Addis Ababa University

College of Natural Science

School of Earth Sciences

Assessing the Quality, Mining and Processing Techniques of Bombawuha Kaolin Deposit, Southern Ethiopia

By

Tilahun W/maryam Zegeye

A thesis submitted to the School of Earth Sciences of Addis Ababa University in partial fulfillment of the requirements for the degree of Master of Science in Resource Geology (Mining Geology)

June, 2018
Addis Ababa, Ethiopia

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Dr. Worash Getaneh (*principal advisor*)

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Originality statement

I hereby declare that this thesis represents my own work and is submitted in partial fulfilment of the requirements for a Master Degree (MSc) in Mining geology. This thesis work has not been previously submitted to Addis Ababa University, or any other institution/organizations for any degree, diploma or other qualifications, and all sources of material used in this thesis have been duly acknowledged.

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Signature Date

This is to certify that, the above statement made by the MSc candidate is correct.

Dr. Worash Getaneh _____________ ____________

Signature Date

Dr. Zerihun Desta _______________ _____________

Signature Date

Dedication

This paper is dedicated to my beloved families.

Abstract

Bombawuha kaolin deposit is a residual type deposit formed by weathering and hydrothermal alteration of granite and pegmatite units. The present study was designed to assess the quality, mining and processing techniques of Bombawuha kaolin deposit by physical observations of the site and different analytical methods. For this purpose, samples of the source rock, kaolin deposit, run of mine, and processed kaolin were collected for analyses. Chemical, and mineralogical (thin section) analyses were applied to examine the source rock of the deposit. For kaolin deposit, and processed kaolin chemical, mineralogical (XRD), and physical properties were investigated. A chemical analysis was also carried out to investigate the composition of run of mine. The result of the study revealed that the source rock of the deposit is composed of higher SiO_2 (72.1%), coloring impurities (1.88% Fe_2O_3, and 0.13% TiO_2), fluxes (5.765 alkalies, and 0.38% alkali earth oxides), and lower Al_2O_3 (16.3%) and loss on ignition (3.85%) values compared to its altered product. It is composed of quartz, k-feldspar, plagioclase, biotite, muscovite, and opaque minerals. The kaolin deposit has light gray to white color, higher grits (79.9-96.7%>63µm), pH (6.27-6.37), lower plasticity (<10%), linear shrinkage (0-3), and specific gravity (2.53-2.60) values. The deposit is constituted by higher SiO_2 (51.5-70.5%), and lower Al_2O_3 (18.1-33.4%) comparing to ideal pure kaolin 46.6 and 39.5% respectively. It also has higher Fe_2O_3 (1.09-1.92%), and lower TiO_2 (0.03-0.17%). The XRD result revealed that kaolinite and quartz are the major minerals of the deposit with minor k-feldspars and illite. Specifically, kaolinized granite and kaolinized pegmatite have different physical and chemical characteristics. The kaolinized granite has higher grits, lower plasticity, and linear shrinkage values. It also has higher SiO_2 (68%), Fe_2O_3 (1.65%) and TiO_2 (0.13%), and lower Al_2O_3 (20.19%) and LOI (7.84%) values compared to the kaolinized pegmatite. Mineralogically, it is composed of kaolinite, halloysite, quartz, and k-feldspar. Kaolinized pegmatite contains quartz, mica (illite), and kaolinite minerals. Although these two units have different characteristics, they are mined together by simple open pit mining method. A run of mine having higher SiO_2 (71.2%), Fe_2O_3 (1.88%), and lower Al_2O_3 (17.95%) is produced for processing. The wet processing method enhanced the quality of kaolin product by producing higher Al_2O_3 (35.5%), lower SiO_2 (45.8%), and Fe_2O_3 (0.99%). It reduced SiO_2 and Fe_2O_3, and increased Al_2O_3 by 36%, 47% and 98% respectively from its crude state. The processed kaolin contains major kaolinite, and minor orthoclase and muscovite minerals. Based on findings of this study, it is concluded that Bombawuha kaolin product can be used in ceramics (bricks, pottery, floor and wall tiles), plastics, paint and rubber filer productions after processing.

Key words: Bombawuha, Impurity, Kaolin, Mining, Processing, Quality

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I would like to express my gratitude to Geological Survey of Ethiopia which provide me useful data of the study area and give me an access of various laboratory works, mainly the physical tests and thin section preparations. I need to extend my sincere thanks to the institution of Ethiopian mineral, petroleum and biofuel corporation (EMPBC) which provides me an access to work at Bombawuha kaolin mine site. I also want to express my deepest respect and thank to the community of all workers of the Bombawuha mine site and processing plant. They were helped me by providing the required access during the field work. Not only this they were also helped me by giving the necessary practical information concerning to the kaolin processing procedures which can intensify my study.

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List of Acronyms

ALS	Australia Laboratories Service
CEC	Cation Exchange Capacity
ECDSWC	Ethiopian Construction Design and Supervision Works Corporation
EIGS	Ethiopian Institute of Geological Survey
EMPBC	Ethiopian Mineral, Petroleum and Biofuel Corporation
EMRDC	Ethiopian Mineral Resource Development Corporation
GSE	Geological Survey of Ethiopia
HGMS	High Gradient Magnetic Separators
ICP-AES	Inductively Coupled Plasma - Atomic Emission Spectroscopy
LL	Liquid Limit
LOI	Loss of Ignition
m	meter
mm	millimeter
PI	Plasticity Index
PL	Plasticity Limit
PPM	Parts Per Million
PPB	Parts Per Billion
PPL	Plane Polarized Light
ROM	Run of Mine
SC-HGMS	Superconducting High Gradient Magnetic Separation
SNNPS	Southern Nations, Nationalities, and Peoples
UK	United Kingdom
USA	United States of America
XPL	Cross Polarized Light
XRD	X-Ray Diffraction
XRF	X-Ray Fluorescent

