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Spatial variation of soil weathering processes in the tropical high reliefs of Cameroon (Central Africa)

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Abstract

The objective of the present work was to characterize the morphological, geochemical and mineralogical features of soil with regard to weathering processes as a function of topography and spatial variation of climate in tropical high reliefs of Cameroon. Field investigations permit to select three study sites Mbalam, Meleta and Secande respectively in the humid tropical zone, pseudotropical mountainous zone and in the tropical dry climate. Macroscopically, the studied soils are thick in Mbalam, medium thick in Meleta and relatively less thick in Secande. Globally, saprolite, a loose loamy clayey horizon and humiferous horizon were observed from the bottom to the top of the profiles. These profiles differ by their thickness, the differentiation of the saprolite horizons and the presence of humiferous horizons. They are characterized microscopically by in situ replacement of primary minerals by kaolinite/halloysite, gibbsite and iron oxides. Theses minerals are associated to anatase in Mbalam and to montmorilonite and calcite in Secande. Geochemical processes involving in the spatial differentiation of soils are monosiallitisation and allitisation in the humid tropical zone, monosiallitisation and high allitisation in the pseudotropical mountainous zone with Al_2O_3 content reaching 41% in the saprolite, and monosiallitisation associated to bisiallitisation in the tropical dry climate of Cameroon. The development of these geochemical processes is conditioned by topography, elevation, rainfall and temperature, which appear as the main factors responsible of the spatial variation of soil weathering processes in the tropical high reliefs of Cameroon.

Keywords: Spatial variation, weathering processes, soil, tropical high reliefs, Cameroon.

Introduction

The humid inter-tropical zone constitutes an original and extreme morphogenetic milieu. It is where the bioclimatic weathering mechanisms are most developed in the earth surface (Tricart, 1961). In almost all environments, physical and chemical weathering processes operate together, but usually one of these categories dominates. Although water plays a role in both weathering processes, it is essential for all types of chemical weathering. The meteoric water is the most important factor. It dissolves CO_2 from the atmosphere, which is needed to alter minerals and rocks, interacts with them and the vegetation it directly influences, and transports dissolved elements and particles to rivers and oceans (Nahon, 2003). The amount of rainwater that falls on the surface of the continents is decisive on the rates of deterioration and thus on the balance sheets. Therefore, where liquid water is absent, biogeochemical weathering is also virtually absent or negligible and largely dominated by physical weathering (Nahon, 2003; Gabler et al., 2008). Chemical weathering, then, is a dominant process in humid tropical regions, favouring formation of deeply weathered profiles (Voicu and Bardoux, 2002; Nahon, 2003; Gabler et al., 2008). Temperature is another principal climatic variable which influences dominant types and rates of weathering. Most chemical reactions proceed

faster at higher temperatures. Low-latitude regions with humid climates consequently experience the most intense chemical weathering (Tardy, 1993; Gabler et al., 2008).

In the tropical environments, the study of rock weathering and its products concerns various geo-disciplines including soil science, geology, geochemistry, geomorphology and civil engineering. Each of these disciplines has historically been involved with the description and/or interpretation of weathered materials (Ehlen, 2005; Gracheva, 2011; Bétard, 2012). However, most studies focusing on weathering deal with the description and/or dating of vertical variations of weathered materials at the profile scale (Herrmann et al., 2007; Nguetnkam et al., 2008; Beauvais, 2009). Soils are globally deep and well differentiated, and landforms appear rounded in humid tropical environment (Gabler et al., 2008; Beauvais, 2009). Although chemical weathering is somewhat less extreme in the mid-latitude humid climates, his influence is apparent in the moderate soil depth and rounded forms of most landscapes in those regions (Gabler et al., 2008). Only a few studies bear on spatial variations of soil weathering processes and their controlling factors at the landscape scale (Bourgeon, 2001; Scarciglia et al., 2005; Bétard, 2012), though in Cameroon, climate varies from humid tropical rainforest in the Southern part to tropical dry savannah in the Far North (Suchel, 1987). In addition, spatial studies of rock weathering and its products devoted exclusively to high reliefs in this humid tropical zone are very rare. The present research focuses on soil developed in the high reliefs of Cameroon. The objectives are (i) to characterize the morphological, geochemical and mineralogical variations in soil properties as a function of topography and spatial variation of climate and (ii) to identify the factors that control soil weathering processes in these high reliefs of tropical zone characterized by steep environmental gradients and their variation along the latitude.

Material and Methods

The study sites are located at Mbalam, Meleta and Secande, respectively in the East, West and Far North regions of Cameroon (Figure 1). These three sites were chosen in relation to their bioclimatic contrasts (Table 1).
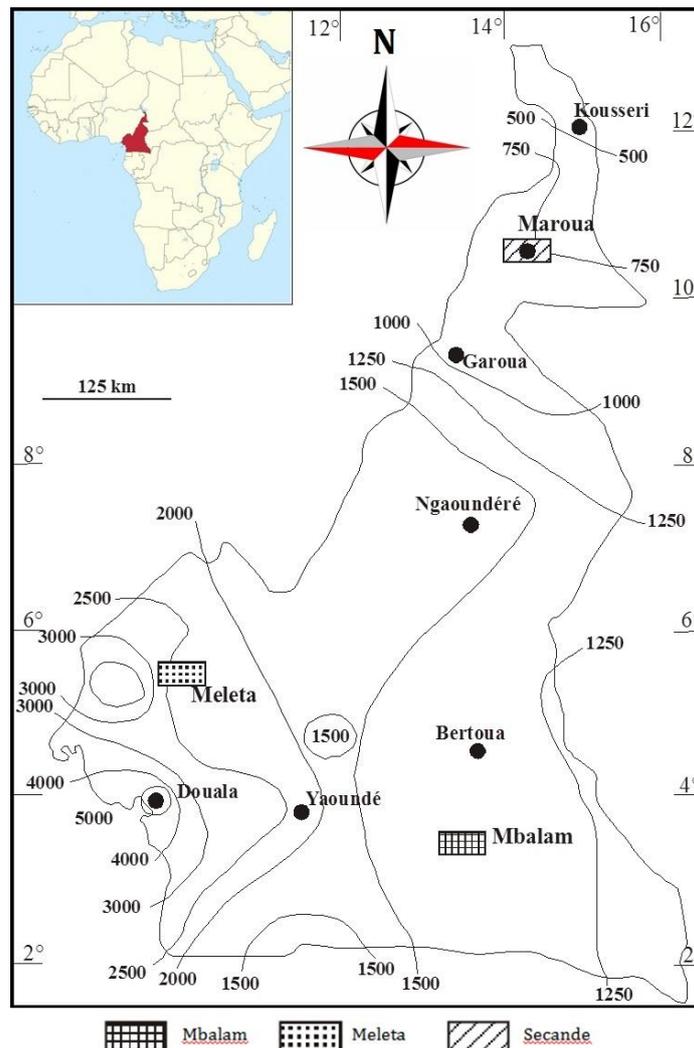

Figure 1. Location of the study area (modified from Nguetnkam et al., 2008).

