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Research Article

Laterization Process Recognition along the Northern Border of the Congo Craton by Geoelectrical and Geotechnical Data

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With the properties of laterites being related to the nature of the rock from which they are derived, twenty vertical electrical surveys and twenty boreholes for geotechnical tests, distributed in two units (plutonic and green belt zones) of the Ntem complex located at the northern limit of the Congo Craton, were implemented to study the formation process of the laterites of this geological structure. The inversion of the geoelectrical data in the plutonic area resulted in three lateritic layers with resistivities of 1090 Ω·m, 1302 Ω·m, and 1122 Ω·m, with induration and leaching indices of 28.9% and 72.56%. In the green belt zone, three lateritic layers were also identified with resistivities of 1080 Ω·m, 943 Ω·m, and 1158 Ω·m, with induration and leaching indices of 28.8% and 72.55%. The similarities of the geomechanical parameters (induration and lixiviation indices) show that these soils experienced similar weathering patterns during the same geological period, confirmed by CBR values, corresponding to PF3 platforms that can be used in road works. However, the average resistivity values in the different geological units (1171.77 Ω·m and 1061.16 Ω·m in plutonic and green belt areas) reflect the observed differences in resistivity values of the bedrock alterations (3413.51 Ω·m and 1569.32 Ω·m in plutonic and green belt areas), showing that these laterites are derived from different bedrock weathering. In addition, the average permeability values obtained in the plutonic zone ($k = 6.24E - 05$ cm/s) and in the green belt zone ($k = 5.82E - 05$ cm/s) confirm this difference. The reduction in the difference between the resistivities of the laterites compared to the difference observed in the bedrock of the two units highlights the leaching process over a long geological period.

1. Introduction

The cost of study of the genesis of laterites by mineralogical and geochemical analysis limits the potential for prospecting, despite their intense use in constructions [1]. The laterites of the Congo Craton, which constitute 80% of this geological unit, in full industrial expansion, do not have detailed information on their mode of formation [2].

The study of laterization, which conditions the properties of this type of soil, is still of little interest because of its cost. However, the availability of a large database of geoelectrical and geotechnical data from water drilling studies and road works, highlighting the physical and mechanical characteristics of the soils, can provide useful information for the interpretation of the laterization process [2].

It is established that the physical characteristics, related to the nature of the soil, give information on the nature of the parent rock. At the same time, the mechanical properties of a soil give an account of the degree of alteration that led to its formation [3]. The comparative analysis of these parameters can inform on the quality of the mother rock and the process of alteration from geological units of different

mineral compositions and ages, to decide globally on the mode of formation of a soil and the geological structure from which it comes [4, 5].

The purpose of this work is to study the genesis of lateritic soils of the Ntem subbasin, which is part of the northern limit of the Congo Craton, in the extreme south of Cameroon, made up of a plutonic complex and a green belt zone. For this purpose, twenty vertical electrical soundings (VES) and twenty boreholes for geotechnical tests (Figure 1) equally distributed on the two geological units of the Ntem unit were deployed (Figure 1), to bring out the physical (resistivity and hydraulic permeability) and geomechanical (induration and leaching indices) characteristics, permitting to conclude, by comparative analysis, on the origin and the mode of formation of the lateritic soils of the northern limit of the Congo Craton.

2. Regional Geology

2.1. Geology. The study area belongs to the Ntem subbasin, whose base is part of the northern boundary cratonic complex of the Liberian-aged Congo Craton (>2800 Ma), in the far south of Cameroon. It is an intrusive plutonic complex made up of charnockite rocks and a ribbed series of granitic gneisses and a belt of greenstone (iron grooves). The charnockites and TTG form a sequence established between 300 and 2700 Ma. Potassium granitoids of crustal origin were introduced between 2660 and 2550 Ma [6–8]. The early Archean greenstones are amphibolites and granulites interpreted as remnants of supracrustal rocks [9, 10]. Their chemical composition refers to the terms tholeiitic and calcalkalic. The pre-Panafrican dolerites that cut the greenstone belts have been linked to a pre-Panafrican distension phase that initiated the rifting of Neoproterozoic trenches in the Congo Craton [6, 9].

2.2. Lateritic Soil Profile. The soil formations of southern Cameroon developed on the stable continental surface by isostatic readjustments and by putting aside the old lineaments (zones of great deformation) [11]. We have hydromorphic soils represented by the alluvial soils of sedimentary basins and the soils of the low swampy depths of forests.

Red and yellow ferric soils are also found, occupying nearly 80 percent of the surface area of the rainforests. These soils are the result of the fertilization process that is predominant in warm, humid climates [12]. These soils have undergone significant climatic variation and the effects of intense pedogenetic processes.

Studies on the genesis and evolution [13] and organization of these soils [14, 15] present highly varied but generally very differentiated soils in three major complexes above the bedrock:

(i) An alteration layer with original structures of preserved bedrock

(ii) An intermediate layer of accumulation of metallic hydroxides and clays with litholithic organization totally or partially transformed

(iii) A top layer of soft, resistant residual minerals (quartz) and secondary minerals (kaolinite, hematite, goethite, gibbsite, and boehmite)

These three units are genetically discontinuous and result from three different phases of weathering and pedogenesis [16].

