scale of a single glacis that comprises ferricrete-free surface areas and (erosional or detrital) ferricrete-capped surface areas (Fig. 11). In other words, the detrital layer does not systematically cover an entire glacis and duricrusting does not necessarily affect an entire glacis surface. Ferricrete-free glacis surfaces may be erosional and expose exhumed regolith developed from bedrock (Fig. 15f). However, the possibility that they actually expose transported (fine-grained) saprolite that escaped duricrusting is not precluded (Fig. 15g). In this case, only a detailed petro-geochemical investigation would allow distinguishing an in-situ saprolite from an overlying transported layer.

Contrary to the inselbergs and residual massifs they contributed to exhume, West African glacis do not expose bedrock but regolith. This could suggest that weathering has

524 turned bedrock leveled by pedimentation into regolith. But observations along river cuts
 525 and in trenches indicate that glacis are essentially cut into a saprolite previously formed
 526 during an earlier weathering period (e.g., Figs. 11, 12b and 15). Observations of the steep
 527 stripped flanks of bauxite plateaus of dry regions show that the relief carved into the bauxitic
 528 surface by the glacis is entirely made of saprolite more than 40 m thick (e.g., Fig. 6a). With
 529 the exception of inselbergs, the lower flanks of residual massifs and low-lying outcrops
 530 exhumed after abandonment of the Low glacis, bedrock is mostly exposed in riverbeds.
 531 The ubiquity of glacis systems throughout West Africa is explained by the fact that they were
 532 easily cut through regolith instead of bedrock, as also shown for the pediments of Central
 533 Australia by Mabbutt (1966). Most of the regolith thickness available for stripping by
 534 pedimentation was likely produced by the Bauxitic (and Intermediate) periods(s) of intense
 535 lateritic weathering (Grimaud et al., 2015). The thin (< 20 m) weathering profiles genetically
 536 linked to each glacis would suggest that weathering phases following pedimentation periods
 537 produced a regolith layer available for stripping during the next pedimentation period (e.g.,
 538 Millot, 1980). This hypothesis would apply to the lowermost parts of glacis cut into bedrock
 539 (e.g., cross-section, Fig. 15) and would be supported by the comparable heights of the
 540 weathering profile and the vertical separation between successive glacis.

541 Notwithstanding the spatial variability in the nature of individual glacis surfaces and
 542 associated regolith, main type-characteristics of ferricretes and weathering patterns of each
 543 glacis system may be synthetized as follows (Grandin, 2008). The High glacis ferricrete can
 544 reach 10 m in thickness in piedmont contexts and the underlying weathering profile rarely
 545 exceeds 20 m. Middle glacis ferricretes do not exceed 5 m and are generally limited to 1 to 2
 546 m. Their underlying weathering profile is reduced to a few meters and is not as kaolinite rich
 547 as that of the High glacis. Ferricretes of functional Middle glacis often show evidence for
 548 dissolution and end up acquiring vacuolar to cavernous textures (Leprun, 1979). The Low

glacis bear a thin (< 1 m) ferricrete or, more generally, at best a carapace. Carbonate concretions may develop under its erosional surface or in its sedimentary overburden and neo-formed clays are mostly smectites.

5. 3. *Recently remobilized regolith and alluviums*

Low glacis are commonly overlain by unconsolidated alluvial and aeolian sediments (Fig. 15h), which are actively reworked by pedimentation during each rainy season (especially in the Soudanian and Sahelian zones; Fig. 2). It is also the case for large functional Middle glacis. Active alluvial fans also occupy upslope sections of functional glacis in piedmont contexts, at least in the dry zones (e.g., Fig. 5). Streams that have incised the glacis sedimentary overburden generally flow atop the ferricrete or the carapace and expose sections that commonly exceed 2 m in thickness. Overburdens occupy huge areas and develop soils that are exploited for agriculture. But those soils almost never derive from weathering profiles connected to the underlying bedrock because they are transported and almost always overly conglomeratic ferricretes (Fig. 15h).

Post-Low glacis (i.e., Quaternary) river alluviums are preserved along the drainage network and often correlate with the unconsolidated glacis cover (Fig. 11; Fig. 15, upper cross-section). The oldest and most remarkable alluvial terrace of regional extent has been reported and correlated from the main rivers of Northern Guinea, Senegal, Southwestern Mali, Ivory Coast and Burkina Faso (Vogt, 1959a, 1959b; Michel, 1969, 1973; Eschenbrenner and Grandin, 1970; Grandin, 1976). This terrace is floored by a cemented conglomerate (the “graviers sous-berge”) that occupies the riverbeds and has been incised of less than a few meters (Fig. 15). Aggradation/incision cycles younger than the conglomerate have been recognized but no systematic regional patterns have been deciphered yet (Thomas and

Thorpe, 1985; Hall et al., 1985; Thomas et al., 1985; Teeuw et al., 1991; Ouangrawa et al., 2000).

6. Extent and variability of the glacia record in West Africa

6. 1. Geomorphic provinces and areal extent of glacia

The compilation of a regional landform-regolith map (Fig. 17) shows that the relics of the three glacia systems occupy an overwhelming areal proportion of the landsurface, with the exception of a few regions of specific geological substrate, topography or active sedimentation. Laterally continuous bauxite-capped landforms of the African Surface form mappable units restrained to some highly-elevated (> 500 m) areas of Pre-Cenozoic sandstones and/or high concentration of dolerite sills (Fig. 17). Paleolandscapes capped by the Intermediate ferricrete are well preserved on Cenozoic sedimentary basins and their margins, as well as on Pre-Cenozoic tabular sandstones flanked by rock escarpments (Fig. 17).

The Archean and Paleoproterozoic granite-greenstone terrains, their adjoining mobile belts and the remaining tabular sediments of the sub-Saharan area are characterized by glacia composite landscapes (Fig. 17) such as those illustrated on Figures 5- 8, 10 and 15. In those landscapes, the High glacia system always occurs as relict plateaus or hills. Distant relict massifs of the Bauxitic and/or Intermediate landscape and inselbergs remain (e.g., Fig. 6a). A large part of the composite glacia landscape geomorphic province is a Middle-Low glacia rolling pediplain locally preserving High glacia remnants as interfluvies (e.g., Figs. 6b). The relative extent of the Low glacia system tends to grow northward going across the Soudanian zone to become maximal in the Sahelian zone where a Low glacia province is defined (Figs. 1 and 17b) as a vast and very flat pediplain with tens of kilometers-wide glacia that are functional. The efficiency of pedimentation is favored by both the Sahelian climate

and the limited (< 40 m) local relief left since the abandonment of the bauxitic African surface along the considered portion of the Niger River Valley (Grimaud et al., 2014; Chardon et al., 2016).

