ELSEVIER

Geomorphology 16 (1996) 87–102

GEOMORPHOLOGY

A tentative classification of paleoweathering formations based on geomorphological criteria

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Received 11 May 1993; accepted 16 August 1994

Abstract

A geomorphological classification is proposed that emphasizes the usefulness of paleoweathering records in any reconstruction of past landscapes. Four main paleoweathering records are recognized: 1. *Paleoweathering formations buried beneath a sedimentary or volcanic cover*. Most of them are saprolites, sometimes with preserved overlying soils. Ages range from Archean to late Cenozoic times; 2. *Paleoweathering formations trapped in karst*: some of them have buried pre-existent karst landforms, others have developed simultaneously with the subjacent karst; 3. *Relict paleoweathering formations*: although inherited, they belong to the present landscape. Some of them are indurated (duricrusts, silcretes, ferricretes,...); others are not and owe their preservation to a stable morphotectonic environment; 4. *Polyphased weathering mantles*: weathering has taken place in changing geochemical conditions.

After examples of each type are provided, the paper considers the relations between chemical weathering and landform development. The climatic significance of paleoweathering formations is discussed. Some remote morphogenic systems have no present equivalent. It is doubtful that chemical weathering alone might lead to widespread planation surfaces. Moreover, classical theories based on sea-level and rivers as the main factors of erosion are not really adequate to explain the observed landscapes.

1. Introduction

A considerable number of papers have been published and great advances were made during the last 20 years on paleoweathering formations. They concern petrographic, mineralogic and geochemical analysis (cf. Nahon, 1991) and also the geomorphological background of weathering. Several types of classification can be made for weathering formations depending upon the purpose. This proposed geomorphologic classification illustrates the importance of chemical processes in long-term landform development. Although such processes were considerably neglected in Davis's and King's models, they get, on the other hand, prime importance in the theory of etching (Büdel, 1957), recently revised by Thomas (1989).

An important definition is the meaning of "paleoweathering formations". Meteoric chemical and biochemical processes are the only ones considered, because they correspond to the French "*altération météorique*". This term is more restricted than the English "*weathering*" because it excludes truly physical processes (e.g. thermal stresses, unloading, frost shattering,...). Contrary to hydrothermal processes, meteoric weathering occurs at or near the Earth–atmosphere interface: processes reflect contemporary bioclimatic and drainage conditions. They depend upon climate *and* other factors such as vegetation, slope and relief.

SSDI 0169-555X(95)00087-9

I define *paleoweathering formations* as weathering formations which were produced in a geomorphologic and/or climatic environment different from the present one. They can be attributed to any structural, lithologic and climatic background. As a result, they are extremely varied and differ in structural, textural, mineralogical and chemical properties. Some of them are in situ (palaeosols for example); others have been reworked and deposited more or less far from the parent-rock.

From a geomorphologic point of view, paleoweathering formations are significant when they allow us to infer the past geomorphologic development leading to the present landscape. In most cases, they offer paleoclimatic or paleomorphologic benchmarks in that development and in a few cases, they have generated original landforms (silcrete-mesas, for example). Four types of paleoweathering formations are defined: buried, trapped in karst, relict, and polyphased.

1.1. Paleoweathering formations buried beneath a sedimentary or volcanic cover

Weathering formations and soils that developed at the surface *before* the deposit of overlying rocks are frequent and geomorphologically interesting. A *preburial* weathering is more or less easily proved by field observations, including: truncated profiles, weathered rock fragments derived from subjacent lithology present in the overlying sediments, channels excavated into the weathered material and filled up with sediments, load structures at the sediment/saprolite boundary (cf. Reinhardt and Cleaves, 1978).

Among this group of formations, we find *saprolites* (defined as isovolumetric weathered formations that retain the primary fabric and structure of the parent rock) marking out *old landscapes*. When exhumed or cut obliquely by the present land surface, they can be observed easily, such as in highly stable cratonic areas, mainly shields and, to a lesser extent, Paleozoic massifs. Good examples have been described and analysed in Canada, Scandinavia and the French Massif Central.

Some of the most ancient weathering profiles ever recorded, in the Elliot Lake–Thessalon area (Ontario, Canada) (Prasad et al., 1993), are related to unconformities below and within the Huronian formation, between 2450 and 2200 m.y. ago. The basal quartz pebble conglomerates associated with the Lower Huronian discordance bear detrital uraninite which is

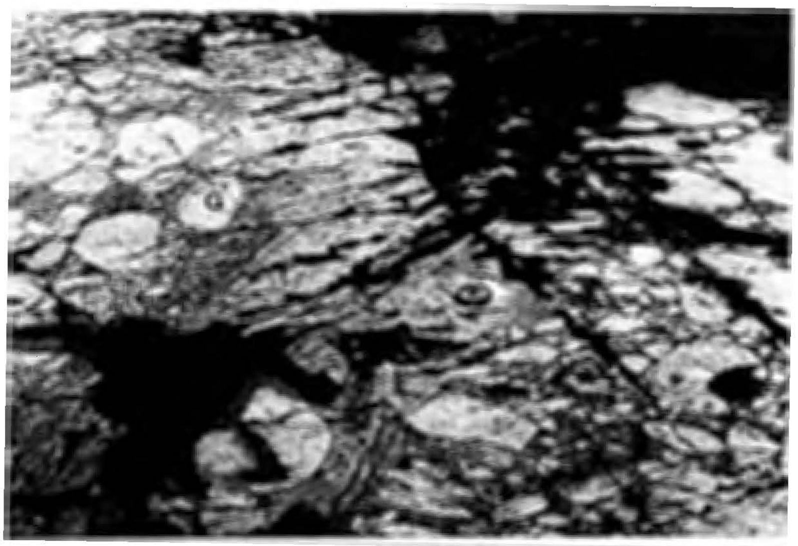

Fig. 1. A sub-Huronian saprolite exposed near the shore of Lake Huron, west of Thessalon (Ontario, Canada). It has developed before 2.48 Ga at the expense of an Archean granite. Granitic corestones (G) are in place and surrounded with fine-grained arkosic sandstone (A). Glacial striae (S) formed during the last Glacial period. (Photo Y. Battiau-Queney; interpretation from Prasad et al., 1993.)

insoluble in a reducing environment. Uraninite was no longer present in the Upper Huronian oxidizing conditions: from the mineralogical and textural composition of paleosaprolites, one can interpret that weathering conditions changed radically from reducing or very low oxygen conditions and cold climate about 2450 m.y. ago to oxidizing conditions and hot climate about 2200 m.y. ago in the Upper Huronian (Roscoe, 1973; Prasad and Roscoe, 1991). Paleosurfaces associated with these very old weathering profiles are now close to the present landsurface and remarkably well preserved (Fig. 1). Mesozoic and Cenozoic sediments are absent, except glacial Pleistocene deposits but, in some places, the present land surface does not differ substantially from Huronian paleosurfaces.

