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In Situ Genesis of Alumino-Ferruginous Nodules in a Soil Profile Developed on Garnet Rich Micaschist in the High Reliefs of South Cameroon Rainforest Zone (Central Africa)

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Abstract: The aim of the study is to highlight in detail using microscopic observations, coupled with mineralogical and geochemical analyses, the genesis of alumino-ferruginous nodules formed during weathering of a garnet rich micaschist in the high reliefs of the south Cameroon plateau. Morphologically, the studied profile is characterized by four horizons from bottom to top: (i) an isalteritic horizon in which there are numerous crystals of garnet with intragranular fracture coatings, which isolate either the original garnet grain fragments or alveolar voids with crystals of gibbsite; (ii) an alloteritic horizon with slightly indurated nodules surrounded by a discontinuous perinodular “micaceous cortex” which marks the original flow structures of the original bedrock, and where intragranular fracture coatings still isolate alveolus with gibbsite crystals; (iii) a nodular horizon characterized in addition to the properties noted below either by an orange-brown birefringent micromass or a darker and undifferentiated micromass; and (iv) a set of clayey and loose horizons with few nodules, which always show gibbsite crystallarias as in other horizons. Mineralogically, traces of kaolinite are recorded only in the weathering garnet in the isalteritic horizon. Other nodules are made of three secondary minerals gibbsite, hematite and goethite. Geochemically, there is a high expression of aluminium in nodules whose composition remains dominated by silica. Globally, those nodules are formed *in situ* from original garnet grains as well illustrated by the presence of discontinuous perinodular “micaceous cortex” and the compartmentalized structure. They are named alumino-ferruginous nodules due to their enrichment in gibbsite, hematite and goethite. This is a typical example of *in situ* formation of nodules from primary minerals which characterize the south Cameroon plateau high reliefs. This process may be extended to the high reliefs of the intertropical rainforest zone not capped in the past by iron duricrust, thus without any iron duricrust relicts.

Keywords: Alumino-ferruginous nodules, micaschist, high relief, microscopy, mineralogy, geochemistry, Cameroon.

1. INTRODUCTION

Micromorphology is a method of studying undisturbed soil and regolith samples with microscopic and ultramicroscopic techniques in order to identify their different constituents and to determine their mutual relations, in space and time [1]. It has been applied in the search for the processes responsible for the formation or transformation of soil, in general, or of specific features, whether natural as nodules or artificial as irrigation crust or plough pans [1]. It is a new approach to examine the history of landscapes, where one can see how the landscape has been humanized over the past years or even how farming techniques have evolved since the Neolithic [2, 3]. In the south Cameroon plateau, characterized by elevations frequently between 600 and 800 m asl, many soil studies have been done based on this micromorphology. Those studies, coupled with mineralogical and geochemical analyses, have reported the predominance of kaolinite in soils, always associated with goethite, hematite and more incidentally gibbsite [4-6]. Gibbsite, although poorly represented in this landscape is a secondary Al-hydroxide of which the occurrence is reported worldwide [7-9]. Higher concentrations of this mineral are normally detected in soils of an advanced weathering stage [9]. Its occurrence is often explained by weathering processes in humid and warm climates in an early stage resulting in a relative quick removal through hydrolysis of most silicate silica, alkali and alkaline earth elements, with only aluminium in the form of gibbsite and/or iron in the form of goethite remaining [10]. Through microscopic observations, the source of this gibbsite mineral is indicated [8, 11, 12]. However, high permeability and good drainage allow the direct formation of gibbsite from primary minerals [13]. Those conditions are brought together mostly in high rainfall and high elevation landscapes [9].

The aim of the present study is to highlight in detail using microscopic observations, the genesis of alumino-ferruginous nodules occurring during weathering of a garnet rich micaschist in the high reliefs which emerge from the south Cameroon plateau. In addition to microscopic observations, mineralogical and geochemical approaches will be used in order to better understand the genesis and the nature of nodules.

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2. ENVIRONMENTAL SETTING

The study site is a small elementary watershed located between 13°24'00" and 13°24'14" East, and between 3°43'33"and 3°44'09" North (Fig. **1**). The climate is an equatorial type with two dry seasons alternating with two wet seasons and a mean annual rainfall of 1640 mm, a mean annual temperature of 23°C and a mean annual relative humidity of the air of 80% [14, 15]. Due to its high altitude (840 m), the studied site emerges from the whole south Cameroon plateau landscape globally situated between 600 and 800 m asl, and is a part of the high reliefs of southern Cameroon rainforest zone. The slopes are slightly inclined