Table 1. Characteristics of the three bioclimatic zones of Cameroon.

Characteristics	Bioclimatic zones		
	Mbalam	Meleta	Secande
Location	South Cameroon	West Cameroon	North Cameroon
Latitude	3°43'33''N-3°44'45''N	5°36'43'-5°38'31''N	10°35'00''-10°40'30'' N
Longitude	13°23'30''E-13°24'30''E	10°04'16''-10°05'49''E	14°16'04''-14°21'34'' E
Altitude	840m	2740m	640m
Climate	Humid tropical (Suchel, 1987)	Pseudotropical with temperate characteristics due to altitude (Morin, 1988)	Dry tropical (Suchel, 1987)
Mean annual rainfall	1640 mm	2507mm	757.2 mm
Mean annual air temperature	23°C	10-12°C	28.53°C
Vegetation	Evergreen forest (Letouzey, 1985)	lawn (*Sporobolus* prairies) strongly degraded by human activities (Morin, 1988)	Ephemeral grasses, strongly degraded by human activities (Letouzey, 1985)
Relief	Half-orange hills, narrow and outstretched valleys (Olivry, 1986)	Mountainous (Morin, 1988)	Mountainous
Slope gradient	Gentle (6-10%)	Steep	Gentle to steep
Bedrock	Garnet-rich micaschist (Vicat, 1998)	Trachyte (Marzoli et al., 1999; Nono et al., 2004; Gountié et al., 2012).	Microgabbro (Dumort and Peronne, 1966; Lasserre,1975).

Field work consisted firstly of morphological analysis of different topographic profiles in the three study sites. One soil pit was thereafter opened in the high topographic position in each site, described in detail and sampled for laboratory analyses. In the laboratory, soil pH was measured potentiometrically in a 1:2.5 soil: solution ratio (Guitián and Carballas, 1976). Bulk density was determined by clod method (Blake and Hartge, 1986). Optical microscope observations were done on rock and soil thin sections. For soil descriptions, the concepts and terms of Stoops (2003) were used. Soil mineralogy was determined by X-ray diffraction (XRD) on total soil powder. Clay fraction was not separated. X-ray diffraction patterns were recorded at room temperature using a classical powder diffractometer (X'pert Pro/Philips PW3710) instrument equipped with Ni-filtered and Cu anode (quartz monochromator, K-α1 wavelength =1.5405600X) operating at 45 kV and 40 mA. This Philips PW3710 instrument operates in continuous scan mode and in step scan mode range from 2° to 70°, with 2θ step of 0.02° and counting time of 0.50s per step. Minerals were identified using XRD coupled with standard saturation (K), solvation (ethylene glycol), and heat (550 °C) treatments (USDA, 2004). X-ray fluorescence for major element analysis was executed with a Philips spectrometer (PW 1404 WD) on total samples powder. Loss on ignition (LOI) was determined by ignition of samples at 1050°C for two hours. The chemical index of alteration (CIA) corresponds to $[Al_2O_3/(Al_2O_3+CaO^*+Na_2O+K_2O)]\times100$, where CaO* is the amount of CaO incorporated in the silicate fraction of fresh rock while Na_2O, K_2O and Al_2O_3 are their concentrations in the analysed soil samples (Nesbitt and Young, 1982).

Results

Morphological, mineralogical and geochemical features of high reliefs' soils in the humid tropical rainforest of Mbalam

The studied profile is about 10 m thick. It is made up from the bottom to top of coarse saprolite, fine saprolite, nodular horizon and a red clayey horizon (Figure 2).

- Coarse saprolite (10- 8.25 m). It is gray yellow with a well preserved bedrock structure and the presence of numerous pink globular garnet crystals. Under the microscope, there are many gibbsite crystals in the domains with biotite and muscovite (Figure 2). Mineralogically, the horizon consists of muscovite, goethite, quartz, gibbsite, kaolinite, hematite and anatase (Table 2). The loose material is mainly composed of SiO_2 (62.60%), with a small amount of Al_2O_3, Fe_2O_3, K_2O, NaO, CaO and MgO (Table 2). In the "ghost" of garnet, Si contents are low meanwhile Al and Mg contents are high (Table 2).

- Fine saprolite (8.25-6.20 m). It is red (2.5YR4/6), with many isalteritic relics, ferruginised friable quartz blocks and nodules. The matrix is clayey, with a very weakly developed blocky structure. Microscopically, it is characterized by a locally undifferentiated and stipple speckled b-fabric (Figure 2). Coarse materials are important (30%), with double spaced porphyric c/f related distribution patterns. The mineralogical composition was similar to that of coarse saprolite below (Table 2). SiO_2 contents decrease and Al_2O_3 contents increase in the matrix, and Fe_2O_3 contents increase slightly in nodules, whereas other oxide contents are almost constant (Table 2);
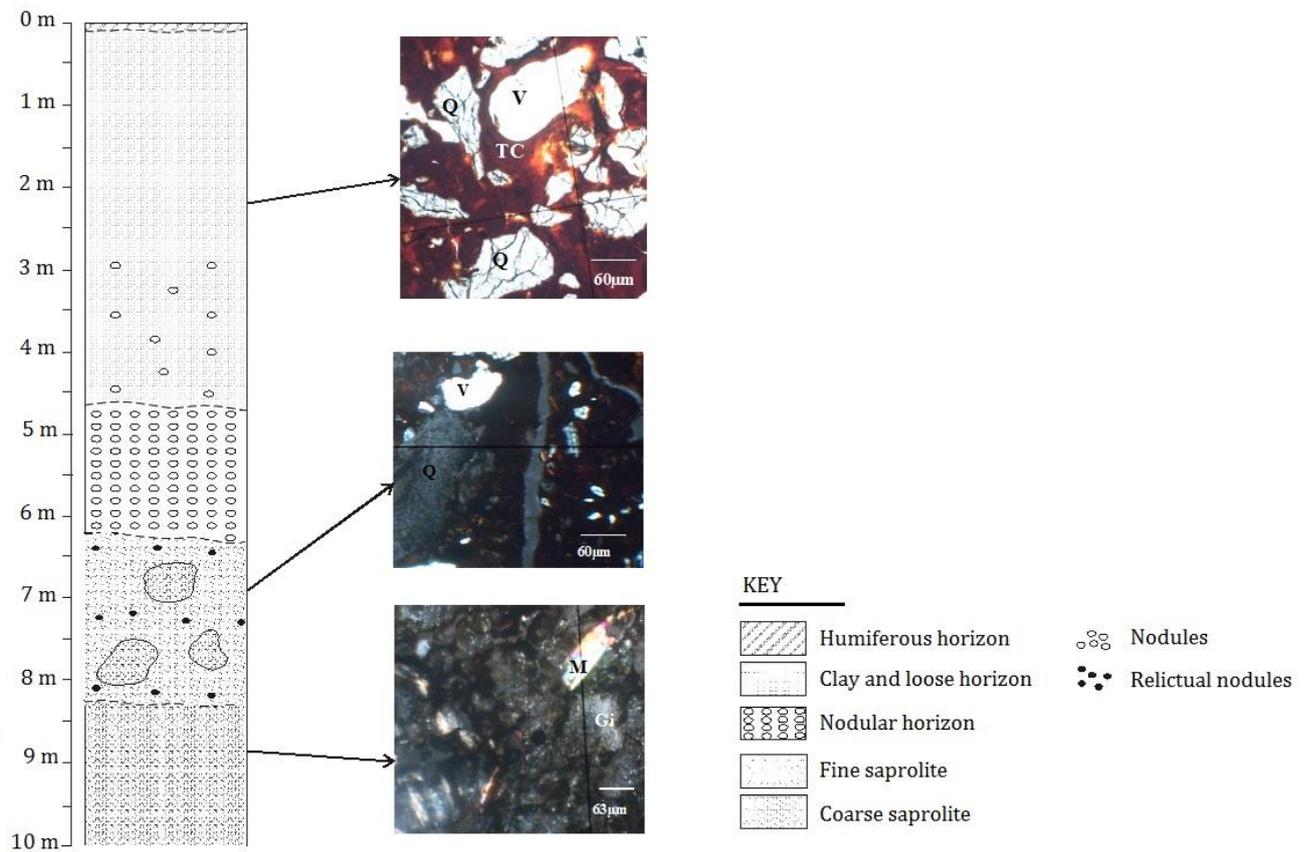
Figure 2. Macroscopic and microscopic organization of soil profile in Mbalam

