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FERRUGINISATIONS IN THE REGION OF KIMPESE (LOWER-ZAIRE)

BY

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SUMMARY. – Three types of indurations, mainly ferric, can be distinguished in the region of Kimpese, respectively "carapaces", "cuirasses" (plates) and "croûtes" (crusts). These ferruginations confer an increased resistance to the top of numerous platforms which are relics of sedimentary fans. The origin of the indurations occurring in this region is investigated, analyses being based on field observations and laboratory studies. They show the importance of palaeoclimatic effects in the construction of these formations.

RÉSUMÉ. – *Les ferruginisations dans la région de Kimpese (Bas-Zaïre).* – Dans la région de Kimpese, trois types d'induration surtout ferrique, ont été reconnus, respectivement les carapaces, les cuirasses et les croûtes. Ces ferruginisations confèrent une résistance accrue au sommet des nombreux lambeaux de glacis d'origine pédimentaire. La genèse de ces types d'induration est analysée dans la région. Les analyses reposent sur les levés de terrain et les études de laboratoire. Elles montrent l'influence prépondérante des données paléoclimatiques.

SAMENVATTING. – *De ijzerhoudende verhardingen in de streek van Kimpese (Beneden-Zaïre).* – In de streek van Kimpese worden drie typen verhardingen aangetroffen, vooral ijzerhoudende : het zijn de „carapaces", de „cuirasses" en de „croûtes". Deze ijzerhoudende verhardingen verlenen een aangroeiende weerstand aan de top van de talrijke overblijfselen van hellingpuin van pedimentaire oorsprong. Het ontstaan van die types verhardingen wordt in dit gebied bestudeerd. De analysen steunen op de opmetingen ter plaatse en op de laboratoriumstudies. Zij tonen de overheersende invloed aan van de paleoklimatische gegevens.

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Introduction

Situation (fig. 1).

The Lower-Zaire situated in the intertropical zone is characterised by a savannah climate. The wet season lasts about 7 to 8 months ; the annual precipitation reaches about 1200 mm.

Two types of vegetation can be observed in this region : 1° dry savannah on the lower level landforms, developed on the schisto-calcaire system ; 2° dense ombrophile forest developed on top of the Bangu massif, which is situated about 300 m above the plain and consists of rocks of the schisto-gréseux system.

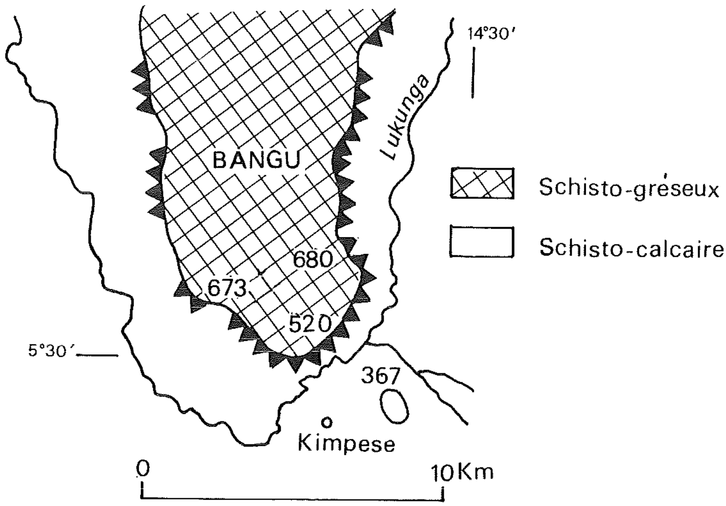

Fig. 1 : The region of Kimpese (Lower-Zaire).

Down the abrupt of the Bangu plateau, numerous platforms can be observed at different levels (about 300 m, 360 m and 400 m). These are relicts of sedimentary fans (VAN KERSCHAVER 1983) inherited from more arid phases. During the subsequent savannah phase, they became resistant by ferruginisations. Therefore they were partially conserved during successive periods of incision in savannah phases.

Ferruginisations.

According to the type of ferric-induration, we distinguish : "carapaces", "cuirasses" and "croûtes". The ferruginisations affect both substratum and allochtonous detrital material. In this region, these kind of indurations only affect calcareous schist and sandstone, never limestone.

Classification of the ferruginisations.

If possible, a good classification must include macro-facies studies as well as micro-facies studies and an accurate knowledge of its genesis. The latter needs a valuable reconstruction of the paleogeographical evolution : geomorphology, drainage and paleoclimates.

The aim of the classification is to develop definitions of the ferruginisation facies usable at least partially in the field.

Our classification of ferruginations has been suggested by MICHEL (1969, p. 351), who distinguishes "carapaces", "cuirasses" and "croûtes latéritiques".

