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GEOLOGY, GEOCHEMISTRY AND ECONOMIC POTENTIAL OF THE BINGO CARBONATITE AND ITS ASSOCIATED LATERITES IN BENI TERRITORY, NORTH KIVU, DEMOCRATIC REPUBLIC OF CONGO (DRC)

BY

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I56/87094/2016

A Dissertation submitted for examination in partial fulfillment of the requirements for award of the degree of Master of Science in Geology of the University of Nairobi

2018

DECLARATION

I declare that this dissertation is my original work and has not been submitted elsewhere for examination, award of a degree or publication. Where other people's work or my own work has been used, this has properly been acknowledged and referenced in accordance with the University of Nairobi's requirements.

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DEDICATION

This work is dedicated to my parents Jean Pierre Kasay and Jeanne Nziavake, to my aunt Christine Kasay and to my personal Sponsor Professor Martin Peter.

ACKNOWLEDGEMENT

This work would not have been possible without the contribution and participation of many people who were involved.

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ABSTRACT

The Bingo carbonatite complex and its surrounding geologic formations which are located in Beni, North Kivu in the Eastern part of the Democratic Republic of Congo, occur along the Western branch of the East African Rift System. The rocks in Bingo carbonatite have undergone intense weathering and many of them are laterites or ferruginous in composition. This research project was carried out at Bingo with the aim of doing the geology of the area by identifying the rock types which surround the carbonatite complex and its associated laterites and by updating the existing geologic map of the area. It was also conducted in order to evaluate the economic potential by giving evidence of minerals and metals which can be mined from the area. To achieve these objectives, petrographical and mineralogical analyses were performed using respectively a microscope and an X-ray diffractometer at the Kenyan Ministry Of Mining and Petroleum.

Geochemical analyses were done using X-Ray fluorescence at the Kenyan Ministry of Mining and Petroleum and Atomic Absorption Spectrometry at the Soil Science Department/ the University of Nairobi. Flame photometry was used in order to check the precision of chemical results for Sodium, Potassium and Magnesium.

Results of petrography and mineralogy revealed that apart from the fresh carbonatite, the surrounding rocks include nepheline syenite, fenites and granodiorite which had never been reported. The mineralogical analysis allowed finding rare minerals including carletonite and polyhalite which are also for the first time being reported in Bingo.

Geochemical results suggest that the Bingo carbonatite is rich in Niobium as pyrochlore. Considering the content of Barium in samples, Bingo pyrochlore is of Bariopyrochlore type. Laterites show a great concentration in Nb, Ba, and some rare earth elements including La, Ce, Y as well as some radioactive minerals such as Th and U. Cerium has a very high concentration in some laterite samples (BS06: 41,500 ppm, BS08: 41,330 ppm, BS11 83,230 ppm) and in some weathered rock samples (BS14: 46,910 ppm, BS18: 56,890 ppm, BS19: 143,900 ppm). The highest Lanthanum concentration is 76,300 ppm in weathered rock sample BS19. Yttrium concentration is found in all samples except in sample BS22. Its highest concentration is 19,920 ppm found in weathered rock sample BS19. The concentrations of Y, La and Ce in rock samples BS14, BS18, BS19 and BS20 are high as well as in laterite samples.

FeO ranges between 39 and 70.9 wt.-% and an average of 39.36 wt.-%. Manganese (MnO) ranges between 8 and 39 wt.-% and an average of 9.46 wt.-%. This is interpreted as a result of high weathering rate in the study area. The presence of apatite in the laterites is evidenced by the high content of P_2O_5. Phosphates range between 7 and 18 wt.-% with an average of 6.95 wt.-% in the samples.

This work recommends that geophysical researches should be done in the study area so as to determine the extent of the Bingo laterites and more geochemical work using latest analytical technologies so as to study more the distribution of rare earth elements within the deposit. It also recommends that trenching and/or drilling should be executed in order to find some fresh samples of the surface weathered rocks.

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LIST OF ABBREVIATIONS/ACRONYMS AND SYMBOLS

XRF : X-Ray Fluorescence

XRD : X-Ray Diffraction

AAS : Atomic Absorption Spectrometry

DRC : Democratic Republic of Congo

REE : Rare Earth Elements

GPS : Global Positioning System

GIS : Geographic Information System

UTM : Universal Transverse Mercator

TAS : Total Alkalis versus Silica

BEBUC : Bourse d’Excellence Bringmann aux Universités Congolaises

KGL : Kilo Gold Limited

SOMUCAR : Société Minière Union-Carbide

EARS : East African Rift System

PPL : Plane Polarized Light

XPL : Crossed Polars

CHAPTER 1. INTRODUCTION

1.1.BACKGROUND INFORMATION

Carbonatites are a variety of igneous rocks which have a composition of more than 50% of carbonates (Woolley & Kempe, 1989). Carbonatites are a great repository of niobium principally as pyrochlore; they may also be very rich in terms of rare earth elements and apatite (Sorensen, 1974; Hutchison, 1983; Mariano, 1989).

Carbonatites have been recognized all over the world. In Africa, more than 850 carbonatite complexes and alkaline rocks have been identified (Woolley, 2001) (see Fig. 1-1). They have been dated from the oldest age of about 2 Ga (Phalaborwa, South Africa) to the present (active carbonatite volcano of Oldoinyo Lengai in Tanzania) (Midende *et al.*, 2014).

Woolley (2001) noted that fifty percent of the African carbonatites are located within the Albertine rift system. The latter is subdivided into two branches: the Eastern branch and the Western branch. In the western branch, 23 alkaline plutonic massifs of the Neoproterozoic age have been discovered (Kampunzu *et al.*, 1985). The Bingo carbonatite complex is among these 23 massifs complexes (Lubala *et al.*, 1985; Woolley, 1989; Woolley, 2001).

The Bingo carbonatite was the focus of researches during the 90's (Woolley *et al.*, 1995) but nowadays it is not a centre of interest except from the exploration's works done during 2010 by the Loncor Incorporated Company (Kibwana, 2010).

This carbonatite complex is visible at the surface and it outcrops on the Mount-Home. One part of the carbonatite occurs as fresh outcrops at the surface, while the other part is partially or totally weathered. That weathered part contains laterites that can be easily found in gullies beneath the Mount-Home. This carbonatite complex is surrounded by Precambrian basement rocks identified as orthogneisses (Woolley *et al.*, 1995). Bingo is a village located in the territory of Beni, North-Kivu province, Democratic Republic of Congo (DRC). It is located about 25 km to the West of Beni highlighted on the map in Fig. 1-1. The approximate geographic coordinates are latitude 0°5'; longitude 29°31'E (Lubala *et. al.*, 1985).

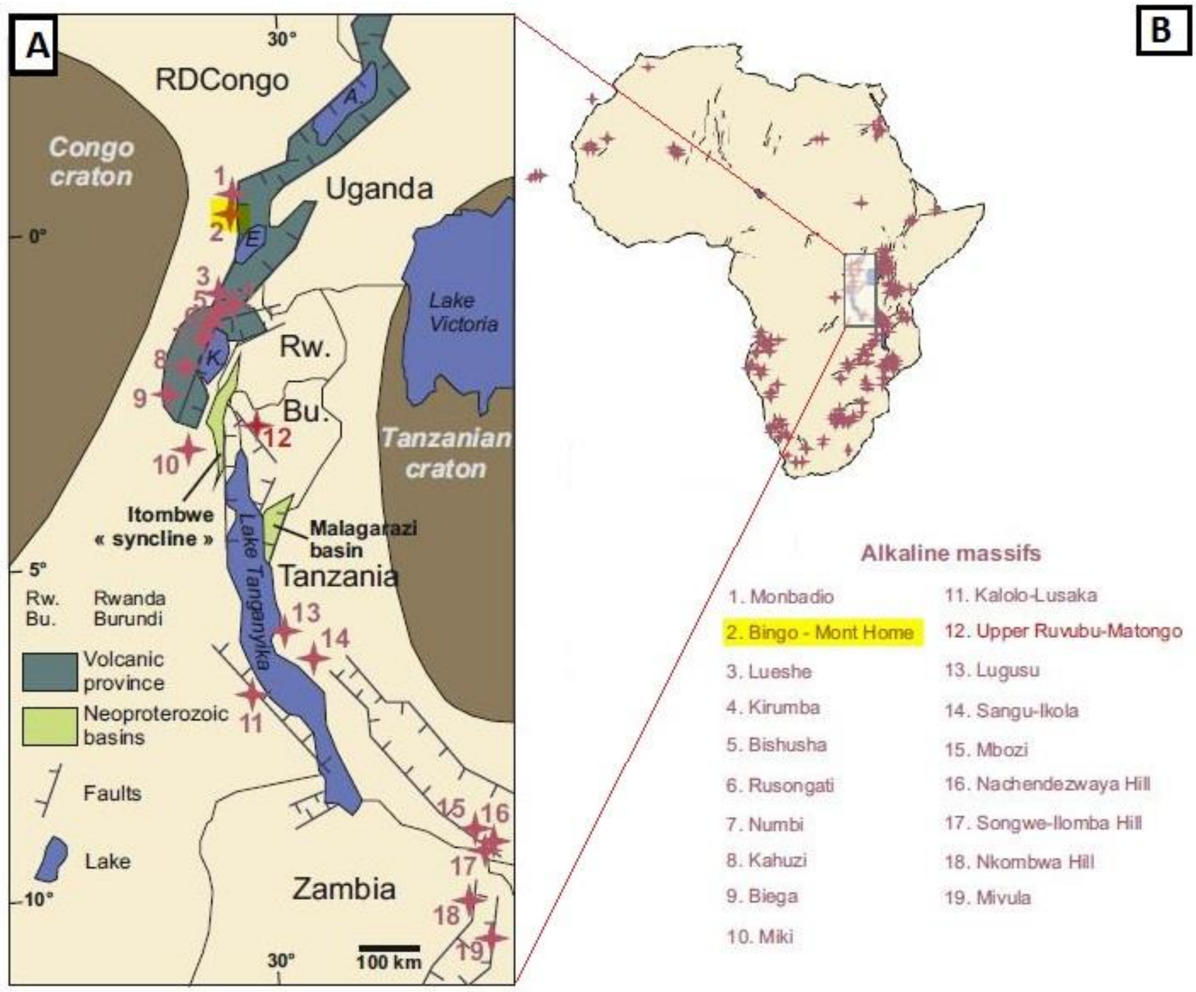


Figure 1-1: (A) The alkaline magmatism inset map along the Albertine rift valley (after Midende et al., 2014). The Bingo carbonatite is highlighted as number 2 in the map. (B) A map showing the distribution of carbonatites in Africa (Woolley, 2001).

1.2.PROBLEM STATEMENT

The Bingo carbonatite complex is one of the richest complexes of the region in terms of metal deposits of niobium (as pyrochlore) and apatite (Maravac *et al.*, 1989); but no exploitation is currently underway.

Amongst the few studies which exist about the Bingo carbonatite complex, one of them was done on the geology and petrochemistry of the fresh carbonatite (Woolley *et al*., 1995). Another unpublished work was done by Kibwana (2010) on the geochemistry of the fresh carbonatite. But none of these works studied the laterites associated with the carbonatites of Bingo. It is recognized that metals are more concentrated in the gossan than in the fresh carbonatite (Mitchell, 2014). It is then important to do the geochemistry of the Bingo carbonatite and its surrounding rocks with its associated laterites in order to study its economic importance in terms of mineral deposits.

The latest geologic map of the Bingo carbonatite was done by Woolley *et al.* (1995), this is why the map needs to be upgraded to recent mapping techniques as it is lacking geographic coordinates and the separation of laterites and fresh rocks is not clear. This has been done along with the mineralogical study of the rock samples in order to discover new mineral species of the study area.

The aim of this study was to investigate the geology, the geochemistry and the economic potential of the carbonatites and associated gossan deposits apart from pyrochlore and apatite which were reported (Woolley and Kjarsgaard, 2008).

Research questions

Regarding the notes mentioned above, the following questions motivate us:

- What is the mineralogy of the laterites, carbonatites and surrounding geologic formations?
- What is the whole rock geochemistry of the Bingo carbonatite and the range of concentration of elements in the associated lateritic gossan deposits?
- What is the economic potential of this carbonatite complex and its associated laterites?

1.3.JUSTIFICATION AND SIGNIFICANCE OF THE RESEARCH

The Bingo carbonatite is known as one of the deposits with viable economic potential in the Eastern part of the Democratic Republic of the Congo. It is therefore important to undertake a detailed study that will lead to a better understanding of its geology and geochemistry. Enhanced knowledge will lead to a better understanding of available economic potentials within the Bingo carbonatite. This research is significant because at the end it will update and provide new data on the geology and geochemistry of the Bingo carbonatite complex, its associated laterites and its surrounding geologic formations.

1.4.OBJECTIVES

1.4.1. Main objective

The main objective of this research was to investigate the geology, the geochemistry and the economic potentials of the Bingo carbonatite and its associated lateritic deposits.

1.4.2. Specific objectives

- To carry out the petrographic and mineralogical analysis of fresh rock samples of the study area in order

- To map the geology and update the geologic map of the Bingo carbonatite and its surrounding rocks,
- To determine the geochemical composition of the Bingo carbonatite rocks and its associated lateritic deposits.
- To evaluate the economic potential of the carbonatite and its associated gossan deposits.

1.5.STUDY AREA

1.5.1. Location and description

The Bingo carbonatite complex is located in the Bingo village. Bingo is situated in the Beni territory in the Northern part of the North-Kivu province, chiefly in the Eastern part of the DR Congo (formerly known as Zaire) (Fig. 1-2). It is around 180 km from the border with Uganda and occurs at approximate coordinates of Latitude 0°5' and longitude 29°31'E (Lubala et. al., 1985). The Beni region map in fig. 1-2 is also in Appendix I of this work.

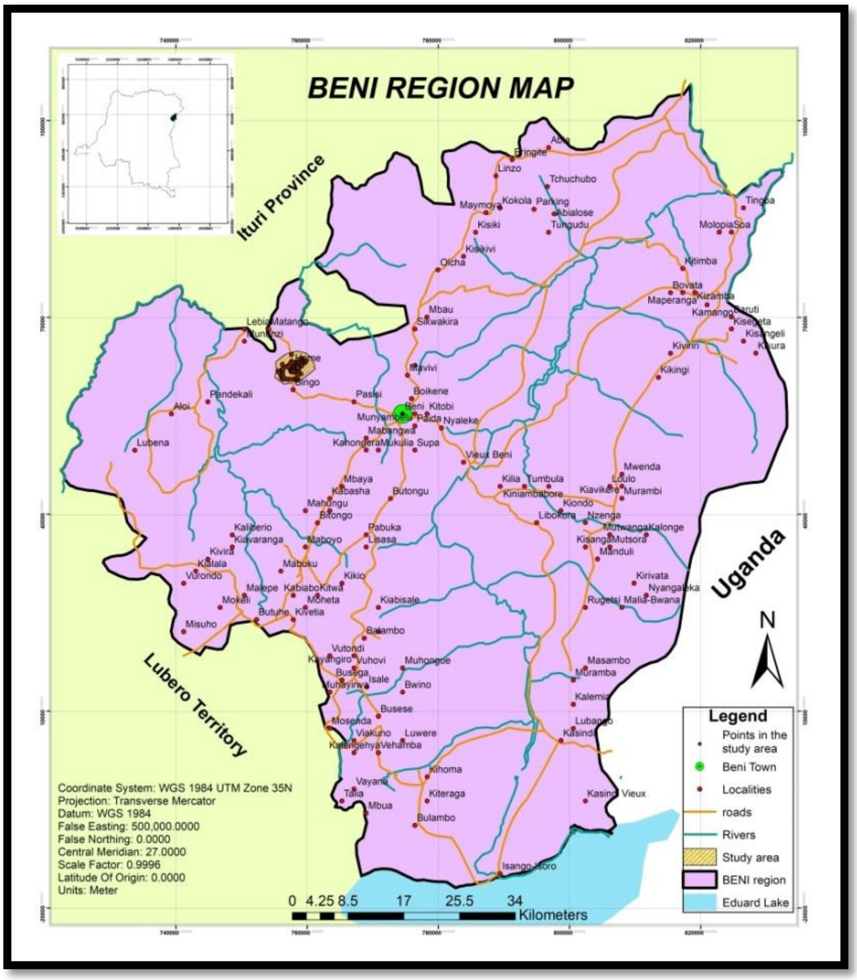


Figure 1-2: Location of Bingo area in Beni territory in the Eastern part of the DR Congo.

1.5.2. Regional climate

The climate in the study area depends upon the regional climatic variations. The Beni territory has a tropical climate with alternations of dry and wet seasons. The area sometimes gets to be hot during the dry season. The highest and the lowest temperatures in Beni are 16.9 °C and 28.9 °C, respectively. The average temperature in Beni is 23.0 °C. January is the driest month with 65 mm of rain (Fig. 1-3). April is the month of the greatest amount of precipitation with an average rainfall of 185 mm. The region gets a lot of rain with an average rainfall of 1582 mm (Fig. 1-3). Majority of people depend on farming as the main agricultural activity. Heavy rains and hot climate enhance weathering of the rocks that produces very deep weathered soils. https://en.climate-data.org/location/4597/

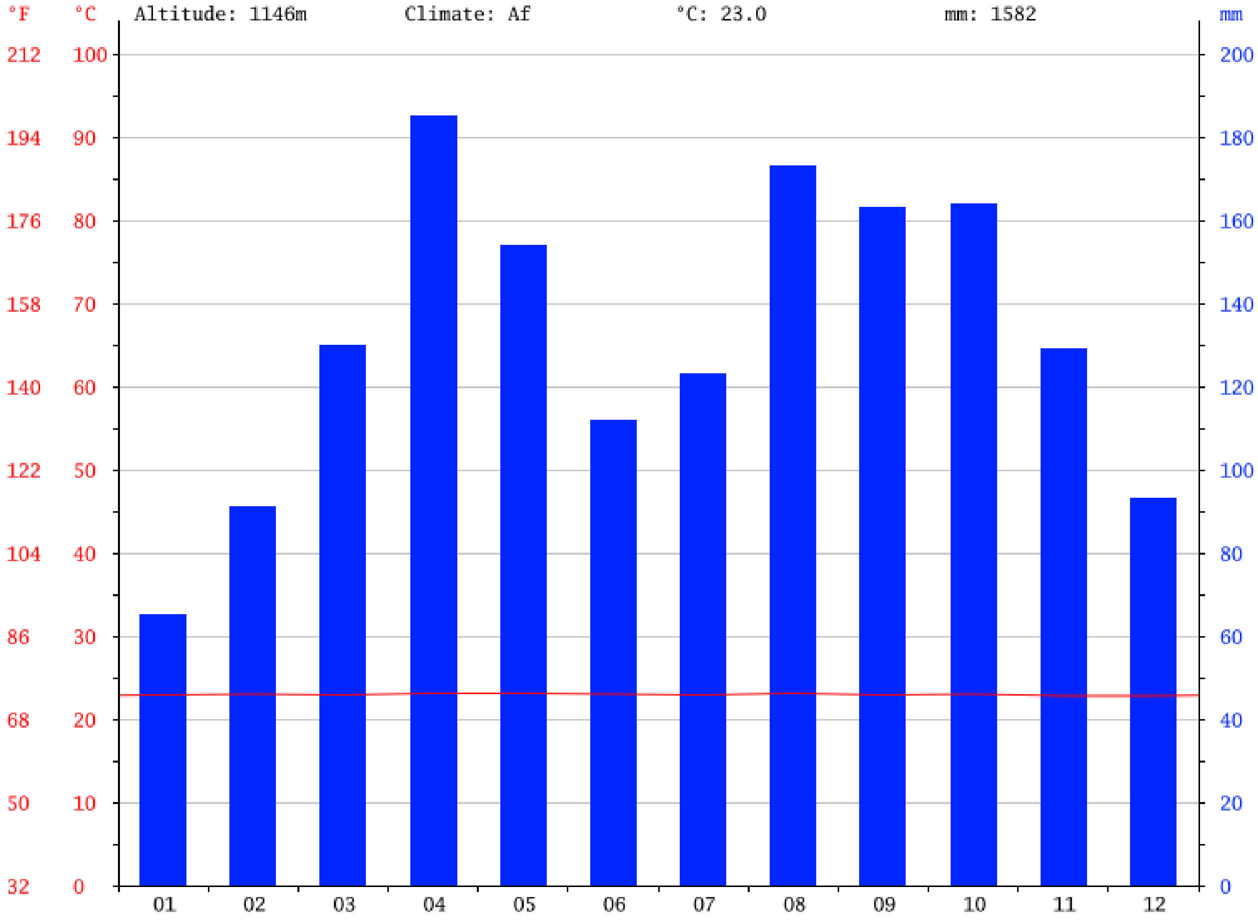


Figure 1-3: Average temperature and rainfall of the Beni region.

1.6.GEOLOGICAL ASPECT OF THE STUDY AREA

1.6.1. Geology of the DR Congo (Formerly called Zaire)

The geological units of the Democratic Republic of Congo were subdivided by Lepersonne (1974) into two main units which were separated by an unconformity and a hiatus in their stratigraphic succession. The two units are the Phanerozoic cover units and the Precambrian basement units. The Phanerozoic units are non-metamorphosed and contain fossils whose ages range from the Carboniferous to the Holocene. The Precambrian basement units are metamorphic terrains found in the Congo basin (Lepersonne, 1974). The subdivision of the DR Congo geology into two units was made according to the philosophy of the existing geologic models for Western Europe in which angular unconformities in folded terrains relate to successive orogenic cycles and the subtabular cover deposits of sedimentary origin are linked to epirogenic movements of the marine transgressions and regressions. This latter idea did not take into account the new geodynamic concepts which were more recently described by Deblond and Track (2000), and it was seen not to be applicable to the Congo Basin case.

Deblond and Track (2000) proposed a new geological framework of the geology of the DRC where the subdivisions of the geologic units were based on the geodynamic processes controlling the evolution of this part of the African plate (from young geologic formations to older geologic formations):

- **The breakup of Pangea, Atlantic Ocean opening and development of continental rifting within African plate** (since 250 Ma): this includes the Phanerozoic Atlantic coastal basins which have been an interest of exploration campaigns for oil and gas. They are basins which elongate from the Gulf of Guinea in the North to the Southern part of the continent in Namibia. In the DRC, oil deposits are located in the Western part and are linked within the Cabinda in the former province of Bas-Congo. the Western branch of the EARS (East African Rift System) is characterized from South to North liking the Upemba graben, the Lake Moero, the Lake Tanganyika, the Ruzizi valley, the Lake Kivu, the Virunga volcanic massif, the Lake Eduard and the Ruwenzori horst (Deblond and Track, 2000). The Lake Eduard in Beni territory and Lake Albert in Ituri province have shown good prospects for oil exploration and exploitation. The Lake Kivu is famous for its spectacular methane gas concentration and the Western rift has an intense Cenozoic volcanic activity with the two active volcanoes of Nyiragongo and Nyamulagira. This intense volcanic activity has given rise to the presence of hot springs which by far provide indicators of good geothermal potentials and energy sources in this part of the country (Vikandy *et al.*, 2008).

- **The assembly of Pangea:** no record of this geodynamic process has been identified in Central Africa.
- **The breakup of Gondwana and Karoo**: the Karoo deposits occur either as a part of the sedimentary pile which is in the “Cuvette Centrale” or as sediments in the rift basins. They have been identified in the Luena and Lukuga basins. The two basins have coal seams locally exposed at the surface. The Karoo sediments have two different origins; the Lower Karoo is composed of fluvial/lacustrine sediments, whereas, the Middle and Upper Karoo are composed essentially of fluvial sediments. The Karoo deposits are of Upper Carboniferous, Permo-Triassic and Lower Jurassic age (Deblond and Track, 2000).
- **The breakup of Rodinia (Neoproterozoic):** during this geodynamic period, evidence of rifting and passive margin evolution are in the Western and Eastern part of the DR Congo. In the Western part, the evidence is in Bas-Congo. In the Eastern part, the rifting and passive margin in Katanga and the Neoproterozoic alkaline plutonic alignment occur in the western rift. This alignment is about 1700 km in length and is composed of twenty-three intrusive massifs including the four known carbonatite complexes in Eastern DRC (see Fig. 1-1) namely from the North to the South: Mombadio, Bingo, Kirumba and Lueshe (Deblond and Track, 2000).
- **The assembly of Rodinia and Kibaran Orogeny (Mesoproterozoic):** this period is represented by the evolution of the Kibaran belt. The belt has a great concentration of tin in the major tin province in Congo (it includes provinces of North and South Kivu, Maniema and Katanga) and other neighbouring countries like Rwanda, Burundi, Western Uganda and Western Tanzania. This tin province is rich in other metals such as tungsten, Nb-Ta, Lithium, Beryllium and gold. The internal domain of the belt has been affected by extensive post-Kibaran tin bearing granites and pegmatites (Deblond and Track, 2000).
- **The pre-Rodinia evolution (Paleoproterozoic):** this period goes from 2.5 - 1.6 Ga. It is known as the Ruzizian belt in Kivu, Maniema and North Katanga.

Fig. 1-4 shows the geologic map of the DR Congo as done after Lepersonne (1974) in KGL masters project (Robinson, 2008).