3. Methods and Materials

3.1. Vertical Electrical Soundings (VES). The electrical method, which is regularly used for aquifer prospecting in Africa, has a large database in the geological units of the Congo Craton. This method consists of injecting an electric current into the soil through two electrodes A and B, while the potential difference is measured, and then measuring the potential drop induced between two other electrodes M and N called potential electrodes ΔV created by sending the current between the electrodes through a potentiometer.

The apparent resistivity (ρ_a) is given by [18]

$$\rho_a(\Omega \cdot \mathrm{m}) = K(m)\frac{\Delta V(\mathrm{mV})}{I(\mathrm{mA})}, \tag{1}$$

where ΔV is the potential measured, I is the known current, and K is the geometric factor of the quadrupole, obtained by

$$K = \frac{2\pi}{(1/MA) - (1/MB) + (1/NB) - (1/NA)}. \tag{2}$$

Vertical electrical surveys (VES), following the Schlumberger principle, were carried out to determine the vertical resistivity profiles of the ground cover at the granitic base. These measurements were made with an ABEM SAS 1000 resistivity meter. Calculations were performed after each measurement to eliminate erroneous measurements.

Geoelectrical profiles and samples for geotechnical testing were deployed on the two units on the northern boundary, to make a comparative analysis of their training modes (Figure 1).

Twenty vertical electrical soundings were carried out on two profiles deployed on two units of the northern boundary of the Northern Congo Craton (Figure 1). The obtained resistivities were inverted using Earth Imager 1D software (https://www.agiusa.com), to extract the geological sections. The interpretation of the obtained geological sections was made from a six-layer model, according to the geological context, presented in Table 1.

Factors influencing the mechanical characteristics of lateritic soils affecting their permeability and hydraulic conductivity were correlated to permeability, deduced from electrical resistivity, as presented in Formula (3), for granitic soils [19].

$$k = \left(3 \times 10^{-30}\right) \times \rho^{8.1}(\mathrm{m/s}) \text{ for } \rho < 2000\,\Omega \cdot \mathrm{m}. \tag{3}$$

This formula established for the laterites of Ghana, like those of the northern limit of the Congo Craton, shows that the resistivities must be in the interval $800 \le \rho \le 1500(\Omega \cdot \mathrm{m})$.

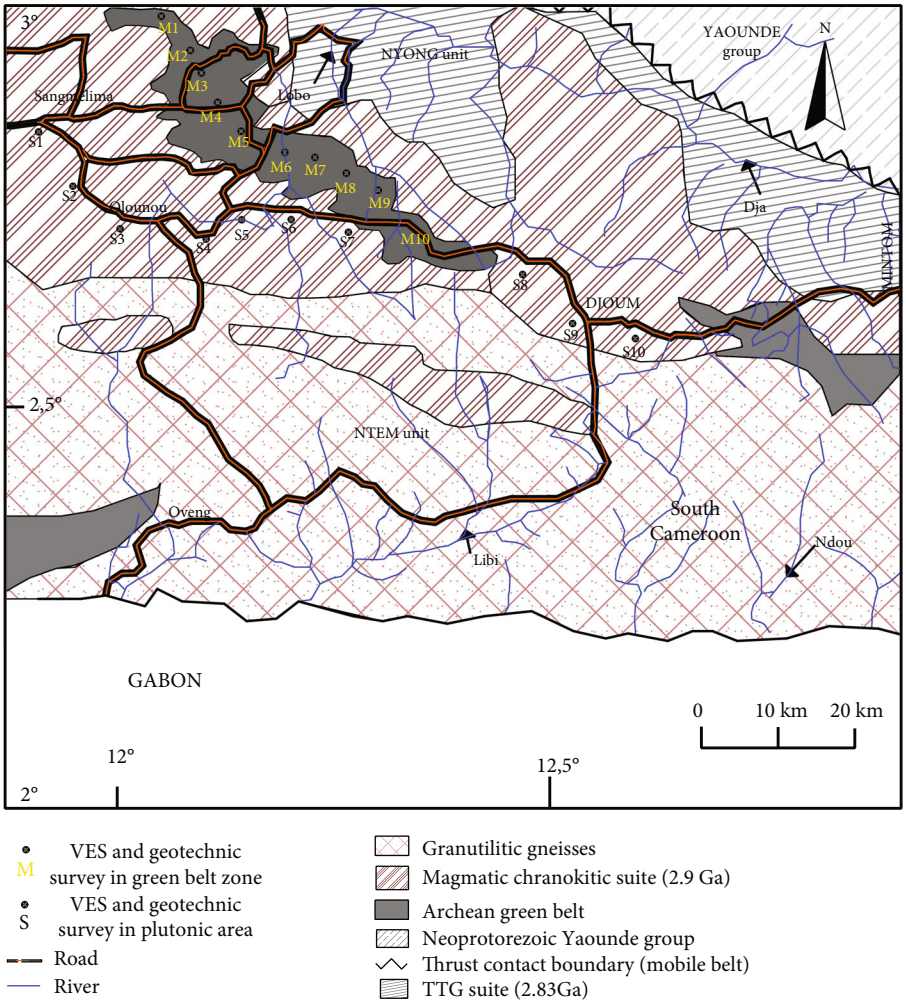

Figure 1: Revised geologic map of the northern border of the Congo Craton [17].