In southeastern Ontario, a *pre-Ordovician paleosurface* has been exhumed (Di Prisco and Springer, 1991; Springer and Gall, 1993). Between 700 and 460 m.y. ago, a major stratigraphic gap marks a long period of erosion. Clastic unmetamorphosed flat lying Middle Ordovician sediments rest unconformably on the Precambrian basement. During that period, most of cratonic North America laid within 20° of the Equator (Irving, 1979; Scotese et al., 1979). The paleosurface can be identified by karstic features, spheroidal weathering (especially in metadolerites) (Fig. 2) and a suite of distinctive mineral

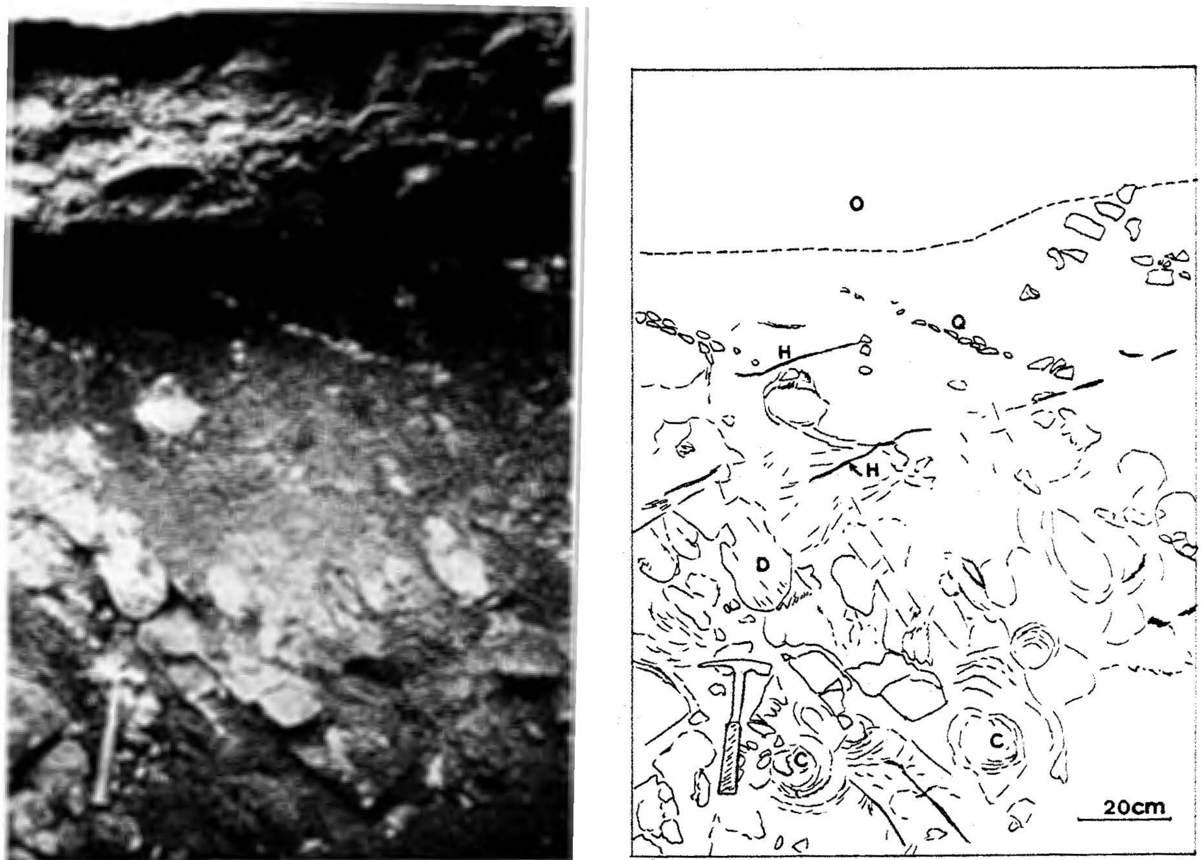

Fig. 2. The Precambrian–Paleozoic unconformity in the Marmoraton iron mine (Hastings County, southeastern Ontario, Canada), with interpretative sketch. Precambrian diorite (D) is overlain by Ordovician strata (O). Just beneath the unconformity, the Precambrian basement is loose, with typical spheroidal weathering around diorite corestones (C) and undisturbed quartz veins (Q). Fracture planes were coated with hematite (H). All these features correspond to a paleosaprolite which predates the deposit of Ordovician strata. (Photo Y. Battiau-Queney; interpretation from Springer and Gall, 1993.)

deposits related to weathering processes not corresponding to the present climatic conditions. Distinguishing paleoweathering features from those of recent weathering is often difficult. This work is relatively easy in that part of Canada because the present climate is quite different from that of the Lower Paleozoic: for example, hematite which is frequently associated with the paleosurface is not observed under Holocene climatic conditions. This pre-Ordovician surface had a considerable, although difficult to assess, paleorelief with hills, depressions and valleys. In some places, the cover rocks have been removed and the exhumed paleosurface was scraped by Pleistocene ice sheets. The ice-scoured landform is not very different from the exposed Lower Paleozoic weathering front (Fig. 3).

In the southern French Massif Central, Triassic paleoweathering profiles that developed on crystalline rocks were subsequently buried beneath transgressive Mesozoic sediments (Schmitt, 1992). These profiles are characterized by low-temperature *albitization* phenomena affecting primary alumino-silicates. This type of weathering is a good paleoclimatic indicator: it implies a hot and dry climate. It needs also a paleotopography with poor drainage. It confidently allows a reconstruction of the post-Hercynian surface where the Mesozoic sedimentary cover has been removed (Schmitt and Simon-Coinçon, 1993).

More generally, the recognition of typical weathering profiles is probably the best, maybe the only accurate way to identify ancient paleosurfaces in the present landscape, especially where they have been deformed and faulted. In many Paleozoic massifs, the frequent stepped-like relief was traditionally interpreted as polycyclic because with a mainly topographic approach it was impossible to identify doming and bending and estimate the denudation rate in Mesozoic and Cenozoic times.

