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Benjamin Sawadogo, Ousmane Bamba, Dominique Chardon

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Benjamin Sawadogo[a,b], Ousmane Bamba[a], Dominique Chardon[a,b,c]*

[a] Département des Sciences de la Terre, Université Joseph Ki-Zerbo, Ouagadougou, Burkina Faso

[b] IRD, Ouagadougou, Burkina Faso

[c] GET, Université de Toulouse, CNRS, IRD, UPS, France.

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*Corresponding author

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

HIGHLIGHTS

- Presentation of a landform-regolith mapping protocol adapted to West Africa
- Landform-regolith map transposed into a soil prospectivity map
- Implications for exploration strategies
- Applicability to the rest of West Africa and inter-tropical mineral provinces

Abstract

In this paper, we present an integrated landform-regolith mapping protocol/chart for West Africa developed using a case from Central Burkina Faso. The chart accounts for (i) the specificities of the ubiquitous, duricrust-capped remnants of the regional paleolandsurfaces - particularly the residual or detrital character of the Fe duricrusts – and (ii) the diversity of the remaining, non-duricrusted portions of the landscape, with an emphasis on the pitfalls encountered in determining the in-situ or transported character of the regolith. The paper also provides field identification criteria and illustrations of the typical West African landform-regolith associations. The landform-regolith mapping chart is integrated into a prospectivity chart, which is used to define exploration guides: (ii) defining sampling strategies, (ii) interpreting potential geochemical anomalies and (iii) targeting lateral extensions of known bedrock mineralizations. The mapping protocol further allows for the definition of a class of landform-regolith associations propitious to supergene mineral concentrations. The mapping protocol is shown to be transposable to wetter contexts and, more generally, to other tropical shield provinces.

keywords: Pediment, Weathering profile, Duricrust, Detrital duricrust, Mineral exploration

1. Introduction

Regolith cover is often an obstacle to mineral exploration in the tropics because of poor or uneven outcrop conditions of the geological substrate. Exploration relies on sampling of surface material (soil, lag, duricrust, or even termite mounds or vegetation) to detect geochemical anomalies resulting from the geochemical dispersion of a primary bedrock mineralization through the regolith. However, interpretation of a surface geochemical anomaly depends on the nature and the history of the regolith. The regolith may occur in situ on the rocks from which it derives by weathering or may have been transported and re-weathered. The main challenges for geochemical exploration are therefore to (i) choose the appropriate spatial density, depth and technique of sampling, (ii) identify the right regolith material to sample and (iii) interpret geochemical anomalies (Anand and Butt, 2010). Landform-regolith mapping is therefore a crucial prerequisite to mineral exploration in the tropics. Several mapping protocols have been developed in the last decades (Butt, 2016), the most popular being derived from, or comparable to, the RED model (Anand et al., 1993; Anand and Butt, 2010). That model categorizes the landscape into 3 regolith-landform regimes: relict (R, for lateritic residuum), erosional (E, for erosional plains and steep slopes) and depositional (D, sediments masking the weathering profile or the bedrock). RED-type models were applied (or slightly adapted) in sub Saharan West Africa (e.g., Zeegers and Lecomte, 1992; Arhin et al., 2015; Butt, 2016). While implicitly or explicitly referring to RED-type models, most authors and exploration geologists categorize the ubiquitous

71 Al-Fe duricrust cover of West Africa as lateritic residuum (i.e., duricrusts are the ultimate
72 residual term of weathering, topping a weathering profile derived from the underlying
73 bedrock) (e.g., Boeglin and Mazaltarim, 1989; Roquin et al., 1990; Zeegers and Lecomte,
74 1992; Bowell et al., 1996; Tardy, 1997; Freyssinet et al., 2005; see Butt and Bristow, 2013).
75 However, most (>80%) part of West Africa is occupied by pediments capped by detrital
76 Fe-duricrusts or unconsolidated detrital sediments (Chardon et al., 2018; see also
77 Bolster, 1999; Butt and Bristow, 2013). These pediments are inherited from 3 Neogene
78 paleolandscape stages of the well documented regional morphoclimatic sequence
79 (Fig.1). The ubiquity of paleo- and active pediment systems in West Africa therefore
80 prompts the reevaluation of landform-regolith mapping protocols.
81 Here we present an integrative landform-regolith mapping chart for West Africa
82 based on the case presented in this paper. We aim at providing geomorphologists,
83 geologists, geochemists and the mineral exploration community with field
84 documentation, identification criteria and illustrations of the typical landforms and
85 regolith. The chart accounts for the specificities of the remnants of the regional
86 morphoclimatic sequence (Fig. 1) - particularly the residual or detrital character of the
87 Fe duricrusts – and the remaining, non-duricrusted portions of the landscape. We show
88 how the resulting landform-regolith map is converted into a soil prospectivity map,
89 which is used for (i) defining sampling strategies, (ii) interpreting potential geochemical
90 anomalies and (iii) targeting lateral extensions of known deposits. The mapping
91 protocol is shown to be applicable to wetter contexts and, more generally, to other
92 tropical shield provinces.
93
94 **2. Context and method**

Our study is based on a regolith mapping project of part of the Goren greenstone belt in North-Central Burkina Faso, in the semi-arid Soudanian climatic zone (Fig. 2). The study area is typical of the greenstone-hosted gold deposits of the Eburnean orogen of the southern West African craton (e.g., Milési et al., 1992; Fig. 2). The belt is the richest in Burkina Faso in terms of gold indices and prospectivity (Castaing et al., 2003). The mapping protocol is illustrated on a typical 7 x 6 km extract (Figs. 3 and 4) of a larger mapped area (26 x 15 km) that allowed for a comprehensive inventory of the spatial diversity of the regolith covers. The geological substrate comprises a typical Birimian greenstone association of low-grade schistose volcanosediments (sandstone-pelite associations interlayered with mafic and felsic volcanics) and metabasic rocks (gabbro, diorite and andesite) (Fig. 3).

For landform-regolith mapping, we used a 1:10 000 scale, 1-m contour base map derived from a smoothed Lidar digital elevation model (e.g., Figs. 3 and 4). Mapping was undertaken along a number of itineraries throughout the landscape (Fig. 3) complemented by photointerpretation that allowed refinement of various map units. Field mapping consisted mostly of (1) landscape interpretations and establishment of landscape chronologies, (2) description and identification of the duricrust-capped remnants of the West African morphoclimatic sequence (Fig. 1), (3) description and classification of the geomorphology and regolith cover of the erosional landforms separating the duricrust-capped remnants and (4) description and classification of the material being actively remobilized by mechanical erosion and transport.

Through comprehensive field investigation the definition of 20 landform-regolith association map units (section 3; Fig. 4) was established. These units may be grouped into 4 main categories on the basis of the nature/degree of genetic link

between the material exposed at the surface and the underlying geological substrate (section 4). This categorization has implication on the intensity of expression of a geochemical anomaly through the regolith that is related to the underlying bedrock mineralization, the occurrence of "transported" anomalies in the regolith or the potential occurrences of bedrock anomalies masked by the regolith.

3. Landform-regolith associations

3.1. Upper paleolandsurfaces

3. 1. 1. Bauxitic (African) paleolandsurface (1BxD)

It is preserved as 120- to 150-m high, duricrust-capped plateaus that are flat or slightly convex, with less than 25 m of elevation amplitude for a single plateau (Fig. 6a and 6b). In the study area, the largest plateau is 1 km long and 40 m wide (Fig. 4). The weathering profile underlying the bauxitic duricrust is 50- to 100-m thick (thickest on mafic rocks). It is observed on the steep sides of plateaus, whose edge consists of a scarp made in the duricrust. The profile consists mainly of a kaolinite rich saprolite underlying a 5 to 10 m thick duricrust. Saprolite is absent on quartzite and silicified volcanosediments, so that the duricrust rests directly on saprock. Duricrusts are of two main types: bauxites, that are massive or breccia-like (Fig. 7a to 7d), and Fe bauxites, that are nodular or pisolitic (Fig. 7e and 7f). Breccia-like bauxites are more common on volcanosedimentary substrate and massive bauxites are equally found on mafic rocks and volcanosediments. Fe bauxites are degraded bauxites enriched in iron (e.g., Boulangé, 1986, 1984) and mostly found on the lowermost portions of wide plateaus.

3. 1. 2. Intermediate paleolandsurface (2InD, 2InC, 2InR)

Relics of that paleolandsurface occur as two duricrust-capped geomorphological types. The most common type (1) is smooth hilly slopes or ridges sloping away from bauxitic plateaus (Fig. 4, Fig. 5 and Fig. 6b). They are stepped under the bauxitic plateaus (most of the time 50 m under the plateau edge) and, in some cases, attached to it in such a way that there is continuity between the Bauxitic and Intermediate duricrusts. The downslope topographic profile of the relics or their surface envelope is convexo-concave to convex. Relics have 50 to 500 m of across-slope width, with a slope ranging from 5 to 20 % and an elevation amplitude of 20 to 75 m. Type 2 relicts are 50- to 500-m-wide isolated plateaus that dominate the lowland by 15 to 60 m (Fig. 6c). Plateaus are inclined (4 to 10 % slope), with an individual elevation amplitude of 10 to 30 m. The disposition and the distribution and slope of type 2 plateaus indicate that the Intermediate paleolandsurface radiated as wide piedmonts around the Bauxite-bearing topographic massifs and that type 1 relics represent upslope portions of these piedmonts. The hilly morphology of type 1 relics appears to result from the collapse of the paleolandsurface by mass wasting after its abandonment by relief inversion. The Intermediate weathering profile comprises a 10 to 50 m thick saprolite horizon, a carapace (that can be more than 10 m thick) and a topping duricrust (5-10 m thick for type 1 and 2-5 m thick for type 2 geomorphological occurrences).

Relics of the Intermediate paleolandsurface are mapped as 3 landform-regolith associations. The first one (*2InD*) is the original duricrust-capped landsurface. The duricrust found on type 1 relics is an Al-Fe duricrust, often dismantled into meter-size blocks (Fig. 8a). This duricrust consists of a mix of Fe oxyhydroxides hosting Al-Fe rich relicts(Fig. 8b) or a pack of nodules / pisoliths(Fig. 8c) recalling that of the Fe bauxites (Fig. 7e).The nodular / pisolitic Al-Fe duricrust appears to be the late result of the

167 weathering process that started by the reworking of the massive or breccia-like bauxite
168 into nodular or pisolitic Fe bauxite. Besides, that type of Intermediate Al-Fe duricrust
169 has been shown to derive from the ferruginization of an evolved bauxitic
170 duricrust(Boulangé, 1986). This is further supported, in the present case, by the
171 common occurrences of bauxites embedded in the Al-Fe Intermediate duricrust that
172 have not been completely "digested" by the ferruginization process (Fig. 8d). Therefore,
173 the duricrust covering the type 1 Intermediate ridges could be mistaken for a duricrust
174 of the Bauxitic paleolandsurface without a careful geomorphological investigation. The
175 duricrust capping isolated Intermediate plateaus (type 2) is a dense, dark-violet Fe
176 duricrust (Figs. 8e and 8f). It is formed by the coalescence of Fe oxyhydroxide nodules
177 and tubes, with a coherent interstitial matrix (less than 10% of the volume) made up
178 mostly of Fe oxyhydroxides and kaolinite.
179 The second landform-regolith association related to the Intermediate
180 paleolandsurface (*2InC*) corresponds to type 1 or 2 geomorphic occurrences that
181 expose the carapace layer instead of the duricrust cap. This configuration results from
182 the stripping of the duricrust or its non-development. The carapace (Fig. 9) is
183 characteristically reddish or dark-red and friable and contains goethitic, - and, to a
184 lesser extent, hematitic - concretions 1 to 30 cm in size. The concretions are
185 pedorelictual and are angular, sub-angular, nodular, tubular or platy; others are cutanes.
186 Concretions are dark-violet and some preserve bedrock fabrics. The carapace matrix is
187 a pulverulent ochre-orange mix of clays and Fe oxyhydroxide nodules (Fig. 9). The
188 carapace with low matrix content (Fig. 9b) should not be mistaken for the nodular
189 Intermediate Fe duricrust (Fig. 8e) or that hosting scattered heterometric nodules (Fig.
190 9c) for a conglomeratic duricrust (see section 3. 2).