In the Saharan zone (Figs. 1 and 17b), low lands consist of active regs, dune fields (ergs) and fluvio-aeolian sandplains that mostly blanket the subdued Intermediate or Low glacis landscapes, whilst crystalline substrate generally crops out. South of the Sahelian zone, bedrock is exposed mostly on the steep dissected slopes of regional topographic massifs upon basement substrate (Figs. 1 and 17).

The bauxitic African Surface was an etchplain i.e., a low-relief continental scale landsurface underlain by a thick regolith resulting from a protracted period of intense weathering and correlatively subdued mechanical erosion. As a result of stepwise dissection of that landsurface by pedimentation, most of its regolith mantle has been removed so that sub Saharan West Africa has become a stripped etchplain, whose remnants are preserved only in a few patches of relict bauxitic landscapes (Fig. 17) and individual occurrences scattered over the sub region (Beauvais and Chardon, 2013; Chardon et al., 2016). The glacis composite landscape province (Fig. 17) constitutes the stripped African etchplain.

6. 2. Climatic zonation of paleo-glacis systems and glacis degradation processes

The preservation of each glacis system depends on (i) the efficiency of planation (i.e., the capacity of pedimentation to form wide glacis), (ii) the intensity of duricrusting and (iii) the magnitude of glacis dismantling (Grandin, 1976). Those three factors are chiefly dependent on latitude (Fig. 18). Their spatial variations from one glacis system to the next could suggest an evolving latitudinal climatic zonation of West Africa over the last ca. 25 Ma notwithstanding the duration of each glacis cycle (Fig. 18).

622 Under dry climate, glacis tend to be preserved in such a way that duricrusting
623 molded their pristine shape and pedimentation-driven landscape dissection leads to
624 plateaus with sharp edges. On-going pedimentation can eventually turn the plateau into a
625 residual hill (Fig. 19a) flanked by concave glacis slopes. Weathering is subdued during this
626 process and mechanical dismantling of the ferricrete takes place while pedimentation
627 disperses its erosional products downslope. Such a morphogenesis typically produces
628 rolling pediplains (Fig. 6b). In zones of intense pedimentation, residual hills are ultimately
629 erased to produce very low amplitude pediplains made of wide glacis. Under humid climates,
630 and typically in the forest, weathering assists degradation of the plateau-flanking slopes that
631 evolve by a combination of compaction of the residuum, creep and colluvial processes to
632 acquire convex profiles, while the ferricrete is being dissolved and dismantled and collapses
633 onto its underlying weathering profile that is reactivated (Fig. 19b). The combination of
634 those processes produces a common type of stone line i.e., a layer of angular or sub-
635 rounded quartz gravels and pebbles, which result from the dislocation of quartz veins by
636 compaction. The resulting residual hills are “demi-oranges” (Thomas, 1994) that form
637 multiconvex plains typical of today’s shields’ tropical rain forest (e.g., Rohdenburg, 1982;
638 Lecomte, 1988; Bitom et al., 2004).

639 Recent morphogenesis (i.e., having taken place after duricrusting of the Low glacis
640 around 3 Ma ago) tends to degrade relict High and Middle glacis. Semi-arid climates of the
641 Sahelian and southern Saharan zones favor the development of very flat pediplains, whereas
642 the sub-equatorial humid climate of the Forest zone drives degradation of glacis to form
643 multi-convex plains. A latitudinal gradient must exist between these two modes of modern
644 morphogenesis across the Soudanian and especially the Guinean zones (Grandin, 1976; Figs.
645 1 and 17). A somewhat comparable latitudinal morphoclimatic gradient applied to each
646 paleo-glacis system, although with potentially contrasted climatic zone widths (Fig. 18).

647 Such a gradient explains systematic limited planation and duricrusting in the South (Fig. 18),
648 further enabling past and recent “humid” morphogenesis in today’s Forest zone.

649 Forest, savanna and semi-arid tropical environments have long been considered as
650 contrasted morphoclimatic contexts (e.g., Büdel, 1982). The latitudinal climatic zonation of
651 both past pediment systems and today’s landform evolution processes over West Africa
652 argues for a continuous spatial pattern of pedimentation - considered as the combination of
653 all slope shaping processes – between an arid end-member and a humid Equatorial end-
654 member across the inter-tropical zone (e.g., Holmes, 1955; Millot, 1980, 1983; Rohdenburg,
655 1969, 1982).

656

657 *6. 3. Morphoclimatic specificity of West Africa, comparison with neighboring regions*

658 The remarkable preservation of the West African glacis systems is related to the sub
659 region having remained for more than 100 Ma in the zone of optimal weathering conditions
660 for the production of Fe and Al crusts (Tardy and Roquin, 1992, 1998; Fig. 2). Such a
661 latitudinal stability is due to the pinning down of the African plate’s rotation pole near the
662 Coast of Guinea (Tardy and Roquin, 1998). Optimal duricrusting worked in two ways for the
663 preservation of glacis. First, weathering/duricrusting produced a major original stock of iron
664 during the bauxitic weathering period i.e., from the Late Cretaceous to the mid Eocene (with
665 a peak between 55 and 45 Ma). This original iron stock was then recycled in the Intermediate
666 landscape and by each glacis system (Grandin, 1976). Second, optimal conditions favored
667 duricrusting of Al-Fe crust dispersed on glacis to form protective duricrusts that favored
668 landscape dissection and paleo-glacis preservation.

669 Regions located further to the East and encompassing the same current latitudinal
670 band as sub Saharan West Africa have undergone a greater northward shift across the inter
671 tropical zone (and beyond) since the Late Cretaceous that likely resulted in a contrasted

morphoclimatic record. Nevertheless, those regions preserve a record of stepped pediment systems that may correlate with those of West Africa (e.g., Fölster, 1964). A “High” glacia system has been reported regionally under what appears as the remnants of the Intermediate ferricrete-capped paleolandscape (De Swardt, 1964; McFarlane, 1976, and references therein) but no systematic correlation scheme has emerged yet. Further South in Central Africa, pediment systems occupy large regions around and within the Congo Basin (Ruhe, 1956; Guillocheau et al., 2015). The latter authors proposed a tentative correlation between their 9-planation surfaces model (among which the 5 latest are pediment systems) and the West African morphoclimatic sequence as synthesized by Beauvais and Chardon (2013). Degradation of glacia systems in Equatorial Africa under perhumid climates would be a challenge for regional morphoclimatic correlation across the intertropical belt.

