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HIGHLIGHTS

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

Abstract

This paper is a contribution to the understanding of surface dynamics of tropical shields over geological timescales. Emphasis is put on the fundamental and applied implications of regolith production and dispersion processes through the formation, dissection and preservation of landforms. It is based on the case study of sub Saharan West Africa, which recorded Neogene stepwise dissection of its topography through the emplacement of three lateritic pediment systems, which still occupy most of its surface. Pediments are erosional / transportation slopes having been weathered and duricrusted. Pediment-regolith associations therefore depend on the parent rock, transport dynamics and preservation of the material having transited on their surface as well as on the intensity of their weathering / duricrusting. Iron oxy-hydroxide-cemented clastic sediments (detrital ferricretes) and unconsolidated clastic sediments are the dominant outcropping material, and as such represent a challenge for mineral exploration that relies on surface geochemical sampling to detect metal concentration in the bedrock. Landform-regolith mapping beyond the scale of modern interfluves combined with paleolandscape reconstitution are relevant to provide exploration guides for (i) interpreting geochemical anomalies on pediments, (ii) tracing their potential source when they have been “transported” on pediments and (iii) targeting 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; Valeton, 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 is key for mineral exploration, which mostly relies on soil geochemical surveys (Butt et al., 2000; Porto, 2016). Throughout the Cenozoic, shield surfaces outside the influence of glaciers have primarily evolved by landscape dissection, the process by which paleolandscapes become isolated as relics overlooking younger active landforms as a result of slow and unevenly distributed erosion. Thereby, the relief of shields increases through geological time (Thomas, 1989; Twidale, 1991), while landscape dissection is instrumental in exhuming regolith available to re-weathering and transportation. Therefore, the study of regolith distribution patterns over shield landscapes should not only provide exploration guides to better access bedrock geology and resources, but also constrain landform evolution processes and sediment delivery of very large cratonic river systems (Beauvais and Chardon, 2013; Grimaud et al., 2015, 2018).

Pediments are common landforms that typically form during, and contribute to, the process of landscape dissection, especially over vast non-orogenic regions of the world (e.g., Dohrenwend and Parsons, 2009). In the broadest sense of the term, pediments may be considered as gently inclined slopes of transportation and/or erosion that truncate bedrock and/or regolith and connect eroding slopes or scarps to areas of sediment deposition or alluvial transportation at lower levels (definition adapted from Oberlander, 1997). Pedimentation involves the physic-chemical processes that concur to form pediments. As transportation slopes feeding rivers with clastic sediments, pediments are a regulating element of the sediment routing system. As transit landsurfaces, pediments also carry transported regolith that masks the geological substrate. They are therefore an obstacle to mineral exploration (Payne, 1969; Pease, 2015) but have not been recognized as such in lateritic environments by exploration geologists and geochemists. Through the work of King (1948, 1967), the pediment concept also contributed to landscape evolution theories (Summerfield, 1991, pp. 457-467). However, no general agreement exists on the recognition criteria, regional correlation and the geomorphic meaning of paleo-pediments. Remaining questions are (i) whether and how pediplains (i.e., regional surfaces of coalescent pediments) can form and be preserved over geological time-scales (10^6-10^7 yr) and (ii) whether they may be gauges of continental deformation or whether they have another geological signification (e.g., Tricart *in* Twidale, 1983; Summerfield, 1985, 1996; Thomas and Summerfield, 1987; Twidale and Bourne, 2013; Dauteuil et al., 2015; Guillocheau et al., 2015, 2017).

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

The present contribution is a review of the West African lateritic pediment systems from the landscape to the sub continental scale. It addresses pediment landform-regolith evolution processes to (i) evaluate the factors controlling the production and preservation of 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; Valeton, 1991; Colin et al., 2005; Chardon et al., 2006; Beauvais et al., 2008;

Beauvais and Chardon, 2013). The African surface is now preserved mostly as bauxite-capped mesas dominating the current landscape. The High, Middle and Low glacis mark the last main dissection stages of the African Surface. Remnants of a massive, nodular or pisolitic ferricrete-capped landscape found below bauxite relics and above the glacis have been used to define an Intermediate Surface (Michel, 1959, 1973; Vogt, 1959a). Bauxitic duricrusts of the African Surface and the ferricretes of the Intermediate Surface top thick (> 80 m) weathering profiles that are preserved on their parental bedrock (Grandin, 1976; Boulangé, 1984, 1986; Boulangé and Millot, 1988; Valeton, 1991).

Each glacis system in the West African sequence shows, in most cases, evidence for duricrusting (or induration), and lateritic weathering, after its formation. Pediments/glacis are the most conspicuous and common active landforms of dry or sub-humid regions of the world (e.g., Dohrenwend and Parsons, 2009). The successive shifts from pedimentation to lateritic weathering/duricrusting of the three glacis systems are indicative of repeated transitions from semi-arid to seasonally contrasted wet tropical climate over West Africa (Tricart et al., 1957; Michel, 1973; Grandin, 1976). Duricrusting took place during climate shifts toward dryer conditions at the ends of humid weathering periods, before abandonment and dissection of one glacis system and formation of a new one (Beauvais and Chardon, 2013). Systematic Ar-Ar geochronology of K-Mn oxides (cryptomelane) from the Mn-rich duricrust and weathering profile of each member of the West African landform-regolith sequence allowed constraining their weathering and abandonment ages (Beauvais et al., 2008; Beauvais and Chardon, 2013; Fig. 4). The African and Intermediate regolith-landform associations yielded 59-45 and 29-24 Ma age groups, respectively. The High, Middle and Low glacis weathered before abandonment at 18-11, 7-6 and around 3 Ma, respectively (Fig. 4). Those age groups would therefore restrain the main pedimentation periods to 24-18, 11-7 and 6-3 Ma for the High, Middle and Low glacis, respectively (Fig. 4). Ages obtained on alunite and jarosite (Vasconcelos et al., 1994), although indicative of lesser weathering intensities than cryptomelane, are compatible with the period of bauxite formation, weathering of the Intermediate landscape until the latest Oligocene (24 Ma) and the 18-11 Ma period of High glacis weathering (Fig. 4).

4. Glacis landforms and landscape chronologies

4. 1. Type-landforms and their spatial arrangements

The three generations of West African glacis remnants are best distinguished on the piedmonts of topographic massifs, which form up to hundreds of meters' high residual reliefs that had not been leveled by pedimentation (Figs. 5 and 6a). Those massifs are typically made of greenstone belt material (andesite, basalt, gabbro, volcano sedimentary rocks) or early Mesozoic dolerite sills hosted by tabular sandstones and preserved from erosion thanks to their capping bauxites and/or Intermediate duricrusts. Glacis are graded upward-concave surfaces sloping away from the massifs (e.g., Grandin, 1976). The stepping of successive glacis relics attests to the polycyclic nature of the landscapes due to renewed periods of pedimentation (Fig. 6a). The uppermost portion of an early glacis (e.g., the High glacis) is commonly eroded in such a way that a peripheral hollow separates the glacis remnant from its upslope relict landscape (Fig. 6a and 7a; e.g., Beauvais et al., 1999). A later glacis (e.g., the Middle glacis) may shape the inner slopes of the peripheral hollow so that it can reach a higher elevation than the relics of the earlier glacis (Fig. 6a). Relative elevation alone is therefore not a reliable criterion to decipher glacis generations given their slopes and their dissection patterns. Careful investigation of the relative geomorphic position, lateral extension and age of landscape elements should therefore be preferred to establish a glacis 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 paleolandscapes are generally re-cut by the Low glacis (e.g., Fig. 6b). Regional correlations of glacis systems chronology may be deciphered along 10-100 km long transects going from piedmont contexts - where the pediment stepping pattern is well defined - to rolling pediplain contexts. Field investigations restricted to the scale of an interfluve or a few interfluves are indeed not sufficient to elaborate a landscape chronology given the lateral variability of the paleolandforms preservation patterns (see section 6.2).

4. 2. Relief dissection patterns

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

In case where a glacis is not strictly stepped into an older glacis, mostly as a consequence of limited base-level fall (i.e., river down-cutting) during its development, a composite (i.e., polygenic) landsurface forms. Slight oblique leveling of the early glacis up to a certain elevation by the younger glacis may lead to a more or less expressed change of slope in that landsurface (Fig. 6). Polygenic development is also mostly expressed in the downslope parts of two successive glacis 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), relics 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 interfluves 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 and consist of bauxite, Intermediate ferricrete, earlier glacis ferricrete, iron oxy-hydroxide nodules and/or quartz debris (Figs. 12b to 12e). Conglomerates' matrixes comprise reworked weathering profile materials ranging from clays to sands (former saprolite) and gravels made of ferruginous nodules and quartz debris. Apart from quartz, the occurrence of fresh bedrock clasts in debris flows is extremely rare, indicating that mostly regolith was stripped-off and/or submitted to landsliding to produce debris flows. When present in glacis transported regolith, bedrock clasts are almost always highly ferruginized to the point of being a massive ferricrete preserving bedrock structures such as schistosity. Such ferricretes are typical of the Intermediate weathering profile (Fig. 12d).

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

Sedimentary patterns vary spatially from coarse flows to braided channels at the scale of single large glacis relics. This indicates space-time interplay of debris flows and sheet floods comparable to those observed on Quaternary or functional alluvial fans and pediments of arid or semi-arid regions of the world (Bull, 1977; Oberlander, 1997; Dohrenwend and Parsons, 2009). Besides, functional glacis 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 glacis before duricrusting (Grandin and Joly, 2008). Water and sediment transport modes on glacis 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 glacis, where alluvial sedimentary facies can be found (e.g., Figs. 8, 9 and 10).

Glacis 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. Glacis 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 glacis sedimentary overburden by oxy-hydroxides to form ferricretes. Such cementation scenarios are attested to by the common examples of glacis 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 glacis 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.

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

Notwithstanding the spatial variability in the nature of individual glacis surfaces and associated regolith, main type-characteristics of ferricretes and weathering patterns of each glacis system may be synthetized as follows (Grandin, 2008). The High glacis ferricrete can reach 10 m in thickness in piedmont contexts and the underlying weathering profile rarely exceeds 20 m. Middle glacis ferricretes do not exceed 5 m and are generally limited to 1 to 2 m. Their underlying weathering profile is reduced to a few meters and is not as kaolinite rich as that of the High glacis. Ferricretes of functional Middle glacis often show evidence for 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 glacis record in West Africa

6. 1. Geomorphic provinces and areal extent of glacis

The compilation of a regional landform-regolith map (Fig. 17) shows that the relics of the three glacis 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 glacis composite landscapes (Fig. 17) such as those illustrated on Figures 5- 8, 10 and 15. In those landscapes, the High glacis 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 glacis landscape geomorphic province is a Middle-Low glacis rolling pediplain locally preserving High glacis remnants as interfluves (e.g., Figs. 6b). The relative extent of the Low glacis system tends to grow northward going across the Soudanian zone to become maximal in the Sahelian zone where a Low glacis province is defined (Figs. 1 and 17b) as a vast and very flat pediplain with tens of kilometers-wide glacis 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).

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

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

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

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

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

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

Regions located further to the East and encompassing the same current latitudinal band as sub Saharan West Africa have undergone a greater northward shift across the inter 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” glacis 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 synthetized by Beauvais and Chardon (2013). Degradation of glacis 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 glacis landform-regolith associations (Fig. 17) prompt caution when targeting suitable spots for surface sampling that would reflect bedrock geochemistry as accurately as possible. Glacis 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

Glacis ferricretes all represent an obstacle to access bedrock geochemistry. There are three main reasons for this. First, they often represent sedimentary covers that are allochtonous (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 weathering, ferricretes would have lost most of the geochemical characteristics of the bedrock (e.g., Tardy et al., 1988; Boeglin and Mazaltarim, 1989; Roquin et al., 1990). Third, solute elemental transfers through the regolith and sedimentary cover down the glacis slope can contribute to absolute elemental accumulation in the ferricrete, especially in iron (Maignien, 1958, 1966; Ollier and Galloway, 1990, Beauvais, 1999; Brown et al., 2003). Therefore, vertical geochemical mass balances through ferricrete-capped glacis weathering profiles are often misleading indicators of weathering-controlled dispersion of bedrock elemental concentrations. Ferricrete-free glacis surfaces pose another sizable exploration issue. Only erosional portions of such surfaces would provide direct access to a saprolite preserved on its parental bedrock (Fig. 15f), providing they are identified as such and not mistaken for transported saprolite (Fig. 15g). Loose sedimentary glacis overburdens (Fig. 15h) mask their substrate. They are commonly thick (> 2m), overly a detrital ferricrete and may be mistaken for soils. It is why even sampling at 50 cm depth - as often undertaken in such material - is not appropriate to attain the saprolite preserved on its parental bedrock.

Only sampling of the bedrock or the in-situ preserved saprolite is reliable for characterizing the geological substrate’s geochemistry (propitious locations would be edges of glacis plateaus that expose weathering horizons under the ferricrete). In all other situations, a surface geochemical anomaly on a glacis can have several meanings. In the best case, the surface is erosional and ferricrete-free, the anomaly signing an underlying bedrock concentration (e.g., Au, Pt, Zn, Cu). The present work however suggests that such configuration is rarely demonstrated. In all other - most common - cases, the anomaly would be ambiguous. It may have been “transported” with the sedimentary cover on the glacis by pedimentation (e.g., Sanfo et al., 1992) or may be the expression of a potentially complex and very wide dispersion halo having been elongated downslope. Such a halo could also at least partly result from geochemical dispersion of a bedrock anomaly through a transported overburden by biological, gazeous or capillarity processes (Anand et al., 2014). Conversely, the absence of a surface anomaly would not preclude the occurrence of an anomaly in the underlying bedrock. In any case, landform-regolith mapping and establishment of a glacis landscape chronology are required around the sampling sites in order to (i) constrain the geomorphological context of the anomaly for locating its potential distant source or (ii) identify glacis covers that mask potential bedrock resource(s) (Bamba, 2009).

7. 2. Geomorphological exploration guides

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

In rolling pediplain contexts, tracing the potential upslope source of a transported anomaly should be straightforward, providing the glacis landscape has not been significantly dissected and preserved its original interfluve (e.g., Figs. 6b and 6c-6e). In such a case, the source of the transported particles cannot be located beyond the preserved glacis interfluve. In dissected rolling pediplains and particularly piedmont contexts, upslope portions of glacis are rarely preserved (e.g., Figs. 6a; 7; 10). Paleolandscape reconstruction at the time the sampled glacis was functional is necessary to evaluate the potential path followed by the glacis sedimentary cover during pedimentation. Instead of a cross-sectional approach, a three-dimensional landscape reconstruction (e.g., Fig. 7) is suitable to take into account the entire upslope drainage area that could have supplied mineralized debris to the anomaly on a glacis. For instance, an anomaly documented in the lowermost portion of a relictual glacis i.e., close to or along a river active at the time of pedimentation, can be sourced from the erosion of all the glacis that were connected downslope to that drain upstream. For functional glacis, delimitation of the upslope area that contributed to a sampling site would be straightforward because this area is constrained by the present-day topography.

Maximal transportation distance on a glacis corresponds to the upslope distance between the considered sampling site and the drainage divide at the end of the activity of the glacis (i.e., before its abandonment and dissection). Reconstruction of the High glacis landscape suggests that paleo-glacis widths have exceeded 20 km (Grimaud et al., 2015; Fig. 10), prompting to undertake landform-regolith mapping and paleolandscape reconstruction on a larger scale than that of the immediate surrounding of the anomaly-bearing glacis relic. South of the Sahelian zone (Fig. 2), dissection of the High glacis pediplain has generally created narrower (1-10 km) Middle and Low glacis flanking subsequent valleys that are often perpendicular to the earlier main river drain delimitating High glacis (Fig. 7). Potential maximal transportation distances on those pediments are therefore reduced compared to those of the High glacis and the transport direction at a high angle to that of the preexisting glacis. The same reasoning as that exposed above applies to the tracking of the source of transported regolith upslope on the Middle and Low glacis, bearing in mind that the cover of these glacis can carry elements that may have previously been transported on an earlier glacis. Potential divide migration from one glacis landscape stage to the next should also be taken into account (e.g., Fig. 8). A given bedrock mineral concentration could indeed have been subjected to pedimentation by successive glacis of contrasting slope directions and therefore may not have always belonged to the same drainage sub-basin (Fig. 20).