191 The third and last landform-regolith association related to the Intermediate
192 paleolandsurface (*2InR*) results from the erosion / collapse of type 1 or 2 landscape
193 relics and concomitant dismantling of their topping duricrust. The typical result is a
194 residual hill covered with dispersed blocks or gravel of Intermediate duricrust. The
195 saprolite and/or carapace layers of the weathering profile can crop out on the slopes or
196 the crestal region of the residual hill.
197
198 ***3. 2.Paleo-glacis systems***
199 Relics of the High and Middle glacis systems are preeminent in the landscape, as it is
200 the case throughout West Africa and particularly on granite-greenstone terrains
201 (e.g.,Grimaud et al., 2015). These systems used to form the piedmonts of the massifs
202 preserving relics of the upper paleolandsurfaces (Figs. 4 and 5).
203
204 *3. 2. 1. Geomorphology*
205 High glacis relics are inclined (4% mean slope) and very slightly concave plateaus (Figs.
206 10a to 10c), with upslope and downslope heights of 10-40 m and 5-15 m, respectively.
207 They have a downslope width ranging from 50 to 700 m and rarely exceed 1km in
208 across-slope length. Relics are not connected to the massifs anymore for a peripheral
209 hollow (Fig. 5) formed after abandonment of the High Glacis. The duricrust capping the
210 High glacis is a 2 to 4 m thick Fe duricrust that marks the edge (scarp) of plateaus and
211 tops a weathering profile less than 30 m thick (Fig. 11a).
212 Middle glacis relics occupy the largest area of all the duricrust-capped
213 paleolandsurfaces (Fig.4). They have lower slopes (1-3%) than those of the High glacis
214 and form low-lying plateaus (< 5 m high) with downslope widths of up to 2 km

(Fig.10d). The middle glacis may form a continuous surface with the High glacis marked by a very subtle break of slope and (especially) a change in the thickness and nature of the capping duricrust (Fig. 10c). A comparable continuity is also very commonly observed between the Middle glacis and the Low glacis / active pediment (Fig.5). The weathering profile under the middle glacis is thin (<3 m), with a carapace-Fe duricrust layer rarely more than 1 m thick (Fig. 11b). The Fe duricrust forms a scarplet at plateau edges.

3. 2. 2. Landform-regolith associations of the High and Middle glacis systems

The typical landform-regolith association of the High glacis (*3HgD*) is a detrital Fe duricrust formed by cemented clastic material. Two common types are distinguished: (i) coarse conglomeratic (Fig. 11c), preferentially found on upper slopes of the relics and close to the high topographic massifs and (ii) finer-grained (sand-gravel granulometry; Fig. 11d) in distal parts of High glacis (i.e., closer to the main drains at the time the glacis was functional). In the first type, pebbles are angular, sub-angular, or rounded. They are mostly bauxitic and Intermediate duricrusts, vein quartz, transported Fe concretions or, more rarely, bedrock. The matrix is a mix of clay, silt, sand and gravel made of reworked saprolite, duricrust clasts, Fe oxyhydroxide nodules and clasts. In the finer-grained type, the nature of the gravel is comparable to that of the coarse conglomeratic type and the matrix does not exceed the sand granulometry. On initial field observations, the detrital nature of the fine-grained duricrust may be overlooked, with fateful implication as to whether the duricrust material formed in-situ or was transported before cementation. The duricrust-capped landform-regolith association for the Middle glacis (*4MgD*) compares to that of the High glacis (*3HgD*) although the

239 coarse conglomeratic type is found only in the uppermost portions of some glacis relics.
240 The Middle glacis Fe duricrust is detrital and has a gravel – sand granulometry. It has
241 vacuoles and is more porous than that of the High glacis (Figs 11e and 11f).
242 Areas of preserved High or Middle glacis exposing the carapace instead of the
243 duricrust have been ascribed to a distinctive association (*3HgC* and *4MgC*, respectively).
244 The High glacis carapace is scoriaceous and highly porous, light-colored (pinkish to
245 yellowish; Fig. 12). If present, Fe nodules are millimeter or centimeter in size and
246 bedrock structures can persist in the carapace, by contrast with the Intermediate
247 carapace. The carapace of the Middle glacis compares to that of the High glacis but Fe
248 concretions are scarce and most of the time invisible macroscopically. In absence of
249 bedrock structures, whether the glacis carapace was formed by weathering of the
250 underlying bedrock is difficult to assess. It may derive from cementation of fine-grained
251 detrital material.
252 Areas of preserved High or Middle glacis exposing the Intermediate carapace
253 layer are not uncommon and have been ascribed specific associations (*3HgOc* and
254 *4MgOc*, respectively). These associations show that the lower parts of the intermediate
255 landscape have been only very weakly eroded by the High and Middle glacis, which
256 removed the Intermediate duricrust without stripping the rest of the underlying
257 Intermediate profile. Although they correspond to glacis surfaces, these associations
258 result from weathering of the underlying bedrock.
259 Finally, similarly to the Intermediate paleolandsurface, some glacis plateaus have
260 been partly eroded, leaving residual hills that are covered with scattered blocks of the
261 original duricrust. These blocks directly overly the carapace, mottled clay or saprolite
262 horizon of the weathering profile. The residual hills correspond to associations*3HgR*

and *4MgR*, for the High and Middle glacis, respectively. These associations are ambiguous as to whether they represent bedrock weathered in situ or transported material. Indeed, exhumed horizons of the weathering profile may still be fine-grained clayey to sandy detrital sediments.

3. 2. 3. Low Glacis system (5LgD)

A specificity of the Low glacis system is that is has remained functional in the area in the form of a regional active pediment. It is why its geomorphology and regolith shall be described in detail in section 3.4. It is however worth mentioning here that upslope portions of the Low glacis are in many locations connected to lower portions of the Middle glacis to form a single surface as a result of polygenic evolution (e.g., Figs. 4 and 5). Also, along portions of some streams, the sedimentary cover of the glacis is locally removed so that the roof of the Low glacis Fe duricrust (*5LgD*) is exposed. The map areal extend of that association is therefore very limited. But it may underlay the sedimentary blanket of the active pediment over significant areas, at least along major drains. The Low glacis Fe duricrust is detrital and mostly conglomeratic, generally thin (<0.5 m) and weakly cemented compared to that of the Middle glacis. More generally in West Africa, the Low glacis may beat best capped by a carapace or may not even be indurated at all (Grandin, 1976).

3. 3. Erosional reliefs (Br, Sa, Wp, LtS)

A considerable portion of the reliefs is not protected by a duricrust and is currently undergoing erosion. That erosion contributes to further exhume bedrock and

286 weathering profile material that constitute detrital sediments feeding the active
287 pediment. Erosional terrains group 4 landform-regolith associations.
288 The first association (*Br*, for Bedrock Slope) refers to hilly bedrock terrains that
289 can reach 100 m in height (Fig. 13a). They form massifs elongate in the direction of the
290 dominant NE structural grain of the rocks, with the structural fabric (schistosity) locally
291 expressed as aligned ridges in the high-resolution topography. Massifs of
292 volcanosediments are generally flat-topped, as opposed to hilly for metabasites. Crests
293 of the massifs can bear scattered blocks of Bauxitic or Intermediate duricrust and very
294 rarely remnants of saprolite. Some slopes of the massifs are incised by ravines and
295 gullies partially filled up with bedrock and duricrust clasts.
296 Association *Sa* designates all the erosional terrains exposing a saprolite. By
297 definition, saprolite derives from weathering of the bedrock. It is very fined-grained
298 (clay-silt granulometry), pulverulent, and kaolinite rich. The saprolite is generally dark-
299 yellowish to reddish on mafic rocks, often with whitish spots as ghosts of plagioclase
300 crystals. On volcanosediments, it ranges in color from whitish to intense yellow. The
301 saprolite commonly preserves ghosts of the schistosity planes and may enclose
302 oriented platy relics of early ferruginized bedrock.
303 Steep slopes and talus of duricrust-capped plateaus constitute a specific
304 landform-regolith association (*WpS* for Weathering Profile Slope). These slopes have
305 exhumed various layers of weathering profiles (saprolite, mottled clay, carapace) that
306 are often covered by screes of duricrust (Figs. 13b to 13d). The slopes are vegetated to
307 various degrees as stream reappearances are common under the duricrust at the edge
308 of plateaus. Badlands are common in these terrains (Figs.13d), providing direct access
309 to the weathering profile in incisions. Importantly, these terrains provide the only

310 access to weathering profiles underneath detrital Fe duricrusts of the High and Middle
311 glacis.
312 The last association of erosional terrains is that of lithosoils (*LtS)*. It consists of
313 hilly terrains with in a thin (<50 cm) unconsolidated layer resting atop the bedrock. This
314 layer derives from the disaggregation of the bedrock and is mostly made of the
315 underlying bedrock clasts, ranging in size from silt to gravel (Figs. 13e and 13f). This
316 association generally occupies smooth reliefs at the foot of the main topographic
317 massifs and above the active pediment (Fig.4). These terrains are generally grass-
318 covered and therefore provide less sediment to the active pediment than the other
319 erosional terrains. Lithosoils are dark-grey on mafic rocks and propitious for agriculture.
320 They are generally lightly ochre on volcanosediments (Figs. 13e and 13f).
321
322 ***3. 4. Active pediment (ApS, ApT, ApF)***
323 The active pediment occupies the largest area. It is a regional surface made of quasi-
324 planar facets connecting the foot of all reliefs to the current main river drains over
325 distances commonly exceeding 10 km (outside the map area of Fig. 4). Its uppermost
326 slopes do not exceed 3 % and its mean slopes are less than 1 %. Over an overwhelming
327 part of its surface, the pediment is covered by a detrital sedimentary layer (association
328 *ApS*, Fig. 14a), which tends to thicken downslope (generally up to several meters in
329 thickness, except near the main river drains where channels more than 10-m deep can
330 be filled-up by sediments). The sedimentary layer – at least its uppermost surface – is
331 reworked at each rainy season and may therefore be considered as transiting on the
332 pediment. Coarse material exposed at the surface of the pediment mostly consists of
333 debris of Al-Fe and Fe duricrust, Fe nodules (Fig. 14b) and vein quartz (more rarely

bedrock), large pebbles being restricted to uppermost slopes near reliefs. There, conglomerates can locally be weakly cemented by Fe oxyhydroxides (Fig. 14c). Downslope, the pediment surface has two main lithologies: a light-colored mix of clay, silt and sand, deriving from weathering profiles (Fig. 14a) or a pellicular ferruginous gravel resting on that same light-colored material (Fig. 14b). Sections exposed in stream cuts show that alluvial gravel layer(s) underlay the fine-grained material (Figs. 14d and 14e), bearing in mind that the Low glacis detrital Fe duricrust may floor the sedimentary cover over significant areas. Weathering of the sedimentary cover is attested at depth by the development of smectite (greenish staining, Figs. 14d and 14e) or carbonate nodulation (white spots). Importantly, the fine-grained sedimentary cover of the active pediment should not be mistaken for a saprolite preserved on its bedrock.

At various locations on the active pediment, stream channels are filled-up along some of their portions by sediments (mostly fine-grained), forming alluvial terraces that may not maintain for more than a few rainy seasons. Although an integral part of the active pediment surface, these sedimentary infillings are distinct and ascribed a specific landform-regolith association (*ApT* for Active pediment Terrace).

Several alluvial fans fed by the badlands on sides of the reliefs have been mapped and are attributed to a landform-regolith association (*ApF*). These fans constitute transient piedmont accumulations of mostly fine-grained sediments (essentially reworked saprolite) and duricrust pebbles that will ultimately make their way on the active pediment surface. The fans can locally reach 10 m in thickness. They are often exploited for placer gold.