7. Implications for mineral exploration

The great extent and spatial variability of the West African glacia landform-regolith associations (Fig. 17) prompt caution when targeting suitable spots for surface sampling that would reflect bedrock geochemistry as accurately as possible. Glacia regolith profiles are indeed composite and polycyclic, resulting from uneven weathering and duricrusting of slopes cut into a pre-existing regolith and/or the bedrock and overlain by discontinuous detrital sedimentary layers.

7. 1. Accessibility to the geological substrate

Glacia ferricretes all represent an obstacle to access bedrock geochemistry. There are three main reasons for this. First, they often represent sedimentary covers that are allochthonous (Figs. 15a-15c, 15e) and do not derive from their underlying regolith by weathering. Second, even if formed exclusively in-situ, and as the most evolved product of

697 weathering, ferricretes would have lost most of the geochemical characteristics of the
 698 bedrock (e.g., Tardy et al., 1988; Boeglin and Mazaltarim, 1989; Roquin et al., 1990). Third,
 699 solute elemental transfers through the regolith and sedimentary cover down the glacia slope
 700 can contribute to absolute elemental accumulation in the ferricrete, especially in iron
 701 (Maignien, 1958, 1966; Ollier and Galloway, 1990, Beauvais, 1999; Brown et al., 2003).
 702 Therefore, vertical geochemical mass balances through ferricrete-capped glacia weathering
 703 profiles are often misleading indicators of weathering-controlled dispersion of bedrock
 704 elemental concentrations. Ferricrete-free glacia surfaces pose another sizable exploration
 705 issue. Only erosional portions of such surfaces would provide direct access to a saprolite
 706 preserved on its parental bedrock (Fig. 15f), providing they are identified as such and not
 707 mistaken for transported saprolite (Fig. 15g). Loose sedimentary glacia overburdens (Fig.
 708 15h) mask their substrate. They are commonly thick (> 2m), overly a detrital ferricrete and
 709 may be mistaken for soils. It is why even sampling at 50 cm depth - as often undertaken in
 710 such material - is not appropriate to attain the saprolite preserved on its parental bedrock.
 711 Only sampling of the bedrock or the in-situ preserved saprolite is reliable for
 712 characterizing the geological substrate's geochemistry (propitious locations would be edges
 713 of glacia plateaus that expose weathering horizons under the ferricrete). In all other
 714 situations, a surface geochemical anomaly on a glacia can have several meanings. In the best
 715 case, the surface is erosional and ferricrete-free, the anomaly signing an underlying bedrock
 716 concentration (e.g., Au, Pt, Zn, Cu). The present work however suggests that such
 717 configuration is rarely demonstrated. In all other - most common - cases, the anomaly would
 718 be ambiguous. It may have been "transported" with the sedimentary cover on the glacia by
 719 pedimentation (e.g., Sanfo et al., 1992) or may be the expression of a potentially complex
 720 and very wide dispersion halo having been elongated downslope. Such a halo could also at
 721 least partly result from geochemical dispersion of a bedrock anomaly through a transported

722 overburden by biological, gaseous or capillarity processes (Anand et al., 2014). Conversely,
 723 the absence of a surface anomaly would not preclude the occurrence of an anomaly in the
 724 underlying bedrock. In any case, landform-regolith mapping and establishment of a glacia
 725 landscape chronology are required around the sampling sites in order to (i) constrain the
 726 geomorphological context of the anomaly for locating its potential distant source or (ii)
 727 identify glacia covers that mask potential bedrock resource(s) (Bamba, 2009).

728

729 *7. 2. Geomorphological exploration guides*

730 Gold anomalies in detrital glacia ferricretes overlying barren bedrock are common.
 731 Studies combining detailed landform-regolith mapping, trench studies, geochemistry and
 732 gold particles characterization allowed documenting km-scale downslope displacement of
 733 gold particles from their bedrock sources (Sanfo et al., 1992, 1993; Parisot et al., 1995;
 734 Ouangrawa et al., 1996; Bamba et al., 2002). For such investigations cannot be undertaken
 735 systematically, the geomorphological approach may prove rewarding in constraining the
 736 potential bedrock source area of a transported anomaly based on the assumption that it has
 737 been displaced down the slopes of a considered glacia.

738 In rolling pediplain contexts, tracing the potential upslope source of a transported
 739 anomaly should be straightforward, providing the glacia landscape has not been
 740 significantly dissected and preserved its original interfluvium (e.g., Figs. 6b and 6c-6e). In such a
 741 case, the source of the transported particles cannot be located beyond the preserved glacia
 742 interfluvium. In dissected rolling pediplains and particularly piedmont contexts, upslope
 743 portions of glacia are rarely preserved (e.g., Figs. 6a; 7; 10). Paleolandscape reconstruction at
 744 the time the sampled glacia was functional is necessary to evaluate the potential path
 745 followed by the glacia sedimentary cover during pedimentation. Instead of a cross-sectional
 746 approach, a three-dimensional landscape reconstruction (e.g., Fig. 7) is suitable to take into

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1802
1803 747 account the entire upslope drainage area that could have supplied mineralized debris to the
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1805 748 anomaly on a glacia. For instance, an anomaly documented in the lowermost portion of a
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1807 749 relictual glacia i.e., close to or along a river active at the time of pedimentation, can be
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1809 750 sourced from the erosion of all the glacia that were connected downslope to that drain
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1811 751 upstream. For functional glacia, delimitation of the upslope area that contributed to a
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1813 752 sampling site would be straightforward because this area is constrained by the present-day
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1815 753 topography.