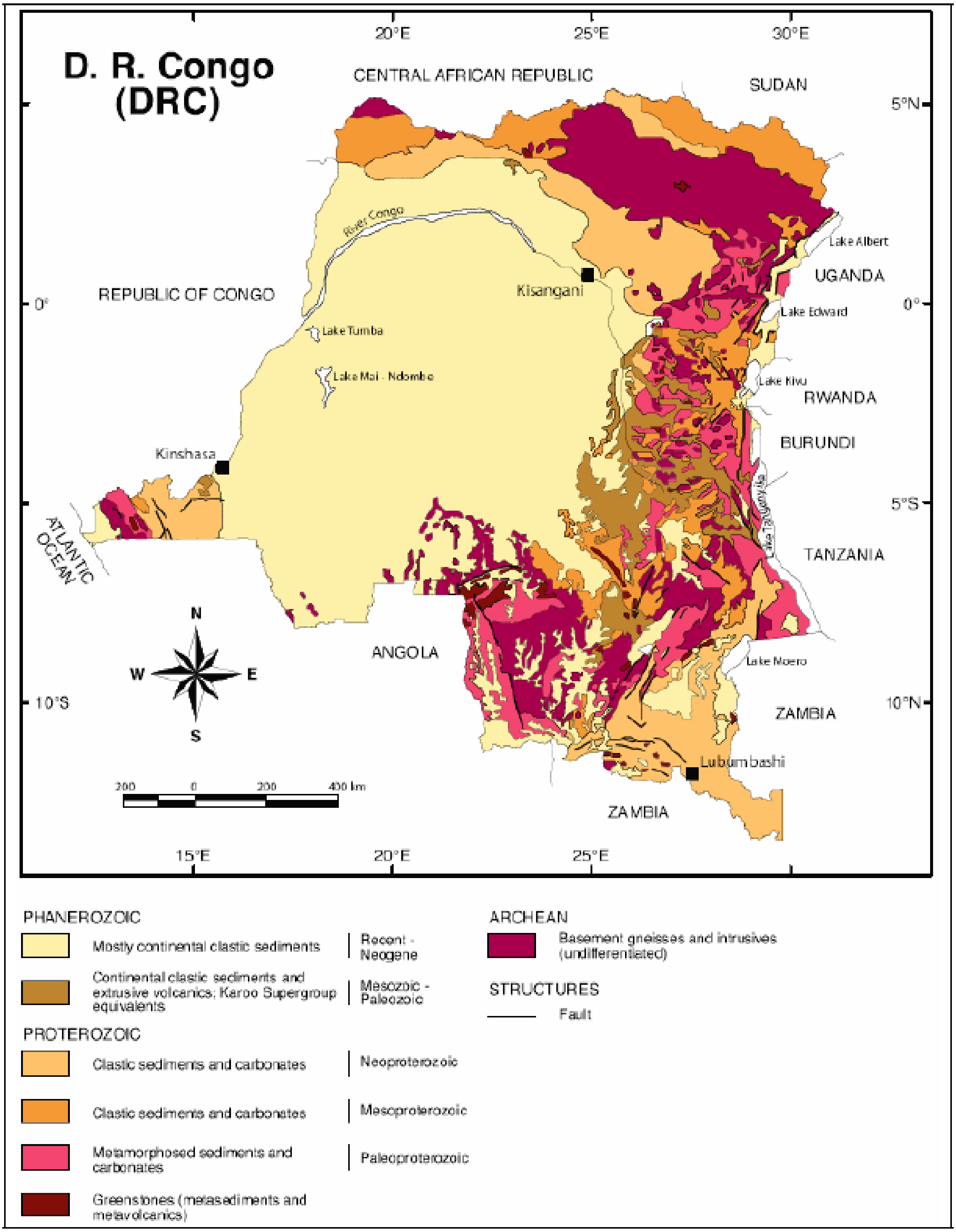


Figure 1-4: Geological map of the DR Congo (after Lepersonne, 1974).

1.6.2. Geology of the Bingo carbonatite

The carbonatite complex of Bingo is closely located in the Neoproterozoic (ca. 750 Ma) alkaline plutonic alignment (Deblond and Track, 2000) even though it has not been dated until now. That alignment has a length of almost 1,700km along the actual western branch of the African Rift. It is constituted of twenty-three intrusive massifs of alkaline rocks (Woolley, 2001). According to Deblond and Track (2000), the composition of rocks ranges from granites through quartz-syenites to feldspathoidal syenites and carbonatites. The alkaline alignment is shown in Fig. 1-5.

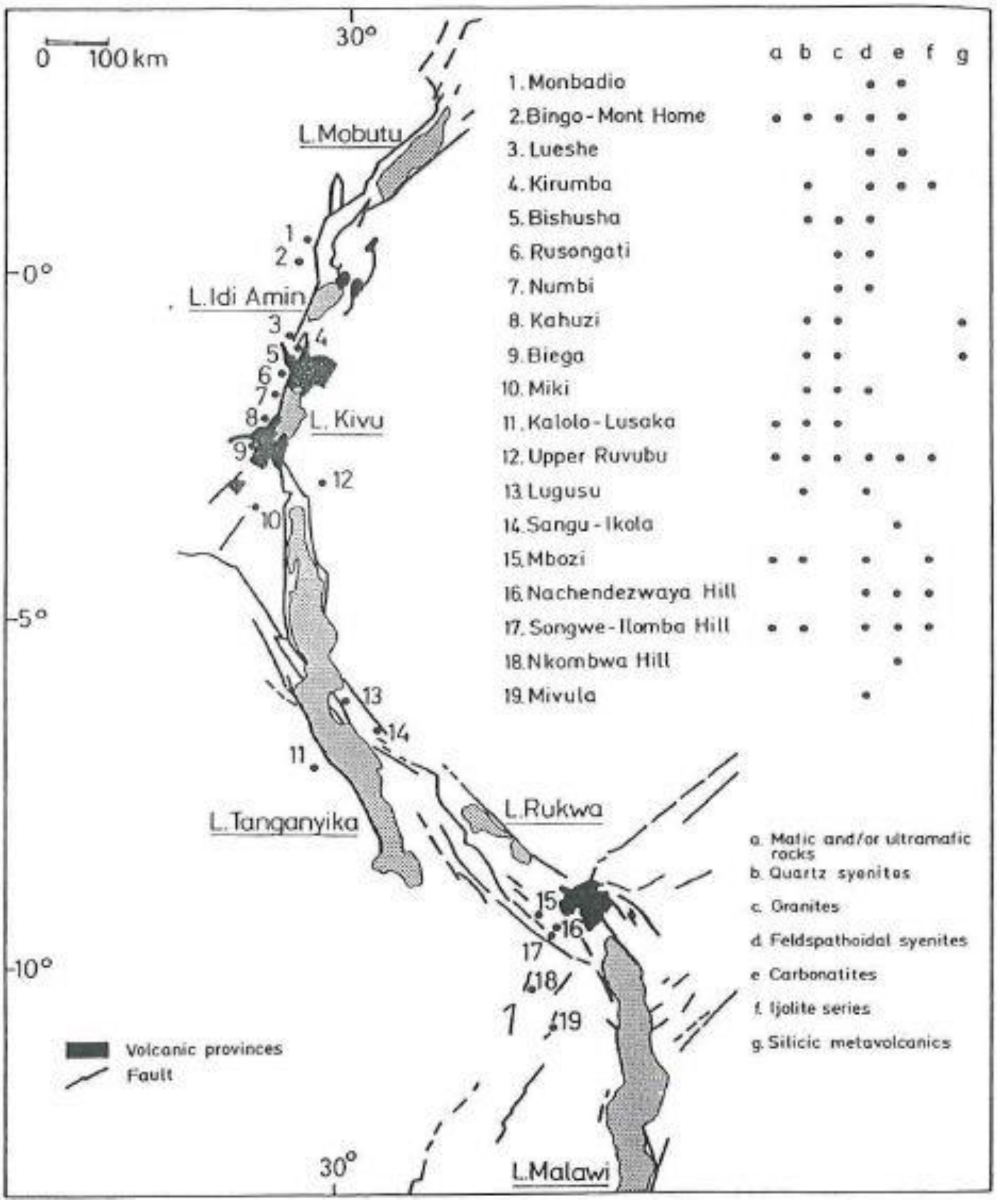


Figure 1-5: The distribution of alkaline rocks and their nature along the Western branch of the African Rift (after Williams et al., 1997).

The carbonatite of Bingo (Fig. 1-6) is a part of an alkaline complex which is constrained between ijolite, nepheline syenite, fenite and it is actually emplaced in Precambrian orthogneisses (Woolley *et al.*, 1995). The area of former exploration and exploitation works was the Mountain Home. Some gullies beneath the Mount Home allow outcrops of the laterites under it to be seen. However, fresh carbonatites are found to the southwest of Mount Home. Wambeke (1971) discovered that the alkaline rocks of the Bingo region are cut by radioactive veinlets with an association of baddeleyite and cassiterite. The Bingo carbonatite is an important niobium deposit which was discovered in 1958 by application of two main exploration methods, geophysical and geochemical methods: the radiometric method and analyses of laterites in the laboratory (Wambeke, 1960). The map (Fig. 1-6) displays the geology of the Bingo carbonatite (Woolley *et al.*, 1995).

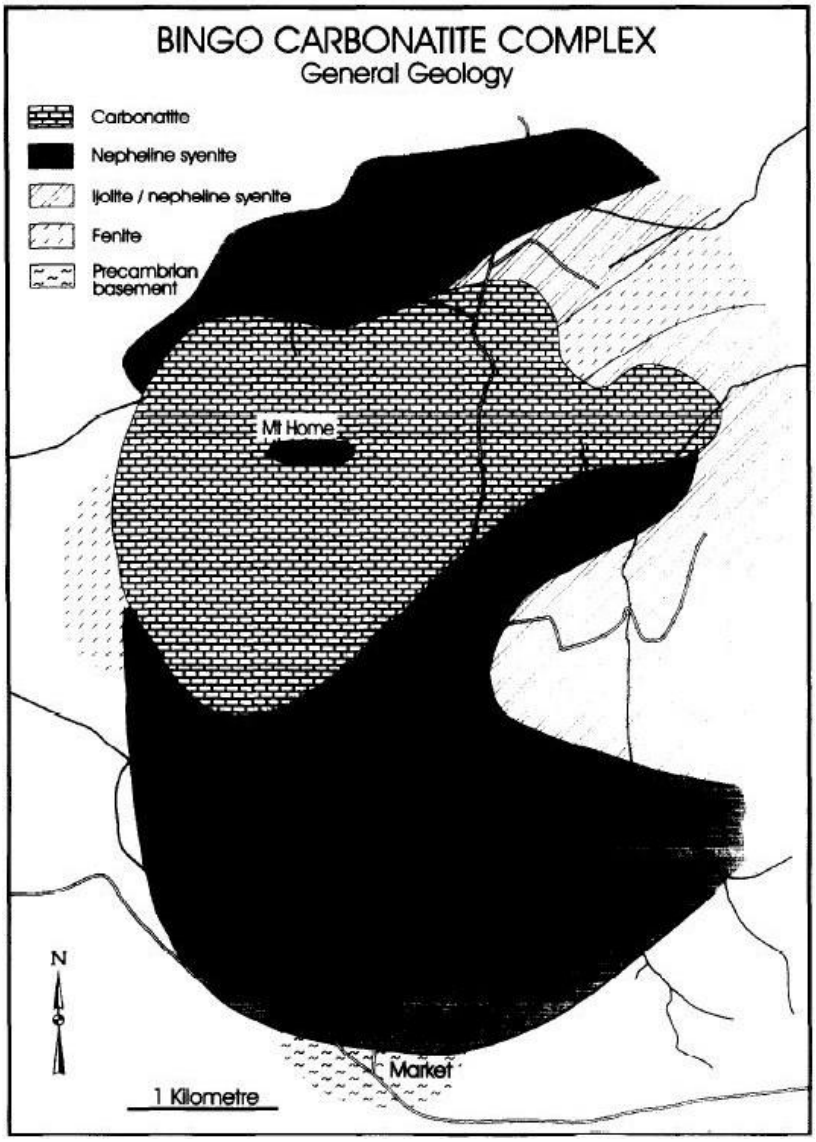


Figure 1-6: Geological map of the Bingo carbonatite (adopted from Woolley et al., 1995).

1.7.DISSERTATION LAYOUT

This dissertation is subdivided into 5 chapters:

Chapter 1: this chapter gives the introductory notes on the general topic. It includes the background information, the problem statement, the justification and significance, the objectives, the geographical and geological setting of the study area and the dissertation layout.

Chapter 2: this chapter develops in details the literature related to the topic of interest. It gives an overview of the previous works done in the study area and the general notes on carbonatites.

Chapter 3: details the methodology used to achieve the objectives assigned. It gives details of the fieldwork and geologic mapping, the geochemical analysis and the mineralogical and petrographical analyses.

Chapter 4: gives the results in detail from the petrographic description of samples, through the petrographic and mineralogical results to the geochemical results.

Chapter 5: deals with conclusions and recommendations.

CHAPTER 2. LITERATURE REVIEW

2.1. PREVIOUS WORKS

The Democratic Republic of Congo is one of the countries in the world with great minerals potential; especially the Eastern, South-Eastern and North-Eastern parts have been identified to be amongst the ones which have many repositories of minerals. The Bingo carbonatite complex is located in the Eastern part of the country together with other carbonatite complexes such as at Lueshe, Kirumba and Monbadio (Fig. 1-1).

The Bingo carbonatite is located within the western branch of the Great African rift valley. Different researches have been carried out on the Bingo carbonatite and its surrounding fenites and silicate rocks (Williams *et al.*, 1997; Wooley *et al.*, 1995; Wambeke, 1971; Kibwana, 2010); many of the researches done in this area are older than 15 years. Though the Bingo carbonatite has not been dated, its age is estimated to be similar to that of Lueshe carbonatite that lies in the same geological setting. Using the K/Ar method, the Lueshe carbonatite has been dated 500 M.y. (Maravac *et al.*, 1989). The closely associated Kirumba carbonatite (see Fig. 1-1) has been dated 555±17 M.y. using Rb/Sr biotite (Kampunzu *et al.*, 1998).

A petrological and geochemical study performed on the Lueshe carbonatite confirmed that it consists mainly of sövites with some alvikites and beforsites as well as a wide variety of light REE (Maravac *et al.*, 1989). Woolley *et al.* (1995) did a geological map with some petrographical studies of Bingo carbonatites and its neighbouring silicate rocks. The report showed that the carbonatite intrusion consists of ijolites cut and nepheline as well as sodalite syenites in their veins. The study concluded that there was no evidence of a genetic relationship between the carbonatite and the igneous silicate rocks. Petrographic study of the fresh rocks of Bingo identified the presence of the rare mineral “gotzenite”. Another research was done by Williams *et al.* (1997) on the composition of the pyrochlore from the carbonatite and laterites of Bingo revealed that it was rich in Barium and Silicon. The compositional variation between the pyrochlore of Lueshe and Bingo indicated that the pyrochlore of Bingo was Bariopyrochlore while that of Lueshe was Kalipyrochlore (Wall *et al.*, 1996; Williams *et al.*, 1997).

A recent work was done by Kibwana (2010) on the geochemistry and petrography of the Bingo carbonatite. The aim of his work was to discover whether there is a possibility to find a deposit by analysis of major and trace elements, but the methodology used did not fit with objectives. And we kindly disagree with some of what he did in his research. It is well known that minerals are concentrated in the laterites and not in the fresh carbonatite (Mitchell, 2014); this is why analyzing fresh carbonatite cannot give real wholesome results from which a deposit of any mineral can be evaluated; what he exactly did, and this is quite not true. Kibwana's report (2010) was limited by the fact that it only analyzed for two trace elements (Nb and Ba), yet it is well known that there is a great range of economic minerals which can be mined from carbonatites including apatite (Phosphates), rare earth elements (Mariano, 1989). Furthermore, Kibwana's report does not mention quite well the methodology and equipment that were used for the analysis of samples.

Last but not least, taken into account all the above works, it is very important to mention that the geochemistry of the Bingo carbonatite related laterites still has missing data in terms of their chemical composition. Moreover, the geological map, designed by Woolley *et al.* (1995), lacks coordinates and approximate extent of the laterites location. The lack of deep geologic and geochemical knowledge of the Bingo carbonatite and its associated laterites has led to its non-exploitation and non-interest for further exploration.

This study postulates that the geochemical study of the laterites of the Bingo carbonatite complex will be very useful in the discovery of a wide range of minerals which can be extracted from it. And this carbonatite complex might be a source of rare earth elements from crandallite in the veinlets' phosphate mineral (Wambeke, 1971).

2.2. GENERAL NOTES ON CARBONATITES

2.2.1. Definition, Origin, types of carbonatites

2.2.1.1. Definition

Carbonatites are igneous rocks with a composition of above 50 % of carbonate minerals and many of them contain concentrations of apatite, magnetite, barite and fluorite (Woolley and Kempe, 1989; Modreski *et al*., 1986). Carbonatite rock name is used for both volcanic (extrusive) and plutonic (intrusive) rocks of that composition.

The aforementioned rocks are mainly found in alkaline igneous provinces in stable cratonic regions and in major rift faulting zones (Wallace and Green, 1988). Among the rifts which have shown great occurrences of carbonatites, the Albertine African Rift Valley and the St Lawrence River Graben are some of the good examples (Evans, 1993). In some areas, however, carbonatites are not associated directly with any alkaline provinces and among examples, the Sangu complex in Tanzania and Kaluwe in Zambia are the best illustrations (Evans, 1993).

2.2.1.2. Origin of carbonatites

The subject related to the origin of carbonatites is very controversial and the controversies will not be considered in this review. Among the theories for the origin of carbonatites, three are widely accepted:

- Carbonatites are generated by immiscibility. In their work, Kjarsgaard and Hamilton (1989) proposed that immiscibility was a major process in the generation of carbonatites and their surrounding silicate rocks. They argued out that immiscibility is the major process by which many types of carbonatites originate more than any other process.
- Carbonatite as a primary mantle melt product from partial melting of CO_2 (Wallace and Green, 1988).
- Carbonatite as a product of residual melts of fractionated nephelinite or melilitite-rich carbonate (Gittins, 1989)

2.2.1.3. Types of carbonatites

Carbonatites are subdivided into many classes depending upon their chemistry or the abundant element. The following classes are the collection of the readings from Le Bas (1981) and Woolley and Kempe (1989):

a. Calcite-carbonatite: when it is coarse-grained it is called sövite and when it is medium to fine-grained, it is named alvikite.
b. Dolomite-carbonatite: which is also termed berfosite.
c. Ferrocarbonatite: it is essentially composed of iron-rich carbonate minerals.
d. Natrocarbonatite: when it is essentially composed of sodium-potassium-calcium carbonates.

Natrocarbonatite is actually known as the extrusive rock product of Oldoinyo Lengai in Tanzania (Woolley and Kempe, 1989). The Bingo carbonatite is a calcite-carbonatite and as it is coarse-grained, it is named sövite.

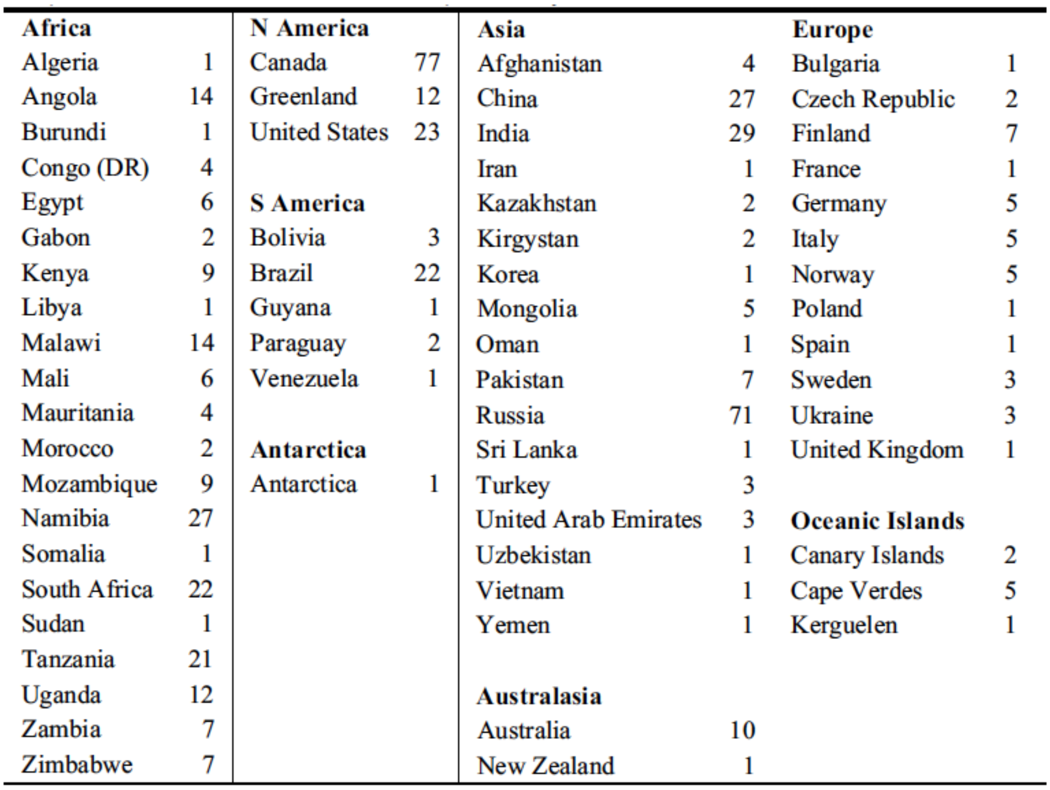
2.2.2. Spatial and Temporal Distribution of carbonatites in the world

In the world, the number of known carbonatites is estimated to be 527 complexes (Woolley and Church, 2005; Woolley and Kjarsgaard, 2008; Woolley, 2001). Most of the carbonatite complexes are known to be intrusive but 49 of these complexes are extrusive and the fittest example is the active carbonatite volcano of Oldoinyo Lengai in Tanzania (Woolley and Church, 2005). The largest number of occurrences of carbonatites, almost half of them, is found in Africa and spatially associated with the African Great Rift valley. The distribution of these carbonatite complexes throughout the world is given in table 2-1 and illustrated in figure 2-1 (Woolley and Kjarsgaard, 2008).

According to Woolley (1989), the spatial and temporal distribution of carbonatites is very important as it has shown some general characteristics in any petrogenetic scheme for their origin. Among the features, he found out that:

- Many carbonatites are related to orogenic belts and divergence and convergence margins in space and time.
- Carbonatites can be found aligned with oceanic fracture zones.
- They generally appear on uplifted or domed areas which extend from tens to thousands of kilometres in diameter.
- Carbonatites are generally associated with major faulting and rifting events that are linked with doming (Berger *et al.*, 2009). Many carbonatites in Africa are within this characteristic as they lie in the African Rift. The Bingo carbonatite is also one of them (Woolley, 2001).
- Time has been a key factor for the generation of carbonatite magmas.
- The end of the Archean was the period in which favourable conditions for the formation of carbonatite magmas were established.

Table 2-1: World Distribution of carbonatites by numbers and countries (Woolley and Kjarsgaard, 2008)



Africa		**N America**		**Asia**		**Europe**	
Algeria	1	Canada	77	Afghanistan	4	Bulgaria	1
Angola	14	Greenland	12	China	27	Czech Republic	2
Burundi	1	United States	23	India	29	Finland	7
Congo (DR)	4			Iran	1	France	1
Egypt	6	**S America**		Kazakhstan	2	Germany	5
Gabon	2	Bolivia	3	Kirgystan	2	Italy	5
Kenya	9	Brazil	22	Korea	1	Norway	5
Libya	1	Guyana	1	Mongolia	5	Poland	1
Malawi	14	Paraguay	2	Oman	1	Spain	1
Mali	6	Venezuela	1	Pakistan	7	Sweden	3
Mauritania	4			Russia	71	Ukraine	3
Morocco	2	**Antarctica**		Sri Lanka	1	United Kingdom	1
Mozambique	9	Antarctica	1	Turkey	3		
Namibia	27			United Arab Emirates	3	**Oceanic Islands**	
Somalia	1			Uzbekistan	1	Canary Islands	2
South Africa	22			Vietnam	1	Cape Verdes	5
Sudan	1			Yemen	1	Kerguelen	1
Tanzania	21						
Uganda	12			**Australasia**			
Zambia	7			Australia	10		
Zimbabwe	7			New Zealand	1		

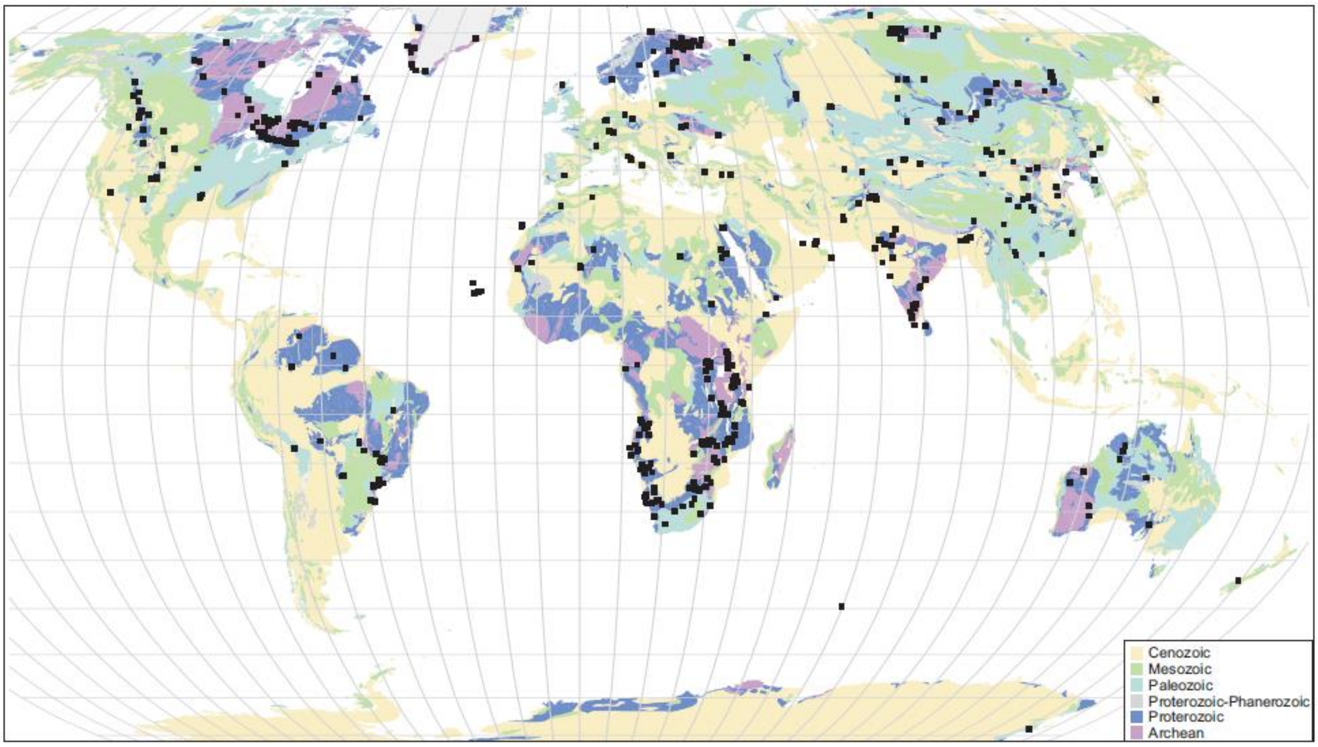


Figure 2-1: Map showing the world distribution of carbonatites according to the data in table 2-1 (After Woolley and Kjarsgaard, 2008).