- Nodular horizon (6.20-4.60 m). It is red (2.5YR4/6), clayey, with fine blocky structure and about 40% of nodules. Under the microscope, nodules are orange-brown (birefringent) or darker, and undifferentiated. The mineralogical composition was similar to that of other horizons below (Table 2). Si, Al and Fe are the most abundant elements both in the matrix (57.38% SiO_2, 15.03 Al_2O_3, 5.62% Fe_2O_3) and in the nodules (47.23% SiO_2, 15.83% Al_2O_3, 8.12% Fe_2O_3). K_2O, MgO, Na_2O and CaO contents remain almost constant but well represented here as in the other horizons (Table 2);

Table 2. Geochemical characteristics of soils developed in the high reliefs in the humid tropical rainforest of Mbalam.

Horizons	Micaschist (Total rock)	Micaschist (Garnet grains)	Coarse saprolite (Fine earth)	Coarse saprolite ("ghost" of garnet)	Fine saprolite (Fine earth)	Fine saprolite (Nodules)	Nodular horizon (Fine earth)	Nodular horizon (Nodules)	Set of clayey and loose horizons
Depth (m)	/	/	9 m	9 m	8 m	8 m	5.5 m	5.5 m	1.25 m
SiO_2	64.01	34.79	62.60	44.23	50.68	42.98	57.38	47.23	52.04
Al_2O_3	14.40	19.34	14.03	19.82	20.34	18.34	15.03	15.83	20.12
Fe_2O_3	6.91	31.16	6.12	5.65	6.02	7.31	5.62	8.12	6.23
CaO	3.01	8.07	2.43	2.20	2.01	2.96	3.13	2.40	1.92
MgO	4.20	0.56	1.98	4.34	3.12	3.01	2.13	2.11	2.70
Na_2O	2.50	0.00	3.11	2.23	2.10	3.36	2.20	3.24	1.32
K_2O	2.08	0.00	3.23	1.38	4.01	2.42	3.12	3.08	4.02
TiO_2	0.71	0.06	0.56	1.21	0.99	1.08	0.79	1.11	0.66
P_2O_5	0.15	0.16	0.31	0.12	0.26	0.31	0.27	0.24	0.09
LOI	2.37	/	6.75	18.53	9.97	17.53	10.36	16.55	10.70
Total	100.34	94.14	101.12	99.70	99.50	99.30	100.03	99.91	99.80
$\frac{Si}{Al}$	/	/	4.00	2.00	2.23	2.10	3.42	2.67	2.32
CIA	65.48	70.56	60.00	62.92	69.04	56.97	64.34	52.38	70.67
pH	/	/	5.2	/	4.4	4.4	4.6	5.2	4.7

Mu: muscovite : 9.96 Å, 9.93 Å, 4.47 Å ; K: kaolinite :7.17 Å, 7.19 Å, 7.21 Å ; Gi: gibbsite : 4.85 Å ; Goe: goethite :4.97 Å, 4.17 Å ; Q: quartz : 4.26 Å, 3.34 Å; He: hematite :2.69 Å, 1.45 Å ; A: anatase : 3.51 Å; F: Feldspar; B: biotite; Ga : garnet.

- Set of red clayey and loose horizons (4.60-0 m). It is constituted of matrix identical to that described in the nodular horizon and a very thin surficial humiferous horizon (0.08 to 0 m). The groundmass has a moderately to highly separated microstructure (Figure 2). Nodules are rare. Coarse materials are important (10 to 20%). It is characterized by double spaced porphyric to open porphyric c/f related distribution patterns. The mineralogical composition was similar to that of other horizons below (Table 2). Si, Al and Fe are the most abundant elements (52.04% SiO_2, 20.12% Al_2O_3, 6.23% Fe_2O_3). They are followed by K (4.02% K_2O), Mg (2.70% MgO), Ca (1.92% CaO) and Na (1.32% Na_2O) which remain present here as in the other horizons (Table 2).

Morphological, mineralogical and geochemical features of high reliefs' soils in the humid tropical mountainous of Meleta