1816
1817
1818 754 Maximal transportation distance on a glacia corresponds to the upslope distance
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1820 755 between the considered sampling site and the drainage divide at the end of the activity of
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1822 756 the glacia (i.e., before its abandonment and dissection). Reconstruction of the High glacia
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1824 757 landscape suggests that paleo-glacia widths have exceeded 20 km (Grimaud et al., 2015; Fig.
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1826 758 10), prompting to undertake landform-regolith mapping and paleolandscape reconstruction
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1828 759 on a larger scale than that of the immediate surrounding of the anomaly-bearing glacia relic.
1829
1830 760 South of the Sahelian zone (Fig. 2), dissection of the High glacia pediplain has generally
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1832 761 created narrower (1-10 km) Middle and Low glacia flanking subsequent valleys that are often
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1834 762 perpendicular to the earlier main river drain delimitating High glacia (Fig. 7). Potential
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1836 763 maximal transportation distances on those pediments are therefore reduced compared to
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1838 764 those of the High glacia and the transport direction at a high angle to that of the preexisting
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1840 765 glacia. The same reasoning as that exposed above applies to the tracking of the source of
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1842 766 transported regolith upslope on the Middle and Low glacia, bearing in mind that the cover of
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1844 767 these glacia can carry elements that may have previously been transported on an earlier
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1846 768 glacia. Potential divide migration from one glacia landscape stage to the next should also be
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1848 769 taken into account (e.g., Fig. 8). A given bedrock mineral concentration could indeed have
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1850 770 been subjected to pedimentation by successive glacia of contrasting slope directions and
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1852 771 therefore may not have always belonged to the same drainage sub-basin (Fig. 20).
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Stream sediment surveys going up river would still be valid in glacia environments, providing that once propitious channel sections are selected, the upslope source tracing protocol described above for glacia environment is applied. The geomorphological exploration guides considered here do not only apply to resources transported as particles such as gold, platinum or diamond, but also to ore deposits such as copper or manganese, which can accumulate by downslope solute transfers through glacia cover (e.g., Sillitoe, 2005; Riquelme et al., 2018).

7. 3. Targeting concealed resource

Glacia being mostly screens over the bedrock and given their extension, the biggest West African exploration challenge is to detect the resources they potentially mask. A way to contribute to targeting such resources is to identify glacia units potentially masking mineralized bedrock lithologies, structures or dikes that were first identified and mapped independently from scattered outcrops or boreholes. By combining the geological map and a landform-regolith map, one obtains by a GIS overlay operation the intersection between polygons representing glacia ferricrete units, on the one hand, and polylines or polygons representing mineralized faults, dykes or rock units, on the other hand. As an illustration of such a GIS request, Figure 21 shows gold, copper and manganese indices over Southwestern Burkina Faso as well as the High glacia ferricrete relics overlying (i.e., intersecting) bedrock lithological units bearing those indices. This representation allows (i) targeting High glacia ferricrete relics potentially masking deposits and (ii) adapting a sampling or drilling strategy accordingly. Those targeted glacia ferricrete units should then be studied in details and eventually be drilled across to attain the projected trace of the mineralized structure under the glacia cover. Such a protocol would typically reveal lateral extensions of ore bodies and

796 may be applied from a regional (10-100 km) (Fig. 21) to a prospect scale (0.1-1 km) if

797 landform-regolith maps of appropriate resolution are produced.

798

799 *7. 4. Other geomorphic exploration pitfalls and overlooked resources*

800 The pervasive occurrence and preservation of convexo-concave rolling pediplains

801 south of the Sahelian zone and the degradation of glacis into concave residual hills under

802 equatorial environments explain why glacis may have been overlooked, especially by

803 workers who did not investigate landforms outside the Forest zone, contrary to Grandin

804 (1976), who worked across an entire regional latitudinal corridor. Exploration geologists

805 have indeed implicitly interpreted residual hills as “demi-oranges” (e.g., Freyssinet, 1993;

806 Freyssinet et al., 2005) although they may result from pedimentation in the case of rolling

807 pediplains or from the degradation of older glacis into convex hills. A consequence of such

808 restrictive interpretation is that ferricretes / lateritic residua are considered as formed and

809 preserved essentially in-situ, whereas they could host material transported prior to

810 weathering/duricrusting. A residual hill can result from the dismantling of a wide glacis on

811 which material has been transported over several kilometers if not tens of kilometers i.e., on

812 a much larger scale than the size of the residual hill. However, detailed exploration

813 geochemical investigations or models are restricted to the slope of a single residual hill (e.g.,

814 Zeegers and Lecomte, 1992; Freyssinet, 1993; Butt, 2016). In glacis landscapes such as those

815 of West Africa, landform-regolith mapping and the establishment of a landscape chronology

816 should therefore be undertaken on a larger scale (1-20 km) than that of the considered

817 anomaly-bearing relief (0,1-1 km).

818 Given the alluvial nature of glacis overburdens, placers must be common on

819 pediments. Detailed work by Thomas and Thorp (1985) or Teuuw (1987, 2002) suggests that

820 alluvial diamonds are hosted by paleo-glacis systems’ residual hills. Recent unconsolidated

glacis overburden is commonly mined for gold placers. Those artisanal mines are valuable proxies of upslope bedrock mineralizations by using the geomorphological guides provided above. Downslope parts of Low glacis and alluvial terraces host gold and diamond placers (e.g., Hall et al., 1985; Teeuw et al., 1991; Ouangrawa et al., 1996). But older glacis ferricretes should also bear numerous unsuspected alluvial placers. Although weathering of the High glacis has contributed locally to eluvial gold concentrations, it is mostly the thick and mature weathering profiles of the Bauxitic and Intermediate paleolandsurfaces that have a high - and still largely overlooked - potential of hosting supergene ore concentrations others than those that are known and actively mined for (Al, Mn and Au).