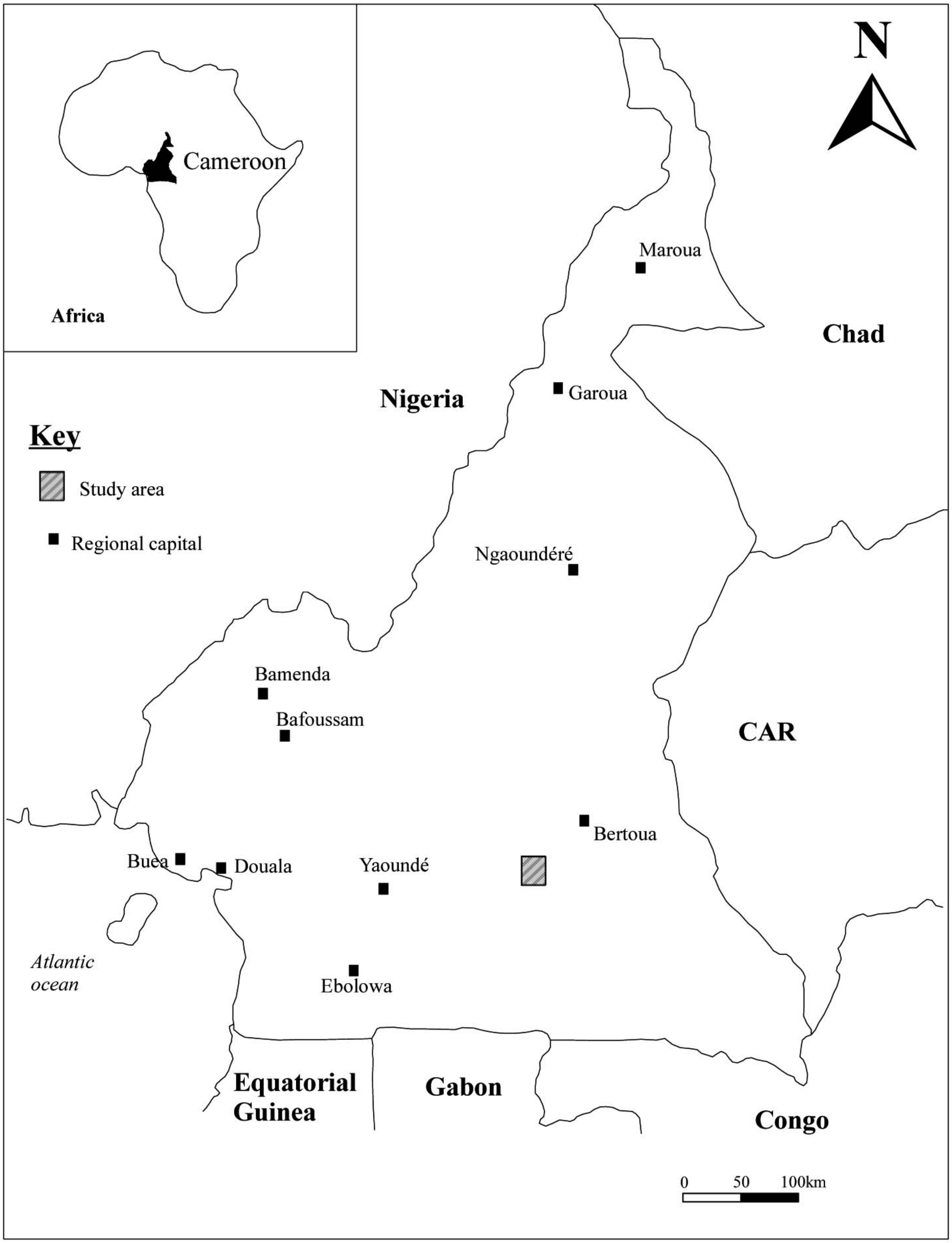

Fig. (1). Location of the study area.

(6-10%), separated from each other by narrow and outstretched valleys. The vegetation is a virgin forest characterized by the presence of large trees below which there is an abundant litter. The bedrock is a garnet rich micaschist. In addition to garnet, muscovite, biotite, feldspar and quartz are also present. Microchemical analyses reveal that garnets are of grossularite rich almandine type as shown in Fig. (**2**) [16, 17].

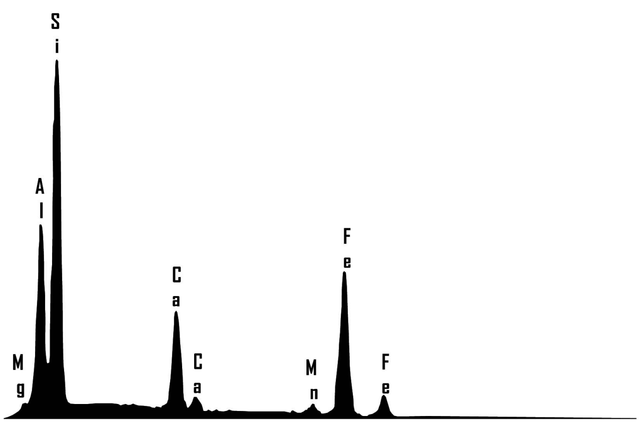

Fig. (2). Microchemical diagram of garnet extracted from the bedrock.

3. MATERIAL AND METHOD

A detailed study of topographic maps of Abong-Mbang at 1:500000 and 1:200000 and the geological map of Vicat (1998) [18] permitted the selection of the study site. The selection of the geomorphological unit on which the pit has been dug was partially based on the works of Bitom *et al.* (2004) [5]. The soil profile was described and samples were collected for laboratory analyses.

In the laboratory, three main types of analyses were conducted: microscopic, mineralogical and geochemical analyses.

Microscopic analyses consisted of observations under polarizing microscope of fifteen soil and two rock thin sections. Soil thin sections were obtained after impregnation with resin and then hardening in the air following the protocol of Hanrion (1976) [19]. Soil thin sections have been described using the terminology proposed by Stoops (2003) [1].

Mineralogical analyses were done *via* X-ray diffraction (XRD) on total samples powders, using a Philips PW2400 XRF spectrometer with copper anode and equipped with a xenon detector, with the following characteristics: wavelength $\lambda = 1{,}54 x 10^{-10} m$, energy E = 40 kV.

Geochemical analyses were made by X-ray fluorescence on total samples powder using a Philips PW 1404 WD XRF spectrometer. The detection limit is 0.01%.

4. RESULTS

4.1. Morphological Characteristics of the Profile

4.1.1. Macroscopic Characteristics of the Profile

The profile has a depth of more than 9 m. It has seven horizons which are, from bottom to top (Fig. **3**):

More than 9.50 to 8.25 m. Isalteritic polychrome horizon with gray yellow or purplish gray millimetre domains with red lining in which the structure of the bedrock is well preserved, sandy-loamy texture, presence of numerous brown pink globular crystals of garnet (10-20% of horizon), presence of blocks of quartz (5-10% of the horizon) and unweathered muscovites.

Gradual and Irregular Boundary

8.25 to 6.20 m. Red alloteritic horizon (2.5YR4/6) with many isalteritic relicts and nodules; nodules are globular and slightly indurated (35-45% of the volume of the horizon); their fracture is dark brown with yellowish lining; presence of ferruginised friable quartz blocks; nodules, blocks of quartz and isalteritic relicts are embedded in a red clayey matrix with a very weakly developed blocky structure. Isalteritic relicts are loose, millimetre to centimetre and show a distinct limit with the matrix.

Gradual and Regular Boundary

6.20 to 4.60 m. Nodular horizon composed of about 40% of nodules embedded in a red clayey matrix (10R4/6) with fine blocky structure; presence of isalteritic duricrust blocks (2%) and numerous brittle ferruginised quartz. Nodules are millimetre, indurated and have globally a smooth and dark brown fracture, sometimes with whitish lining.