In the DR Congo, carbonatites are mainly located in the Eastern part of the country within the Western branch of the East African Rift System. They are found in Monbadio, Bingo, Lueshe and Kirumba areas. The carbonatites of Lueshe and Kirumba were dated and gave ages of 833 and 803 Ma, respectively (Woolley and Kjarsgaard, 2008). The other two carbonatites (i.e. Bingo and Monbadio) have not been dated.

2.2.3. Fenitization

Fenitization is defined as the alkali metasomatism process related to the alkaline igneous activity (Le Bas, 2008). It is the common type of metasomatic alteration which is related particularly to carbonatite intrusions. Fenitization halo surrounds carbonatite complexes (Simandl, 2015), and it accompanies all intrusions of nepheline syenites, ijolites and ultrabasic and alkaline rocks. The common alkali metasomatisms in fenitization are feldspathization or phologopitization (Le Bas, 1981).

It occurs in stable parts of the continental areas and around alkaline complexes. Fenitization also is the result of Na and/or K-rich fluids related to the cooling of intrusions of carbonatites or ijolites. The resulting rocks which form from fenitization are known as fenites. Fenites form from progressive metasomatism in the country rocks which surround the alkaline complexes. They are produced by solid-state transformation of older wall rocks by infiltration of alkaline hydrothermal solutions from carbonatite magma. The composition of these fenites depends upon two different features: the nature of the affected country rocks and the igneous complexes from which fenitizing fluids evolve (Pirajno, 2009).

2.2.4. The economic importance of Carbonatites

Carbonatites are a major source for many minerals of economic importance. They are important occurrences of Niobium, phosphates, Rare Earth Elements, vanadate, fluorite, vermiculite and many key minerals (Mariano, 1989). The concentration of these minerals depends greatly on the fact whether the carbonatite is primary (not weathered) or weathered. The minerals' concentrations of laterites associated with carbonatites are far above those of the fresh carbonatite (Mitchell, 2014).

In the following discussion, we will give a review of economic minerals mined from carbonatites and their associated laterites.

- **Niobium**

Niobium is the main metal element that is mined from carbonatite. It is found in pyrochlore which is the most important mineral from which niobium is mined and it is the principal mineral in carbonatite (Mariano, 1989). During pronounced lateritic weathering of carbonatites, Pyrochlore is totally destroyed and niobium partitions into supergene REE minerals of the crandallite group (Mariano, 1989).

Niobium is present in primary and secondary mineral deposits associated with carbonatites depending upon the climate conditions of each region. The commonly known supergene deposits of niobium are the Brazilian deposits which account for 92% of the Nb world's production. And the primary St. Honoré carbonatite (Quebec) is famous for its Nb production which can go up to 7% of the world's production (Mitchell, 2014).

Supergene Nb deposits are found in laterites from extreme weathering of fresh carbonatites. The concentrations of minerals are high in the laterites and they can be easily exploited. Araxa, Catalao I and II (Brazil) and Seis Lagos (USA) are examples of Nb mineral deposits found in laterites (see table 2-2).

According to Mitchell (2014) and Wall *et al.* (1996), similar supergene deposits are found in Bingo and in Lueshe (the Democratic Republic of the Congo), in Sukulu (Uganda), in Mabouiné (Gabon) and at Mt. Weld (Australia).

The concentration of Niobium in primary carbonatite is usually low and this often leads geologists to classify or to qualify them as large tonnage-low grade disseminated ore deposits (Mitchell, 2014). The host rocks or the primary Nb include rocks of magmatic origin mainly of melilitite, nephelinite and aillikite group. Primary Nb deposits are "the result of early crystallization of Nb-bearing minerals in magma chambers followed by crystal fractionation, magma mixing and redistribution of Nb minerals by density currents" (Micthell, 2014).

- **REE (Rare Earth Element)**

Carbonatites have a distinctive aspect of the presence of high anomalous REE contents. The REE minerals in carbonatite can be of three different types: magmatic REE, hydrothermal REE and supergene REE minerals (Mariano, 1989). When REE minerals are primary, it means they directly originated from carbonatite melts and an example of such deposit is located in the Mountain Pass, the USA where bastnaesite and parasite elements are dominant.

Hydrothermal REE minerals are precipitated from hydrothermal solutions. As tabulated in table 2-2, they are situated in Bayan Obbo, China (Verplank and Van Gosen, 2011), Karonge, Burundi and Wingu Hill in Tanzania (Mariano, 1989; Berger *et al*, 2019). Supergene REE minerals are those found in carbonatite-derived laterites (e.g. in Araxa and Catalao I, Brazil; Mrima hill in Kenya and Mt. Weld in Australia) (Mariano, 1989). China has got the largest reserves of REE in the world (Evans, 1993). Light REE are the commonest minerals found in carbonatites, and in particular lanthanum, cerium and neodymium (Verplank and Van Gosen, 2011).

- **Apatite**

According to Mariano (1989), the economic value of phosphate in carbonatite is larger than the values of other commodities for which carbonatites are mined. Phosphate is mined from primary carbonatite and pyroxenite in Tapira, Minas Gerais (Brazil), in Patrocinio, Minas Gerais, Brazil (see table 2.2.). By the way, phosphate is mined from a secondary deposit in Araxa, Minas Gerais, Brazil (see table 2-2).

The three (Niobium, REE and apatite) are the main minerals for which carbonatites are mined. However, carbonatites include other economic concentrations of titanium, vermiculite, fluorite, barite, strontium, vanadium, copper, thorium and uranium mineralizations (Evans, 1993; Mariano, 1989; Verplank and Van Gosen, 2011). Presently only one carbonatite complex is known to be a source of Copper in the world and it is located in South Africa (Phalaborwa) but others may contain traces of copper at uneconomical level (Evans, 1993).

- **Titanium**

Titanium may form its own minerals or may substitute for other elements in most carbonatites. It is an important element in carbonatites and related alkaline rocks. Titanite is the most Ti ore which is found in carbonatites in good quantities. Rutile and brookite are abundant in hydrothermal deposits associated with carbonatites. Perovskite is one the accessory minerals which are found in carbonatites, in fenites and alkaline rocks. Table 2-2 gives the locations from which Titanium is mined from carbonatite complexes.

- **Fluorite**

Fluorite is very common in carbonatites and genetically related alkaline rocks. In carbonatites, fluorite concentrations of economic importance are confined to late hydrothermal activity. The Mato Preto carbonatites in Brazil contain a significant amount of fluorite (see Table 2-2).

Table 2-2: Economic minerals of carbonatites, their localities and associated mineralization (After Mariano, 1989).

Commodity	Locality	Mineralization
REE	Mountain Pass USA	Bastnaesite in carbonatite, with REO (Rare Earth Oxides).
	Bayan Obo, Inner Mongolia, China	Hydrothermal bastnaesite and monazite associated with iron ore
	Gakara-Karonge, Burundi	Hydrothermal veins of high-grade bastnaesite and minor monazite
	Araxa, Minas, Gerais, Brazil	Supergene REE minerals in laterite associated with rare earth oxides (REO)
Niobium	Araxa, Minas Gerais, Brazil	Pyrochlore in laterite
	Catalao I, Goias, Brazil	Pyrochlore in laterite
	Catalao II, Goias, Brazil	Pyrochlore in carbonatite
	Tapira, Minas Gerais, Brazil	Pyrochlore in carbonatite
	St. Honoré, Quebec, Canada	Pyrochlore in carbonatite
	Oka, Quebec, Canada	Pyrochlore in carbonatite
	Sarfartôk, Greenland	Pyrochlore veins in carbonatite
	Lueshe and Bingo, Eastern DR Congo	Pyrochlore in laterite
Phosphate	Tapira, Minas Gerais, Brazil	Primary apatite in carbonatite and pyroxenite
	Araxa, Minas Gerais, Brazil	Secondary apatite with barite and ferric iron oxides
	Patrocinio, Minas Gerais, Brazil	Primary magmatic apatite in carbonatite and pyroxenite
	Catalao I, Goias, Brazil	Primary and secondary apatite in carbonatite and pyroxenite
	Jacupiranga, Sao Paulo, Brazil	Primary apatite in carbonatite
	Anitapolis, Santa Catarina, Brazil	Primary apatite in pyroxenite and glimmerite and residual apatite
	Ipanema, Sao Paulo, Brazil	Primary apatite in glimmerite
	Phalaborwa, South Africa	Primary apatite in phoscorite, pyroxenite and carbonatites
	Cargill, Ontario, Canada	Eluvial apatite
	Martinson Lake, Ontario, Canada	Eluvial apatite
	Sukulu, Uganda	Residual apatite in weathered carbonatite
Titanium	Tapira, Minas Gerais, Brazil	Anatase in laterite
	Catalao I, Goias, Brazil	Anatase in laterite measured
	Patrocinio Area, Minas Gerais, Brazil: includes Serra Negra, Salitre I and Salitre II	Anatase in laterite
	Serra de Maicuru, Para, Brazil	Anatase in laterite

	Powdehorn complex, Gunnison Co., Colorado USA	Perovskite in pyroxenite
Fluorite	Amba Dongar, India	Hydrothermal overprint on fenites at the contact between carbonatite and country rock
	Okorusu, Namibia	Hydrothermal overprint on fenites at the contact between carbonatite and country rock
	Mato Preto, Parana, Brazil	Hydrothermal carbonatite
	Tchivira, Quilengues, Angola	Hydrothermal infillings in brecciated fenite at the contact between ijolite and carbonatite

CHAPTER 3. MATERIALS AND METHODS

3.1. INTRODUCTION

In this chapter, materials and methods used during the research work are presented. These materials and methods made it possible to attain the assigned specific objectives. Fieldwork and laboratory analyses were the main activities carried out during this research project. The fieldwork component was done in Bingo (DR Congo) for a period of two months while the analyses were done both at the Kenya Ministry of Mining and Petroleum and at the Departments of Geology and Soil Sciences, at the University Of Nairobi.

3.2. DESKTOP STUDY AND DOCUMENTATION

During this phase, the search for relevant publications about the geology of the study area was done. Existing topographic and geologic maps of the Bingo carbonatite complex were reviewed and useful information gathered was used in defining the itinerary and process of updating the existing geologic map. Relevant publications were helpful in understanding the regional and local geology of the Beni area where the Bingo complex is situated. Research papers on the neighbouring carbonatites (e.g. the one of Lueshe, Kirumba, Matongo) were critically reviewed. The interest, here, was to have a comprehensive understanding of the regional geology and to figure out existing knowledge gaps of research done on the Bingo carbonatite.

3.3. FIELDWORK AND GEOLOGICAL MAPPING

The purpose of this activity was to collect samples of rocks and laterites from the Bingo carbonatite complex and to update the local map including the carbonatite and its surrounding geological formations.

Fieldwork investigations were performed through the following three different activities:

- Collection and description of laterite samples from the adit,
- Collection and description of rock samples and their respective outcrops,
- Local mapping.

The following materials were used during fieldwork;

i. A GPS (Garmin eTrex) for taking geographic coordinates and navigation.
ii. A Geological Hammer to break and cut rock samples.

iii. A Compass (Silva) to take some visible structural measurements, rivers flow orientations and adit orientations.
iv. A Camera: to take pictures on the field.
v. Sample bags to wrap and seal up the samples.
vi. Dilute hydrochloric acid: to test carbonate rocks.
vii. Magnetic pen to test for the presence of magnetic minerals in the rock and laterites.
viii. Torch to light up the adit. Notebook and pencil: to write all descriptions about outcrops and hand samples. Tape measure to measure the extent of outcrops and dimension of the adit.
ix. Scale ruler to plot samples' points on the grid map.

3.3.1. Collection and description of laterites from the adit

In Bingo, the exploitation of Niobium was underway until the 1990s by different companies. SOMUCAR was the last to do exploitation in that area. Exploitation was done by underground adits from which samples of laterites for this research project were collected. The very first activity was to take coordinates and orientations of the adit at its entry.

The orientation of the adit is given from 96° E to 276° W. Since there is no possibility to take geographical coordinates inside the adit, samples coordinates were determined using main entry coordinates (Fig. 3-1).

Figure 3-1: Main entry of the Bingo carbonatite adit at UTM coordinates X=758644; Y=62317

To explain well the location of samples in the adit, the geologic map of the adit is represented in the results and discussions chapter (see Fig. 4-1), it displays where the samples were collected, as well.

In total, 11 samples were taken from the adits. The sampling method was done by channel sampling on the walls of the adit. Samples were collected with reference to particular characteristics (change in colour, change in orientation of layers). There is a difference in colour from Yellow, red, black and sometimes mixed colours. Samples were coded BS+ their number. B stands for Bingo and S stands for the sample.

3.3.2. Collection and description of fresh and weathered rocks

Fresh rock samples were collected from outcrops using geological hammer and GPS. They were marked by a marker and wrapped in a sample bag. The first description was done on the outcrop and the second on the hand sample.

Samples of fresh rocks include carbonatites, fenites, nepheline syenites and partially weathered carbonatites. The geological map which was done by Woolley *et al.* (1995) (in Fig. 1-5) was very helpful for establishing the field itinerary and for localizing these rocks, although some are very weathered making it difficult to delineate the boundary. In total, 11 rock samples were collected randomly from the study area. Randomly means that they were collected from every place where we found outcrops. 5 samples were collected from fresh rocks and 6 were from weathered rocks.

Hydrochloric acid was used to discriminate the carbonatites from other rocks. The rareness of outcrops was due to a thick lateritic soil and a development of vegetation on the soil. The description, in some areas, was done on loose blocks which were thought to be a reflection of the underlying geology of the region; this method was also applied by Woolley *et al.* (1995).

Due to logistic limitations, we were able to collect a total of 22 samples (i.e. 11 laterites and 11 rock samples) from the study area. During transportation from DR Congo to Kenya, 2 laterite samples were stolen during our transition to Uganda. This is why geochemical analyses were performed on only 20 samples which reached Nairobi/Kenya.

3.3.3. Update of the Bingo carbonatite geological map

In this phase, past maps were useful (Woolley *et al.*, 1995). Geographic coordinates allowed doing the geologic map grid. Geologic and geometric sampling map of the adit was done by hand and then digitized using ArcGIS 10.3.

For the geological map of the study area, correlations between geological formations for the map were established using the Woolley's map of Bingo (1995) (Fig. 1-5). The update of the map provided the delimitation between fresh and partially weathered carbonatites and laterites.

ArcGIS 10.3 was used for this task. In this software, the scanned map was imported and it was georeferenced. After georeferencing, the map was digitized. The geological map and the map of the adit were done using this software.

3.4. GEOCHEMICAL ANALYSIS

3.4.1. Sample preparation

For every analysis, sample preparation is one of the first processes in which samples normally are made ready for analysis.

For geochemical analysis, the first step was to pulverize the samples of laterites and the fresh/partially weathered rocks. The pulverization was performed by a pulverizing machine (laboratory pulverizer) to grains of 100 microns in diameter. Samples were pulverized in order to get them homogeneous. After pulverization, the samples were packed again and sealed, then taken through chemical analyses. The latter was carried out by X-Ray Fluorescence (XRF) and Atomic Absorption Spectrometry (AAS).

For AAS, crushed and ground samples required to be digested for them to be analyzed. The digestion of samples was done following the steps summarized after Thompson and Wood (1982):

- 0.1gm of crushed rock/laterite powder sample was weighed using an analytical balance and it was put in a 100mls plastic bottle.
- 1ml of Aqua Regia (Nitric Acid + Hydrochloric acid, molar ratio 1:3) was added to the sample and placed in a fume hood for an overnight digestion.
- 3mls of HF (Hydrofluoric Acid) was added and the contents were left to stand until dissolution took place.

- 10mls of saturated Boric acid was placed into a 50mls volumetric flask
- With a small addition of de-ionized water, the sample was placed into the 50mls volumetric flask.

3.4.2. X-Ray Fluorescence (XRF)

- *Principles of operation*

This was achieved by the XRF at the Kenyan Ministry of Mining and Petroleum; the interest was to figure out the presence and concentration of major, trace and rare earth elements of the pulverized samples.

This was carried out by the BRUKER XRF, S1 TITAN model. Analyses were done on the powder of the pulverized laterites and rocks. All the 20 samples went through geochemical analyses using that equipment.

- *Procedure*

The process was to take a measure of 10 grams from the samples. All the values of the concentration of elements were recorded in the computer and were given in terms of their percentages. Since trace elements were determined in per cent, their concentrations were converted to ppm by multiplying each of them by 10^4.

- *Quality control*

Precision: precision is about the reproducibility of results obtained from a known analyzed sample. XRF results were tested by using one blind sample which was added to the 20 samples. Then the readings were compared using the equation provided by Maxwell (1968), in formulae 3.1, which takes into account the standard deviation (SD) over the mean of readings. Formulas 3-1 and 3-2 were used for the precision determination of results.

$$P = \frac{2SD}{X} \qquad \textit{Formula 3-1}$$

$$SD = \sqrt{\frac{\sum(X-\bar{X})^2}{N}} \qquad \textit{Formula 3-2}$$

Where:

P : Precision at 95% confidence.

SD : is the standard deviation.
N : Number of readings.
X : Each value in the data set or the readings of analyses of the same sample.
$\bar{X}$: Mean of the values (readings) for each elements.

Accuracy: it is about the closeness of the results to international standards. The calibration of the S1 TITAN XRF was done according to a certificate of calibration given by the Seller BRUKER. General instrument performance was checked by taking ten measurements of the supplied Duplex 2205 sample and then calculating the average measured values. The average measured value for each element had to be within the acceptable limits.

One issue with the Bruker S1 Titan XRF model is that it was unable to analyze for Na_2O and that was a limitation of this method. This is why in order to determine the concentration of Na_2O in the samples and to test the accuracy and precision of XRF analyses done; AAS was used in the laboratory of the Soil Department of the University Of Nairobi. In this second process of chemical analysis Na_2O, MgO and K_2O were determined.

3.4.3. Atomic Absorption Spectrometry (AAS)

- *Principle of operation*

This was achieved by the Atomic Absorption Spectrometer at the laboratory of the Department of Soil Sciences (University Of Nairobi); the interest was to figure out the presence and concentration of Na, K and Mg of samples. Analyses were performed on prepared digested samples.

- *Procedure*

The standards were prepared and then analyzed to calibrate the equipment. Standards analyses produced a normalization curve of emission against concentration in ppm. The readings were recorded in ppm and were later converted to wt.-%. AAS was giving elemental concentrations in ppm (which we called readings), and then those readings were used in formula 3.3 for determining their total concentration in the sample.

$$\boldsymbol{Extractable\ element\ (ppm) = Readings\ in\ ppm \times \frac{A}{Wt}} \qquad \textit{Formula 3-3}$$

Where A is the total volume of the extract or the total digested volume (in our case it was 50ml) and Wt is the weight of air-dry soil or the digested quantity (in our case it was 0.1g)

- *Quality control*

Precision: AAS results were tested by taking the samples through flame photometry at the Department of Soil Science, University of Nairobi. The same samples were also analyzed using AAS at the Kenyan Ministry of Mining and Petroleum. The precision was determined at 95 per cent confidence. Formulas 3-1 and 3-2 were used for this purpose.

Accuracy: Standards for AAS were prepared using the stock standard solution (1000ppm). The preparation was done in 100ml volumetric flasks and working standards solutions were made at 0ppm, 5ppm, 10ppm, 15ppm and 20ppm.

By the end of these analyses, the degree of enrichment and concentration of elements were determined in the two different systems (fresh and weathered rocks and laterites). It was able to determine what metal or metals can be extracted from the laterites apart from the Niobium.

3.4.4. Data analysis

Oasis Montaj, MS Excel, WinRock and PetroGraph beta2 software were used for the interpretation and the making of graphs.

Oasis Montaj was used for making geochemical maps for trace elements.

MS Excel was used for correlation of major elements and trace elements.

WinRock was used for chemical classification diagrams of different rocks of the study area.

Petrograph beta2 software allowed building Harker and triangular diagrams.

3.5. MINERALOGICAL AND PETROGRAPHICAL ANALYSIS

3.5.1. Sample Preparation

The preparation of samples for the petrographic study was done through the following procedure:

- Cutting a slab of rock using a diamond saw.
- Lapping the slab sample through different plates using carborundum grit and water on a metal surface.
- Drying the slab sample and glue on its lapped face a glass slide using epoxy resin.
- Grinding the surface flat using carborundum and water on a glass.

- Polishing again the samples to make them thinner up to 30 Microns. This step should be repeated several times to make sure the sections were thinner to be analyzed and viewed through the microscope.
- Buffing the surface using gamma alumina powder and water as a lubricant on a soft cloth lag.

3.5.2. Qualitative and quantitative XRD (X-Ray Diffraction)

This was performed by Bruker X-Ray Diffractometer (second generation) at the Kenyan Ministry of Mining and Petroleum. XDR allowed determining the bulk mineralogical composition of the samples. In total, 10 samples among the pulverized ones were analyzed for their mineralogical composition. 5 samples of laterites (BS01, BS02, BS04, BS05 and BS10) and 5 pulverized fresh rocks samples (BS13, BS15, BS16, BS21 and BS22) were analyzed.

- *Principle of operations*

XRD works on the principle of irradiation. When a sample is irradiated, it emits x-rays which are diffracted in a way that is characteristic of the analyzed compounds. XRD provides spectra patterns whose pick angles and intensities are measured. The pick angles allow determining the type of the sample constituent compounds; whereas, the intensities of the picks are useful in the determination of the sample constituent compounds.

XRD is used for qualitative and quantitative phase analysis of powder minerals, for the identification of crystalline materials. Apart from mining purposes, it is used in a broad knowledge domain such as biology, pharmacy, and painting (Chauchan and Chauchan, 2014; Bunaciu *et al.*, 2015).

- *Procedure*

10g powdered samples were weighed and analyzed. The results of XRD were recorded as spectra of elements as well as in percentages. The specific mineral which was given by the instrument was then redefined according to the group in which it belongs.

- *Quality control*

Precision: a blind sample was added to samples and was analyzed. The results were compared with the true sample and formula 3-1 and 3-2 using the Maxwell (1968) equations were used. The accepted value was specified in confidence level measurement at 95%.

Accuracy: for the calibration, a corundum sample (Al_2O_3) was placed in the instrument. That corundum sample was provided by Bruker Company.

3.5.3. Petrographical analysis

This was done were using NIKON ECLIPSE LV100POL optical microscope at the Kenyan Ministry of Mining and Petroleum. The optical properties of determined minerals were done under both Plane Polarized Light (PPL) and under crossed polars (XPL). Petrographic analyses were performed on only 5 fresh rock samples. The aim of this study was to interpret the mineralogical composition of samples collected from the field.

CHAPTER 4. RESULTS AND DISCUSSIONS

4.1. GEOLOGIC MAP OF THE ADIT AND SAMPLES' LOCATION

Below (Fig. 4.1.) is the geologic map of the adit and gullies done from the sampling and descriptions of the laterites. It shows the laterite samples locations (see also Appendix II). A total of 11 samples were collected from different parts of the adits. The sample locations were determined by their distance either from the main entrance of the main adit or from the intersections of a secondary adit and the main adit.

