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Petrology and Structural Characterization of Post-Neoproterozoic Dolerites from the Kimberlite Fields in the Kéniéba Region (Western Mali)

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Abstract

Post-Neoproterozoic dolerites from the Kéniéba region (Western Mali) are often associated with kimberlites. The rarity of kimberlite outcrops led to the study of doleritic rocks, spatially associated with them. The petrographic and lithogeochemical study showed that the dolerites of the Kéniéba kimberlitic fields are of tholeiitic nature and of the E-MORB (Enriched-Mid Ocean Ridge Basalt) type. This reflects an enrichment over time, compared to the Birimian dolerites of the volcano-sedimentary greenstone belt of Toumodi, in central Côte d'Ivoire. Furthermore, these dolerites are enriched in SiO_2, TiO_2, Zr and poor in Fe_2O_3, MgO. These dolerites would have formed in a late to post-orogenic intracontinental context during the breakup of Gondwana. Structurally, Kéniéba dolerites are often associated with kimberlite pipes, fractures and large deep structures identified using aeromagnetic images. Taking into account the fact that kimberlites do not outcrop in the Kéniéba region, the geochemical study coupled with the interpretation of aeromagnetic data proved to be very useful for the search for pipes.

Keywords

Dolerites, Kimberlitic Fields, Petrology, Structures, Kéniéba, Mali

1. Introduction

The kimberlite fields of the Kéniéba region are located in western Mali where the first kimberlite was discovered between 1955 and 1957 by the DFGM. Numerous exploration works carried out by mining companies followed this discovery. Around thirty pipes and kimberlitic dikes have been revealed within the Birimian formations, mainly composed of metasediments and intrusions of granitoids covered by neoproterozoic sandstones formations. All of these formations are crossed by occurrences of doleritic to gabbroic nature which were established during magmatic activities, approximately 180 My ago [1], following which the Gondwana was dislocated. The kimberlite occurrences of Kéniéba are often located along certain structures controlling the dolerites, some of which are of Turonian age (92 My), [2].

Several generations of dolerite intrusions are present in the Kéniéba sector, of which eight (8) have been the subject of this study. These basic intrusions penetrate fractures and/or faults to form dikes which extend over large areas. The occurrences of dolerites correspond to the last phase of basic volcanism, and generally precede the kimberlite occurrences which appear in the form of explosions.

In the region, the kimberlites appear in the form of clusters forming groups of three (3) to five (5) kimberlite pipes and which are aligned on fractures oriented along the WNW-ESE direction (125˚ to 127˚) which intersect the NE-SW directions (15˚ to 20˚) which form a very tight network of dikes [3].

The structural data clearly show control of kimberlite clusters by structures associated with dolerites which are distributed in two systems of different directions: latitudinal and sub-meridian. Many diamonds have been discovered at Kéniéba, in areas relatively close to the dolerite dikes. However, the petrographic and structural characteristics associated with the emplacement of these dolerites, as well as their relationships with the kimberlites, are not yet clearly established.

This work aims to establish the petrological and structural characteristics of these post-Neoproterozoic dolerites from the kimberlitic fields of the Kéniéba region, compared to certain Birimian dolerites from the West African craton.

2. Location and Geological Setting of the Study Area

The Kéniéba region is located in the west of Mali, on the border with Senegal (**Figure 1**). The study area is geologically associated with the Kédougou-Kéniéba Inlier (KKI) which is underlain by volcanic, volcano-sedimentary formations and granitoid intrusions [4] [5].

Knowledge of the geology of the Malian part of the KKI has been greatly improved as part of a cooperation program between the government of the Republic of Mali and the BRGM/Geosystem Maps consortium, which led to the production of the geological map at 1/200,000 [3]. The establishment of the formations of the Kéniéba region are associated with the Eburnean orogeny dated approximately between 2030 and 1830 My [6]. These formations are represented by metamorphic rocks of the greenschist facies, namely, metagrauwackes as well as granitoid intrusions [7]. They are limited to the east by the vast sedimentary cover of the Neoproterozoic domain.