In Mesozoic and Cenozoic paleoweathering formations, friable saprolites may be preserved: for example, deep kaolinitic saprolites are present in south Sweden on the Precambrian basement (Lidmar-Bergström, 1989) (Fig. 4). Weathering of basement rocks, mainly granite, took place before the deposition of Cretaceous limestone. Patches of saprolite with scattered Cretaceous outliers mark a hilly peneplain which is the *exhumed sub-Cretaceous surface*. To the north, this surface is cut by a subhorizontal Tertiary surface where no kaolin or Cretaceous outliers have ever been found. In south Sweden, detailed features of the paleoweathering

Fig. 3. A Precambrian paleosurface recently stripped by human activity (location: Hastings County, 5 km east of Marmora, southeastern Ontario, Canada). The Grenvillian marble is cut by a dyke. The paleosurface shows a low relief (1 to 2m) controlled by the set of fractures. The general landforms of this old paleosurface are not very different from a glacially moulded landscape, although they were never in contact with ice. (Photo Y. Battiau-Queney; interpretation from Springer and Gall, 1993.)

front have been remarkably well described by Lidmar-Bergström (1989). Among other things, this study shows that sub-Cretaceous weathering features are, in some places, initial forms for the development of Pleistocene glacial "roches moutonnées".

Among buried paleoweathering formations, a sec-

Fig. 4. Exhumed Cretaceous landforms in Skåne (southern Sweden). (a) A general view of the abandoned quarry of Blaksudden (Ivöklack). Before quarrying, the Precambrian basement, a coarse grained granite, dated around 1350 Ma, was buried beneath upper Cretaceous limestone. On the upper part of the slope (to the right), the Cretaceous lies directly on the Precambrian granite which presents rounded forms looking like "roches moutonnées" although never in contact with ice. In the middle and lower parts of the slope, Cretaceous strata have buried a thick kaolinitic saprolite developed at the expense of granite prior to burial. It appears in white on the photo. In (b) a huge granitic boulder (probably in situ, or not far from its primary site) has been exhumed by quarrying. Onion-skin weathering is well developed at its surface. (Photos Y. Battiau-Queney; data from Lidmar-Bergström, 1989.)

ond group concerns the reddish horizons lying below (or interbedded with) Cenozoic basalts. Good examples exist in Iceland and the French Massif Central. From research conducted on weathered granite buried by basaltic lavas (Pierre, 1989; Pierre and Dejou, 1990), the role of thermal metamorphism, red baking from heating at the contact with hot magma, is nearly negligible. Through precise dating of basalts, a unique opportunity exists to know the weathering conditions that prevailed before burial and to study paleoclimatic change from Miocene to Pleistocene.

In west and northwest Iceland, between 64 and 66°N, a thick lava pile has developed during the last 20 millions years. Basaltic flows are interbedded with sedimentary layers (clays, lignite, hydroclastite and tephra). Kaolinitic paleosols are common in the Miocene section; they reflect a warm and wet climate with broad-leaved forest (Friedrich, 1968). They disappeared during the Pliocene as the climate grew cooler (Buchardt, 1978). In Iceland, weathered profiles are well dated from the age of the over and underlying lava; they give precise information on the bioclimatic environment (Roaldset, 1983). The formation of thick kaolinitic saprolites in northwest Iceland 14–15 m.y. ago must be addressed in any global climatic reconstruction.

The examples above show that buried paleoweathering formations are most valuable paleogeomorphologic and climatic indicators, provided that the geochemical processes are correctly interpreted. An isolated profile has no real significance, because in a given bioclimatic environment, weathering profiles differ according to the position on the slope. In contrast, when a series of paleoprofiles can be placed in a regional geochemical system, as has been done in southern Massif Central, the ancient landscape may be confidently reconstructed (Simon-Coinçon, 1989).

"Crypto-weathering" formations where weathering took place *beneath* overlying rocks do not have a real paleogeomorphologic significance. In that case, weathering processes depend upon the meteoric waters flowing through the sedimentary or volcanic cover. If the cover is sufficiently thick, they do not generally reflect or provide information about the surficial environment.

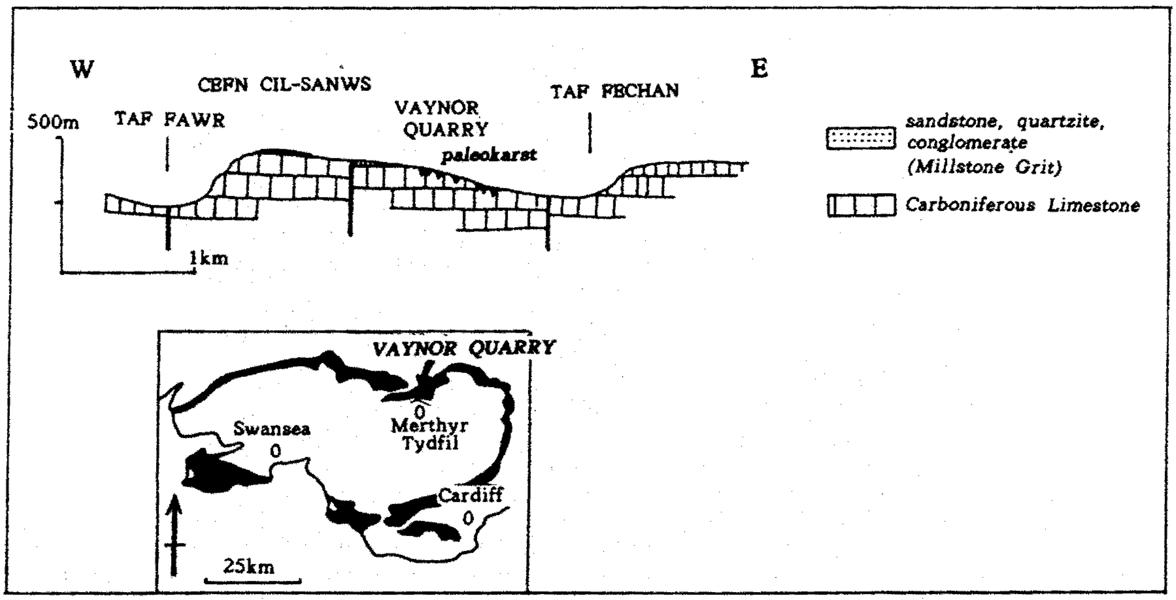

Fig. 5. The geological environment of the Vaynor quarry (South Wales, United Kingdom). On the map, Carboniferous Limestone outcrop is in black. In Welsh, "Taf fawr" (or "fechan") means "large (or small) river", "Cefn" a "rounded hill".

