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ARTICLE

Geochemical Characterization and Petrogenetic Implication of Recent Mafic Magmatism from Foumbot-Koutaba (West-Cameroon) and Their Potential as Sustainable Natural Resources

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ABSTRACT

The Foumbot-Koutaba area which is part of the Noun plain, a component of Cameroon Volcanic Line (Central Africa) has experienced recent magmatism from 65 Ma up to date. Field and petrographic studies show that the recent mafic magmatic rocks of the area consist of basalts, dolerites and huge pyroclastics deposits. The rocks present doleritic (dolerites), porphyritic microlitics, aphyric (basalts) and vesicular (pyroclastics) textures. Geochemical studies show that the mafic rocks studied have high contents of FeOt (08.22–12.55% by weight) and V (130.83–255.19 ppm), low in SiO_2 (47.15–54.57%), medium to high in MgO (5.33–12.58%) and Mg # (58–66) and the compatible element contents (Cr = 31.70–352.11 ppm, Co = 41.24–135.74 ppm and Ni = 48.01–148.89 ppm) which indicate that the magma parent of these mafic rocks would be of mantle origin and would have undergone a very low rate of contamination during their ascent. All

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samples have high Ba (185–1990 ppm) and Sr (350–708 ppm), higher than average values in the crust (Ba = 259–628 ppm and Sr = 282–348 ppm) which justifies the hypothesis of a very low contamination rate. The basalts were controlled by fractionation of olivine and apatite, while the dolerites would be the products of the accumulation of plagioclase. The pyroclastics of the study area are pozzolans low carbon cement materials. They are used artisanally for mortars to make construction blocks with pozzolan cement and water mixtures. Moreover, dolerite shows nice plagioclase laths, beautifying the rocks for tiles manufacture. The value of denstity (2.7) and water absorption (0.4%) are good for low carbon dimension stones production to replace tiles made of clay that pollute the environment through pyroprocess during their manufacture. Also, the huge outcrops of basalts are good resources for gravel and sand production. All these recent mafic materials are good resources for sustainability.

Keywords: Foumbot-Koutaba; Mantle Origin; Pozzolan; Tiles; Sustainability; Resources

1. Introduction

The Foumbot-Koutaba study area (part of Cameroon Volcanic Line) has undergone recent magmatism, with rocks comprising dolerites, basalts and large deposits of pozzolanic pyroclastites above the granitogneissic basement formations[1–4]. The study of these rocks could foster the understanding of petrogenesis related to the recent geological formations of the Cameroon Volcanic Line (CVL), which remains debate matter. Several hypotheses have been put forward: the hypothesis of an emerging continental or oceanic rift[5, 6], the hot line hypothesis[7] and the lithospheric fissure hypothesis[8, 9]. The Cameroon Volcanic Line is a volcano-tectonic megastructure oriented N030°E. It consists of an alignment of oceanic and continental volcanic massifs and anorogenic plutonic complexes from the island of Pagalu in the Gulf of Guinea to Lake Chad[10]. It is approximately 1600 km long and 100 km wide. The oceanic segment of the Cameroon Volcanic Line includes Pagalu, Sao Tome, Principe and Bioko massifs. They are made up of several petrographic types such as basalts, basanites, phonolites and trachytes of the alkaline series[11, 12], as well as transitional basalts of the tholeiitic series observed at Principe[13]. The continental segment includes Mount Cameroun, 4100 m[14] , Mount Manengouba, 2391 m[15], Mount Bambouto, 2744 m[16], Mount Oku, 3011 m[17], the Mbam massif[18], the Adamaoua plateau[19], the Ntumbaw[20], the Mount Koupé[21] and the Bamenda Mountains[22]. This continental segment also includes plains of Tombel[23], Kumba[24], Mbo[25], Noun[26] and Tikar[27]. Petrologically, continental volcanism is subdivided into three series (transitional, alkaline, tholeiitic)[28–30].

Magmatism in the Cameroon Volcanic Line began 65 Ma ago[31], and continues till now on the Mount Cameroon volcano[32]. Geochronological data show that there is no systematic age progression between the different volcanic massifs of the CVL[33]. Recent mafic magmatism in the Foumbot-Koutaba region is made up of basatic and doleritic lavas whose age varies between 65 Ma and nowadays. Some basalts are 10.43 ± 0.28, 4.59 ± 0.12 and 0.20 ± 0.20 Ma old. Ancient effusive episodes (11–4 Ma) in Foumbot region were followed by an explosive event (0.4–0 Ma) that formed pozzolanic pyroclastic deposits[34].

From a practical point of view, the rocks of the Foumbot-Koutaba zone offer interesting potential for sustainable development, due to their use in construction and public works to meet population needs. Pozzolans can be used to manufacture low-carbon mortars[35]. Due to their aesthetic and physico-chemical properties, the dolerites of the area are also interesting for the production of low-carbon ornamental stones (tiles, tables, gravestones, etc.), as they just need to be cut into different sizes and polished, unlike clay-based tiles, which are less resistant, energy-consuming and contribute to environmental pollution. The enormous deposits of basalt are also important resources for the production of gravel and quarry sand (with the perishable nature of river sand).

The objective of this work is to understand the petrogenesis of recent magmatic mafic rocks of the study area and to assess the usefulness of these rocks for sustainable development in the context of the fight against climate change. The study area is part of the Bamoun Plateau and the Noun Plain. The area lies between latitudes 5°26’ and 5°42’ North and longitudes 10°33’ and 10°47’ East on the Cameroun Volcanic Line (**Figure 1**). This area is established on two entities: the

Noun plain, with an average altitude of 1100 m, and the Bamoun plateau, with an average altitude of 1200 m.