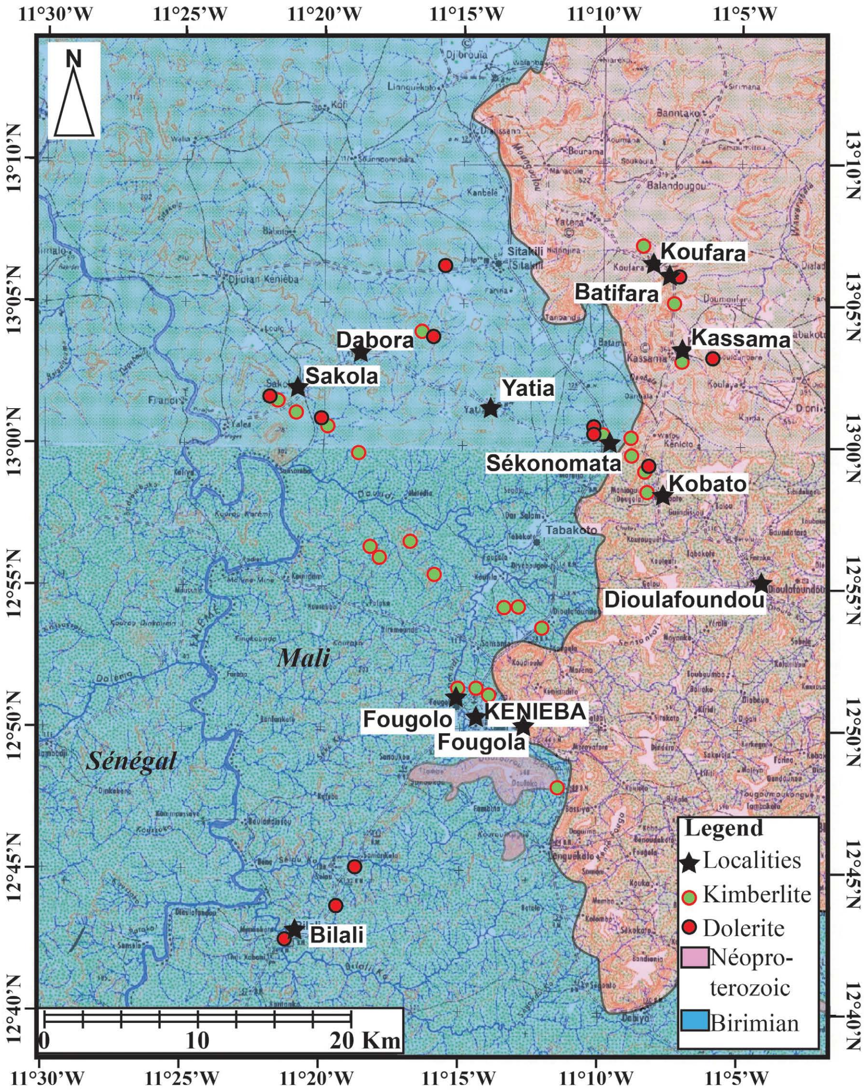

Figure 1. Simplified geological map of the study area and location of some occurrences of kimberlites and dolerites.

3. Materials and Methods

The material includes field data (samples), laboratory data and aeromagnetic images. The first phase consisted of the collection of field data, through sampling of dolerites (generally in the form of dikes), both in the Birimian formations and in the Neoproterozoic formations. The preparation of twelve (12) thin sections at the Basement Geology Laboratory of the Félix Houphouët-Boigny University of Abidjan (Côte d'Ivoire) made it possible to determine the petrographic characteristics of dolerites and surrounding rocks.

Geochemical analyzes (done at the Mineral Laboratories, Bureau Veritas Commodities, Vancouver, Canada) also made it possible to clarify the petrographic nature, lineages and environments of the establishment of these dolerites. A comparison of the lithogeochemical data of the dolerites of Kéniéba with those of other regions made it possible to better characterize them.

Structural data were collected in the immediate environment of these dolerites. An interpretation of aeromagnetic imagery made it possible to identify major geological structures.

4. Results

4.1. Petrographic Characteristics of Dolerites

In the field, dolerites appear in the form of dikes and sometimes associated with microgabbros. The coloring oscillates between dark gray and black. These are micro-grained rocks reflecting their semi-depth origin. In thin sections, the mineralogy consists essentially of entangled plagioclase rods, pyroxenes (orthopyroxenes and clinopyroxenes), amphiboles and a few fine quartz crystals (Figure 2). These rocks present intergranular, microgabbro and subophitic textures.

4.2. Lithogeochemical Characteristics of Dolerites

The major element data (Table 1) show an average composition of SiO_2 (49.94% - 52.35%), MgO (5.94% - 8.62%), Fe_2O_3 (9.01% - 12.47%), Al_2O_3 (14.01% - 15.33%), $Na_2O + K_2O$ (2.26% - 4.05%) and Na_2O/K_2O (0.5 - 3.71) and relatively low values of TiO_2 (0.76% - 1.3%) (Table 1).

A study of the chemical composition of basic rock dikes located in the fields of Bilali (Bilali south), Sékonomata and Kobato showed a slight increase in TiO_2