830

831 **8. Pediments, pediplains and the topographic evolution of shields**

832 *8. 1. Implications for pedimentation in lateritic landscapes*

833 Thanks to the protective effect of the ferricretes and limited regional denudation, 834 there is a significant spatial and temporal variability in the glacis record from the scale of a 835 single pediment to that of the African sub region. As composite landform-regolith 836 associations, pediments erode, collect, transport, sort, transform and store regolith through 837 space and time. An overwhelming part the of the West African pediments are cut exclusively 838 in a thick (>20 m) preexisting regolith mantle and a single pediment may be both cut through 839 preexisting regolith upslope and through bedrock downslope. The very common occurrence 840 of rolling pediplains also shows that pediments encompass the entire regional relief and 841 therefore cap interfluvies. The West African case study therefore suggests that lateritic 842 pediments may not be appropriately distinguished by morphogenic classifications based on 843 (i) the shape or position of pediments in the landscape (Cook and Mason, 1973), (ii) the 844 relations between regolith and the bedrock as criteria of the pedimentation process 845 (Twidale, 1983), (iii) the nature of the material being cut (Dresch, 1957; Tricart, 1972;

846 Oberlander, 1989) or (iv) the thickness of the transported overburden (Applegarth, 2004) (see
847 Dohrenwend and Parsons, 2009 for review). Likewise, a comprehensive definition of the
848 physical and chemical processes involved in pedimentation would be therefore, to our view,
849 vain. Pre-Neogene weathering was instrumental at preparing the thick regolith mantle made
850 available to stepwise pedimentation. But evaluation of the role of weathering during the
851 formation of glacis would not be straightforward given the imprint of the post
852 pedimentation weathering and duricrusting of the pediments. At best, an increasing
853 activation / influence of the pedogenetic processes is expected in pedimentation across the
854 latitudinal gradient towards the Equator (e.g., Millot, 1980, 1983; Rohdenburg, 1969, 1982).

855

856 *8. 2. Relations to epeirogeny*

857 Pediment systems carved the African surface while it was being submitted to long
858 wavelength (10^3 km) deformation that contributed to the growth of the basin-and-swell
859 topography of the continent after 40 Ma (Burke and Gunnell, 2008; Chardon et al., 2016). The
860 most prominent element of that physiography in West Africa is the Hoggar swell; but more
861 subtle uplift is also suggested along the marginal upward that constituted the eastern
862 extension of the Guinean rise up to the Jos Plateau (Grimaud et al., 2014, 2018; Chardon et
863 al., 2016; Fig. 2). The stepping patterns of pediment systems may not be used as a proxy of
864 that deformation because glacis have a roughly spatially consistent and reduced (< 80 m)
865 elevation range above local base level, which itself varies with river networks from sea level
866 to above 1300 m for the highest regional topographic massifs excluding the Hoggar
867 (Grimaud et al., 2014; Fig. 2). In details, the stepping pattern of successive glacis has been
868 compartmentalized amongst sub drainage areas due to spatially variable incision of river
869 segments bounded by stationary knickzones, which were already part of the West African
870 landscape before settlement of the High glacis pediplain for most of them (Grimaud et al.,

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2103 871 2014). Furthermore, glacis systems did not level out regional rock escarpments, which were
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2105 872 already imprinted in the Paleogene Bauxitic and (mostly) Intermediate landscapes and
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2107 873 remained almost stationary since then (De Swardt, 1964; Grandin and Delvigne, 1969; Burke
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2109 874 and Gunnell, 2008; Grandin and Joly, 2008; Grimaud et al., 2014, 2015; Fig. 17). Glacis
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2111 875 systems therefore adapted their slopes to differentiated and uneven river levels and
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2113 876 contributed in this way to distributed landscape dissection and dismantling down to the
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2115 877 scale of lowermost-order drains a few kilometers long (e.g., Figs. 8, 9, 10). In other words,
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2117 878 outside the provinces of relict African and Intermediate landscapes (Fig. 17), virtually no 20 x
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2119 879 20 km area of the West African topography escaped settlement of new glacis during the main
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2121 880 pedimentation periods, with the exception of Low glacis pedimentation at lowermost
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2123 881 latitudes (Fig. 18).

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2125
2126 882 Thorough documentation of stepwise Cenozoic dissection of the West African sub
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2128 883 region therefore precludes the stepping of successively younger pediplains bounded
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2130 884 upstream by escarpments, which would produce continental-scale staircase patterns of
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2132 885 pediplains from the crest of swells down to sea level or the base level of intracratonic basins.
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2134 886 Such a model is suggested by Burke and Gunnell (2008, their Figure 16A) on the crest and
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2136 887 slopes of the Guinean Rise (Fig. 2). Staircase pediplains models derive from that of King
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2138 888 (1948, 1967) in which continent-wide and flat pediplains graded to sea level form by
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2140 889 escarpment/knickzone retreat far inland. For King, a pediplain is abandoned as a
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2142 890 consequence of uplift by the formation of a subsequent pediplain below a new retreating
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2144 891 escarpment, which will ultimately bound and protect the relic of the early pediplain in the
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2146 892 continental interior. King's paradigm is also explicit in the procedure that would allow
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2148 893 retrieving long-term continental uplift histories from the inversion of current river
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2150 894 longitudinal profiles (Paul et al., 2014). This procedure is indeed based on a quantitative
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2152 895 model that explicitly requires inlandward retreat of river knickzones in response to uplift and
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is therefore invalidated by the well-documented West African case study (Grimaud et al., 2014). A staircase model of pediplains has also been proposed by Guillocheau et al. (2015, 2017) for the Congo basin and its surrounding swells and by Dauteuil et al. (2015) for Namibia. The definition of a pediment system by these authors as a flat pediplain connected upslope to pediments (pediment valleys) and higher up to rivers incising the older upstanding landsurface across escarpments (e.g., Guillocheau et al., 2015) therefore contrasts with that implied by the West African case study. The difference between the two models is not only conceptual. Regional correlations of West African glacia systems are based on well-preserved regolith-landform associations and geomorphic criteria, whereas those of Central and Southwestern Africa have to rely mostly on topographic correlations and escarpment identification in contexts of advanced degradation of the regolith-landform associations or in absence of type-regolith-landform associations in arid Southwestern Africa. The topographic approach would intrinsically favor a Kingian model and vice-versa.

The West African case study indicates that pediments achieved local planation and formed from the development of the drainage network instead of by dominant range retreat. The difficulty to relate the regional stepping patterns of pediment systems to an inferred pattern of uplift over West Africa suggests that shield landscape dissection schemes would primarily be driven by long-term climatic oscillations driving pedimentation / weathering periods along low-abrasion capacity river networks (e.g., Tricart 1959; Beauvais and Chardon, 2013).