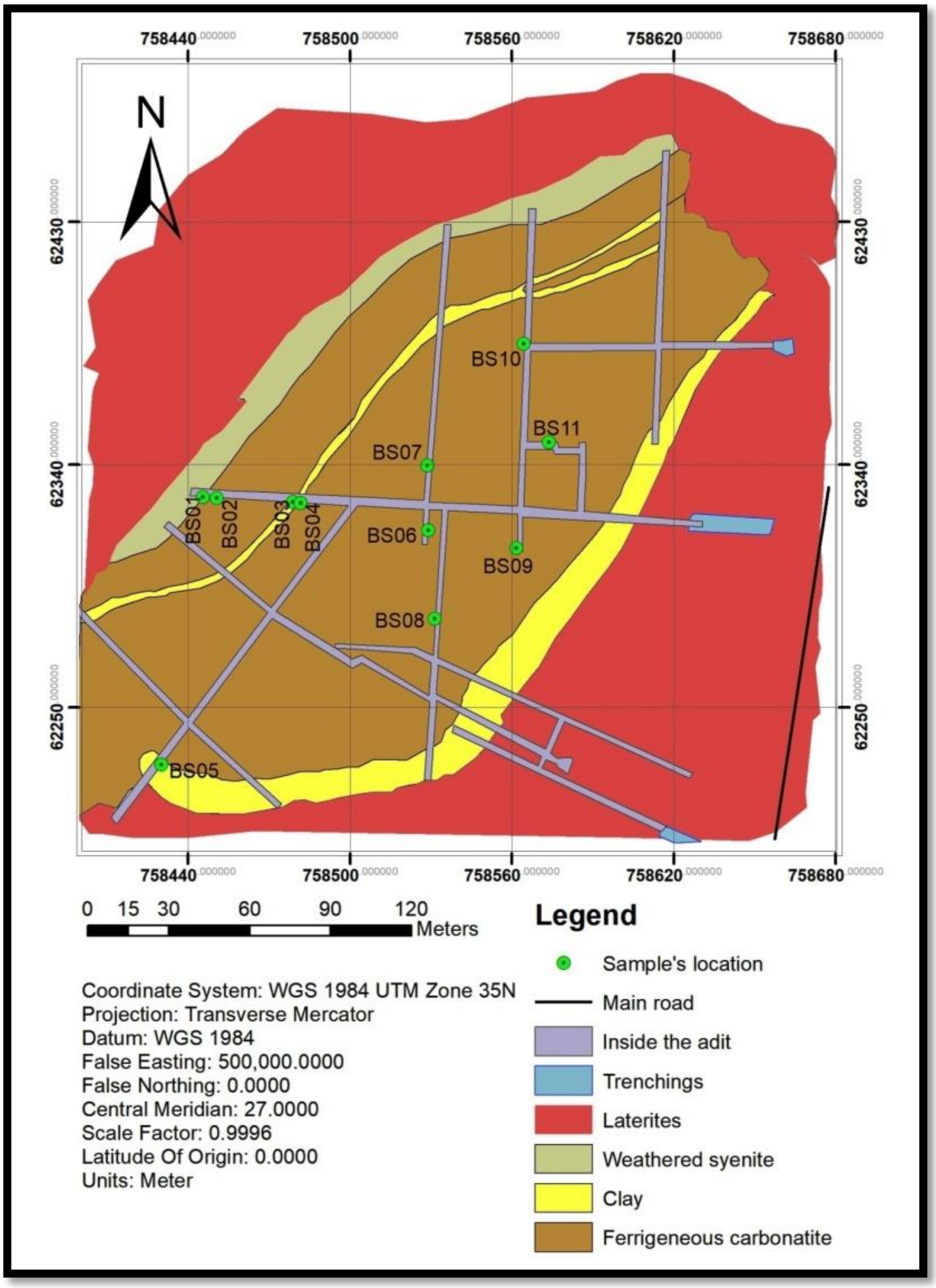


Figure 4-1: Sample location map in relation to the geology and geometry of the adits of Bingo.

4.2. DESCRIPTIONS OF SAMPLES

4.2.1. *Hand specimens from the adits and their wall rock*

Table 4-1: Laterites sample location coordinates and description as collected from the Bingo adits

N°	Sample Code	UTM Eastings	UTM Northings	Colour	Hand specimen description
1	BS01	35N 758445	62328	Brown	Laterite sample with a presence of yellow goethite minerals. It is non-magnetic and non-carbonaceous. The picture is in figure 4-2
2	BS02	35N 758450	62327	Reddish black	This laterite sample has some yellow goethite minerals. It is magnetic. It is non-carbonaceous as it did not react with dilute HCl. (Fig. 4-2)
3	BS03	35N 758478	62326	Grey	Laterite sample grey in colour and very soft. There is a presence of small yellowish goethite grains and reddish magnetite. No reaction with dilute HCl. It is magnetic.
4	BS04	35N 758481	62326	Grey	Black and heavy sample. It is not magnetic, and it is not carbonaceous. Its heaviness and blackness suggested it could be magnetite. (Fig. 4-2)
5	BS05	35N 758430	62229	Black	The sample is black in colour and soft. It has goethite. It is magnetic in some places. It is carbonaceous as it reacted with dilute HCl. (Fig. 4-2)
6	BS06	35N 758528	62316	Grey yellow	This laterite sample has goethite minerals. It is non-carbonaceous.

7	BS07	35N 758528	62340	Dark-orange	This laterite sample is in between yellow and orange with some black grains identified as magnetite.
8	BS08	35N 758531	62283	Dark yellow	This laterite sample is in between black and yellow. It is carbonaceous as it reacted with dilute HCl.
9	BS10	35N 758564	62385	Black	It is non-carbonaceous. It was taken from a weathered rock. (Fig. 4-2)
10	BS11	35N 758573	62348	Dark yellow	The laterite has in some places some white to yellow minerals which are goethite.

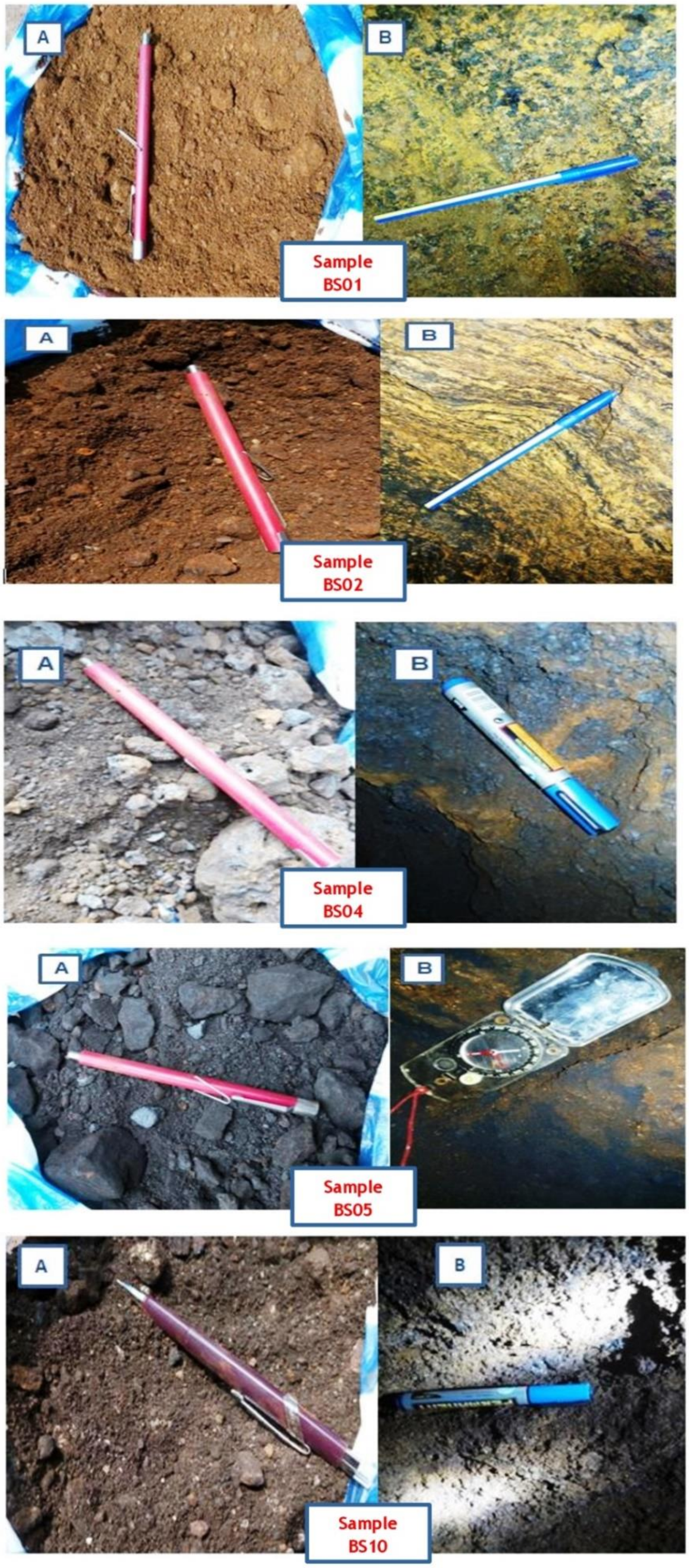


Figure 4-2: Photographs of sample (A) and wall rock (B) for samples BS01, BS02, BS04, BS05, BS10 collected from the adits of Bingo carbonatite laterites.

4.2.2. Description of rocks and outcrops

Table 4-2: Rock sample location coordinates and description as collected from the Bingo study area

N°	Sample Code	UTM Eastings	UTM Northings	Colour	Grains	Outcrop and hand specimen description
1	BS12	35N 757941	62638	Black	No grains	Massive weathered rock with some blackish minerals rich in magnetite. It is non-carbonaceous.
2	BS13	35N 757208	62731	White to grey	Coarse-grained	Some parts are slightly weathered. There is a presence of cracks on the outcrop. Weathered oxidized minerals are hematite and black minerals are magnetite. It has calcite. It is carbonaceous. (Fig. 4-3)
3	BS14	35N 757969	63124	Black	Massive	Black heavy weathered rock sample. Red minerals in the sample are limonite. It has also magnetite and non-carbonaceous.
4	BS15	35N 757394	62946	Grey	Coarse-grained	The sample has ferromagnesian minerals notably amphibole and white minerals are feldspar. There is a slight reaction with HCl in some places of the rock. (Fig. 4-3)
5	BS16	35N 759263	63724	Yellowish-blackish	Fine-grained	The outcrop is surrounded by loose blocks. It has ferromagnesian minerals notably amphibole. The yellow minerals are due to alteration of ferromagnesian minerals and are cancrinite. (Fig. 4-3)
6	BS17	35N 759212	62649	Dark orange	Massive	The outcrop is partially weathered rich in magnetite. The rock sample is magnetic. Yellow minerals are hematite and limonite. The rock is weathered and it is non-carbonaceous.
7	BS18	35N 758605	62361	Black	No grains	Weathered Outcrop is in the slope of Mount Home. The rock sample is

						also weathered and rich in magnetite.
8	BS19	35N 758228	62235	Black	No grains	Black rock rich in magnetite (attraction of the magnetic pen)
9	BS20	35N 75800	62180	Black		Weathered rock sample black in colour with some small and little white minerals.
10	BS21	35N 756174	62112	Grey	Coarse-grained	The outcrop is small on the slope of a mountain. It is fresh and hard to be cut by a hammer. Black minerals are pyroxene and amphibole. White minerals are notably feldspar and quartz. (Fig. 4-3)
11	BS22	35N 756216	62882	Dark green	Fine-grained	Some minor non-penetrative micro-fissures are visible above it. The hand sample is fine-grained rich in ferromagnesian minerals. It has feldspar plagioclase and it is a bit green in colour. It has some biotite and a small amount of quartz. The rock is a granodiorite. (Fig. 4-3)

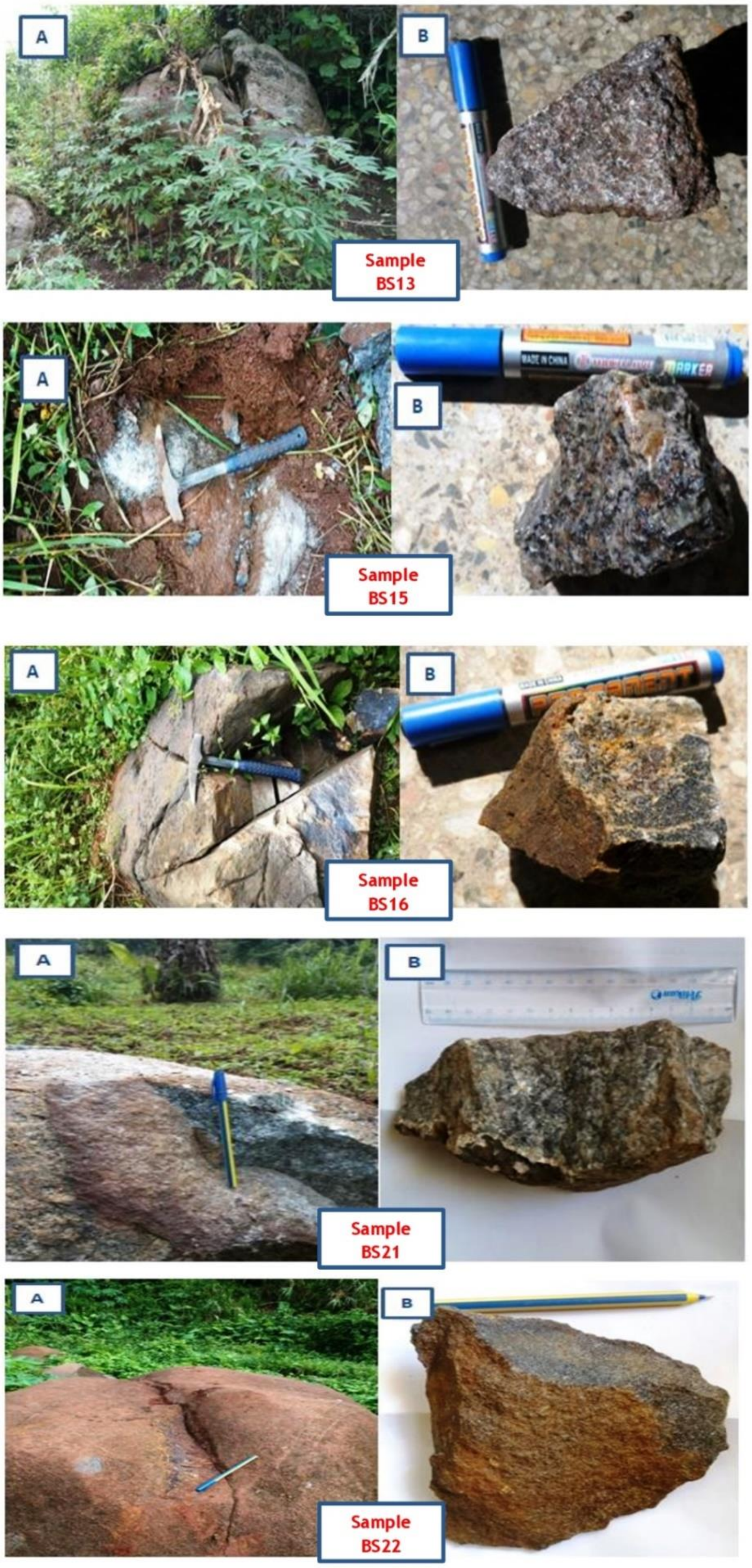


Figure 4-3: Outcrops (A) and hand samples (B) pictures for BS13, BS 15, BS16, BS21, BS22 collected from the Bingo study area.

4.2.3. *Sample grid map of rock samples' locations in the field*

In the grid map below, a total of 20 samples are plotted in their respective locations.

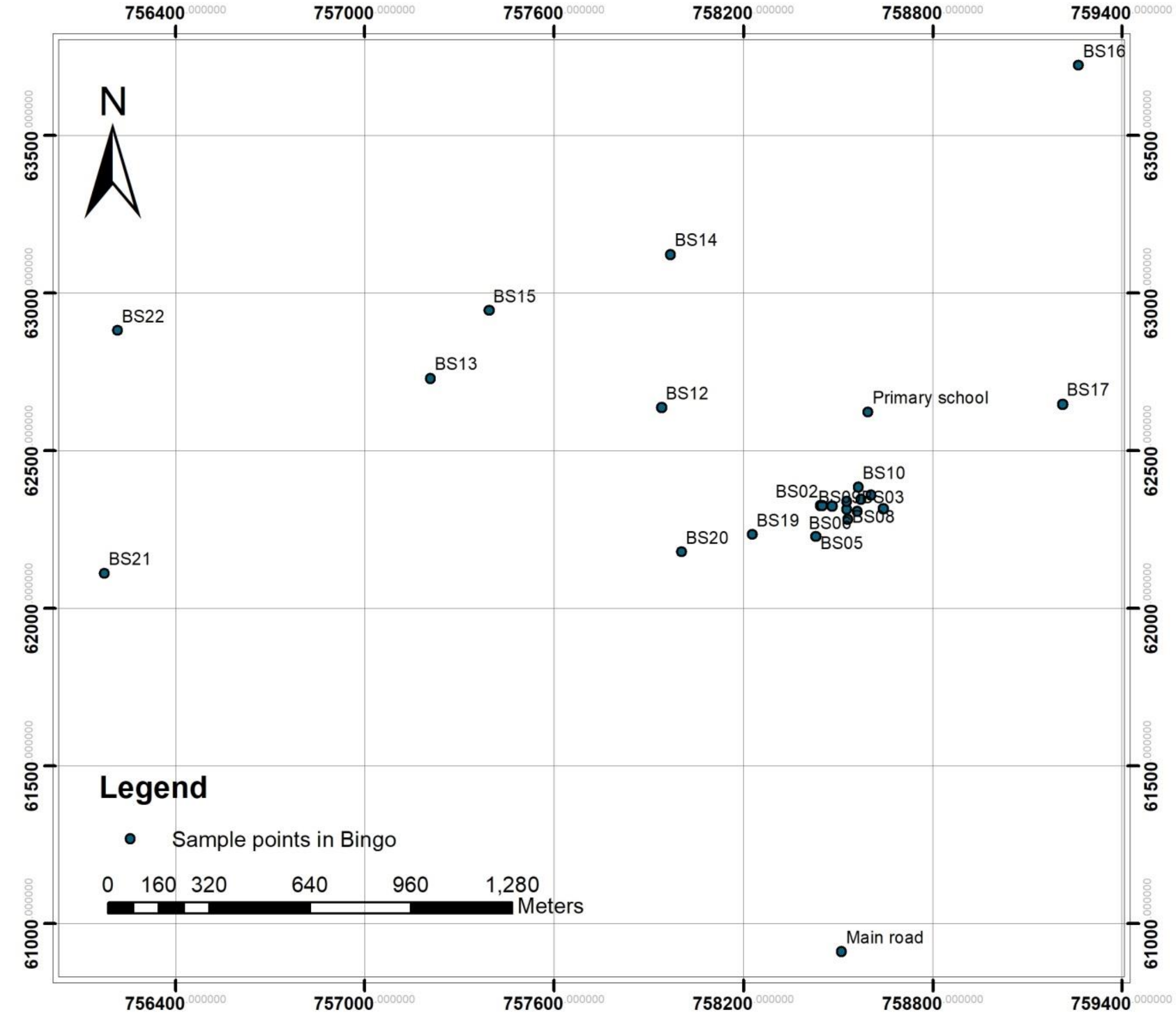


Figure 4-4: Sample location grip map of the study area in Bingo showing the locations from where samples were collected.

4.3. GEOLOGY AND PETROGRAPHIC ANALYSES

This section deals with the microscopy and mineralogy of samples of fresh rocks. The preparation of samples and analyses were done at the Kenyan Ministry of Mining and Petroleum. Thin sections were studied under plane polarized and under crossed polarized light; microphotographs of mineralogical textures (thin sections) were captured using a computer connected to the microscope. X-Ray Diffractometer was used for the mineralogical analysis of samples.

4.3.1. Thin sections and mineralogical analysis

- **Calcite Carbonatite (Sample BS13)**

It is a coarse-grained rock, grey in colour. Under the microscope, the thin section shows the presence of calcite by its rhombohedral cleavage, its very high relief which changes with rotation and its simple twinning. Some parts of the section have spaces of alteration and they are iron oxides for most of them. Some of them are pyrochlore. The opaque minerals which appear black in the section are magnetite. The rock is composed of calcite, with some minor apatite. Apatite is detectable by its low birefringent hexagonal prisms with high relief. Calcite carbonatite is among the widespread rocks in the study area.

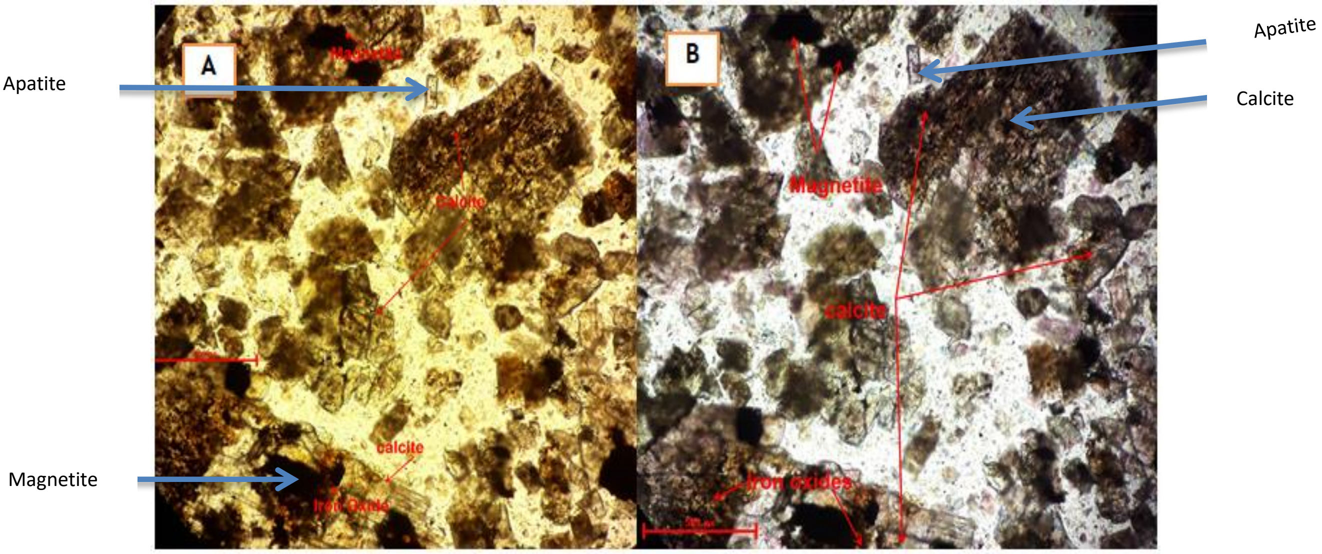


Figure 4-5: Microphotographs of sample BS13 thin sections under PPL (A) and under XPL (B) showing calcite, apatite and magnetite (Magnification x40).

Mineralogy

The mineralogy as given by XRD (in table 4-3) shows that the rock sample is very rich in carbonate minerals with calcite and dolomite more than 63 vol.-%. Other minerals including Trembathite (10.9) and billingsleyite (16.3) account for 27.2 vol.-%. Trembathite is an evaporate mineral of the boracite or borate group classified in the tektoborates group. Billingsleyite is a sulfide mineral which occurred in a high-grade silver ore. https://www.mindat.org/min-675.html

Table 4-3: Mineralogical composition of sample BS13 from XRD analysis.

Mineral		**Chemical formula**	**Vol. %**
Carlinite		Tl_2S	1.9
Carbonate minerals	Calcite	$CaCO_3$	39.7
	Dolomite	$CaMg(CO_3)_2$	24.1
Ikunolite		Bi_4S_3	5.2
Trembathite		$(Mg,Fe)_3B_7O_{13}C$	10.9
Cobaltite		CoAsS	1.9
Billingsleyite		Ag_7AsS_6	16.3
Total		-	**100**

Figures 4-6 and 4-7 show the X-ray diffraction pattern as recorded by the XRD machine. The spectra show exactly minerals and their abundance in the carbonatite rock sample.

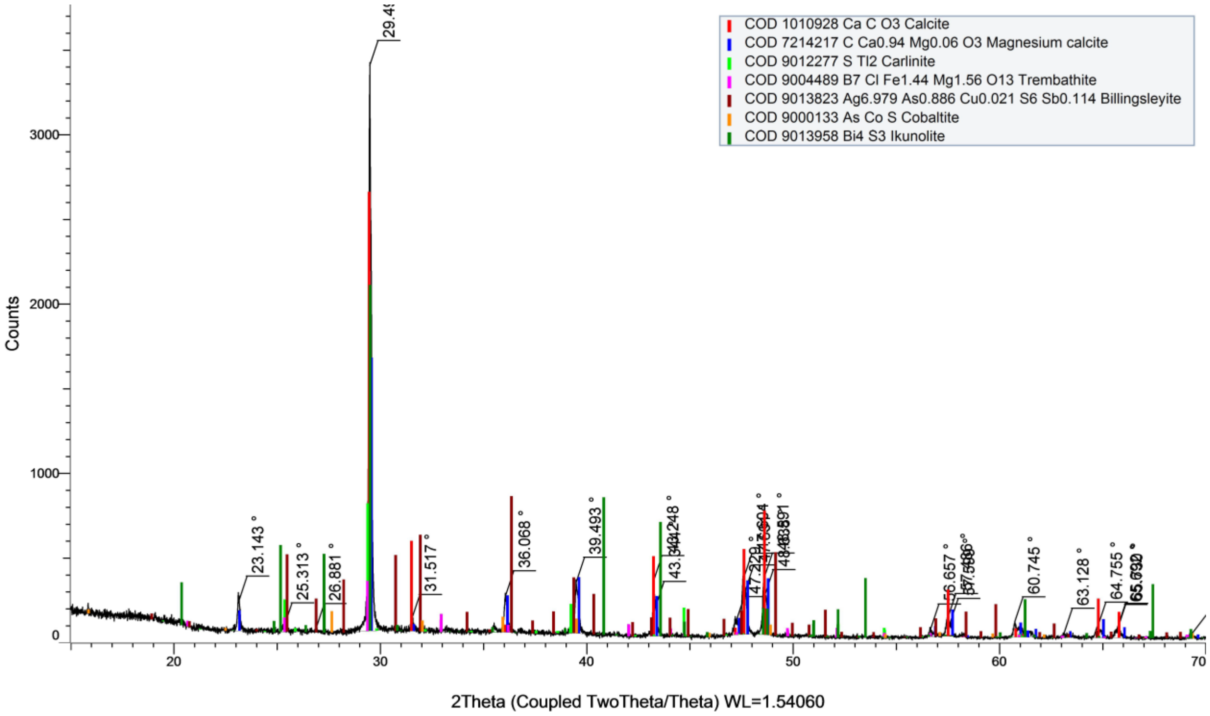


Figure 4-6: X-Ray diffraction pattern sample BS16 showing the presence of calcite, dolomite, carlinite, trembathite, cobaltite and billingsleyite.