4. Terrain classification, implications for mineral exploration

4. 1. Lateritic residuum with potential supergene enrichment

That category of regolith comprises the associations related to the upper paleolandsurfaces and the upper part of their weathering profile preserved by the paleo-glacis (blue on Fig. 15). These associations expose the carapace horizon (*2InC, 2InR, 3HgOc*, *4MgOc)* or the duricrust (*1BxD, 2InD*) topping a thick weathering profile resulting from protracted (>20 My) periods of intense weathering(Valeton, 1991; Beauvais and Chardon, 2013). They may therefore host anomalies forming typical mushroom-shaped halos rooted in the bedrock (e.g., Freyssinet et al., 2005; Fig. 16b).These terrains are therefore suitable for geochemical sampling. However, elements known to be mobile in supergene environments such as As, Ag, Zn, Cu, Ni, Co or U (e.g., Tardy, 1997)would be preferentially leached in the residuum (mottled clay, carapace and duricrust) of the weathering profile (these elements could still be anomalous at low concentrations, possibly reflecting an underlying mineralization). Conversely, the residuum is more likely to concentrate non-mobile metals (e.g., Al, Zr, Ti, Sb, W) than the underlying saprolite because it has undergone volume loss and because these elements are typically hosted by minerals such as quartz, zircon, rutile or anatase that can survive most intense weathering (e.g., Valeton, 1994; Freyssinet et al., 2005; Salama et al., 2020).

Weathering profiles of the upper paleolandsurfaces are known for their supergene mineral deposits in Al, Fe and Mn (e.g., Grandin, 1976; Valeton, 1994). Upper paleolandsurface remnants are preserved mostly on greenstone belts and dolerites sills, which host most known primary bedrock concentrations in West Africa (e.g., Au, Zn, Pb, Cu, Ni; Milési et al., 1992). The potential for supergene concentration in these weathering profiles is therefore high, but still largely unexplored. Of particular interest

382 are metals such as Ti, Zr, V, Nb, Cr, Sn, W, Th, Hf and rare earth elements (Boulangé,
383 1984; Braun et al., 1993; Tardy, 1997; Butt et al., 2000; Sidibé and Yalcin, 2019) that
384 would be pre-concentrated in the bedrock.
385
386 ***4. 2. In-situ regolith and bedrock***
387 This category groups erosional terrains (*Br, Sa, Wp, LtS*; Figs. 15) etched down to the
388 bedrock or covered with unconsolidated regolith that is connected to the geological
389 substrate from which it derives (green on Fig. 15). They are mostly restricted to the
390 slopes and interfluves of the main topographic massifs. They are suitable for
391 geochemical sampling because they should express anomalies connected with the
392 bedrock. Identification and mapping of these terrains become crucial away from the
393 main topographic massifs because they represent the only access to in-situ regolith in
394 the low land. In these low land contexts, they are found only on the sides of paleo-
395 glacis relict plateaus (*Sa, WtS*; Figs. 4 and 15). Low-lying composite paleo-pediment
396 landscapes being the norm rather than the exception in West Africa (Chardon et al.,
397 2018), particular attention should be given to this landform-regolith category.
398 Dispersion halos are generally narrow or nearly absent in the saprolite or the bedrock
399 (Freyssinet et al., 2005; Bamba, 2009; Anand and Butt, 2010; See Fig; 16), which form an
400 overwhelming part of these landform-regolith associations. This therefore requires a
401 dense sampling grid - typically 50 m - to make sure a mineralization is not missed.
402
403 ***4. 3. Transported regolith***
404 *4. 3. 1. Exploration challenges*

405 This category comprises the detrital Fe duricrusts of the paleo-glacis (*3HgD, 4MgD*) and
406 the sedimentary cover of the active pediment (*ApS, ApF, ApT*). That domain represents
407 by far the widest and most continuous of the study area (Red on Fig. 15). It is also the
408 case over most of Central and Northern Burkina Faso and more generally over the
409 northern Soudanian zone and the Sahelian zone (Fig. 2). This category of regolith
410 masks the weathering profile and the bedrock. This means that mineral deposits may
411 be hidden under these covers (Fig. 16a). Mineralized material can be transported on the
412 pediment or the paleo-glacis, part of that material being trapped in the pediment
413 sedimentary cover (loose or duricrusted) to form a "transported" anomaly (e.g., Fig.16d
414 and 16e). Upward gaseous transfers and insect or plant root activity can bring
415 mineralized material to the surface of the sedimentary cover(Anand et al., 2016; Salama
416 et al., 2016). But the expression of an anomalous halo rooted in the bedrock through a
417 duricrusted pediment sedimentary cover, although possible, is unlikely.
418 Transported regolith can host secondary metal concentration such as alluvial
419 placers, as exemplified by gold on active pediments in Burkina Faso(Ouangrawa et al.,
420 2000; Bamba, 2010). Paleo placers should be considered in the detrital Fe duricrust of
421 the paleo-glacis (*3HgD, 4MgD*). Besides, gold and base metal deposits have been
422 discovered in detrital duricrusts in other lateritic environments (Anand et al., 2019;
423 Salama et al., 2019). Solute transport of metals (e.g. Cu, Mg, U, Ni, Au, REE; Boulangé
424 and Colin, 1994; Sillitoe, 2005; Reich and Vasconcelos, 2015; Xueqiu et al., 2016) down
425 the slope of pediments can also lead to exotic deposits, mostly in pediment
426 sedimentary cover. These deposits would produce dispersion halos comparable to
427 those formed by mechanical transport on pediments (e.g., Fig.16d and 16e).
428

4. 3. 2. Sampling strategy

Classical soil sampling at 40-50 cm depth would most likely not attain the in-situ regolith, as the transported cover is systematically thicker. By definition, paleo-glacis duricrusts, which are all detrital, are not suitable for aiming at the regolith sitting on its parental bedrock. Sampling leaves or the bark of deeply rooted trees such as Acacia or Eucalyptus or termite mounds would be recommended (e.g., Gleeson and Poulin, 1989; Anand et al., 2014; Salama et al., 2016; Arhin et al., 2018). But systematic sampling by aircore or auger is the most appropriate to attain the saprolite underlying the transported cover. In doing so, the orientation and spacing out of the boreholes should be adapted to the potential width of the prospected mineralized bodies as the dispersion halo may be narrow or even absent in the saprolite (Fig.16). Typically, narrow (<20 m) Au-bearing quartz dikes or REE-mineralized pegmatite dikes would easily be missed if samples are more than 100 m apart. In such a case a 50-m spacing would be required. Aircore or auger sampling of the saprolite requires rigorous description of the material drilled before reaching the saprolite, as well as diagnostic identification criteria of the saprolite itself (heterogeneity, texture, occurrence of pedorelics, lithorelics, lithostructures or relict minerals, see description of association *Sa*, section 3.3). These tests should help prevent mistaking the saprolite seating on its parental bedrock for fine-grained transported material. Once the in-situ character of the regolith is attested, one should favor sampling of residuum material instead of saprolite (see section 4.1).

4. 3. 3. Mechanical dispersion on glacis / pediment and "transported" anomalies

Paleo-glacis relics and active pediments are not necessarily obstacles to exploration. They can also keep tracks of a mineralization exhumed in their upslope geomorphic

environment. Indeed, glacis / pediments are erosional and transportation slopes. Their detrital overburden therefore can bear erosional products of mineralized bodies and even placers (Fig. 16). Mechanical dispersion of these products on glacis / pediments should produce very wide halo stretched down slope, over hundreds of meters to several kilometers (Sanfo et al., 1993; Parisot et al., 1995; Ouangrawa et al., 1996, 2000; Bamba, 2009, 2010). Identification of such anomalies on the active pediment may be used to track its primary (endogenous) source upslope thanks to a topographic map at the appropriate resolution. The same approach may be used on paleo-glacis systems, providing the landscape at the time the considered glacis was functional is reconstituted(Chardon et al., 2018).

4. 4. Other regolith

The last category groups Paleo-glacis relicts exposing their carapace layer (*3HgC, 4MgC*) and the residual hills of paleo-glacis systems (*3HgR, 4MgR*) that also generally expose the carapace (orange on Fig. 15). That category has the smallest areal extent. In this category, determination of the in-situ or transported character of the regolith is not straightforward. Indeed, a glacis carapace formed by the weathering of a fine-grained transported cover may not be distinguished from one that evolved from saprolite resting on its parental bedrock. Caution is therefore required in sampling and interpreting surface geochemical results, as such material can display an anomaly rooted in the bedrock, a transported anomaly or can mask a bedrock anomaly. Only auger or aircore drilling of the deep regolith proved to seat on its bedrock can avoid errors in interpreting the geochemistry. The same care should apply to the description

476 of the drilled material down to the bedrock as in the case of the transported regolith
477 (section 4.3.2).
478
479 **5. Exploring for the lateral extension of an existing ore body**
480 The prospectivity map (Fig. 15) may be used to look for the suspected continuity of a
481 steep planar ore body. In the present case, the NE trend of steeply dipping mineralized
482 structures is outlined by the pattern of artisanal pits aligned on the structures (Fig. 15).
483 The pits are restricted to the green domain (in situ regolith and bedrock; Fig. 15), as
484 access to the mineralization is facilitated there by the absence of duricrust and partial
485 or complete ablation of the in-situ regolith. Linear extrapolation of the mineralized
486 trends will allow identifying the categories of regolith susceptible to overly a lateral
487 extension of the mineralization. Given the expected behavior of a deeply rooted
488 anomaly upward through each category of regolith (Fig. 16), one can check whether a
489 lateral extension of the mineralization is expressed in the regolith. Outside the green
490 domain (in situ regolith and bedrock; Fig. 15), an extension would typically not be
491 noticed by surface sampling in the red domain (transported regolith) and potentially
492 the orange domain (other regolith) (Fig. 15). In the green domain, soil sampling on the
493 extrapolated structural trend would be sufficient. In the red and orange domains,
494 trenches across the extrapolated trend, auger drilling or inclined aircore drilling would
495 be needed to attain the regolith preserved on its parental bedrock. That approach
496 should be complemented by sampling of the weathering profile exposed on the talus
497 of paleo-glacis relict plateaus (*Wp*; Fig. 4, green in Fig. 15) along the extrapolated trace
498 of the mineralization. Finally, the potential intersection of a mineralized trend with a
499 blue domain (lateritic residuum; Fig. 15) would lead to suspect an enrichment in the

500 residuum in that domain if the considered element is non-mobile in the supergene
501 environment.
502
503 **6. Concluding remarks**
504 In this paper we have proposed a landform-regolith mapping protocol adapted to the
505 West African morphoclimatic context. That protocol particularly takes into account the
506 detrital nature of the Fe duricrusts capping the ubiquitous relics of the paleo-pediment
507 systems and considers the detrital sediments covering the functional pediment that
508 may be mistaken for weathering material preserved in-situ. The landform-regolith
509 mapping chart is declined into a prospectivity chart, which is used to recommend
510 adapted exploration strategies. The mapping protocol further allows for the definition
511 of exploration guides for supergene mineral concentrations.
512 The mapping chart is pertinent for greenstone terrains of the Soudanian and
513 Sahelian morphoclimatic zones (typically savanna environment and drier; Fig. 1). It can
514 also be applied to the vast low-relief areas of composite paleo-glacis landscapes
515 lacking relics of the upper paleo land surfaces, which encompasses the various
516 geological substrates of the sub region. In wetter (southern) West Africa (Guinean and
517 Forest zones, Fig. 1), the Low glacis did not develop. Field reconnaissance indicates that
518 away from topographic massifs having kept tracks of the upper paleo land surfaces, the
519 Middle glacis is rarely duricrusted. It is capped by a carapace or, more commonly, it is
520 not weathered beyond the mottled clay stage. In these terrains, a careful study of
521 landforms and associated regolith should lead to the recognition / use of the
522 associations defined in the present work.

The ubiquity of paleo- and active lateritic pediments in West Africa where Fe duricrusts had all long been considered as residual by exploration geologists urges reevaluation of landform-regolith mapping practices, dispersion models and exploration strategies. The mapping protocol developed for the West African context may prove useful elsewhere on the African continent and more generally on other tropical shields of the world. If, as in West Africa, lateritic pediments may have been overlooked in other shield terrains of the world, the renewal of the methods to access bedrock resources would be required, because they may still be underestimated.