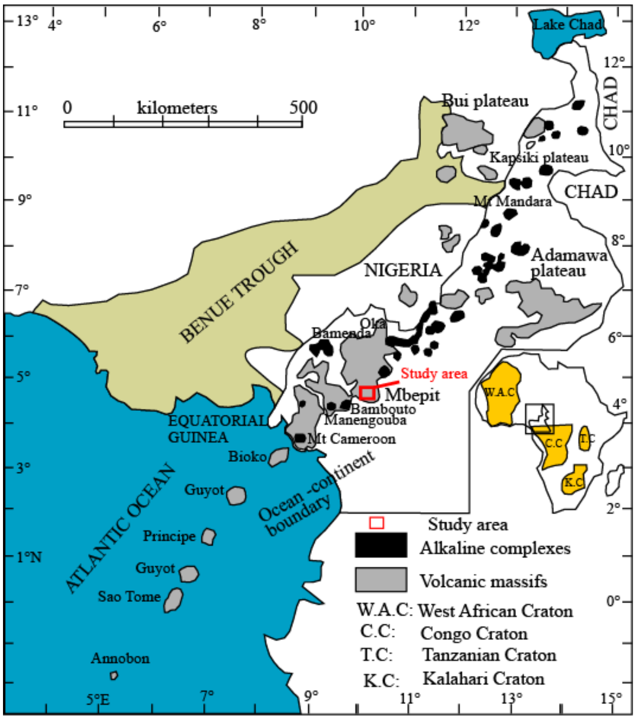

Figure 1. Localization of the area on the Cameroon Volcanic Line (CVL) adapted from [36].

2. Methodology

25 representative samples were collected, of which 20 were selected for geochemical analysis and thin section preparation. Laboratory work involved petrography and geochemical analysis of whole rock, density and water absorption tests. The procedures are explained in Mounjouohou et al. (2021) [4] and Ntieche et al. (2022) [37]. Geotechnical analyzes focused on density and water absorption tests of dolerites, knowing that low density rocks often have high porosity. It is accepted that ornamental stone must have very low porosity to ensure its durability and also a low water absorption rate.

3. Results

3.1. Petrographic Studie

The petrographic study shows that the rocks of recent mafic magmatic rocks in the study area are basalts, dolerites and pyroclastites (**Figure 2**).

3.1.1. Basalts

Basalts outcrop in the form of lavic flows and primatic basalts. The basalts have porphyritic and aphyritic microlitic textures (**Figure 3**). They contain plagioclase (10–20%), pyroxene (5–15%), olivine (10–20%) and oxides (5–10%). The groundmass (40–60%) consists of plagioclase microlites and a few pyroxene and olivine crystals. The phenocrysts are plagioclase and pyroxene. Oxides are either isolated or included in other minerals. Basalts with a more or less aphyric microlitic texture contain very small crystals (0.09 mm) of plagioclase, pyroxenes, feldspars and oxides, whereas those with a porphyritic microlitic texture contain plagioclase and pyroxene phenocrysts embedded in a paste made up of plagioclase microlites and feldspar and olivine microcrystals (**Figure 3c,d**).

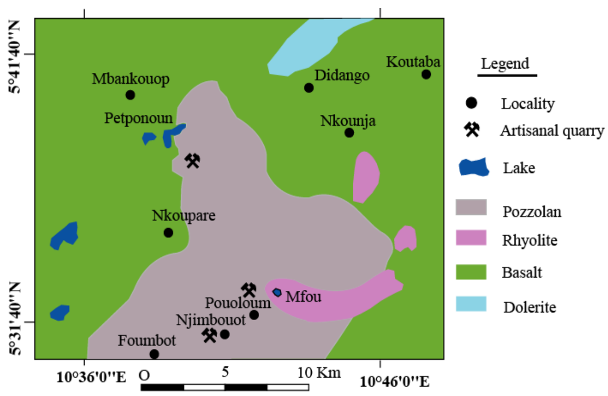

Figure 2. Geological map of the Foumbot-Koutaba area.

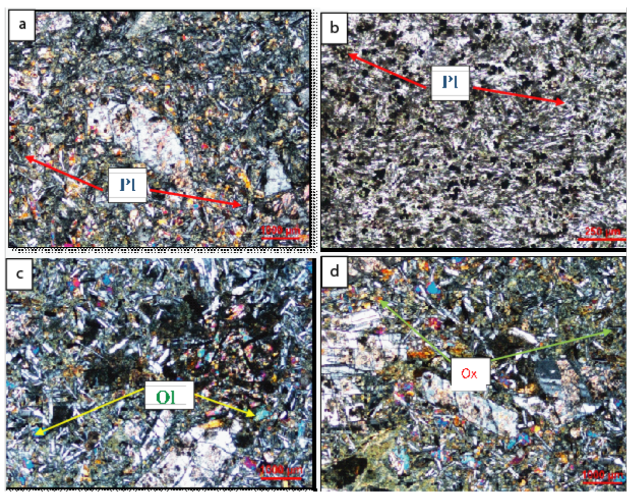

Figure 3. Microscopic photographs showing textures in basalts. **a**) Microlitic texture in basalt. **b**) Microcrystals of plagioclase and oxides in basalt. **c**) Porphyritic microlitic texture and resorption reaction of plagioclase by oxide. **d**) Porphyritic microlitic texture in basalt. Pl = Plagioclase, Ol = Olivine, Ox = Oxides.

3.1.2. Dolerites

These rocks have doleritic macrotextures characterised by centimetric plagioclase laths oriented in several directions (**Figure 4**), often giving the rock the appearance of bird's footprints. Dolerites are rocks with a basaltic composition. Plagioclases are the most abundant and are present as microlites with their polysynthetic twins. Pyroxene and olivine microcrystals are associated with plagioclase crystals. The alkali feldspar are represented here by sanidine (**Figure 4a**).