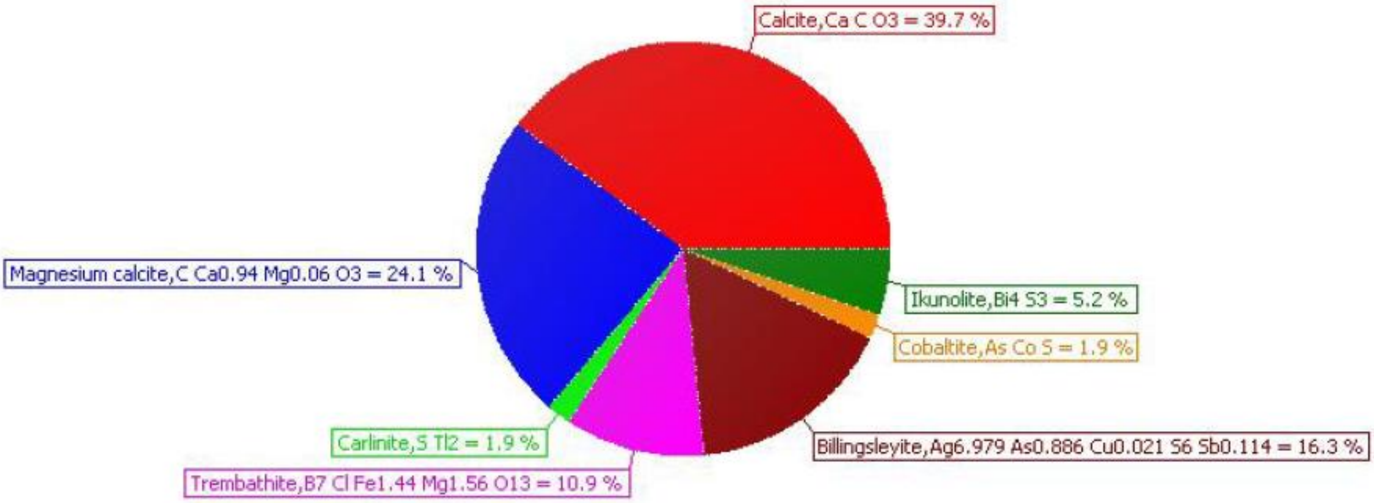


Figure 4-7: Distribution diagram showing the percentage of each mineral in the sample BS13.

- **Fenites (Sample BS16)**

It is a coarse-grained, light–grey rock sample. Under the microscope, the section shows twinning muscovite and quartz.

Magnetite and pleochroic biotite are visible. The plagioclases are seen by their cleavage. The change in colour from pink to green and the twinning of the minerals suggest the presence of Muscovite because of its optic characteristic of birefringence. Some pleochroic biotite and plagioclase are visible. In the end, the thin section of the rock is named a fenite.

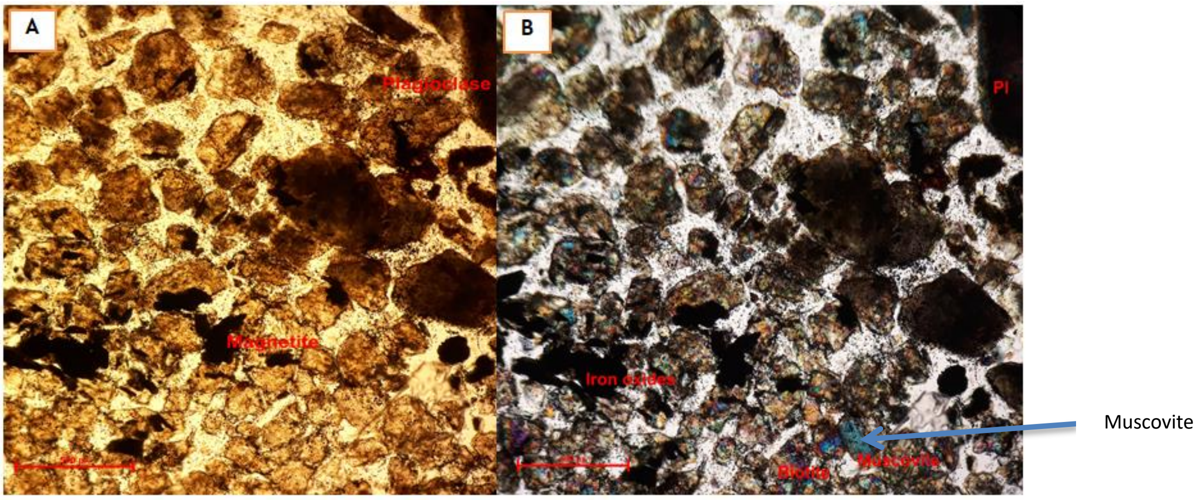


Figure 4-8: Microphotograph of fenites as taken under PPL (A) and under XPL (B) showing muscovite, biotite, magnetite and plagioclase (Magnification x40).

Mineralogy

The mineralogical composition as shown in table 4-4, the rock sample has a high concentration of alkali feldspar (microcline, orthoclase and sanidine) and a number of plagioclases (albite). Alkali feldspars account for 87.7 vol.-%, and plagioclases account for 11.8 vol.-%.

Considering the hand sample description, petrographic studies and the mineralogical composition, the rock is a fenite.

Table 4-4: Mineralogical composition of sample BS16 from XRD analysis.

Mineral		**Chemical formula**	**Vol. %**
Alkali feldspars	Microcline	$K(AlSi_3O_8)$	43.8
	Orthoclase		31.2
	Sanidine-high		12.7
Plagioclases (Albite)		$NaAlSi_3O_8$	11.4
Montbrayite		$(Au,Sb)_2Te_3$	0.9
Total		**-**	**100**

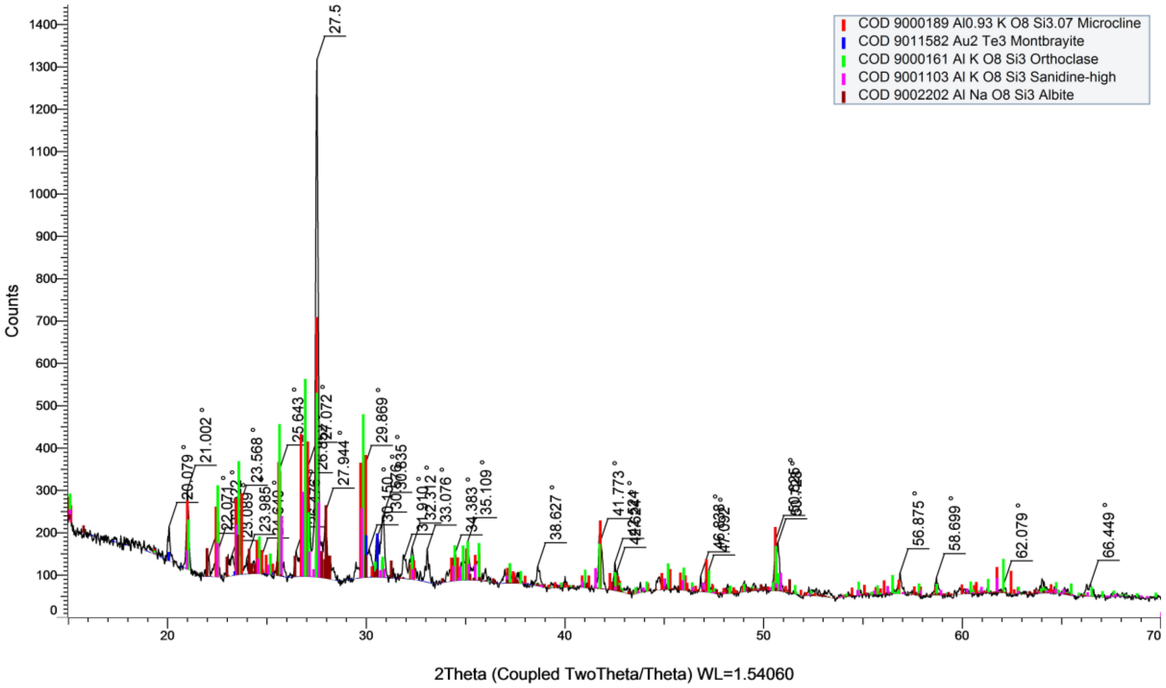


Figure 4-9: X-ray diffraction pattern showing microcline, sanidine, orthoclase and albite in sample BS16.

- **Fenites (Sample BS21)**

This rock is coarse-grained and grey in colours with some black spaces occupied by magnetite. Under the microscope, the section shows the presence of biotite which is pleochroic and variably brown or green in colour. The change in colour goes from brown to black pleochroic haloes. The change in absorption colour is clearly seen and the parallel cleavage is noticeable. The photograph (Fig. 4-10 A) was taken under plane polarized light. Other minerals are ferromagnesian and especially olivine. Under crossed polars, the photograph (Fig. 4-10 B) shows exactly the green ferromagnesian minerals of olivine and dark brown biotite. Some other green minerals in some small spaces are chlorite which is a weathering product of biotite. The rock is a fenite.

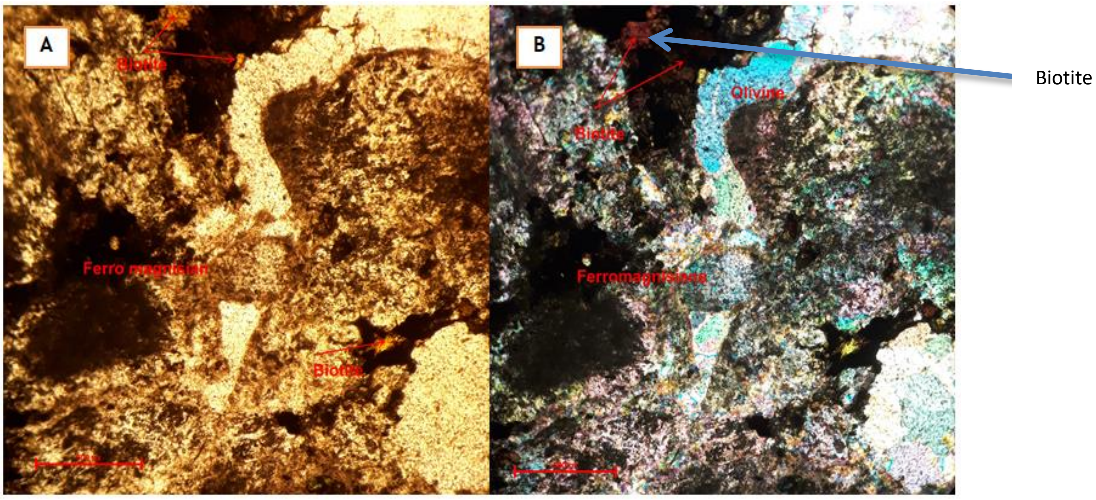


Figure 4-10: Microphotographs of fenite thin sections under PPL (A) and XPL (B) showing biotite (Magnification x40).

Mineralogy

The mineralogical composition (table 4-5) has given a concentration of quartz with 13.4 vol.-%, of albite (Alkali feldspar) 44.4 vol.-%, as major minerals. Berlinite is an aluminium phosphate and accounts for 12.2 vol.-%. Canfieldite is a rare silver tin mineral which in polymetallic veins formed very late in the paragenetic sequence; it accounts for 10. Lanarkite which represents 3.1 vol.-% is a sulfate mineral consisting of lead. Another lead mineral in the list (in table 4-5) is damaraite which accounts for 2.7 vol.-% in the sample. Morenosite is a sulfate mineral containing nickel and accounts for 4.9 vol.-% in the sample. Columbite is one of the minerals with less content of 1.9 vol.-%.

Table 4-5: Mineralogical composition of Sample BS21 from XRD analysis.

Mineral	Chemical formula	Vol. %
Lanarkite	$Pb_2(SO_4)O$	3.1
Quartz	SiO_2	13.4
Morenosite	$NiSO_4.7H_2O$	4.9
Columbite	$(Fe,Mn)Nb_2O_6$	1.9
Damaraite	$Pb_3Cl(OH)O_2$	2.7
Proudite	$CuPb_7.5Bi_9.33(S,Se)_{22}$	1.3
Fornacite	$Pb_2Cu(CrO_4)(AsO_4)(OH)$	6.2
Plagioclases (Albite)	$NaAlSi_3O_8$	44.4
Canfieldite	Ag_8SnS_6	10.0
Berlinite	$AlPO_4$	12.2
Total	**-**	**100%**

The X-ray diffractometer patterns for this sample are in Appendix VII of this work.

- **Plagioclase granodiorite (Sample BS22)**

The rock is medium to coarse-grained containing mostly plagioclase feldspar and biotite. Under the microscope, the thin section shows quartz phenocrysts along with some plagioclases in the matrix of the rock. The colour of the rock suggests it is rich in mafic minerals (amphibole and hornblende). Biotite can easily be seen and the presence of ferromagnesian minerals is denoted by the presence of pleochroic minerals (which change their colours from different angles). The green minerals are chlorite which is actually a weathering product of biotite. Some plagioclases are detected through their cleavage of about 90°.

Under crossed polars, plagioclases are pleochroic from green to purple. They appear like separated lines. The opaque minerals are iron oxides and especially magnetite as the hand sample was magnetic when tying a magnetic pen on some blackish part of the rock. But some parts of the thin sections were darker than other suggesting that the thin section was a bit too thick. Quartz is detectable by its low relief and low birefringence.

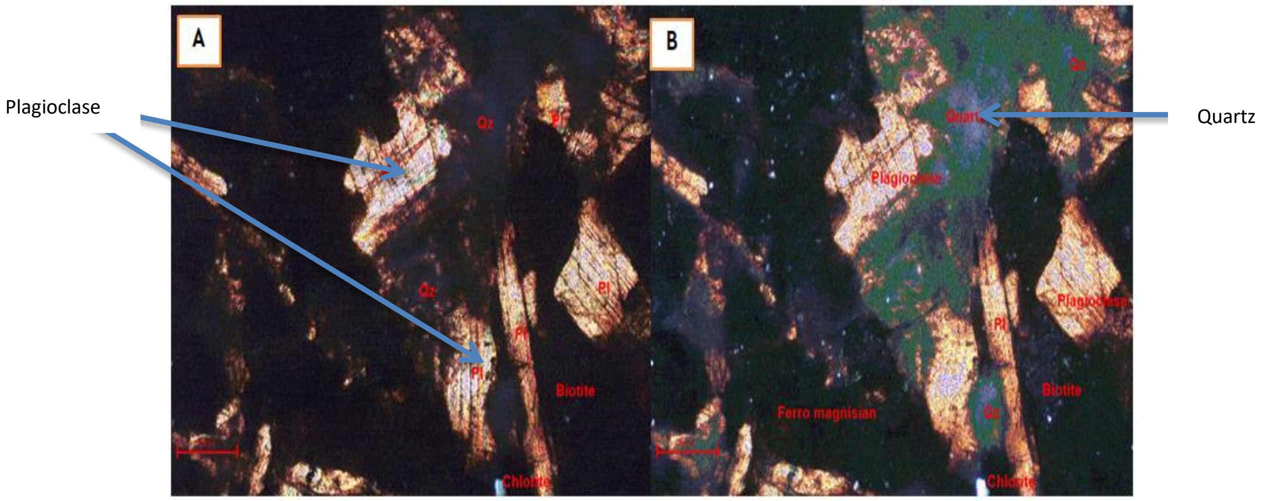


Figure 4-11: Plagioclase granodiorite thin section under PPL (A) and under XPL (B) showing plagioclases and quartz(Magnification x40).

Mineralogy

From the XRD results, the mineralogical composition of the rock is given in table 4-6. The plagioclases (albite) account for 63 vol.-%, more than the half of the composition. Polyhalite which is a magnesium, calcium and potassium sulfate mineral accounts for 22.9 vol.%, it is a unique salt mineral which can be used as a fertilizer and it has other potential uses for industry. Polyhalite is not mentioned in other previous works. The rock has a little composition of quartz (5.5%). Berlinite, which accounts for 3.8 vol.-% is a rare high hydrothermal or metasomatic phosphate mineral. Vasilyevite (accounting for 4.4 vol.-%) is a triclinic carbonate pinacoidal mineral that contains bromine, chlorine, iodine, mercury and sulfur.

Table 4-6: Mineralogical composition of sample BS22 from XRD analysis.

Mineral	**Chemical formula**	**Vol. %**
Quartz	SiO_2	5.5
Polyhalite	$K_2Ca_2Mg(SO_4)_4.2H_2O$	22.9
Vasilyevite	$(Hg_2)^{2+}{}_{10}I_3Br_2Cl(CO3)O6$	4.4
Phosphates (Berlinite)	$AlPO_4$	3.8
Plagioclases (Albite)	$NaAlSi_3O_8$	63.5
Total	**-**	**100.1**

The X-ray diffraction pattern is shown in Fig. 4-12. From this mineralogical analysis, the results indicate that the plagioclase feldspars are abundant by the presence of albite. Other minerals are minor in terms of their concentrations. Polyhalite is also one of the minerals which are in this rock sample.

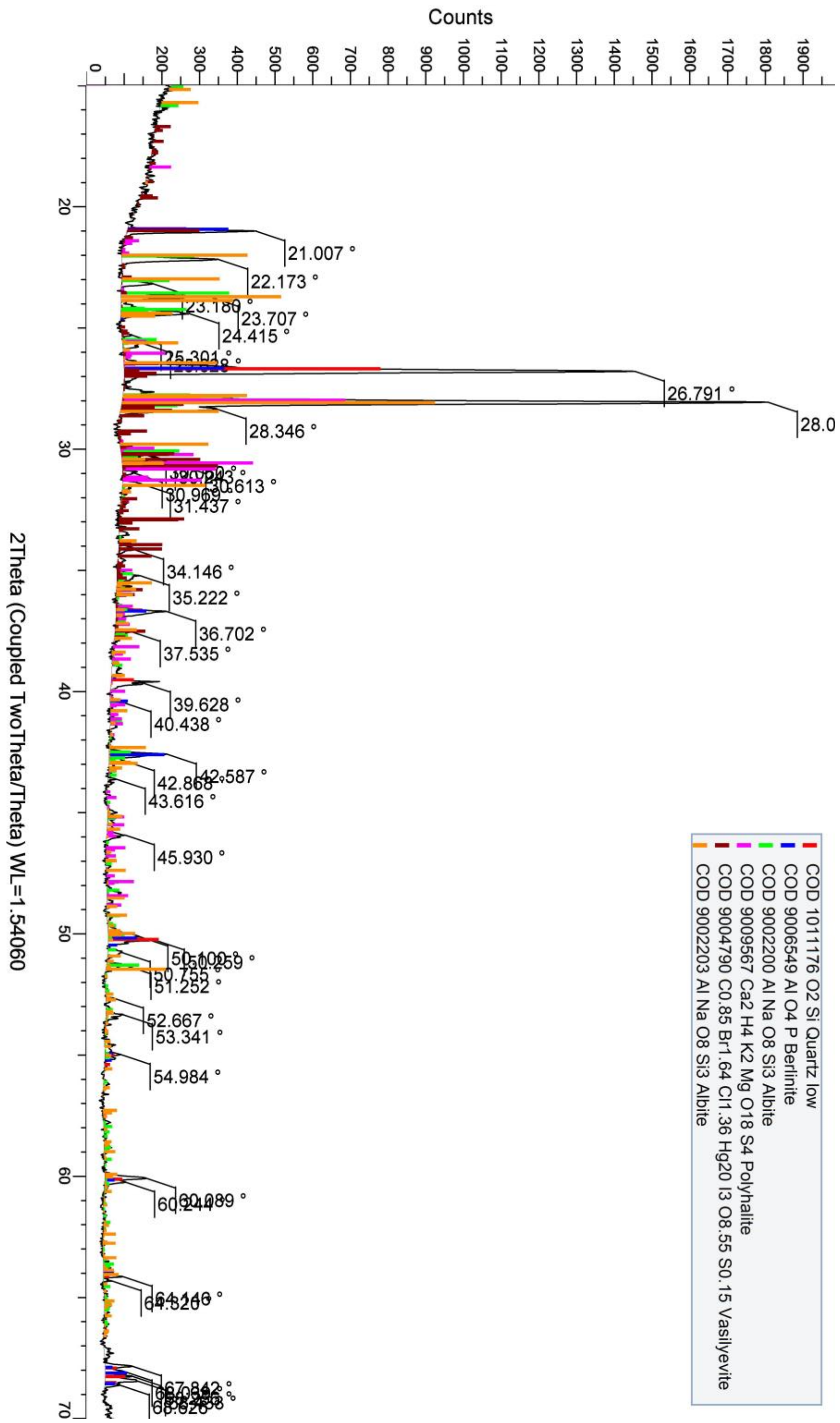


Figure 4-12: X-ray diffraction pattern showing Quartz, Berlinite, Albite, Vasilyevite in sample BS22.

4.3.2. *Geologic map of Bingo*

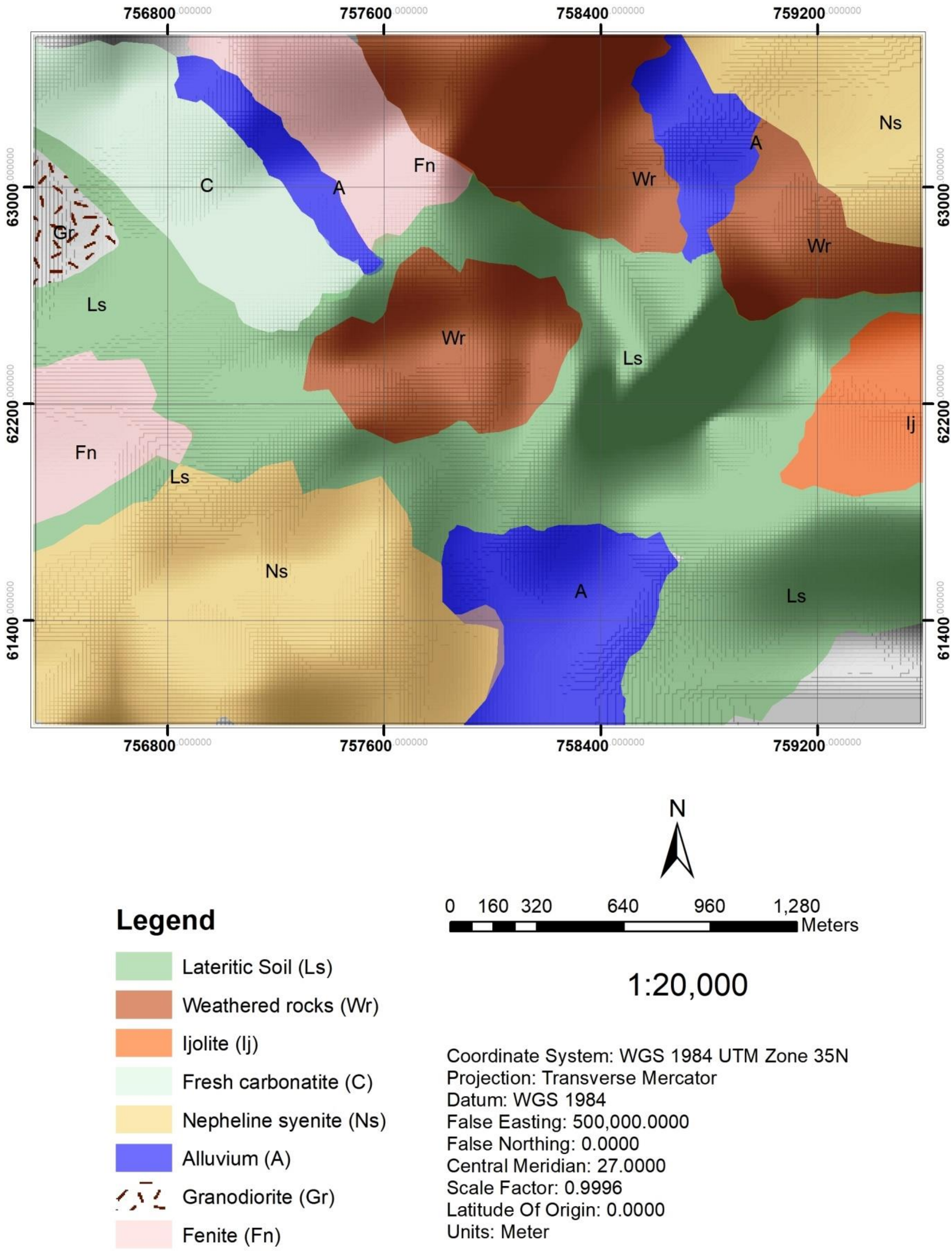


Figure 4-13: Geologic map of the study area including the Bingo carbonatite and its surrounding geologic formations.

4.3.3. Discussion on petrography and mineralogy of laterites and rocks

Mineralogical aspect

The mineralogical analysis of rocks has given a broad range of minerals. In the carbonatite samples, calcite is by far the mineral which is high in concentration. It is followed by plagioclases (feldspar plagioclases) and other accessory minerals including mica, microcline, orthoclase, quartz. X-ray diffraction patterns for rock samples are in the Appendix list.

By the way, the mineralogical analysis of some selected samples of laterites gave some impressive results and they allowed finding out a very rare mineral called carletonite which had never been reported in the Bingo complex. Some other results from this analysis revealed some other common minerals such as ringwoodite, goethite and skinnerite. The XRD patterns of the laterites samples are found in Appendix V, VI and VII. In this discussion, minerals of high concentrations and new aspect will be reviewed.