Acknowledgments

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Figure captions

Figure 1. Synthetic representation of the West African morpho-climatic sequence of duricrusted lateritic paleolandsurfaces(after Chardon et al., 2018). Abandonment ages of the paleolandsurfaces are after Beauvais et al.(2008)and Beauvais and Chardon (2013).

Figure 2. Climatic zonation of West Africa with location of the study area in the southern West African craton.

Figure 3. Geology and topography of the study area with the main field stations, itineraries and the artisanal mining pits (1 m contour topography, UTM , zone 30N, WGS84).

Figure 4. Landform-regolith map and chart.The contours are 1 m. Associations 3HgOc, 4MgOc and ApT are documented in the wider study area but not on that specific map extract.

Figure 5. Synthetic cross-section showing the main landform-regolith associations in their geomorphic context. The line of section is located on the map of Figure 4. Only the geomorphological type 1 of the Intermediate paleolandsurface occurs on that cross-section.

Figure 6. Geomorphology of upper paleolandsurfaces. (a) Bauxitic plateau. The plateau is 2-km-wide and 130 m high. (b) Ridges of the Intermediate paleolandsurface 50 m under a bauxitic plateau (type 1 geomorphic occurrence). Dry grass-covered upslope portion of the active pediment in the foreground. (c) Plateaus of the Intermediate paleolandsurface (type 2 occurrences; height 60 m). The lowland consists in the active pediment.

Figure 7. Main petrographic types of duricrustscapping the bauxitic paleolandsurface (*1BxD*). (a)-(b) Heterogeneous breccia-like bauxite. (c) Massive bauxite. (d) Massive bauxite preserving pedorelics of pinkish saprolite. (e) Nodular Fe bauxite. (f) PisoliticFe bauxite (pisoliths have dark nucleus and violet cortexes). Geological substrates are volcanosediments for (a)-(c) andmetabasic rocks for (d)-(f).

Figure 8. Main types of Intermediate duricrust (*2InD*). (a)-(d) are Al-Fe duricrustsfrom ridges flanking bauxitic plateaus (geomorphic type 1); (e) and (f) are Fe duricruststypical of isolated plateaus (geomorphic type 2). (a) Dismantledduricrust. (b) Heterogeneous type with relict white / yellowish Al-Fe patches in dark-violet Fe-rich medium (mostly Fe oxyhydroxides and kaolinite). (c) Nodular to proto-pisolitic (yellowish nodules cortexes are made of clay minerals, mostly kaolinite). (d) Bauxitic duricrust relic (white) partly "digested" in an Intermediate Al-Fe duricrust (dark). (e) ConcretionalFe duricrust made of coalescent nodules (dark-violet on fresh cut). (f) Dark-violet Fe duricrust with tubular voids filled with a mix of clay minerals and Fe oxyhydroxides. (e) and (f) are essentially of the same type, and may hostclayey pedorelics.

Figure 9. Main types of carapace of the Intermediate weathering profile. (a) Nodular, with abundant matrix. (b) Packed nodular (i.e., with less abundant matrix). (c) Conglomerate-like, with abundant angular and sub-angular nodules and concretions. This type generally occurs right under the duricrust horizon in the weathering profile (nodule-rich layer forming the "root" of the duricrust).

Figure 10. Geomorphology of paleopediment systems. (a) High glacis forming the piedmont of a bauxitic plateau. (b) Stepped relics of the High and Middle glacis on the piedmont of a bauxitic plateau (background). (c) Composite (polygenic) glacis relic made of the High glacis (upslope) and the Middle Glacis (downslope) (maximum height of plateau: 25 m). One notes a difference in the thickness of the duricrust between the High and the Middle glacis. The break of slope between the two glacis systems is rarely detectable in the field but is visible on high-resolution topography. (d) Low-lying relics of the Middle glacis (a few meters high). The plateau relic in the foreground is capped by a Fe duricrust forming a scarplet. That in the background has become residual hills topped only the carapace layer (the duricrust has been eroded away). This corresponds to the *4MgR* association (Fig. 4).

Figure 11. Regolith types of the paleo-pediment systems. (a) Upper weathering profile of the High glacis (on volcanosedimentary substrate). S: saprolite horizon, MC: mottled clay horizon, C: Carapace horizon, D: Fe duricrust. (b) Carapaceand topping duricrust of the Middle glacis. The duricrust is a cemented conglomerate made of gravel- and cobble-sized pebbles. (c) Conglomeratic Fe duricrust of the High glacis formed by debris flow. Light-colored cobbles are bauxites and dark ones are Intermediate Fe

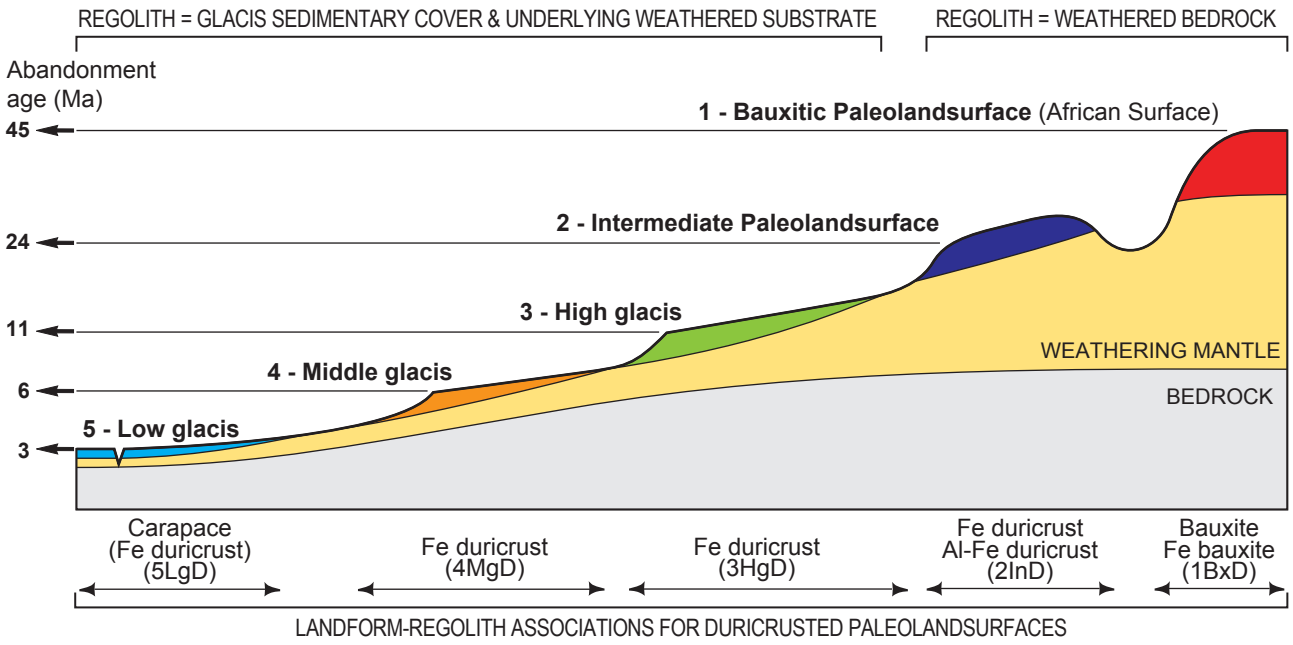
732 duricrust; the matrix is made of gravel-sized Fe oxyhydroxide nodules and clasts. (d)
733 Detrital Fe duricrust of the High glacis, typical of the lowermost portions of glacis relics.
734 Pebbles are mostly bauxite clasts (light colored) and Fe oxyhydroxide nodules. The
735 matrix is made of a mix of clay minerals and Fe oxyhydroxides (orange color) as well as
736 Fe oxyhydroxide-rich patches. (e) Detrital Fe duricrust of the Middle glacis comparable
737 to (d) except for the occurrence of vacuoles, a higher porosity and a higher quartz
738 content. (f) Gravel-sized conglomeratic Fe duricrust of the Middle glacis with a
739 dominant vacuole-rich clayey matrix.
740
741 **Figure 12**. (a) Typical sandy vacuolar carapace of the High glacis. Before exposure,
742 voids were filled with a loose clayey mix of clay minerals and Fe oxyhydroxides. (b) High
743 glacis carapace with preserved bedrock structure, resulting from iron impregnation in
744 the upper saprolite.
745
746 **Figure 13.**Erosional terrains. (a) Hilly bedrock landscape (metabasic rocks). (b) Saprolite
747 exposed as a result of stripping of the bauxitic paleolandsurface (preserved in the
748 background). (c) Kaolinite (saprolite) exposed in a gully along a steep slope of a
749 bauxitic plateau (note scree blanketing the saprolite to the right). (d) Talus under the
750 edge of a duricrust-capped High glacis plateau (height: 25 m). Ravines and gullies on
751 the talus slope provide access to various horizons of the weathering profile underlying
752 the duricrust. In the foreground: active pediment showing detrital material (reworked
753 saprolite) in transit in ephemeral streams. (e)-(f) Surface aspect of lithosols on
754 metabasicvolcanosedimentary rocks, respectively.
755

Figure 14. Geomorphology and regolith of the active pediment. (a) General view of the pediment surface with two main types of sedimentary cover: gravel (brown) and light-colored clayey -silty material (bauxitic plateaus in the background). (b) Detailed view of the gravel, which consists in a very thin blanket on the clayey-silty material.(c) Weakly cemented debris flow material resting directly on the saprolite horizon of a truncated weathering profile (uppermost portion of the pediment). (d)-(e) Stream cutsthrough the pediment detrital sedimentary cover. (d) Clayey-sandy layer topping a gravel layer. Greenish staining of the gravel layer indicates post-alluvial development of smectite. (e) Two gravel layers topped by clay-sandy material. The lower gravel layer has undergone slight smectitic weathering.

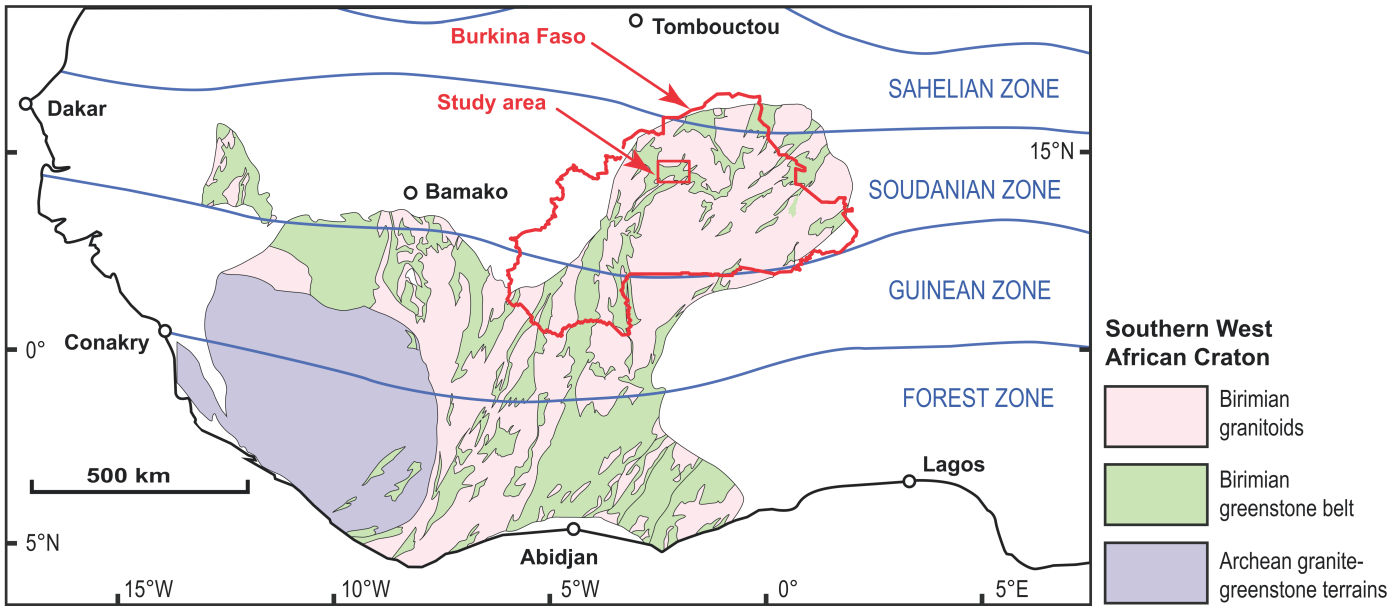
Figure 15. Soil prospectivity map deduced from the landform-regolith map of Figure 4.Compare to Figure 4 to see howeach landform-regolith associations has been assigned to one of the four categories of regolith (see text for further explanation). The mineralized structural trends are based on the alignment of the artisanal mining pits.