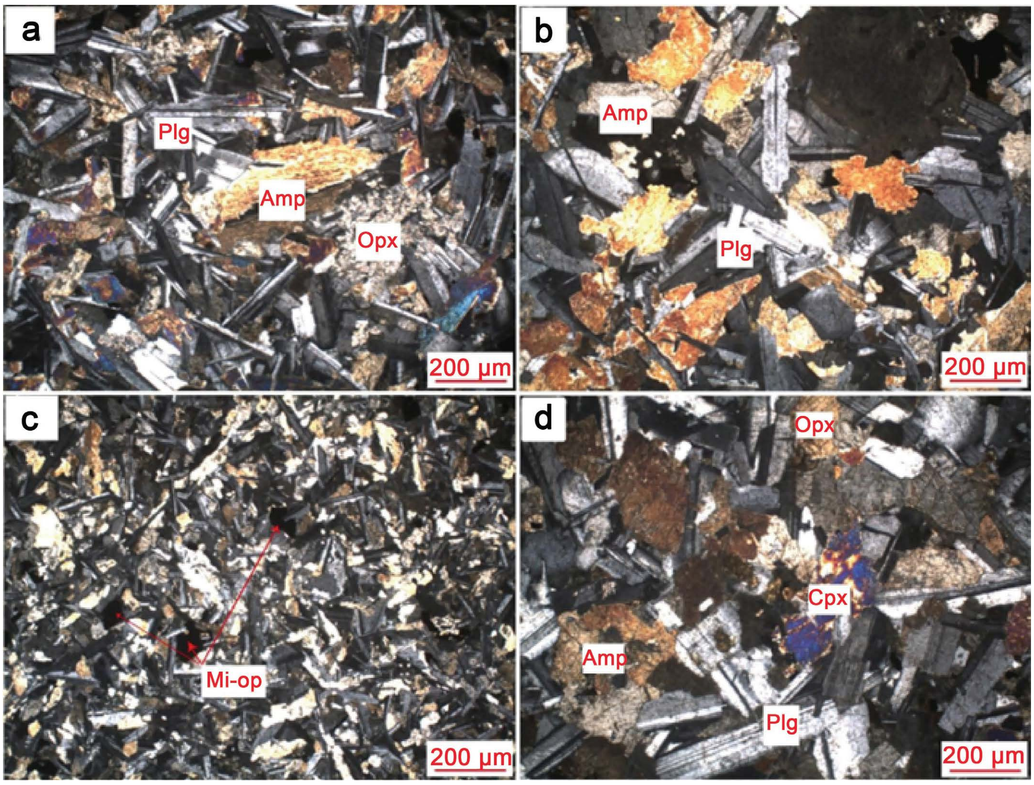

Figure 2. Microscopic appearance of dolerites, with intergranular (a and d), micogabbro (b), subophitic (c) textures. *Plg: Plagioclase; Opx: Orthopyroxene; Cpx: Clinopyroxene; Amp: Amphibole; Mi-op: Opaque minerals.*

Table 1. Chemical composition in major elements (% by weight) of representative samples of dolerites across the Kéniéba kimberlite province.

	DOL-1A %	DOL-1B %	DOL-1C %	DOL-1D %	DOL-2 %	DOL-3B %	DOL-4 %	DOL-5 %
SiO_2	51.99	49.94	52.23	51.92	52.08	51.29	49.95	52.35
Al_2O_3	14.05	15.33	14.02	14.55	14.2	15.1	14.93	14.01
Fe_2O_3	11.53	12.47	11.83	11.87	11.47	*9.01*	12.35	11.84
MgO	6.82	6.04	6.14	6.26	6.62	*8.62*	5.94	6.13
CaO	10.34	9.47	9.86	9.99	10.22	12.11	8.41	9.8
Na_2O	2.07	1.97	2.19	2.13	2.07	1.78	1.35	2.17
K_2O	0.94	0.97	0.98	0.93	0.82	0.48	2.7	1.18
TiO_2	*1.22*	*1.28*	*1.29*	*1.27*	*1.3*	*0.76*	*1.26*	*1.26*
P_2O_5	0.16	0.17	0.17	0.17	0.19	0.1	0.17	0.16
MnO	0.18	0.17	0.18	0.18	0.17	0.15	0.22	0.17
Cr_2O_3	0.023	0.019	0.011	0.015	0.037	0.079	0.018	0.014
LOI	0.5	2	0.9	0.9	0.6	*0.4*	2.5	0.7
Sum	99.91	99.92	99.91	99.92	99.92	99.94	99.9	99.91

inside and in the immediate vicinity of the kimberlites as well as the heavy rare earths like Hf, Y and Nd (**Table 1** and **Table 2**). A dike located outside the kimberlite field shows a TiO_2 content of less than 1% (DOL-3B), which seems to correspond to normal levels in the Kéniéba dolerites.

The Batifara dolerite dike (DOL-2) located at 1.2 km from the kimberlite intrusion of the same name gives a content of 1.3% while the TiO_2 content in the Kassama dike (DOL-3B) located approximately 2.7 km to the East is 0.76%. For dikes located between 300 and 10 m from the kimberlite intrusion (in the field of influence), the grade reaches between 1.22% and 1.28%. It can be noted that chemical analyzes show that the composition of the dolerites is substantially identical in the Kéniéba area. Only the contents of samples DOL-4 and DOL-5 which come from the immediate environment of the kimberlites show relatively high K_2O contents compared to the other samples.

In the SiO_2 *vs* $Na_2O + K_2O$ diagram (**Figure 3(a)**), the Kéniéba dolerites are located in tholeiitic rocks. Comparatively, the Birimian dolerites of the Toumodi region (in Côte d'Ivoire [8]) are less alkaline and less siliceous than those of Kéniéba (more siliceous). This tholeiitic trend of dolerites is confirmed by the AFM diagrams of Irvine and Baragar ([9] **Figure 3(b)**) and SiO_2 *vs* FeO_t/MgO (**Figure 3(c)**). The Kéniéba dolerites are more titaniferous (**Figure 3(d)** and **Figure 3(e)**), less chromiferous (**Figure 3(f)**) and richer in zirconium (**Figure 3(g)**) than those of Toumodi region. Furthermore, the dolerites of Kéniéba are more depleted in titanium than those of Nakyn in Siberia (2.17% - 4.69% [10]) and those of Vilyui Middle Paleozoic paleorift of the east of the Siberian Platform, in Russia (2.48% - 2.6% [11]). The Kéniéba dolerites have an affinity for sub-alkaline basalts (**Figure 3(h)**).

Table 2. Chemical composition of dolerites in trace elements of dolerites from certain kimberlite fields of Kéniéba.