Table 1: Rock resistivity range.

Material	Range resistivity (Ω·m)	
Gneiss	6.8×10^6	3×10^6
Granite	3×10^2	10^6
Granite (*weathered*)	30	500
Laterite	800	1500
Lateritic soil	120	750

Laterite nature parameters can be correlated with apparent resistivity values. Table 2 gives some values of permeabilities of tropical soils [20].

3.2. Geotechnical Parameters. Twenty manual drillings of one- to five-meter depth were carried out according to the standard XP P94 202-12 [21], on the lateritic appearances of the two units of the northern limit of the Congo Craton, described above. These boreholes were drilled at the points of the vertical electrical soundings presented above (Figure 1). Tests on laterite soil samples included particle size analysis, specific gravity, Atterberg limits (liquidity and plasticity limit) [1], natural water content, CBR, and Proctor [1, 21]. The results of these geotechnical tests, which are used for road construction studies, are available in large numbers on this geological unit.

The index of potential induration or degree of virtual armor is considered as one of the parameters, likely to better reflect the evolution of physical properties of weathering products of lateritic soils, which is related to the density of solid grains (γ_s), but the parameters of this relationship are according to the soil [22].

The physical soil data from the Ngoumou-Mbalmayo-Bengbis areas in the northern boundary of the Congo Craton provide the following relationships between solid grain density (γ_s) and potential induration index (I_{ip}) as well as with potential lixiviation index (I_{lp}) [22].

$$I_{ip} = -18.6\gamma_d + 68.15,$$
$$I_{lp} = -14.64\gamma_d + 103.5. \quad (4)$$

4. Results and Discussion

4.1. Vertical Electric Soundings (VES)

Table 2: Permeability of some residual tropical soils [30].

Reference	Soil type	Country	Parent rock	Permeability K (cm/s)
Vargas [31]	Residual gneiss	Brasil	Gneiss	3×10^{-7} à 6×10^{-6}
	Residual basalt	Brasil	Basal	2.10^{-7}
Terzaghi and Robertson [32]	Sasumua clay	Kenya	Volcanic ash	0.8×10^{-7} à 7×10^{-7}
Matyas [33]	Sasumua clay	Kenya	Volcanic ash	2×10^{-7} à 6×10^{-8}
Fruhauf and Willis [34]	Laterite	Hawaï	Basalt	1.48×10^{-4} à 5.4×10^{-7}
de Graft-Johnson et al. [35]	Lateritic clay	Ghana	Granite	7.5×10^{-5} à 1.7×10^{-7}

Table 3: Compiled VES data in the green belt zone.

	Layer	M1 BIDJONG	M2 LYTECH	M3 FERM	M4 FOUNDA	M5 GENDA	M6 HOSPI	M7 LYCLA	M8 PREFECT	M9 TRIBUNE	M10 EVEA
1	Resistivity (Ω·m)	724.8	197.1	626	782.3	507.9	188.8	197.4	152.8	304.8	314.3
	Depth (m)	0.3	0.5	0.3	0.8	0.2	0.3	0.4	0.5	0.2	1
2	Resistivity (Ω·m)	979	820.7	1093	1382.9	1321.2	1213.6	820.7	274.5	418.9	675.7
	Depth (m)	1	2.8	1.8	2	0.8	0.5	1.6	1.4	0.3	3
3	Resistivity (Ω·m)	1557.1	883.8	1449.5	776.3	1453.3	1337.9	883.8	1440.3	487.3	1413.6
	Depth (m)	3.9	4.5	4	6	4.4	5.5	4	3.4	2.5	5
4	Resistivity (Ω·m)	1308.2	613.5	951	951.8	987.9	355.5	613.5	1217	1292.5	992.1
	Depth (m)	8.8	9.1	8.8	14.5	9	12.9	9.1	9.4	24.9	17.2
5	Resistivity (Ω·m)	1133.9	1377.1	521.8	1331.6	468	844.9	1377.1	590.5	370	807.9
	Depth (m)	17.6	16.7	22	39.7	22.2	27.9	19.8	21.1	29.4	53.9
ρ_{mean} (laterite)		1226.27	1042.51	1146.41	945.55	1237.88	1274.24	851.67	1323.95	1292.5	1042.51

4.1.1. Green Belt Zone. Ten vertical electrical soundings were carried out in the Meyomessala subdivision on laterite surface outcrops (Figure 1). The geoelectrical cross sections, summarized in Table 3, with extracts in Figure 2, show structures of low surface thickness, low resistivity, comparable to lateritic soils, whose minimum value is $152.8\,\Omega \cdot \mathrm{m}$, obtained at station M8 (subdivision), while the maximum value is $724.8\,\Omega \cdot \mathrm{m}$, obtained at station M1 (Bidjong Public School). The thickness of these layers is between 0.2 and 0.8 meters. A second, more resistive layer with values up to $1382\,\Omega \cdot \mathrm{m}$ (station M4), like a lateralized soil but with an average thickness of 0.5 meters, was observed globally.