Stream sediment surveys going up river would still be valid in glacis environments, providing that once propitious channel sections are selected, the upslope source tracing protocol described above for glacis 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 glacis cover (e.g., Sillitoe, 2005; Riquelme et al., 2018).

7. 3. Targeting concealed resource

Glacis 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 glacis 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 glacis ferricrete units, on the one hand, and polylines or polygones 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 glacis ferricrete relics overlying (i.e., intersecting) bedrock lithological units bearing those indices. This representation allows (i) targeting High glacis ferricrete relics potentially masking deposits and (ii) adapting a sampling or drilling strategy accordingly. Those targeted glacis ferricrete units should then be studied in details and eventually be drilled across to attain the projected trace of the mineralized structure under the glacis cover. Such a protocol would typically reveal lateral extensions of ore bodies and may be applied from a regional (10-100 km) (Fig. 21) to a prospect scale (0.1-1 km) if landform-regolith maps of appropriate resolution are produced.

7. 4. Other geomorphic exploration pitfalls and overlooked resources

The pervasive occurrence and preservation of convexo-concave rolling pediplains south of the Sahelian zone and the degradation of glacis into concave residual hills under equatorial environments explain why glacis may have been overlooked, especially by workers who did not investigate landforms outside the Forest zone, contrary to Grandin (1976), who worked across an entire regional latitudinal corridor. Exploration geologists have indeed implicitly interpreted residual hills as “demi-oranges” (e.g., Freyssinet, 1993; Freyssinet et al., 2005) although they may result from pedimentation in the case of rolling pediplains or from the degradation of older glacis into convex hills. A consequence of such restrictive interpretation is that ferricretes / lateritic residua are considered as formed and preserved essentially in-situ, whereas they could host material transported prior to weathering/duricrusting. A residual hill can result from the dismantling of a wide glacis on which material has been transported over several kilometers if not tens of kilometers i.e., on a much larger scale than the size of the residual hill. However, detailed exploration geochemical investigations or models are restricted to the slope of a single residual hill (e.g., Zeegers and Lecomte, 1992; Freyssinet, 1993; Butt, 2016). In glacis landscapes such as those of West Africa, landform-regolith mapping and the establishment of a landscape chronology should therefore be undertaken on a larger scale (1-20 km) than that of the considered anomaly-bearing relief (0,1-1 km).

Given the alluvial nature of glacis overburdens, placers must be common on pediments. Detailed work by Thomas and Thorp (1985) or Teuuw (1987, 2002) suggests that 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 elluvial 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 that those that are known and actively mined for (Al, Mn and Au).

8. Pediments, pediplains and the topographic evolution of shields

8. 1. Implications for pedimentation in lateritic landscapes

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

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

8. 2. Relations to epeirogeny

Pediment systems carved the African surface while it was being submitted to long wavelength (10^3 km) deformation that contributed to the growth of the basin-and-swell topography of the continent after 40 Ma (Burke and Gunnell, 2008; Chardon et al., 2016). The most prominent element of that physiography in West Africa is the Hoggar swell; but more subtle uplift is also suggested along the marginal upward that constituted the eastern extension of the Guinean rise up to the Jos Plateau (Grimaud et al., 2014, 2018; Chardon et al., 2016; Fig. 2). The stepping patterns of pediment systems may not be used as a proxy of that deformation because glacis have a roughly spatially consistent and reduced (< 80 m) elevation range above local base level, which itself varies with river networks from sea level to above 1300 m for the highest regional topographic massifs excluding the Hoggar (Grimaud et al., 2014; Fig. 2). In details, the stepping pattern of successive glacis has been compartmentalized amongst sub drainage areas due to spatially variable incision of river segments bounded by stationary knickzones, which were already part of the West African landscape before settlement of the High glacis pediplain for most of them (Grimaud et al., 2014). Furthermore, glacis systems did not level out regional rock escarpments, which were already imprinted in the Paleogene Bauxitic and (mostly) Intermediate landscapes and remained almost stationary since then (De Swardt, 1964; Grandin and Delvigne, 1969; Burke and Gunnell, 2008; Grandin and Joly, 2008; Grimaud et al., 2014, 2015; Fig. 17). Glacis systems therefore adapted their slopes to differentiated and uneven river levels and contributed in this way to distributed landscape dissection and dismantling down to the scale of lowermost-order drains a few kilometers long (e.g., Figs. 8, 9, 10). In other words, outside the provinces of relict African and Intermediate landscapes (Fig. 17), virtually no 20 x 20 km area of the West African topography escaped settlement of new glacis during the main pedimentation periods, with the exception of Low glacis pedimentation at lowermost latitudes (Fig. 18).

Thorough documentation of stepwise Cenozoic dissection of the West African sub region therefore precludes the stepping of successively younger pediplains bounded upstream by escarpments, which would produce continental-scale staircase patterns of pediplains from the crest of swells down to sea level or the base level of intracratonic basins. Such a model is suggested by Burke and Gunnell (2008, their Figure 16A) on the crest and slopes of the Guinean Rise (Fig. 2). Staircase pediplains models derive from that of King (1948, 1967) in which continent-wide and flat pediplains graded to sea level form by escarpment/knickzone retreat far inland. For King, a pediplain is abandoned as a consequence of uplift by the formation of a subsequent pediplain below a new retreating escarpment, which will ultimately bound and protect the relic of the early pediplain in the continental interior. King's paradigm is also explicit in the procedure that would allow retrieving long-term continental uplift histories from the inversion of current river longitudinal profiles (Paul et al., 2014). This procedure is indeed based on a quantitative model that explicitly requires inlandward retreat of river knickzones in response to uplift and 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 glacis 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 increasing throughout the Cenozoic and should then be considered as transient over the very long term. But the punctuated pedimentation scheme they developed does not match that of the Davisian cycle of erosion. The main specificity of the West African landscape dissection patterns by pedimentation is a progressively reduced area submitted to abrasion through time, leaving increasingly wider relict surfaces of limited or no denudation as a result of landscape dissection (Fig. 10). The stepping patterns of pediment systems have no clear dependency on sea level variations and/or epeirogeny and contribute to limited (3-9 m/My) and distributed denudation. In contexts of enhanced uplift and correlatively higher denudation such as the upper slope of the Hoggar swell (surface uplift and denudation > 30 m/My since ca. 35 Ma; Chardon et al., 2016; Grimaud et al., 2018), pediplains could not form or be preserved on geological time scales.

Once duricrusted and/or abandoned as a result of dissection, pediments preserve the underlying regolith from erosion. Regional-scale pediment systems (pediplains) form and maintain over geological timescales in environments submitted to low river incision or erosion rates (<10 m/Ma) and limited epeirogenic uplift. Under that condition, the maintenance of very slowly evolving pediment landscapes poses the chicken-and-egg issue of knowing whether the low erosional efficiency of pedimentation dictates the limited transport and incision capacity of the river network or vice-versa. In any case, pediments are buffer landsurfaces between the regolith mantles they contribute to exhume and the rivers they feed with reworked regolith (Grimaud et al., 2015). Pedimentation is transport-limited given the large amount of (old) regolith still being stored in West African landscapes, which generates subdued and nearly constant erosion fluxes over the long-term (< 0.01 $km^3/km^2/My$). Above a 10 m/My incision/erosion rate threshold, rupture of the pedimentation regime is expected, paleo-landforms being erased. It is only above several tens of meters per million years of long-term erosion that denudation would potentially become measurable by low-temperature thermochronology (Beauvais et al., 2016). The regional preservation of pediments / pediplains indicative of very slow denudation should then prevent retrieval of denudation scenarios from low-temperature thermochronology for periods encompassing pediments timespan of formation and over periods following their abandonment. Dated relict pediments should be used instead as strict constraints on the late temperature-time exhumation path provided by low-temperature thermochronology.

8. Conclusions

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

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

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

constitute by far the most common type of pediment surface. Fe-duricrusting and ferricretes constitute a necessary condition for glacis dissection and preservation of relictual landscapes.

3 – Lateritic pediment surfaces are not suitable for geochemical sampling aiming at obtaining reliable information about the composition of the bedrock or an elemental concentration anomaly. The two main reasons for this are (i) the transported nature of the material exposed at the surface and (ii) the lost of the geochemical characteristics of the bedrock through the weathering processes.

4 - Landform-regolith mapping beyond the scale of modern interfluves followed by reconstitution of past pediment landscape stages provides geomorphological exploration guides for interpreting surface geochemical anomalies on pediments and tracing their potential sources in case they have been “transported” on pediments. Mapping of landform-regolith associations may also be used to target pediments masking suspected mineralizations.

5 - Past and present latitudinal climatic zonation of pedimentation and weathering at the scale of the sub region suggests a gradient of pedimentation processes from an arid to a perhumid end-member across the intertropical zone. They also explain why pediments may have been overlooked in humid equatorial environments, with important implications for mineral exploration.

6 – Successive pediment systems have affected progressively reduced area over time, preserving increasingly wider relictual landsurfaces. Climatic oscillations dictated pedimentation-driven, local planation that adapted slopes to very large, spatially differentiated, knickzone bearing river networks. The spatially consistent and limited (< 80 m) stepping pattern of pediments is independent from elevation or distance to base level. Hence, pediments and pediplains may not be used as gauges of uplift except near coastlines.

Pediments form and are preserved regionally over geological timescales only for < 10 m/My erosion regimes and are therefore indicators of very slow shield denudation.

7 – Lateritic pediments have been overlooked in the tropical belt because lateritic duricrusted landscapes refer exclusively to in-situ weathering of bedrock for most geologists and geochemists. Further investigations will hopefully help deciphering pediment landform-regolith associations for a better access to the geological substrate of tropical shields and its resources that may still be underestimated. Investigating pediments as markers of past morphogenesis is a powerful tool for understanding surface dynamics of shields and their sediment routing system, which contribute to a significant proportion of the Earth sedimentary budget and global biogeochemical cycles.

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References

Anand, R., Lintern, M., Noble, R., Aspandiar, M., Macfarlane, C., Hough, R., Stewart, A., Wakelin, S., Townley, B., Reid, N., 2014. Geochemical dispersion through transported cover in regolith-dominated terrains - toward an understanding of process. Soc. Econ. Geol. Spec. Publ. 18, 97-125.

Applegarth, M.T., 2004. Assessing the influence of mountain slope morphology on pediment form, South-Central Arizona. Phys. Geogr. 25, 225-236.

Aubréville, A., 1949. Climats, forêts et désertification de l'Afrique tropicale. Société d'Editions géographiques maritimes et coloniales, Paris.

Bamba, O., 1996. L'or disséminé dans les Albitites de Larafella (Burkina Faso), évolution dans les altérites et les cuirasses ferrugineuses : Métallogénie - Pétrologie – Géomorphologie. Ph D Thesis, Aix-Marseille III University, Marseille, 261p.

Bamba, O., 2009. Morphopédologie et anomalie géochimique. Can. J. Earth Sci. 46, 939-948.

Bamba, O., Parisot, J.-C., Grandin, G., Beauvais, A., 2002. Ferricrete genesis and supergene gold behaviour in Burkina Faso, West Africa. Geochem. Explor. Environ. Anal. 2, 3-13.

Baratoux, L., Metelka, V., Naba, S., Jessell, M.W., Gregoire, M., Ganne, J., 2011. Juvenile Paleoproterozoic crust evolution during the Eburnean orogeny (similar to 2.2-2.0 Ga), western Burkina Faso. Precambrian Res. 191, 18-45.

Beaudet, G., Coque, R., 1994. Reliefs et modelés des régions tropicales humides : mythes, faits et hypothèses. Ann. Géogr. 577, 227-254.

Beauvais, A., 1999. Geochemical balance of lateritization processes and climatic signatures in weathering profiles overlain by ferricretes in Central Africa. Geochim. Cosmochim. Acta 63, 3939-3957.

Beauvais, A., Ritz, M., Parisot, J.C., Dukhan, M., Bantsimba, C., 1999. Analysis of poorly stratified lateritic terrains overlying a granitic bedrock in West Africa, using 2-D electrical resistivity tomography. Earth Planet. Sci. Lett. 173, 413-424.

Beauvais, A., Ritz, M., Parisot, J.C., Bantsimba, C., 2003. Testing etching hypothesis for the shaping of granite dome structures beneath lateritic weathering landsurfaces using ERT method. Earth Surf. Process. Landf. 28, 1491-1491.

Beauvais, A., Ritz, M., Parisot, J.C., Bantsimba, C., Dukhan, M., 2004. Combined ERT and GPR methods for investigating two-stepped lateritic weathering systems. Geoderma 119, 121-132.

Beauvais, A., Chardon, D., 2013. Modes, tempo, and spatial variability of Cenozoic cratonic denudation: The West African example. Geochem. Geophys. Geosyst. 14, 1590-1608.

Beauvais, A., Ruffet, G., Henocque, O., Colin, F., 2008. Chemical and physical erosion rhythms of the West African Cenozoic morphogenesis: The ^{39}Ar-^{40}Ar dating of supergene K-Mn oxides. J. Geophys. Res.-Earth Surf. 113, F4007.

Beauvais, A., Bonnet, N.J., Chardon, D., Arnaud, N., Jayananda, M., 2016. Very long-term stability of passive margin escarpment constrained by Ar-40/Ar-39 dating of K-Mn oxides. Geology 44, 299-302.

Bishop, P., 2007. Long-term landscape evolution: linking tectonics and surface processes. Earth Surf. Process. Land. 32, 329-365.

Bitom, D., Volkoff, B., Beauvais, A., Seyler, F., Ndjigui, P.D., 2004. Rôle des héritages latéritiques et du niveau des nappes dans l’évolution des modelés et des sols en zone intertropicale forestière humide. C.R. Géoscience 336, 1161-1170.

Boeglin, J.L., Mazaltarim, D., 1989. Géochimie, degrés d'évolution et lithodépendance des cuirasses ferrugineuses de la région de Gaoua au Burkina Faso. Sci. Géol. Bull. 42, 27-44.

Bolster, S.J.S., 1999. Regolith mapping: Is it really necessary? Aus. Inst. Geoscent. Bull. 30, 125-135.

Bonvallot, J., Boulangé, B., 1970. Note sur le relief et son évolution dans la région de Bongouanou (Côte d'Ivoire). Cah. ORSTOM Sér. Géol. 2, 171-183.

Boulangé, B., 1984. Les formations bauxitiques latéritiques de Côte d'Ivoire. Trav. Doc. ORSTOM 175, 1-342.

Boulangé, B., 1986. Relation between lateritic bauxitization and evolution of landscape. Trav. Int. Com. Stud. Bauxite, Alumina & Aliminum (ISCOBA) 16-17, 27-44.

Boulangé, B., Millot, G., 1988. La distribution des bauxites sur le craton ouest-africain. Sci. Géol. Bull. 41, 113-123.

Boulangé, B., Sigolo, J.B., Delvigne, J., 1973. Descriptions morphoscopiques, géochimiques et minéralogiques des faciès cuirassés des principaux niveaux géomorphologiques de Côte d'Ivoire. Cah. ORSTOM Sér. Géol. 5, 59-81.

Boulet, R., 1970. La géomorphologie et les principaux types de sols en Haute-Volta septentrionale. Cah. ORSTOM Sér. Pédol. 8, 245-271.

Bowden, D.J., 1987. On the composition and fabric of the footslop laterites (duricrusts) of the Sierra Leone, West Africa, and their geomorphological significance. Z. Geomor. N.F. 64, 39-53.

Bowden, D.J., 1997. The geochemistry and development of lateritized footslope benches: The Kasewe Hills, Sierra Leone. Spec. Publ. Geol. Soc. 120, 295-305.