	DOL-1A ppm	DOL-1B ppm	DOL-1C ppm	DOL-1D ppm	DOL-2 ppm	DOL-3B ppm	DOL-4 ppm	DOL-5 ppm
Ba	198	205	200	213	258	*142*	346	220
Be	1	1	1	2	<1	1	1	2
Co	42.6	46.8	43.9	42.8	41.9	41.5	60.6	43.5
Cs	1.0	1.3	1.1	1.0	1.0	0.6	0.9	1.6
Ga	15.2	16.6	16.3	15.5	15.3	13.0	16.6	15.4
Hf	3.0	2.9	3.0	3.2	3.2	1.7	3.1	3.2
Nb	8.4	8.8	9.0	8.4	9.5	5.2	8.7	8.6
Rb	31.7	36.3	32.9	32.3	22.4	*14.8*	58.7	40.0
Sn	<1	1	<1	<1	<1	<1	<1	<1
Sr	187.5	173.7	197.3	183.2	220.6	*176.3*	195.5	199.8
Ta	0.6	0.6	0.6	0.6	0.5	0.4	0.6	0.5
Th	2.9	2.9	2.8	2.9	2.5	1.6	2.9	2.9
U	0.6	0.8	0.6	0.7	0.4	0.3	0.7	0.7
V	263	280	283	264	257	211	273	277
W	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	0.5
Zr	106.0	112.9	115.6	113.3	113.6	*61.9*	111.7	112.8
Y	22.4	22.5	23.4	23.5	23.3	*15.6*	22.3	24.1
La	13.1	2.12	13.9	13.8	14.0	*8.4*	15.0	14.1
Ce	28.0	0.36	30.1	28.8	31.1	16.9	34.0	29.4
Pr	3.50	2.47	3.72	3.68	3.88	2.16	3.66	3.76
Nd	15.2	0.85	15.6	16.0	17.1	9.5	15.1	16.0
Sm	3.46	4.22	3.96	3.74	3.79	2.26	3.75	3.80
Eu	1.19	0.65	1.17	1.22	1.22	*0.76*	1.16	1.23
Gd	4.13	4.09	4.38	4.24	4.28	*2.63*	4.23	4.27
Tb	0.67	1.13	0.73	0.71	0.70	0.44	0.67	0.73
Dy	4.42	3.44	4.39	4.36	4.33	2.90	4.19	4.41
Ho	0.87	15.0	0.94	0.96	0.85	0.56	0.86	0.94
Er	2.49	3.48	2.74	2.64	2.50	1.76	2.45	2.59
Tm	0.34	28.7	0.39	0.38	0.37	0.24	0.37	0.37
Yb	2.23	13.1	2.31	2.34	2.21	1.45	2.16	2.39

In the diagrams normalized to the MORB (Mid Ocean Ridge Basalt) [14], the Kéniéba dolerites are distinguished from the Birimian dolerites by a strong enrichment in light rare earths (**Table 3**). Compared to the primitive mantle and poorly mobile elements [15], the Kéniéba dolerites are forty times more enriched in light rare earths than those of the Toumodi Birimian dolerites (**Figure 4(a)**). In the diagram of Anders and Grevesse [16], the Kéniéba dolerites