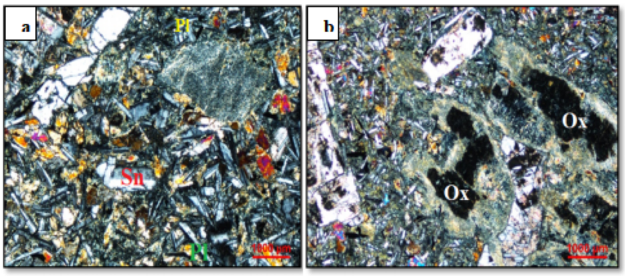

Figure 4. **a**) Sanidine crystal in a dolerite. **b**) Resorption reaction of feldspars by oxide in a dolerite. Pl = Plagioclase, Ox = Oxides, Sn = Sanidine.

3.1.3. Pyroclastites

Pyroclastites are pozzolans made up of particles or fragments of rocks ejected from volcanoes, regardless of their shape, size or composition (**Figure 5**). These pyroclastites are made up of ash and lapillis. The ash is very fine, with less than 2 mm diameters. Lapillis has diameters between 2 and 64 mm.

Figure 5. Pozzolan deposit in the locality.

3.2. Geochemical Studies

According to the TAS (Total Alkali Silicate) diagrams of Le bas et al.[38], the chemical composition of the lavas includes mafic terms (**Figure 6**) consisting of basalts and dolerites. According to the digram of Peccerillo and Taylor[39], the lavas are alkaline magmas (**Figure 7**).

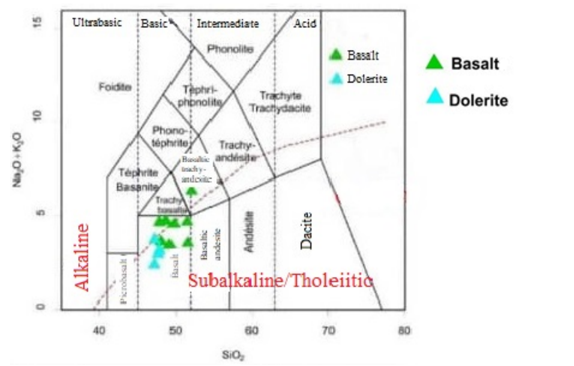

Figure 6. Position of rocks of the Foumbot-Koutaba zone lavas according to Le bas et al. (1986).

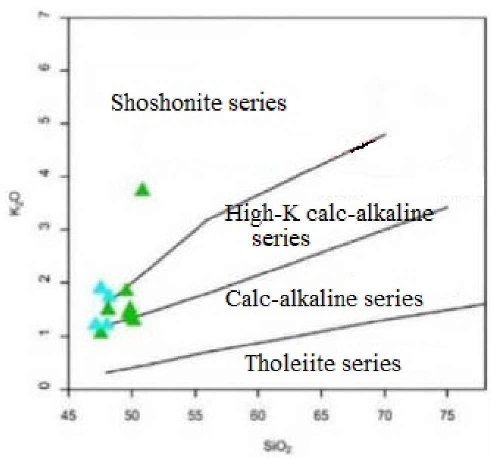

Figure 7. Position of rocks of the Foumbot-Koutaba zone lavas in the diagram SiO_2-K_2O diagram according to Peccerillo and Taylor (1976). (Legend in **Figure 6**).

3.2.1. Basalts

Major elements

The lavas have silica concentration between 47.56 and 50.84 wt%, indicating undersaturation. The rocks have high and medium concentration of Al_2O_3 (11.25–15.16 wt%), Fe_2O_3 (9.61–12.5516 wt%), CaO (7.69–11.9716% wt%), TiO_2 (0.54–3.23% wt%), MgO (5.33–12.5816 wt%) and low contents of MnO (0.11 to 0.4816 wt%), P_2O_5 (0.14–0.56 wt%). Na_2O (1.15–3.17% wt%) and K_2O (1.05–3.74 wt%) concentrations are varied. The high TiO_2 content (0.54–3.23 wt%) reflects the crystallisation of ferrotitanium oxides. The high Fe_2O_3 content (9.61–12.5516%) reflects the fractionation of ferromagnesians (olivines and pyroxene). The sum of alkalis (Na_2O_3+K_2O = 2.35–6.19% wt%) is high. Basalts are alkaline and shoshonitic (**Figure 7**). Major and trace elements such as Al_2O_3, P_2O_5 and Zr show a negative correlation with SiO_2 in basalts (**Figure 8**).

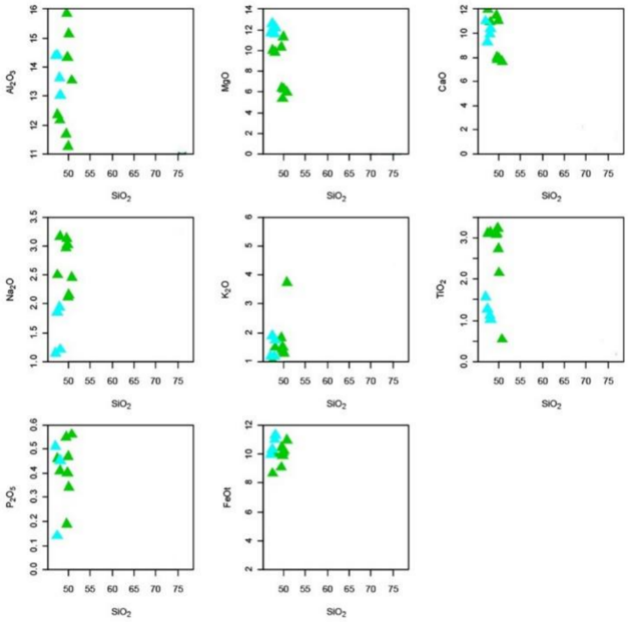

Figure 8. Behavior of major elements versus SiO_2. (Legend in **Figure 6**).