A third layer with resistivities of the order of $800 - 1500\,\Omega \cdot \mathrm{m}$, like lateritic structures with an average thickness of about 3 meters, was observed globally.

A fourth layer made of structures within the resistivity range of lateritic structures with a maximum at station M1 (Bidjong Public School) of $1308.2\,\Omega \cdot \mathrm{m}$ and a minimum value of $333.5\,\Omega \cdot \mathrm{m}$ obtained at station M6 (Meyomessala Hospital), with 7.5 m thickness, which can be assimilated to the altered granitic structures, is also observed.

The fifth and sixth layers are constituted by structures with a higher resistivity range than the laterite, like gneiss-granite structures. We note that the thickness of the alteration is on average 30 meters.

4.1.2. Plutonic Area. Ten vertical electrical soundings were deployed on the Sangmelima-Djoum road, on lateritic outcrops, Figure 1, as shown in some of the pseudosections presented in Figure 3 and whose results are compiled in Table 4; the surface layers are equivalent to leached lateritic structures, with an average resistivity of $300\,\Omega \cdot \mathrm{m}$ and an average thickness of 0.75 m. A second layer of average resistivity $286\,\Omega \cdot \mathrm{m}$ with a thickness of approximately 1.13 m and a third layer of average resistivity with an average thickness of 3.6 m were observed.

The fourth layer has an average value close to $946\,\Omega \cdot \mathrm{m}$, which suggests the predominance of lateritic soils. However, at station S3 (Eye'e), a resistivity of $403.7\,\Omega$·m not assimilable to lateritic structures was recorded. At the fifth and sixth layers, resistivity values not assimilable to lateritic structures were recorded. In this geological unit, an average depth of 27.6 meters was observed for rock alterations.

4.1.3. Geoelectrical Parameters. The different geoelectrical sections revealed three layers of laterite structures, as

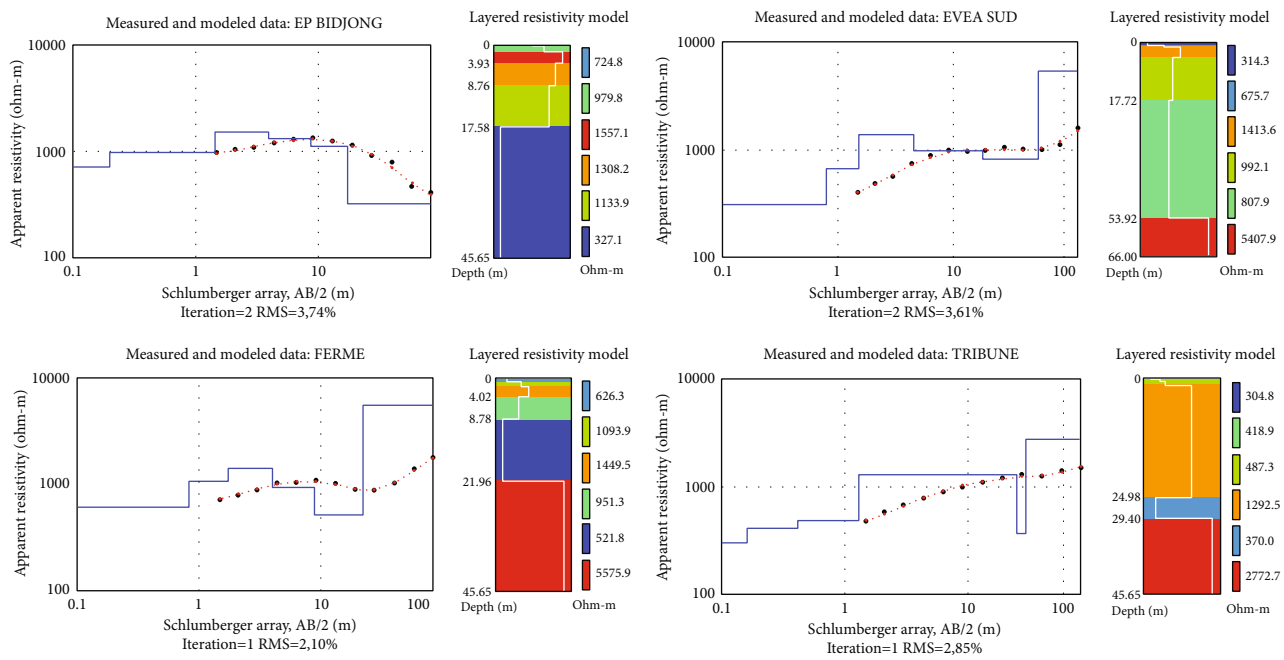

Figure 2: Geoelectrical sections in the green belt zone.