Chapter One

1. Introduction

1.1 Background

Kaolin is one of the most widely distributed gift of nature at which its products play a great role in the advancement of our civilization. The name kaolin is derived from a Chinese word which means high ridge (Kao-ling) where the clay was originally discovered and used. The term kaolin may be either a mineral group name of halloysite, kaolinite, dickite, and nacrite or a rock name. Of these minerals, kaolinite is the principal mineral of kaolin composed of silica, alumina and water (Tsolis-Katagas and Papoulis, 2004). The mineral phases of quartz, micas, unaltered feldspars, anatase, hydrated iron oxide, montmorillonite and rutile are the common extra impurity minerals of kaolin (Jepson and Rowse, 1975). Kaolin is characterized by parallel layered tetrahedral sheets of silica and alumina and is classified under phyllosilicates family (AL-Shameri and Rong, 2009).

Genetically, kaolin is mainly formed by weathering and hydrothermal processes of granitic and pegmatitic rocks. It can also be formed in various feldspar bearing sedimentary and metamorphic rocks. On the basis of origin, kaolin deposits can be categorized as primary/residual and secondary/sedimentary deposits. The primary/residual kaolin deposits are formed by the in-situ weathering and/or hydrothermal processes of feldspar bearing rocks. Whereas the secondary/sedimentary kaolin deposits are formed by the erosion, transportation and redeposition of kaolin that was formed somewhere else (Murray and Keller, 1993).

As far as kaolin's application is considered, kaolin is extensively consumed for different industrial applications depending on the availability of markets, market location, transportation costs, physical and chemical properties as well as the degree of processing required for end use (Solomon Tadesse, 2009). Kaolin can be used as a building material in the form of bricks and roof tiles. Other uses are in making of refractories, manufacture of wall and floor tiles, porcelain, earthenware, pipe for drainage and sewage. Kaolin can also be consumed in the paper, rubber, paint, plastics, cosmetic and pharmaceutical industries depending on product quality (Román et al., 2015; Murray, 2002). The quality of kaolin product depends on geologic properties (chemical, mineralogical, and physical characteristics) of kaolin deposit as well as the employed mining and processing techniques (Ali and Dikko, 2015). The geologic properties of kaolin deposit could be affected by the availability of undesirable impurities. Kaolin is found in different parts of Ethiopia such as Tigray, Amhara, Oromia and SNNPS regions.

The Bombawuha kaolin deposit is found in southern Ethiopia. It is the leading kaolin occurrence of the country followed by the Kombolcha kaolin deposit found in Harar (Said Mohamed and Sentayehu Zewdie, 2000). Bombawuha kaolin deposit was discovered in 1980s, south of Bore in the Regional State of Oromia, Guji zone. After the discovery and the exploration study, mining of the kaolin deposit is proceeded to supply for different industries. Tabor Ceramics and Melkasa Aluminium Sulphate and Sulphuric Acid Factories are the two main customers of Bombawuha kaolin product. The surface mining method mainly simple open pit mining method is operated for the extraction of this deposit. Bombawuha kaolin deposit has been exploited since 1992 and beneficiated by wet processing method (GSE,2011).

The aim of the present study is to assess the quality of Bombawuha kaolin by chemical, physical and mineralogical characteristics of the crude and selected beneficiated products. This is because, quality/properties of kaolin product depend on the presence of impurities in the crude kaolin, and the employed mining and processing techniques. Examination of physical, chemical and mineralogical properties helps to identify and quantify the impurities of kaolin. This helps to propose suitable mining technique if there is dilution effect as well as to select and modify beneficiation sequences and processes for the removal of the associated impurities. Suitable purification methods upgrade the quality of the raw material. Upgrading the quality of kaolin is to mean that maximizing the desired component (i.e. percent of kaolinite mineral) and reducing the undesirable associated impurity minerals. The investigation also helps to evaluate the industrial suitability by examining the physical and geochemical characteristics comparing with the standard specifications. Therefore, this research helps to understand the physical, chemical and mineralogical characteristics of kaolin, and associated impurities. It also enables to select suitable processing techniques for the removal of undesirable impurities for further quality enhancements. That is why this research is initiated and designed to assess the quality, mining and processing techniques of Bombawuha kaolin deposit to overcome the existing problem.

1.2 Description of the study area

1.2.1 Location and accessibility

Bombawuha kaolin deposit is located in southern Ethiopia about 430 km from Addis Ababa. It is far from Hawassa 160 km along the road Wendogent to Kibre Mengist. The kaolin deposit is found on the map sheet NB 37-6 in the northern tip of the Adola gold field. Bore and Kiberemengist towns are found towards north and south of the study area respectively. Yirbamoda and Meleka are also the nearest new towns found north and south of the area respectively. Geographically, the area is bounded between 665000 to 675000 m N latitude and 470000 to 480000 m E longitude (Fig.1.1). The area is accessed by the main asphalt road which passes from Addis Ababa to Kiberemengist. In addition to the main asphaltic road, there are also other gravel roads and byways that connect the nearby villages of the area. The gravel roads serve the local people for transportation by motor cycles.