Figure 16. Idealized geochemical dispersion halos in West African granite-greenstone terrains. In (a), the mineralization (and its potential halo) is truncated by a glacis/pediment. In (b),the mineralized structure crops out; there is no dispersion halo and therefore little chance to detect the mineralization. In (c), a mushroom-shape halo forms entering the residuum of the weathering profile and an in-situ geochemical anomaly may be detected. In (d) and (e), a dispersion halo forms by mechanical transport of mineralized material in the pediment detrital cover. Transported cover in (a) would essentially be a detrital Fe-duricrust and in (d) and (e) unconsolidated detrital

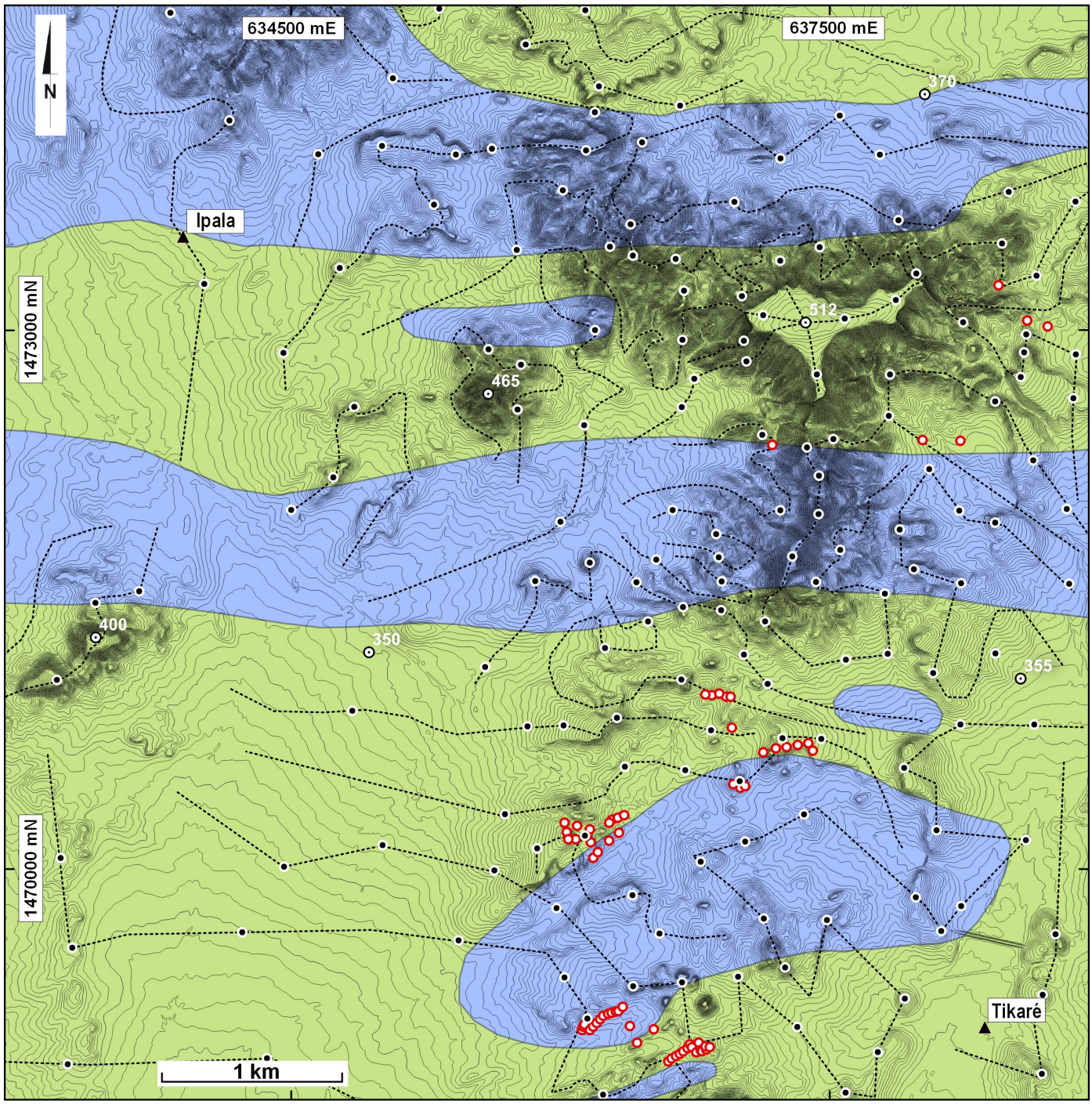
sediments. In (e), the halo may be detected by surface sampling, whereas in (d) it is buried and therefore inaccessible. Situation (a) would typically occur under relics of the High or Middle glacis, situation (c) under relics of the bauxitic and/or Intermediate paleo land surfaces, whereas situations (d) and (e) would be typical of the active pediment, bearing in mind that detrital Fe duricrust-capped paleo-glacis systems can host (d) and (e) types of halo. These types of halo can also form by downslope element transport in solution, on the pediment sedimentary cover.