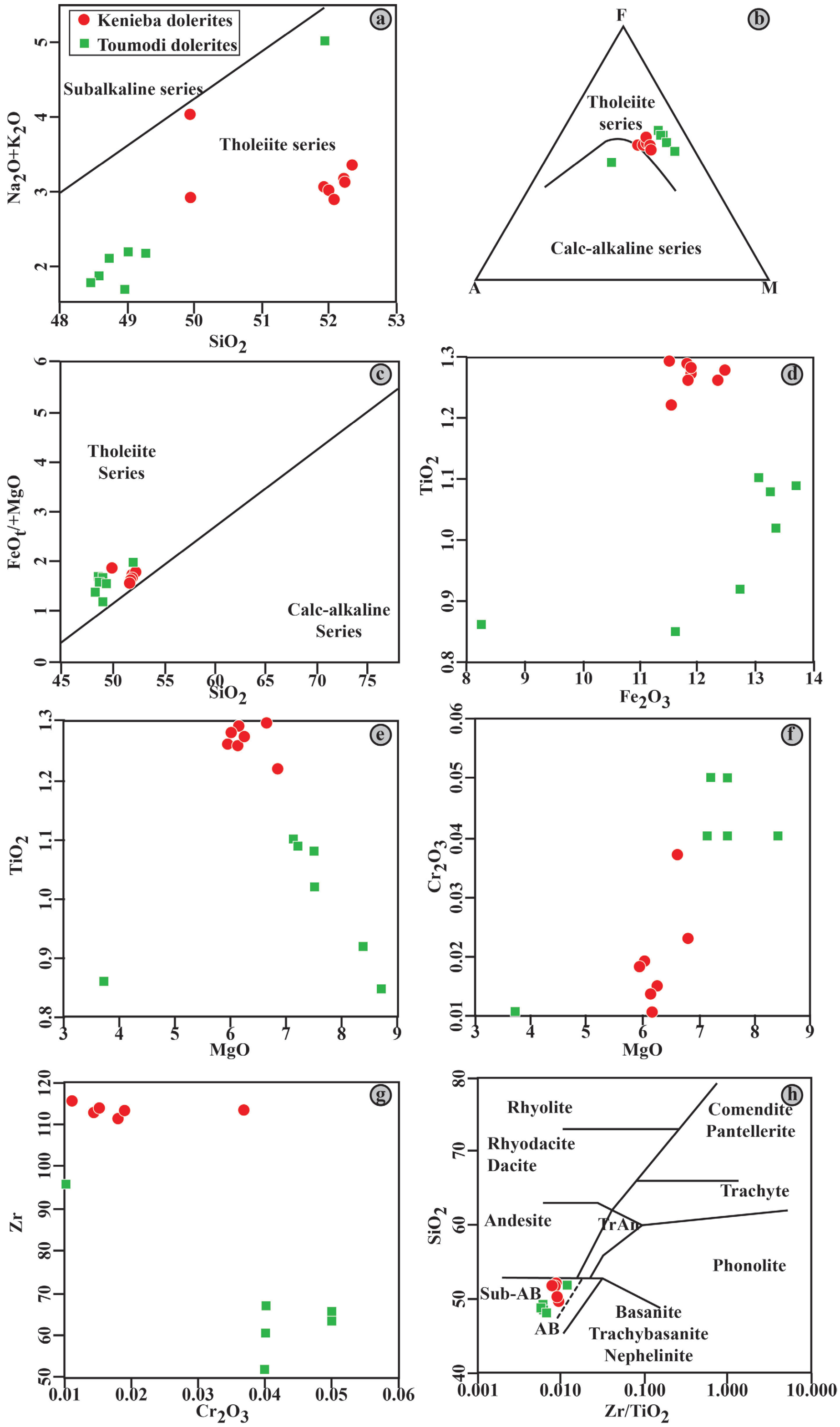

Figure 3. Classification of dolerites. (a) SiO_2 *vs* $Na_2O + K_2O$ diagram; (B) AFM diagram (($Na_2O + K_2O$)-FeO*-MgO) from Irvine and Baragar [9]; (c) SiO_2 *vs* FeO_t/MgO diagram from Miyashiro [12] (1974); (d) Fe_2O_3 *vs* TiO_2 diagram; (e) MgO *vs* TiO_2 diagram; (f) MgO vs Cr_2O_3 diagram; G: Cr_2O_3 *vs* Zr diagram; (h) Zr/TiO_2 *vs* SiO_2 diagram [13], with TrAn = Trachy-Andesite; Sub-AB = Sub-Alkaline Basalt; AB = Alkaline Basalt.

Table 3. Pearson correlation matrix (n) of the major elements of the Kéniéba dolerites.

Variables	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	Cr_2O_3
SiO_2	1										
Al_2O_3	**−0.870**	1									
Fe_2O_3	−0.215	−0.159	1								
MgO	0.116	0.243	**−0.983**	1							
CaO	0.400	0.022	**−0.924**	**0.920**	1						
Na_2O	**0.770**	−0.619	0.069	−0.116	0.280	1					
K_2O	−0.535	0.148	0.534	−0.535	**−0.809**	**−0.727**	1				
TiO_2	0.071	−0.414	**0.942**	**−0.948**	**−0.810**	0.284	0.364	1			
P_2O_5	0.058	−0.374	**0.865**	**−0.863**	**−0.748**	0.231	0.327	**0.964**	1		
MnO	−0.400	−0.010	0.644	−0.635	**−0.846**	−0.568	**0.934**	0.528	0.498	1	
Cr_2O_3	−0.054	0.392	**−0.936**	**0.956**	**0.825**	−0.265	−0.428	**−0.918**	**−0.787**	−0.581	1

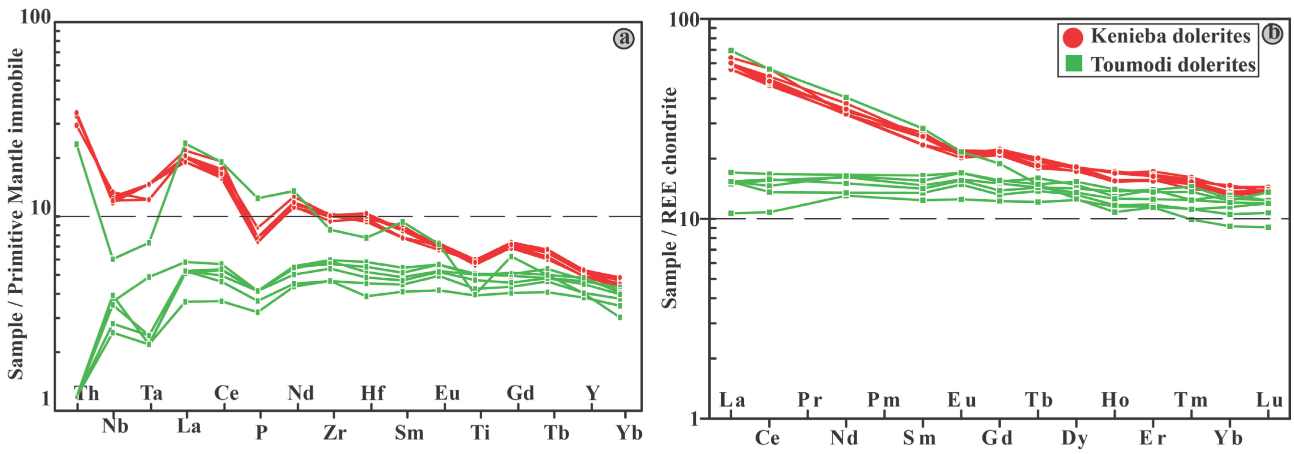

Figure 4. Spidergrams for dolerites from the kimberlite fields of Kéniéba (in red) and that of Toumodi (in green).

are sixty (60) times more enriched in light rare earths than the chondrites, while the Birimian dolerites show a weak fractionation of rare earths, with a slight positive anomaly in Europium (**Figure 4(b)**).