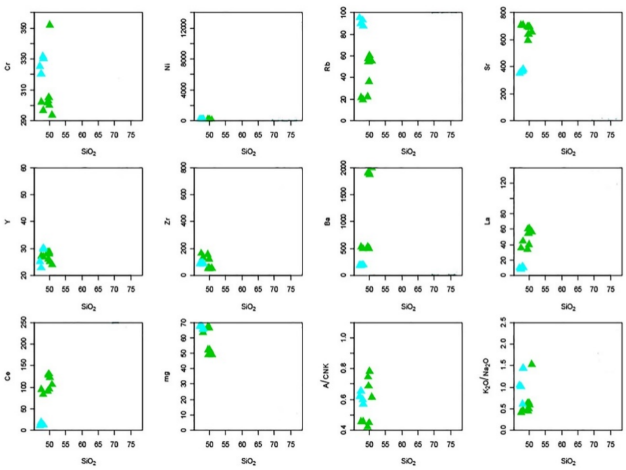

Figure 9. Behavior of trace elements versus SiO_2. (Legend in **Figure 6**).

Trace and rare earths elements

The samples are characterised by high levels of incompatible elements: Rb (19.2–95.37 ppm), Sr (350.12–708.91 ppm) and Yb (1.04–1.89 ppm). Compatible elements have variable concentrations Ni (60.02–148.89 ppm), Co (43.97–135.74 ppm), Cr (293.77–352.11 ppm) V (130.83–200.55 ppm), Sc (17.03–38.13 ppm). The samples are characterised by high Sr (350.12–708.97 ppm), La (34.18–60.45 ppm), Nd (36.74–60.98 ppm) and Eu (2.07–2.74 ppm) values. The spectra show an enrichment in light rare earths (**Figure 10**). The concentrations of Ni (100.78 to 129.38 ppm) and Cr (320.53 to 332.81 ppm) are high and correspond to rock contents originating from partial melting of the mantle (Ni > 200 ppm and Cr > 400 ppm). It is also important to note that these low Ni and Cr values may arise from partial melting or fractional crystallization processes. The rare earth spectrum normalized to chondrite values shows a slight enrichment of LREE (La/SmN = 1.67–2.03) compared to HREE (**Figure 11**).

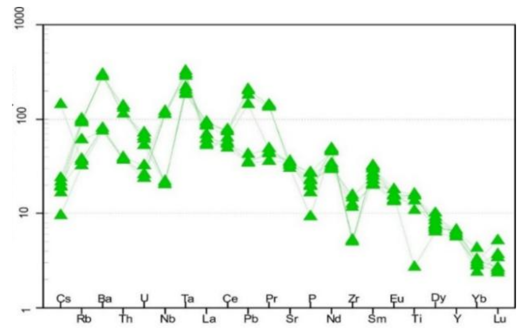

Figure 10. Trace element patterns of basalts from the Foumbot-Koutaba sector, normalised to chondrite values according to Sun and McDonough [40].

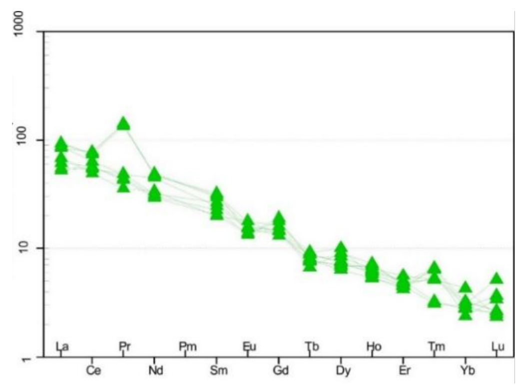

Figure 11. Rare earth patterns of basalts from the Foumbot-Koutaba sector normalised to chondrite values according to Sun and Mc Donough [40].

3.2.2. Dolerites

Major elements

Rocks have a silica concentration ranging from 47.15 to 48.22 wt%. The concentration of Al_2O_3 varies from 13.03 to 14.40 wt% and MnO from 0.12 to 0.14 wt%, while Fe_2O_3 varies from 11.04 to 12.57 wt %. The CaO content ranged from 9.29 to 11.01. The concentrations of Na_2O (1.15–1.95%), K_2O (1.20–1.89 wt%), TiO_2 (1.03– 1.57% by weight) and P_2O_5 (0.14–0.51 wt%) are relatively low. Loss on ignition varies from 0.91 to 1.38%.

Trace and rare earths elements

Concentrations of Ni (100.78 to 129.38 ppm) and Cr (320.53 to 332.81 ppm) are high and correspond to the levels found in rocks derived from partial melting of the mantle (Ni > 200 ppm and Cr > 400 ppm) (**Figure 12**). The rare earth spectrum which normalised to chondrite values shows a slight enrichment of LREE (La/Sm_N = 1.67–2.03) compared with HREE (**Figure 13**).

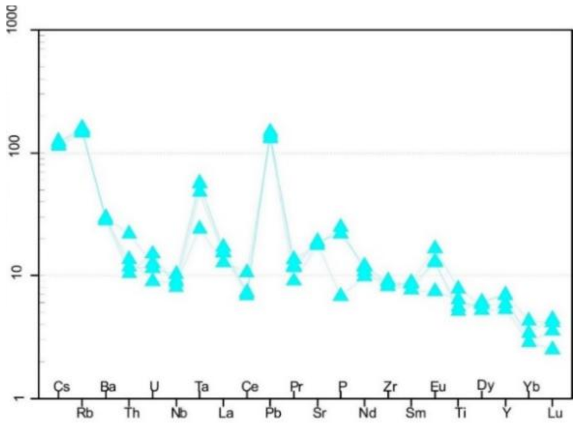

Figure 12. Trace element patterns of dolerites from the Foumbot-Koutaba sector, normalised to chondrite values according to Sun and McDonough (1989).