"*Carapaces*" are the result of a partial induration mainly ferric, realised in the oscillating zone of a water-table, weathering and indurating seasonly. Leaching is responsible for the micro- and macro-alveoles ; exudation is responsible for migrations of iron and its induration.

The macroscopical aspect is an iron-rich skeletal horizon, characterised by linear alveoles, in the substratum, as well as in detrital material.

Extreme evolution of "carapaces" results into a nearly ironcemented horizon. Loss of alveoles lead to decrease of permeability. A macroscopic resemblance with cuirasses is possible.

"*Cuirasses*" are indurated ferric pavements, composed by almost fresh allochtones detrital material, essentially nodules of carapaces. The constituents are cemented together by an iron-rich clay that massively fills up the interspaces and decreases porosity. This kind of induration process occurs in a savannah-climate with an alternating wet and dry season, in areas with a restricted drainage as swampy depressions (dembos). They are characterized by important iron migrations during the wet season. Fixation of iron is due to very strong evaporation in a short lapse of time as a result of high temperatures (induration is most important during the dry season).

Degradation of "cuirasses" is caused by the weathering of the coarse material. The indurated cement of the interspaces get a skeletal function. Microscopical resemblance with the "carapace" exists.

"*Croûtes*" are buried horizons, underlying carapaces. Their microconglomeratical aspect is due to neoformations : nodules and discontinuous frameworks, essentially composed of Mn, leached from the overlying "carapace". Voids are filled up mainly by flocculated clay. This lack of coherence provides a high porosity. "Croûtes" probably result from a general lowering of water-tables, due to a slight change of the climate, inducing vertical erosion.

These definitions result from observations in the region of Kimpese (Lower-Zaire). They are not necessarily applicable to all the intertropical areas, where other substrata have been indurated as in Shaba, the Kalaharian lowersands (ALEXANDRE-PYRE 1971).

1. "Carapaces"

Two types can be distinguished : the carapace developed within the substratum of calcareous schists and the carapace developed in allochtonous material. Macroscopically they are very similar and composed by a dense whole of alveoles : "nid d'abeilles", within an iron-rich skeleton.

1.1. "Carapaces" developed in the substratum of calcareous schists.

1.1.1. Macroscopical aspect and kind of material (fig. 2, photogr. 1 and 2).

The violet calcareous schists (photogr. 1) belong to the schisto-calcareous system. They are characterised by thin layering and a very small grain-size.

The macroscopical aspect of the carapace is very constant. It consists of an iron-cemented skeleton, with numerous alveoles, due to weathering and mechanical replacement. The kidney-like alveoles are oriented according to the schistosity planes. Numerous tubular conducts and diaclases of different directions affect this horizon. In most cases conducts traverse the carapace as deep as the underlying horizon, consisting of weathered substratum. This conducts have diameters of about 2 to 3 cm, their walls are often covered by a red to dark brown indurated iron-coating.

"Carapaces" are generally redbrown. In some cases some violet material of the substratum is still conserved and corresponds to a slight indurated carapace. Bright red colours correspond to an intense enrichment of iron oxyhydrates and an important mechanical resistance. Induration is more important in the upperpart of the horizon.

The contact with the underlying weathered violet calcareous schists is quite abrupt. In this "carapaces" schistosity is conserved, this indicates a constancy of the volume in spite of an important loss of material, responsible for the high porosity.

1.1.2. Microscopical analysis.

A comparative study of the thin sections of weathered substratum and of the overlying "carapace", shows a clear evolution between both.

a) Substratum (photogr. 3).

Between crossed polarizers, the substratum shows a clear foliation, accentuated by the arrangement of the numerous muscovite flakes. In plain light, one can observe a ponctuation of diffuse ferric-iron, grading locally to a more dense nodular texture. These irregular rounded or ovoïd nodules are about 100 µm in diameter. Between crossed polarizers nodules can be observed who fixed muscovite in there initial orientation. At high magnification ironoxides are observed to infiltrate between the (001) clivages of muscovites, perturbating slightly their initial arrangement. This is only observed by an important addition of iron within the weathered substratum and without an important modification of the foliation of the rock.

b) "Carapace" (photogr. 4).