8. 3. Pediment landscape evolution processes and the sediment routing system

Surface process models suggest that non-orogenic continental surfaces such as that of Africa develop non-steady state (transient) landscapes with a Davisian behavior of long-term decreasing slope angle (Davis, 1899; Bishop, 2007). African landscapes saw their relief

921 increasing throughout the Cenozoic and should then be considered as transient over the
922 very long term. But the punctuated pedimentation scheme they developed does not match
923 that of the Davisian cycle of erosion. The main specificity of the West African landscape
924 dissection patterns by pedimentation is a progressively reduced area submitted to abrasion
925 through time, leaving increasingly wider relict surfaces of limited or no denudation as a
926 result of landscape dissection (Fig. 10). The stepping patterns of pediment systems have no
927 clear dependency on sea level variations and/or epeirogeny and contribute to limited (3-9
928 m/My) and distributed denudation. In contexts of enhanced uplift and correlatively higher
929 denudation such as the upper slope of the Hoggar swell (surface uplift and denudation > 30
930 m/My since ca. 35 Ma; Chardon et al., 2016; Grimaud et al., 2018), pediplains could not form
931 or be preserved on geological time scales.

932 Once duricrusted and/or abandoned as a result of dissection, pediments preserve
933 the underlying regolith from erosion. Regional-scale pediment systems (pediplains) form
934 and maintain over geological timescales in environments submitted to low river incision or
935 erosion rates (<10 m/Ma) and limited epeirogenic uplift. Under that condition, the
936 maintenance of very slowly evolving pediment landscapes poses the chicken-and-egg issue
937 of knowing whether the low erosional efficiency of pedimentation dictates the limited
938 transport and incision capacity of the river network or vice-versa. In any case, pediments are
939 buffer landsurfaces between the regolith mantles they contribute to exhume and the rivers
940 they feed with reworked regolith (Grimaud et al., 2015). Pedimentation is transport-limited
941 given the large amount of (old) regolith still being stored in West African landscapes, which
942 generates subdued and nearly constant erosion fluxes over the long-term (< 0.01
943 km³/km²/My). Above a 10 m/My incision/erosion rate threshold, rupture of the
944 pedimentation regime is expected, paleo-landforms being erased. It is only above several
945 tens of meters per million years of long-term erosion that denudation would potentially

946 become measurable by low-temperature thermochronology (Beauvais et al., 2016). The
 947 regional preservation of pediments / pediplains indicative of very slow denudation should
 948 then prevent retrieval of denudation scenarios from low-temperature thermochronology for
 949 periods encompassing pediments timespan of formation and over periods following their
 950 abandonment. Dated relict pediments should be used instead as strict constraints on the
 951 late temperature-time exhumation path provided by low-temperature thermochronology.

952

953 **8. Conclusions**

954 Throughout its surface, Sub Saharan West Africa preserves three Neogene (24-3 Ma)
 955 lateritic pediment systems as well as functional pediments along the southern fringe of the
 956 Sahara. A review of the landform-regolith associations, landscape chronologies, ages and
 957 stepping patterns of the pediments as well as their spatial distribution and active
 958 degradation modes bears implications for the long-term landscape evolution processes of
 959 shields and mineral exploration strategies in the tropical belt. Those implications may be
 960 summarized as follows.

961 1 – Pediments occupy an overwhelming surface of the sub region and contributed to
 962 removal of a thick lateritic regolith mantle resulting from intense pre-Neogene weathering.
 963 Each pediment system formed by the process of relief dissection and incorporated
 964 landforms inherited from earlier landscapes. Depending on the nature of the geological
 965 substrate, pediment paleolandscape stages comprised regions of multiconcave pediplains
 966 and regions of multi-convexo-concave pediplains (called rolling pediplains).

967 2 - A great spatial diversity exists in the pediments regolith associations owing to the nature
 968 of the substrate pediments have leveled, the origin, transport dynamics and preservation of
 969 the materials that have been transiting on their surface and the intensity of weathering and
 970 duricrusting their have undergone. However, detrital ferricretes and loose clastic sediments

971 constitute by far the most common type of pediment surface. Fe-duricrusting and ferricretes
 972 constitute a necessary condition for glaxis dissection and preservation of relictual
 973 landscapes.
 974 3 – Lateritic pediment surfaces are not suitable for geochemical sampling aiming at
 975 obtaining reliable information about the composition of the bedrock or an elemental
 976 concentration anomaly. The two main reasons for this are (i) the transported nature of the
 977 material exposed at the surface and (ii) the lost of the geochemical characteristics of the
 978 bedrock through the weathering processes.
 979 4 - Landform-regolith mapping beyond the scale of modern interfluves followed by
 980 reconstitution of past pediment landscape stages provides geomorphological exploration
 981 guides for interpreting surface geochemical anomalies on pediments and tracing their
 982 potential sources in case they have been “transported” on pediments. Mapping of landform-
 983 regolith associations may also be used to target pediments masking suspected
 984 mineralizations.
 985 5 - Past and present latitudinal climatic zonation of pedimentation and weathering at the
 986 scale of the sub region suggests a gradient of pedimentation processes from an arid to a
 987 perhumid end-member across the intertropical zone. They also explain why pediments may
 988 have been overlooked in humid equatorial environments, with important implications for
 989 mineral exploration.
 990 6 – Successive pediment systems have affected progressively reduced area over time,
 991 preserving increasingly wider relictual landsurfaces. Climatic oscillations dictated
 992 pedimentation-driven, local planation that adapted slopes to very large, spatially
 993 differentiated, knickzone bearing river networks. The spatially consistent and limited (< 80
 994 m) stepping pattern of pediments is independent from elevation or distance to base level.
 995 Hence, pediments and pediplains may not be used as gauges of uplift except near coastlines.

996 Pediments form and are preserved regionally over geological timescales only for < 10 m/My
 997 erosion regimes and are therefore indicators of very slow shield denudation.
 998 7 – Lateritic pediments have been overlooked in the tropical belt because lateritic
 999 duricrusted landscapes refer exclusively to in-situ weathering of bedrock for most geologists
 1000 and geochemists. Further investigations will hopefully help deciphering pediment landform-
 1001 regolith associations for a better access to the geological substrate of tropical shields and its
 1002 resources that may still be underestimated. Investigating pediments as markers of past
 1003 morphogenesis is a powerful tool for understanding surface dynamics of shields and their
 1004 sediment routing system, which contribute to a significant proportion of the Earth
 1005 sedimentary budget and global biogeochemical cycles.
 1006
 1007 **Acknowledgments**
 1008 This work is published with the support of IRD (JEAi FasoLith). It has been mostly funded by
 1009 the TopoAfrica project (ANR-08-BLAN-572 0247-02), the West African eXploration Initiative
 1010 (WAXI) and the CNRS. Further support from TS2P (the Transform Source-to-Sink Project)
 1011 funded by Total Exploration and Production is acknowledged. The paper benefited from the
 1012 comments and suggestions of three anonymous reviewers. We acknowledge AMIRA
 1013 International, the industry sponsors and the Geological Surveys / Departments of Mines in
 1014 West Africa for their support of the WAXI project (P934A).
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Figure captions

Figure 1. Definition of the main elements of a lateritic weathering profile.