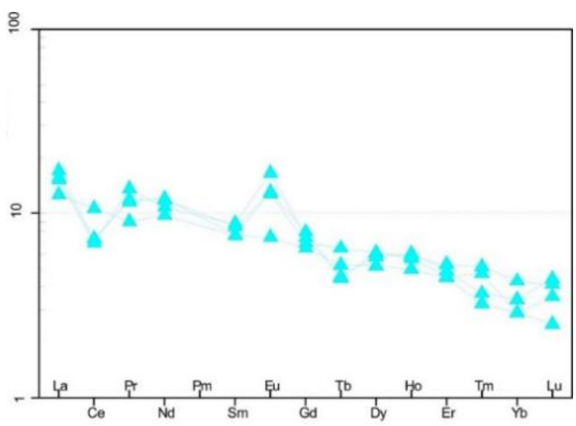

Figure 13. Rare earth patterns of dolerites from the Foumbot-Koutaba sector normalised to chondrite values according to Sun and Mc Donough (1989).

Dolerites shows high concentration in Sr (350.12–380.45 ppm) and Y (22.78–30.15 ppm). Yb (1.27–1.89) ppm) are low. V concentration varied from 142.98 ppm to 165.20 ppm and that of Cs from 2.38 to 2.61 ppm (**Table 1**).

There are relatively low concentrations of HFSE elements (Nb Hf, Zr). The Ta content (0.89–2.11) is average, while those of Th (0.84–1.75 ppm) and U (0.18–0.30 ppm) are variable. According to Harker diagram, as the SiO_2 content increases, the elements Sr and Ba Zr decreases. Concerning rare earths elements, there is an enrichment in light rare earths (LREE) and a depletion in heavy rare earths (HREE) (La/Yb) N = 3.72–6.02.

The dolerites show moderately fractionated patern (La/Yb) N = 3.72–6.02 marked by positive Eu anomalies, ((Eu/Eu*) N= 1.05–2.04).

3.3. Use of Pozzolan, Dolerite and Basalts as Sustainable Resources

3.3.1. Pozzolan

Pozzolan are artisanally used in the area for mortar by mixtures pozzolan+cement+water. This formulation leads to the production of blocks, as in Rome (Pozzolo), from which Pozzolan takes its name, by substituting cement by pozzolan. Cameroon's pozzolans offer great potential in building material domain. Cement manufacture produces very huge quantities of CO_2, so partial replacement of cement by pozzolan will help fight against pollution due to clinker production by pyropreccessing for decarbonation of calcite ($CaCO_3$) at a high temperature, close to 1500°C ($CaCO_3 \rightarrow CaO + CO_2$)[41].

The results show that pozzolans from the area can be incorporated directly into mortar to make wall filling blocks (**Figure 14**). The use of pozzolans helps to protect the environment by reducing the rate of CO_2 emissions into the atmosphere associated with the manufacture of portland cements.

Figure 14. Blocks made with mixtures (pozzolan-cement) in the locality.

Table 1. Composition of major and trace elements in volcanic rocks.