The texture of the substratum within the "carapace" is deeply modified. Between crossed polarizers we see that the number of muscovites has seriously diminished and that they lost their orientation. Diffuse iron spots become more continuous and the number of nodules of about 300 µ has obviously increased. Some of the muscovites were trapped by them, in their primary arrangement. So they were protected against ulterior weathering and loss of orientation. An increasing quantity of diffuse iron oxides shows at high magnification, goethite coatings formed between muscovite lamellae. These coatings are partially responsible for the loss of their orientation and for their splintering. Secondary nodules formed around those splinters. More evoluated "carapaces" are deeply affected by internal weathering. The result of the oxido-reduction process is now visible on a microscopical scale, showing an alternation of iron-enriched red patches, and of white-yellowish depleted patches. In this case nearly the whole material has been reworked. The processes responsible for internal reworking are related to seasonal alternation.

In the wet season, hydration, in presence of iron-solutions, is responsible for weathering. Starting with the most alterable minerals it gradually transforms the whole horizon into fine material, most of it becomes kaolinite. Mechanical translocations are responsible for the presence of voids and argillans. Illuviations affect the weathered material.

In the dry season, desiccation happens, mainly in the fine clay material, this by dehydration. At the same time iron migrates to the joints and precipitates in the clay around them. In this way kaolinite is replaced by ferric-iron. It confers an increasing resistance to the horizon.

The process can go on and rework the whole horizon, starting at the top of it and moving downwards. In this way the initial texture of the substratum of calcareous schists is entirely modified.

The macroscopical skeleton is conserved, by the fact that initial weathering took place along the joints of schistosity, where an important iron precipitation fixed these walls.

The processes of oxido-reduction and mechanical removal responsible for the macro- and microscopical facies of the carapaces, also confered them a very important porosity.

1.1.3. Chemical analysis.

The weathered substratum and the "carapaces" contain respectively 5% and about 20% to 30% total iron. According to CAHEN (1954, p. 221) the fresh substratum has a total iron content of only about 3%. The maintenance of the initial volume in carapaces is due to the formation of a resistant iron-oxide skeleton, nevertheless the alveoles represent a loss about 50% of the material of this horizon. The high iron-content is probably due to an absolute iron-enrichment (D'HOORE 1954, pp. 48-49). This means that only the carapace fixed important quantities of iron.

1.1.4. Genesis of "carapaces" in calcareous schists.

Microscopical and chemical analyses illustrate the mechanism of iron-enrichment. First, diffuse iron spots and iron nodules impregnate a slightly weathered rock. An important increase of iron, mainly in contact with the laminae of the muscovites, is responsible for muscovite splintering. A more advanced internal weathering affects the external part of the minerals, giving rise to clay formation and to illuviation, together with iron migration and precipitation.

The rather sharp contact with the underlying homogeneous weathered substratum and the high iron-content of the carapace in contrast to the underlying horizon indicates alternating processes :

- *Reduction* and *mechanical removal,* responsible for the alveoles ;
- *Oxidation,* necessary to the elaboration of the iron-skeleton.

These conditions occur in a seasonly regularly oscillating water-table :

- During the wet season, iron rich solutions hydrate the material and induce weathering. The fine material formed in this way mainly clay, is susceptible to mechanical translocation (clay illuviations) ;

– During the dry season, desiccation of the clays due to dehydration, is responsible for iron migration and precipitation on the edge of joints and vughs.

The "carapace" build up by continuous reworking gets in consequence an increasing resistance due to iron-fixation.

1.2. "Carapaces" developed in allochthonous material.

These carapaces are developed in the same area as those formed in the substratum, sometimes there is even a lateral contact between them. Confusion is then possible.

1.2.1. Macroscopical aspect and kind of material.

A detailed macroscopical study reveals distinct differences between both carapaces. Alveoles oriented by schistosity planes in the substratum, show a subhorizontal disposition in the detrital material. Their aspect is very similar. They are less elongated and somewhat smaller. Voids and cavities of about 5 to 10 cm or more in diameter are observed. In some cases resistant blocks have been conserved in the carapace, they are : silicified chert, quartzites and quartz.

The alveole walls are generally covered by ferric deposits as observed in the substratum.

1.2.2. Examination with binocular.

In the binocular one observes heterogene and heterometric fragments in a rather fine, ocre-yellow matrix. The initial nature of the coarse fragments is no longer recognisable, as a result of intense weathering. The only elements that can be recognized are : cherts, quartzites, quartz of different aspects, particularly spherical quartz grains of about 500 μm.

1.2.3. Microscopical analysis and genesis (fig. 2, photogr. 5 and 6).

In the microscope one observes a heterogeneous detrital material, in a predominant white-yellow matrix. Grains show different sizes and different colours. They figure as patches with a diffuse boundary. Cracks and conducts go as well through the grains, as through the matrix. It indicates a high degree of weathering of the material and explains the fact that only few grains are recognizable. The whole consists of a ± polyhedral grid of continuous ferric-laminae within the groundmass. At high magnification one observes several parallel superposed ferric coatings, with intercalation of thin covers of yellowish clay. It indicates a kind of zonal accretion, typical for the grid, whose skeleton confers a certain resistance to the horizon. The interstitial detrital material is in some cases replaced by clay illuviations ; both are pointed with diffuse iron dots. The aspect of the darns depends upon the degree of evolution of the horizon. Nevertheless, generally this horizon conserves a very good porosity.