The studied profile in the humid mountainous zone of Meleta is about 2 m thick. It constituted of three horizons, which are from bottom to top: a saprolite, a yellowish red horizon and a black humiferous horizon (Figure 3).
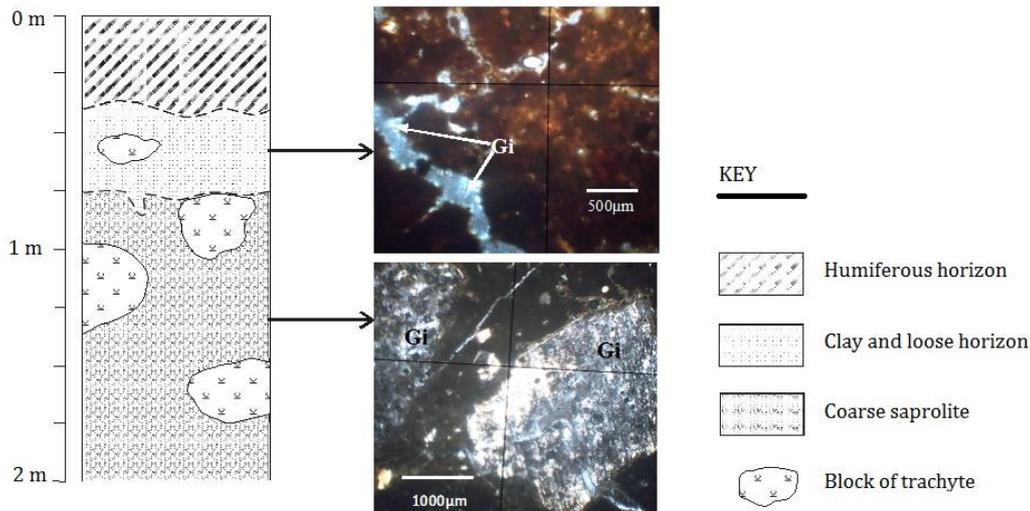

Figure 3. Macroscopic and microscopic organization of soil profile in Meleta.

- Saprolite (2-0.75m). It is composed of yellow brown (10YR6/8) and whitish gray (7.5YR7/0) domains. It is porous, characterized by loamy texture and massive structure, with a well preservation of the structure of the parent rock. Under the microscope, sanidine phenocrysts are partially or totally pseudomorphosed by gibbsite microcrystals (Figure 3). It is constituted of gibbsite, halloysite, quartz, magnetite, goethite and sanidine. On the geochemical point of view, the most important oxides are Al (41.10-39.10% Al_2O_3), Si (23.50-22.70% SiO_2) and Fe (8.94-6.63% Fe_2O_3). Little quantities of Ti (0.44-0.73 % TiO_2) and P (0.25-0.29% P_2O_5) are detected. The alkali and alkaline earth elements quantities are very weak (Table 3).

Table 3. Geochemical characteristics of soils developed in the high reliefs in the humid tropical mountainous of Meleta.

Horizons	Alkaline trachyte	Saprolite		Yellowish red clayey and loose horizon	Black humiferous horizon
Depth (m)	/	1.25-2 m	0.75-1.25 m	0.45-0.75 m	0-0.45 m
SiO_2	58.00	22.70	23.50	23.80	21.50
Al_2O_3	18.40	42.10	39.10	34.00	20.30
Fe_2O_3	5.63	6.63	8.94	8.75	7.05
CaO	2.10	0.01	0.00	0.08	0.23
MgO	0.41	0.09	0.13	0.29	0.30
Na_2O	6.56	0.00	0.00	0.20	0.15
K_2O	5.23	0.08	0.12	0.60	0.48
TiO_2	0.44	0.44	0.73	1.08	0.97
P_2O_5	0.14	0.25	0.29	0.32	0.35
LOI	2.01	26.20	28.00	30.20	48.10
Total	98.92	98.50	100.66	99.30	99.13
$\frac{Si}{Al}$	/	0.49	0.54	0.63	0.95
CIA	56.98	95.08	94.62	92.14	88.15
pH	/	5.4	5.3	5.0	3.9
Mineralogy	Sa Px Op	Sa Ma Ha Gi Q	Ma Ha Gi Goe Q	Ma Ha Gi Goe He Q	Ma Ha Gi Goe He Q

Ma : magnétite : 2.53 Å; Gi : gibbsite : 4.85 Å; Goe : goethite : 4.18 Å ; Q : quartz : 4.29Å, 3.37Å; He : hématite : 2.69 Å ; Ha : halloysite : 10 Å, 7.20 Å ; Sa : sanidine ; Px : pyroxene ; Op : opaque minerals.

- Yellowish red horizon (0.75-0.45m). Beyond the yellowish red colour (5YR4/4), the horizon is clayey, with a fine blocky structure. Under the microscope, the groundmass has moderate separated subangular blocky microstructure, with compound packing voids and undifferentiated b-fabric (Figure 3). Gibbsite crystals are observed in some voids. In addition to the mineralogical composition noted in the saprolite, hematite is present (Table 3). On the geochemical view point, Al (34.00% Al_2O_3), Si (23.80% SiO_2) and Fe (8.75% Fe_2O_3) remain the most important oxides. Ti (1.08% TiO_2), K (0.60% K_2O), P (0.32% P_2O_5), Mg (0.29% MgO) and Na (0.20% Na_2O) are weakly represented and Ca is almost absent (0.08% CaO) (Table 3).

- Humiferous horizon (0.45-0m). It is black (2.5YR2.5/0), characterized by high matrix porosity a loamy texture and a blocky structure. Mineralogically, gibbsite, halloysite, goethite, hematite and quartz still the main minerals (Table 3). On the geochemical view point, Si (21.50% SiO_2), Al (20.30% Al_2O_3) and Fe (7.05% Fe_2O_3) are also the most important elements. The other elements Ti (0.97% TiO_2), K (0.48% K_2O), P (0.35% P_2O_5), Mg (0.30% MgO), Ca (0.23% CaO) and Na (0.15% Na_2O) remain weakly represented (Table 3).

Morphological, mineralogical and geochemical features of high reliefs' soils in the dry tropical zone of Secande

The Secande studied soil profile was ~ 2 m thick. Four main horizons were distinguished from the bedrock to the surface: a coarse saprolite, a fine saprolite, a loose loamy clayey horizon and a humiferous horizon (Figure 4).
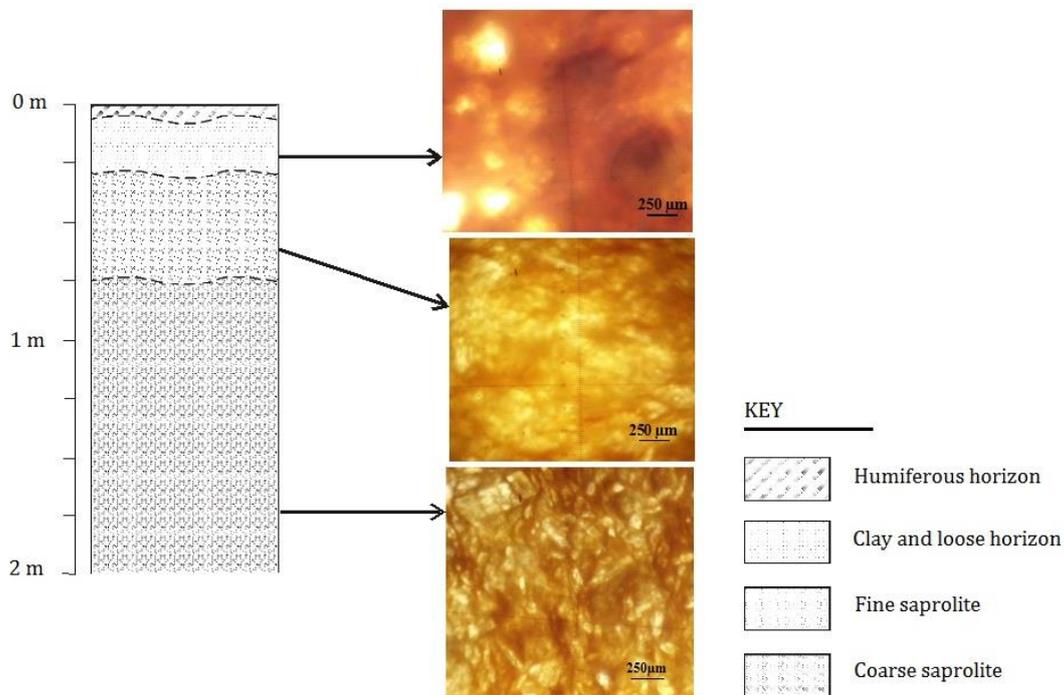
Figure 4. Macroscopic and microscopic organization of soil profile in Secande