Research into the geotectonic environment of the Kéniéba dolerites, through different diagrams, shows that the Kéniéba dolerites belong to the late to post-orogenic intracontinental domain in a compressive to distensive context of the volcanic arc type on the edge of the continent [17] [18] (**Figure 5(a)**) and correspond to within-plate basalts ([19] **Figure 5(b)**).

The statistical analysis of the relationships between chemical elements in dolerites required the use of principal components analysis or PCA [20] [21]. Regarding the major elements, the data matrix consists of eleven variables: SiO_2, Al_2O_3, Fe_2O_3, MgO, CaO, Na_2O, K_2O, TiO_2, P_2O_5, MnO, Cr_2O_3. The principal components were calculated from a correlation matrix. In the case of correlations, the most significant are displayed in bold (**Table 3**). The correlation matrix

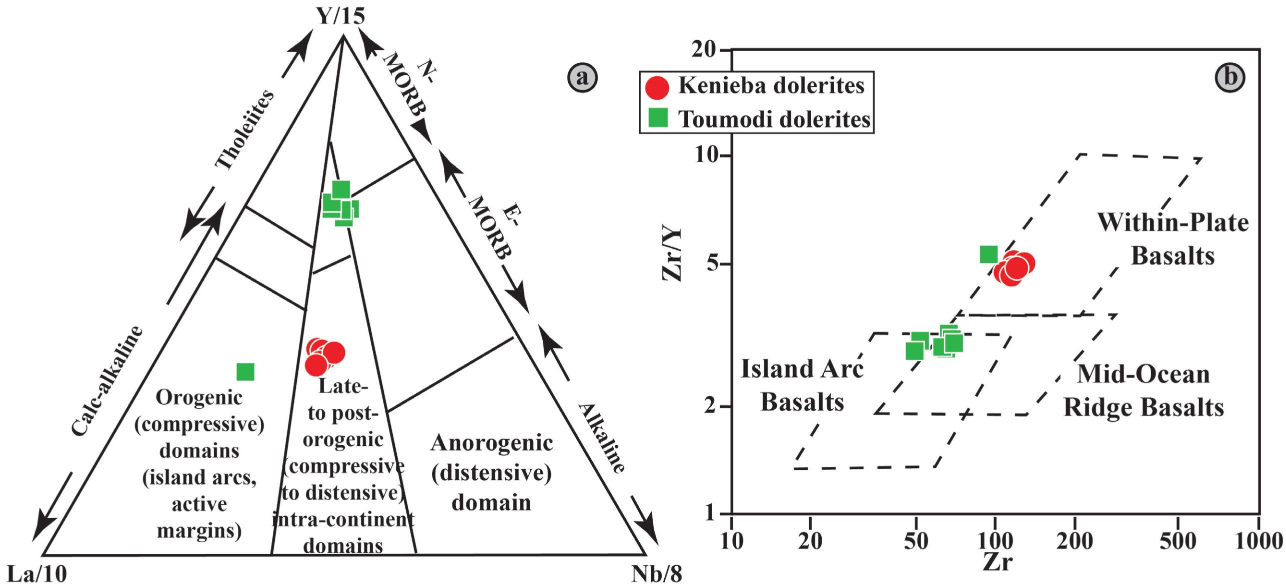

Figure 5. Geotectonic environment of dolerites. (a) Diagram La/10_Y/5_Nb/8 [17], with N-MORB = Normal Mide Ocean Ridge Basalt; E-MORB = Enriched-Mid Ocean Ridge Basalt; (b) Binary diagram Zr vs Zr/Y [19].

gives a first idea of the existing associations between the different variables. Thus, we note the following correlations (**Table 3**).

- Strong positives correlations (0.9) between: Fe_2O_3 and TiO_2, P_2O_5; MgO and Cao, Cr_2O_3; K_2O and MnO; TiO_2 and P_2O_5;
- Strong negatives correlations (<−0.9) between: Fe_2O_3 and MgO, CaO, Cr_2O_3; MgO and TiO_2; TiO_2 and Cr_2O_3.

The correlation matrix indicates a strong correlation between: TiO_2 and P_2O_5; Na_2O and SiO_2; MgO and Cr_2O_3; MnO and K_2O; TiO_2 and Cr_2O_3 (**Figure 6**).

4.3. Structural Characterization of the Doleritic Dikes of Kéniéba

The establishment of West African dolerite dikes can be associated with the opening (rifting) of the Atlantic Ocean, on the one hand, and on the other hand, with late to post-Eburnean distensions [22] [23]. From the aeromagnetic image of Kéniéba, dolerites appear in the form of a network of lineaments affecting Birimian units, as well as intrusions and sedimentary covers (Neoproterozoic), (**Figure 7**).

The color contrast on the magnetic map draws a boundary between the two domains, and highlights the numerous dikes of basic rocks (grouped under the generic name of dolerites) in the form of lineaments.

A combination of airborne photo-geological and geophysical images (magnetic, electromagnetic, and radiometric) made it possible to trace major tectonic structures [24]. The interpretation of the map sheets shows an orientation of the major faults following a NW-SE direction with its different branches which are N-S, NE-SW, and E-W along which the dikes of a basic nature are set up. And it must be remembered that the kimberlites are arranged in a WNW-ESE orientation.