	Basalts							
Echantillons	BZ1	BZ2	BZ3	BZ4	BZ5	BZ6	BZ7	BZ8
SiO_2	50.84	49.72	49.85	50.16	48.12	49.56	47.56	50.01
Al_2O_3	13.54	15.86	14.33	15.16	12.16	11.67	12.35	11.25
Fe_2O_3	12.17	11.58	10.97	11.37	11.09	10.07	9.61	11.22
MnO	0.15	0.48	0.32	0.41	0.15	0.12	0.13	0.11
MgO	5.94	6.33	5.33	6.25	9.82	10.32	10.05	11.28
CaO	7.69	8.01	7.85	7.95	10.92	11.45	11.97	11.06
Na_2O	2.45	3.13	3.02	2.15	3.17	2.96	2.50	2.12
K_2O	3.74	1.42	1.50	1.28	1.49	1.84	1.05	1.35
TiO_2	0.54	3.09	3.23	2.15	3.12	3.08	3.11	2.74
P_2O_5	0.56	0.19	0.40	0.34	0.41	0.55	0.46	0.47
LOI	3.00	0.95	0.50	0.40	0.22	0.26	0.31	0.28
Sum (%)	100.62	100.76	97.30	97.62	100.67	101.88	99.10	101.89
Sc	17.03	18.38	17.05	18.01	18.63	20.01	19.23	18.04
V	130.83	150.14	135.41	145.60	198.98	200.55	201.45	189.78
Cr	293.77	302.78	305.01	352.11	296.77	301.25	302.15	299.79
Co	114.26	135.74	117.54	128.91	43.97	54.01	50.31	56.44
Ni	72.14	60.02	65.10	70.11	133.03	148.89	137.79	138.13
Cu	67.68	75.79	74.08	70.75	84.03	95.02	88.02	93.07
Zn	94.67	97.22	90.17	100.25	102.51	107.34	103.22	104.55
Ga	16.84	18.09	17.01	19.15	18.03	16.02	17.38	15.45
Rb	55.01	57.34	54.87	60.09	19.20	22.39	21.46	36.16
Sr	658.53	597.35	638.75	697.32	706.55	695.79	708.91	689.33
Y	24.16	26.08	28.13	25.12	26.95	28.61	27.09	28.51
Zr	52.74	55.12	54.18	52.36	132.38	154.23	163.20	122.85
Nb	13.41	14.32	14.12	13.50	73.65	79.54	75.02	74.59
Cs	0.35	0.45	0.41	0.50	0.20	0.40	3.00	0.40
Ba	1990.85	1894.31	1910.27	1872.13	494.22	528.11	531.41	497.32
La	56.91	60.32	54.62	60.45	44.37	34.18	35.44	40.05
Ce	105.98	127.23	130.74	123.15	82.96	90.84	94.02	95.31
Pr	12.29	36.13	35.24	34.21	9.06	12.31	11.32	10.89
Nd	55.92	60.18	58.34	60.98	42.13	39.75	38.01	36.74
Sm	10.00	12.14	13.11	12.58	8.04	10.81	9.19	8.32
Eu	2.36	2.45	2.16	2.74	2.75	2.37	2.07	2.11
Gd	7.20	8.02	7.89	8.74	7.14	8.04	9.71	10.32
Tb	0.78	0.87	0.75	0.91	0.87	0.66	0.81	0.77
Dy	4.28	5.03	4.78	6.78	5.15	6.10	5.65	4.60
Ho	0.79	0.87	0.91	0.81	0.94	1.08	0.97	1.02
Er	1.97	2.00	2.14	1.85	2.21	2.01	2.45	2.10
Tm	0.21	0.43	0.35	0.45	0.22	0.36	0.35	0.45
Yb	1.27	1.05	1.35	1.25	1.22	1.43	1.88	1.42
Lu	0.17	0.23	0.35	0.25	0.17	0.18	0.16	0.18
Hf	1.58	2.03	1.65	2.05	3.47	4.58	3.42	4.15
Ta	8.07	6.77	7.02	7.50	10.54	11.02	12.02	11.25
Pb	21.59	31.15	30.12	27.09	5.19	6.34	5.12	5.31
Th	9.02	10.50	9.02	11.10	3.09	3.15	3.01	2.97
U	1.44	1.22	1.31	1.05	0.52	0.64	0.52	0.47
Na_2O/K_2O	0.66	2.20	2.01	1.68	2.13	1.61	2.38	1.57
Al_2O_3/Na_2O	5.53	5.07	4.75	7.05	3.84	3.94	4.94	5.31
A/CNK	0.98	1.26	1.16	1.33	0.78	0.72	0.80	0.77
A/NK	2.19	3.49	3.17	4.42	2.61	2.43	3.48	3.24
Sr/Y	27.26	22.90	22.71	27.76	26.22	24.32	26.17	24.18
Al_2O_3/TiO_2	25.07	5.13	4.44	7.05	3.90	3.79	3.97	4.11
Th/Ta	1.12	1.55	1.28	1.48	0.29	0.29	0.25	0.26
Zr/Hf	33.38	27.14	32.84	25.54	38.15	33.67	47.72	29.60
Y/Nb	1.80	1.82	1.99	1.86	0.37	0.36	0.36	0.38
Rb/Sr	0.08	0.10	0.09	0.09	0.03	0.03	0.03	0.05
La/Sm	5.69	4.97	4.17	4.81	5.52	3.16	3.86	4.81
Na_2O+K_2O	6.19	4.55	4.52	3.43	4.66	4.80	3.55	3.47
(La/Yb) N	31.08	40.04	28.06	33.54	25.23	16.58	13.08	19.56
(La/Sm) N	3.56	3.11	2.61	3.01	3.45	1.98	2.41	3.01
(Eu/Eu*) N	0.85	0.75	0.65	0.79	1.10	0.77	0.67	0.69

	Dolerites			
Echantillons	BDZ1	BDZ2	BDZ3	BDZ4
SiO_2	47.52	48.22	47.15	48.03
Al_2O_3	14.40	13.03	14.39	13.62
Fe_2O_3	11.44	12.55	11.04	12.20
MnO	0.12	0.14	0.13	0.12
MgO	12.58	12.20	11.69	11.58
CaO	9.29	10.41	11.01	9.97
Na_2O	1.85	1.21	1.15	1.95
K_2O	1.89	1.74	1.20	1.20
TiO_2	1.28	1.03	1.57	1.12
P_2O_5	0.14	0.45	0.51	0.45
LOI	1.15	1.08	1.38	0.91
Sum (%)	101.66	102.06	101.22	101.15
Sc	28.15	38.13	30.23	35.48
V	165.20	142.98	157.12	160.74
Cr	320.53	330.14	325.10	331.81
Co	41.24	54.12	50.13	45.28
Ni	100.78	129.38	115.18	125.10
Cu	91.21	87.45	89.74	92.01
Zn	108.88	112.05	110.23	11.32
Ga	16.49	18.56	17.20	19.02
Rb	90.14	87.49	95.37	93.21
Sr	360.66	380.45	350.12	370.65
Y	22.78	30.15	25.28	29.71
Zr	96.04	87.33	85.33	92.73
Nb	5.76	6.74	5.32	6.02
Cs	2.59	2.38	2.61	2.45
Ba	185.35	197.23	189.58	195.31
La	8.23	10.15	9.89	11.03
Ce	17.82	12.16	11.56	12.25
Pr	2.29	3.04	3.45	2.93
Nd	12.22	15.08	13.52	14.78
Sm	3.09	3.12	3.58	3.45
Eu	1.14	2.01	2.55	1.97
Gd	3.52	4.32	4.04	3.76
Tb	0.52	0.44	0.45	0.64
Dy	3.50	4.12	3.90	4.12
Ho	0.74	0.87	0.90	0.85
Er	1.96	2.31	2.14	1.99
Tm	0.22	0.35	0.25	0.32
Yb	1.27	1.89	1.50	1.27
Lu	0.17	0.28	0.30	0.24
Hf	2.59	3.08	2.18	2.97
Ta	0.89	2.11	1.77	2.06
Pb	19.52	21.52	20.15	22.33
Th	1.09	0.94	0.84	1.75
U	0.18	0.23	0.30	0.25
Na_2O/K_2O	0.98	0.70	0.96	1.63
Al_2O_3/Na_2O	7.78	10.77	12.51	6.98
A/CNK	1.11	0.98	1.08	1.04
A/NK	3.85	4.42	6.12	4.32
Sr/Y	15.83	12.62	13.85	12.48
Al_2O_3/TiO_2	11.25	12.65	9.17	12.16
Th/Ta	1.22	0.45	0.47	0.85
Zr/Hf	37.08	28.35	39.14	31.22
Y/Nb	3.95	4.47	4.75	4.94
Rb/Sr	0.25	0.23	0.27	0.25
La/Sm	2.66	3.25	2.76	3.20
Na_2O+K_2O	3.74	2.95	2.35	3.15
(La/Yb) N	4.49	3.72	4.57	6.02
(La/Sm) N	1.67	2.03	1.73	2.00
(Eu/Eu*) N	1.05	1.66	2.04	1.66