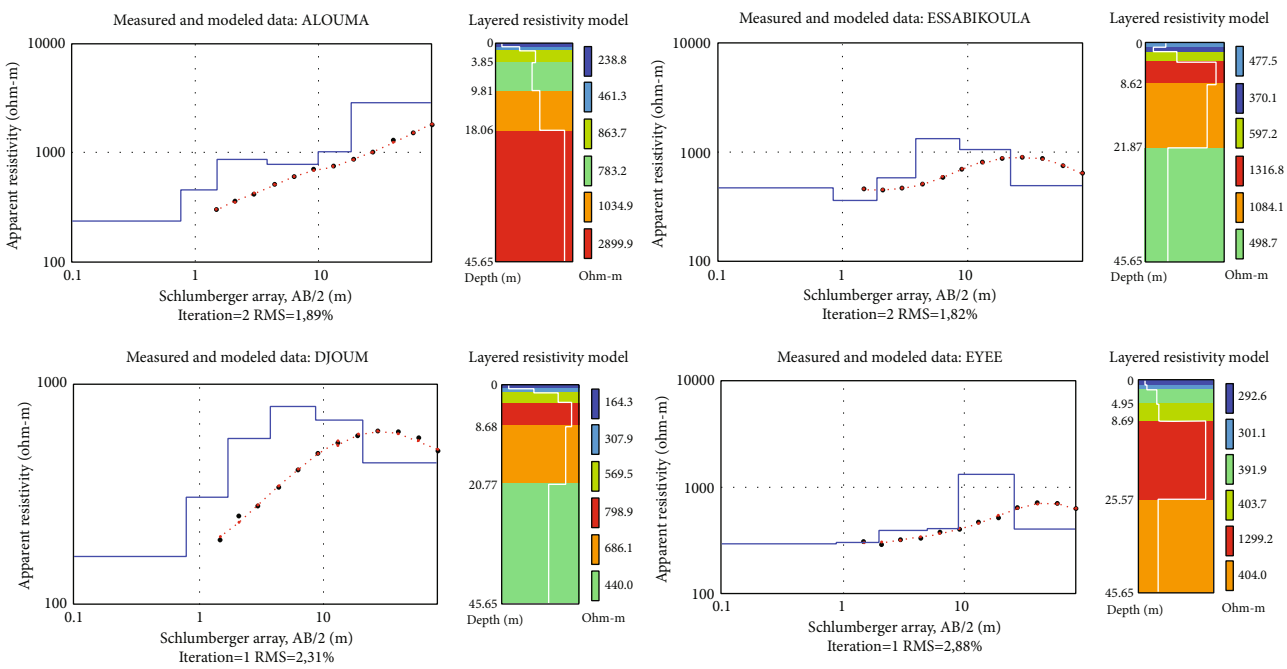

Figure 3: Geoelectrical sections in the plutonic area.

considered by [23, 24] with the following physical characteristics, summarized in Table 5:

(i) Upper layer: in the plutonic zone, the laterites have the following average values: 8.66 m thick, permeability of 2.85-10 cm/s, and 1090 Ω·m resistivity, while in the green belt zone an average thickness of 1.47 m, permeability of 1.41-08 cm/s, and 1080.16 Ω·m resistivity were obtained

(ii) Middle layer: in the plutonic zone, average values of 9.32 m for thickness, 2.12-08 cm/s for permeability, and 1302 Ω·m resistivity were obtained. The following average values were obtained in the green belt area: 4.35 m thickness, 1.17-07 cm/s for permeability, and 943 Ω·m resistivity

(iii) Deep layer: in the plutonic zone, an average permeability of 4.86-09 cm/s with an average thickness of

Table 4: Compiled VES data in the plutonic area.

		S1 BIDJONG	S2 ESSABIK	S3 EYEE	S4 MEKA'A	S5 MEYOM	S6 NGAM	S7 NKOME	S8 ALOUMA	S9 DJOUM	S10 DJOUM 2
1	Resistivity (Ω·m)	537	477.5	292.6	74.5	52.2	284.2	924	238.8	164.3	43
	Depth (m)	0.3	0.5	0.5	0.2	1	0.3	2.5	0.2	0.45	0.1
2	Resistivity (Ω·m)	472	370.1	301.1	143.6	100.7	458.2	126.7	461.3	307.9	112.6
	Depth (m)	0.5	1	1.1	0.8	3.5	1.3	5	1.5	2	0.5
3	Resistivity (Ω·m)	186.3	597.2	391.9	600.7	651.5	113.6	1298.8	863.7	569.5	288.8
	Depth (m)	4.1	3.5	5	2.5	6	3.9	13.5	3.85	4	2
4	Resistivity (Ω·m)	859	1316.6	403.7	1384.5	1170.8	1102.4	730.8	783.2	998.9	914.8
	Depth (m)	5.1	8.6	8.7	7.2	17.7	14.3	21.2	9.81	8.68	12.86
5	Resistivity (Ω·m)	1452.5	1084.1	1299.2	923.5	344.8	415.9	312.7	1034.9	686.1	338.2
	Depth (m)	15.6	21.9	25.6	17.5	41.6	38.8	33.9	18.06	20.77	43.01
6	Resistivity (Ω·m)	748.6	498.7	404	480.2	3240.4	3425.8	1836.5	2899.9	440	1719.1
	Depth (m)	45.7	44	48	42	51	44.5	41	45.65	47	46
ρ_{mean} (laterite)		1117.00	1194.71	1299.20	1130.75	1170.80	1102.40	1836.5	863.70	998.90	914.80