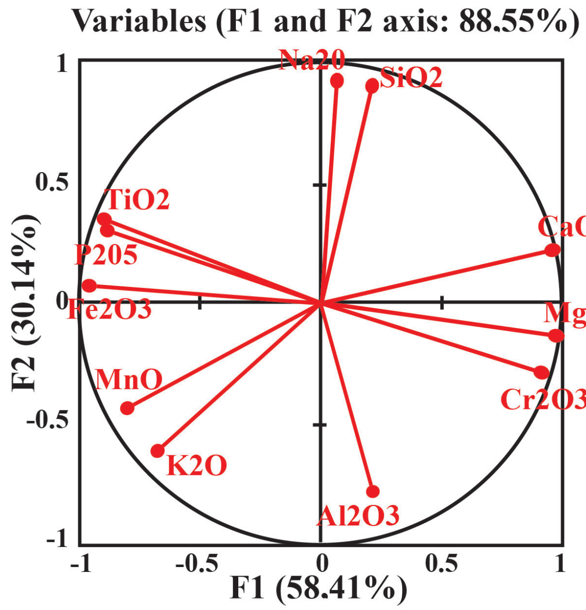

Figure 6. Correlation matrix of major elements.

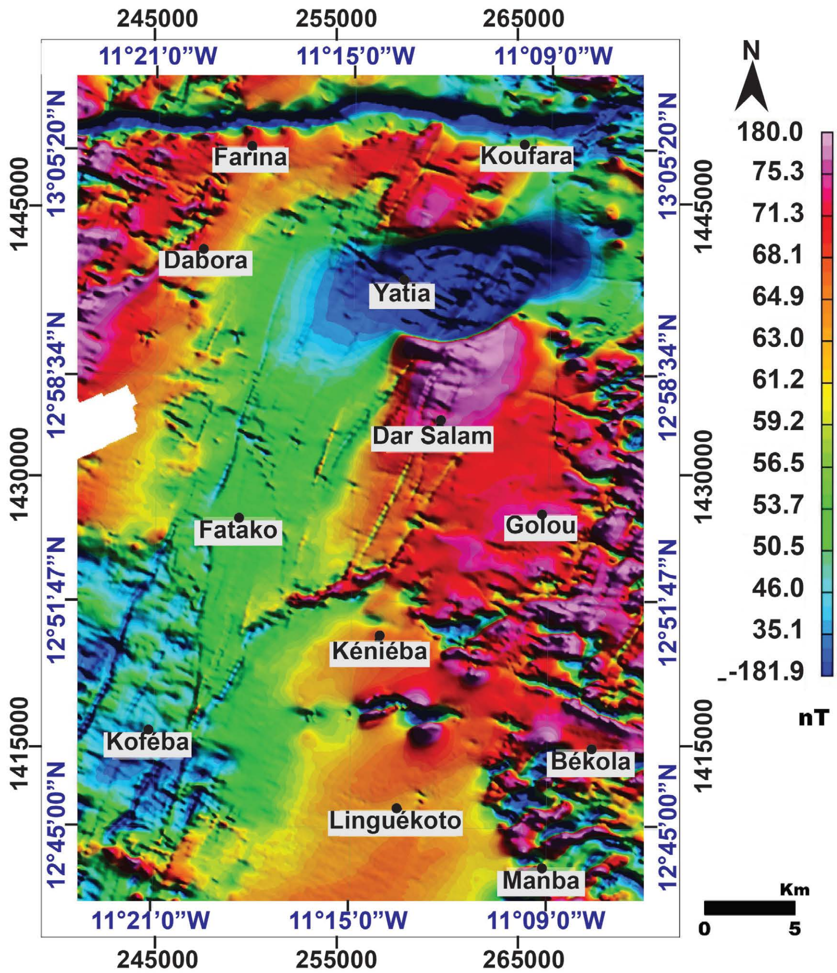

Figure 7. Map of the total magnetic field showing dolerite swarms in the form of lineaments [24].

Three main directions frequently appear WNW-ESE, E-W, NE-SW for doleritic dikes which coincide with major fractures. The last two directions are the majority among which the almost E-W orientations are intersected by those of submeridian direction; which suggests different tectonic episodes [22] [24] [25] [26].

The general interpretation of the different structural features of the aeromagnetic map made it possible to develop a synthetic structural model (**Figure 8** [24]). This model, whose major axis in the shape of a horse's tail is oriented NE-SW, defines a set of dextral and sinistral faults. The correlative analysis of the spatial distribution of diamondiferous and non-diamondiferous dolerite and kimberlite samples collected in the study area, with the interpreted structures (**Figure 8**), shows that they are mainly located in fault zones.

5. Discussion

The study of doleritic rocks in the Kéniéba region was carried out in two stages during which we carried out an analysis of lithogeochemical (petrography and