3.3.2. Dolerites

The main valorisation perspective of dolorites in order to embodied carbon is to use them as ornamental stone (tiles, tables, and stonegrave…) which are low-carbon construction material, unlike clay-based tiles, which have to be heated at high temperatures of about 800°C. Clay-based tile production contributes to pollution by CO_2emission since a lot of energy is needed in this case. Studies show that dolerites have very good aesthetic and physico-chemical characteristics, making them ideal for cutting and polishing. These include good colouring and chromaticity (black), nice decorative patterns (sparse plagioclass laths), good density (2.7) and water absorption (around 0.4%), all of which attest the beauty and durability of the product (**Figure 15**).

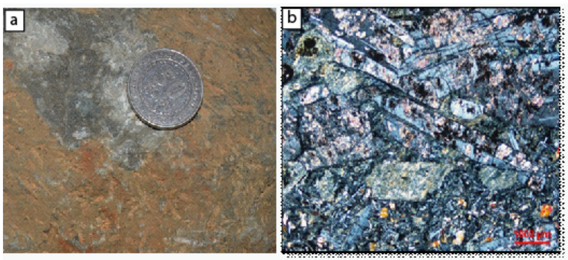

Figure 15. Dolerites. **a**) macrotextures, note the presence of centimetric plagioclase. **b**) microtextures.

3.3.3. Basalts

Basalts are crucial for the establishment of quarries (**Figure 16**) or the production of gravel and quarry sand (**Figure 17**) as the quantity of natural sand in rivers is decreasing. Those are very helpful for house construction and socio-economical development.

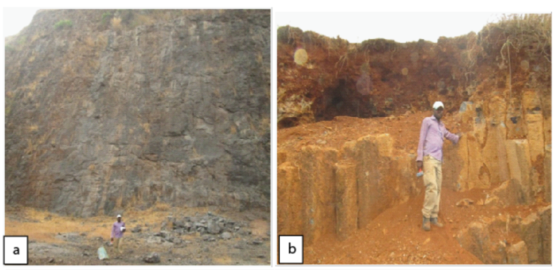

Figure 16. Photos showing basalt outcrops. **a**) Njimelap basaltic wall. **b**) Mamevouo prismatic basalts.

4. Discussion

4.1. Rock Petrogenesis

Origin

The mafic rocks (basalts, dolerites) in the Foumbot-Koutaba area have high FeOt (08.22–12.55 wt%) and V (130.83–255.19 ppm) contents and low SiO_2 (47.15–54.57%) contents. Also, the average to high MgO (5.33–12.58%) and Mg # (58–66) values and compatible element (Cr = 31.70–352.11 ppm, Co = 41.24–135.74 ppm and Ni = 48.01–148.89 ppm) indicate that the parent magmas of these mafic rocks are of mantle origin and have not undergone crustal contamination or have undergone a very low level of contamination during their ascent.

Figure 17. Basalts potential as natural resources.

Crustal contamination

All samples have elevated Ba (185–1990 ppm) and Sr (350–708 ppm), which are higher than those of the middle continental crust (Ba = 259–628 ppm and Sr = 282–348 ppm; Wang et al.[42] suggest insignificant crustal contamination in this case. The absence of strong negative Eu and Ti anomalies in chondrite-normalised rare-earth diagrams and primitive mantle-normalised multi-element diagrams also argues against the possibility of extended crustal contamination. The mafic rocks in this study encountered very negligible crustal contamination during their ascent.

Fractional crystallization and accumulation

Compared to primitive mantle magmas, the highly variable MgO, Mg#, and Ni contents of mafic rocks suggest that some levels of fractional crystallization occurred during mafic rock setting[43]. The slight negative Sr anomalies in the multi-element diagrams which normalized to the primitive mantle suggest that plagioclase fractionation would not have played an important role in the evolution of parental magmas. The negligible Eu anomalies in the rare earth (REE) diagrams normalized to chondrites are consistent with this interpretation with the exception of dolerites which present remarkable Eu anomalies. The doleritic magma would have undergone the accumulation of plagioclase. This assertion is supported by the positive Eu anomalies in the dolerite multielement diagram. As evidenced by the low MgO, Co, Ni and Cr contents of certain basalts, the parental magmas would have undergone significant fractionation of olivine and clinopyroxene [44] unlike the parental magmas of dolerites. The negative P anomalies in the multi-element diagrams normalized to the primitive mantle of the basalts probably demonstrate the fractionation of apatite compared to dolerites which instead demonstrate an accumulation of apatite. Besides fractional crystallization, crystal accumulation may also have played an important role during the evolution of the magma system. The low rates of positive Ti anomalies in basalt argue for low accumulation of Ti-Fe oxide (e.g. magnetite, ilmenite and rutile).

In summary, the parent magma of basalts and dolerites have experienced different evolutionary processes. The basalts were controlled by the fractionation of olivine and apatite, while the dolerites are thought to be the products of the accumulation of plagioclase.

Nature of the mantle source

The rocks are characterized by selective enrichment of LILEs and LREEs and depletion in certain high ionic charge elements and heavy rare earths. These geochemical signatures could be attributed to partial melting of an enriched mantle source [45]. The parent magmas of these mafic rocks have not experienced significant crustal contamination. Therefore, the geochemical characteristics of these samples were mainly inherited from their magma source, and they might arise mainly from the partial melting of an enriched subcontinental lithospheric mantle. A similar enriched lithospheric mantle has been well detected beneath the Cameroon Volcanic Line [29].