Table 5: Physical and mechanical parameters.

Station	γ_d	$I_{ip}(\%)$	$I_{lp}(\%)$	k(cm/s)	Station	γ_d	$I_{ip}(\%)$	$I_{lp}(\%)$	k(cm/s)
S1	2.04	30.31	73.65	$6.24E-05$	M1	2.00	31.03	74.22	$5.82E-05$
S2	2.07	29.73	73.20	$3.35E-05$	M2	2.09	29.36	72.90	$2.09E-05$
S3	2.19	27.50	71.44	$4.99E-05$	M3	2.02	30.66	73.93	$1.37E-04$
S4	2.17	27.91	71.76	$4.33E-05$	M4	2.05	30.10	73.49	$2.98E-05$
S5	2.12	28.80	72.46	$2.15E-05$	M5	2.14	28.43	72.17	$4.66E-05$
S6	2.23	26.76	70.85	$1.32E-05$	M6	2.33	24.91	69.39	$3.12E-05$
S7	1.89	33.00	75.77	$4.98E-05$	M7	2.01	30.84	74.07	$2.09E-05$
S8	2.15	28.30	72.07	$4.86E-06$	M8	2.11	29.03	72.64	$4.81E-05$
S9	2.16	28.15	71.95	$4.86E-06$	M9	2.19	27.50	71.44	$4.78E-05$
S10	2.11	28.99	72.61	$9.71E-07$	M10	2.19	27.50	71.44	$3.52E-05$
Mean	2	28.90	72.56	$6.24E-05$	Mean	2.11	28.88	72.55	$5.82E-05$

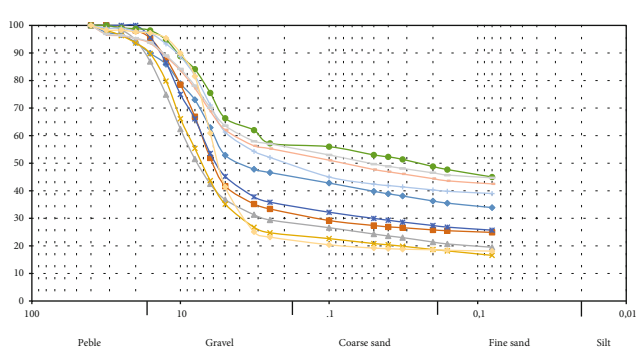

Figure 4: Sieve analysis of laterite in the green belt zone.

19.7 m and 1122 Ω·m resistivity was obtained, while the average value of permeability is 1.53-05 cm/s with an average thickness of 21.24 meters and 1158 Ω·m resistivity recorded in the green belt zone

4.2. Geotechnical Parameters

4.2.1. Green Belt Zone. The particle size analysis of samples from the Meyomessala area, Figure 4, revealed a few elements superior to 31.5 mm; the fine fraction oscillates in average around 23%, which shows that the characteristics of these lateritic soils are similar to those of the fine fraction. With the values of the uniformity coefficients ($1.11 \leq C_u \leq 1.6$) and

Table 6: Geotechnical results in the green belt zone.

	Atterberg limit			PROCTOR			CBR	G	Bearing capacity			Class
	LL	IP	IC	γ_s (t/m^3)	γ_d (t/m^3)	W (%)	95%	%	E	PF	Sol	GTR
M1	62.7	30.5	1.675	2.77	2	13	13	0.62	65	PF2	S3	B6 ts
M2	76.2	38.1	1.678	2.86	2.09	11.2	34	0.54	170	PF3	S4	A3 s
M3	59	33.3	1.308	2.86	2.02	13.9	25	0.34	125	PF3	S4	B6 ts
M4	66.4	31.3	1.701	2.74	2.05	11.5	51	0.3	255	PF4	S5	B6 ts
M5	64.9	26.8	1.954	2.97	2.14	11	54	0.42	270	PF4	S4	B6 ts
M6	59	33.3	1.46	3.13	2.33	10.5	49	0.5	245	PF4	S5	A3 ts
M7	76.3	36.2	1.782	2.94	2.01	13.8	28	0.34	140	PF3	S4	A3 ts
M8	75.2	33.9	1.935	2.66	2.108	9.5	41	0.42	205	PF4	S5	A3 ts
M9	71	33.6	1.723	2.92	2.19	10.5	26	0.4	130	PF3	S4	A3 ts
M10	60.4	31.6	1.648	2.92	2.19	10.5	34	0.3	170	PF3	S5	B6 ts
Mean	67.11	32.86	1.686	2.8744	2.1128	11.54	35.5	0.418	177.5	PF3	S4	A3 ts