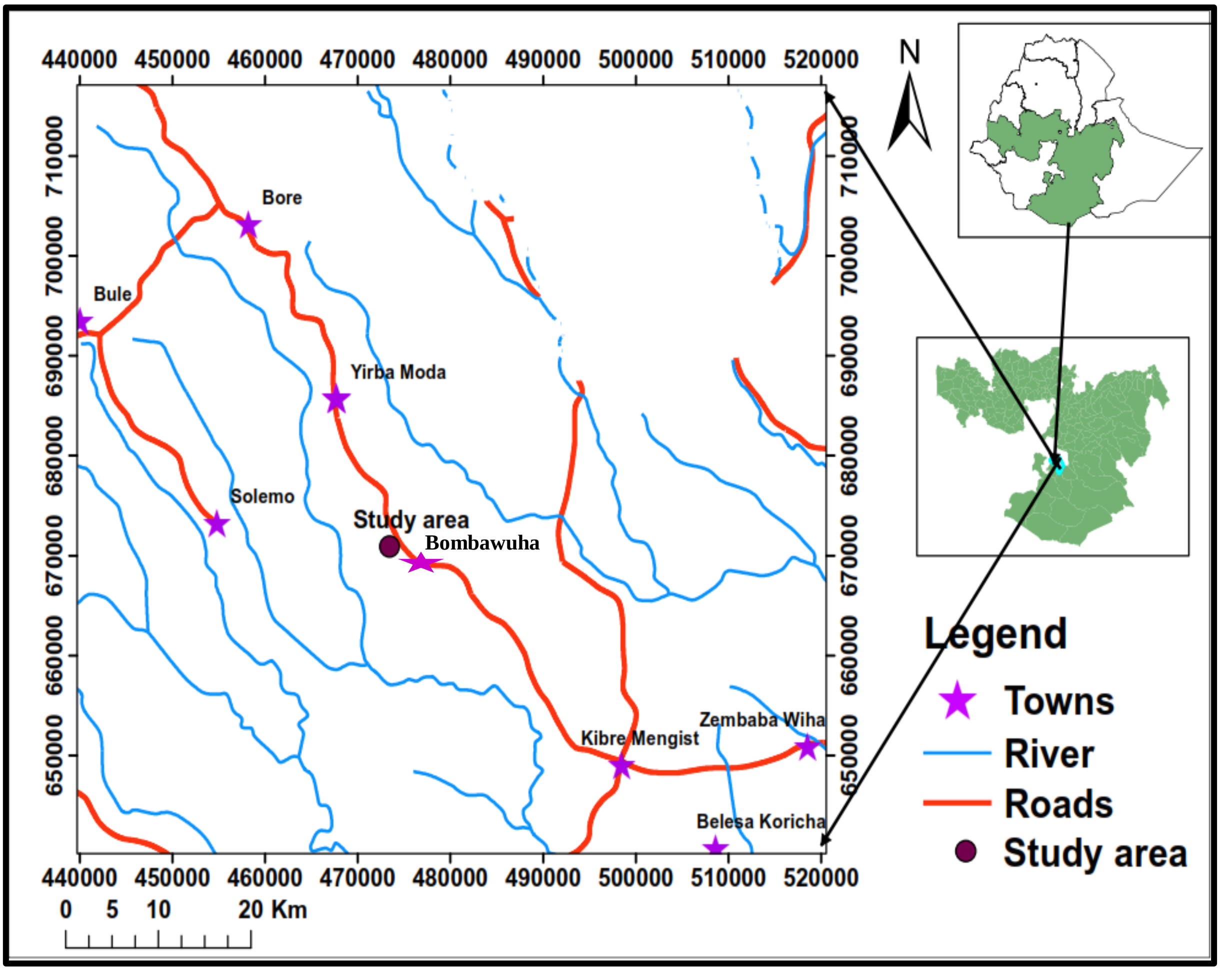


Figure 1.1: *Location map of the study area*

1.2.2 Climate of the study area

According to Sabov et al. (1985) the climatic condition of the area can be considered as a subtropical with two main rainy seasons. April to May with monthly rainfall of 100 to 200mm is the first round. The other rainy season ranges from September to October with 150 to 300 mm. Eight months of the year are related almost to the dry season having a monthly rainfall range of 0.0 to 30mm. There is no significant variation between the highest and lowest annual temperatures recorded in the study area. November is the coolest month with its mean temperature being $+18.7^{0}$c whereas the hottest one is March, with its mean temperature $+21.9^{0}$c.

1.2.3 Physiography and vegetation

The study area is characterized by the flat lying and hill topography with big and slightly dense forests. The slope of the terrain is moderately steep. The terrain is also covered by forest partly, especially south-western parts of the deposit. It has some difficulties to pass across the densely forested landscapes. At this time, the introduction of kaolin mining and the increasing number of population that use the land for agricultural activities causes an intensive deforestation of the area. There were a number of wild animals like 'dikula' hosted in the area before some decades as the people of the area said. Presently, due to the deforestation of the area the animals are not hosted there. Only some wild animals are hosted in the area like monkeys, 'gureza', vulture and other birds.

1.3 Problem statement

Kaolin is one of the most globally distributed industrial mineral resources which can be consumed as a raw material in different industries depending on its quality. This industrial mineral resource is distributed in different parts of Ethiopia. Bombawuha kaolin deposit has been one of the main providers to kaolin consumer industries of the country primarily Tabor Ceramics and Melkasa Aluminium Sulphate and Sulphuric Acid Factories. However, the consumption of Bombawuha kaolin decrease from time to time by the existing industries. Specially, the former factory is retreating and decreases its consumption. This causes to decrease the market value of Bombawuha kaolin. Thus, the quality of Bombawuha kaolin deposit become doubtful as a result of declining the consumption by the existing consumers. The declining of consumption of this kaolin may be related to quality. The presence of undesirable impurity minerals may affect the geological properties (physical, chemical and mineralogical) of kaolin and then inhibit the end use of the product in industries. Thus, this needs an investigation on the physical, chemical and mineralogical properties of the kaolin deposit as well as the adopted mining and processing techniques. Due to this reason this research is designed to assess the quality, mining and processing techniques of Bombawuha kaolin deposit in order to overcome the existing problem.