2. Paleoweathering formations trapped in karst

Trapped formations, frequent in karstic areas, can be classified in two different groups:

2.1. Paleoweathering formations have buried pre-existent karst features

Good examples exist in Carboniferous limestone quarries on the north edge of the South Wales coalfield (Battiau-Queney, 1986). A tower and cockpit karst was buried beneath a loose unsorted material that was deposited as a result of the destruction of deep kaolinitic soils developed on nearby non-carbonate rocks (Figs. 5 and 6). The subaerial origin of karstic landforms is proven by the preservation of vertical grooves on limestone walls. The absence of post-depositional diagenetic reactions in the infilling material results from the abundant clay fraction and low permeability of this material. Karst processes ceased after upper Cenozoic burial.

In this case, the conjunction of tropical type karst and kaolinitic soils and saprolites is a *good paleoclimatic indicator*. The sudden destruction of soils and resulting burial of karst implies a strong bioclimatic deterioration with rapidly increasing erosion: a rhexistasic event according to Erhart (1955).

2.2. Burial and subjacent karst have developed simultaneously

Several examples occur in Wales but one of the most interesting cases was found in southwest Ireland, near Tralee (Co. Kerry), in the huge Ballyegan Carboniferous limestone quarry (Battiau-Queney and Saucerotte, 1985; Battiau-Queney and Arbey, 1989). Weathering developed on black illitic and pyritic shales overlying limestone and progressed with simultaneous subjacent karstic processes. Because of solution subsidence, collapsed blocks of shales were trapped in developing cavities and wrapped with a complex infilling material (Fig. 7) that is unsorted, poorly or not stratified. Mottled or black clay masses are mixed with ochreous sand. It is not possible to recognize a simple vertical weathering profile. Nevertheless, chemical and mineralogical analysis give evidence of intense chemical processes in a well drained environment (Figs. 8 and 9). In some cavities, the upper part of the infilling material contains abundant gibbsite and cliachite revealed by X-ray diffraction and differential thermal analysis. Large

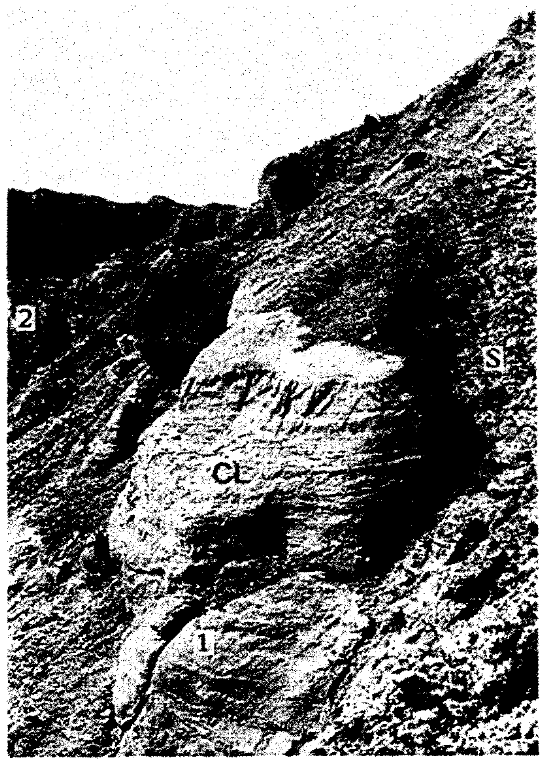

Fig. 6. Buried paleokarst in the Carboniferous Limestone Vaynor quarry (north edge of the South Wales coalfield, Fig. 1). Several huge cavities can be observed where the local limestone (CL) has been buried beneath a reddish brown material (S). The limestone faces are smooth and convex (1) or nearly vertical and carved with rillenkarren, channels and grooves (2). These last features prove the subaerial origin of the karstic landforms. The preburial landscape was irregular with several metres high pinacles and towers. The infilling material is loose and unsorted; locally, up to 50% of the particles have a size less than 2 μm. and are mainly composed of kaolinite, but subangular or slightly rounded boulders, several decimetres long, are also present. The lack of sorting and absence of stratification suggest a transport by mud flows. The mineralogical composition is consistent with a provenance from sandstone strata overlying the Carboniferous Limestone and still outcropping here and there above the quarry. It is evident that the source material was deeply weathered with profiles belonging to the ferrallitic type. The rapid stripping of saprolites and soils and the subsequent burial of paleokarstic features imply a catastrophic event (instantaneous at the geological time scale): it is a good example of a *rhexistasic* crisis. (Photo Y. Battiau-Queney; data from Battiau-Queney, 1986.)

authigenic quartz crystals are widespread. The presence of gibbsite does not indicate a wet tropical climate; the drainage conditions because of strong karstic downward percolation and leaching were much more important. Because the whole area has been buried beneath glacial or periglacial deposits, processes that lead to the formation of gibbsite are inactive.

3. Relict paleoweathering formations

Contrary to the buried formations, they are preserved at the surface and belong to the present landscape, except for a thin cover of Pleistocene deposits common in temperate and cold regions, but they are inherited and no longer being altered in the present weathering environment. According to resistance to erosion, two geomorphological groups can be distinguished:

3.1. Indurated paleoweathering formations responsible for characteristic landforms

Silcretes and ferricretes are the most widespread of them, especially in tropical regions. Silcretes form in two ways (Thiry et al., 1991): near the land surface (pedogenic silcretes) or at a deeper level (groundwater silcretes). Both types are generally more resistant to erosion than the underlying rock, which leads to frequent relief inversion. In Australia, this is the origin of flat-topped hills and plateaux edged with steep concave scarps (Langford-Smith, 1978). Some authors have considered that silcretes could be useful stratigraphic markers to date landforms and paleosurfaces. This is difficult to assess, at least in stable areas, because the geochemical processes of silcrete formation could have been active several times since the early Mesozoic. Nevertheless, typical pedogenic silcretes (with illuviation structures, a frequent columnar horizon and, at the top,

Fig. 7. Detail of the infilling material in a karstic cavity of the Ballyegan quarry (exact location shown in Fig. 8). A mass of pyritic Namurian shale is well seen on the top right. It has collapsed in a solution doline and was deeply weathered after collapse, in a complex geochemical system (see Fig. 9). On the left, shale passes progressively into an heterogeneous argillaceous sandy material with alternated white and ochreous stripes. Kaolinite is the main clay mineral. The direction of stripes proves that the material was still sagging during the last episodes of weathering, before the deposit of periglacial formations. Strong leaching characterizes this type of karstic environment. Prior to the Pleistocene climate cooling, abundant gibbsite and cliachite (Fig. 9) could form at the top of the cavities (Fig. 8) thanks to high rainfall combined with strong leaching of silica.