Bowell, R.J., Afreh, E.O., Laffoley, N.d.A., Hanssen, E., Abe, S., Yao, R.K., Pohl, D., 1996. Geochemical exploration for gold in tropical soils - four contrasting case studies from West Africa. Trans. Inst. Min. Metall. 105, B12-B33.

Brammer, H., 1955. Visit to Haute Volta, 30th January-3rd March 1955. Gold Coast Dept. Soil Land-Use Surv. Techn. Rep. 9, 1-48.

Brammer, H., 1956. A note on former pediment remnants in Haute Volta. Geogr. J. 122, 526-527.

Brown, D.J., Helmke, P.H., Clayton, M.K., 2003. Robust geochemical indices for redox and weathering on a granitic laterite landscape in Central Uganda. Geochim. Cosmochim. Acta 67, 2711-2723.

Brückner, W.D., 1955. The mantle rock (laterite) of the Gold Coast and its origin. Geol. Rundsch. 43, 307-327.

Büdel, J., 1982. Climatic geomorphology. Princeton University Press, Princeton.

Bull, W.B., 1977. The alluvial-fan environment. Progr. Phys. Geogr. 1, 222-270.

Burke, K., Durotoye, B., 1971. Geomorphology and superficial deposits related to Late Quaternary climatic variation in South-Western Nigeria. Z. Geomor. N.F. 15, 430-444.

Burke, K., Gunnell, Y., 2008. The African erosion surface: A continental scale synthesis of geomorphology, tectonics, and environmental change over the past 180 million years. Geol. Soc. Am. Mem. 201, 1-66.

Butt, C.R.M., 2016. The development of regolith exploration geochemistry in the tropics and sub-tropics. Ore Geol. Rev. 73, 380-393.

Butt, C.R.M., Bristow, A.P.J., 2013. Relief inversion in the geomorphological evolution of sub-Saharan West Africa. Geomorphology 185, 16-26.

Butt, C.R.M., Lintern, M.J., Anand, R.R., 2000. Evolution of regoliths and landscapes in deeply weathered terrain - implications for geochemical exploration. Ore Geol. Rev. 16, 167-183.

Butt, C.R.M., Zeegers, H., 1989. Classification of geochemical exploration models for tropically weathered terrains. J. Geochem. Explor. 32, 65-74.

Castaing, C., Le Metour, J., Billa, M., Donzeau, M., Chevremont, P., Egal, E., Zida, B., Ouedraogo, I., Koté, S., Kaboré, B.E., Ouedraogo, C., Thieblemont, D., Guerrot, C., Cocherie, A., Tegyey, M., Itard, Y., Milesi, J.P., 2003. Carte géologique et minière du Burkina Faso à 1/1 000 000. BRGM/BUMIGEB.

Chardon, D., Chevillotte, V., Beauvais, A., Grandin, G., Boulangé, B., 2006. Planation, bauxites and epeirogeny: One or two paleosurfaces on the West African margin? Geomorphology 82, 273-282.

Chardon, D., Grimaud, J.L., Rouby, D., Beauvais, A., Christophoul, F., 2016. Stabilization of large drainage basins over geological time scales: Cenozoic West Africa, hot spot swell growth, and the Niger River. Geochem. Geophys. Geosyst. 17, 1164-1181.

Colin, F., Vieillard, P., 1991. Behavior of gold in the lateritic equatorial environment - Weathering and surface dispersion of residual gold particles at Dondo Mobi, Gabon. Appl. Geochem. 6, 279-290.

Colin, F., Beauvais, A., Ruffet, G., Henocque, O., 2005. First Ar-40/Ar-39 geochronology of lateritic manganiferous pisolites: Implications for the Palaeogene history of a West African landscape. Earth Planet. Sci. Lett. 238, 172-188.

Cook, R.U., Mason, P.F., 1973. Desert Knolls Pediment and associated landforms in the Mojave Desert, California. Rev. Géomorph. Dyn. 22, 49-60.

Dauteuil, O., Bessin, P., Guillocheau, F., 2015. Topographic growth around the Orange River valley, southern Africa: A Cenozoic record of crustal deformation and climatic change. Geomorphology 233, 5-19.

Daveau, S., Lamotte, M., Rougerie, G., 1962. Cuirasses et chaines birrimiennes en Haute-Volta. Ann. Géogr. Franç. 387, 260-282.

Davis, W. M., 1899. The geographical cycle. Geogr. J. 14, 481-504.

De Swardt, A.M.J., 1964. Lateritisation and landscape development in parts of Equatorial Africa. Z. Geomor. N.F. 8, 313-333.

Dohrenwend, J.C., Parsons, A.J., 2009. Pediments in arid environments, in: Parsons, A., Abrahams, A. (Eds.), Geomorphology of desert environments, 2 ed. Springer Netherlands, The Netherlands, pp. 377-411.

Dresch, J., 1952a. Dépôts de couverture et relief en Afrique occidentale française. Proc. XVIIth Int. Geogr. Congr., Washington, 323-326.

Dresch, J., 1952b. Dépôts superficiels et relief du sol au Dahomey septentrional. C. R. Acad. Sci. Paris 234, 1566-1568.

Dresch, J., 1957. Pédiments et glacis d'érosion, pédiplaines et inselbergs. Inf. Géogr. 21, 183-196.

Eschenbrenner, V., Grandin, G., 1970. La séquence de cuirasses et ses différentiations entre Agnibiléfrou et Diébougou (Haute-Volta). Cah. ORSTOM Sér. Géol. 2, 205-246.

Fölster, H., 1964. Morphogenese der Südsudanesischen Pediplane. Z. Geomor. N. F. 8, 393-423.

Fölster, H., 1969a. Late Quaternary erosion in SW-Nigeria. Bull. Ass. Sén. Et. Quat. Ouest Afr. 21, 29-35.

Fölster, H., 1969b. Slope development in SW-Nigeria during late Peistocene and Holocene. Göttinger Bodenkdl. Ber. 10, 3-56.

Fölster, H., Moshrefi, N., Ojenuga, A.G., 1971. Ferralitic pedogenesis on metamorphic rocks, SW-Nigeria. Pédologie 21, 95-124.

Freyssinet, P., 1993. Gold dispersion related to ferricrete pedogenesis in South Mali: application to geochemical exploration. Chron. Rech. Min. 510, 25-40.

Freyssinet, P., Butt, C.R.M., Morris, R.C., Piantone, P., 2005. Ore-forming processes related to lateritic weathering. Econ. Geol. 100th Anniversary volume, 681-722.

Gavaud, M., 1977. Les grands traits de la pédogenèse au Niger méridional. Trav. Doc. ORSTOM 76, 1-102.

Goldfarb, R.J., André-Mayer, A.S., Jowitt, S.M., Mudd, G.M., 2017. West Africa: The World's premier Paleoproterozoic gold province. Econ. Geol. 112, 123-143.

Grandin, G., 1976. Aplanissements cuirassés et enrichissement des gisements de manganèse dans quelques régions d'Afrique de l'Ouest. Mém. ORSTOM 82, 1-276.

Grandin, G., 2008. Les cuirasses latéritiques - aluminisation et ferruginisation, in: Dewolf, Y., Bourrié, G. (Eds.), Les formations surperficielles. Genèse - typologie - classification - paysages et environnements - ressources et risques. Ellispes, Paris, pp. 362-372.

Grandin, G., Delvigne, J., 1969. Traits généraux de l'évolution du réseau hydrographique dans la région du confluent Bandama - N'Zi (Côte d'Ivoire). Bull. Ass. Sén. Et. Quat. Ouest Afr. 23, 7-14.

Grandin, G., Hayward, D.F., 1975. Aplanissements cuirassés de la péninsule de Freetown (Sierra Leone). Cah. ORSTOM Sér. Géol. 7, 11-16.

Grandin, G., Joly, F., 2008. Glacis - Genèse, dynamique et formations corrélatives, in: Dewolf, Y., Bourrié, G. (Eds.), Les formations surperficielles. Genèse - typologie - classification - paysages et environnements - ressources et risques. Ellipses, Paris, pp. 201-216.

Grimaud, J.L., Chardon, D., Beauvais, A., 2014. Very long-term incision dynamics of big rivers. Earth Planet. Sci. Lett. 405, 74-84.

Grimaud, J.L., Chardon, D., Metelka, V., Beauvais, A., Bamba, O., 2015. Neogene cratonic erosion fluxes and landform evolution processes from regional regolith mapping (Burkina Faso, West Africa). Geomorphology 241, 315-330.

Grimaud, J.L., Rouby, D., Chardon, D., Beauvais, A., 2018. Cenozoic sediment budget of West Africa and the Niger delta. Basin Res., doi:10.1111/bre.12248.

Guillocheau, F., Chelalou, R., Linol, B., Dauteuil, O., Robin, C., Mvondo, F., Callec, Y., Colin, J.-P., 2015. Cenozoic landscape evolution in and around the Congo Basin: Contraints from sediments and planation surfaces, in: De Wit, M.J. et al. (Eds.), Geology and resource potential of the Congo Basin. Springer-Verlag, Berlin Heidelberg, pp. 271-313.

Guillocheau, F., Simon, B., Baby, G., Bessin, P., Robin, C., Dauteuil, O., 2017. Planation surfaces as a record of mantle dynamics: the case example of Africa. Gondwana Res., doi: 10.1016/j.gr.2017.1005.1015.

Gunnell, Y., 2003. Radiometric ages of laterites and constraints on long-term denudation rates in West Africa. Geology 31, 131-134.

Hall, A.M., Thomas, M.F., Thorp, M.B., 1985. Late Quaternary alluvial placer development in the humid tropics. The case of the Birim diamond placer, Ghana. J. Geol. Soc. 142, 777-787.

Hilton, T.E., 1963. The geomorphology of North-Eastern Ghana. Z. Geomor. N.F. 7, 308-325.

Holmes, C.D., 1955. Geomorphic development in humid and arid regions: a synthesis. Am. J. Sci. 253, 377-390.

King, L.C., 1948. On the Age of the African land-surfaces. Q. J. Geol. Soc. Lond. 104, 439-459.

King, L.C., 1967. The morphology of the Earth, second ed. Oliver and Boyd, Edinburgh.

Lamotte, M., Rougerie, G., 1953. Les cuirasses ferrugineuses allochtones. Signification paléoclimatique et rapports avec la végétation. IV Réun. African. de l'Ouest, Abidjan, 89-90.

Lamotte, M., Rougerie, G., 1962. Les apports allochtones dans la formation des cuirasses ferrugineuses. Rev. Géomor. Dyn. 13, 145-160.

Le Cocq, A., 1986. Carte pédologique et carte des capacités agronomiques des sols à 1/100 000, Région de Bassar (Togo). ORSTOM, Notice explicative 102, 1-103.

Lecomte, P., 1988. Stone line profiles - Importance in geochemical exploration. J. Geochem. Explor. 30, 35-61.

Lecomte, P., Zeegers, H., 1992. Humid tropical terrains (rainforests), in: Butt, C.R.M., Zeegers, H. (Eds.), Regolith exploration geochemistry in tropical and subtropical terrains. Elsevier, Amsterdam, pp. 241-294.

Leprun, J.C., 1979. Les cuirasses ferrugineuses des pays cristallins de l'Afrique occidentale sèche - génèse, transformation, dégradation. Sci. Géol. Mém. 58, 1-224.

Mabbutt, J.A., 1966. Mantle-controlled planation of pediments. Am. J. Sci. 264, 78-91.

Maignien, R., 1958. Le cuirassement des sols en Guinée, Afrique Occidentale. Mém. Serv. Carte Géol. Alsace Lorraine 16, 1-239.

Maignien, R., 1966. Compte rendu de recherches sur les latérites. UNESCO, Paris.

Markwitz, V., Hein, K.A.A., Jessell, M.W., Miller, J., 2016. Metallogenic portfolio of the West African craton. Ore. Geol. Rev. 78, 558-563.

McFarlane, M.J., 1976. Laterite and landscape. Academic Press, London.

Mensching, H., 1966. Flächenbildung in der Sudan-und Sahel-Zone (Ober-Volta und Niger). Z. Geomor. N.F. 10, 1-29.

Metelka, V., Baratoux, L., Naba, S., Jessell, M.W., 2011. A geophysically constrained litho-structural analysis of the Eburnean greenstone belts and associated granitoid domains, Burkina Faso, West Africa. Precambrian Res. 190, 48-69.

Metelka, V., Baratoux, L., Jessell, M.W., Barth, A., Jezek, J., Naba, S., 2018. Automated regolith landform mapping using airborne geophysics and remote sensing data, Burkina Faso, West Africa. Remote Sens. Environ. 204, 964-978.

Meyer, B., 1992. A detailed soil differentiation of slopes with slight inclination in the Niamtougou plain in North-Togo. Z. Geomor. N.F. 91, 124-134.

Michel, P., 1959. L'évolution géomorphologique des bassins du Sénégal et de la Haute-Gambie, ses rapports avec la prospection minière. Rev. Géomorph. Dyn. 10, 117-143.

Michel, P., 1969. Les grandes étapes de la morphogenèse dans les bassins des fleuves Sénégal et Gambie pendant le Quaternaire. Bull. IFAN 31, 293-324.

Michel, P., 1973. Les bassins des fleuves Sénégal et Gambie, étude géomorphologique. Mém. ORSTOM 63, 1-752.

Michel, P., 1974. Les glacis cuirassés d'Afrique occidentale et centrale. Géomorphologie des glacis : Colloques scientifiques de l'Université de Tours, Tours, France, pp. 70-80.

Milesi, J.P., Ledru, P., Feybesse, J.L., Dommanget, A., Marcoux, E., 1992. Early Proterozoic Ore-Deposits and Tectonics of the Birimian Orogenic Belt, West Africa. Precambrian Res. 58, 305-344.

Millot, G., 1980. Les grands aplanissements des socles continentaux dans les pays subtropicaux, tropicaux et désertiques. Mém. H. Sér. Soc. Géol. France 10, 295-305.

Millot, G., 1970. The geology of clays. Springer-Verlag, Berlin.

Millot, G., 1983. Planation of continents by intertropical weathering and pedogenetic processes. II^{nd} International Seminar on lateritisation processes, Sao Paulo, Brazil, July 4-12 1982, 53-63.

Nahon, D.B., Boulangé, B., Colin, F., 1992. Metallogeny of weathering : an introduction. in: Martini, I.P., Chesworth, W. (Eds.), Weathering, soils and paleosols. Elsevier, Amsterdam, pp 445-467.

Nahon, D., Millot, G. , Paquet, H., Ruellan, A., Tardy, Y., 1977. VII. Digestion et effacement des cuirasses ferrugineuses par les encroûtements calcaires en pays aride, Sahara et Mauritanie. Sci. Géol., Bull. 30, 289-296.

Oberlander, T.M., 1989. Slope and pediment systems, in: Thomas, D.S.G. (Ed.), Arid zone geomorphology. Belhaven, London, pp. 56-84.

Oberlander, T.M., 1997. Slope and pediment systems, in: Thomas, D.S.G. (Ed.), Arid zone geomorphology. Wiley, Chichester, pp. 135-163.

Ollier, C.D., Galloway, R.W., 1990. The Laterite Profile, Ferricrete and Unconformity. Catena 17, 97-109.

Ollier, C.D., Pain, C.F., 1996. Regolith stratigraphy: principles and problems. AGSO J. Aust. Geol. Geophys. 16, 197-202.

Ouangrawa, M., Grandin, G., Parisot, J.-C., Baras, E., 1996. Dispersion mécanique de l'or dans les matériaux de surface : exemple du site aurifère de Piéla (Burkina-Faso). Pangea 25, 25-40.

Parisot, J.-C., Ventose, V., Grandin, G., Bourges, F., Debat, P., Tollon, F., Millot, L., 1995. Dynamique de l'or et d'autres minéraux lourds dans un profil d'altération cuirassé du Burkina Faso (Afrique de l'Ouest). Intérêt pour l'interprétation de la mise en place des matériaux constituant les cuirasses de haut-glacis. C.R. Acad Sci. Paris 301, 295-302.

Paul, J.D., Roberts, G.G., White, N., 2014. The African landscape through space and time. Tectonics 33, 898-935.