1.4 Objectives

1.4.1 General objective

The main objective of the study is to assess the quality, mining and processing techniques of Bombawuha kaolin deposit.

1.4.2 Specific objectives

The specific objectives of the study are:

- To investigate the physical, chemical and mineralogical characteristics of kaolin deposit
- To examine the major impurities that decrease the quality of kaolin and identify their sources
- To assess and propose the mining and processing techniques of kaolin for better quality

1.5 Methodology

In order to accomplish the overall research work three main phases were followed. These are; pre-field work, field work and post-field work.

1.5.1 Pre-field work

Before going to the field, different literatures related to the area were collected and reviewed. This detailed reviewing and organizing of previous works and literatures related to the present study has an implication to understand the geology of the area, to have an over view about the nature of the kaolin deposit and its production techniques as well as to design effective research method.

1.5.2 Field work

The initial field investigation involves various activities including observation, description and taking a note about the geology of the area. Observation and description of the geology of kaolin deposit and its surrounding lithological exposure was undertaken. The physical characteristics (such as color, softness, hardness and grain size variation), associated coarse minerals (mainly quartz and mica) as well as textural and structural features of the kaolin deposit were described. Sampling of both kaolin clay (crude kaolin and beneficiated kaolin product) and some surrounding rocks were also made. The kaolin samples were collected from both outcrops of kaolinized granite and pegmatite on the basis of variation in physical characteristics such as color, grain size variation, texture, and mineral content. In addition to the deposit, the production activities including mining, and processing procedures of the kaolin were also observed. Afterwards, all the collected samples were labelled accordingly and put into sampling bags for various subsequent laboratory analyses.

1.5.3 Post field work (laboratory analysis)

After the field work was completed, the main task had become distributing of the collected samples for their analyses and tests at different laboratories. The prepared representative samples (Table 1.1) were analyzed for the mineralogical, geochemical composition, and some physical properties including grain size distribution, plasticity, linear shrinkage, specific gravity and pH at different (local and foreign) laboratory sites.

Table 1.1: *Descriptions of samples and their corresponding analytical methods*

Sample descriptions				Analytical Methods							
				Mineralogy		Geochemical	Physical tests				
Sample type		Code	Quantity	Petrography	XRD analysis		Grain size	Plasticity	Linear shrinkage	pH	Specific gravity
Rock		BR-1	3	3	_	1	_	_	_	_	_
Kaolin	Deposit	BK-1 to BK-5	5	_	3	5	2	2	2	2	2
Kaolin	Run of mine	BM-1	1	_	_	1	_	_	_	_	_
Kaolin	Processed	BP-1	1	_	1	1	_	_	_	1	1
Total	_	_	10	3	4	8	2	2	2	3	3

i. Mineralogical analysis

The mineralogical analysis of the collected representative samples was examined using petrographic microscope (mainly for the surrounding rock samples) and X-Ray Diffractometer (for the kaolin clay samples) instruments. From the collected representative samples, three samples were selected for the preparation of thin sections and petrographic studies and four samples were selected for X-ray diffraction analysis. The petrographic analysis was mainly engaged to examine the mineralogy of the rocks using the prepared thin sections. The thin sections of the samples were prepared in Geological Survey of Ethiopia (GSE) and were examined and described petrographically for variations in texture and mineralogy of the rocks. The X-ray diffraction analysis was employed to investigate the mineralogy of the crude kaolin deposit and processed kaolin products. The X-ray diffractometer is an instrument used to identify individual minerals present in the kaolin samples. From the selected four samples three of them were taken from the crude kaolin of the deposit and the other one was taken from the beneficiated kaolin products, and then collectively sent to Switzerland (at University of Freiburg) for laboratory analysis to determine the minerals qualitatively. The mineralogy of these kaolin samples was studied using powder X-ray diffraction (Rigaku Ultima IV diffractometer). The diffractometer is equipped with a Position Sensitive Detector(PSD) D-tex and the tube was operated at 40kV and 40mA. The diffractograms were recorded from 5 to 80^0 2-Theta. Phase determination was performed with the help of the module auto search of the Rigaku PDXL-2 software package.

ii. Geochemical analysis

Eight representative samples were selected for the geochemical analysis purpose from the entire collected samples. The samples were taken and collected from four diffent sites (raw materials) including the source rock, crude kaolin (kaolin deposit and run of mine) and beneficiated kaolin products. The amount of the selected representative samples for this analysis become varied Table 1.1. These selected representative samples were given to ALS minerals Geochemistry found in Addis Ababa for preparation, drying and pulverization processes of the samples. The final whole chemical composition (major, minor and LOI) analysis of these prepared kaolin clay samples were determined in Ireland using Inductively Coupled Plasma-Atomic Emission Spectroscopy (ICP-AES).

iii. Physical tests

In addition to mineralogical and geochemical analysis, investigation of the physical properties of the representative kaolin samples was undertaken. These properties are; grain size distribution analysis, Atterberg limits (plasticity), specific gravity, pH and linear shrinkage. From the collected samples, two most representative samples of the crude kaolin were selected for the grain size distribution analysis, Atterberg limits (plasticity), linear shrinkage tests, specific gravity and pH value determination. One sample of the processed kaolin was also selected for specific gravity and pH value determination. The Atterberg limits (plasticity) and linear shrinkage tests were carried out in the Ethiopian Construction Design and Supervision Works Corporation (ECDSWC) whereas the rest were tested and analyzed in Geological Survey of Ethiopia. The grain size distribution of the samples was analyzed using sieve analysis. During the analysis 200g of the sample was used from each sample. This mass of the sample was allowed to pass through various sized sieve openings. Finally, the retained mass on each sieve was determined. The plasticity test was also carried out to determine the Atterberg limits [plastic limit (PL), liquid limit (LL) and plastic index (PI)] using Atterberg apparatus from the selected two samples. During determination of plasticity test, the prior procedure was finding the value of liquid limit and plastic limit. After that, the plastic index was determined by taking the arithmetic difference of the two limits. These two samples were also used to conduct the dry linear shrinkage test. The general adopted methodology of this research work looks like the following chart.