- Coarse saprolite (2-0.75 m). The coarse saprolite was yellowish (10YR 7/8), compact, massive, with many fissures surrounding compact undifferentiated blocks. The original structure of the bedrock was preserved. Under the microscope, all the primary minerals had disappeared, and the preservation of the bedrock structure was marked by numerous remnants of altered plagioclases shape (Figure 4). The groundmass was characterized by a double spaced fine, ranging from equal to enaulic c/f-related distribution pattern. It showed a yellowish red birefringent micromass. The secondary minerals were montmorilonite, kaolinite, goethite, quartz, feldspar and calcite (Table 4). From the geochemical point of view, SiO_2 was the most represented oxide (53.90-53.10 %). It was followed by Al_2O_3 (15.00-14.70 %), Fe_2O_3 (10.75-10.90 %), Na_2O (4.11-4.33 %), MgO (1.76-2.06 %) and CaO (1.02-2.06 %) (Table 4).

- Fine saprolite (0.75-0.30 m). The fine saprolite was reddish yellow (7.5YR 6/8), loamy and massive. There were many fissures surrounding small gray compact blocks, globally embedded in loose loamy texture matrix. The structure of the bedrock was preserved only in gray compact blocks. Under the microscope, remnants of altered plagioclases shape had almost disappeared. The groundmass was yellowish, characterized by weakly separated granular microstructure (Figure 4). Secondary minerals were montmorilonite, kaolinite, goethite, quartz, feldspar and calcite (Table 4). From the geochemical point of view, SiO_2 remained the dominant oxide (52.10%), followed by Al_2O_3 (15.55 %), Fe_2O_3 (11.20%), Na_2O (4.76 %) and CaO (3.23 %) (Table 4).

Table 4. Geochemical characteristics of soils developed in the high reliefs in the dry tropical zone of Secande

Horizons	Microgabbro	Coarse saprolite (Bottom)	Coarse saprolite (Top)	Fine saprolite	Loamy clayey horizon	Humiferous horizon
Depth (m)	/	2-0.75		0.75-0.30	0.30-0.07	0.07-0
SiO_2	48.90	53.90	53.10	52.10	51.60	50.80
Al_2O_3	16.95	15.00	14.70	15.55	16.25	15.90
Fe_2O_3	10.55	10.75	10.90	11.20	11.80	11.85
CaO	9.55	1.02	4.22	3.23	3.02	5.12
MgO	6.87	2.06	1.76	1.78	1.68	1.76
Na_2O	2.50	4.11	4.33	4.76	3.55	3.02
K_2O	1.17	0.46	0.27	0.31	0.24	0.30
TiO_2	1.15	1.06	1.14	1.20	1.23	1.20
P_2O_5	0.20	0.22	0.28	0.21	0.08	0.10
LOI	3.38	9.05	8.88	10.10	11.50	10.30
Total	101.39	100.85	99.81	100.68	101.26	100.62
$\frac{Si}{Al}$	2.59	3.22	3.24	3.00	2.85	2.86
CIA	56.18	51.51	50.95	51.54	54.92	55.27
pH	/	7.50	7.60	7.80	6.70	6.50
Mineralogy	A F B Ca	Mo K Goe Q F Ca	Mo K Goe Q F Ca	Mo K Goe Q F Ca	Mo K Goe Q F Ca	Mo K Goe Q F Ca

Mo= montmorillonite: 10Å, 15.48Å, 17.64Å; K= kaolinite: 7.1Å, 3.57Å; Goe= goethite: 4.17Å, 2.45Å; Q= quartz: 4.29Å, 3.37Å, 2.12Å, 1.82Å; F= feldspath: 3.24;   Ca= calcite: 3.89Å; B: biotite; A: amphibole.

- Loose loamy clayey horizon (0.30-0.07 m). The horizon was reddish yellow (5YR 6/8), loose and loamy clayey. It was weakly blocky to massive, characterized by a high matrix porosity and the presence of many rootlets. Under the microscope, remnants of altered plagioclases shape were not visible. The groundmass had a vughy microstructure and reddish micromass (Figure 4). It had a speckled and cloudy limpidity (Figure 4). The mineralogical composition was similar to that of saprolite. From geochemical point of view, compared to the coarse and fine saprolite, all the major oxides contents showed a very little variation and remained widely dominated by SiO_2 (Table 4).

- Humiferous horizon (0.07-0 m). The humiferous horizon was yellowish red (5YR 5/8), loamy clayey, characterized by a weakly expressed lumpy structure, a high matrix porosity and the presence of many rootlets. The mineralogical composition was similar to that of the underlying horizons. From geochemical view point, compared to the below horizons, all the major oxides contents showed a very little variation and remained largely dominated by SiO_2. This oxide was followed by Al_2O_3, Fe_2O_3, CaO, Na_2O and MgO as the well represented oxides (Table 4).

Evaluation of weathering trend and intensity

Selected major element–Al_2O_3 variation diagrams plotted on an anhydrous basis are given for each group in Figure 5. The elements plotted are the mobile species CaO, Na_2O, and K_2O, along with Fe_2O_3 (total iron as Fe_2O_3), as a representative of a less mobile element, although Fe abundances may also be influenced by sesquioxide development. Globally, Na_2O, K_2O, CaO and Fe_2O_3 contents exhibit very weak correlations with Al_2O_3 (Figure 5). In detail, these correlations are more expressed on trachyte and microgabbro, except for Fe_2O_3 (Figure 5).

In Mbalam, the $\frac{Si}{Al}$ ratio varies between 2 and 2.67 and CIA ranged from 52.38 to 70.67 (Table 2). In the triangular diagram SiO_2-Al_2O_3-Fe_2O_3, all points appear localized on the SiO_2-Al_2O_3 axis. There is a shift toward the SiO_2 pole, indicating the importance of Al in these soils, whose composition are dominated by Si due to the presence of primary minerals, quartz and muscovite (Figure 6).