Distinct and Irregular Boundary

4.60 to 3.30 m. Dense deep red horizon (10R4/4), clayey, weakly expressed blocky structure, presence of ferruginous millimetre nodules (about 10% of the horizon).

Gradual and Irregular Boundary

3.30 to 1.50 m. Red aliatic horizon (10R4/4), clayey, fragile with fluffy consistency, high matrix porosity, presence of millimetre ferruginous nodules (about 3% of the horizon).

Gradual and Irregular Boundary

1.50 to 0.08 m. Compact red horizon (10R4/4), clayey, fine blocky structure, presence of dark red and shiny clay skins on some aggregates, low biological porosity mainly of tubular type.

The three red horizons located above the nodular horizon, although displaying different structural characteristics have identical mineralogical and geochemical characteristics in the humid tropical zone [20].

The transition to the humiferous surface horizon is gradual and regular.

0.08 to 0 m. Very dark red humiferous horizon (10R2.5/2), clay-sandy texture, weakly expressed lumpy structure, presence of numerous millimetre roots and rootlets, high matrix porosity.

4.1.2. Microscopic Characteristics of Soils

Macroscopic observations made in the field have permitted the identification of four major horizons at the studied site. These are: (1) isalteritic horizon, (2) alloteritic horizon, (3) nodular horizon and (4) a set of upper loose horizons.

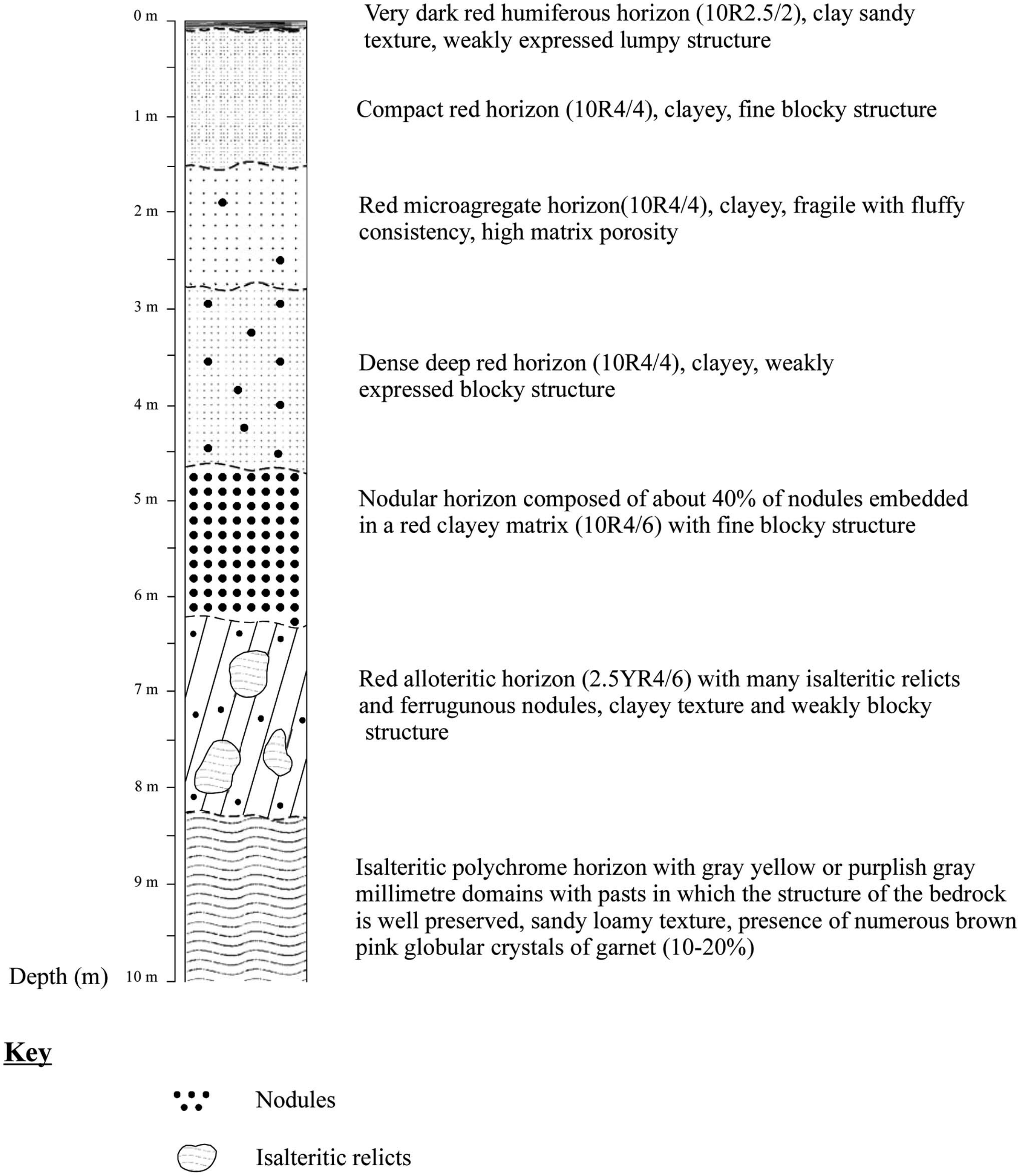

Fig. (3). Macroscopic organization of the studied soil profile.

4.1.2.1. Isalteritic Horizon

The isalteritic horizon is yellowish gray with reddish lining. It is characterized by the well preserved structure of the original foliated rock. Under the polarizing microscope, the groundmass consists mainly of coarse material (about 80% of the groundmass). The micromass represents less than 5% of this groundmass.

Coarse material is composed of quartz, muscovite, biotite and garnet (Fig. **4**). Most minerals are being altered. Quartz crystals are cracked and sometimes fragmented. They are frequently encrusted by a ferruginous dark brown and undifferentiated micromass.

Garnets are fractured and contain inclusions of quartz and muscovite (Fig. **5a**). There are orange brown to yellow-orange iron oxides which highlight the contours of the mineral or are intragranular fracture coatings, highly birefringent and goethititic, which isolate either the original garnet grain, or alveolar voids formed by the dissolution of these original garnet grains. Within some alveolar voids and even on some intragranular fractures, there are crystals of gibbsite.