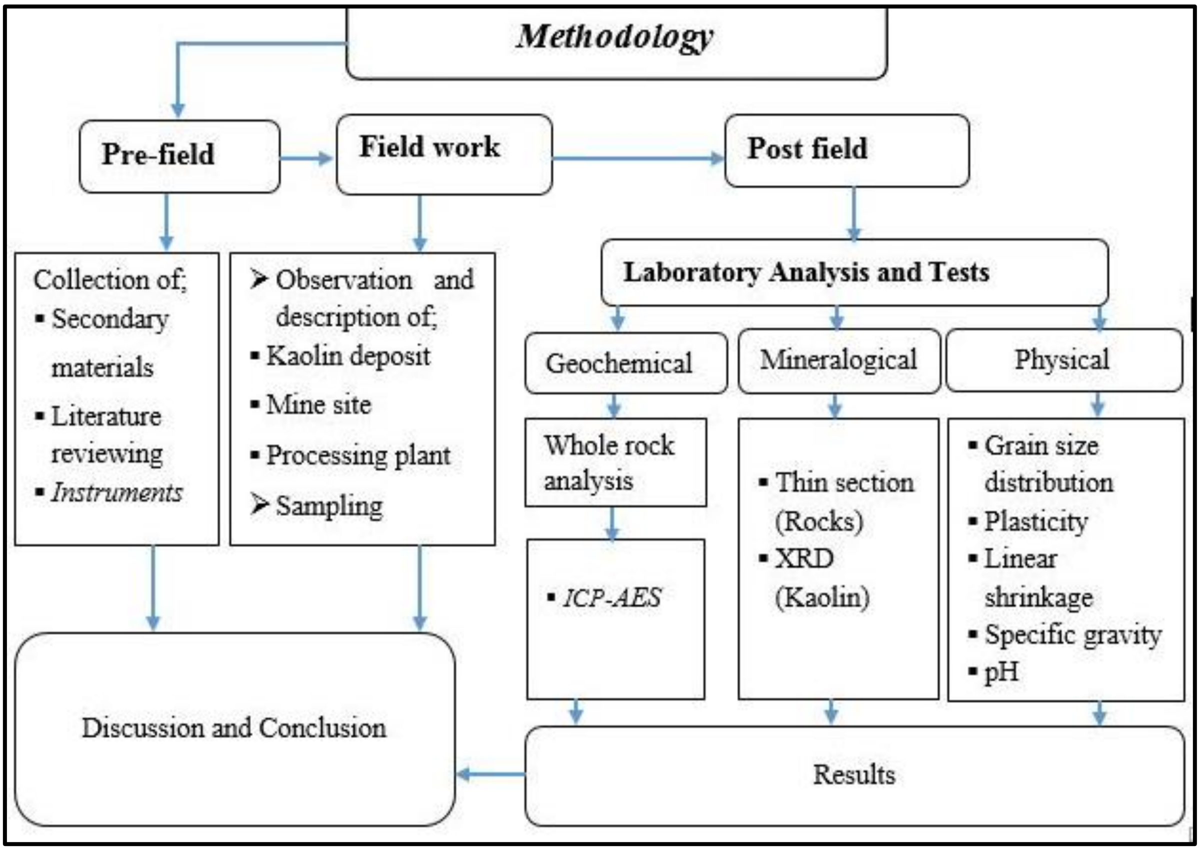


Figure 1.2: *The methodology flow chart of the research study*

1.6 Significance of the study

This research work will have an implication to the beneficiaries and any of readers by providing some new findings. Different individuals and organizations are expected to benefit from the generated new findings of the research. The Ethiopian mineral, petroleum and biofuel corporation and other mining companies, individual researchers and Geological Survey of Ethiopia are among the beneficiaries of the output of this research. The research work will also serve as reference material for the new coming students while they are studding their research work.

1.7 Limitation of the study

The major problem met during the study was lack of full physical and geochemical laboratories in the country. The lack of such services hindered the availability of crucial data on viscosity, brightness and firing properties of the studied material. These tests are required for higher quality demanding industries such as paper and fine ceramics (porcelain) industries. Absence of geochemical laboratories (X-Ray Fluorescent and X-Ray Diffraction) and full physical tests in the country required further efforts and limited the amount of the collected data.

1.8 Chapter scheme

This thesis work has seven chapters that are discussed independently. Seven tables and twenty-nine figures are also contained in different chapters of this document.

Contents	
Chapter [1]	▪ This chapter covers the introduction part, problem statement, description of the study area, objective, methodology and significance of the study ▪ Mineralogical, geochemical and physical analytical methods are adopted and are clearly discussed
Chapter [2]	▪ This chapter covers the literature reviews dialed about kaolin resource (genesis of kaolin, physical and chemical properties of kaolin, impurities and the effect of impurities on the properties of kaolin as well as industrial applications of kaolin) ▪ The mining and processing methods of kaolin are also discussed here
Chapter [3]	▪ In this chapter brief over view of the regional geology and local geology are discussed ▪ The petrographic mineralogical description of rocks and the field description of kaolin deposit are also clearly documented here
Chapter [4]	▪ The adopted mining and processing techniques Bombawuha kaolin deposit are described in this chapter separately
Chapter [5]	▪ This chapter mainly deals about the properties of kaolin deposit ▪ The geochemical, mineralogical and physical analysis result are documented in this chapter
Chapter [6]	▪ The results of different laboratory analyses and tests are briefly discussed in this chapter ▪ It covers the quality of kaolin deposit, impurities, production techniques of kaolin, quality of processed kaolin and effectiveness of wet processing system, quality enhancement techniques and industrial suitability of Bombawuha kaolin products
Chapter [7]	This is the last chapter that deals with the conclusion and recommendations of this research work