In Meleta, the $\frac{Si}{Al}$ ratio varies between 0.49 and 0.95 and CIA ranged from 56.98 to 95.08 (Table 3). A representation in the triangular diagram SiO_2-Al_2O_3-Fe_2O_3 showed that all points appear localized on the SiO_2-Al_2O_3 axis, with a shift toward the Al_2O_3 pole, in line with the high expression of Al in the studied soil in the form of gibbsite (Figure **6**).

In Secande, the $\frac{Si}{Al}$ ratio was high, ranging between 2.85 and 3.24 and CIA ranged from 50.95 to 55.27 % (Table 4). A representation in the triangular diagram SiO_2-Al_2O_3-Fe_2O_3 showed that all samples were also localized on the SiO_2-Al_2O_3 axis, toward SiO_2 pole in line with high $\frac{Si}{Al}$ ratio (Figure 6). This is indicative of an excess of SiO_2 in the studied soils and confirmed the presence of montmorillonite.
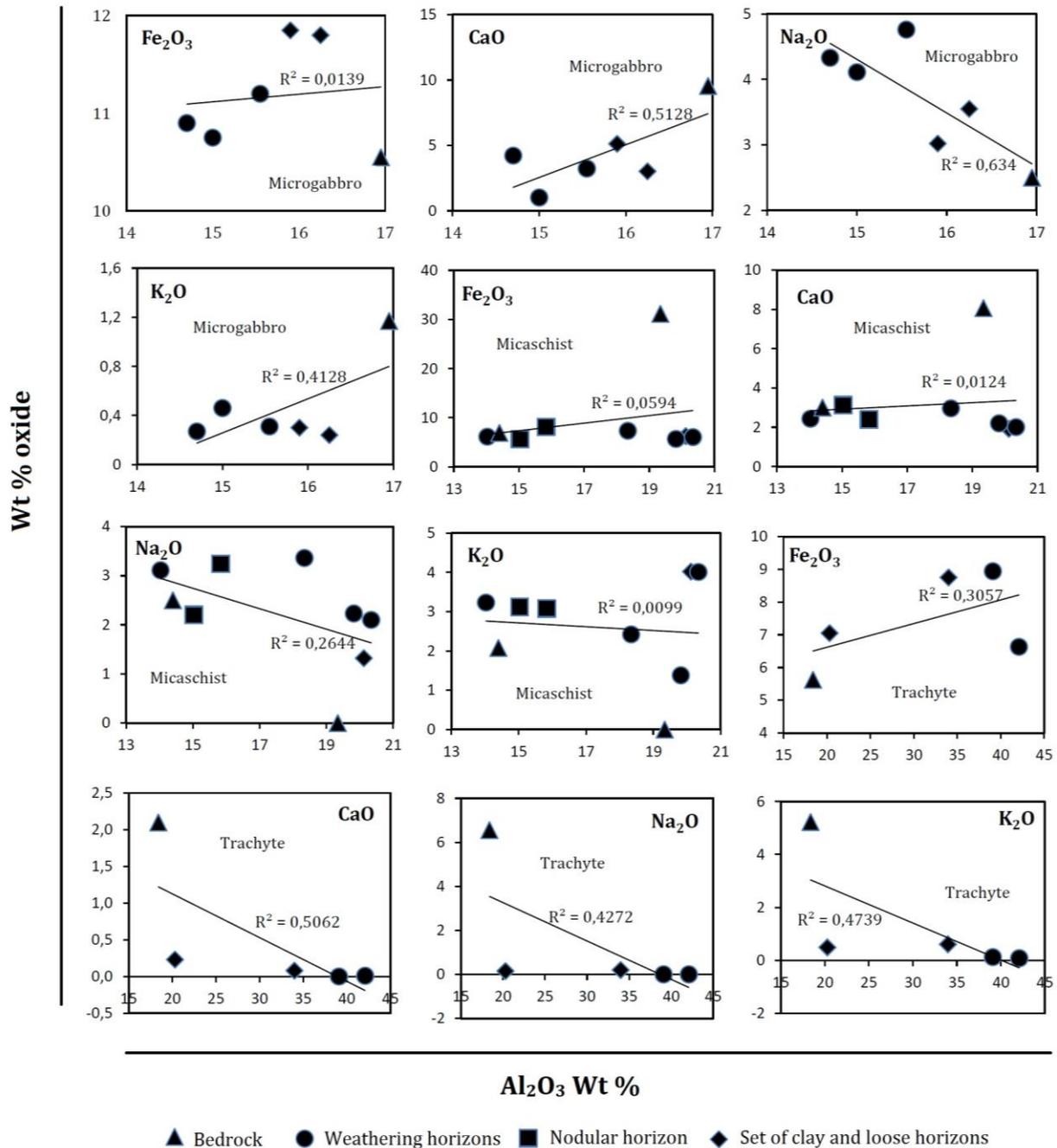
Figure 5. Major element–Al2O3 variation diagrams for samples collected in the studied profiles