Conditions for the formation of "carapaces" in detrital material are similar to those in the substratum. A seasonly oscillating water-table is necessary, and also a relative enrichment of ferric-iron at the beginning of the dry season, when lowering of the water-level gives rise to an oxidation of the horizon.

During the wet season weathering, the main process affects grains and blocks as well as the matrix and transforms them into clay, mainly kaolinite impregnated by iron solutions. It is probable that the coarse material was subject to a former weathering period.

Fig. 2.

Photogr. 1 – Carapace developed in the substratum of calcareous schists. The schistosity is reflected by the parallel arrangement of the alveoles. Belòw, the weathered calcareous schists.
– Quarry of the Cinat-Kimpese, S-SW entry.

Photogr. 2 – Iron-cemented skeleton and alveoles, elongated according to the schistosity.
– Idem Photogr. 1 – Detail.

Photogr. 3 – Weathered substratum of calcareous schists with muscovites.
Note : – linear orientation of muscovites
(X P) – small diffuse dots of iron
– iron nodules with muscovites (110, 36 μm).
– Road Kinshasa-Matadi, at 1,2 km W of the station of Kimpese.

Photogr. 4 – Carapace on substratum of calcareous schists with muscovites.
Note : – numerous diffuse dots of iron
(X P) – most of the muscovites are fractured into splinters
– almost all of the muscovites have lost their initial orientation.
– Same place as Photogr. 3.

Photogr. 5 – Carapace in allochtonous, detrital material.
Note : – reticulation composed of lamellae of ferric-iron
(P L)
– Road Kinshasa-Matadi, at 0,6 km W of the station of Kimpese.

Photogr. 6 – Carapace in allochtonous, detrital material.
Note : – well developed polyhedric reticulation.
(P L)
– Road Kinshasa-Matadi, at 10 km E of the station of Kimpese.