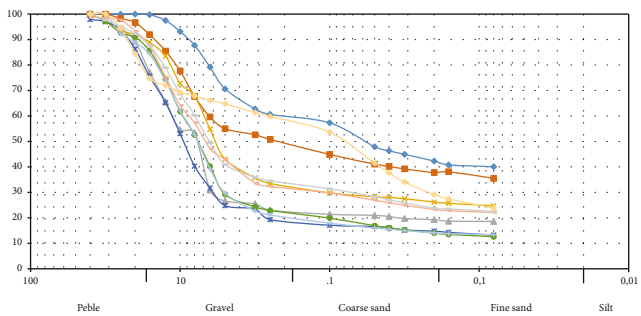

Figure 5: Sieve analysis of laterite in the plutonic area.

those of the curvature coefficient ($1.07 \le C_c \le 1.6$), it is therefore plausible to conclude that these soils have well-graded grain size structures and assimilate them to their fine particles, usable in road works.

The values of specific weight obtained in this area are in the range of $2.00 \le \gamma_d \le 2.33$. The values of Atterberg limits resulted in values of liquidity limits between 59% and 73.3% with an average value of 62.78%; the plasticity index in this area is between 26.8% and 38.10% with an average value of 30.96%, as shown in Table 6.

The average value of the optimum water content required for compaction in road works, obtained from the modified Proctor test, is for this area in the range $9.50 \le w_{opt} \le 13.90$; mean = 10.60. It is noted that the lower value is globally higher than the natural water content values ($1 \le w_{nat} \le 10$).

The specific weight values are in the order of $2.0 \le \gamma_d \le 2.33$; mean = 2.05. The CBR index is of the order of $13 \le \text{CBR} \le 54$; mean = 35.5: with an average swelling of 0.35 mm ($0.3 \le G \le 0.62$; mean = 0.35). These different results show that the lateritic soils of this area are made of materials insensitive to water, very little deformable.

The resulting platform is a PF3 platform, on average, according to the GTR ("Guide de Terrassements Routiers") classification with Young's modulus of 177.5 MPa, which can be used as a foundation or base layer for secondary roads.

4.2.2. Plutonic Area. The samples from this area have a sieve case of more than 35% (40% at S1); however, the average obtained is 16.1% (sieved at 80 μm), which shows that the behavior of these lateritic soils is also comparable to that of the fine fraction, as can be seen in Figure 5. The values of the uniformity coefficient ($1.07 \le C_u \le 1.6$) and the curvature coefficient ($1.07 \le C_c \le 1.6$) show that these lateritic soils are well graded.

The results reported in Table 7 show dry weight values inferior to those obtained previously ($1.89 \le \gamma_d \le 2.23$); the average value of water content is 9.9%. The high values of specific weight in these two zones indicate the richness of ferromagnesian minerals in the source rock that had an impact on the formation of these laterites [8, 25]. The average value of the liquidity limit was obtained at 63%, between 62.2% and 78%, while the plasticity index has a maximum value of 38.4%, a minimum value of 22.4%, and an average of 28.86%.

The average optimum water content obtained by the modified Proctor test is in the following range: $9.40 \le w_{opt} \le 19.60$; mean = 9.80. The average value of the dry specific weight is between $1.89 \le \gamma_d \le 2.23$; mean = 2.06. The CBR index is between $23 \le \text{CBR} \le 50$; mean = 27.71, with swelling between $0.21 \le G \le 0.60$; mean = 0.31, which shows that the lateritic soils in this area are also made of water-insensitive materials with very low deformability. The platform obtained is like that obtained in the plutonic zone with a bearing capacity of 171 MPa giving a class A3 ts according to [26].

4.2.3. Geomechanical Parameters. The values of induration index (I_{ip}), reflecting the hardness of the laterites, and leaching index (I_{lp}), which presents the leaching of the bedrock, show low variations in the two geological units, namely, 28.9% in the plutonic zone and 28.88% in the green belt zone, for the induration index, and 72.56% in the plutonic zone and 72.55% in the green belt zone, for lixiviation index.

4.3. Laterization Process of the Northern Boundary of the Congo Craton. The successive climatic variations during the period of laterization of the northern boundary of the

Table 7: Geotechnical results in the plutonic area.