Most muscovites remain intact and still have vivid polarization colour effects. Others are altered and show the polarization colour effects of kaolinite. Both kaolinite and muscovite contours are stressed by iron oxides.

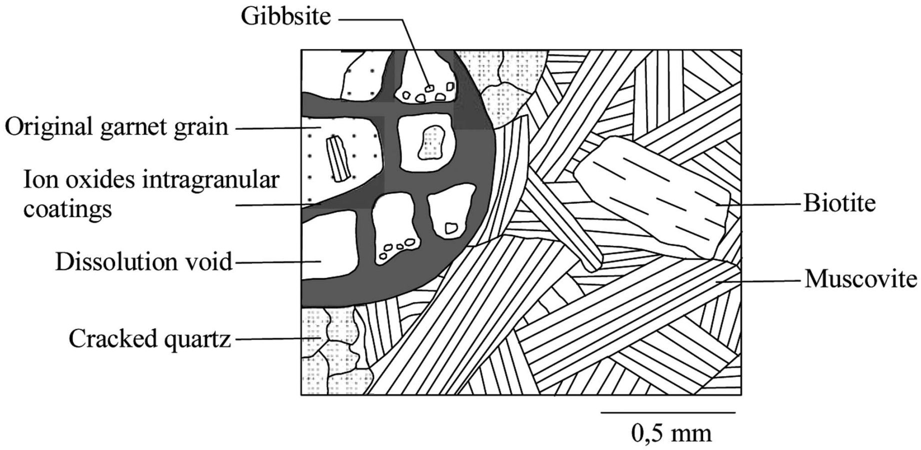

Fig. (4). Microscopic organisation of the isalteritic horizon.

Biotites are altered and show also the polarization colour effects of kaolinite. Their cleavages are highlighted by brown iron oxides which may opacify some crystals.

In domains with biotite and muscovite, there are many gibbsite crystals, showing the direct transformation of micas into gibbsite (Fig. **5b**). Many accordions of kaolinite are also present (Fig. **5c**, **d**). They are corroded (Fig. **5c**) and their size varies between 0.25 and 0.75 mm. Within kaolinites, there is an individualization of gibbsite crystals (Fig. **5d**), covered by a brown ferruginous veil. This seems to be an alteration of kaolinite into gibbsite, which may appear in iron oxides rich environment.

4.1.2.2. Alloteritic Horizon

Alloteritic horizon consists of red loose clay matrices in which there are isalteritic relicts and slightly indurated nodules.

Loose clay matrix. Under the microscope, loose clay matrices are characterized by a weak to moderate separated granular microstructure. It shows a red micromass weakly birefringent with locally an undifferentiated b-fabric, but sometimes with a stipple speckled b-fabric. Many sequins of muscovites are dispersed in the red micromass (Fig. **6**). They are generally ferruginised. Except their edges which are opacified by iron oxides, these muscovites still preserve their vivid polarization colour effects.

In addition to muscovite, coarse material consists of angular and corroded quartz grains, generally highly fissured. Their size varies greatly and the largest crystals reaching 0.5 mm. Coarse materials represent about 30% of the red loose clay matrix, with double spaced porphyric related distribution patterns.

Voids represent about 30% of the red loose clay matrix, and are mostly star-shaped vugs. Their diameter is variable and may reach 0.75 mm.

Nodules. Microscopically, nodules present clearly the compartmentalized structure of the garnets described in the isalteritic horizon (Fig. **6**). Their limits are highlighted by a dark ferruginous undifferentiated micromass. The intragranular fractures isolate alveolus in which there are gibbsite crystals (Figs. **5e**, **6**) and sometimes quartz and muscovite crystals. Original garnet grains have totally disappeared. Most nodules have a fine discontinuous cortex of muscovite (Figs. **5e**, **6**).

Compared to the “ghosts” of garnets observed in the isalteritic horizon (Fig. **5a**), nodules are characterized here by the absence of relicts of original garnet grains and by ferruginous yellowish brown and very birefringent intragranular fracture coatings, essentially of goethite nature. One can note the persistence of quartz and muscovite inclusions, and the maintenance of discontinuous “micaceous cortex” which marks the original flow structures of the original bedrock. Such nodules from the isovolumetrically alteration of garnets have been called alteromorph nodules by Stoops (2003) [1]. Some nodules are pseudomorphosed completely by iron oxides. They show a dark undifferentiated micromass of hematitic nature in their inner part, while on their limits there are yellowish brown and very birefringent fracture bits, of goethitic nature. Globally, there is a development of fissures which isolate partially the nodules from the micromass.

Isalteritic Relicts. Isalteritic relicts have the same characteristics as those described in the isalteritic horizon. However, one can note that some muscovites are weathered; they have lost their vivid polarized colour effects and take those of kaolinite. There are many gibbsite crystals between muscovite sheets. In the final stages of weathering, muscovites seem to be resolved into smaller clusters crystalline gibbsite not conserving the original form of the mineral, generally covered by a ferruginous yellowish veil, marking a direct alteration of muscovite into gibbsite.

4.1.2.3. Nodular Horizon

The nodular horizon consists of a red clayey matrix in which there are nodules and millimetre to centimetre iron isalteritic duricrust.

The internodular groundmass has the same characteristics as that observed in the alloteritic horizon. Cracked quartz plates of varying sizes with the largest reaching 1mm x 6mm.