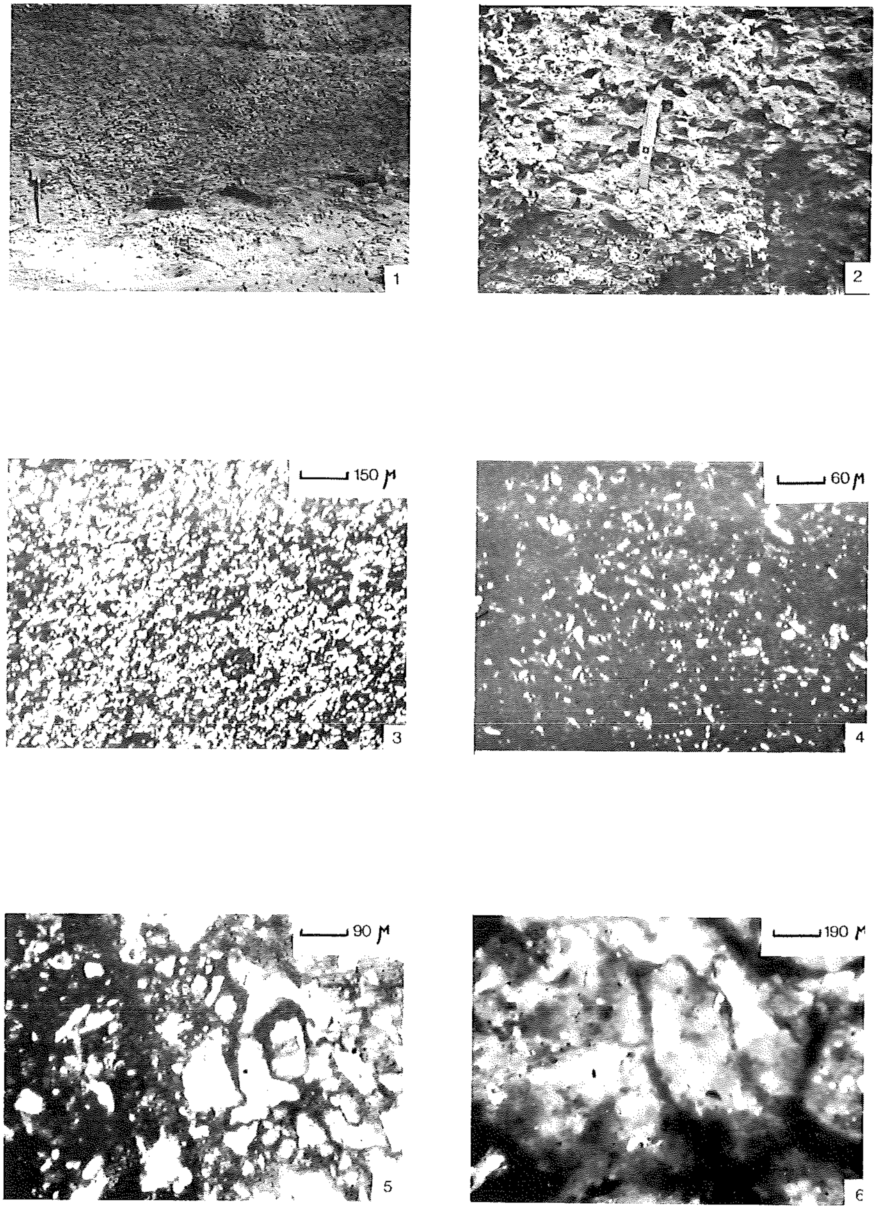

Fig. 2.

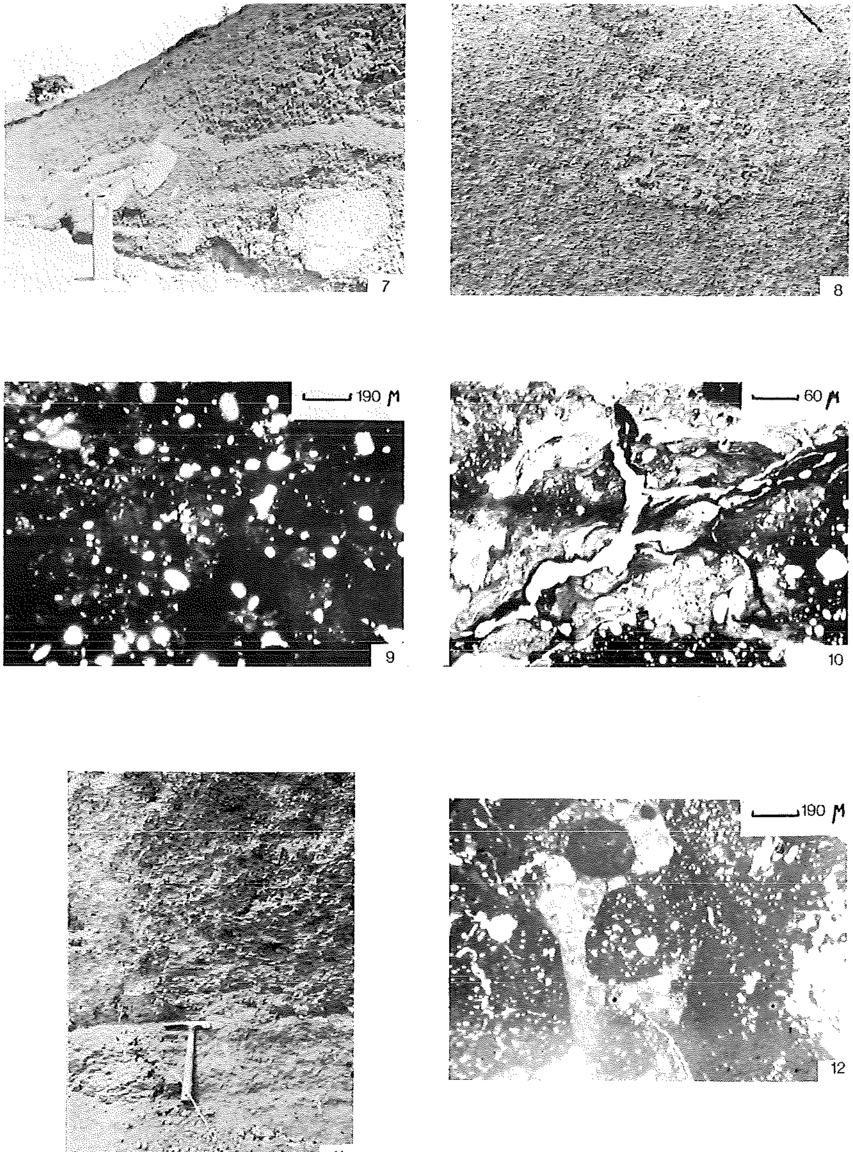

Fig. 3.

During the dry season dissecation cracks affect the whole weathered material, their pattern correspond to a more or less polythedral grid. Dehydration promotes migration of iron solutions, perpendicular to the cracks. In this way iron is fixed up by oxidation in the clays surrounding the cracks. They form internal ferric iron coatings by replacing of the kaolinite.