Figure 2. Topography, drainage, climatic zonation and political borders of Sub-Saharan West Africa. Climatic zones are adapted from Aubréville (1949). Savannas typically encompass the Guinean and Soudanian zones. For convenience, the Saharan, Sahelian and Soudanian zones are grouped in the present work as “dry regions”. Al: Algeria; Be: Benin; BF: Burkina Faso; C: Cameroon; G: Gambia; GB: Guinea Bissau; Gu: Guinea; IC: Ivory Coast; L: Liberia; Ma: Mali; Mau: Mauritania; Mo: Morocco; Na: Nigeria; Ni: Niger; Se: Senegal; SL: Sierra Leone; T: Togo.

Figure 3. Gold dispersion model through the regolith for ferricrete-capped West African landscapes (adapted from Freyssinet et al., 2005). The model is mostly based on the examples of the Syama mine (e.g., Fig. 2) and Banankoro prospect (Mali).

Figure 4. Synthetic representation (a) and Ar-Ar chronology (b) of the West African landform-regolith sequence (modified after Beauvais and Chardon, 2013 and Grimaud et al., 2015). Ar-Ar dates (solid circles) are from Beauvais et al. (2008) for cryptomelane samples from Tambao locality (Fig. 2). Ar-Ar dates from Syama (Southern Mali) are from Vasconcelos et al. (1994) (Fig. 2). Colored vertical stripes correspond to the weathering periods of each generation of landform-regolith association as deduced from Ar-Ar dating in Tambao.

Figure 5. Remnants of the West African morphoclimatic sequence as exposed in the Goren greenstone belt near Kaya, Central Burkina Faso. Above: east-looking GoogleEarth view;

below: interpretation based on field survey and photointerpretation (vertical exaggeration: x3). Areas in white are steep post-High glacia incision slopes exposing saprolite. Position of the 501 m height spot is 13.040825°N / 1.211588°E.

Figure 6. Sketch cross-sections of the two main glacia landscapes in West Africa. (a) Piedmont of a bauxite-capped mesa in greenstone belt terrain (inspired from field surveys in the Kongoussi area, Northern Burkina Faso). Dashed lines represent the maximum original extent of each glacia surfaces. (b) Rolling pediplain of the Middle glacia over granitoid or sandstone terrains. Bedrock is shown in grey and saprolite in yellow. Note the different scales in (a) and (b).

Figure 7. Three successive glacia landscape stages of West African granite-greenstone terrains (modified after Eschenbrenner and Grandin, 1970). (a) High glacia stage. (b) Early settlement of the Middle glacia (yellow). (c) Installation of the Low glacia (light blue). The model is based on regional field surveys in Northern Ivory Coast and Southwestern Burkina Faso across the Guinean and Soudanian zones (Fig. 2).

Figure 8. Dissection patterns of West African glacia systems (modified after Grandin and Joly, 2008). (a) Piedmont configuration of downslope-decreasing incision through time. (b) Piedmont configuration of downslope-increasing incision through time. Patterns (b) are favored along main river segments of enhanced/accelerated down cutting (i.e., base-level lowering), as opposed to patterns in (a) that are produced along main river segments of mitigated/reduced down cutting (see Grimaud et al., 2014). (c)-(e) dissection scenarios of a rolling pediplain. A High glacia rolling pediplain (c) may be degraded in two main types of landscapes depending on where dissection focuses. Landscape (d) results if erosion

predominates along the main river drains of the initial rolling plain. Landscape (e) results if erosion predominates in crestal regions of the initial rolling plain (black arrows point to the main river drain i.e., the local base level). In (d), the main slope portions of former glacis are preferentially preserved. In (e), mostly valley bottoms of the former rolling pediplain are preserved. In this case, the relief inversion concept strictly applies, as lower parts of the ancient landscape become the highest parts of the new landscape.

Figure 9. (a) High glacis ferricrete relicts over southwestern Burkina Faso. (b) Corresponding geomorphic map reconstitution of the High glacis pediplain (modified after Grimaud et al., 2015).

Figure 10. Idealized cross-sections of the successive landscape stages in West Africa. Black arrows locate the main river drains and white arrows the drainage divides. Such a landscape evolution model would typify the Soudanian or Sahelian zones (Fig. 2), where the original shapes of High and Middle glacis inverted landforms are preferentially preserved as plateaus (see Fig. 19).

Figure 11. Detailed cross-section of a Middle glacis near Bania, ca. 100 km south of the Ivory Coast – Burkina Faso border (modified from Eschenbrenner and Grandin, 1970). Upslope part of the Middle glacis is an erosional, ferricrete-free surface exposing exhumed (old) saprolite that was turned into mottled clays at the surface. Downslope part of the glacis is erosional in the sense that it stripped-off the saprolite, but is depositional in the sense that it carries a detrital colluvial layer that passes downslope to river alluviums. The ferricrete developed by duricrusting of most of the transported material. A thin weathering layer developed into the bedrock under the downslope portion of the glacis.

Figure 12. Field illustrations of glacis conglomeratic overburdens. (a) Block-supported debris flow (High glacis near Timbou, Guinea). The cobble is a bauxite. (b) Heterogeneous debris-flow facies underlain by dolerite core stones (High glacis near Kokoro, Burkina Faso). Cobbles are made of bauxite. The fine-grained saprolite and mottled clay horizons are missing from this weathering profile, suggesting its truncation by the debris flow. (c) Debris-flow with bauxite (light colored) and Intermediate ferricrete clasts in a matrix made of iron oxy-hydroxide nodules and pebbles (High glacis, near Basnéré, Burkina Faso). (d) Conglomerate comprising exclusively Intermediate ferricrete clasts (Middle glacis, near Kaya, Burkina Faso). (e) Matrix-supported debris flow with Intermediate ferricrete cobbles (carapace of the Low glacis, near Matam, Senegal). (f) Basal alluvial channel carved in a sandstone saprolite (High glacis, south of Bobo Dioulasso, Burkina Faso). Channel material consists of quartz pebbles and iron nodules in a kaolinite-rich silty clay matrix. Cementation increases upward in the channel. Only cases (b) to (d) are ferricretes.