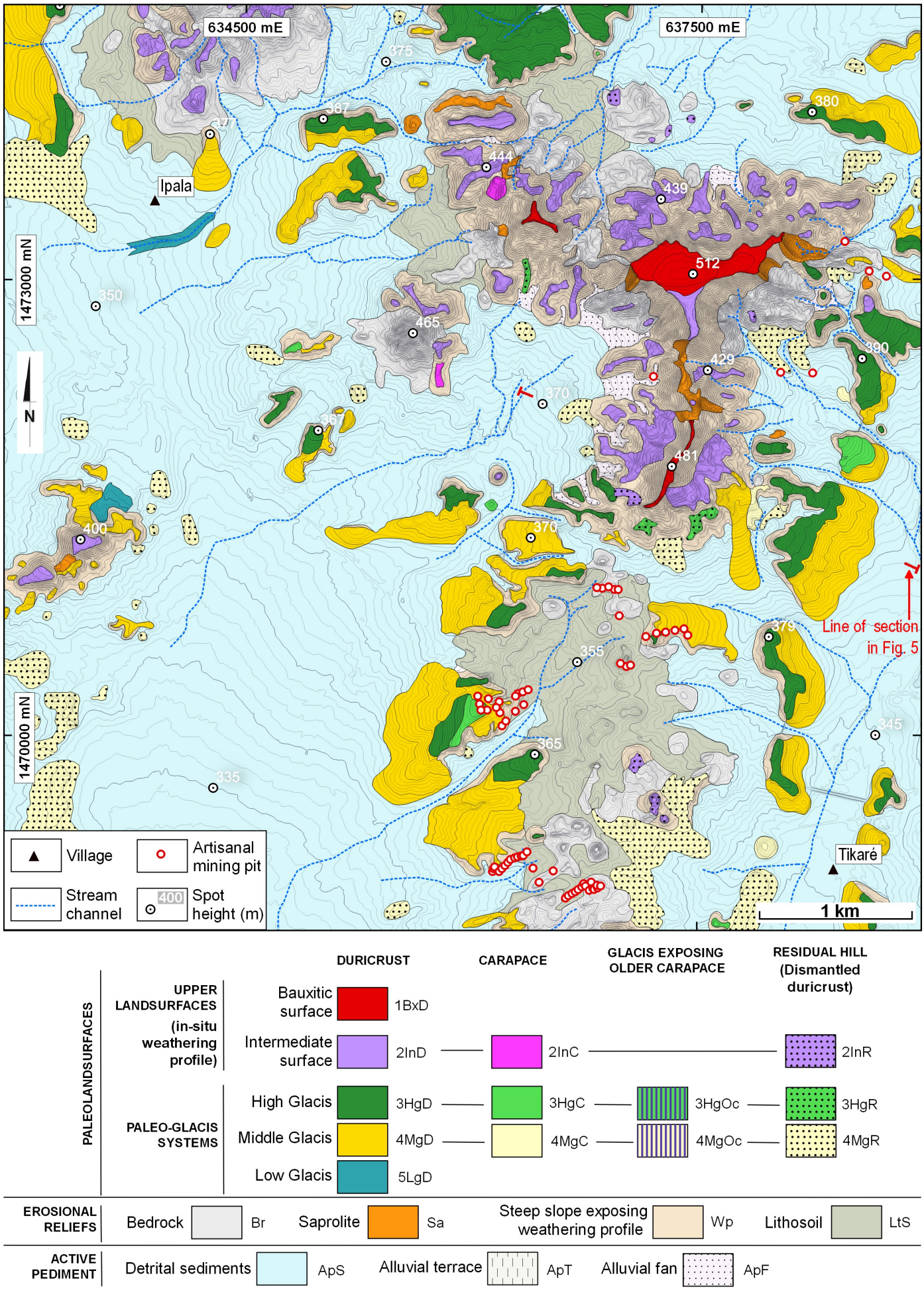
Sawadogo et al. Figure 1



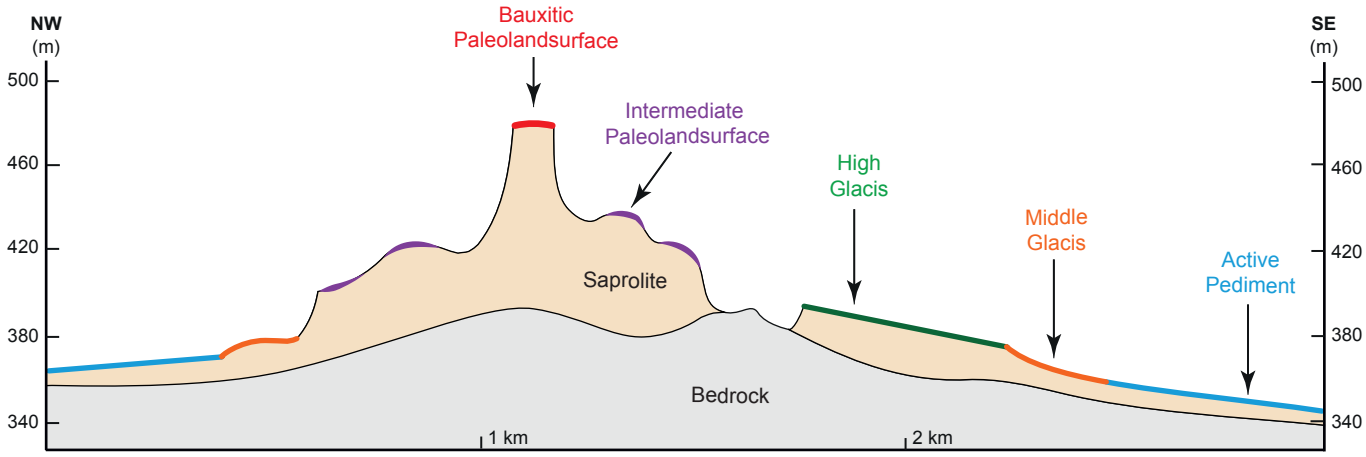
Sawadogo et al. Figure 2



Sawadogo et al. Figure 3

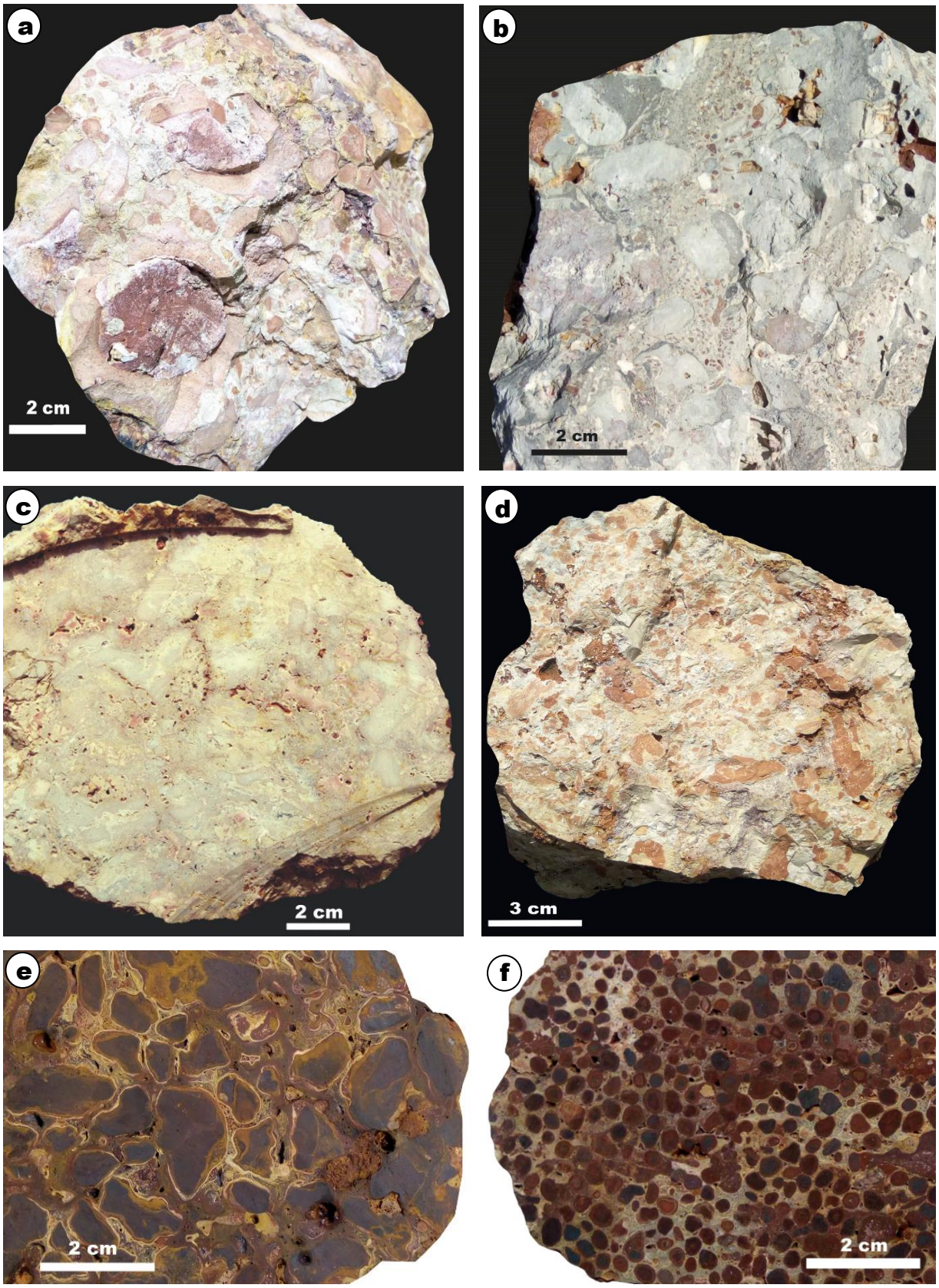


Sawadogo et al. Figure 4

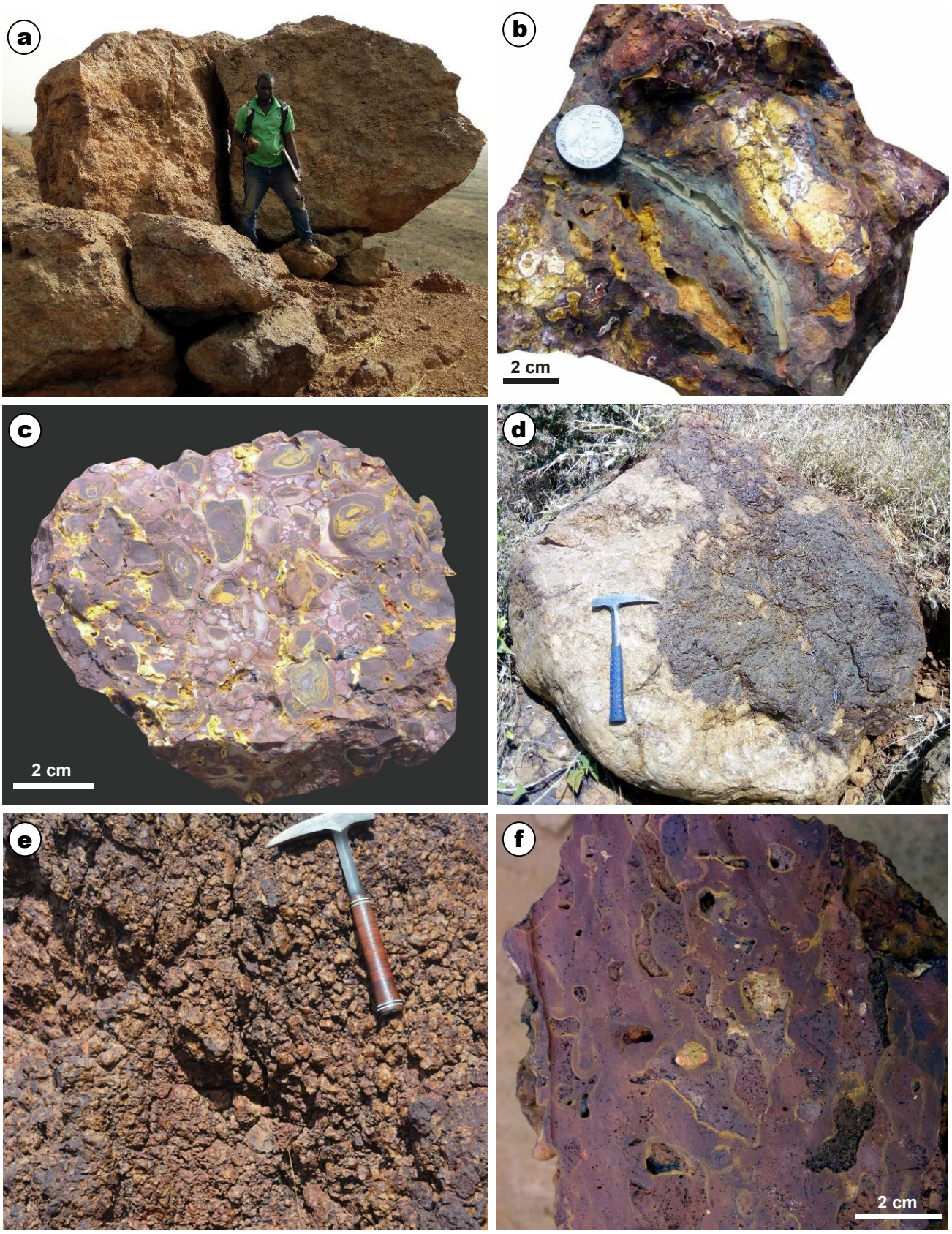


Sawadogo et al. Figure 5

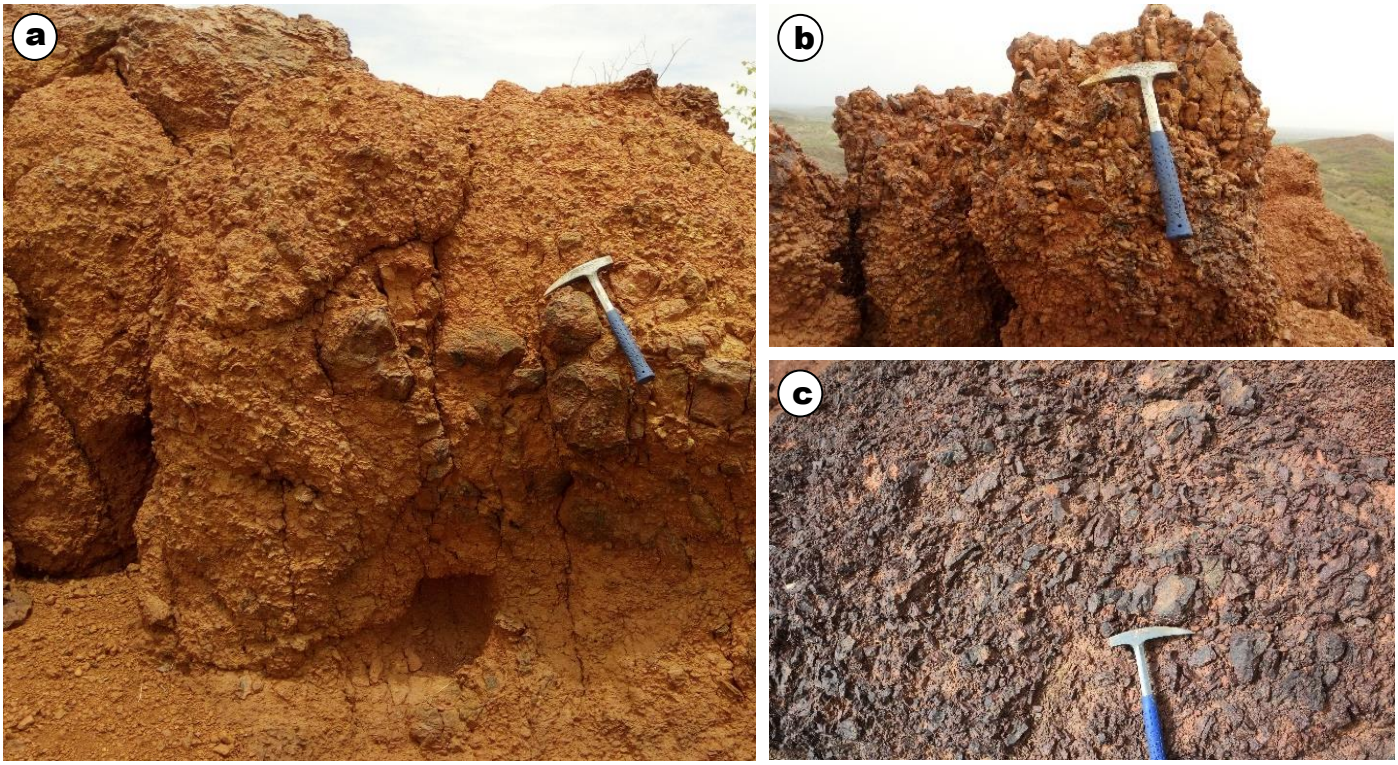