Seasonal repetition of these processes is responsible for formation of several parallel laminae, this by shrinking of the iron-charged clays by dehydration. In the meantime the whole material is reworked into neoformated clay, charged with iron solutions. Mechanical translocation of clay is responsible for the parallel disposition of the argillans filling up cracks and conducts. Each parallel clay layer has a different colour, from pale yellow to dark yellow, and to dark brown due to difference in iron-content.

By constancy of the conditions and continuity of the processes the whole inside of the grid can be reworked and becomes iron-cemented.

Fig. 3.

Photogr. 7 – Lateritic cuirasse buried under a detrital deposit; the cuirasse contains boulders of reworked older cuirasses.
– Road Kimpese-Luozi, S of Malanga.

Photogr. 8 – Lateritic cuirasse composed of a concentration of ferric nodules, ferric grenailles, quartz and polymorphic sandstone.
– Idem Photogr. 7 – Detail.

Photogr. 9 – Upperpart of a cuirasse
Note : – white spots : quartz
(P L) – greyish parts : iron oxides
– black parts : manganese oxides
– Depression S of Kimpese.

Photogr. 10 – Degradation of a cuirasse by clay-illuviations
Note : – the successive clay-illuviations with a different content of iron
(P L) – internal migration of iron towards the joints.
– Depression S of Kimpese.

Photogr. 11 – The hammer indicates the position of the croûte, below the allochtonous carapace (Photogr. 6). Note the sharp transition between both.
– Road Kinshasa-Matadi, at 10 km E of the station of Kimpese.

Photogr. 12 – Croûte
Note : – dark parts : Mn, with a nodular or a lamellar facies.
(P L) – pale zones : voids filled up by floculated clays.
– Same place Photogr. 11.

In this extreme case, the typical macroscopical aspect of the iron-cemented skeleton, with a multitude of alveoles, is lost. Only a few microscopical voids persist, reducing entirely the porosity of the horizon, that becomes very massive and resistant. In that case, there is some macroscopical resemblance with the "cuirasse". Evolution of this nearly total hardening starts always on top of the horizon, in exceptional conditions (longer oxidation period), an entire reworking goes on till the lowest limit of the horizon.

In most cases only a part of the horizon gets this massive aspect.

2. "Cuirasses"

As well the characteristics of the material (mainly relatively fresh coarse material), as the morphological environment of formation (swampy depressions : dembos), and the mechanism of iron enrichment (absolute increase) and the process of induration (important evaporation by high temperature), distinguish the "cuirasses" from the "carapaces". Nevertheless, in some extreme cases of evolution slight resemblances can be observed.

2.1. Macroscopical examination : aspect and kind of material (fig. 3, photogr. 7 and 8).

The cuirasses have a conglomeratic aspect, due to the presence of heterogeneous coarse grain-supported material. The constituents are mainly slightly rounded nodules derived from carapaces situated higher up, on the slopes. The rest of the coarse material is almost resistant to weathering : "grenailles" (well rounded), quartz, quartzites, silex, polymorphic sandstone and sometimes blocks of reworked cuirasses.

The mean size of the coarse material is about 0,5 cm in diameter, but some blocks reach about 0,5 m in diameter. The interspaces are filled by a yellow-ocre fine material, which is massively cemented by ferric iron.

Vertical profiles show sections in large braided channels overlying the substratum. These are remains of the primary sedimentary structure and testify of the mechanism of the transport of the material by rillwash, active during more arid periods. In the center of the depression a pavement of several meters in diameter is observed. This concentration of coarse material took place before the cuirasse formation. This needs alternating wet and dry seasons, wet responsible for the enrichment with iron solutions, dry necessary to the precipitation and induration of iron, mainly ferric, with some Mn. Cuirasses are generally reddish brown to dark brown. In the top of the horizon, the Mn-content sometimes becomes relatively important. In some cases, subhorizontal black laminae of Mn, covers the top of the cuirasse horizon. The whole horizon can reach a thickness of about 2 to 3 cm of Mn.

Cementation by ferric iron assures the mechanical resistance of the cuirasses, which is somewhat more important in the upper part of the horizon.

Some termite conducts have no internal ferric coating, their activity is posterior to the cementation of the cuirasse. Nevertheless, some rare cracks with a grid pattern, probably due to dessication, are filled up by a brilliant ferric precipitation. This bursting happened before or contemporary to the ferruginisation.

2.2. Microscopical examination (fig. 3, photogr. 9).

The study of thin sections shows clearly the conglomeratic character of the cuirasses. They are composed of a nearly grain-supported coarse material surrounded by a ferric-skeleton, corresponding roughly to the interspaces.