Payne, A.L., 1969. Exploration on pediments. Econ. Geol. 64, 117.

Pease, R.C., 2015. Understanding Pediments for Mineral Exploration, in: Pennell, W.M., Garside, L.J. (Eds.), Geological Society of Nevada's Symposium, Sparks, May 14-23, 2015. New Concepts and Discoveries, pp. 1365-1372.

Pélissier, P., Rougerie, G., 1953. Problèmes morphologiques dans le bassin de Siguiri (Haut Niger). Bull. I.F.A.N. 15, 1-47.

Pèltre, P., 1977. Le "V Baoulé" (Côte d'Ivoire centrale). Héritage géomorphologique et paléoclimatique dans le tracé du contact forêt - savane. Trav. Doc. ORSTOM 80, 1-198.

Porto, C.G., 2016. Geochemical exploration challenges in the regolith dominated Igarape Bahia gold deposit, Carajas, Brazil. Ore Geol. Rev. 73, 432-450.

Riquelme, R., Tapia, M., Campos, E., Mpodozis , C., Carretier, S., González, R., Muñoz, S., Fernandez-Mort, A., Sanchez, C., Marquardt, C., 2017. Supergene and exotic Cu mineralization occurs during periods of landscape stability in the Centinela Mining District, Atacama Desert. Basin. Res., doi: 10.1111/bre.12258.

Rohdenburg, H., 1969. Hangpedimentation and klimawechsel als wichtigste faktoren der flächen- und stufenbildung in den wechselfeuchten tropen an beispielen aus Westafrica, besonders aus dem schichtstufenland Südost-Nigerias. Göttinger Bodenkdl. Ber. 10, 57-133.

Rohdenburg, H., 1982. Geomorphologisch-bodenstratigraphischer Vergleich zwischen dem Nordostbrasilianischen Trockengebiet und immerfeucht-tropischen Gebieten Sfidbrasiliens mit Ausf'tihrungen zum Problemkreis der Pediplain-Pediment-Terrassentreppen. Catena Suppl. 2, 74-122.

Roquin, C., Freyssinet, P., Zeegers, H., Tardy, Y., 1990. Element distribution patterns in laterites of southern Mali. Consequence for geochemical prospecting and mineral exploration. Appl. Geochem. 5, 303-315.

Ruhe, R.V., 1956. Landscape evolution in the High Ituri, Belgian Congo. Publ. Inst. Nat. Et. Agron. Congo Belge 66, 1-108.

Sanfo, A., Colin, F., Delaune, M., Boulangé, B., Parisot, J.-C., Bradley, R., Bratt, J., 1993. Gold: a useful tracer in sub-Sahelian laterites. Chem. Geol. 107, 323-326.

Sanfo, Z., Grandin, G., Parisot, J.-C., Pale, F., 1992. Aplanissements latéritisés anciens, glacis récents et indices d'or dans la région d'Aribinda (Burkina Faso), in: Schmidt, J., Gall, Q. (Eds.), Mineralogical and geochemical records of paleoweathering. ENSPM Mém. Sci. Terre, Paris, pp. 1-16.

Scott, K.M., Pain, C.F., 2008. Introduction, in: Scott, K.M., Pain, C.F. (Eds.), Regolith Science. Springer Science, Dordrecht, pp. 1-6.

Sillitoe, R.H., 2005. Supergene Oxidized and Enriched Porphyry Copper and Related Deposits. Econ. Geol. 100th Anniversary Volume, 723-768.

Summerfield, M.A., 1985. Plate tectonics and landscape development on the African continent, in: Morisawa, M., Hack, J.T. (Eds.), Tectonic geomorphology. Allen & Unwin, Boston, pp. 27-51.

Summerfield, M.A., 1991. Global geomorphology. Longman Scientific & Technical, Harlow.

Summerfield, M.A., 1996. Tectonics, geology, and long-term landscape development, in: Adams, W.M., Goudie, A.S., Orme, A.R. (Eds.), Physical geography of Africa. Oxford University Press, Oxford, pp. 1-17.

Tardy, Y., 1997. Petrology of laterites and tropical soils. Balkema, Rotterdam.

Tardy, Y., Mazaltarim, D., Boeglin, J.L., Roquin, C., Pion, J.C., Paquet, H., Millot, G., 1988. Lithodépendance et homogénéisation de la composition minéralogique et chimique des cuirasses ferrugineuses latéritiques. C. R. Acad. Sci. Paris 307, 1765-1772.

Tardy, Y., Roquin, C., 1992. Geochemistry and evolution of lateritic landscapes, in: Martini, I.P., Chesworth, W. (Eds.), Weathering, soils and paleosols. Elsevier, Amsterdam, pp. 407-444.

Tardy, Y., Roquin, C., 1998. Dérive des continents, paléoclimats et altérations tropicales. Editions BRGM, Orléans.

Teeuw, R.M., 1987. Variations in the composition of gravel layers across the landscape. Examples from Sierra Leone. Geo-Eco. Trop. 11, 151-169.

Teeuw, R.M., 2002. Regolith and diamond deposits around Tortiya, Ivory Coast, West Africa. Catena 49, 111-127.

Teeuw, R.M., Thomas, M.F., Thorp, M.B., 1991. Geomorphology applied to exploration for tropical placer deposits, Alluvial mining. Elsevier Applied Science, London, New York, pp. 458-480.

Thomas, M.F., 1978. The study of inselbergs. Z. Geomor. N. F. 31, 1-41.

Thomas, M.F., 1980. Timescale of landform development on tropical shields - A study from Sierra Leone, in: Cullingford, R.A., Davidson, D.A., Lewin, J. (Eds.), Timescales in Geomorphology. Wiley, Chichester, pp. 333-354.

Thomas, M.F., 1989. The role of etch processes in landform development. 2. Etching and the formation of relief. Z. Geomorph. N. F. 33, 257-274.

Thomas, M.F., 1994. Geomorphology in the tropics: A study of weathering and denudation in low latitudes. Wiley & Sons, New York.

Thomas, M.F., Thorp, M.B., 1985. Environmental change and episodic etchplanation in the humid tropics of Sierra Leone: the Koidu etchplain, in: Douglas, J., Spencer, T. (Eds.), Environmental change and tropical geomorphology. George Allen & Unwin, London, pp. 239-267.

Thomas, M.F., Thorp, M.B., Teeuw, R.M., 1985. Paleogeomorphology and the occurrence of diamondiferous placer deposits in Koidu, Sierra Leone. J. Geol. Soc. 142, 789-802.

Thomas, M.F., Summerfield, M.A., 1987. Long-term landform development: key themes and research problems, in: Gardiner, V. (Ed.), International Geomorphology 1986, Part II. John Wiley & Sons, London, pp. 935-956.

Tricart, J., 1972. The landforms of the humid tropics, forests and savannas. Longman, London.

Tricart, J., Michel, P., Vogt, J., 1957. Oscillations climatiques quaternaires en Afrique Occidentale. Fifth Congr. INQUA, Madrid-Barcelona, 1957, 187-188.

Tricart, J., 1959. Observations sur le façonnement des rapides des rivières intertropicales. Bull. Sect. Géogr. Com. Trav. Hist. Sci. LXXI, 289-313.

Twidale, C.R., 1983. Pediments, peneplains, and ultiplains. Rev. Géomor. Dyn. 32, 1-35.

Twidale, C.R., 1991. A Model of Landscape Evolution Involving Increased and Increasing Relief Amplitude. Z Geomor. N.F. 35, 85-109.

Twidale, C.R., Bourne, J.A., 2013. Do pediplains exist? Suggested criteria and examples. Z. Geomor. 57, 411-428.

Valeton, I., 1991. Bauxites and Associated Terrestrial Sediments in Nigeria and Their Position in the Bauxite Belts of Africa. J. Afr. Earth Sci. 12, 297-310.

Valeton, I., 1994. Element Concentration and Formation of Ore-Deposits by Weathering. Catena 21, 99-129.

Vasconcelos, P.M., Brimhall, G.H., Becker, T.A., Renne, P.R., 1994. Ar-40/Ar-39 Analysis of Supergene Jarosite and Alunite - Implications to the Paleoweathering History of the Western USA and West-Africa. Geochim. Cosmochim. Acta 58, 401-420.

Vogt, J., 1959a. Aspects de l'évolution morphologique récente de l'ouest africain. Ann. Géogr. Franç. 367, 193-206.

Vogt, J., 1959b. Observations nouvelles sur les alluvions inactuelles de Côte d'Ivoire et de Haute-Guinée, 84ème Congr. Soc. Sav., Dijon, pp. 205-210.

Ye, J., Chardon, D., Rouby, D., Guillocheau, F., Dall'asta, M., Ferry, J.N., Broucke, O., 2017. Paleogeographic and structural evolution of northwestern Africa and its Atlantic margins since the early Mesozoic. Geosphere 13, 1254-1284.

Zeegers, H., Lecomte, P., 1992. Seasonnally humid tropical terrains (savannas), in: Butt, C.R.M., Zeegers, H. (Eds.), Regolith exploration geochemistry in tropical and subtropical terrains. Elsevier, Amsterdam, pp. 203-240.

Zeegers, H., Leprun, J.C., 1979. Evolution des concepts en altérologie tropicale et conséquences potentielles pour la prospection géochimique en Afrique occidentale soudano-sahélienne. Bull. Bur. Rech. Géol. Min. 2-3, 229-239.

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 glacis 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 glacis 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 glacis surfaces. (b) Rolling pediplain of the Middle glacis 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 glacis landscape stages of West African granite-greenstone terrains (modified after Eschenbrenner and Grandin, 1970). (a) High glacis stage. (b) Early settlement of the Middle glacis (yellow). (c) Installation of the Low glacis (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 glacis 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 glacis 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 glacis, 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 glacis. 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 glacis 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 landsfurface). 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).

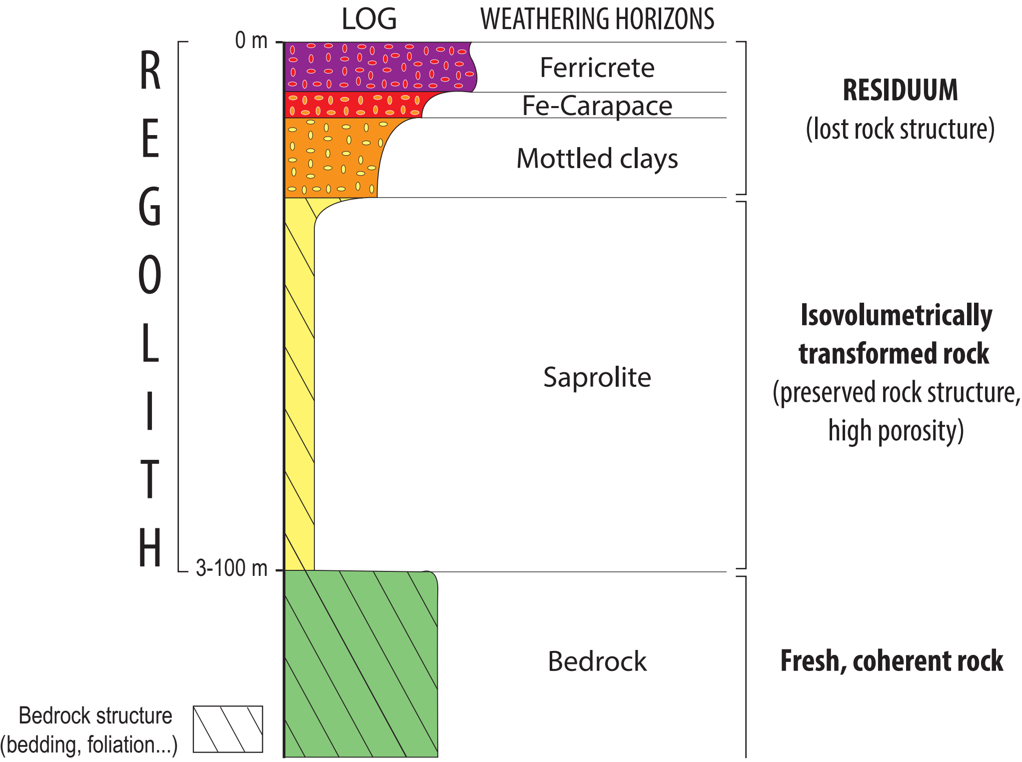
Figure 17. Simplified geology (a) and regolith-landform map (b) of West Africa. Landform-regolith provinces are distinguished on the basis of the generation of landform-regolith association best preserved in the present-day landscape. (a) is adapted from Ye et al. (2017); (b) is from the present work. 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).

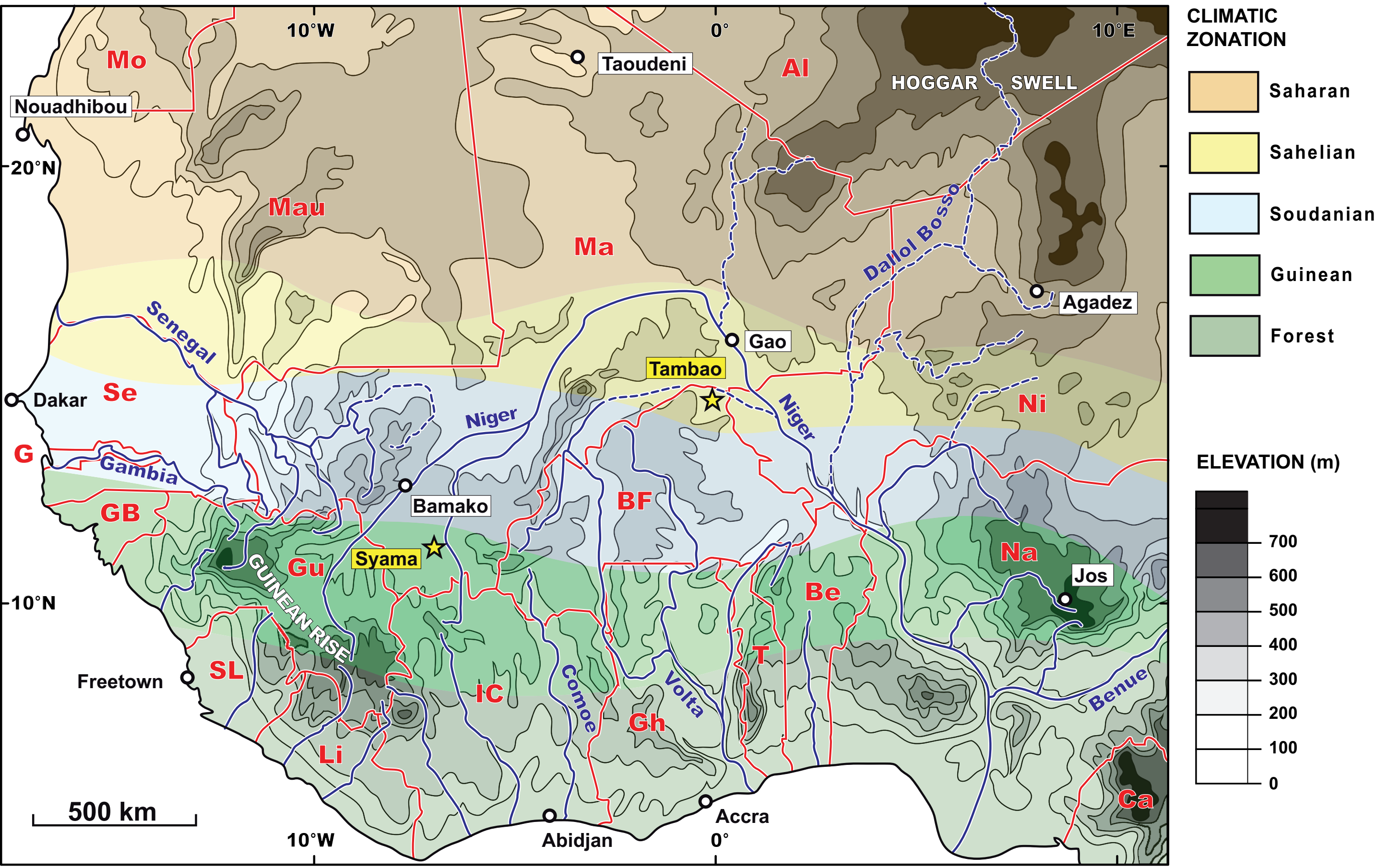
Figure 19. Comparative scenarios of glacis ferricrete plateau degradation leading to a residual hill. (a) Under arid or semi-arid climate. (b) Under humid climate typical of rainforest environments (modified after Grandin, 1976).