Nodules show a groundmass consisting of an orange-brown birefringent micromass (goethitic) or a darker and undifferentiated micromass (hematitic) (Fig. **5f**, **g**). The compartmentalized structure described in the underlying

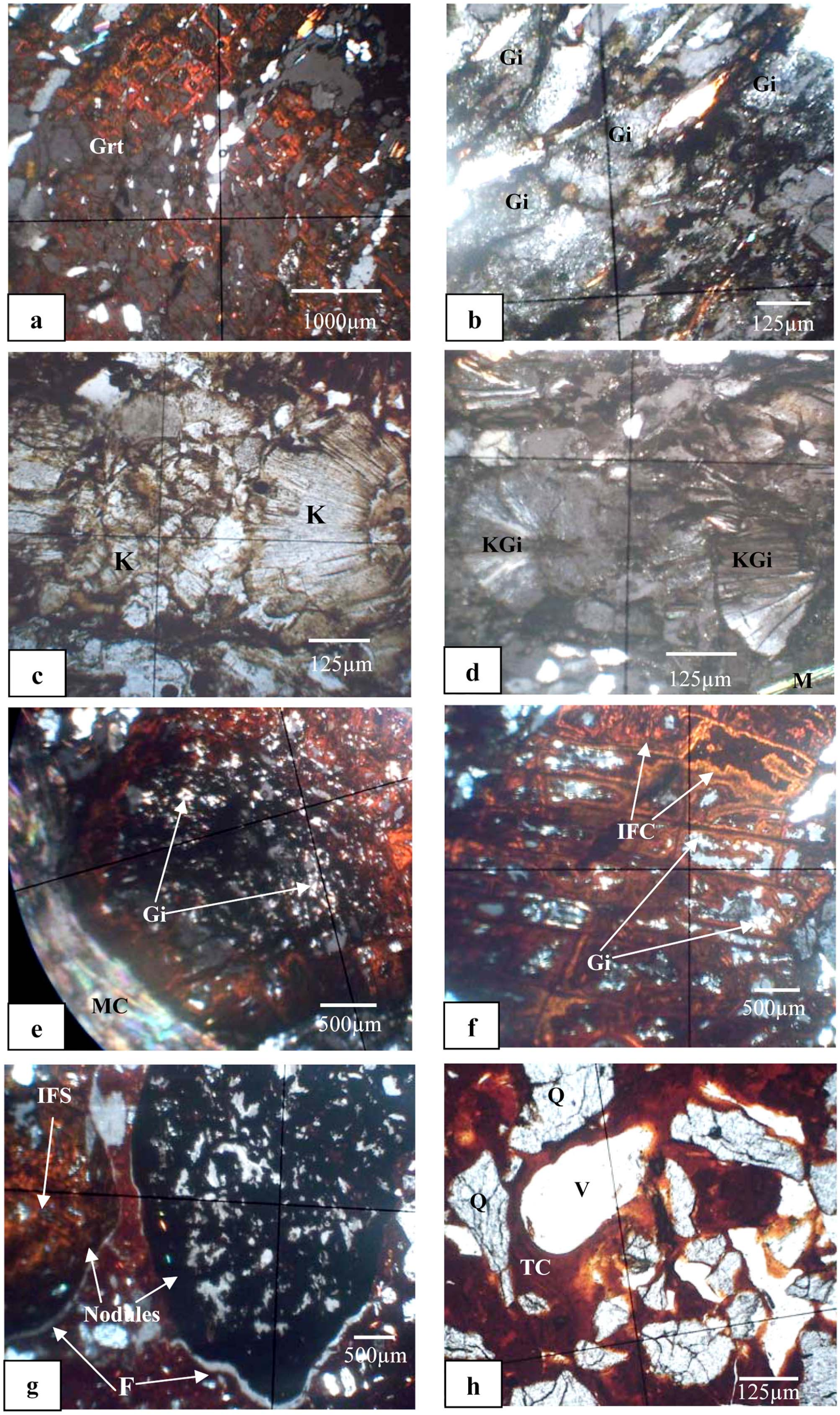

Fig. (5). Microscopic organization of the studied soils (Grt: garnet; Gi: gibbsite; K: kaolinite; KGi: gibbsite crystals within kaolinite; M: mica; MC: micaceous cortex; IFC: intragranular fracture coatings; F: fissures; TC: typic coatings; Q: quartz; V: Void). (**a-d** from the isalteritic horizon; **e** from alloteritic horizon; **f**, **g** from the nodular horizon; **h** from the compact horizon of the Set of clayey and loose horizons).

horizon is still visible, but very blurred. The intragranular fracture coatings are much thicker and most of the alveolar voids are erased. However, many highly birefringent crystals of gibbsite are observed within voids (Fig. **5f**). Inclusions of cracked quartz and altered muscovite are still present. The cracked quartz and muscovite are ferruginised. The discontinuous perinodular “micaceous cortex” and fissures which isolate partially the nodules from the micromass observed in the alloteritic horizon remain clearly visible (Fig. **5g**).

Isalteritic iron duricrust blocks seen under polarized microscope present the characteristics of isalteritic relicts described in the former horizons, but very ferruginised and even show orange and birefringent coatings on void walls. In addition, nodules found within them have many alveolar voids (dissolution voids). Most muscovites show the polarization colour effects of kaolinite. Crystallization of gibbsite remains observable within alveolar voids and between muscovite sheets.

4.1.2.4. Set of Clayey and Loose Horizons

It is subdivided from bottom to top into a dense deep horizon, an aliatic horizon, a compact horizon and a humiferous horizon at the surface. Microscopic observations have not been made in the humiferous horizon.

The internodular groundmass described in the nodular horizon occupies about 60% of the volume. It has a moderately to highly separated microstructure, with characteristics similar to those described below. It contains a few nodules smaller or equal to 3 mm in diameter. The contours of these nodules are distinct, directly in contact with micromass. Nodules always show gibbsite crystallarias as in other horizons observed in the lower part of the soils.

Coarse material represents 10 to 20% of the groundmass, with double spaced porphyric to open porphyric related distribution patterns. It consists mostly of subangular quartz grains, cracked and epigenisied by iron oxides. The largest crystals reach 2 mm in diameter. Quartz grains are associated with a few small size muscovites. Beside the coarse material, there are isalteritic relicts consisting essentially of altered and ferruginised muscovites, with gibbsite crystallarias.

Voids represent 20 to 25% of the groundmass. They are irregularly shaped and mostly represent compound packing voids. Their diameter reaches 1.5 mm.

The compact horizon below the humiferous horizon is characterized by the presence of red typic coatings on the walls of some voids (Fig. **5h**).

In order to better understand the genesis of nodules in the soil profile, mineralogical and geochemical characteristics are presented for both in loose and in indurated materials.

4.2. Mineralogical Characteristics

Mineralogical disparities exist between loose and indurated materials.