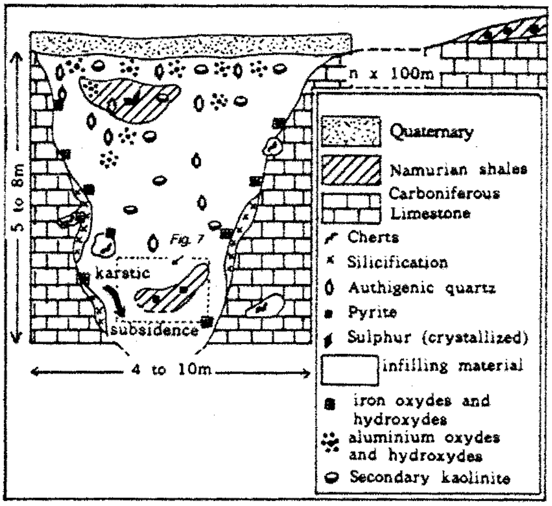

Fig. 8. Schematic representation of a karstic cavity in the Ballyegan quarry, east of Tralee (Co. Kerry, southwest Ireland). The infilling material was deeply weathered during and after it collapsed. Secondary minerals depend on the parent rocks (pyritic black shales and, in a less quantity, sandstones) *and* the strong leaching environment of these karstic cavities.

dominant dissolution and eluviation features) are good indicators of paleoenvironment. They infer stable land surfaces with minimal erosion and shallow water tables together with seasonal or cyclic wet and dry climate (Thiry and Milnes, 1991)

Ferricretes result from indurated pedologic horizons with the accumulation of iron oxyhydroxides. The main process involved is an epigenetic replacement of argillaceous or sandy-argillaceous matrix by aluminous hematite (Nahon, 1991). Based on observations by Nahon, as a result of climatic change from a tropical humid to an alternating dry and wet seasonal climate, ferrallitic soils are replaced by lateritic soils with an upper indurated iron crust above a soft nodular iron crust and mottled clay below. In this case, ferricretes are formed during a dry and wet seasonal tropical climate.

In southern South Australia where terrestrial landscapes have existed since the end of Paleozoic, widespread ferricretes outcrop on present highland surfaces and have been attributed previously to Mesozoic or early Cenozoic weathering phases. Nevertheless for Milnes et al. (1985), these crusts result from "complex reworking and continuous weathering of an ancient uplifted landscape of possible Mesozoic age" and lead to the intricate patterns of sediments and soils forming the present regolith. In that case, it is very difficult to trace a sharp boundary between active, relict and paleoweathering. The

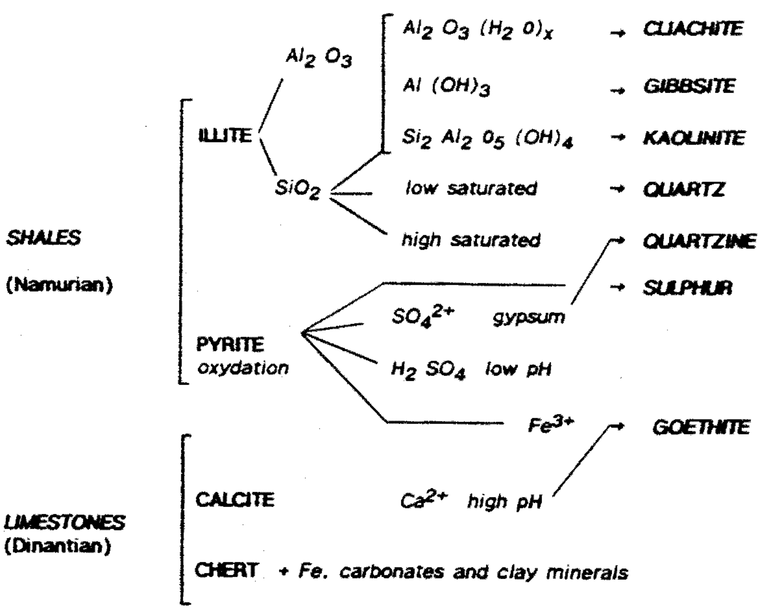

Fig. 9. Summary of the main pedogenic neoformations observed at Ballyegan.

pedologic mantles of the highland surfaces are the cumulative product of leaching and weathering through the Mesozoic and Cenozoic. They cannot be assigned to a distinct climatic event and used as morphostratigraphic markers. On the other hand, they imply a long term stable cratonic regime.