Figure 13. Photograph (left) and interpretation (right) of a composite glacis ferricrete composed of a conglomeratic layer overlying a vermiform facies developed from the underlying mottle clays (High glacis, near Tikaré, Burkina Faso). The fine-grained material is likely preserved on its parental bedrock from which it derived by weathering. However, a transported origin cannot be precluded (see text for further explanation).

Figure 14. Glacis ferricretes derived from fine-grained material. (a) and (b) are exposed weathered surfaces and (c) and (d) are fresh cuts. (a) Fine-grained nodular ferricrete (Middle glacis, near Kedougou, Eastern Senegal). (b) Nodular ferricrete (High glacis, Niokolo Koba national park, Eastern Senegal). (c) Vermiform ferricrete (High glacis, near Kongoussi,

Central Burkina Faso). (d) Proto-nodular ferricrete (High glacia, near Tambakounda, Eastern Senegal). The iron oxy-hydroxides nodules are in dark grey / black. Nodular and vermiform ferricretes, and especially those exposed on weathered surfaces, should not be mistaken for conglomeratic ferricretes. Nodules generally have amoeboid / knucklebone shapes that distinguish them from gravels or cobbles.

Figure 15. Type-logs of West African glacia. Bottom cross-sections illustrate potential geomorphic contexts of the logs. In (a), the ferricrete is confined to the cover conglomerate and underlain by a weathering profile derived from bedrock. (b) Same as (a) but with the ferricrete extending beyond the base of the conglomerate (the conglomerate may also occupy part, or the entire thickness of, the carapace). (c) The ferricrete is restrained to the cover conglomerate that rests upon a truncated weathering profile. (d) Weathering profile developed from exhumed bedrock. (e) The glacia weathering profile affects both a fine-grained transported cover and the underlying bedrock. (f) Erosional surface exposing a truncated weathering profile (mottled clays formed at the surface). (g) Fine-grained cover overlying a truncated weathering profile. (h) Detrital sediments overlying a conglomeratic ferricrete. Question marks indicate contacts that may not be readily detected between comparable saprolites of contrasted origins (in-situ and transported). Emoticons refer to the suitability of the surface sampling medium for bedrock exploration geochemistry. The problem in (d) is that the ferricrete may not be distinguished from that in (e) (see text for further explanation). On the bottom cross-section, the residuum (mostly ferricrete and carapace) is shown by a single reddish color. Cover material and weathering horizons distribution patterns may be more uneven than shown on the cross-sections and further complexity may arise from later dissection / denudation.

Figure 16. Denudation / weathering scenario for the establishment of a typical West African lateritic glacis system. (a) Cross-section of a common landform-regolith association. The old surface is preserved as a mesa capped by a duricrust topping in-situ formed weathering profile I (i.e., for instance, the Bauxitic or Intermediate landsurface). The younger surface is a glacis whose development led to relief dissection of the upper/older surface. (b) Sequential development of the regolith profile for a given column located in (a). Stage 1 results from older weathering (and therefore dominant “chemical” denudation) leading to the establishment of landscape I and its underlying weathering profile (I). Stage 2 shows the configuration after shaping of the glacis by pedimentation, which has stripped off weathering profile I and eroded part of the underlying bedrock. Stage 3 shows the configuration after the weathering (II) and ultimate duricrusting of the glacis surface (ferricrete is restricted here to the transported overburden; e.g., case of Figs. 15a-15c) as a consequence of climate change. Columns in (a) and (b) are not to scale. Paleolandscape I could as well be a preexisting glacis. In this case, weathering profile I could already be composite (with an in-situ and a transported part).

Figure 17. Simplified geology (a) and regolith-landform map (b) of West Africa. Landform-regolith provinces are distinguished on the basis of the generation of landform-regolith association best preserved in the present-day landscape. (a) is adapted from Ye et al. (2017); (b) is from the present work. See Figure 2 for comparison with topography and climatic zonation. The sedimentary cover is overwhelmingly silico-clastic and mainly consists of sandstones and siltstones. The main rivers are shown both in (a) and in (b).

Figure 18. Paleo-zonation of the development and preservation patterns of the West African glacis systems (modified after Grandin, 1976).

Figure 19. Comparative scenarios of glacia ferricrete plateau degradation leading to a residual hill. (a) Under arid or semi-arid climate. (b) Under humid climate typical of rainforest environments (modified after Grandin, 1976).

Figure 20. Cross-section illustrating transport of mineralized material on successive glacia to form “transported” geochemical anomalies. The black star represents a surface geochemical anomaly expressed through a weathering profile and the white stars represent anomalies mechanically transported on glacia. Large grey arrows show material transport paths on glacia. Mineralization B first produced a dispersion halo and a surface anomaly through the old weathering profile. This mineralized weathering profile was then stripped off by pedimentation to form glacia 1, eventually leading to a transported anomaly on the new glacia surface. Formation of glacia 2 later led to reworking of the same mineralization that was still preserved under glacia 1. But this time, because of the creation of a new drainage divide, mineralized elements were transported in an opposite direction down the glacia 2 slope. Bedrock mineralization B is currently concealed under glacia 2.

Figure 21. Gold and copper occurrences and High glacia ferricrete remnants overlying mineralized bedrock map units, Southwestern Burkina Faso (same map area as Fig. 9). Sources are Baratoux et al. (2011) and Metelka et al. (2012) for bedrock geology and Castaing et al. (2003) and the 1/200,000 scale geological maps for mineral occurrences (artisanal and industrial mining sites, prospects and soil geochemical anomalies). Specific mineralized bedrock map units such as detrital sediments and ultramafic rocks are too small to be represented at this scale (4 and 0.4 km² for the entire map area, respectively).

Chardon et al., Figure 1

Chardon et al., Figure 2

Chardon et al., Figure 3

Chardon et al., Figure 5

Chardon et al., Figure 6

Chardon et al., Figure 7

Chardon et al., Figure 8

Chardon et al., Figure 9

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Chardon et al., Figure 14

Chardon et al., Figure 15

Chardon et al., Figure 16

Chardon et al., Figure 17

Chardon et al., Figure 18

Chardon et al., Figure 19

Chardon et al., Figure 20

Chardon et al., Figure 21