Chapter Two

2. Theoretical Background of Kaolin and Methods of Production

2.1 Kaolin resources

Kaolin is characterized by unique physical and chemical properties (Murray and Kogel, 2005). It is chemically inert over a wide pH range, non-abrasive, has fine particle size, has low heat and electrical conductivity, white, has good brightness and opacity (Sabov et al., 1985). The physical characteristics of individual kaolins such as brightness, whiteness, opacity, gloss, film strength, and viscosity vary from deposit to deposit (Wondafrash Mammo, 2011). The most known kaolin resources of the world are the primary deposits of Cornwall in UK and the sedimentary deposits in Georgia and South Carolina in the USA (Murray, 2007).

2.1.1 Genesis and types of kaolin deposit

Kaolin is a phyllosilicate clay material which is derived from granitic igneous, metamorphic and sedimentary rock units as a consequence of hydrothermal leaching or weathering activities (Wilson, 2004; Egbai, 2013; Evans, 1993). During the formation of kaolin, the cations of potassium, sodium, and calcium are removed from the parent mineral due to acidic leaching water (Ali and Dikko, 2015). The mineralogy, chemistry and morphology of the parent minerals determines the formation of kaolin (Murray,1991). Kaolin is formed under low pressures and temperature conditions (María and Ruiz, 2000). Its formation is part of the rock formation processes (Fig. 2.1). Igneous and metamorphic rocks are the main source of kaolin deposit. It is formed due to the decomposition of feldspar and mica minerals on the surface of the earth (Wondafrash Mammo, 2011). The amount of kaolin deposit formed depends on the geological period of time and the rate of weathering and size of the parent material. It is also controlled by geology and geochemistry of the parent rock, climatic and topography of the area (Weaver, 1985). Based on their origin, kaolin deposits can be categorized in to primary (residual) and secondary (sedimentary). These deposits are identified on the basis of physical, chemical and mineralogical characteristics (Kogel, 2014).

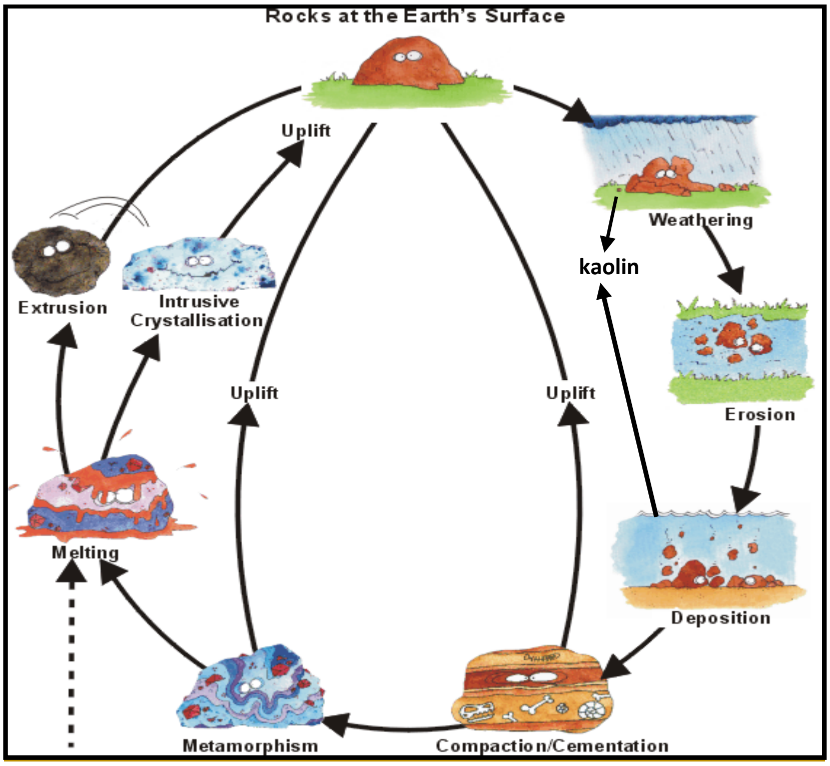


Figure 2.1: *Geologic process of kaolin formation as an integral part of rock cycles (modified from Shafer, 2014)*

i. Residual kaolin deposits

Residual kaolin also called primary kaolin deposits are in-situ deposits that are primarily located at the site of formation as overlaying of the outcrop source rocks (Chen et al., 2004). These deposits are formed either by the weathering or hydrothermal alteration (Sabov et al., 1985; Wilson, 2004). They are not transferred by transporting agents and contain large amounts of unaltered rock fragments and free silica i.e. relict texture, high grit and lower clay content (Wondafrash Mammo, 2011). They are characterized by white colour and low plasticity. This deposit is affected by the impurities either from the parent rock constituent minerals which are not removed by weathering while kaolinization, or the impurities which were brought in by the ground water (Murray and Keller, 1993). Due to the higher amount of abrasive minerals/grits that are survived the alteration process it needs complex processing system (Refaei et al., 2017).

ii. Sedimentary kaolin deposits

Sedimentary kaolin also called secondary kaolin deposit is a type of kaolin deposit formed when the preexisting kaolin is transported and deposited somewhere else. They are formed by the external forces (exogenous geological processes) such as erosion and transportation at special geological conditions (Evans, 1993). Due to this reason these deposits are not common as the primary kaolin deposits (Murray, 2007). They are more contaminated as compared to the primary kaolin deposits. They are also characterized by various colours and of higher plasticity

(Manukaji, 2013). They are also enriched with the impurities (iron-bearing minerals and fine grained anatase) (Bloodworth et al., 1989).