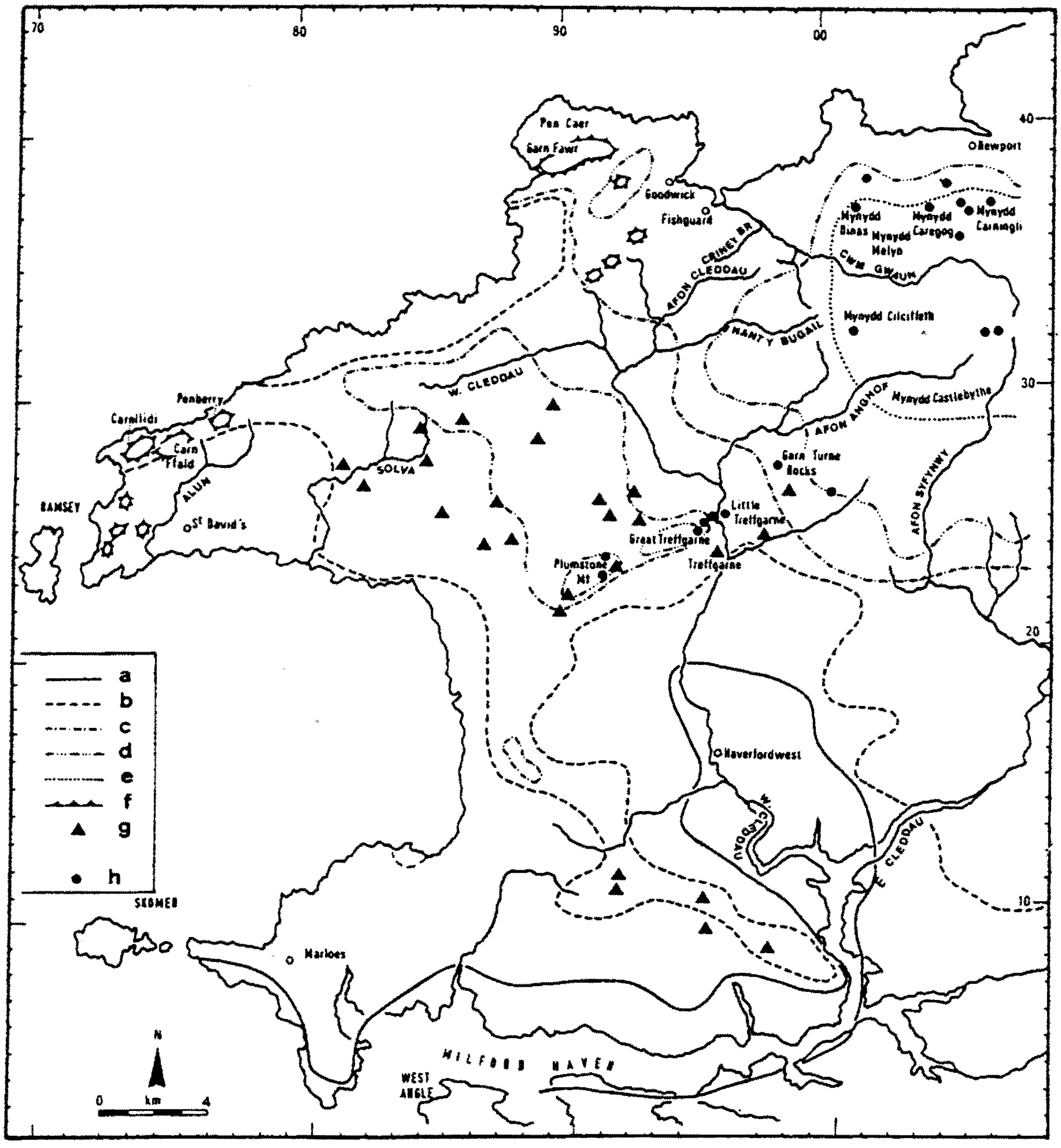

Fig. 10. Location of known paleoweathering profiles and tors in southwestern Dyfed (Wales). Contours (in metres) of the main paleosurface: (a) 61 m, (b) 91 m, (c) 122 m, (d) 152 m, (e) 305 m. (f) inselbergs, (g) in situ deep regolith, (h) tor. (Reproduced from Battiau-Queney, 1980.)

3.2. Non-indurated surficial formations

Contrary to ferricretes and silcretes the long term preservation of friable formations does not occur because of strong resistance: it needs a stable morphotectonic environment with low relief. Among them, *clay-with-flints* is widespread on chalk plateaus in the western Paris Basin (Battiau-Queney, 1993) and in southeast England (Jones, 1981). Flinty chalk has weathered in terrestrial conditions near the land surface since the early Tertiary. Locally, marine sediments were deposited during short transgressions, leaving sand and gravel which are now mixed with clay-with-flints. This is a complex formation which results from successive weathering episodes under wet or dry climate in a stable geodynamic regime: chemical processes and karstic solution at the contact of chalk and clay lead to a slow lowering of the land surface balanced by crustal uplift. This is an example of *chemical planation surface*. In lower and middle Pleistocene, the rapid deepening of valleys and the cooling climate changed the weathering environment of chalk. Clay-with-flints became a paleoweathering formation, possibly reworked by periglacial processes and covered with loess. Clay-with-flints cannot be attributed to a particular period of weathering (Paleocene or Miocene, for example) because it results from a *long duration pedogenic development*. At any time, from late Cretaceous to Pliocene, the previously weathered material acted as a parent rock for continuing weathering.

More frequent are the discontinuous remnants of ancient weathering mantles preserved at or near the present landsurface, generally on the interfluves. They have been recorded in the Northern Appalachians (Bouchard and Pavich, 1989) and in most Paleozoic massifs of Western Europe: in Scotland (Hall, 1986), Wales (Battiau-Queney, 1980, 1984), Scandinavia (Lundqvist, 1985; Peulvast, 1985; Lidmar-Bergström, 1988), Finland (Fogelberg, 1985), Brittany (Estéoule-Choux, 1983), the French Massif Central (see for example: Simon-Coinçon, 1989). Emplacement is generally located outside the valleys that developed in late Cenozoic. In Southern Pembrokeshire (Wales), some of them are located on low plateaus when tors are present on hills just above (Fig. 10). Tors have been exhumed from the paleoweathering mantle in uplifted areas (Battiau-Queney, 1987).

Remnants of the paleoweathering mantles depend on the structural properties of the parent-rocks: they are deeper where occur closely spaced fractures. Insofar as they are discontinuous and not well dated, they do not allow a precise reconstitution of the ancient landscape but they give interesting paleoclimatic and paleogeomorphologic information. Maybe some of them formed during the last Interglacial stage (Bouchard and Pavich, 1989), but in other cases depth and mineralogical properties of weathered rock suggest that they date to Tertiary time, a conclusion also consistent with emplacement outside the youngest valleys.

4. Polyphased weathering mantles

In tectonically stable areas, some weathering profiles and soils are partially the result of the present bioclimatic environment and partially inherited from the past. They have developed during a long period with climate changes such that weathering has taken place in changing geochemical conditions. Each time the geochemical conditions change, new processes lead to transformations in structure and mineralogy inside the profile.

"Normal" weathering profiles which commonly comprise soil over saprolite are organized vertically in different horizons and laterally in sequences corresponding to the slope system. Each horizon develops at the expense of the underlying horizon and, at the same time, feeds the subjacent horizon with the exported products (Nahon, 1991). After Nahon, in the case of plurimetric profiles, a complete profile requires a span of time exceeding 1 to 3 millions years. During this long period, climate and vegetation probably changed several times. Therefore, the different parts of the profile have developed at different rates at different times. Upper horizons directly exposed to the surface exhibit features corresponding to the most recent environment. Lower horizons may be inherited from paleoenvironmental conditions. Nevertheless, if the weathering front continues to lower, it does so in a geochemical environment which is determined by the present drainage conditions. The latter depend on climate, slope and relief and also the porosity of saprolite and overlying horizons. A complex system exists in which paleoprocesses exert a strong influence on present weathering.