Sawadogo et al. Figure 6



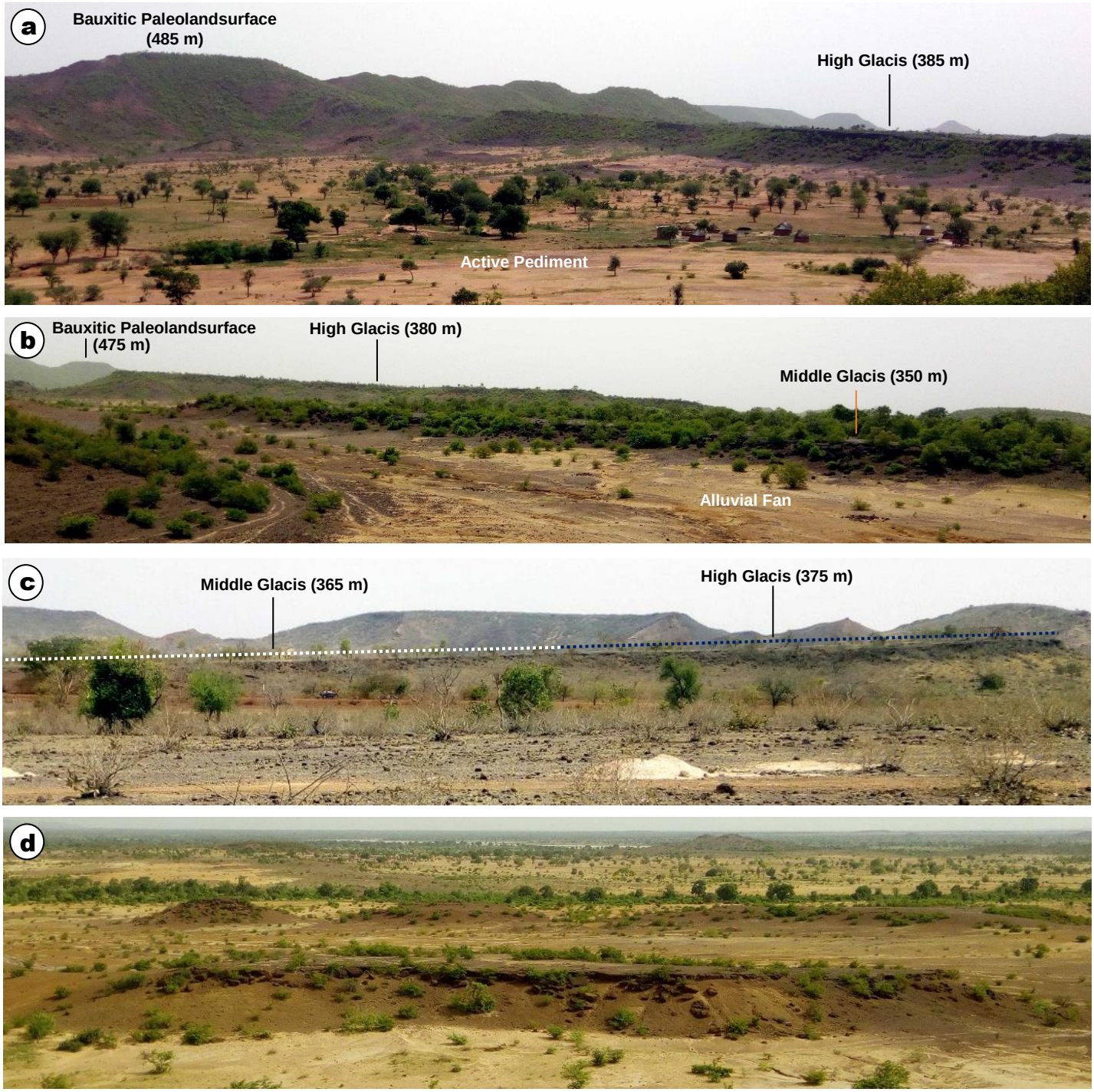
Sawadogo et al. Figure 7



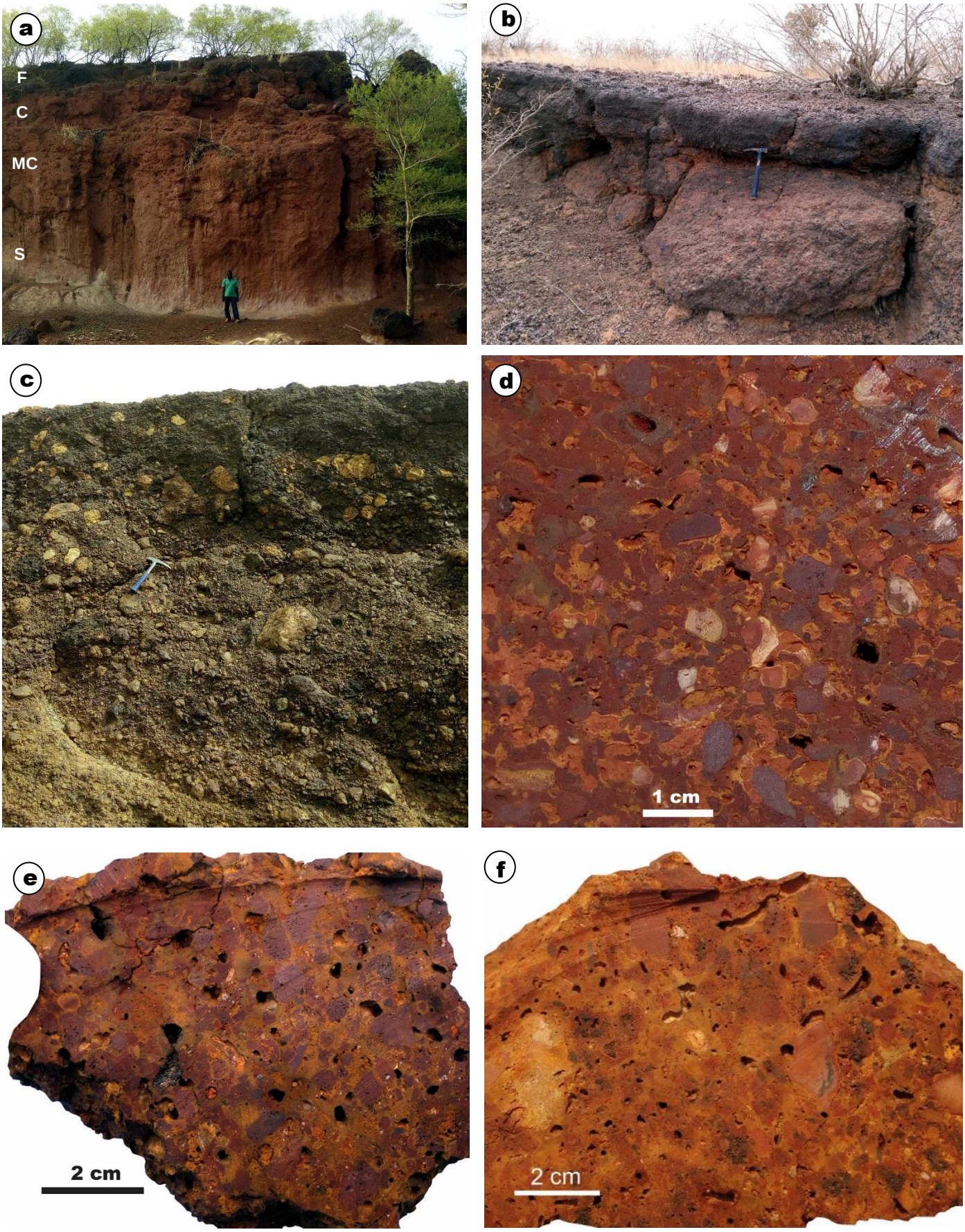
Sawadogo et al. Figure 8



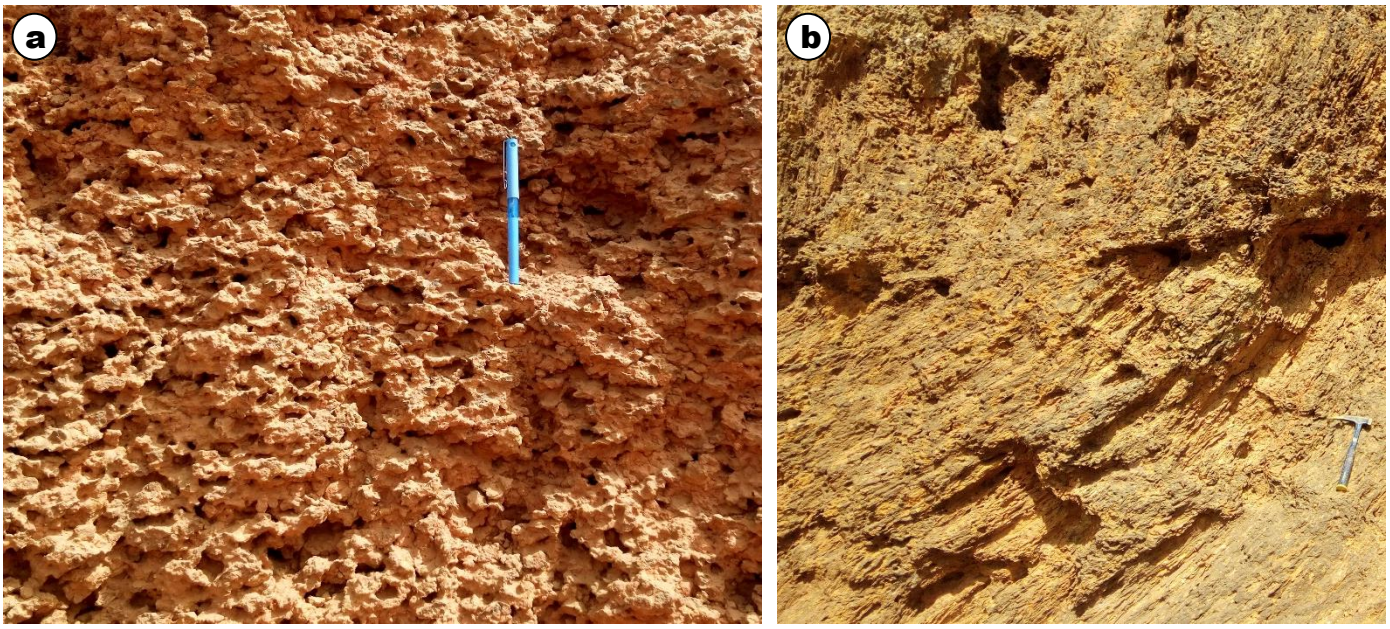
Sawadogo et al. Figure 9



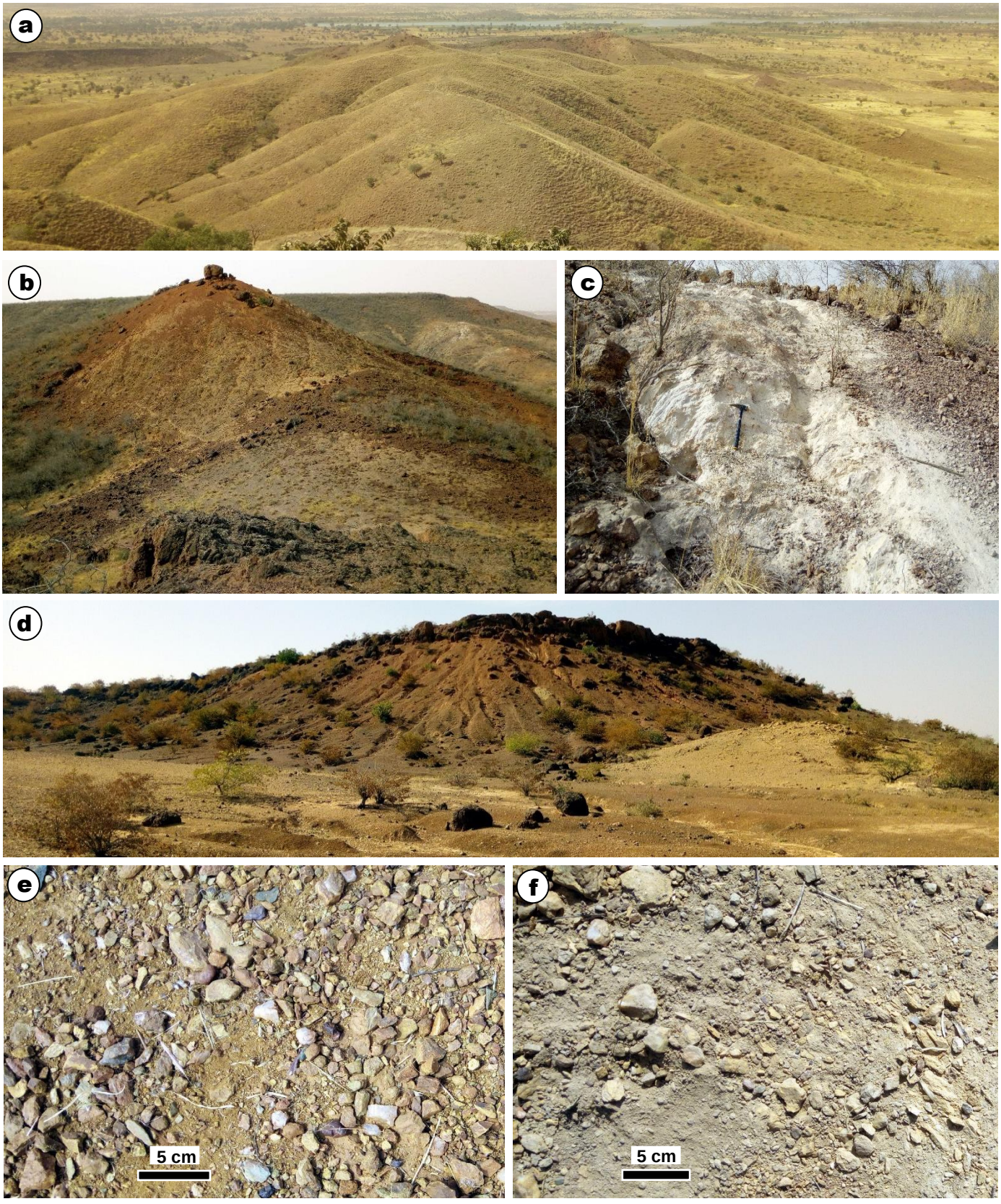
Sawadogo et al. Figure 10



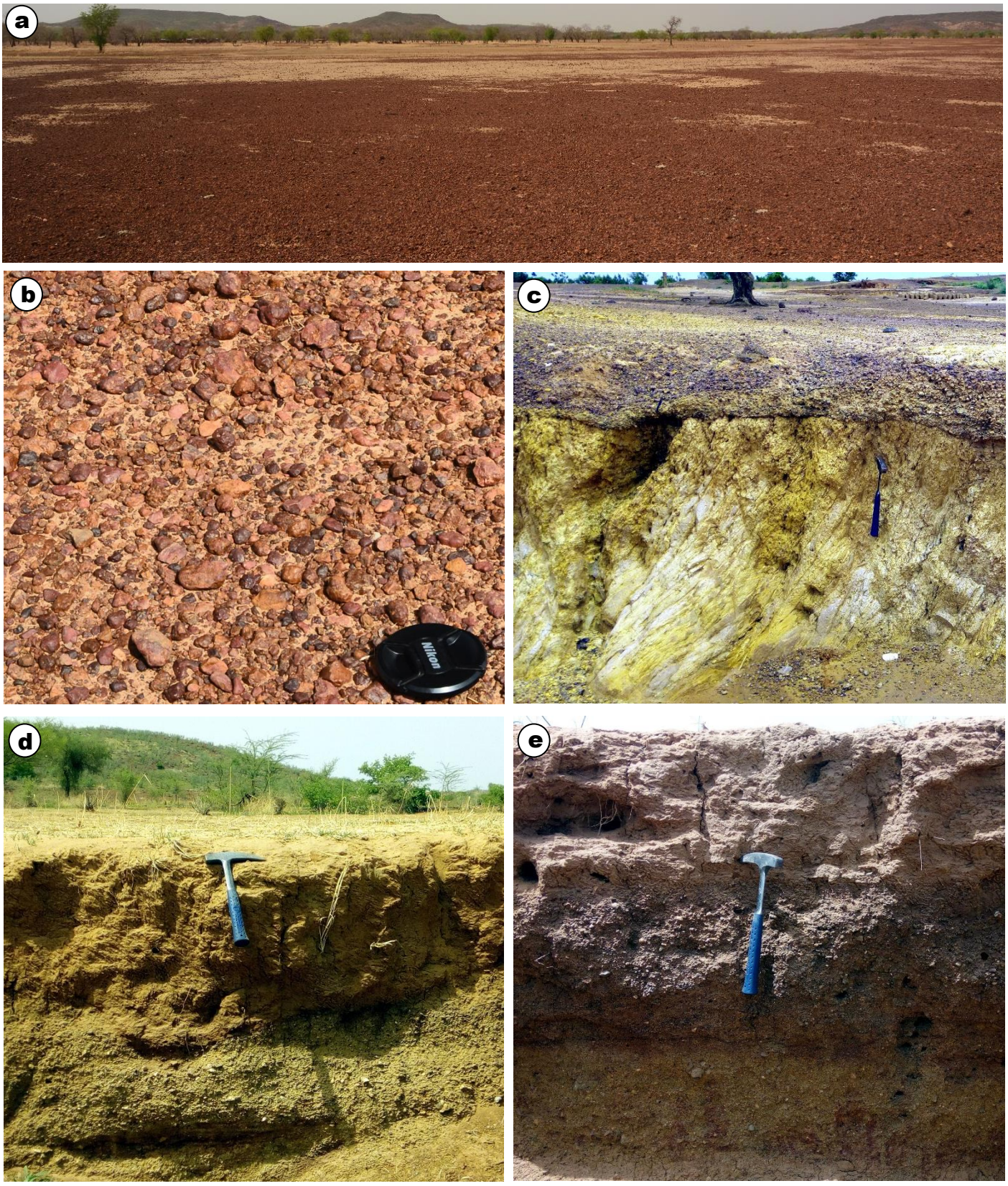