Figure 20. Cross-section illustrating transport of mineralized material on successive glacis 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 glacis. Large grey arrows show material transport paths on glacis. 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 glacis 1, eventually leading to a transported anomaly on the new glacis surface. Formation of glacis 2 later led to reworking of the same mineralization that was still preserved under glacis 1. But this time, because of the creation of a new drainage divide, mineralized elements were transported in an opposite direction down the glacis 2 slope. Bedrock mineralization B is currently concealed under glacis 2.

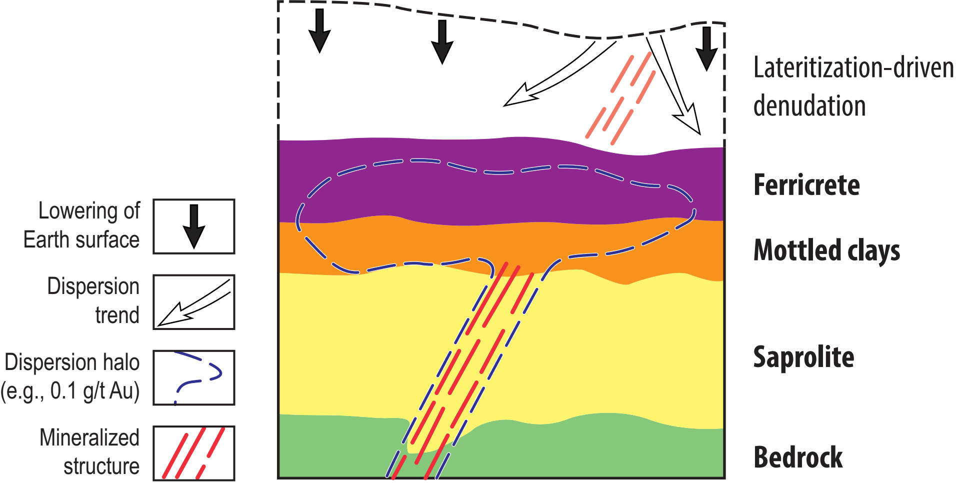
Figure 21. Gold and copper occurrences and High glacis ferricrete remnants overlying mineralized bedrock map units, Southwestern Burkina Faso (same map area as Fig. 9). Sources are Baratoux et al. (2011) and Metelka et al. (2012) for bedrock geology and Castaing et al. (2003) and the 1/200,000 scale 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 km^2 for the entire map area, respectively).