A good example occurs in the *Appalachian Piedmont* from Georgia to New Jersey (Pavich, 1985, 1989; Battiau-Queney, 1988). The Piedmont plateau truncates metamorphic and plutonic rocks that display thick weathering profiles (15 to 20 m). The Appalachian Piedmont has been a terrestrial area subject to subaerial erosion since the Triassic in most places (Maryland, for example). It was not submerged by Mesozoic seas after the opening of the Atlantic ocean. Everywhere, the weathering profiles of these areas present some characteristics of true ferrallitic soils (*Ultisols* according to the Soil Conservation Service Taxonomy, Seventh Approximation, 1975). Saprolitization is not a simple physical disintegration but the result of complex geochemical processes: hydrolysis of plagioclases and biotite, weathering products characterized by 1/1 type phyllosilicates (particularly kaolinite) and hydroxides of iron and/or alumina. The final products (clay minerals and hydroxides) depend upon the parent rock and also landscape position related to divides and valley bottoms. Saprolites show lateral variations along the slope according to changes in the drainage conditions.

Based on data from Virginia presented by Pavich (1986), a uniform layer of saprolite 1 cm thick forms in about 3000 years. Assuming a constant rate of weathering, the saprolites presently observed could have formed in about 3 millions years. It is unlikely that the weathering rate has been constant because of the Pleistocene cool and cold climates, and also because of variations in the rate of uplift which controls the lowering of the weathering front.

Because of the range of latitude, from south Georgia to New Jersey (Fig. 11), two pedologic provinces can be differentiated according to the importance of periglacial inheritance (Battiau-Queney, 1988, p. 56). In Georgia and the Carolinas, typical periglacial features are absent from the Piedmont profiles. This absence could mean that chemical weathering processes were continuously active through Pliocene and Pleistocene. In New Jersey, northern Maryland and Delaware cryoturbed material and fossil ice-wedges are frequent in the upper horizons. Saprolites in these areas are at least partially inherited from pre-glacial climates although chemical weathering processes are still active during hot and wet summers. Because climate warmed after the Wisconsinan, preglacial saprolites that were not destroyed have greatly facilitated the drainage of percolating water and, therefore, the lowering of the weathering front has continued.

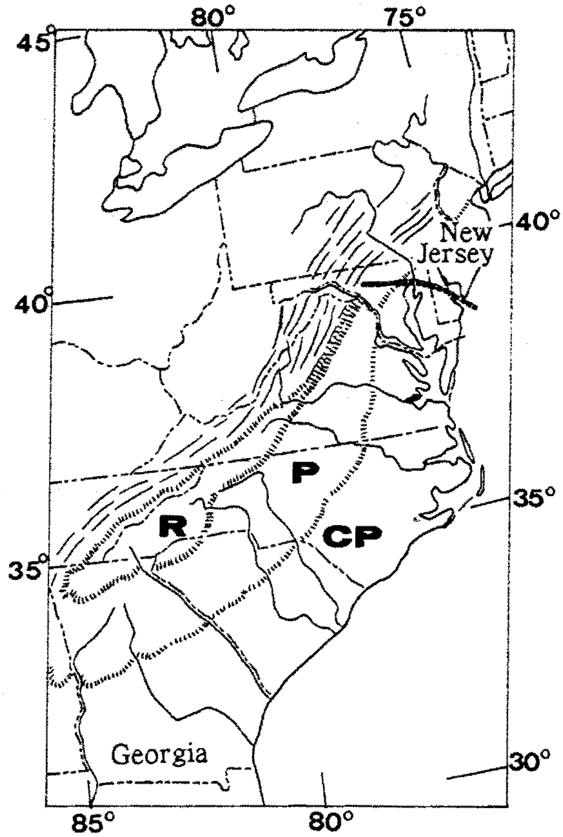

Fig. 11. Location map of the Appalachian Piedmont, from New Jersey to Georgia (USA). R: Blue Ridge; P: Piedmont; CP: Coastal Plain. Hachured lines mark the limits of Coastal Plain, Piedmont and Blue Ridge. The thick dashed line marks the approximate south limit of known periglacial features. During the last Glacial period, a high thermal gradient existed on both sides of this line.

In this example, saprolites have formed more or less continuously in an open system but the thickness does not increase indefinitely through time. Thickness depends on several factors acting simultaneously: crustal uplift, deepening of the weathering front, conversion of saprolite to soil with volume and mass loss (Pavich, 1986), and surficial denudation. The final result is the lowering of the land surface. The present landscape of the Appalachian Piedmont consists of elements of different ages: interfluves with thick saprolite belong to *an "old" but still active surface* that constantly lowers itself. Valleys have developed since the upper Miocene in response to crustal uplift. Slopes are covered with Pleistocene and Holocene deposits.

5. Paleoweathering and landform development

Through the examples cited above, the age of paleoweathering formations that have been preserved near the present land surface ranges from Archean to Cenozoic. Chemical weathering has ever been active at the surface of exposed land, provided there was enough rainfall and that it was not freezing. Paleoweathering formations may be useful tools in any tentative reconstitution of past landscapes if the complex relations between geochemical processes, climate, and topographic environment are well known. Unfortunately, incomplete preservation is a problem.

Thirty years ago, it was generally admitted that rock weathering was mainly depending on climate (see for example Pedro, 1968). The relative amount of the dominant weathering products, especially clay minerals and hydroxides, differ in tropical humid, tropical with alternating seasons, temperate, and cold climates. Tardy (1969) claims that the controlling factor of the weathering rate is average rainfall, but other important factors are the amount of CO_2 initially dissolved in water percolating through rock, the "residence time" of water in contact with parent minerals, and the temperature of the weathering environment (Nahon, 1991). Furthermore, in a given climatic area weathering profiles differ laterally along the slope according to changes in the drainage conditions. Numerous examples are cited by Nahon (1991): in tropical humid regions of French Guiana and Brazil, ferrallitic profiles which developed over plateaus grade downslope to true podzols with a darkish surficial horizon overlying a white sandy horizon and then a dark-brown humic horizon. In these tropical humid regions, podzolisation can develop upslope at the expense of "normal" ferrallitic profiles simultaneously to the development of stream valleys.