Sawadogo et al. Figure 11



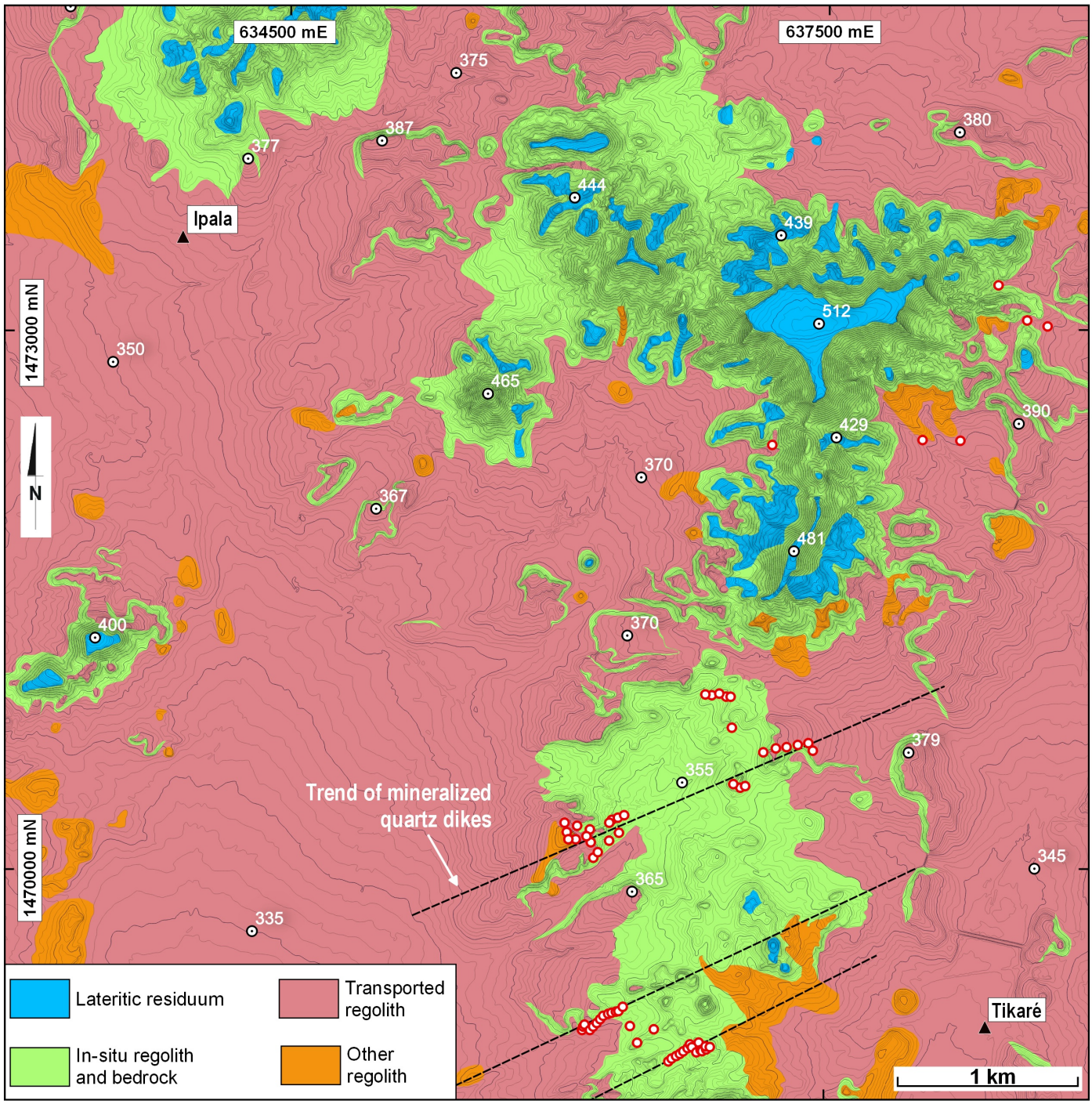
Sawadogo et al. Figure 12



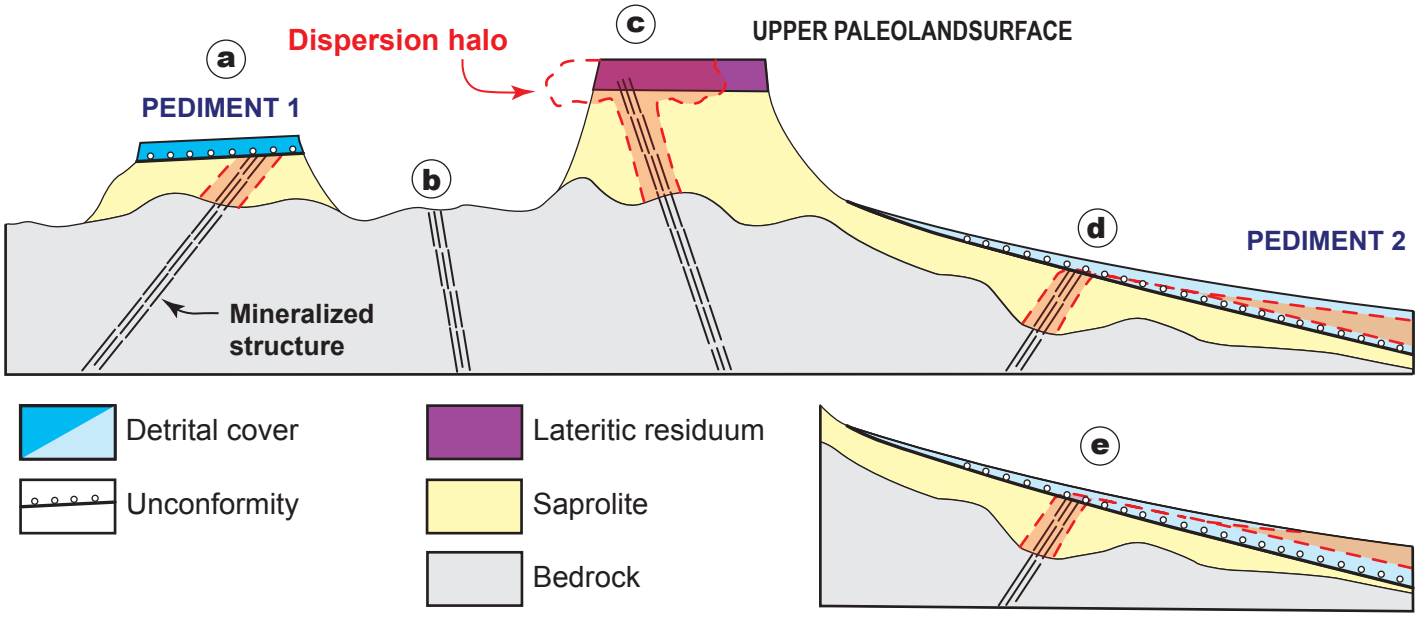
Sawadogo et al. Figure 13



Sawadogo et al. Figure 14



Sawadogo et al. Figure 15



Sawadogo et al. Figure 16

IDEALIZED DISPERSION MODELS IN WEST AFRICAN GRANITE-GREENSTONE TERRAINS