Loose materials are constituted mainly of gibbsite and kaolinite (Table **1**); these two minerals are associated with quartz and muscovite, and sometimes to goethite and/or hematite (Table **1**). Gibbsite is slightly more abundant than kaolinite at the base of the profile, while the tendency reverses somewhat in the surface. Muscovite is fairly well represented, but its proportions decrease from bottom to top of the profile where it exists only in traces (Table **1**). Quartz is everywhere well represented (Table **1**). Goethite and hematite hardly coexist within the studied loose materials; goethite is thus present alone in the isalteritic horizon, while in the rest of the loose materials, only hematite is present (Table **1**). In addition, anatase is observed in the alloteritic and the nodular horizons (Table **1**).

Indurated materials (nodules and “ghosts” of garnet) are constituted mainly of gibbsite, this mineral being associated with goethite, hematite and quartz (Table **1**). Gibbsite reaches its maximum expression in the nodules of the nodular horizon. As for iron oxides that go together with gibbsite, goethite expresses itself in equivalent quantity in all the indurated materials, whereas hematite reaches its maximum in the nodules of the nodular horizon. Quartz remains well represented (Table **1**). Beside these minerals,

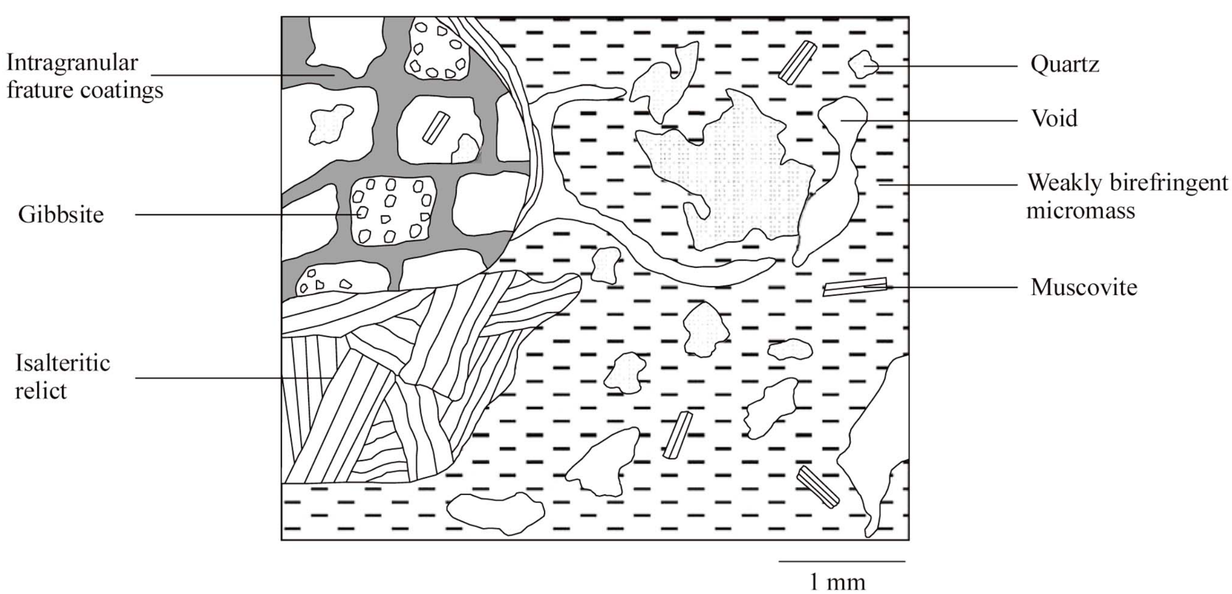

Fig. (6). Microscopic organisation of the alloteritic horizon.

Table 1. Mineralogical Composition of Soils

Horizons	Minerals	M	K	Gi	Goe	He	Q	A
Set of clayey and loose horizons	(1.25 m)	+	+++	++	/	+	++++	/
Nodular horizon	Nodules (5.5 m)	+	/	++++	++	++	+++	/
	Fine earth (5.5 m)	++	++	++	/	+	++++	+
Alloteritic horizon	Nodules (8 m)	+	+	+++	++	+	+++	+
	Fine earth (8 m)	++	++	++	/	+	++++	+
Isalteritic horizon	Garnet "ghost" (9 m)	++	+	+++	++	+	++	+
	Isalterite (9 m)	+++	+	++	+++	/	+++	/

/: non identified; +: traces; ++: very deficient; +++: deficient; ++++: abundant; M: muscovite; K: kaolinite; Gi: gibbsite; Goe: goethite; Q: quartz; He: hematite; A: anatase

one can observe in non negligible quantities muscovite, sometimes associated with traces of kaolinite and anatase (Table **1**). Kaolinite and anatase, detected in the nodules of the weathering horizons, are completely absent in the nodules of the nodular horizon (Table **1**).

4.3. Geochemical Characteristics

Geochemical disparities also exist between loose and indurated materials.

In loose materials, it can be noted that all the major elements are well represented, including alkali and alkaline-earth (Table **2**). Contents vary thus between 50.68 and 62.60% SiO_2 for Si, the most abundant element, 14.03 and 20.34% Al_2O_3 for Al, 5.62 and 6.23% Fe_2O_3 for Fe, or 1.32 to 4.02% of oxide for bases K, Na, Ca or Mg (Table **2**). Titanium is also present, but in lesser quantities (0.56 to 0.99% TiO_2), as well as phosphorous whose contents hardly pass 0.31% P_2O_5 (Table **2**). The $\frac{Si}{Al}$ ratio, widely higher than 1 (2.23 to 4) (Table **2**), is consistent with the strong persistence of the primary minerals, quartz and muscovite, in the studied soils. In detail, one can note that silica contents decrease from the isalteritic horizon (9 m) to the alloteritic horizon (8 m), increase thereafter from the alloteritic horizon to the nodular horizon (5.5 m), before decreasing at last from the nodular horizon to the surface horizon. Aluminium presents behaviour rigorously inverse to that of silica, while iron is almost constant from the base to the top of the profiles (Table **2**). Globally, there is enrichment in aluminium from the isalteritic horizon at the base of the profile to the loose clayey upper set at the surface (Fig. **7** and Table **2**).