Since Al is more immobile than the alkali elements (Na^+ and K^+) and Ca^{2+}, changes in CIA reflect changes in the proportions of feldspar and the various clay minerals developed in the soil profiles (Nesbitt and Young, 1982). The CIA values are directly represented on the A-CN edge of the A-CN-K triangle (Figure 7) as the elements involving this edge are the same as needed for the calculation of CIA. High CIA values reflect the removal of labile cations relative to stable residual constituents during weathering, and low CIA values indicate the near absence of chemical alteration (Nesbitt and Young, 1982). CIA values are directly represented on the A–CN–K triangle. The CIA corresponds to the horizontal projection on a vertical scale ranging from 0 (A–CN join) to 100 (A apex), where the fresh feldspar join has a value of 50. In the dry tropical ecosystem, weathering is less developed and soil samples are plotted in the interval of CIA corresponding to rock discoloured by weathering to fresh rock although soils are developed on microgabbro (Figure 7). In the humid high reliefs of Meleta at 2740 m a.s.l. on contrary, all material are decomposed and/or disintegrated to soil, favoured by the volcanic nature of the bedrock (Figure 7). In the humid rainforest high reliefs, around 50% of material are decomposed and/or disintegrated to soil, in line with the presence of muscovites in all horizons (Figure 7).
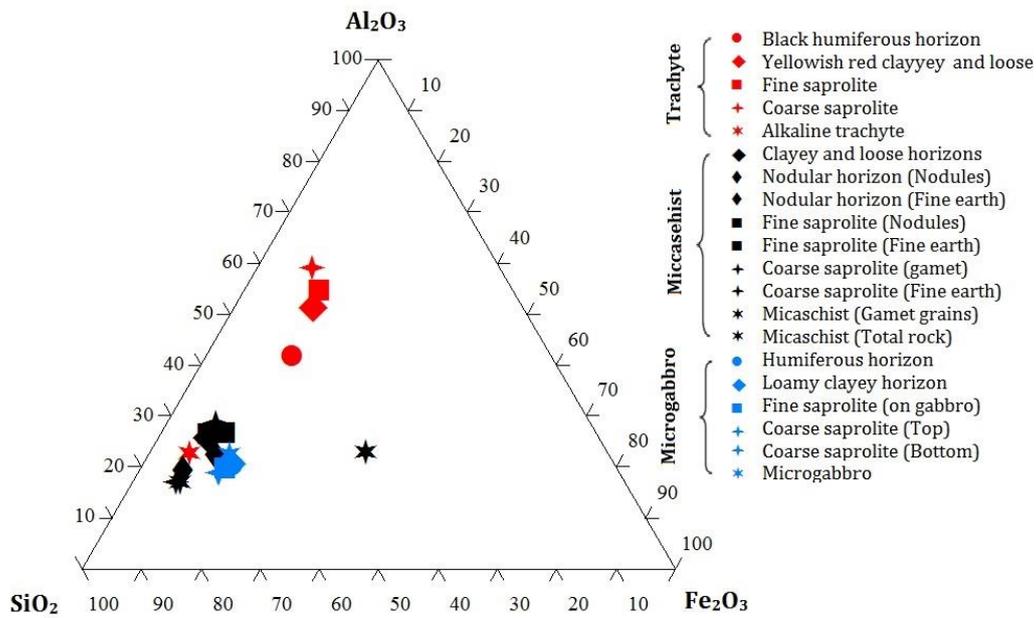
Figure 6. Geochemical composition of the studied soils in SiO_2-Al_2O_3-Fe_2O_3 diagram
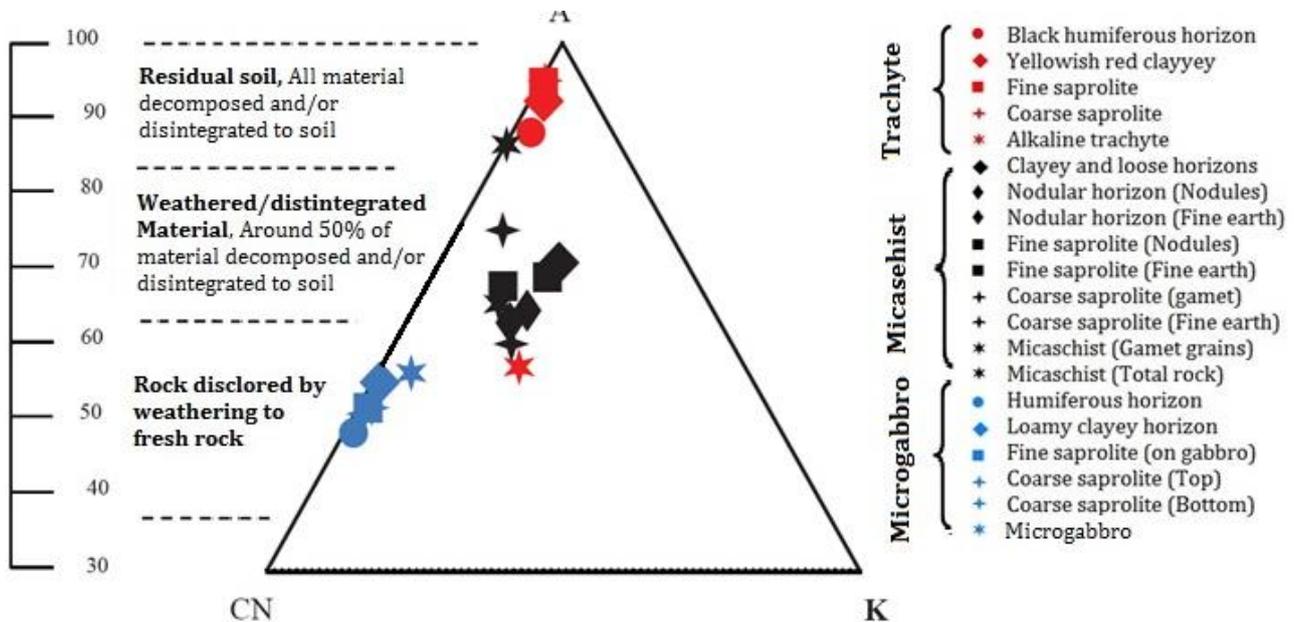
Figure 7. A-CN-K diagram illustrating weathering intensity (CIA values) of all samples collected from the studied profile. The CIA scale is divided into the simplified typical weathering profile described by the Geological Society of London in Lambe (1996)

Discussion

Morphological organization of soils

The studied soils in the high relief of Mbalam are about 10 m thick. This relative high thickness is common to soils developed in the humid tropical rainforest zone which are globally deep and well differenctiated (Beauvais, 1991; Beauvais and Collin, 1993; Irfan, 1996; Voicu and Bardoux, 2002; Nahon, 2003). Their morphology, of ABC type, is characteristic of the humid tropical rainforest zone (Tardy, 1993; Beauvais, 2009; Dzemua et al., 2011). It is however different from observations already made by many authors in this landscape marked by the presence of iron duricrust (Martin, 1966; Novikoff, 1974; Martin et al., 1981; Muller et al., 1981; Muller and Bocquier 1986; Muller, 1987; Colin et al., 1989). It is the result of lateritization processes which homogenize the weathering products through intense leaching of the alkaline, alkaline-earth elements and some silica of the parent rock, and lead to a mineralogical reorganization of silica, alumina and iron oxide (Delvigne, 1965; Nahon, 1991; Beauvais and Roquin, 1996). This process develops in landscape consisting of plateaus ranging globally from 600 to 700 m in elevation and weakly inclined slopes in Central Africa (Beauvais, 1991), well represented in Cameroon as the Southern Cameroon plateau. The

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study site emerges from this whole Southern Cameroon plateau by its altitude of about 840 m above sea level (a.s.l.). This position enhances soil permeability and drainage (Garner, 1972), leading thus to the development of gibbsite observed under the microscope (Aleva, 1994).

In Meleta, although remaining in the humid tropical zone and on volcanic products susceptible to weather faster, soils are less thick (~2 m), constituted of saprolite, yellowish red horizon and a thick black humiferous horizon and characterized by the presence of gibbsite under the microscope. The less thickness might be related to environmental conditions, characterized by a low temperature which slowdowns microbiological activities, leading to an accumulation of organic matter and the formation of thick humiferous horizon in the soil surface. Temperature increases the agitation of the molecules, promotes their release from the crystalline networks and their dissolution (Delvigne, 1965). It facilitates the exchange between the ions carried by the solutions and the cations trapped in the crystalline structures (Delvigne, 1965). Low temperature might therefore slowdowns the thickening of soil profiles. Direct weathering of feldspars into gibbsite might be an indication of excellent drainage and high soil permeability (Delvigne, 1965; Gardner, 1972), favoured by the mountainous high reliefs.