2.1.2 Kaolinite structure and isomorphous substitutions

The chemical property of kaolin is determined by its structure and associated undesired minerals such as quartz, titanoferrous and ferruginous (Murray, 1999). The platy morphology of kaolin is because of the arrangement of atoms in the structure. The tetrahedral silica sheet alternating with an octahedral alumina sheet constitute the 1:1 layered structure called dioctahedral (López-Galindo et al., 2007; Kulkarni and Jadhav, 2016). Dickite, kaolinite, nacrite and halloysite are group of kaolin minerals which have the same ideal chemical formula, $Al_2Si_2O_5(OH)_4$ (Cygan and Tazaki, 2014). Figure 2.2 represents the basic structure of the kaolinite mineral. Theoretically, this mineral has a chemical composition of 46.54% SiO_2, 39.50% Al_2O_3 and 13.96% H_2O (Murray, 2007).

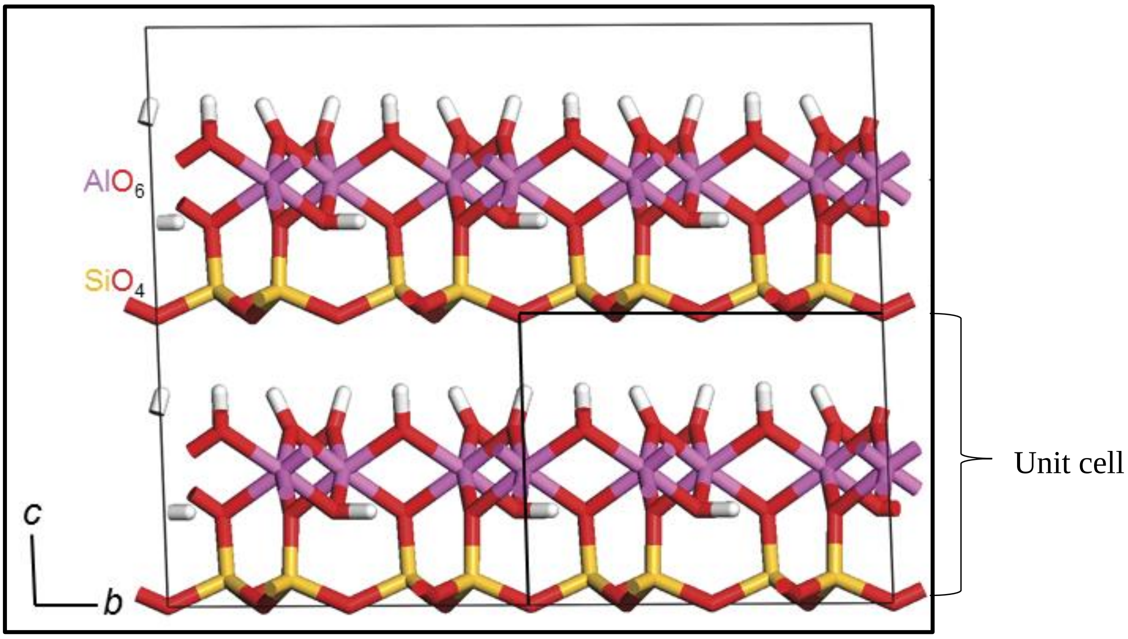


Figure 2.2: *The molecular model of kaolinite, $Al_2Si_2O_5(OH)$ mineral (after Cygan and Tazaki, 2014)*

The kaolinite particles are not easily broken down and the layers are not easily disintegrated because of the ordered, well packed and compacted structure and higher molecular stability (Miranda-Trevino and Coles, 2003). Kaolinite is also characterized by low isomorphous substitution typically neutral phases, higher shear strength, low compressibility, hydraulic conductivity and shrink-swell capacity, cation exchange capacity (1-15 meq/l00g) properties (Cygan and Tazaki, 2014). However, the presence of impurities which are dependent on the genesis of the mineral may affect the structure and properties of kaolinite (Miranda-Trevino and Coles, 2003; Balan et al., 1999). Incorporation of impurities on to the surface of kaolinite mineral is due to the isomorphous substitution of divalent cations during kaolinization process (Manju et al., 2001). Chemical composition, geometric arrangement of atoms and ions and their binding electrical forces are determinant factors of kaolin properties (Barton and Karathanasis, 2002).

2.1.3 Physical and chemical properties of kaolin

The physical and chemical properties of kaolin govern its end industrial application. The processes of formation, particle-size distribution, mineralogical composition and structural order affects the physical and chemical properties of kaolin (Aparicio et al., 2004; Ariffin et al., 2008). Some properties of kaolin that govern its industrial use are explained as follows.

i. Color and Brightness

Pure kaolin is dominantly characterized by white or near to white color. It can be gray, pink, red, or cream depending on the presence of various impurity phases (Siddiqui et al., 2005). The color and brightness of kaolin depends on the availability of titanium and iron bearing impurities (Olaremu, 2015). They are the most governing properties of industrial applications of kaolin. The requirement of color and brightness of kaolin depends on the specifications industries. For example, the brightness greater than 80% would be required for kaolin to be used in paper-filling or paper-coating (Siddiqui et al., 2005).

ii. Grain size distribution

The particle size distributions also determine the industrial uses of kaolin. Many properties of kaolin, including brightness and dispersibility in liquids depend on the average size and uniformity of the kaolin particles (Siddiqui et al., 2005). The grain size distribution of kaolin also controls other properties like plasticity, softness (smoothness), viscosity, whiteness, strength, shrinkage, and other mechanical, optical and printing characteristics of paper sheets (AL-Shameri and Rong, 2009). Kaolin readily disperse in water as the grain size becomes finer and finer. Generally, the plasticity, brightness and smoothness of kaolin increases with decreasing the grain size of the clay material (Murray, 2007).