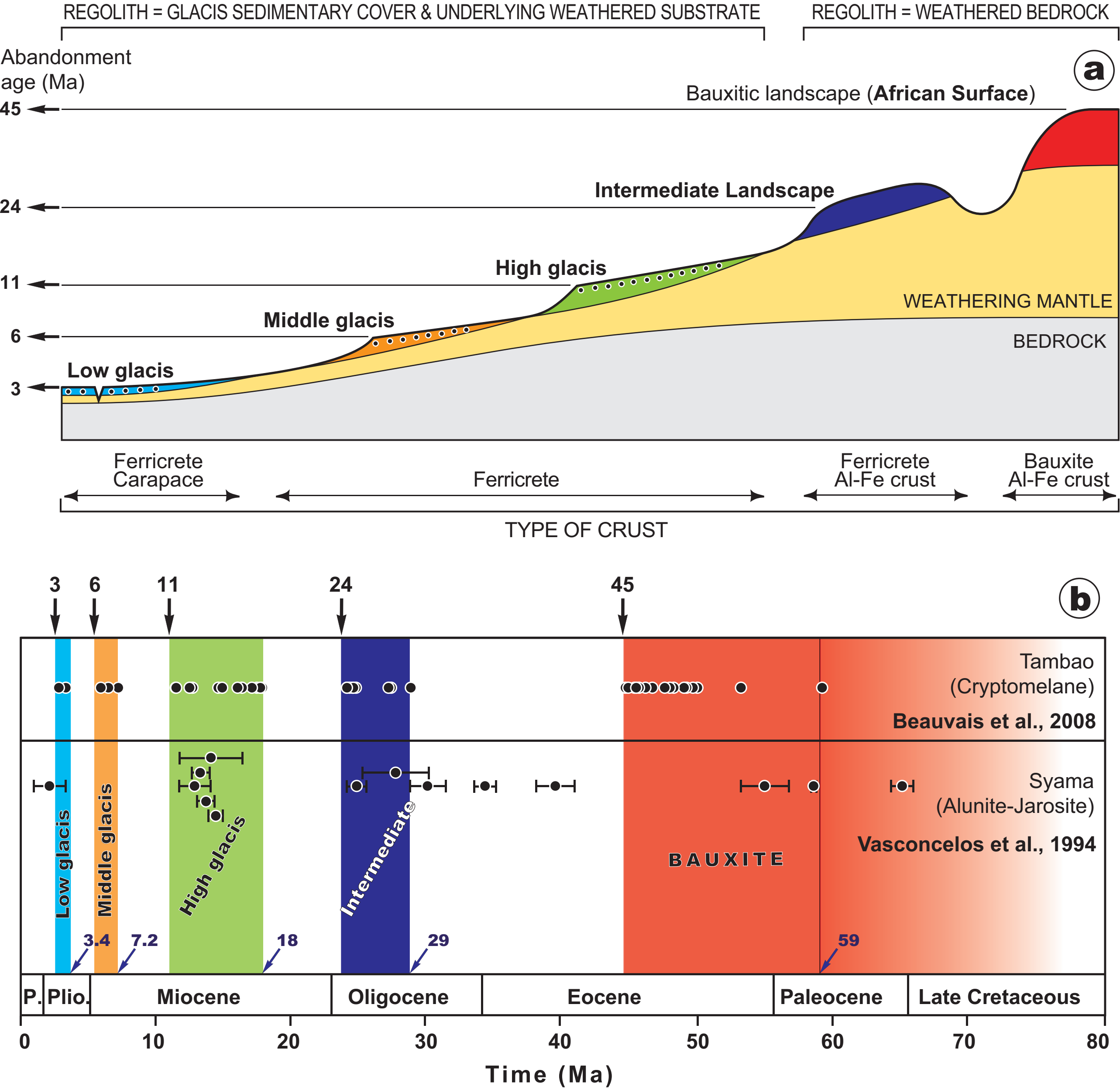
Chardon et al., Figure 1



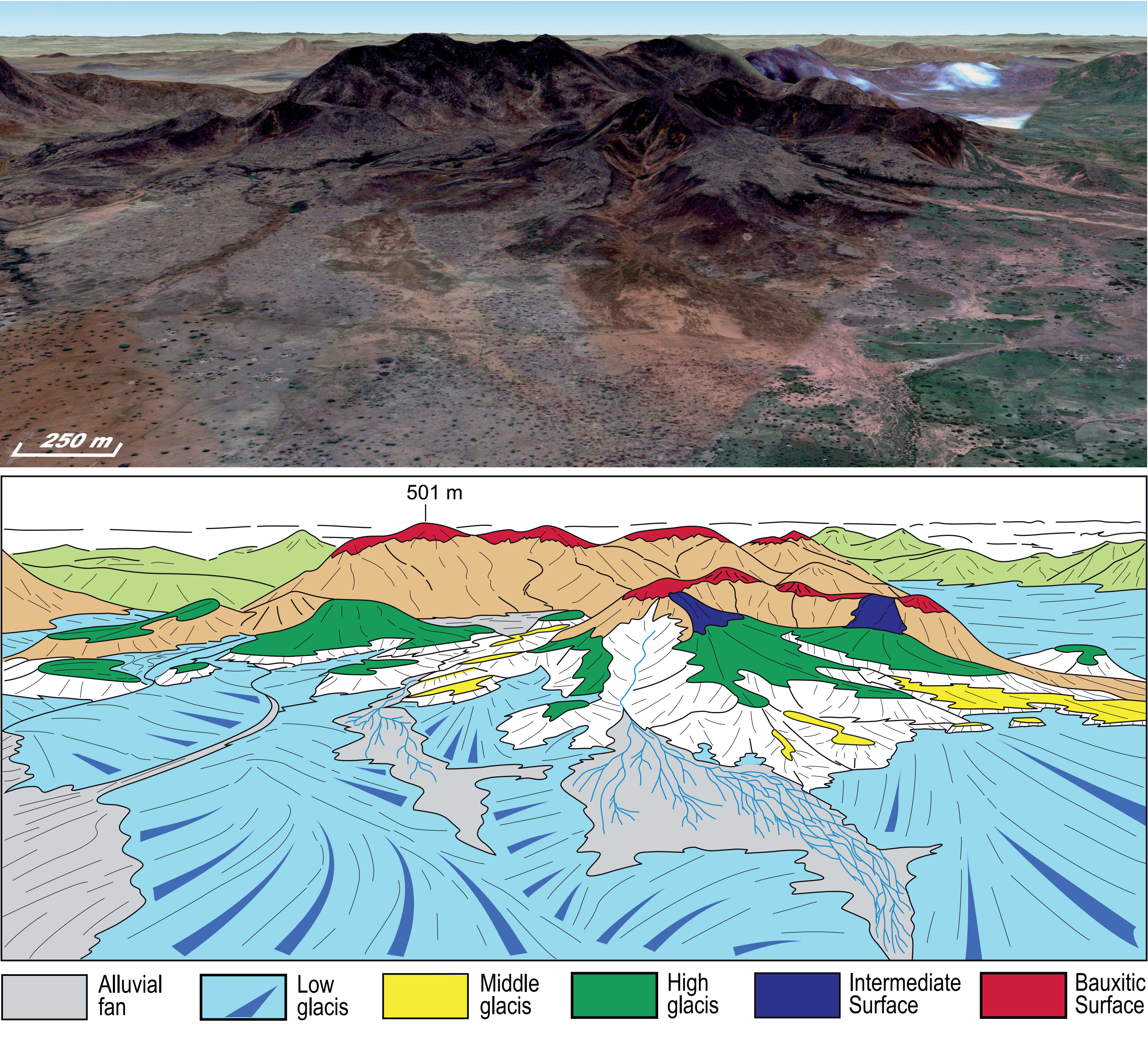
Chardon et al., Figure 2



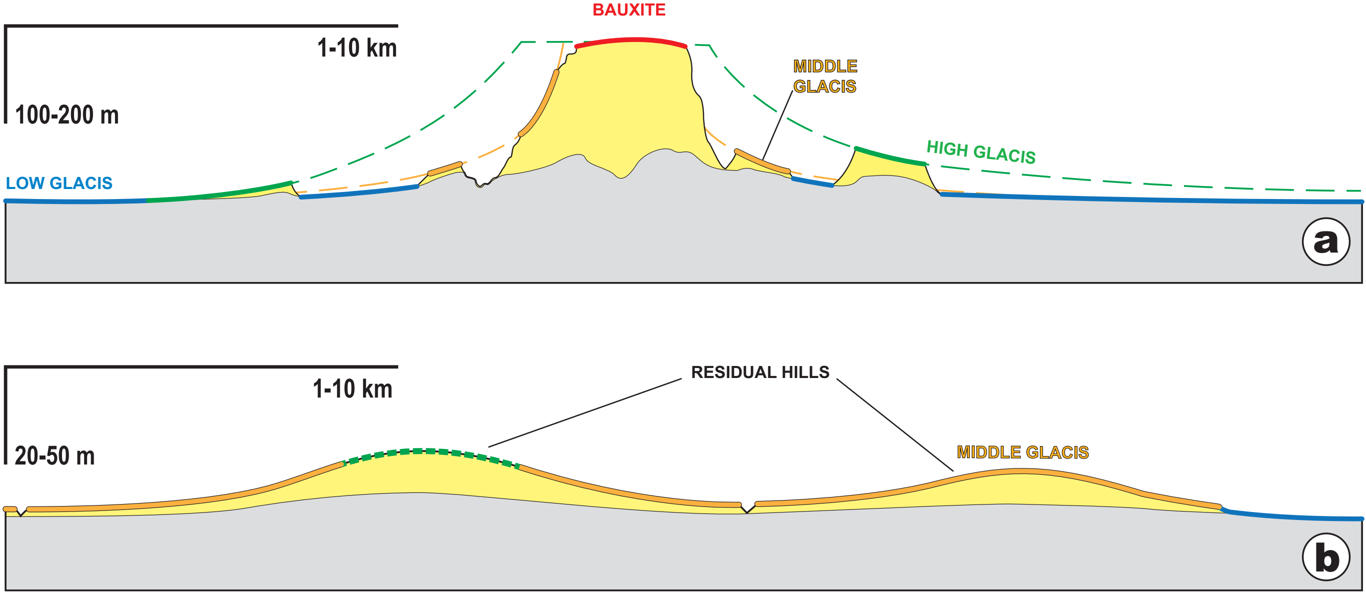
Chardon et al., Figure 3



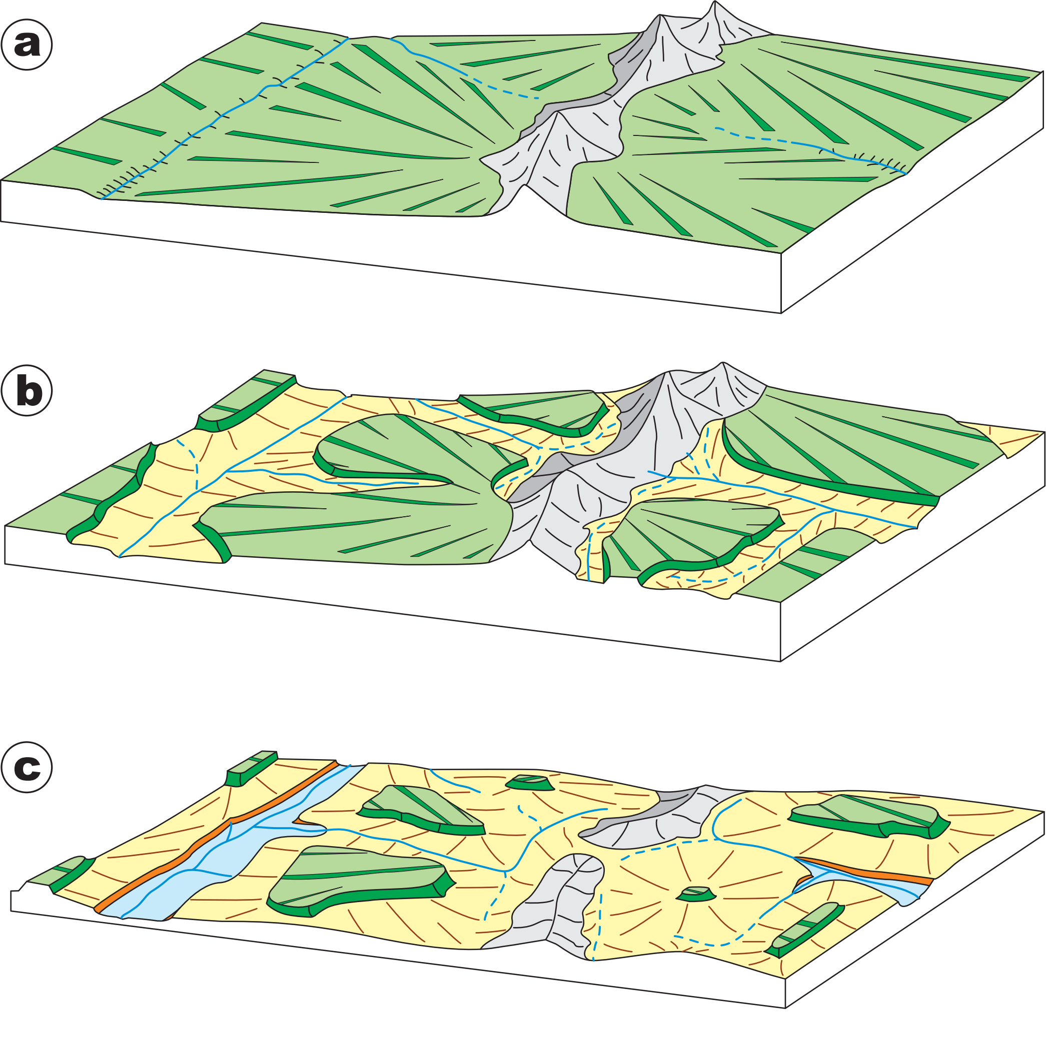
Chardon et al., Figure 4



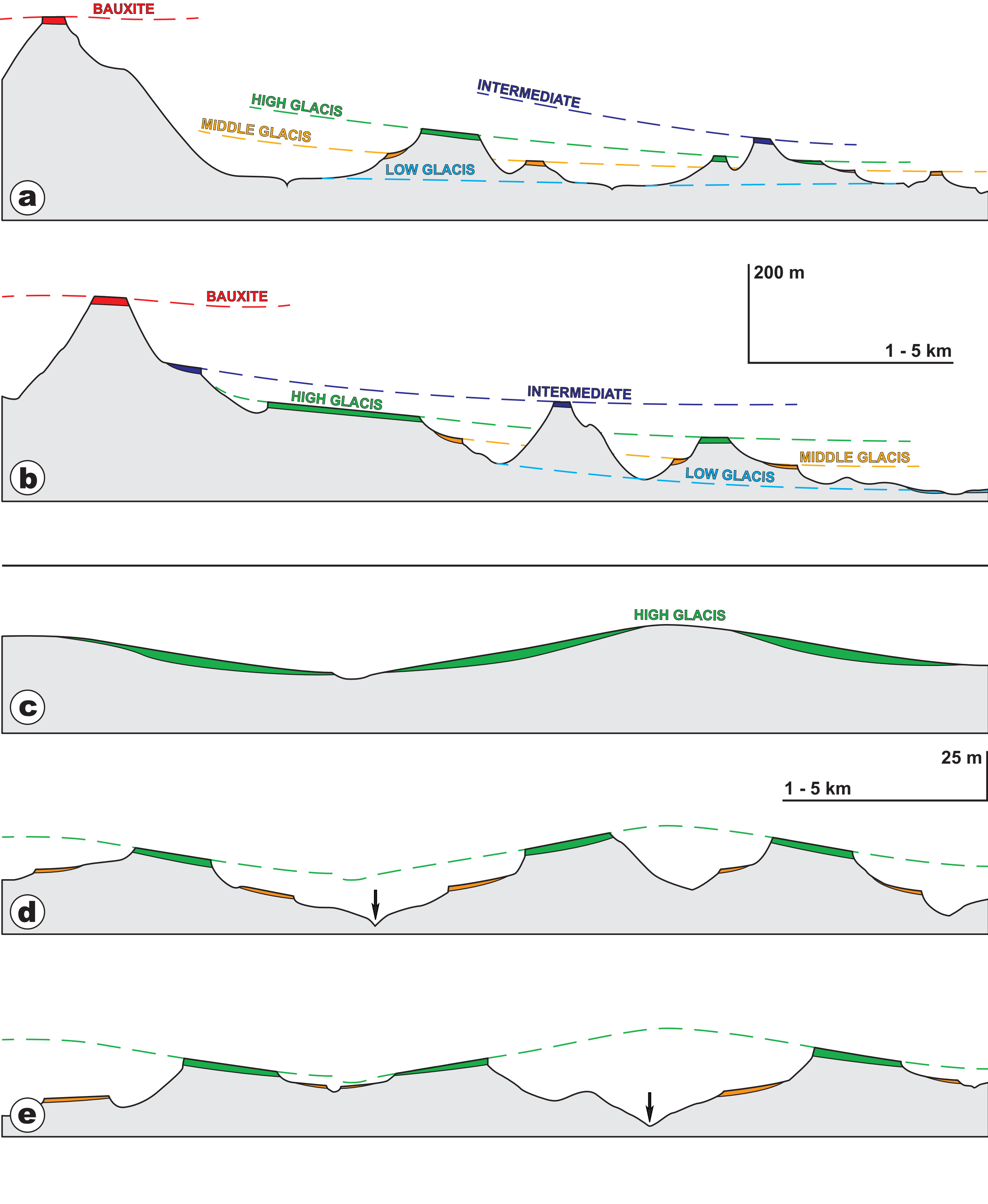
Chardon et al., Figure 5



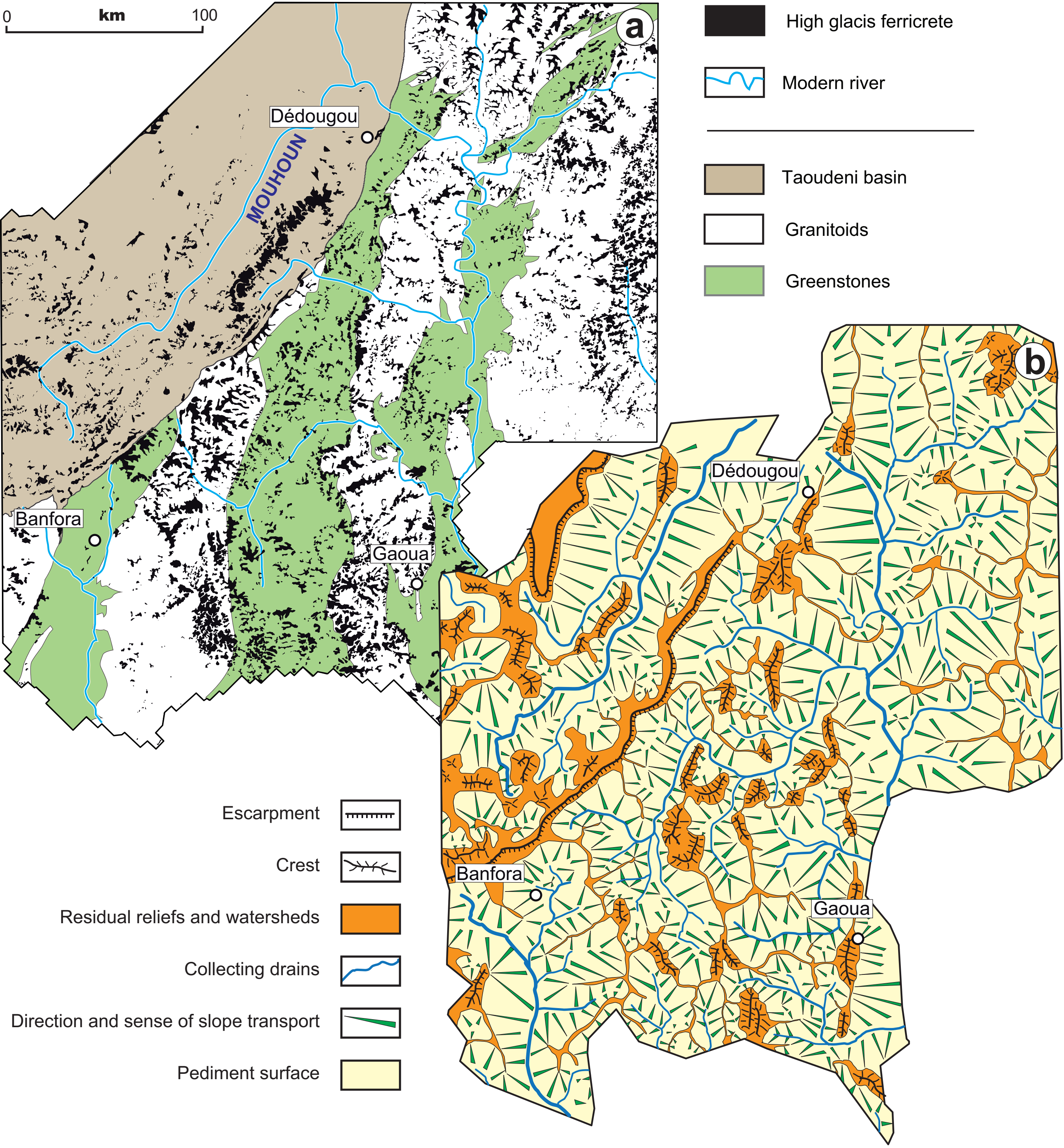
Chardon et al., Figure 6



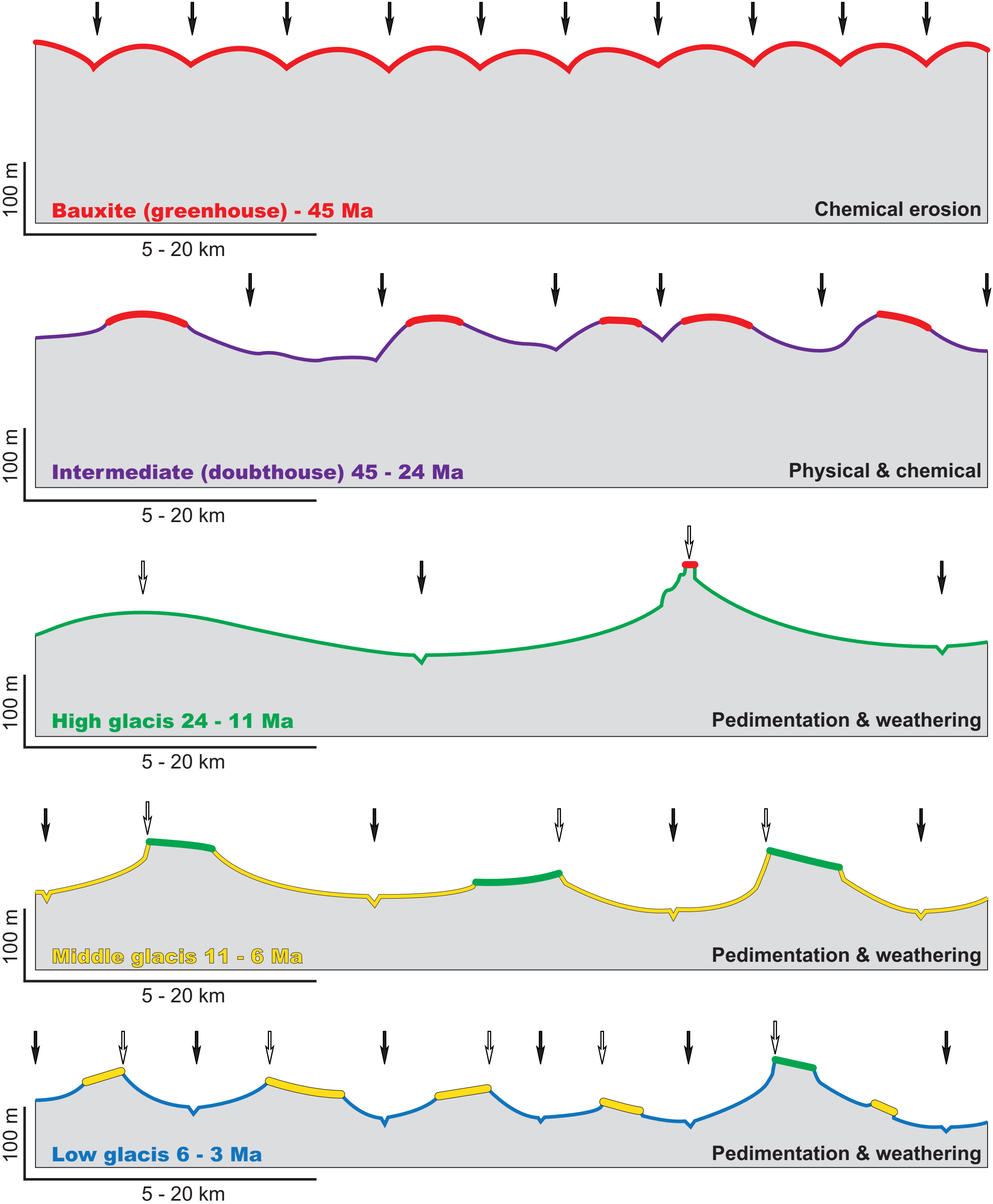