For all these reasons, the climatic significance of an *isolated* paleoweathering formation (saprolite and soil, duricrust or trapped formations) is doubtful. On the contrary, widespread paleosaprolites with distinctive structure and mineralogy can be confidently used although they are truncated and discontinuous. In Wales, for example, the lowest part of the weathering profiles inherited from upper Cenozoic wet and warm climates are widely preserved on various parent-rocks. They are associated with typical buried or relict landforms in quartzite and limestone (Battiau-Queney, 1984, 1985). The most valuable paleoformations as climatic indicators are those buried beneath a sedimentary or volcanic cover (first type of this paper) or relict formations (third type). Trapped formations in karstic areas (second type) are also interesting because they often record climatic data from the period which preceded or accompanied burial.

If chemical weathering processes depend on climate at a regional scale, they are also controlled by structure and tectonics both at larger and smaller scales. On a global basis, one of the main geomorphologic problems is to establish the relationship between paleoweathering formations and landscape development. A general assumption is that present geomorphic systems can be confidently applied to most paleoenvironments, according to the principle of uniformitarianism which was first enunciated by Hutton in 1785: "the present is the key to the past". Nevertheless, before the spreading of dense terrestrial vegetation in Devonian, chemical weathering processes were active when the landsurface was not protected from surficial erosion; no equivalent exists to these remote morphogenic systems. They were probably much more efficient than the "modern" ones with regard to the denudation rate. Presently, the rate of chemical weathering is highest in a wet tropical climate where a dense rain forest protects from surficial denudation processes. *Biostasie* (Erhart, 1955) leads to very thick saprolites and soils. In Archean and Proterozoic times, we can hypothezise geomorphic systems with rapid geochemical weathering rates and *thin* saprolites because the weathered material was eroded progressively as it was produced if drainage was good. With a very low biological activity, pedostructures were limited to the effects of drying and wetting at the surface. Such conditions probably have favored a high rate of lowering of the landsurface.

Even in the most favourable conditions, *it is doubtful that chemical weathering alone might lead to widespread planation surfaces*, independent from structure and reduced to marine base-level. This results from the main characteristics of chemical weathering:

- Because it needs percolating water, chemical weathering strongly depends on the *permeability* of the parent-rocks, which itself depends on structural and textural properties of these rocks, especially the effective porosity and density of fractures. In most cases, permeability varies considerably from place to place. Thus, the weathering front, as it can be seen at the base of paleo-profiles, is usually very irregular with relief exceeding several metres and frequently a few tens of metres.
- Chemical weathering progresses according to the circulation of water through the parent-rock and saprolite. Depths of more than 100 m and exceptionally as great as 600 m of weathered rock have been recorded in humid tropical regions (Fairbridge and Finkl, 1980). *The weathering front may be much lower than the valley bottoms*, if leaching is still active. Leaching depends on the hydraulic gradient in groundwater which is dependent on rainfall and vertical relief Clearly, *the depth of the weathering front is not fundamentally controlled by sea-level*. The rate of uplift, which depends on global tectonics, however, is much more important.

In contrast to chemical weathering, denudation processes are less structurally controlled and more dependent on the slope and valley system. Each time the rate of surficial denudation was faster than the rate of chemical weathering, saprolite was stripped and the weathering front exposed. An irregular *etch surface* (Wayland, 1934; Mabbutt, 1961) was created which might have initiated the detailed shape of many glaciated areas (see above in Sweden).

The development of a planation surface requires successively (Büdel, 1957; Mabbutt, 1961; Fairbridge and Finkl, 1980; Thomas, 1989) or simultaneously (Pavich, 1985) deep chemical weathering *and* surficial erosional processes. But landscape evolution does not lead necessary to a planation surface. Twidale (1986) has shown that in the Flinders Ranges, South Australia, relief amplitude has increased through time. This is the normal evolution in the case of strong lithologic contrast, as in the Applachian Ridge and Valley province. Consequently, patchy remnants of paleosaprolite mark out a *paleotopography* which is not necessary a *paleosurface* (in the sense of a planation surface). Thomas (1989) thinks that *etching* processes "account for landscapes of both extreme planation and those of marked relief". The cratonic regime, characterized by sustained and slow uplifting and balanced by surficial denudation, is the most favorable to planation. Even in this example, inselbergs may persist and relief increase with time. A good example of this type of long term evolution exists in Anglesey, a small Welsh island which has responded like a stable shield since Lower Paleozoic (Battiau-Queney, 1984, 1989). Widespread remnants of paleosaprolite mark out a very old paleotopography with low relief except for a few residual rocky hills that are true inselbergs, according to the process of etching described by Thomas (1989). Although nearly at sea-level, Anglesey's *etchplain* is the oldest of this region.

When in situ paleoformations are not sufficient to reconstitute ancient landscapes, formations trapped in karst add useful information: they give stratigraphic data that help to reconstitute any lost sedimentary cover and also record rhexistasic events caused by changing climate or tectonics. When they exist, such as on the southwest border of the French Massif Central (Simon-Coinçon and Astruc, 1991), trapped formations have often preserved the best records of the past environment.

6. Conclusion

From a geomorphological point of view, formations attributable to chemical paleoweathering can be differentiated in four main groups:

1. Buried formations. The oldest recorded date back to Archean times. The youngest formed in late Cenozoic. They may be valuable paleogeographic and climatic indicators when placed in a regional geochemical system.

2. Formations trapped in karst. Some have buried pre-existent karstic voids and basins and others have developed simultaneously with subjacent karst. They help to reconstitute paleogeography.
3. Relict formations. They belong to the present landscape and have been preserved either because they offer a strong resistance to erosion or because they formed in tectonically stable regions.
4. Polyphased weathering formations are partially inherited, partially still active. They characterize long term stable cratonic regions.

Paleoweathering records confirm the importance of chemical processes in the development of landforms and suggest that classical theories based on sea-level control and rivers as the main factors of erosion are not really adequate to explain the observed landscapes.

Acknowledgements

I wish to thank Milan Pavich and a second, anonymous, reviewer. Their comments were much appreciated and greatly helped me to improve the original manuscript. I would also like to thank J.D.Vitek who helped me to improve my English. This research was partially supported by the Centre National de la Recherche Scientifique and got much benefit from discussions with other members of IGCP 317.

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