Some of the coarse material "grenailles" show more or less parallel aggradation coatings, which are slightly eroded on the surface, due to mechanical erosion before their deposit. The interstitial sandy-clay fine material is cemented. This massive ferruginations consist of yellow-brown laminae. The intergranular ferric concretions reduce very much the porosity. This element is one of the most important features of distinction between carapaces and cuirasses. The massive, complete ferric induration of the fine material is responsible for the conservation of the initial sedimentary features.

The profile shows a more advanced evolution of the very top of the horizon, where detrital elements are covered by concentric manganese-coatings. In the lower part this coatings are composed by ferric-iron. Near the surface the number of continuous coatings increases till about ten. These external coatings cover several nodules, indicating a post-sedimentary deposit.

Lamellar horizontal crusts cover the top of the cuirasses. They are composed by alternating massive black Mn precipitations of about 30 to 50 μm, intercalated by a bad structured material, composed of clay and detrital sands with a slight ferric induration. The brown-blackish colour suggests the presence of organic material. Rill-wash filtered by vegetation is responsible for the presence of this fine detrital inondation deposit. After evaporation, Mn precipitates on top of it. The Mn-content is about 20%, the iron content about 6,5%. Within the cuirasse, we obtain 2% of Mn near the top and about 0,015% downwards. The Mn enrichment is obvious in the summital sequences of the cuirasses.

2.3. Formation of cuirasses.

Formation of cuirasses requires well defined conditions of topography and sedimentology, related to alternating climates.

During a primary savannah episode carapaces are elaborated within the horizon of a seasonly oscillating water-table.

During a more arid period, very exceptional rainfalls are characterized by important quantities of water, delivered in a very short time. In this way, sedimentary fans and large depressions develop on feet of high reliefs, this by the abrasif material, mostly by detrital nodules of carapaces, in charge of sheetfloods.

On slopes, the upper part of carapaces is cut off. This material covers depressions by several meters.

During the recent savannah period, a permanent water-table established near the surface. At the end of the rain-season, depressions become swampy. This hydromorph zones are enriched by iron and Mn solutions, due to oblique movement of subcutanean infiltrating water. Conditions of restricted drainage and of high daily temperature are responsible for a high daily evaporation, after each rain.

The process responsible for the precipitation of sesquioxides, is related to evaporation affecting rising capillary waters, charged with Fe and Mn-rich solutions. Induration of Fe and Mn mainly happens during dry season.

The intergranular cement is rather ferric to the base of the horizon, manganiferous to the top. Mn is more soluble than Fe and precipitates later. Intergranular goethite and pyrolusite laminations fill up the pores.

Direct superficial evaporation is responsible for the elaboration of cyclothemic Mn-laminations on top of the cuirasses.

Briefly, conditions propitious to the formation of lateritic cuirasses can be resumed as follows : (a) a depression with allochthonous detrital material, composed of coarse nearly grain-supported material, intercalated by a fine fraction, (b) a bad drainage of the area, (c) a vertical infiltration deficit. Restricted drainage prohibit percolation of water-charged with elements. Precipitation of these elements and the neo-formation of ferric iron crystals permit development of a compact, massive cuirasse.

Further evolution of the cuirasses results in a nearly complete weathering of the coarse material. The new-formed clays become susceptible to illuviation (fig. 3, photogr. 10). The indurated interspaces become now the resistant skeleton of the horizon. The form of this skeleton is determined by the boundaries of the disappeared grains.

2.4. Localisation of the "cuirasses".

Two kinds of positions can be distinguished :

2.4.1. On the feet of the high reliefs, *"cuirasses de piémont"* occurs. These "cuirasses" have a longitudinal slope of about 1%, their extension can surpass 1 km in length and in width. Initially, these indurated surfaces were developed in a slight depression. At present, as a result of the downwasting of the landscape, these relict formations are generally situated on top of the platforms. The mechanical resistance of these formations is responsible for the maintenance of this inverted landscape forms.

2.4.2. On top of the platforms, consisting of a "carapace", or of a substratum (limestone or calcareous schist), in which the *"cuirasse en lanière"* is developed. The elongated, straight disposition of this "cuirasse" is due to the association with the underlying grid of joints and diaclases. Their length is variable and can surpass 1 km, their width does not surpass 20 m. This formation developed in allochtonous sedimentary material that is massively indurated by ferric iron and Mn. The "cuirasse" has an erosive contact with the supporting "carapace", or the substratum. The top of the platforms remains flat, no level transition between the "carapace" and the "cuirasse" is visible. At present, these areas are covered with a series of swamps, which have the same disposition as the underlying karstic joints. This surface hydromorphism, on top of the platforms, indicates a restricted drainage, probably due to dissolution clays at the base of the formation.