Chardon et al., Figure 7



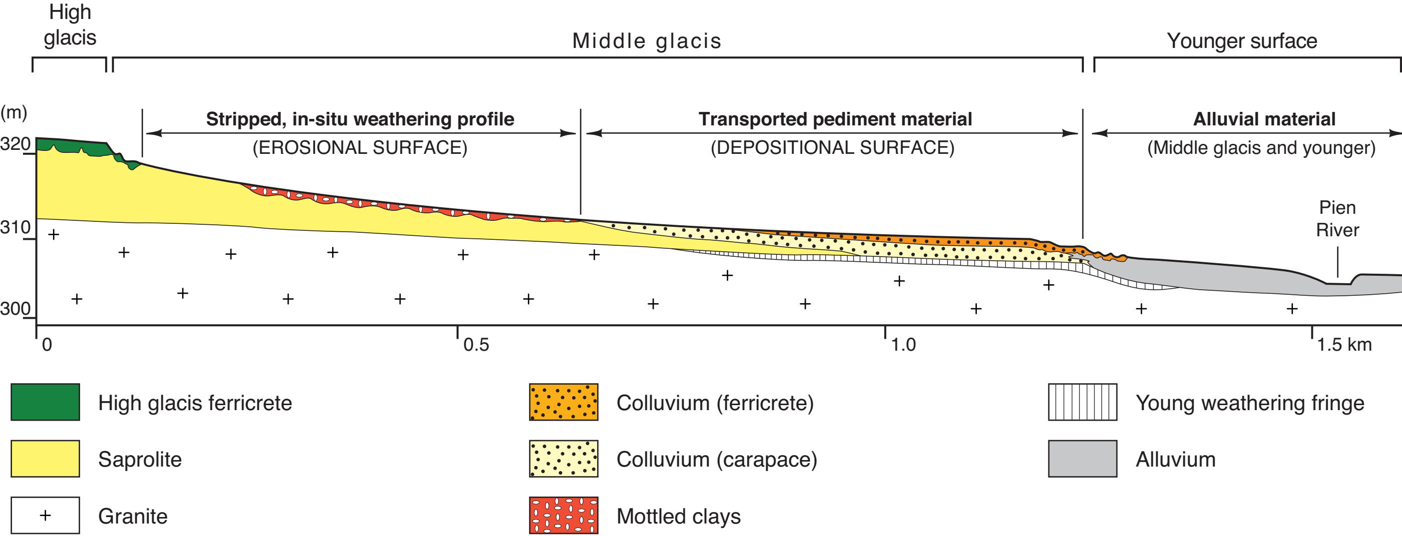
Chardon et al., Figure 8



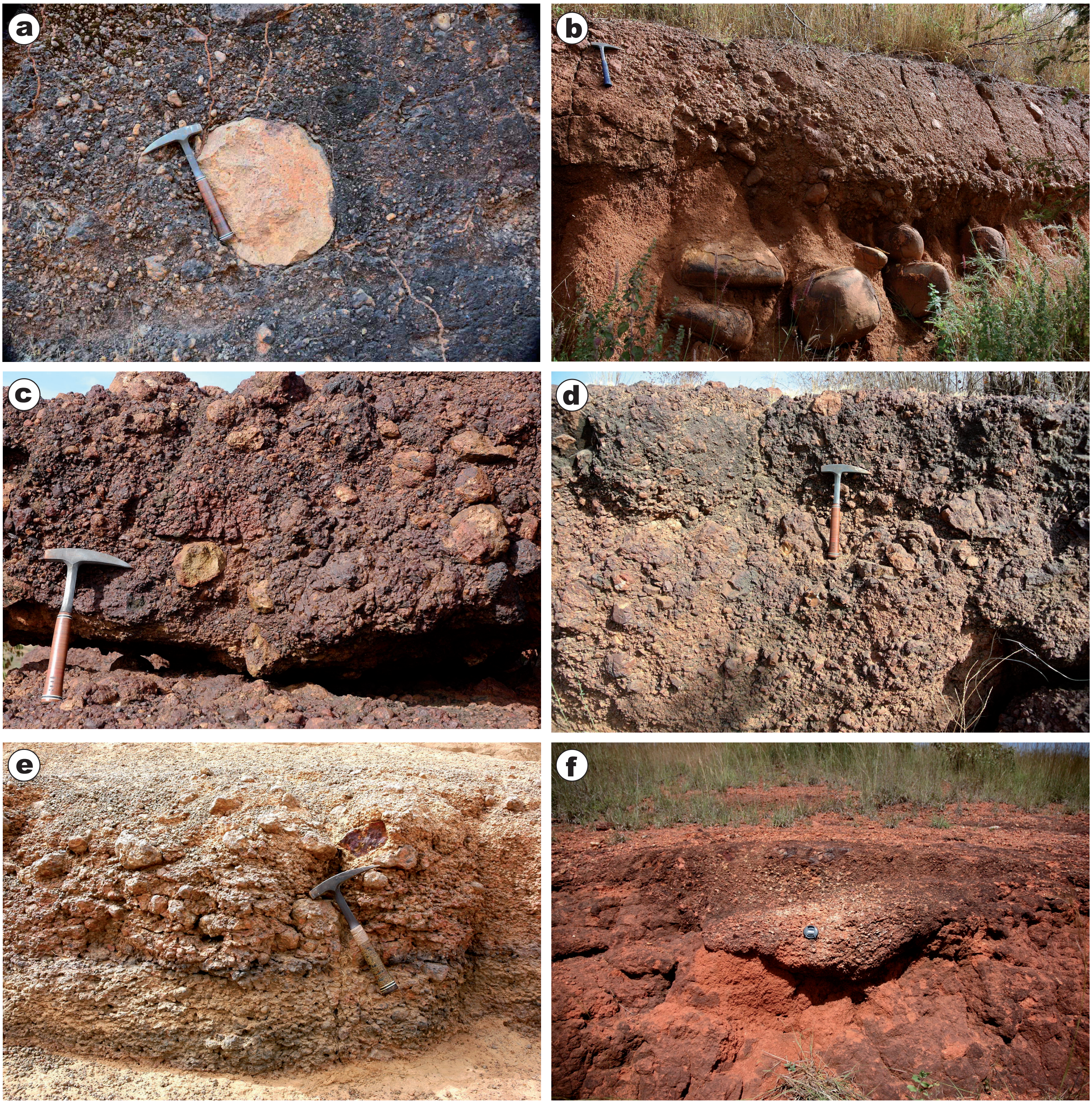
Chardon et al., Figure 9



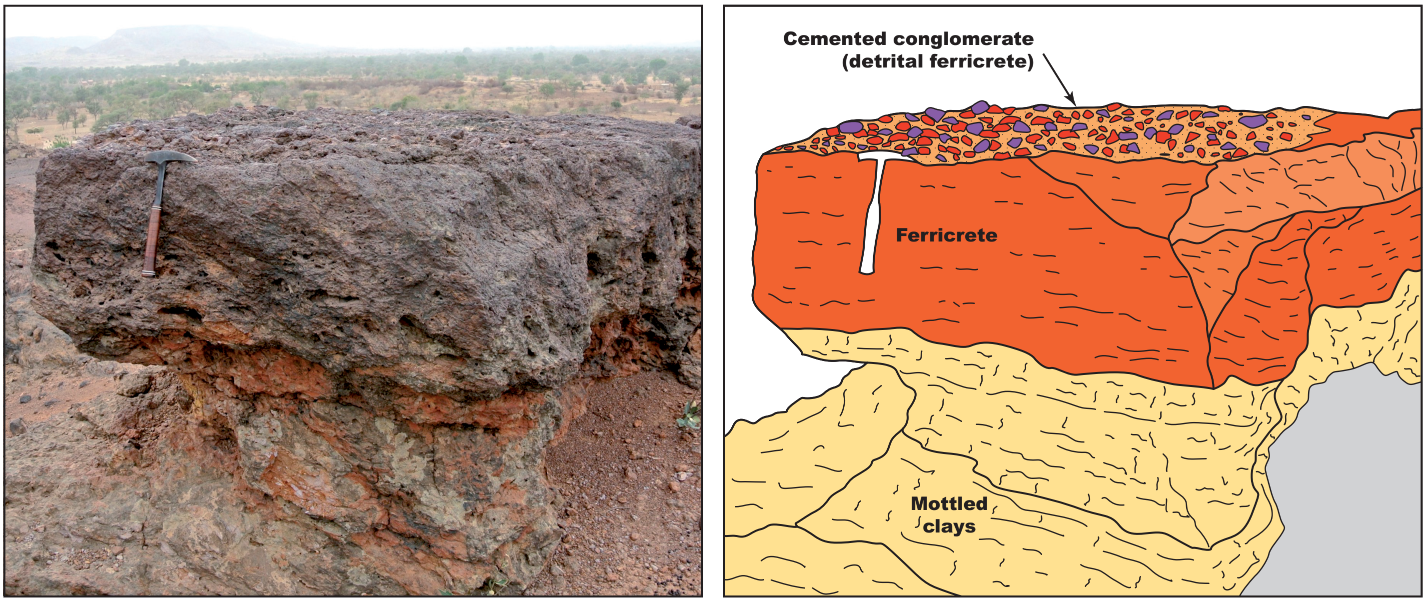
Chardon et al., Figure 10



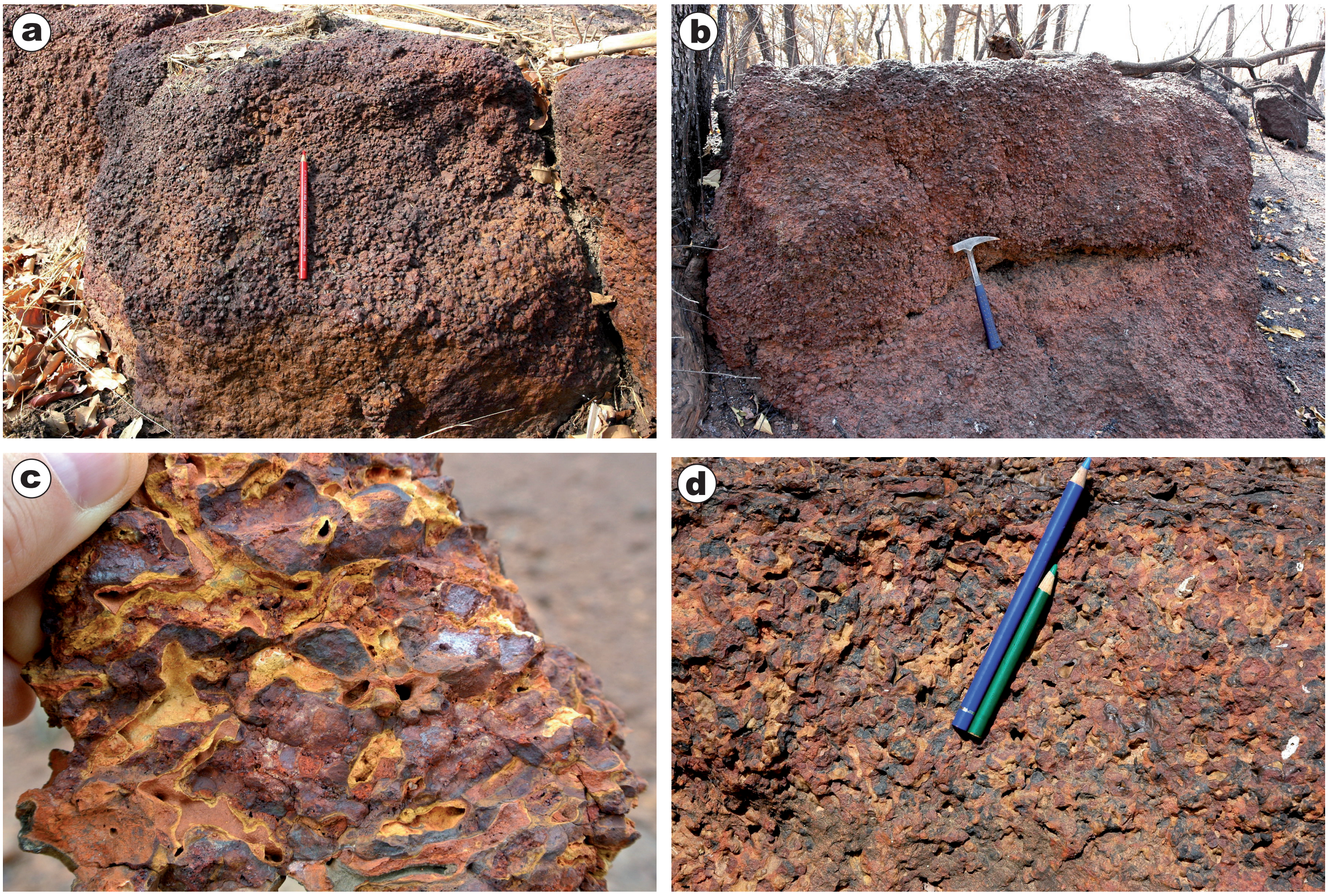
Chardon et al., Figure 11



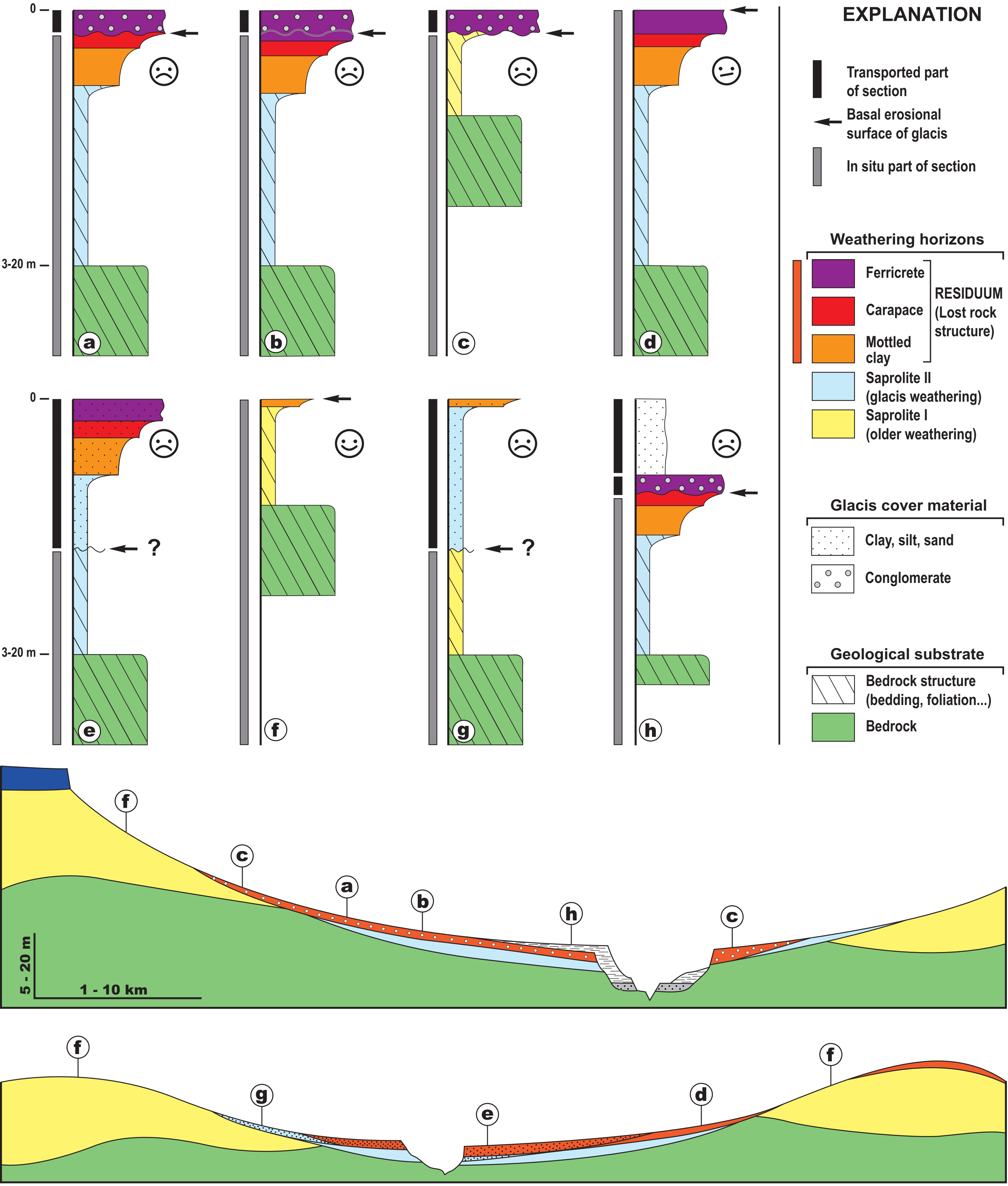
Chardon et al., Figure 12



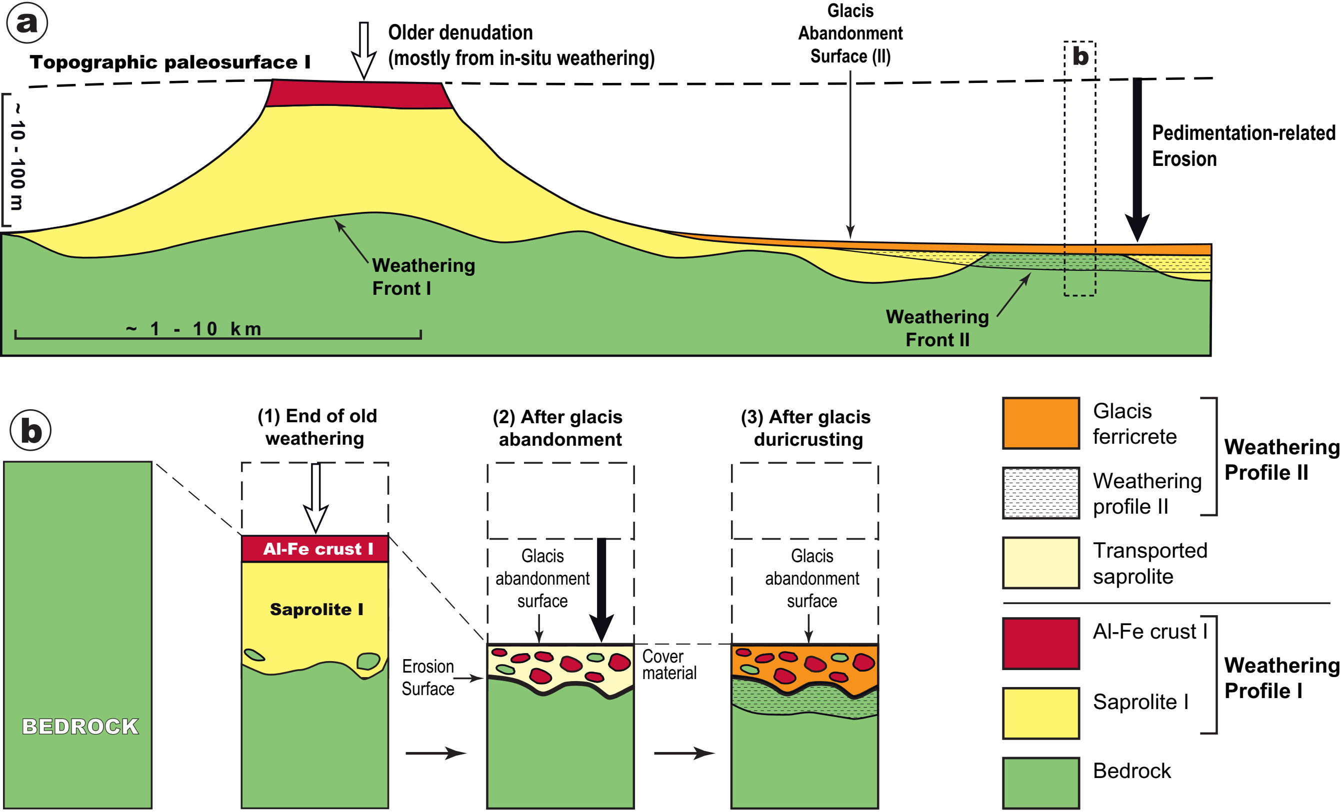
Chardon et al., Figure 13