In Secande, the thickness of soil is also ~ 2 m as in Meleta, but largely dominated by that of the saprolite (~1.70 m) at the base of the profile. This low thickness might be due to the dry Sudano-Sahelian climate, which did not allow intense chemical weathering (Nguetnkam et al., 2008). The humeferous surface horizon observed here is thin and also similar to that described in Mbalam. Globally, in the dry climate, the A horizon would be very thin because there are few plants to become organic matter, and the C horizon would still be present, with nutrients still locked into minerals, because there is not enough water to promote weathering and leaching of minerals, or development of a B horizon (Sindelar, 2015). In addition, in the tropical zone, the humification process is weak and the mineralization is on contrary fast, leading thus to the formation of a thin humeferous surface horizon.

Mineralogical and geochemical characterization of soils

In tropical regions, it is mainly through the quantity of water which percolates into the weathering system that the climatic control exercises its influence on weathering processes (Pédro, 1968; Bourgeon and Pédro, 1992; Bétard, 2012). When hydrolysis is the prominent way of weathering as experiencing in the study area, the development of a particular process (mono- or bi-siallitisation) depends on the rate of removal of silica and basic cations, which itself is influenced by the amount of water flowing into the weathering system (Nguetnkam et al., 2008; Bétard, 2012).

In Mbalam, chemical weathering leads to the decomposition of the entire primary mineral except muscovite and quartz, promoting the development of soils composed of kaolinite, gibbsite, aluminous goethite, hematite and traces of anatase. The first stage of garnet-rich micaschist weathering corresponds to a more or less isovolumentric process, with preservation of the overall fabric of the rock. This suggests in situ replacement of primary minerals by kaolinite and gibbsite, confirmed by microscopic observations. The presence of kaolinite in the saprolite characterizes the more advanced stages of weathering, and the intensive tropical weathering is reflected in the formation of iron and aluminium sesquioxides, goethite and gibbsite (Aristizábal et al., 2005). The neoformation of kaolinite and gibbsite is favoured by the morphoclimatic and hydrological environment of southern Cameroon: the rains are abundant, the hydrographic network, dense and marbled, reflects a good drainage, favoured by the steep slope and good permeability. In this context, the solutions are diluted and renewed regularly, which allows dissolution and almost the total leaching of the bases and partial silica, as evidenced by the results of the chemical analysis (Nguetnkam et al., 2008). The high expression of the bases in the soil profile would be due to the presence of muscovite in all the horizons.

In Meleta, characterized by temperatures ranging between 10 and 12°C, there is low SiO_2 content and high Al_2O_3 content in soils, compared to the parent rock and the site of Mbalam. Also, bases are almost inexistent, and the triangular diagram SiO_2-Al_2O_3-Fe_2O_3 showed that all points were localized on the SiO_2-Al_2O_3 axis, with a shift toward the Al_2O_3 pole. These characteristics lead to the neoformation of 1:1 clay minerals (halloysite) with important amounts of gibbsite, resulting in monosiallitisation process associated to high allitisation in this tropical mountainous environment (Pédro, 1966).

In Secande in the dry tropical zone, weathering leads to the coexistence of monosiallitisation with bisiallitisation, producing a mixture of 2:1 (montmorillonite) and 1:1 (kaolinite) clay minerals. Monosillitisation and bisiallitisation are induced by the morphoclimatic and hydrological conditions prevailing in the study area: rains are scarce and little distributed during the year, high temperature induces a strong evaporation (Ngounou Ngatcha et al., 2005) and high topographic position enhances drainage. The combination of these factors leads to the relative concentration of bases and silica, as shown by the results of

the chemical analysis, and creates the favourable conditions for the genesis of montmorillonite and kaolinite (Pédro, 1966; Nahon, 1991; Velde, 1995; Paquet and Clauer, 1997). Similar coexistences of kaolinite and montmorillonite have been reported in the literature by many authors (Amouric and Olives, 1998; Meunier, 2003; Nguetkam et al., 2008). They are carried out via the interstratified clay minerals, beidellite-montmorillonite and beidellite-montmorillonite-kaolinite (Nguetkam et al., 2008).

Spatial variation of soil properties in the tropical high reliefs of Cameroon

The surface geochemical signature in soil is always unique in some respects, due to differences in geological, geomorphological and environmental settings. The mobilization and redistribution of elements during weathering follow thus various pathways, as different elements are affected differently by the various pedogenic processes, including dissolution of primary minerals, formation of secondary minerals, redox processes, transport of material, and ion exchange (Middleburg et al. 1988; Ozaytekin and Uzun, 2012). Soils' genesis and mantles' weathering are not an instantaneous phenomenon and requires long time periods to develop. According to Lageat and Gunnell (2001), tropical soils and weathering mantles may be considered as palimpsests reflecting "average" bioclimatic conditions that prevail at timescales of 1 to 10 Myr. Thus the duration of the Quaternary period appears to be an order of magnitude likely to control soil and saprolite development, given the propagation rates of weathering fronts estimated for tropical regions (1 to 10 m·Ma^{-1}: Boeglin and Probst, 1998; Braun et al., 2005; Théveniaut and Freyssinet, 1999; Thomas, 1994). This leads to the soil differentiation in each study site according to the bioclimatic conditions which vary from the equator to the tropical dry climate in Cameroon. In the Meleta site, the rate of percolation is dependent on the ratio rainfall/evapotranspiration. This ratio increases with elevation, since rainfall increases and temperature decreases. Consequently higher shares of gibbsite can be expected (Hermann et al., 2007). The high expression of gibbsite here contrary to Mbalam could be attributed to high elevation and rainfall which induced high drainage. As a general rule, Tardy et al. (1973) state that in very humid climates and under excellent drainage conditions, gibbsite can appear. The absence of gibbsite in Secande might thus be attributed to low rainfall, low topography and high evaporation rate which did not facilitate the total evacuation of bases, leading to the maximum development of 2:1 clay minerals in this area, toward 1:1 clay minerals which remain present. In the tropical high reliefs, topography, elevation, rainfall and temperature appear as the main factors responsible of the soil properties.

Conclusion

The study of spatial variation of soil weathering processes in the tropical high reliefs of Cameroon lead to the following conclusions:

-soils are very thick in humid rainforest tropical high reliefs and this thickness decrease with increasing elevation and latitude;

-geochemical processes involved in the spatial differentiation of soils are monosiallitisation and allitisation in the humid tropical zone, monosiallitisation and high allitisation in the pseudotropical mountainous zone and monosiallitisation associated to bisiallitisation in the tropical dry climate of Cameroon;

-topography, elevation, rainfall and temperature appear as the main factors responsible of the spatial variation of soil weathering processes in the tropical high reliefs.

Acknowledgements

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