The field observations have been corroborated by cave studies. A dense grid of galleries, with a bayonet-like pattern, crosses the underground at several levels. Intense dissolution along diaclases and joints, over long distances, can be observed. Some of the diaclases are partially filled up by an indurated "cuirasse"-material and voluminous detrital "cuirasse"-blocks, issued from the cave ceilings are found between the typical cave deposits. They indicate a progressive destruction of the "cuirasse" due to karstic activity.

3. "Croûtes"

The horizon below the "carapaces" shows a slight induration of the friable material, with a granular aspect (fig. 3, photogr. 11). The indurated debris are about 1 to 2 mm in diameter. The grid surrounding the alveoles in "carapaces" has no complete development in "croûtes".

3.1. Aspect and kind of material (fig. 3, photogr. 12).

The studied "croûte" is formed in allochthonous material. Chemical analyses show a high concentration of Mn, up to 3%. In the overlying "carapaces" only 0,015% of Mn was found. A microscopical examination shows two possible facies : a nodular one and a lamellar one. The last contributes to the formation of a discontinuous Mn-grid. Mn-nodules are spheric or ovoid, with in some cases concentric growth-coatings.

In most cases, voids, due to weathering, are filled up by pyrolusite crystals.

Mn-laminations have a slight resemblance with the ferric-laminations composing the grid in "carapaces". The scarcely developed Mn-grid confers no cohesion to the weathered material, neither do the iron that is represented as diffuse ponctuations. The whole is conserving a good porosity. Big pores are covered by an agglomerated yellowish clay, conferring a high permeability to the "croûtes".

On weathered calcareous schists, croûtes underlying "carapaces", are not quite evident. The cementation is only visible with the microscope which shows discontinue patches of ferric-laminae, roughly oriented by schistosity. Chemical analyses show a negligible Mn content of about 14 p.p.m. No growth due to induration is observed. "Croûtes" on calcareous schist are defined by analogy of position, with "croûtes" in allochthonous material. These "croûtes" cannot be recognized in the field.

3.2. Formation of "croûtes".

The formation of "croûtes" is related to their position : they are underlying "carapaces" and susceptible to a systematic lowering of the watertable, due to climatic changes. Before the lowering, the horizon was affected by reduction with an important leaching from the overlying carapace (during formation). After becoming oxidant, the same horizon received the most mobile elements, principally Mn. This horizon composed of allochthonous material became very porous probably due to preceding weathering and to the presence of agglomerated clays.

Formation of Mn-nodules and laminations took place in the same time as the lowering of the water-table and the climatic change.

The more stable tri-valent Fe resisted easier to this mobilisation. It was of little importance to the formation of the very porous "croûtes".

On weathered calcareous schist, a limited permeability reduced the oxidizing effect and Mn was not retained.

The formation of "croûtes" is due to an important and a quick lowering of the water-table. Only a desertification of the climate can explain them.

More and more drier seasons were responsible of the lowering and of the leaching of the most mobile cations. Their fixation happened in very permeable horizons, which become oxidized. Flocculation of clays increased the aptitude of oxidation.

Formation of "croûtes" beneath carapaces probably corresponds to a very short period of climatic transition from savannah till desertification. A more slow transition should have left a more diffuse and progressive contact between "carapace" and "croûte".

Conclusion

Ferric indurations can affect detrital material as well as the substratum of calcareous schist.

According to their aspect and their genesis, one can distinguish :

- Ferric "carapaces" affecting the allochthonous material or the substratum without preference. "Carapaces" are composed by a grid of alveoles, comparable to a "nid d'abeilles". They conserve a high porosity and in consequence a high permeability. They developed under a savannah-climate, in a horizon affected by a seasonly oscillating water-table ;
- Laterized "cuirasses" are massive and very compact, they are enriched by Mn in their upper part. They developed in an allochthonous material localized in depressions with a restricted drainage. Their induration is due to an important evaporation of the interstitial water ;
- "Croûtes" are weakly coherent and very crumbly, due to an incomplete induration, characterized by spherical or ovoidal Mn-nodules. Such an horizon results from the general lowering of the water-table and from a remobilisation of the Fe and the Mn, leached down from the overlying "carapaces" or "cuirasses".

"Carapaces" and "cuirasses" are very resistant to chemical weathering and to mechanical processes. Karstic dissolution, characterised by piping, is one of the principal degradation processes in "cuirasses".

Old "carapaces" and "cuirasses" can generally be observed in an inverted position in the relief.

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