Geochemical characteristics of the indurated materials remains close to those of the loose materials, with a good representation of all the major elements, including bases, with Si remaining the most abundant element (42.98 to 47.23% SiO_2) before Al (15.83 to 19.82% Al_2O_3) and Fe (5.65 to 8.12% Fe_2O_3) (Table **2**). The $\frac{Si}{Al}$ ratio varies between 2 and 2.67 (Table **2**), revealing an excess of Si in these materials, provided as free alumina in the form of gibbsite. In the same way, in the triangular diagram SiO_2-Al_2O_3-Fe_2O_3, all points appear localized on the SiO_2-Al_2O_3 axis, with a shift toward the SiO_2 pole (Fig. **7**). It shows the importance of Al in these materials, whose composition remains dominated however by Si. Abundance of Si, as well as the presence of the bases in considerable quantities is in agreement with the relative enrichment in primary minerals, quartz and muscovite. There is a strong decrease of Fe contents from the original garnet in the bedrock to the slightly weathering garnet in isalteritic horizon, and a slightly increase in content in the nodules in the nodular horizon (Fig. **7** and Table **2**).

5. DISCUSSION

Lateritic weathering is an important process. It is estimated to have affected about a third of the earth's land surface, including much of Australia, India, Brazil and intertropical Africa [10]. In these regions, bedrocks are commonly weathered to depths of 10 to > 100 m, depending on climate, regional tectonic stability and nature of the parent rock [10, 21-24]. The studied profile, develops on garnet rich micaschist and under an equatorial climate, reaching a thickness of several metres and consists mainly of loose matrix and nodules. Generally, the presence of nodules characterizes a long period of deep lateritic weathering which had occurred during the early Tertiary [10]. Contrary to the typical lateritic characteristics [24], the studied profile is not depleted in alkalis and alkaline earths. This is related to the nature of the bedrock which contains in addition to garnet, micaceous minerals, present in all parts of the profile as confirmed by microscopic observations. According to Tardy (1993) [24], two types of nodules are distinguished: agradation nodules and degradation pisolites. Agradation nodules are formed by centripetal accumulation of iron from spots which become nodules with diffuse boundaries and later rounded true nodules with distinct boundaries. Degradation nodules or degradation pisolites are formed progressively from massive duricrust, nodular or metanodular duricrust, and characterised by their concretionary structure. Their inner core is hematitic, with dark and undifferentiated b-fabric, while their external part is goethitic, thus highly birefringent. Nodules described in the studied profile are fundamentally different from degradation and agradation nodules as seen in Fig. (**5a**, **e**, **f**, **g**).

Careful observations of Al and Fe contents in nodules from the isalteritic horizon to the nodular horizon clearly

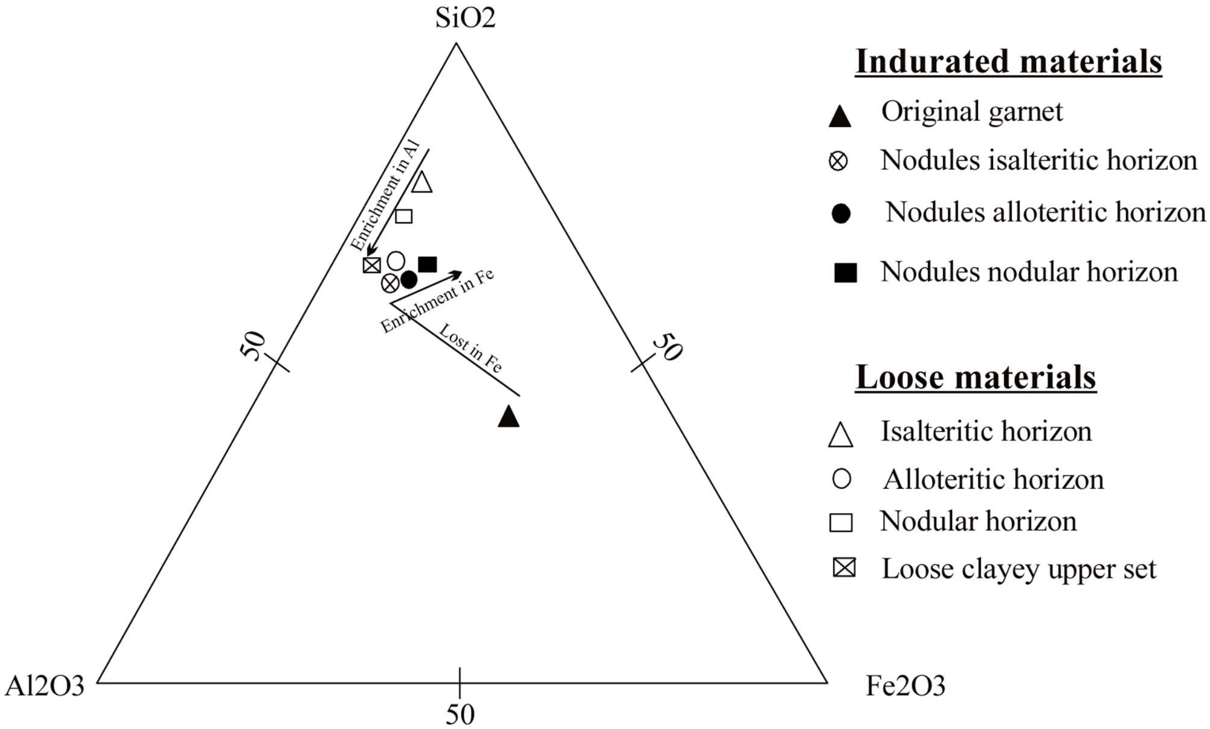

Fig. (7). Evolution of aluminium in loose materials and iron in indurated materials from bottom to top of the profile.