Carletonite ($KNa_4Ca_4Si_8O_{18}(CO_3)_4$ (F,OH).H_2O)

XRD results (Fig. 4-14) on one the ground laterite sample (BS04) indicate the presence of a very rare mineral which is called carletonite. This mineral was not yet discovered by any work in the Bingo laterite. In the X-ray diffraction pattern shows a great intensity in the sample. Carletonite is a mineral found in the nepheline syenite and is associated with some other minerals like calcite, apophyllite, fluorite and pectolite. It belongs to the phyllosilicates group of silicates. It is a very rare mineral and it is only known to occur in its type locality in the Poudrette quarry, Mont Saint-Hilaire in Canada (Chao, 1971; Frost *et al.*, 2013). Carletonite is one of the big discoveries found from the mineralogical analysis of this work done in Bingo. It can be used as a mineral specimen and sometimes as a gem.

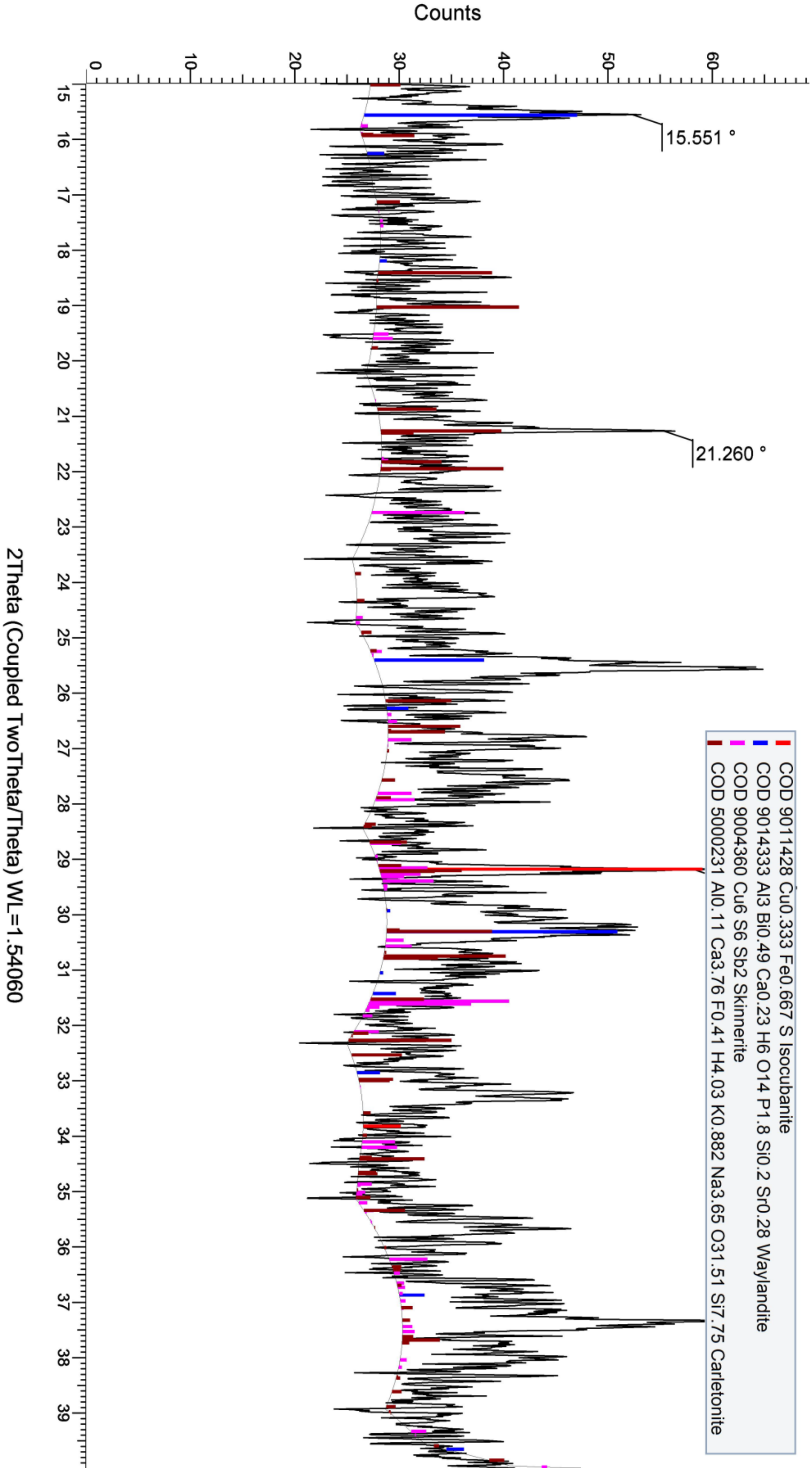


Figure 4-14 : X-ray diffraction patterns of sample BS04 in showing the predominance of carletonite with skinnerite, isocubanite and waylendite.

Polyhalite $K_2Ca_2Mg(SO_4)_4 \cdot 2H_2O$

This mineral is concentrated at a level of 22.9 vol.-% in sample BS22. It is a unique salt mineral which is mainly used as a fertilizer. It is composed of Ca, Mg, and K phosphates. This is the first time this mineral has been reported from Bingo carbonatite complex.

Calcite and dolomite

Calcite is one of the major minerals of the carbonatite of Bingo. According to the X-ray diffractometer patterns (Fig. 4-6, 4-7), it is sometimes and in some areas associated with dolomite. But as the carbonatite sample reacted to dilute HCl, it is concluded that the sample BS13 was calcite carbonatite.

From XRD results of the calcite carbonatite, calcite and dolomite account for almost 60 vol.-% of the mineralogical composition of this rock, the two accounting respectively for 39.7 and 24.1 vol.-%. This carbonatite is rich in sulfide minerals such as ikunolite, cobaltite, carlinite and billingsyelite. During their work Woolley *et al.* (1995) found also calcite among the minerals of the Bingo complex and other accessory minerals including micas.

Petrographical thin sections

The petrographic analysis of 5 samples (BS13, BS15, BS16, BS21 and BS22) was performed at the Kenyan Ministry of Mining and Petroleum. The study revealed that Bingo has a variety of not only alkaline rocks but also intermediate rocks. According to Woolley *et al.* (1995), alkaline rocks are calcite carbonatite, nepheline syenite, ijolite, trachyte and fenite. Apart from these rocks, it was found through this work that there is a presence of plagioclase granodiorite which is located a bit far behind Mount Home. It is medium to fine-grained and it does not seem to be related to the Bingo complex. The majority of outcrops in the study area are either partially weathered or totally weathered due the intense rain and the thick residual soil which develops above them.

Calcite Carbonatite: the outcrop of fresh carbonatite is found at the Northern part of Mount Home around the flank. This outcrop is coarse-grained and contains, apart from calcite, micas, aegirine and magnetite.

Plagioclase granodiorite: this rock is fine-grained and its outcrops are found behind the Mount Home summit in the valley. Its presence is hard to be examined as it is not associated with other rocks of the area and its aspect is a bit different. The presence of this silicate rock can be interpreted as being crystallized from the magma which produced the carbonatite intrusion. It could also be part of what was earlier mentioned as a country rock by Woolley *et al.* (1995).

Nepheline syenite – ijolite: these rocks are located at the NE side of the Bingo carbonatite complex. They are fine-grained and they are composed of microcline 43.8 %, orthoclase 31.2 %, sanidine-high 12.7 % and albite 11.4 vol.-%.

Fenites: among the thin sections, two are fenites. These fenites were identified respectively in the South Western and North Western sides of the carbonatite complex, and the other one at the mount Home summit. When doing the geologic map, it was estimated that these 2 fenite outcrops were correlated.

4.2. GEOCHEMICAL ANALYSES

4.2.1. Introduction

This section describes and interprets the geochemistry of laterites, partially weathered and fresh rocks collected from the study area. The purpose was to figure out the degree of enrichment and concentration of elements in these geologic formations in order to determine the mineral potential of the Bingo carbonatites and the surrounding areas on one hand and to confirm the names given to rocks during the hand sample description and the petrographic analysis on the other hand. The Harker's diagrams study allowed highlighting of the nature of the carbonatite and finding correlations between elements.

The geochemical diagrams and graphs were plotted using Winrock, Petrograph 2 beta and Microsoft Excel. The geochemical map of elemental concentrations in the field was done using Oasis Montaj.

4.2.2. Major and Trace elements analysis.

Major and trace elements were analyzed using X-Ray Fluorescence method at the Kenyan Ministry of Mining and Petroleum. The elements analyzed included major elements, trace elements and some rare earth elements. The results are presented in Tables 4-7 and 4-8. The major elements are given in weight percent. Some elements were not determined in some samples by this method due to the limitations of the XRF equipment. These elements were sodium and magnesium; this necessitated the carrying out of analysis for these elements using the Atomic Absorption Spectrometry (AAS) method at the departments of Geology and Soil Sciences of the University of Nairobi.

Table 4-7: Chemical analysis of sample BS01 to BS12 from the Bingo area. Analysis was done using XRF and AAS methods. Major Elements in weight percent and trace elements in parts per millions (ppm)

	BS01	**BS02**	**BS04**	**BS05**	**BS06**	**BS07**	**BS08**	**BS10**	**BS11**	**BS12**
SiO_2	4.921	1.086	2.089	1.623	4.021	3.969	3.073	4.871	4.636	6.01
Al_2O_3	7.85	8.161	8.64	11.449	9.668	10.641	7.582	15.91	15.658	11.952
CaO	0.399	0.462	0.606	0.682	0.36	0.512	0.337	1.448	0.743	0.159
MgO	2.6	0.207	4.311	0.622	0.406	3.97	5.8	4.46	5.14	4.477
Na_2O	1.045	4.38	10.48	4.043	2.022	1.078	1.955	1.011	3.067	1.382
K_2O	1.927	0.133	3.352	1.205	0.241	2.409	4.337	4.698	4.096	3.372
TiO_2	5.936	6.47	8.033	3.86	2.603	2.989	2.919	2.687	1.069	2.174
MnO	0.635	11.475	39.289	20.729	10.94	2.785	5.011	8.682	4.302	20.387
FeO_{tot}	70.902	58.872	13.819	36.791	56.091	63.845	59.773	39.991	40.66	47.933
P_2O_5	5.352	8.684	8.908	10.254	8.649	8.036	7.155	14.956	14.923	2.206
Total	101.567	99.93	99.527	91.258	95.001	100.234	97.942	98.714	94.294	100.052
Trace elements in ppm										
Rb	210	90	-	-	-	40	-	100	-	-
Sr	3130	5530	6120	14820	3320	7030	3190	24600	7760	3590
Y	420	550	630	1970	260	830	370	1480	330	520
Zr	2000	2880	1510	2490	1960	2610	2190	4760	2060	560
Nb	7390	12200	27880	11020	32340	23740	34130	21610	29670	3550
Ba	16350	45290	135740	93430	2320	7930	4400	19880	1720	62060
Ce	-	-	-	-	41500	290	41330	1800	83230	-
La	-	2010	-	8410	270	7240	340	17470	1720	3670
Th	360	940	2180	1820	3890	2440	3130	3270	4020	1140
Sn	390	340	1290	780	870	1220	130	-	1100	-

Table 4-8: Chemical analysis of sample BS13 to BS22 from the Bingo area. Analysis was done using XRF and AAS methods. Major Elements in weight percent and trace elements in parts per millions (ppm)

	BS13	**BS14**	**BS15**	**BS16**	**BS17**	**BS18**	**BS19**	**BS20**	**BS21**	**BS22**
SiO_2	1.261	4.006	61.497	63.147	1.565	3.941	0.404	0.191	53.456	73.636
Al_2O_3	2.295	13.96	20.1	15.529	3.802	13.415	7.159	4.024	16.078	15.645
CaO	49.171	0.439	2.118	2.522	0.203	0.758	1.493	0.323	6.291	1.688
MgO	1.16	1.24	0.547	0.688	1.086	1.07	0.912	1.277	8.371	0.764
Na_2O	9.098	7.132	9.435	2.426	4.651	6.268	7.077	11.513	1.509	3.706
K2O	2.46	4.21	4.336	8.43	1.5	2.28	2.48	4.57	0.544	1.69
TiO2	0.151	2.153	0.468	0.627	8.649	2.192	0.469	3.163	0.73	0.229
MnO	2.384	11.728	0.13	0.072	0.605	6.301	17.748	10.873	0.158	0.039
FeO_{tot}	6.872	47.596	1.324	3.588	73.81	49.356	43.483	58.548	8.96	2.057
P_2O_5	0.462	8.411	0.08	2.172	3.314	11.211	18.685	5.392	0.175	0.125
Total	75.314	100.875	100.035	99.201	99.185	96.792	99.91	99.874	96.272	99.579
Trace elements in ppm										
Rb	-	40	150	390	150	-	30	80	30	50
Sr	13620	7630	2360	1190	1830	7600	29380	1770	220	920
Y	140	1170	30	20	110	1130	19920	700	40	-
Zr	1500	1000	560	390	800	3860	2970	240	-	190
Nb	1630	19750	970	150	11280	24320	23990	24670	-	-
Ba	2280	22410	4330	4110	6360	8690	64700	26960	-	680
Ce	-	46910	-	-	-	56890	143900	5910	-	-
La	-	6310	-	-	-	1800	76300	3170	-	-
Th	-	910	-	-	1300	3740	1180	1270	-	-
Sn	-	290	-	100	680	360	860	110	-	100

4.2.3. Major elements Presentation

Major and trace elements concentrations of samples collected from the study area are shown in table 4.7 and 4.8 of this section. The laterites samples are from BS01 to BS11 and the rock samples are from BS12 to BS22. The results show that most of the samples have a wide range of composition and are rich in iron (FeO) and (MnO). Their concentrations are relatively high, giving values of up to 70 and an average of 39 wt.-% for FeO, and up to 39 and an average of 8 wt.-% for MnO. The highest concentrations are mostly observed in laterite samples. Phosphate oxides (P_2O_5) are also enriched in weathered and laterite samples (maximum of 18.68 and average of 6 wt.-%). However, the fresh rock samples tend to be enriched in SiO_2 with the highest concentration being 73 wt.-%. The only fresh carbonatite sample has the highest CaO concentration value of 49 wt.-%.

4.2.4. Correlation Matrix for major elements

The Pearson correlation coefficients were used to test the dependence between major oxides. The results were plotted using petrograph beta2 and MS Excel. The Pearson correlation matrix (table 4-9) is important as it gives the strength of correlation between elements. From this matrix, a positive correlation between two oxides means their mode of delivery into the study area is similar.

Table 4-9: The Pearson Correlation matrix for major elements oxides

	SiO_2	Al_2O_3	CaO	MgO	Na_2O	K_2O	TiO_2	MnO	FeO tot	P_2O_5
SiO_2	1									
Al_2O_3	0.662	1								
CaO	-0.055	-0.34	1							
MgO	-0.32	0.062	-0.144	1						
Na2O	-0.137	-0.227	0.169	-0.275	1					
K2O	0.249	0.287	-0.054	0.326	0.188	1				
TiO2	-0.481	-0.473	-0.306	0.103	0.092	-0.3	1			
MnO	-0.403	-0.152	-0.216	0.254	0.399	-0.0007	0.442	1		
FeO tot	-0.68	-0.484	-0.375	0.201	-0.135	-0.247	0.572	-0.01	1	
P_2O_5	-0.592	-0.08	-0.323	0.347	-0.021	-0.023	0.098	0.311	0.271	1

In the Harker diagrams presented in fig. 4-15, oxides (P_2O_5, FeO_{tot}, MnO, TiO_2, K_2O, Na_2O, MgO, CaO) are correlated against SiO_2.

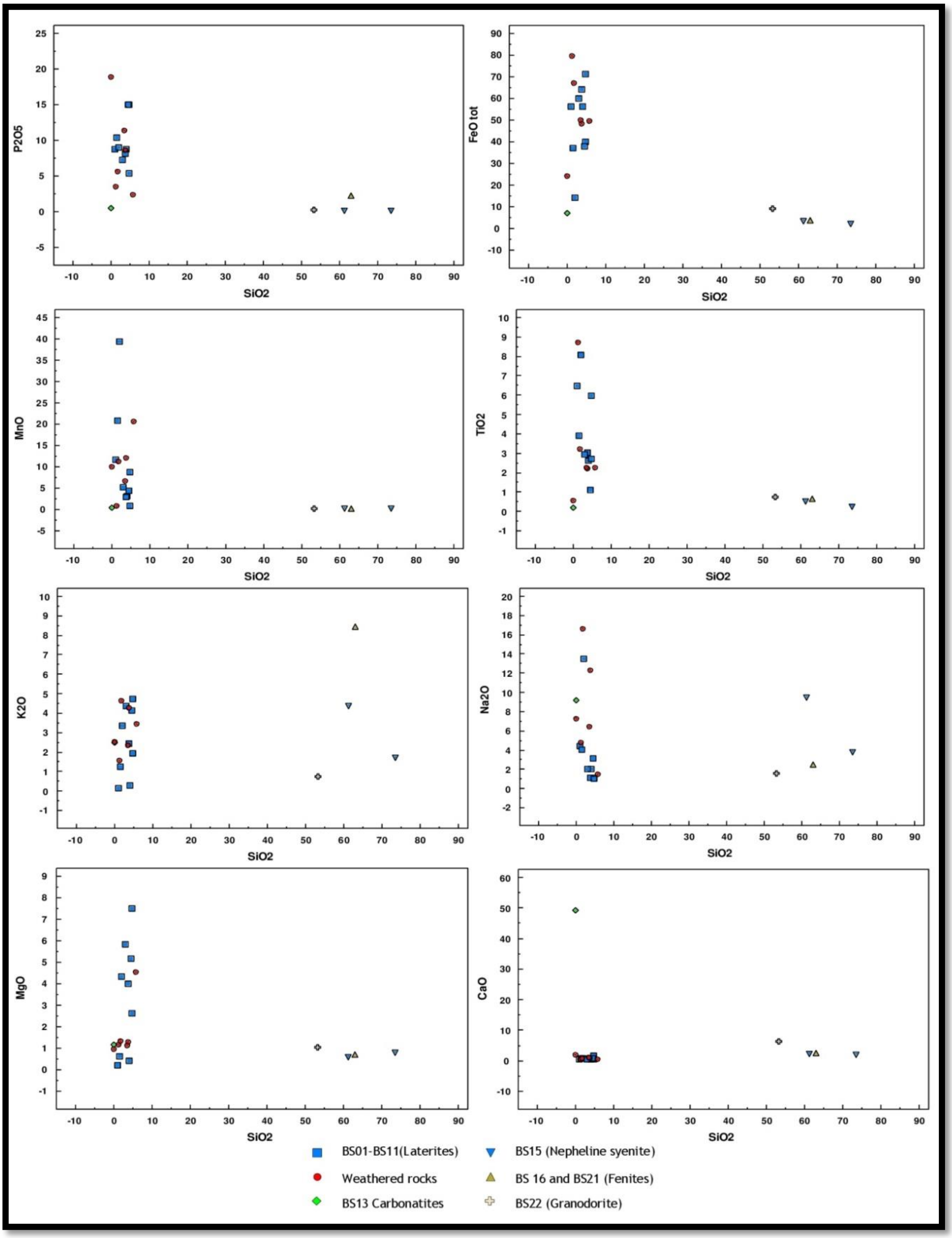


Figure 4-15: Harker variation diagrams for major elements of laterites, carbonatite and associated rocks of Bingo showing correlations between elements.

From these diagrams (Fig. 4-15), it is noted that SiO_2 correlates negatively with FeO_{tot}, MnO, MgO, CaO and TiO_2 which means that their delivery mode in the Bingo study area is not similar. And this fact is true because the content of SiO_2 is very low when the contents of those oxides go higher (Table 4-7, Table 4-8). The positive correlation between SiO_2 and Al_2O_3 means the two are delivered in similar ways in the Bingo study area.

4.2.5. Rock Classification Diagrams

The purpose of studying these major elements was to find out the rock name and their chemical classification. Some classification diagrams were used for the purpose of deciphering and checking the names which were given to the rocks during the Petrographical and mineralogical analyses.

The Total Alkali-Silica (Fig. 4-16) was made using the Petrograph software. In this diagram, 4 rocks which had a composition of SiO_2 above 50% (Sample BS15, BS16, BS21 and BS22) were plotted. From the previous results and descriptions, it is shown that samples BS16 and BS21 were fenite with one plotting in granite field and another in syenite field. Furthermore, the carbonatite and laterite samples which had low concentrations of silica were not plotted either. Sample BS22 plotted in the quartz diorite (granodiorite) area and it confirmed the findings of the Petrographical and mineralogical studies. Sample BS15 plotted in the nepheline syenite area (Fig. 4-16) and again this confirmed the petrographical studies.

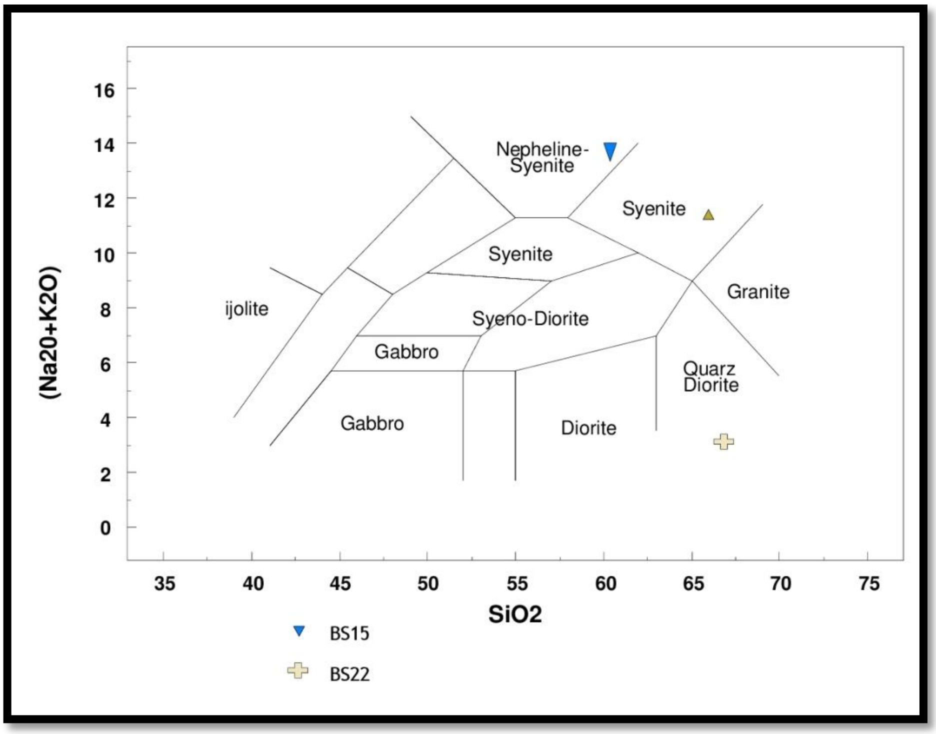


Figure 4-16: Representative samples from Bingo area plotted on the (Na_2O+K_2O) vs. SiO_2 chemical classification and nomenclature diagram (after Cox et al., 1979).

In TAS-Plutonic diagram (Middlemost, 1994) (Fig. 4-17), plutonic rocks are samples BS15 and BS22. Sample BS15 plotted in the Alkali Feldspar Syenite field and sample BS22 plotted in the granodiorite field. The two names confirmed very well the results of petrography and mineralogy. Again samples BS16 and BS21 were not well plotted as they are fenites.

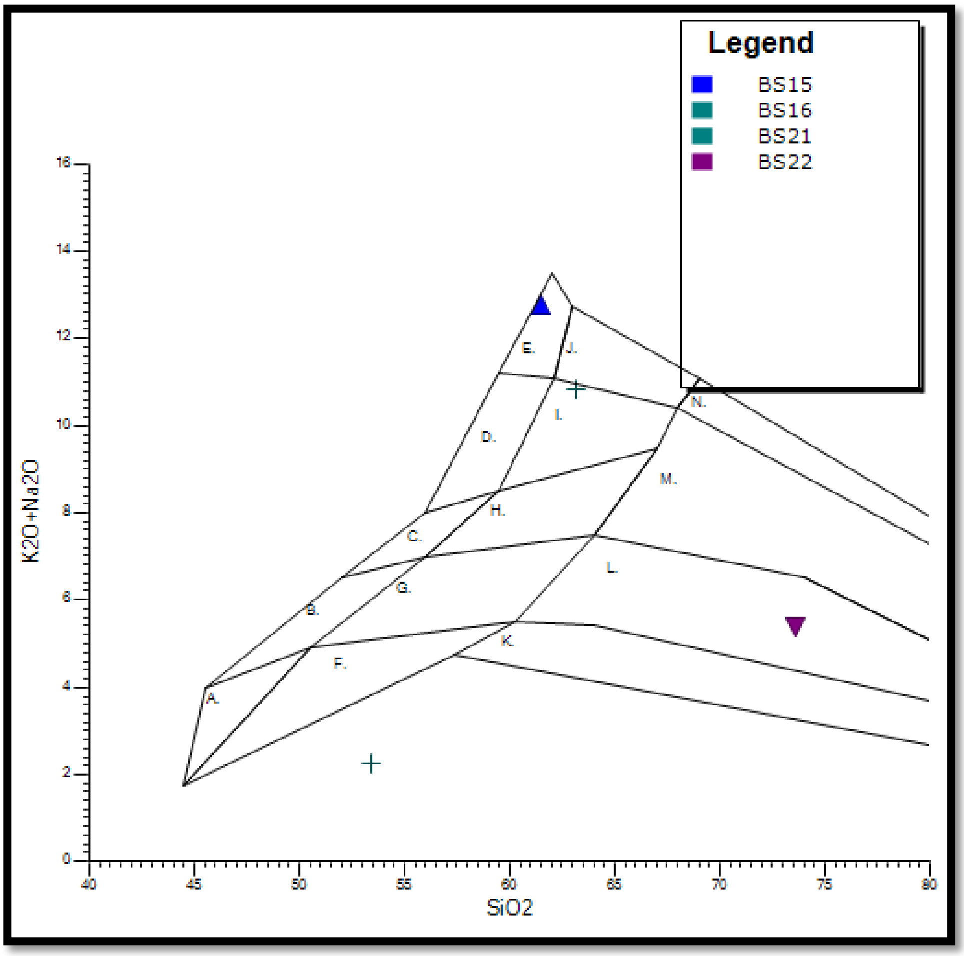


Figure 4-17: Total Alakli vs Silica diagram for Plutonic rocks (after Middlemost, 1994) showing the chemical classification of rocks of the study area.