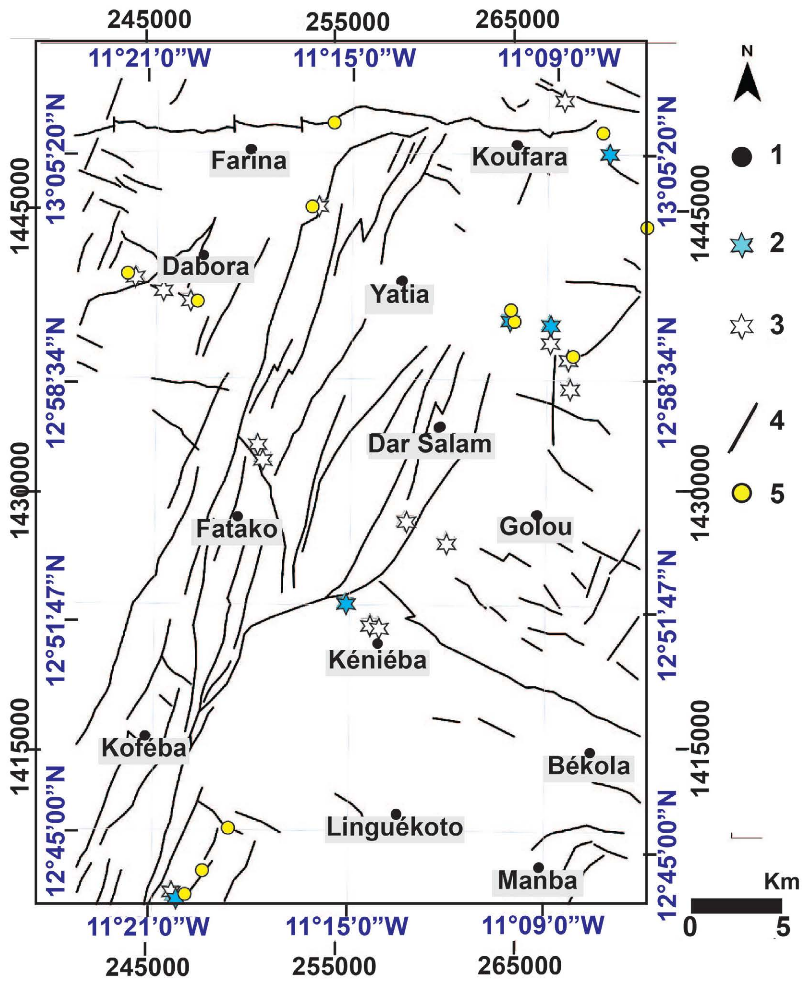

Figure 8. Synthetic structural map [24]. 1: Names of localities; 2: Samples of diamondiferous kimberlites; 3: Non-diamond kimberlite samples; 4: Interpreted faults. 5: Dolerites.

petrology) and structural data. The results of the analysis during this study show similar values for dolerites located in the field of influence of kimberlites. Only one sample taken outside the field of influence of the kimberlites (DOL-3B) presents relatively low contents of major elements and certain rare earths compared to the others. Thus, we can retain the idea of partial mantle fusion at relatively high pressures. The kimberlites appear in the form of explosions in the dolerites which supposes that the dolerite dikes were already in place at the time of the intrusion of these kimberlites. The ascent of kimberlite magma enriched in certain major elements (TiO_2, Fe_2O_3, CaO and Zr) creates metasomatism in contact with dolerite with enrichment of these major elements at the level within the limits of the zones of influence of the kimberlites; as noted in Russia [11]. We do not notice any significant difference between the major elements in the dolerites located in the field of influence of the kimberlites unlike those located outside the field of influence. These dolerites are chemically enriched than those of the Birimian of Toumodi in Côte d'Ivoire [8] and those of Burkina Faso [27]. Therefore dolerites enriched in TiO_2, Fe_2O_3, CaO and Zr can be used in the Kéniéba area as a search criterion for kimberlite.

The reinterpretation of the aeromagnetic data highlighted three types of structures according to their direction, filled by dolerite dikes. Several generations of dolerites are each represented by a privileged direction. Among the three types of direction, we generally have East-West, NE-SW, WNW-ESE. This last direction corresponds to those that can be observed for the dolerite dikes in the southwest of Côte d'Ivoire [28] and those of Birimian in the north of Burkina Faso [27].

The age of doleritiques intrusions is associated with tectono-magmatic events that appeared on the African plate at the time of the dislocation of Gondwana. Among these events, we note that which occurred in the Jurassic which saw the establishment of large swarms of dolerites oriented following NE-SW which appear on maps of the region [23] [29] [30] [31] [32]. The lineaments constitute networks of dikes following the WNW-ESE direction which are Cretaceous and which control the Kéniéba kimberlites. Elsewhere in the country, dolerites dating from the Carboniferous appear like those of the Taoudéni basin represented by E-W directions.

It is accepted that the kimberlites in this area are younger than the doleritic dikes they cross. However, the dating work of kimberlites using the Rb/Sr method on phlogopite showed an age of 1070 Ma for the Sékonomata pipe [33]; which seems improbable when referring to the position of the kimberlites which intrude the dolerites. The significance of such an age could probably lie in contamination [34].

Furthermore, we do not have recent dating concerning the kimberlites, however, elements of information could be provided by a more precise knowledge of the positions respective kimberlites and dolerites [35]. Kobato's pipe, located on the Neoproterozoic plateau, is crossed by a dolerite dyke. It is the same for that of Bilali North in the Birimian plain. It's necessary therefore admit, that at least these pipes predate the doleritic intrusions, at least to those of supposed age Middle or upper Cretaceous.

6. Conclusion

Post-Neoproterozoic dolerites from the Kéniéba region (Western Mali) are often associated with kimberlite pipes. They are tholeiitic in nature, of the E-MORB type and are more enriched in titanium than the Birimian dolerites of Toumodi, in central Côte d'Ivoire. These dolerites would have formed in a late to post-orogenic intracontinental context during the dislocation of Gondwana, according to the pre-rifting period of the Atlantic Ocean. Structurally, Kéniéba dolerites are often associated with kimberlite pipes, fractures and large deep structures identified using aeromagnetic images. Given the fact that the Kéniéba kimberlites are difficult to observe in the field, the study of certain dolerites can be a helping tool and an indicator in the search for kimberlites in the region.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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