Two main mechanisms are generally proposed to explain the enrichment of the subcontinental lithospheric mantle : (1) reactions between the mantle wedge and hydrated fluids derived from the subducted slab [46, 47] and (2) the incorporation of components of the continental crust into the mantle before partial melting by subduction or delamination of the lower crust [48]. During subduction processes, different types of metasomatic agents, such as slab-derived fluids and molten silicates or carbonates from sediments, would result in distinctive concentrations of rare earths in mantle wedge materials [45]. The depletions of Nb and Ta relative to K and La have also been considered to be the results of initial partitioning and equilibria between rutile and the fluids or bottom of the subducted slab [42, 46]. Therefore, the mafic rocks most likely originate from a lithospheric mantle metasomatized primarily by fluids derived from the subducted plates. The more or less high Zr / Hf ratios (25.54–47.72) of the basalts studied compared to those of the primitive mantle (Zr / Hf = 36) demonstrates the participation of the metasomatized lithospheric mantle in the genesis of the rocks studied [42, 46].

In general, subducted ocean fluids typically carry significant amounts of Rb, Ba, Th and U. Therefore, positive anomalies of Rb, Ba, Th and U in multi-element diagrams normalized to the primitive mantle would be expected in magmas derived from a melting of a mantle metasomatized by such lithospheric agents.

However, it should be noted that all samples in this study have clearly negative Th-U anomalies; which contrasts with the aforementioned trace element imprints. It has been suggested that Th–U depletion could be induced by the incorporation of crustal materials recycled into the mantle source, such as plagioclase-rich oceanic gabbros or lower continental crust [49, 50]. Oceanic gabbros are characterized by positive Sr and Eu anomalies [49]. The positive Sr and Eu anomalies in the dolerite samples studied support the scenario associated with the participation of recycled oceanic gabbros in the mantle source. Additionally, the Nb/Th ratio in the early mantle has been shown to be 8 and approximately 1.1 in the continental crust [51, 52].

Mafic rocks have Nb/Th ratios ranging from 1.22 to 25.25 (Nb/Th > 8 and < 8). These reports show the intervention of phenomena that participated in this variation. Given the negative Th and U anomalies, lower continental crust appears to be the best proxy in answering this question, indicating that ancient lower continental crust may have been recycled into the mantle before partial melting (**Figure 18**).

Potential as sustainable natural resources

Regarding pozzolans resources, they are basaltic, but originate from explosive dynamism unlike the basalts set up by effusive dynamism, and which are essential for the manufacture of gravels and quarry sands. The volcanic glasses formed within these pyroclastites, due to the explosive dynamism, are responsible for the pozzolanic activity, because crystallized minerals do not react as hydrolic pozzolanic materials (containing vesicules) but act like sands in mortars. The reaction can also be explained by the fact that pozzolan amorphous particles can combine with calcium hydroxide to form cement complexes. This result was demonstrated by Hwang et al. [53] in the study of the effect of adding rice husk ash as pozzolanic materials on the compressive strength of concrete formulated with this material. The pozzolanic activity of these pyroclastic materials allows them to consume lime (Ca $(OH)_2$) and portlandite (CH) to form hydrates (CSH) which are cement components. The mantle origin of the dolerites and their hypovolcanic character have contributed to their good density and beauty, which are fundamental for ornamental stone manifacture. Also, the loss on ignition (LOI) values testify the very low degree of alteration and the freshness of the rocks.

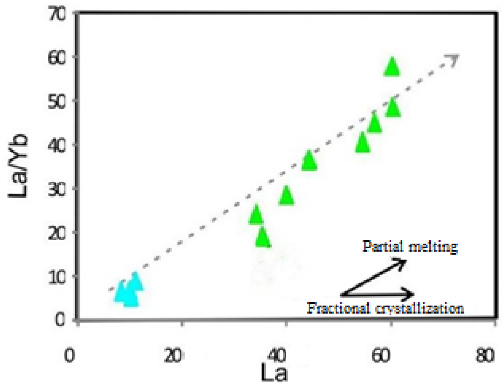

Figure 18. La/Yb vs La diagram for fractional crystallization discrimination and partial melting. (Legend in **Figure 6**).

The pyroclastics of the study area are pozzolans low carbon cement materials which are good for partial replacement of clinker that pollute the environment. Additionally, dolerite are low carbon materials appropriate for dimension stones production to replace tiles made with clay that pollute the environment through pyroprocess during their manifacture.

5. Conclusions

The study area is made up of magmatic mafic recent rocks composed of basalts, dolerites and pozzolanic pyroclastites. Geochemical studies show that basaltic and doleritic lavas are of mantle origin. They would have undergone a very low rate of crustal contamination during their ascent. The parental magmas of the basalts and dolerites have undergone different evolution processes. The basalts were controlled by the fractionation of olivine and apatite, while the dolerites would be the products of the accumulation of plagioclase. They could come mainly from the partial melting of an enriched subcontinental lithospheric mantle.

The pyroclastites of the study area are important for developing ecological mortars based on natural pozzolans and are an affordable and sustainable option for the construction industry and the socio-economic development of populations. Dolerites and basalts are important natural resources for the ornamental stone industry and also for the production of gravel and sand to meet population needs as well as sustainable development.

Author Contributions

A.M.M.: Conceptualization, Data curation, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing—original draft, Writing—review & editing. B.N.: Conceptualization, Data curation, Methodology, Resources, Visualization, review & editing. M.N.: Data curation, Resources, Visualization, review & editing. A.Y.: Data curation, Resources, Software, review. A.M.: Data curation, Methodology, Resources, Visualization, Writing—review & editing. All authors have read and agreed to the published version of the manuscript.

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Conflict of Interest

There is no conflict of interest.

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