	Atterberg limit			OPM			CBR	G	Bearing capacity			Class
	LL	IP	IC	γ_s (t/m^3)	γ_d (t/m^3)	W (%)	95%	%	E	PF	Soil	GTR
S1	73	38.4	1.55	2.84	2.04	13.2	24	0.6	120	PF3	S4	A3 th
S2	78.3	33.2	1.98	2.74	2.07	11	23	0.46	115	PF2	S3	A3 ts
S3	75	28.8	2.20	2.86	2.19	9.4	30	0.21	150	PF3	S4	A3 ts
S4	78.3	34.7	1.58	2.87	2.17	9.8	50	0.3	250	PF4	S5	B6 ts
S5	68	30.5	1.80	3.04	2.12	11.8	31	0.4	155	PF3	S4	B6 ts
S6	63.5	31.5	1.73	2.93	2.23	10	37	0.31	185	PF3	S3	B6 ts
S7	68	33.6	1.66	2.96	1.89	19.6	34	0.42	170	PF3	S4	B6 ts
S8	76.2	28.2	2.32	2.93	2.15	11.4	49	0.4	245	PF4	S5	B6 ts
S9	62.2	22.4	2.35	2.71	2.16	10	36	0.34	180	PF3	S4	B6 ts
S10	62.8	37.6	1.37	2.91	2.11	11.4	27	0.35	135	PF3	S3	B6 ts
Mean	70.5	31.9	1.86	2.8776	2.11	11.76	34.1	0.379	171	PF3	S4	A3 ts

Congo Craton make it difficult to interpret the principle of laterite formation in this area [27]. However, two main types of mechanisms generally contribute to the formation of laterites in this type of geological structure, namely, alteration and transfer mechanisms [27].

The large similarities observed in the mechanical parameters of the laterites on the two geological units (lixiviation and induration index) show that they have undergone similar formation processes during the same geological periods.

An average resistivity of 1171.77 Ω·m was obtained for the lateritic soil of the plutonic zone, with an average resistivity of 3413 Ω·m, obtained for the alterations of the basement, essentially composed of charnockitic granitoids. However, an average resistivity of 1061.16 Ω·m was obtained for the lateritic soils of the green belt area, with an average resistivity of 1569.32 Ω·m, for the alteration of the basement, of basic origin, on which these laterites are based. We note that the variations in resistivity observed on laterites are also observed on source rocks with different orders of magnitude, probably induced by lixiviation.

The hydraulic permeability values ranging from 7.5×10^{-5} to 1.7×10^{-7}, the classification of [20], of which an extract is shown in Table 2, indicate that they are derived from granitic rocks. The variation in resistivity that ranges between the laterites of the green belt zone and the plutonic zone shows that they are derived from different rocks. It seems likely that these laterites are the result of metamorphism of the alterations of the mother rock along a long geologic period, highlighted by the reduction in the difference between the resistivities of the laterites compared to the difference observed in the bedrock of the two units.

5. Conclusion

Due to the high cost of laterite formation by geochemistry, this method is not commonly deployed for the study of large-scale geological structures, such as the Congo Craton, which is composed of multiple units and whose top layer is 80% laterite [17, 28, 29].

The objective of this work was to study the lateralization process of the northern border of the Congo Craton, using available data, such as vertical electrical soundings, to bring out the physical parameters, related to the nature of the rock, coupled with geotechnical tests, whose mechanical parameters show the degree of alteration of the bedrock.

To do this, twenty vertical electrical soundings and twenty soil samples for geotechnical tests (CBR, Proctor, dry density, Atterberg limits, and granulometric analysis) were taken in the green belt and plutonic zones, which constitute the main geological units of the northern border of the Congo Craton, in order to determine by comparative analysis the formation process of these laterites [5].

The different results showed three lateritic sets considered by the geochemical study (lower alteration layer, middle layer, and upper layer), with similarities in the mechanical data, translated by a CBR of 35.5 in the green belt zone and 34.1 in the plutonic zone. Induration and leaching indices are 28.8% and 72.55% in the green belt zone and 29.9% and 72.56% in the plutonic area. These converging results show that these laterites developed after similar alteration processes and periods.

The inversion of the geoelectrical data resulted in a first layer in the plutonic zone with a resistivity of 1090 Ω·m and 1080 Ω·m in the greenbelt zone, followed by a second layer with a resistivity of 1302 Ω·m in the plutonic zone and 943 Ω·m in the greenbelt zone and then a third layer with a resistivity of 1122 Ω·m in the plutonic zone and 1158.74 Ω·m in the green belt zone. However, a global difference was observed with resistivities of 171.77 Ω·m and 1061.16 Ω·m in plutonic and green belt areas. These differences were also found between the granitic source rocks, with a contrast in resistivity between the plutonic granites and the granites of the green belt zones. The average resistivity of the green belt granite is $\rho_a = 3413.51\,\Omega \cdot \mathrm{m}$, and the average resistivity of the plutonic granite is $\rho_a = 1569.32\,\Omega \cdot \mathrm{m}$.

Given the differences in resistivity and permeability ($k = 6.24E - 05$ cm/s in the plutonic area and $k = 5.82E - 05$ cm/s, in the green belt zone), which reflect the impact of the source rock, it appears that the laterites in this zone are derived from different parent rocks, formed in a similar manner, highlighted by the similarities in the leaching and induration index.

Data Availability

Data are available at Geolab (geotechnical data) (http://geolabsarl.com) and Geofor (geophysical data) (info@geofor.org).

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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