Table 2. Chemical Composition of Soils and Parent Rock

Horizons \ Oxides (%)		SiO_2	Al_2O_3	Fe_2O_3	TiO_2	K_2O	Na_2O	CaO	MgO	P_2O_5	LOI	Total	$\frac{Si}{Al}$
Set of clayey and loose horizon	**(1.25 m)**	52.04	20.12	6.23	0.66	4.02	1.32	1.92	2.70	0.09	10.70	99.80	2.32
Nodular horizon	**Nodules (5.5 m)**	47.23	15.83	8.12	1.11	3.08	3.24	2.40	2.11	0.24	16,55	99.91	2.67
	Fine earth (5.5 m)	57.38	15.03	5.62	0.79	3.12	2.20	3.13	2.13	0.27	10.36	100.03	3.42
Alloteritic horizon	**Nodules (8 m)**	42.98	18.34	7.31	1.08	2.42	3.36	2.96	3.01	0.31	17.53	99.30	2.10
	Fine earth (8 m)	50.68	20.34	6.02	0.99	4.01	2.10	2.01	3.12	0.26	9.97	99.50	2.23
Isalteritic horizon	**Garnet "ghost" (9 m)**	44.23	19.82	5.65	1.21	1.38	2.23	2.20	4.34	0.12	18.53	99.70	2.00
	Isalterite (9 m)	62.60	14.03	6.12	0.56	3.23	3.11	2.43	1.98	0.31	6.75	101.12	4.00
Garnet rich Micaschist	**Garnet grains***	34.79	19.34	31.16	0.06	0.00	0.00	8.07	0.56	0.16	/	94.14	/
	Total rock	64.01	14.40	6.91	0.71	2.08	2.50	3.01	4.20	0.15	2.37	100.34	/

*: Results obtained from microchemical analyses.

show a regular decrease in Al content and a regular increase in Fe content from bottom to top (Table **2**). In the same way, there is a regular increase in the $\frac{Si}{Al}$ ratio from bottom to top in those nodules. This regular evolution of Al and Fe contents and the $\frac{Si}{Al}$ ratio, may characterize the fact that those nodules have been formed *in situ* from the original garnet grains in the bedrock. This *in situ* evolution of nodules from original garnet is also confirmed by the gradual boundaries between different horizons and, more specifically, by the recurrent presence of a fine discontinuous perinodular "micaceous cortex" around different nodules in all horizons. The compartmentalized structure noted in the abundance of weathered garnet in the isalteritic horizon, which increases from bottom to top of the profile concomitantly with the disappearance of the original garnet fragments and the increase in thickness of different intragranular fracture coatings as seen in Fig. (**5f**), also confirm the *in situ* evolution of nodules from the original garnet grains. From the bedrock to the isalteritic horizon, there is a strong decrease in Fe content (Fig. **7**), which lead thus to a relative accumulation of Al in the form of gibbsite crystals in different nodule voids. Progressively to the top of the profile, there is a slight increase in Fe content in those nodules leading thus to the formation of alumino-ferruginous nodules which are either goethitic or hematitic, containing both gibbsite crystals, in the nodular horizon (Fig. **5f**, **g**).

Generally, gibbsite has to be suspected as parent materials that weather to a coarse grained saprolite or C-horizon allowing free downward drainage and which contain sufficient aluminium like granite and gneiss or other magmatic and metamorphic rocks [9, 25]. This is consistent with the presence of garnet rich micaschist containing garnet of grossularite rich almandine type which is at the base of the formation of alumino-ferruginous nodules. In addition, elevation plays an important role for gibbsite occurrence. Bhattacharyya *et al*. (2000) [26] found gibbsite in India in Ultisols above 1200 m asl. Macias Vasquez (1981) [27] and Herrmann *et al*. (2007) [9] found gibbsite in soils above 1400 m asl, respectively in Galicia in Spain and in the northern Thailand highlands. In the same way, Felix-Henningsen *et al*. (1989) [28] found gibbsite above 1000 m asl in subtropical southeaster China. In the south Cameroon plateau, gibbsite occurs in notable quantities only above 800 m asl, in high reliefs. Below 800 m asl, nodules are essentially of ferruginous in nature with kaolinite as main mineral which accompany iron oxides [4, 29-31]. This is inconsistent with Tardy *et al*. (1973) [32] who mention that kaolinite succeeds gibbsite in tropical soils. In the studied profile, kaolinite is almost absent in nodules. They are thus essentially rich in gibbsite, hematite and goethite and hence the name of alumino-ferruginous nodules. In the south Cameroon plateau high reliefs, genesis of nodules has particularities because of the slope. High rainfall and the excellent internal drainage did not allow the formation of iron duricrust in the Tertiary. Contrary to the convexo-concave and plan tabular interfluves that dominate the south Cameroon plateau below 800 m asl where nodules are formed from iron duricrust decomposition [4, 5, 23, 24, 30, 31], nodules here are mainly alteromorph or pseudomorph of primary mineral as the original garnet in this study, formed by Si-loss *via* leaching from theses primary minerals and relative and/or absolute accumulation of iron and/or aluminium in the form of oxides. The formation of nodules from primary minerals through Si-loss, relative and/or absolute accumulation in primary minerals is a particularity of the south Cameroon high reliefs, and may be extended to the high reliefs of the intertropical rainforest zone not capped in the past by iron duricrust, thus without any iron duricrust relicts.

6. CONCLUSION

Soil that developed on micaschist with garnet in the high relief of the south Cameroon plateau are composed of loose and indurated materials. Indurated materials described here are essentially nodules. They are formed *in situ* by isovolumetric weathering of original garnet of grossularite rich almandine type, through Si-loss and relative and/or absolute accumulation of iron and/or aluminium in the form of oxides, hence the so called alumino-ferruginous nodules. This *in situ* genesis of alumino-ferruginous nodules is clearly illustrated by the presence of fine discontinuous perinodular “micaceous cortex” around different nodules in all horizons, persistence of the compartmentalized structure noted in the originate garnet in all nodules and presence of gibbsitic crystallarias in most nodules. This genesis of alumino-ferruginous nodules from primary minerals is a particularity of the high relief of the south Cameroon plateau, and may be a characteristic of the high relief geomorphological unit in the humid tropical rainforest zone.

ACKNOWLEDGEMENTS

Authors acknowledge the support of VLIR-UOS for permitting attendance at an intensive microscopic training course on soil thin sections in order to improve the quality of petrographic observations. We are grateful to the anonymous reviewers whose comments and suggestions substantially improved the quality of this paper.

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Received: May 29, 2011 Revised: June 28, 2011 Accepted: August 5, 2011