A. *Diorite Gabbro.* ***B.*** *Monzodiorite.* ***C.*** *Monzonite.* ***D.*** *Syenite.* ***E.*** *Alkali Feldspar Syenite.* ***F.*** *Quartz Diorite.* ***G.*** *Quartz Monzodiorite.* ***H.*** *Quartz Monzonite.* ***I.*** *Quartz Syenite.* ***J.*** *Alkali Felds. Qtz. Syenite.* ***K.*** *Tonalite.* ***L.*** *Granodiorite.* ***M.*** *Granite.* ***N.*** *Alkali Feldspar Granite.*

The Carbonatites IUGS ternary diagram using the concentration of CaO, MgO and FeOt+MnO (Fig. 4-18) showed that the carbonatite sample BS13 plotted in the calciocarbonatite field. Calciocarbonatite is also termed sovite. Other laterite samples (BS01 to BS12) and partially weathered rocks plotted in the Ferrocarbonatite field (see Fig. 4-18) as they were enriched in Iron and manganese oxides.

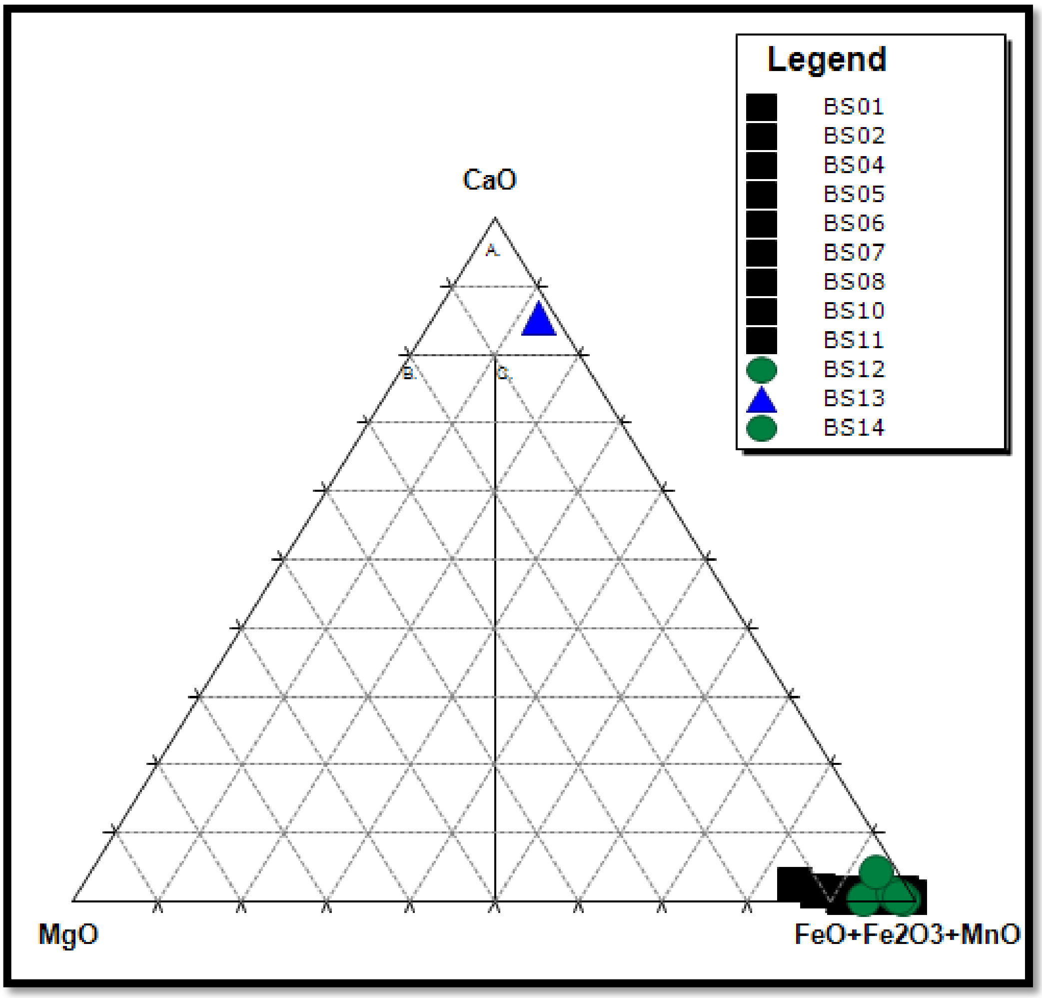


Figure 4-18: Ternary diagram of carbonatites classification (after Woolley and Kempe, 1989) of the carbonatite sample collected from the study area.

Classification Legend: ***A.*** *Calciocarbonatite.* ***B.*** *Magnesiocarbonatite.*
C. *Ferrocarbonatite*

4.2.6. Discussion on the major element geochemistry

From the study of the major element geochemistry, it has been shown that laterites are highly enriched in Iron (FeO ranging between 39 and 70.9 wt.-% and an average of 39.36 wt.-%), Manganese (MnO ranging between 8 and 39 wt.-% and an average of 9.46 wt.-%) and phosphorous (P_2O_5 ranging between 7 and 18 wt.-% with an average of 6.95 wt.-%). This is exemplified by the deep weathering in the field area. This weathering has allowed also the laterites to show great concentrations in other minerals of interest. As far as the rock chemical classification diagrams are concerned, they allowed giving the chemical classification of plutonic rocks of the field and they confirmed the mineralogical and petrographical analyses carried out. The granodiorite found in the field area is part of the country rock. The presence of calciocarbonatite is also sustained by the ternary diagram which was made using the geochemical data of CaO, MnO and FeO_{tot}. The high content of CaO (49 wt.-%, see table 4.7.) in the carbonatite sample (BS13) and its reaction with dilute hydrochloric acid are the evidence that magnesiocarbonatite is absent in the Bingo area.

4.2.7. Presentation of Trace elements concentration

4.2.7.1. Niobium geochemical map

Niobium is among the most important trace elements mined from most of the carbonatite occurrences. The same case is proved in Bingo laterites and carbonatites as they are highly enriched in that element. The laterites from the adits are by far the most important repositories of this metal of value (Mitchell, 2014). It is found especially in the pyrochlore of Bingo, which is qualified to be a bariopyrochlore in opposite to the Lueshe kalipyrochlore (Williams *et al.*, 1997; Wall *et al.*, 1996).

The map showing the distribution of the Nb concentration in the study area is in figure 4-19. The highest concentration, shown pink in colour, is located at the respective coordinates of laterites samples collected from the adits. The very great concentration in this field proves that the deposit is actually economical in Niobium content. This map was done and correlation was made from the geochemical results of the 20 samples collected from the field.

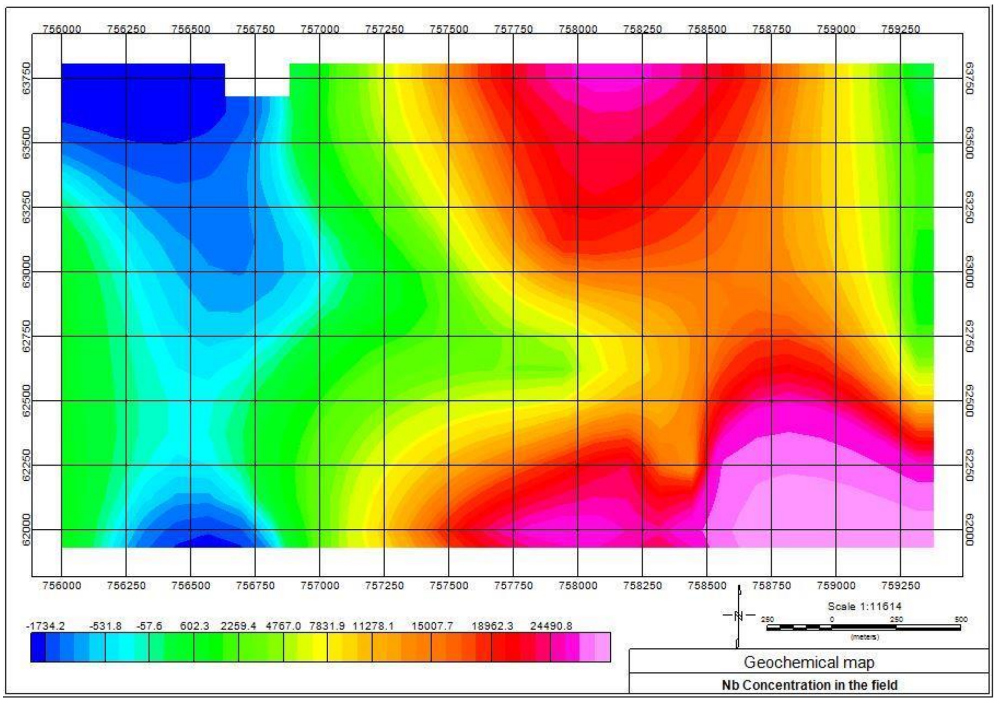


Figure 4-19: Niobium Geochemical map showing its distribution in the study area.

Geochemically, the increase of Nb content in carbonatite is explained by the magma differentiation series. The concentration increases from ultramafic rocks to felsic or alkaline rocks (Ultramafic-Mafic-Acid-Alkali) (Goldschmidt, 1954; Vlasov 1964). The high Nb anomalies are found mostly in the laterites (due to secondary enrichment) and carbonatites and the low Nb anomalies are mostly found in the basic and acid rocks of the study area. The Nb content is lower than the Clarke value of the earth's crust in ultrabasic and basic rocks; this is explained by the fact that Nb is an incompatible element and thus it usually concentrates in the late stages of differentiation (Vlasov, 1964).

4.2.7.2. Barium geochemical map

Barium is the second element in terms of trace elements abundances which are found in the Bingo carbonatite. This is why the bariopyrochlore is related to this carbonatite as the source of Niobium (Hogarth, 1977).

Again the concentration of this particular trace element is higher in samples which were collected from the adits. In fact, all the laterite samples have a great concentration of trace elements. The map which shows how barium concentration is distributed in the study area is presented in figure 4-20; it was made using the geochemical data of 20 samples collected from the study area. The geochemical results of different samples gave a concentration of Ba ranging from 20 ppm to 135000 ppm (see tables 4-7 and 4-8).

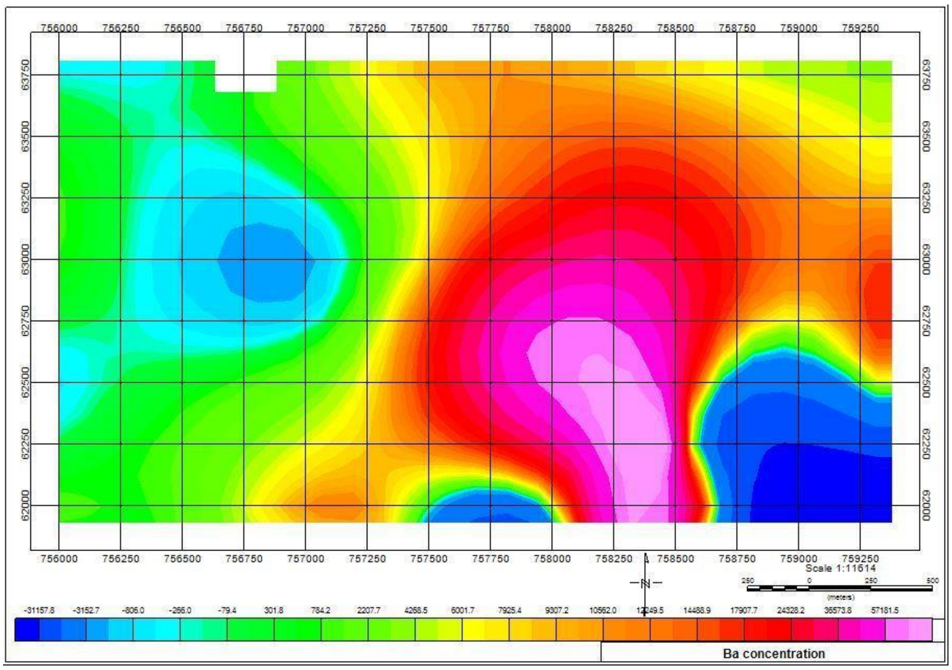


Figure 4-20: Barium geochemical map of its concentration in the study area.

4.2.7.3. Evolution of other trace elements in samples (Zr, Sr, Rb, Th, Y, Sn, Ce, La)

Zirconium (Zr)

Zirconium is also a trace element of interest which was analyzed and which showed some high concentration values. In fact, Zr is found in baddeleyite (Zirconium oxide mineral) in the Bingo carbonatite complex (Wambeke, 1971). This element is much enriched in laterite samples and other weathered samples (Fig. 4-21 a).

Strontium (Sr) and Rubidium (Rb)

Though they were not determined in all samples, Strontium and Rubidium have shown a similar distribution in laterite samples as well as rock samples, but it is necessary to mention that Strontium was higher and common in many samples than rubidium (Fig. 4-21 b and d). the highest Sr value is 29,380 ppm in sample BS19; whereas, the highest Rb concentration is 390 ppm in sample BS16. The lowest Sr concentration is 220 ppm and 30 ppm for Rb. Sr was found in all samples but Rb was rare in some samples. Laterite and weathered rock samples have high content of Sr compared to fresh rock samples.

The fact that Sr is more enriched in samples than Rb is explained by their geochemical behaviour as radioactive isotopes of rubidium decay to strontium whose concentration increases with time (Faure and Powell, 1972). Carbonatites have high concentrations in Sr.

Sr is very useful even during exploration programmes as it is one of the best geochemical indicators for carbonatites in the field (Mariano, 1989).

Thorium (Th)

Thorium is also among elements which are enriched in carbonatite complexes as radioactivity is one of their characteristics (Fig. 4-21c). Geochemically, this element is lithophile and it is found in many minerals including monazite (which is very common in carbonatites), and it is also dispersed in zircon, apatite and uraninite. The highest values of thorium are found in the Bingo laterites and this is explained by the fact that they formed from weathering of intrusive rocks (carbonatites, syenites). BS18 is the sample with the highest Th content which goes up to 3,740 ppm.

The huge concentration of this element in the field area has to be considered as an environmental concern related to radioactivity (Verplanck and Van Gosen, 2011); Thorium is also an element which is used in exploration geophysics (radiometric method) for discovering and deciphering of carbonatite deposits. According to Mariano (1989), the most Th bearing minerals in carbonatites are perovskite, pyrochlore and REE minerals. He continued mentioning that despite anomalous concentrations of Th in carbonatites, no indication had proved they may be concentrated to a level of sufficient economic deposits.

Yttrium (Y), Lanthanum (La) and Cerium (Ce)

Y, La, Ce are the LREE identified in samples from the Bingo carbonatite (Fig. 4-21f). These elements are common in many carbonatite complexes. As noted by Verplanck and Van Gosen (2011), carbonatite REE deposits have shown a great concentration of these particular Light REE and amongst them, Lanthanum, Cerium and Yttrium are by far the most represented elements. Ore-bearing minerals of REE include bastnasite ($Ce(CO_3)F$), monazite ((Ce, La, Th, U)PO4) and xenotine ($Y(PO_4)$). Furthermore, almost all these three elements (Y, La and Ce) are concentrated in the laterite samples like other described trace elements. The association of La and Ce is interpreted as the presence of monazite and bastnasite in the Bingo laterites. The highest value of Yttrium is interpreted as denoting the concentration of xenotine in the study area.

Cerium has a very high concentration in some laterite samples (BS06: 41,500 ppm, BS08: 41,330 ppm, BS11 83,230 ppm) and in some weathered rock samples (BS14: 46,910 ppm, BS18: 56,890 ppm, BS19: 143,900 ppm), other samples had low or no concentration. We explained this by the fact that Cerium has very low elemental mobility due to the stability and low solubility of monazite. The least cerium concentration is 290 ppm in sample BS07.

Lanthanum shows almost the same trend as Cerium but poorer (Fig. 4-21f). The highest Lanthanum concentration is 76,300 ppm in weathered rock sample BS19. The same sample has the highest concentration in Cerium. The lowest Lanthanum concentration is 270 ppm in laterite sample BS06. Its concentration was not found in some laterite and rock samples.

Yttrium concentration is found in all samples except in sample BS22. Its concentration is average. The highest Y concentration is 19,920 ppm found in weathered rock sample BS19, BS18 and BS20 have respectively 1,130 ppm and 700 ppm.

Comparing the concentrations of Y, La and Ce, weathered rock samples BS14, BS18, BS19 and BS20 have high concentrations compared to other rock samples (BS13, BS15, BS16, BS17, BS21, and BS22) collected from the study area. Laterites have also high concentrations of trace elements.

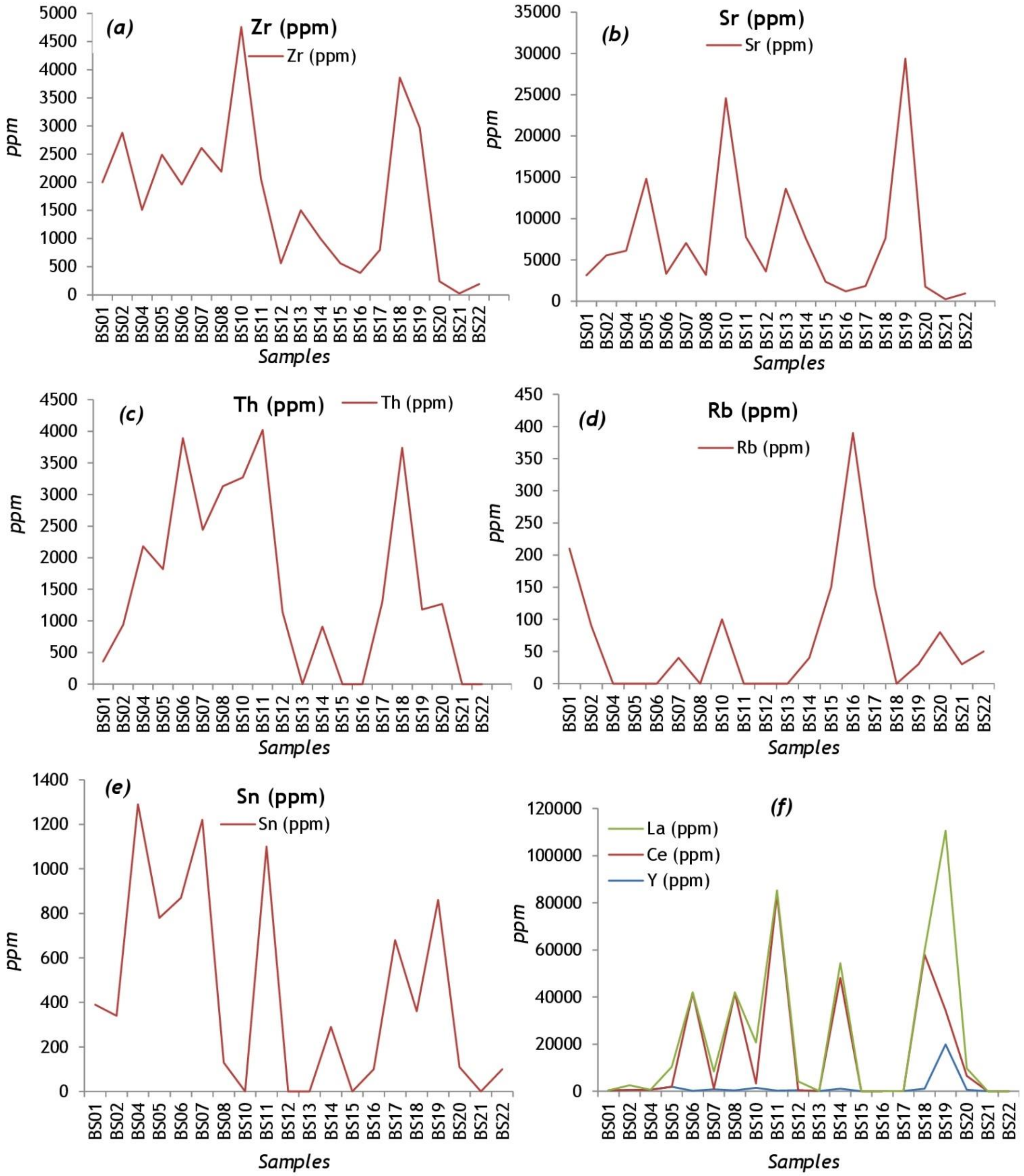


Figure 4-21: Plots of trace elements concentration (Zr, Sr, Th, Rb, Sn, La, Ce, Y) in samples collected from Bingo.

4.2.8. *Correlation Matrix of trace elements*

The correlation matrix (table 4-10) was done in order to find out how elements are related to each other and also to discover how strong the correlations between different elements are. It was done using MS Excel and it permitted to discover the significant correlations in order to make their plots in Harker's or binary diagrams. Binary diagrams were very important for linear correlations and they allowed determining the correlation between elements because it was very crucial to know whether these elements deposited in the same environmental conditions.

Table 4-10: Correlation matrix using the Pearson Product-Moment coefficient of correlation

Nb	1									
Ba	0.16	1								
Zr	**0.52**	0.13	1							
Sr	0.25	0.31	**0.69**	1						
Rb	**-0.45**	-0.27	-0.24	-0.24	1					
Y	0.21	0.30	0.30	**0.72**	-0.13	1				
Ce	**0.62**	-0.27	0.26	0.02	-0.37	0.01	1			
La	0.21	0.28	0.37	**0.80**	-0.12	**0.98**	-0.02	1		
Th	**0.85**	0.04	**0.64**	0.22	**-0.46**	-0.02	**0.68**	0.02	1	
Sn	**0.57**	**0.42**	0.28	0.18	-0.28	0.25	0.26	0.22	**0.5**	1
	Nb	**Ba**	**Zr**	**Sr**	**Rb**	**Y**	**Ce**	**La**	**Th**	**Sn**

Values which are above the correlation coefficient and for which it is considered significant are given in the Rollinson table (Rollinson, 1993). In order to determine whether a correlation coefficient is significant it is important to determine the degree of freedom. Every degree of freedom is used by either the one-sided test or the two-sided test respective numerical values which are in the Rollinson table.

The degree of freedom is the number of samples minus 2. The degree of freedom for this case was 20-2=18. In this work, we decided to use the one-sided test because the alternative to the null hypothesis was different from zero.

Inspection of tabulated values for *(r)* in the Rollinson table shows that at the 5% significance level and 18 as degrees of freedom, the tabulated value for *(r)* is given by 0.378. All calculated values of the correlation coefficient which are equal and/or greater than 0.378 are statistically significant at the 5% level. And this practically means that there is 95% chance that the relationship observed in the sample also applies to the population which is actually the Bingo carbonatite complex and its surroundings (Rollinson, 1993). In the correlation matrix (table 4-10) significant correlation coefficients are in bold and red in colour. Correlation plots of significant correlations are presented in figure 4-22.

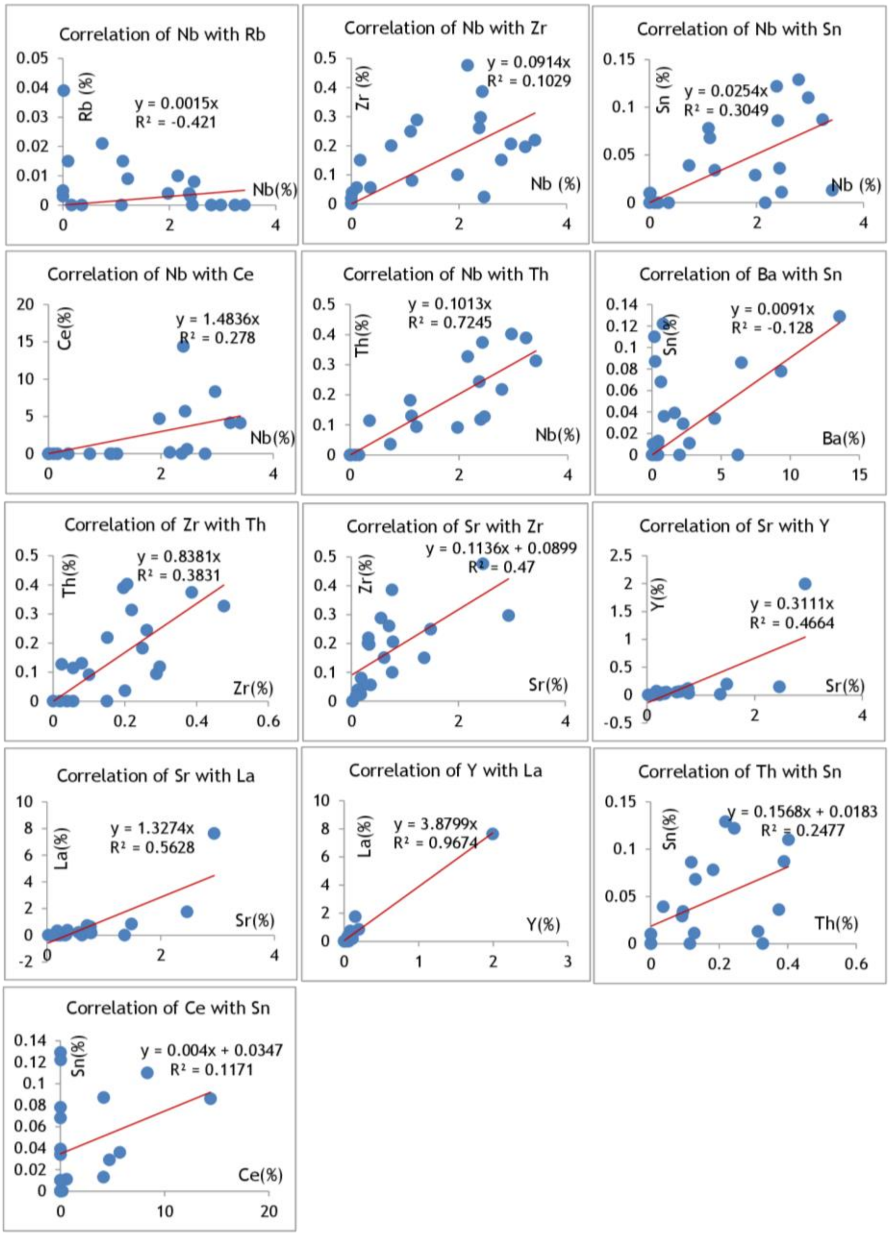


Figure 4-22: Harker's plots of trace elements correlations with a significant Pearson Correlation Coefficient.