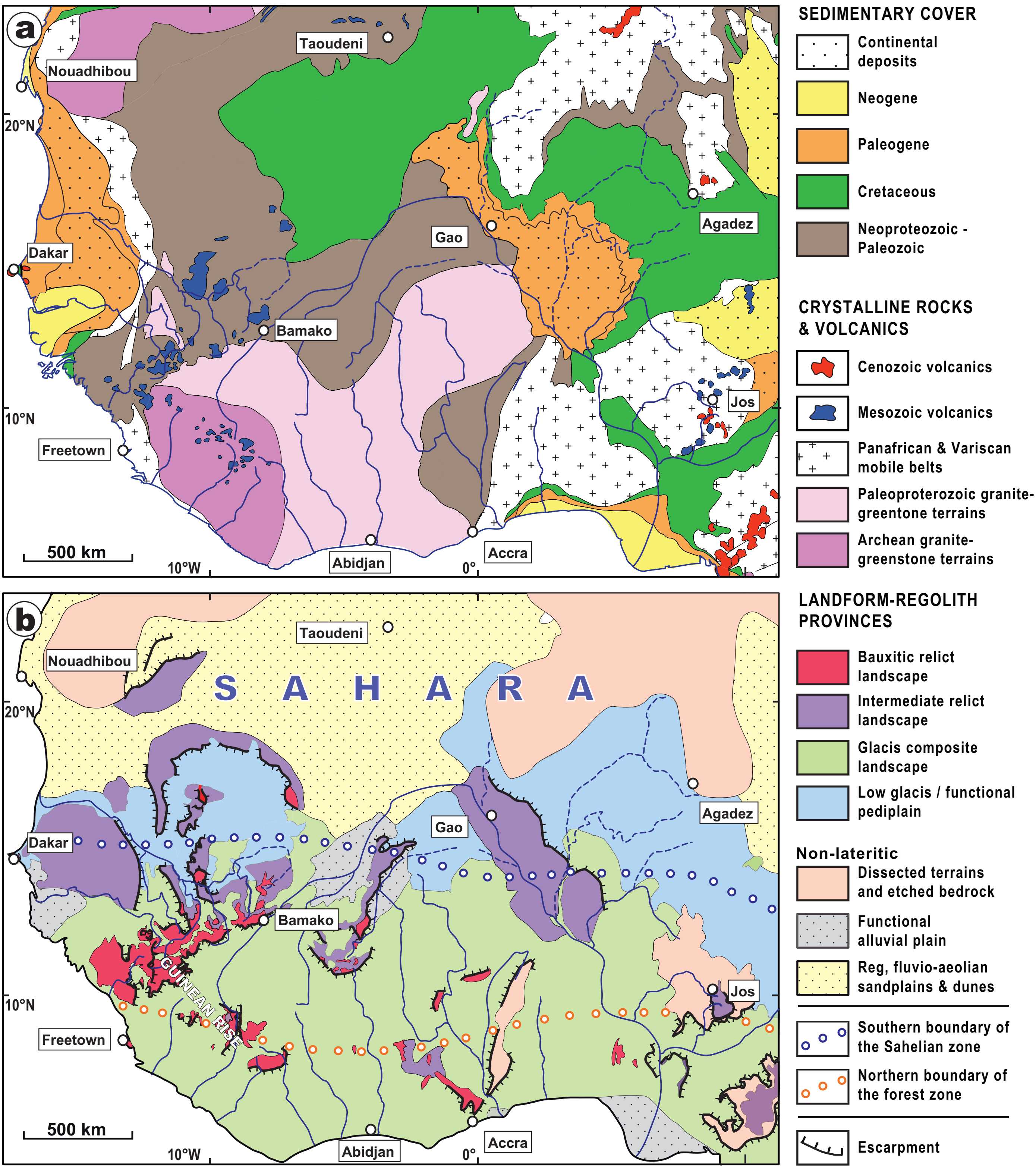
Chardon et al., Figure 14



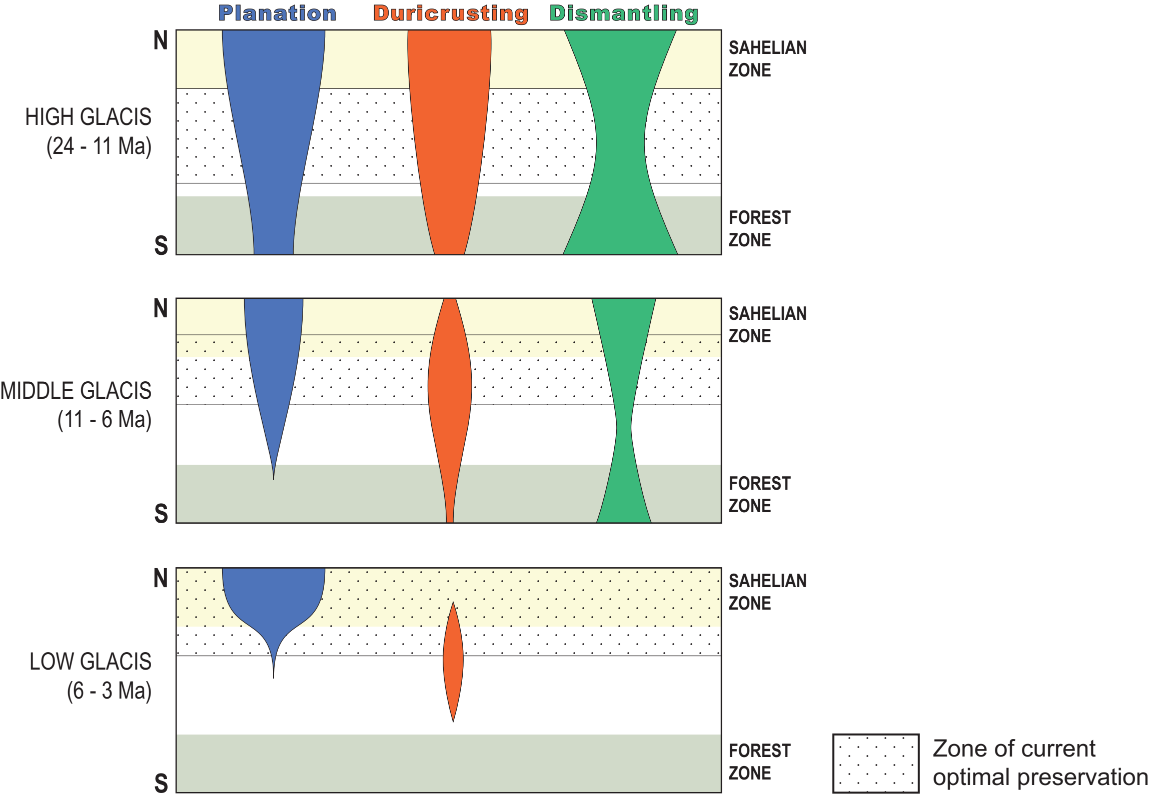
Chardon et al., Figure 15



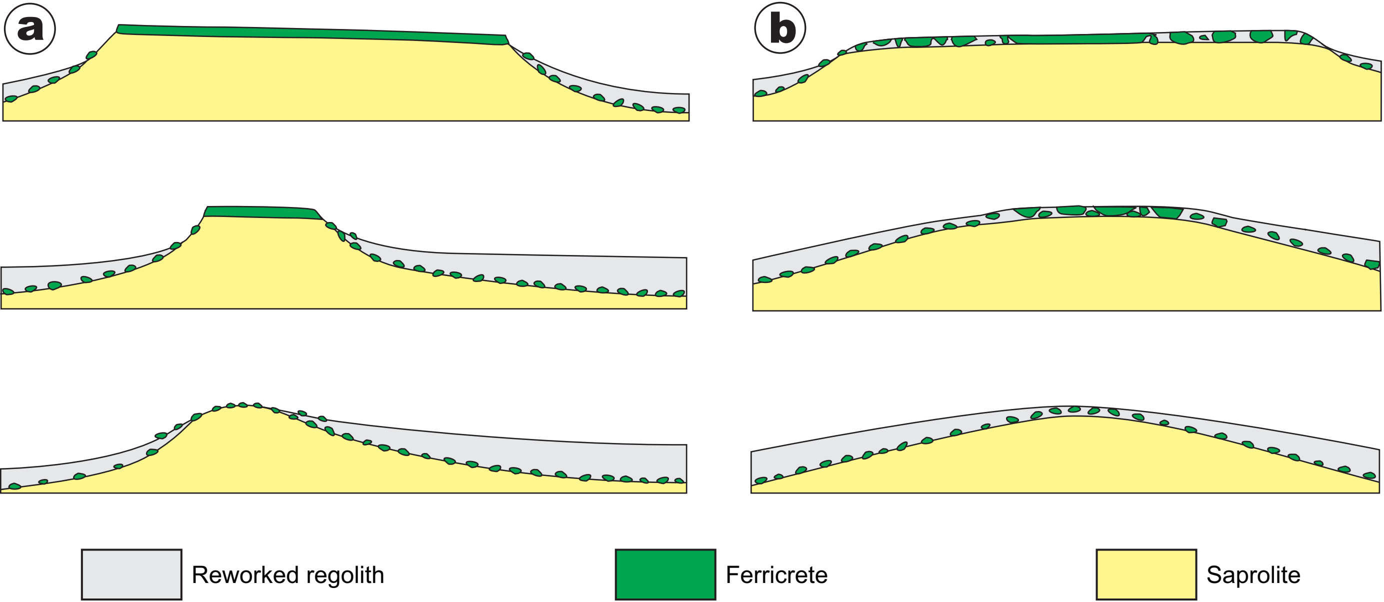
Chardon et al., Figure 16



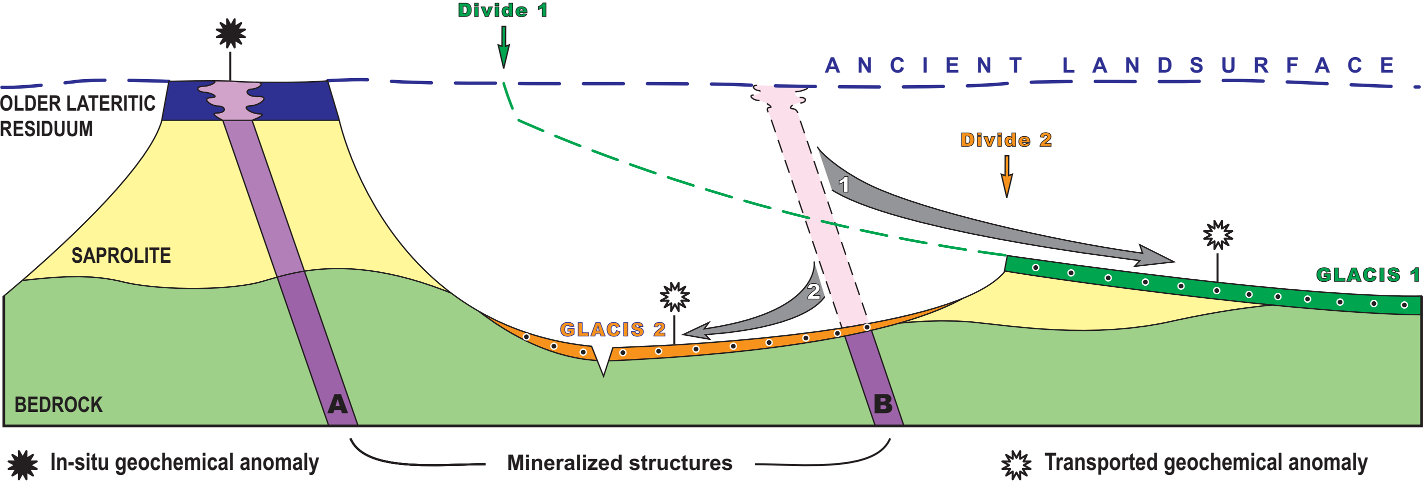
Chardon et al., Figure 17



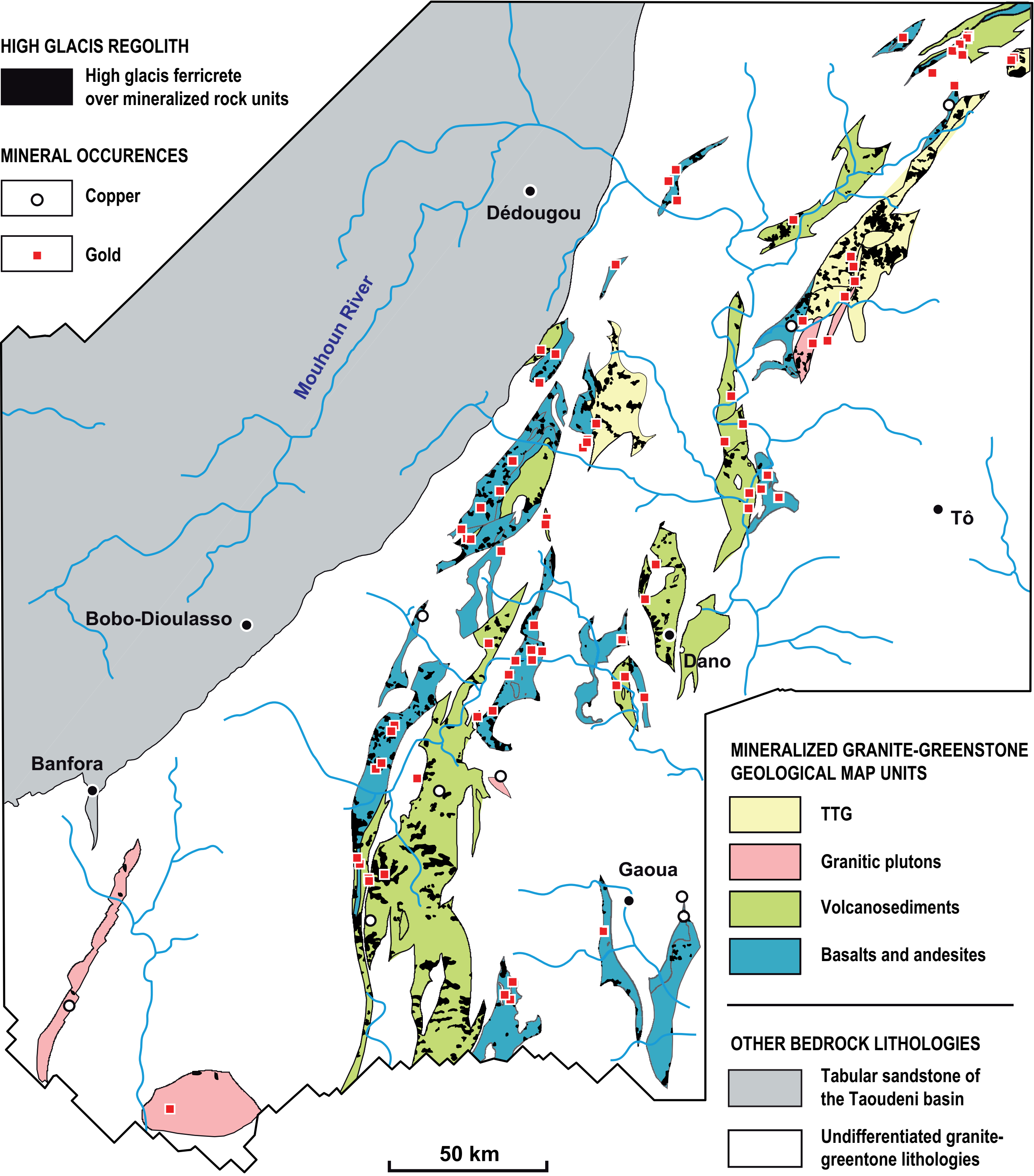
Chardon et al., Figure 18



Chardon et al., Figure 19



Chardon et al., Figure 20



Chardon et al., Figure 21