Figure 4-22 shows the correlation of elements which have significant correlation coefficient as presented from the matrix correlation in table 4-10. The correlation is between Nb-Zr, Nb-Rb, Nb-Ce, Nb-Th, Nb-Sn, Ba-Sn, Zr-Th, Zr-Sr, Sr-Y, Sr-La, Y-La, Ce-Th, Th-Sn. All linear correlations have shown a positive relationship between those elements, this means that the increase of one element is related to the increase of another element in samples. This geochemical relationship between elements means that the conditions which favoured their deposition were the same for all of them. And it is important to mention that these elements are always found associated in many carbonatite complexes.

4.2.9. Discussion on trace mineral chemistry

Carbonatite complexes are big repositories of niobium and other metals of interest while most of the Niobium is contained in pyrochlore (Chakhmouradian *et al.*, 2015). They have been exploited for their concentration in minerals of pyrochlore, apatite, rare earth elements, fluorite, and vermiculite (Mariano, 1989). Carbonatites in regions of high temperature and humidity can show a thick lateritic weathering over a long period of time. Too much weathering result in the destruction of minerals and the only ones which can survive are magnetite, pyrochlore and apatite and they tend to be abundant in the laterites alongside with iron and manganese (Mariano, 1989). Laterites from carbonatites are richer in iron, manganese and trace elements than any other fresh rock (Mitchell, 2014). Bingo laterites have huger concentrations of these metals compared to surrounding rocks which include fenites, granodiorites and nepheline syenite. As they did not reveal an economic concentration, the Bingo deposit is only limited to the laterites.

Results of trace elements reveal that the study area, which is mostly occupied by fresh carbonatites and their laterites with other weathered materials, has high concentrations of Niobium, Barium and some rare earth elements (La, Ce, Y). The niobium of Bingo is associated in bariopyrochlore (Williams, 1997; Hogarth, 1989) and its concentration is by far greater to be economically exploitable. The rare earth elements are mostly included in bastnasite and monazite. These two minerals are very common in many carbonatites. REE minerals have been of great importance in the latest electronic technology advances.

Apart from these elements, the Bingo carbonatite and laterites show a huge concentration of Thorium. Thorium is one of the radioactive elements which has some side effects related to nuclear radiation.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

5.1. CONCLUSION

This research project was carried out at Bingo in North Kivu in the Democratic Republic of Congo with the main objective of investigating the geology and the geochemistry of the Bingo carbonatite and its associated lateritic deposits. In the purpose of achieving this, three specific objectives were defined. They are as following:

- One of the objectives was to map the geology and update the geologic map of the Bingo carbonatite and the surrounding areas. This was done by carrying out detailed field mapping that was followed by petrographic and mineralogical analysis of the samples.

  From the results, it was possible to map the geologic and geometric map of the adits from where the laterite samples were collected. The geologic map of the study area was done by using the coordinates and rock names of samples from the field.

  From the mineralogical study, a rare mineral “carletonite” has been, for the first time, found from alkaline rocks of Bingo. Another Ca, K and Mg sulfate mineral called polyhalite was determined; it is mainly used as a fertilizer.

  The petrographical study also enabled the identification and location of granodiorite, nepheline syenite, fenite and carbonatite in the study area. The granodiorite which is part of the country rock has not been mentioned in earlier geological reports of the area.

- The other objective was to carry out geochemical analysis of the major and trace elements composition of the Bingo carbonatite rocks, and of its associated lateritic deposit. From the results of geochemical analyses, it was found that laterites from the Bingo were rich in niobium (respectively by 0.2 and 3.41 wt.-%) and barium (lowest and highest values are respectively 0.1 and 13.57 wt.-%). And this fact explains the reason for this Bingo carbonatite to be qualified a bariopyrochlore. Some rare earth elements including Cerium, Lanthanum and Yttrium were found to be of high concentrations in the laterite samples. Cerium has a very high concentration in some laterite samples (BS06: 41,500 ppm, BS08: 41,330 ppm, BS11 83,230 ppm) and in some weathered rock samples (BS14: 46,910 ppm, BS18: 56,890 ppm, BS19: 143,900 ppm), other samples had low or no concentration. Cerium has very low elemental mobility due to the stability and low solubility of monazite. The highest Lanthanum concentration is 76,300 ppm in weathered rock sample BS19. Yttrium concentration is found in all samples except in sample BS22. Its highest concentration is 19,920 ppm found in weathered rock sample BS19. The concentrations of Y, La and Ce in rock samples BS14, BS18, BS19 and BS20 are high as well as in laterite samples.

Apart from these trace elements, other major elements were found in great concentrations and among them Iron (FeO) ranging between 39 and 70.9 wt.-% and an average of 39.36 wt.-%. Manganese (MnO) ranging between 8 and 39 wt.-% and an average of 9.46 wt.-%; this is specifically due to the high rate of weathering which is observed in the field area. Phosphate (P_2O_5), ranging between 7 and 18 wt.-% with an average of 6.95 wt.-%, showed high concentrations. In a global scale, its presence is explained by the fact that carbonatite complexes have in their economic importance the presence of apatite (Hogarth, 1977).

- The last objective was to evaluate the economic potential of the gossan in laterites associated with the weathered carbonatite. From the results, it was clear that the laterite samples (BS01-BS12) were by far richer in Niobium, Barium and rare earth elements than the rock samples (BS13-BS22). And this is also explained by the fact that earlier explorations performed by previous geologists were mainly done in the adits targeting the gossan. The potential is still there and further exploitation is still possible.

5.2. RECOMMENDATION

The following are the recommendations from this work:

- Trenching and deep pitting are required as many outcrops in Bingo are weathered and covered by surficial soils. This activity will allow getting fresh samples from that area and being sure of their identification and location. It will also help to determine the thickness of the laterites so as to evaluate the tonnage and grade of the deposit. Drilling should also be considered, besides trenching and deep pitting as this may result in a better understanding of the mineralization in the area.

- Further geochemical analyses using the latest analytical equipment technologies like ICP-MS are very necessary, so as to identify critical rare earth elements that can confirm whether the Bingo complex may be a repository for those elements. The adits should be systematically described and sampled every 10 meters.

- Detailed geophysical surveys (radiometric and magnetic methods) are recommended so as to determine the extent of the laterite deposit with good precision.

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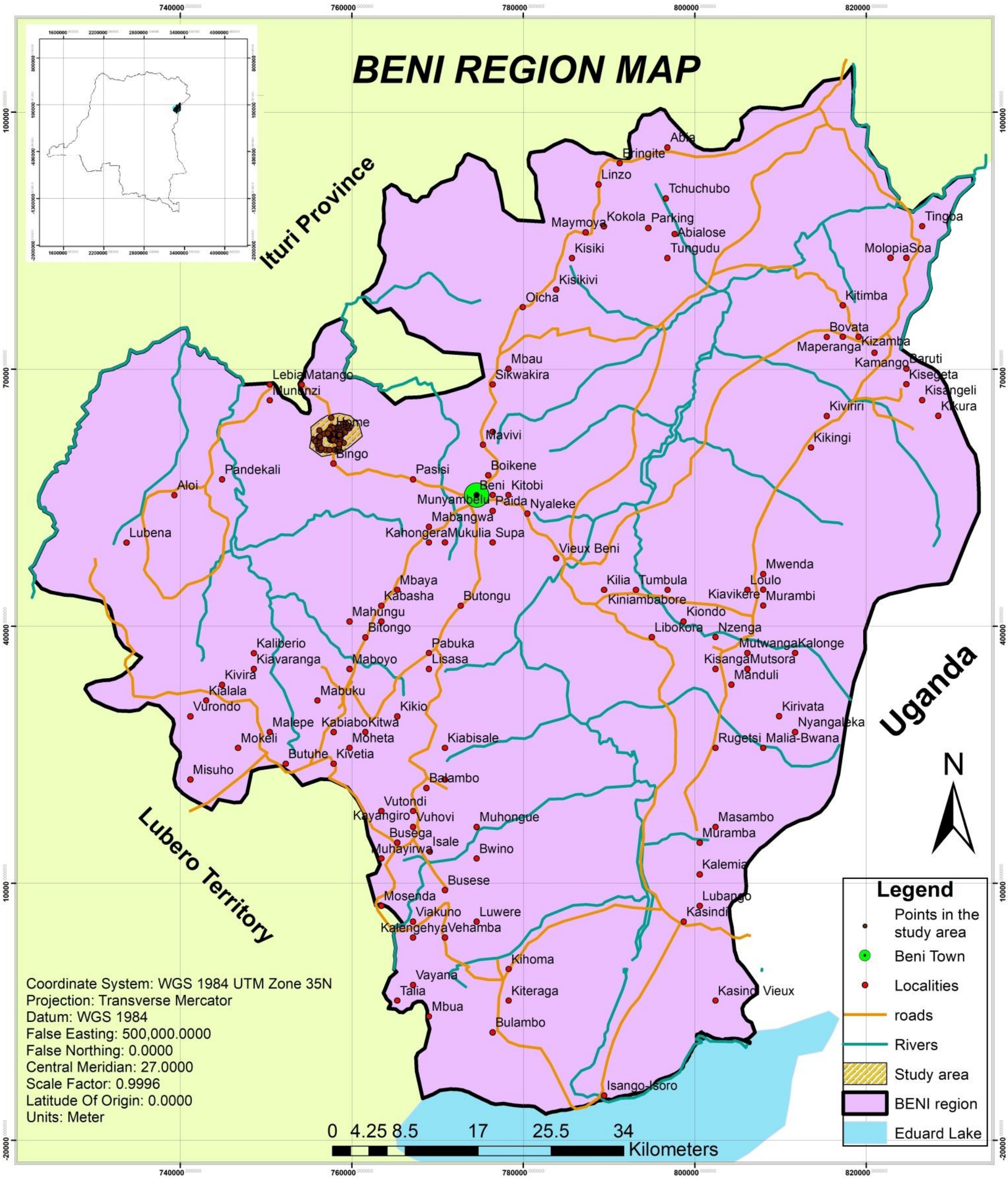
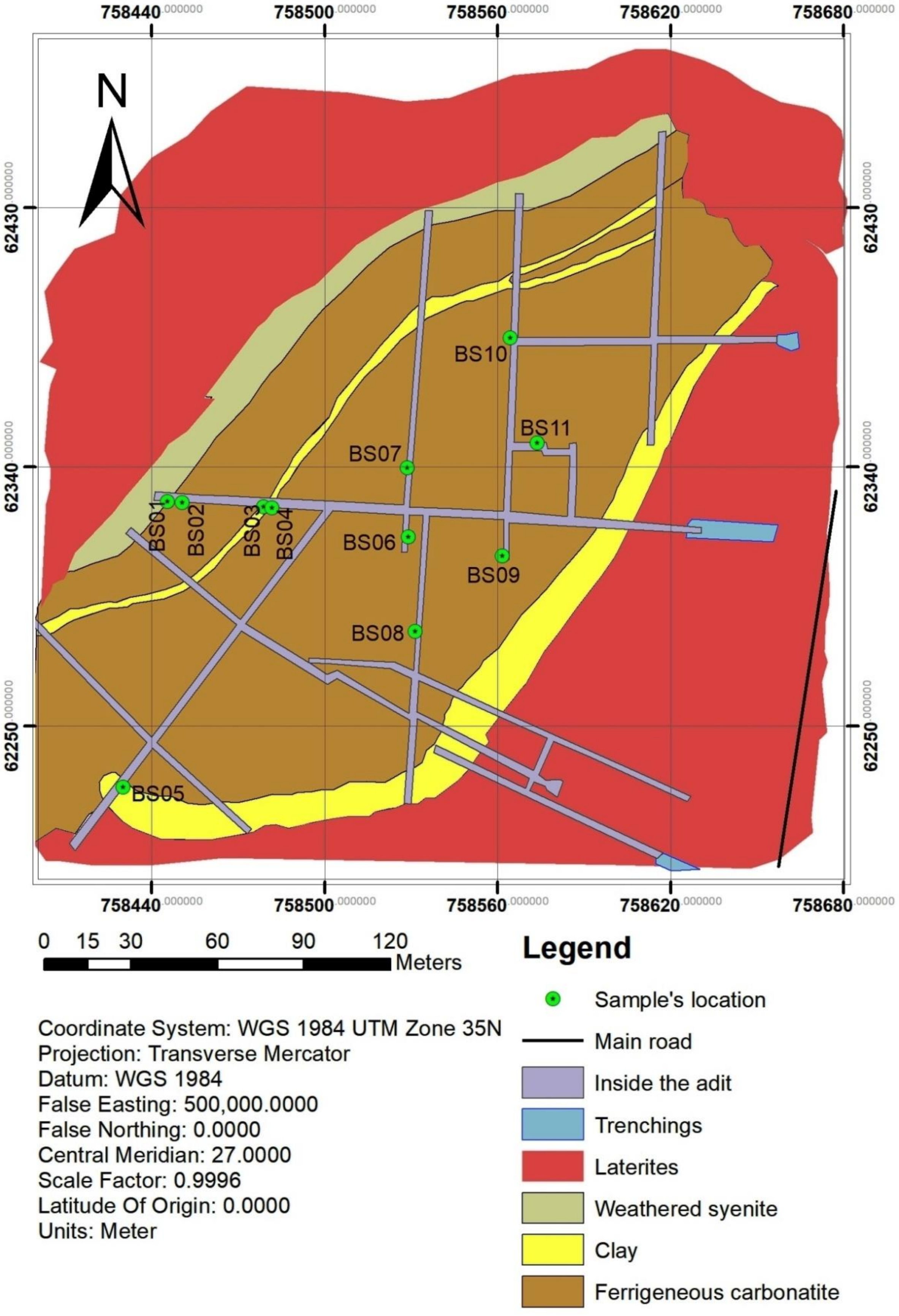
APPENDICES

APPENDIX I: GEOGRAPHIC MAP OF THE BENI REGION



APPENDIX II: GEOLOGICAL MAP AND ADIT GEOMETRIC OF BINGO



APPENDIX III: PHOTOGRAPHS OF LATERITE SAMPLES

Sample BS03


Sample BS06


Sample BS07

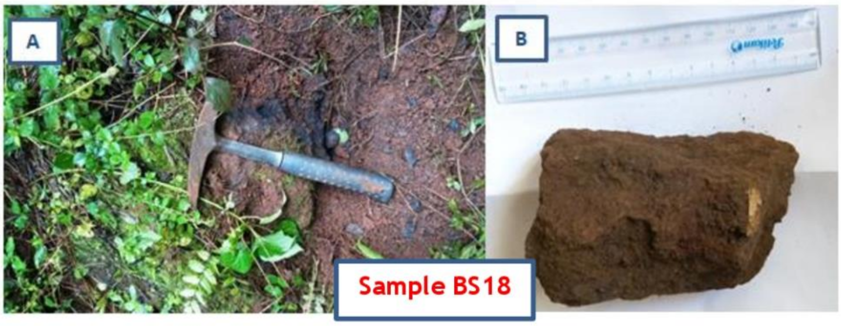

Sample BS08


Sample BS11

APPENDIX IV: PHOTOGRAPHS OF ROCK SAMPLES AND THEIR OUTCROPS

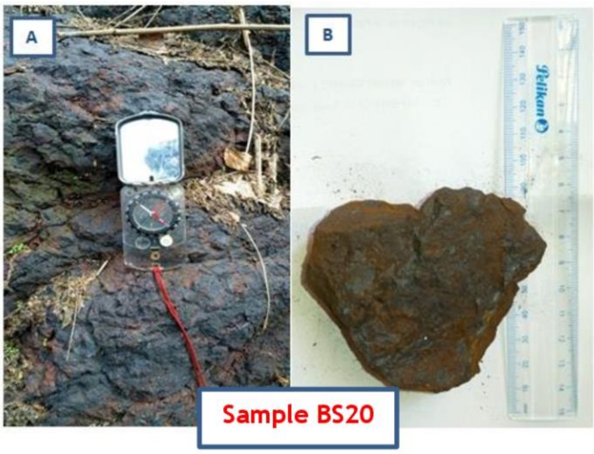
Sample BS12

Sample BS17



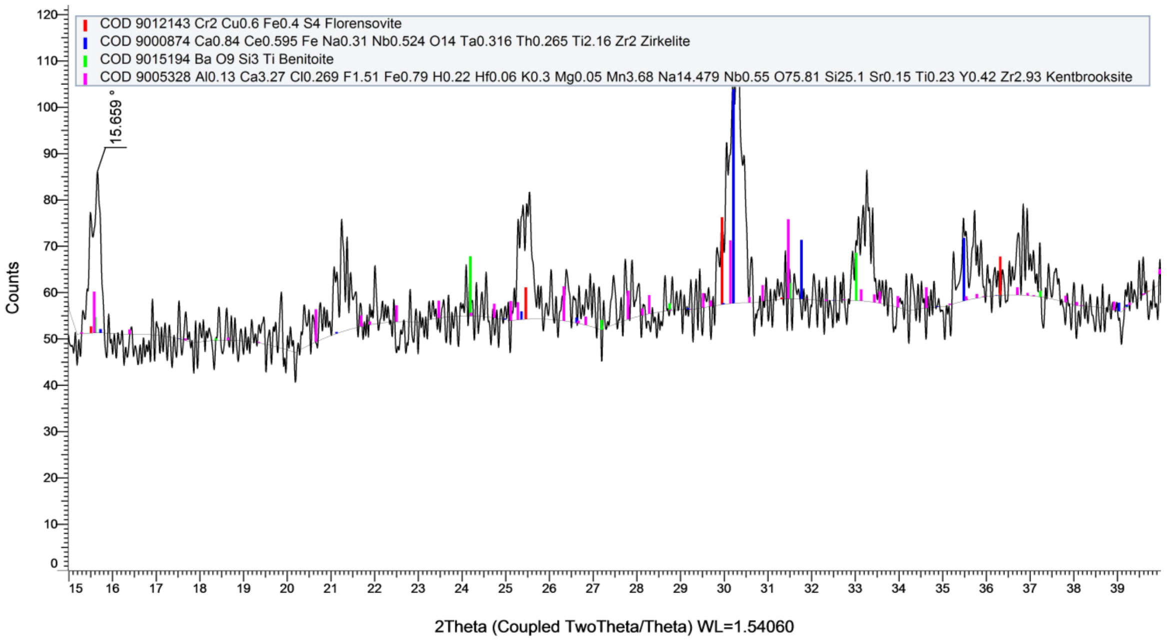
Sample BS18

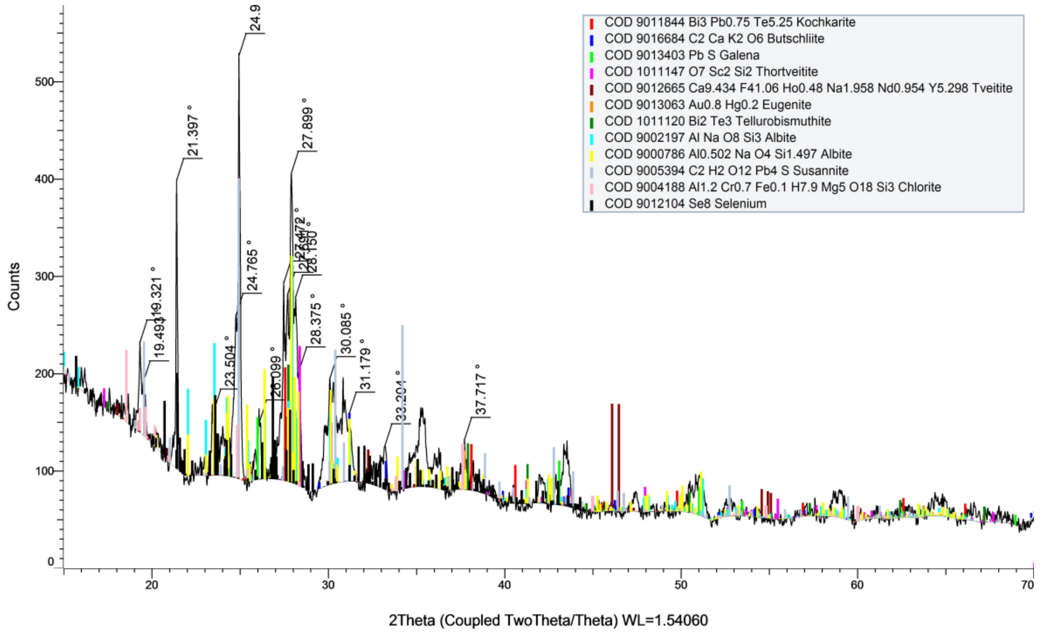
Sample BS19

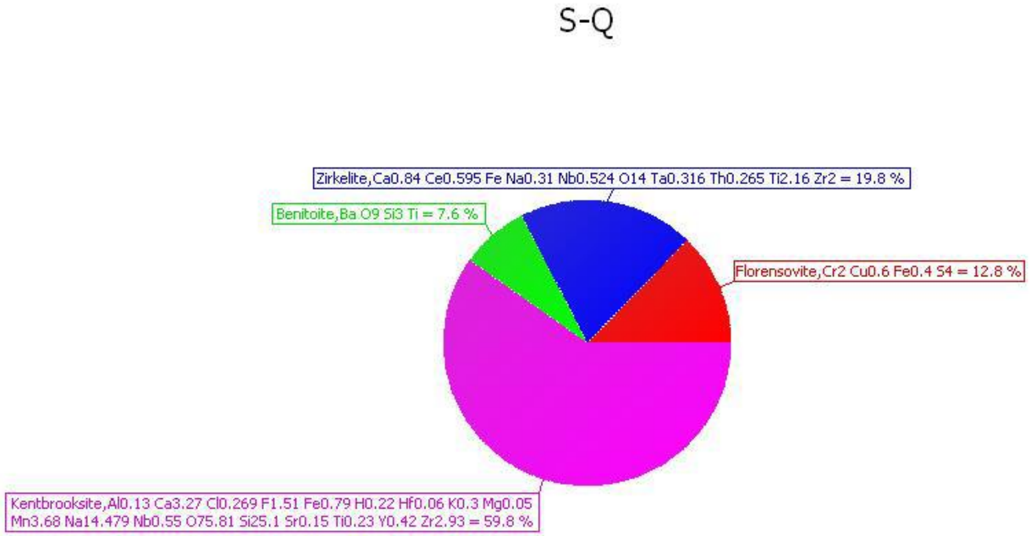


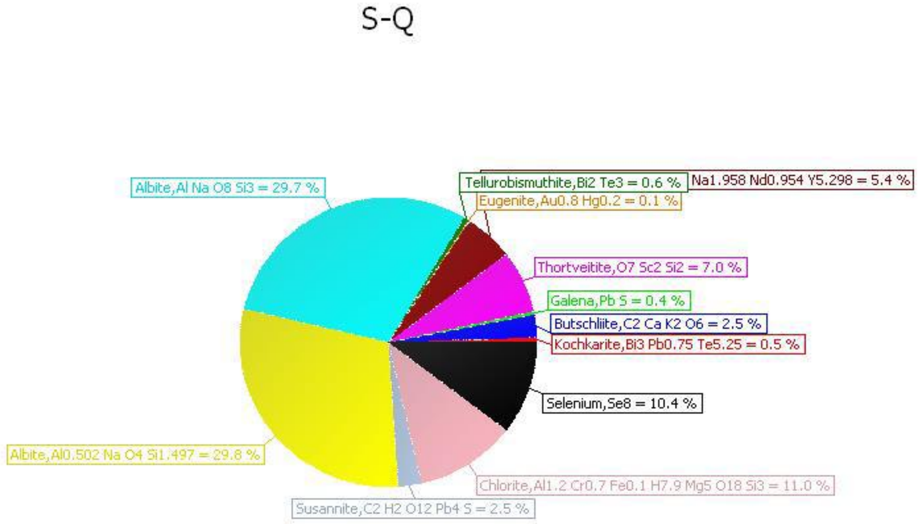
Sample BS20

APPENDIX V: XRD PATTERNS AND DISTRIBUTION DIAGRAMS FOR SAMPLE BS10 AND SAMPLE BS15 FROM BINGO









APPENDIX VI: XRD PATTERNS AND DISTRIBUTION DIAGRAMS FOR SAMPLE BS01 AND SAMPLE BS08 FROM BINGO