iii. Plasticity

Plasticity is also another property of kaolin that allows a material to be deformed continuously without rupture till the applied force is removed and retains its new shape when the applied force is removed (Valášková, 2015; Murray, 1999). The plasticity is obtained from the Atterberg limit tests. The Atterberg limit tests include liquid limit and plastic limit. The plasticity (plastic index) is calculated from these two limits by taking their arithmetic deference values (Siddiqui et al., 2005) *i.e. PI=LL-PL*. PI is a measure of the range of moisture content over which the material behaves plasticity (Bain, 1971; Siddiqui, 2005). Plasticity depends on the grain size, morphology and surface character of the particles (Andrade et al., 2011). The optimum plasticity is developed under large proportion of colloidal particles and large amount of water (Heckroodt, 1991). The plastic behavior of kaolin is an essential property in the production of ceramics. However, the presence of undesirable hard particles such as quartz and feldspar grains may lead it to be abrasive and non-plastic and affects its end industrial use (Wilson, 2004).

iv. Linear shrinkage

The linear shrinkage is also a property of kaolin which is affected by the grain size distribution and shapes of the particles. Kaolin deposit with more siliceous and less quantities of clay particles are characterized by low linear shrinkage (Jubair et al., 2011).

v. pH and cation exchange capacity

Kaolin is the least reactive clay that depends highly on the pH of the environment to enhance or inhibit the adsorption of metals on to its flat exposed surfaces or broken edges (Miranda-Trevino and Coles, 2003). The adsorption of cations and releasing of hydrogen ions leads to decrease the pH value (Ahmedin, 2007). The physical and chemical properties of kaolinite is affected by the adsorbed cations (Miranda-Trevino and Coles, 2003). The adsorption of cations on to the surface of kaolin is much higher in the acidic environment and leads to contain much undesirable impurities (Ahmedin, 2007). Pure kaolin is characterized by compacted structure, low shrink-swell capacity and low cation exchange capacity (Eze et al., 2012). It is considered that cation exchange occurs due to the broken bonds around the crystal edges, the substitutions within the lattice, and the hydrogen of exposed surface hydroxyls that may be exchanged (Ma and Eggleton, 1999).

The particle size and pH value strongly affect the CEC of kaolinite. The low pH value (higher acidity) implies the effect of ongoing weathering process and more cations are adsorbed or substituted during weathering (Manju et al., 2001). The presence of iron bearing minerals such as pyrite made kaolin to be highly acidic (lower pH value) which gives rise to higher cation exchange capacity value (Ma and Egleton, 1999). The low values of CEC are probably representative of pure kaolinite and could be increased due to impurities and pore sizes (Olaremu, 2015).

2.1.4 Industrial application of kaolin

Kaolin is a natural industrial material characterized by diverse applications (Chandrasekhar and Ramaswamy, 2006). Kaolin can be employed for different industrial applications by applying different technological processes for its beneficiation and treatments (Worash Getaneh and Solomon Tadesse, 2015). Kaolin is extensively used in the production of paper, plastics, adhesives, rubber, paint, refractories, cement, bricks, ceramics, agriculture, pharmaceuticals (Román et al., 2015; Murray, 2002). Purification of the crude kaolin is essential for the reduction of the impurities of kaolin in order to meet the requirements of various industries (Murray, 2007). The physical, chemical and mineralogical characteristics of kaolin are the determinant parameters of industrial utilization (Ali and Dikko, 2015). Hence, it is required that kaolin has to be fully tested and analyzed in order to evaluate its industrial application (AL- Shameri and Rong, 2009).

The paper industries are the most and largest consumers of kaolin resources both as filling and coating agents in order to smooth the surface of the paper, improve brightness, opacity, gloss and ink receptivity (Murray, 2007). The grain size distribution and brightness of kaolin are the most critical and desirable properties or specifications that controls its end application (Murray, 2000). Thus, fine and uniform particle size, easily disperse in water, soft and low abrasiveness are some of the required properties of kaolin for paper filling (Siddiqui et al., 2005).

Kaolin is also used in the production of ceramics. The most important properties of kaolin as a raw material for the ceramic production are plasticity, particle size distribution, cation exchange capacity, strength, fired colour, drying and firing shrinkage. It also requires low quantities of iron and titanium (Murray, 2007). The main characteristic of kaolin minerals is their ability to disperse in water (Valášková, 2015). Kaolin can be used in the rubber industries because of its reinforcing and stiffening properties (Murray, 2007). Kaolin is also used in paint industries because of its chemical inertness and insoluble in the paint system, dispersion properties, and low cost. The use of kaolin as pigment in the paint is to provide colour, opacity and gloss (Alabi and Omojola, 2013). It also has enumerable application in various field areas, such as, cable insulation, specialty films, fertilizers and plastic industry. Kaolin has very attractive application in the purification of water on which our life depends. It is also used in pharmaceutical preparations as a filtering agent (Murray, 2002).

2.1.5 Impurities of kaolin

Pure kaolin does not occur in nature, they contain mixtures of different clay and associated minerals. The impurity minerals are derived from the parent rock during kaolinization (Murray, 2007). Impurities are materials which are found associated to the main required minerals and degrades its properties and value. The impurities impair the quality of kaolin and affects its end utility in various industrial requirements (Miranda-Trevino and Coles, 2003). The type and amount of impurities present in kaolin is mainly dependent on the bulk-rock composition. Hence, the purity of kaolin deposit depends on the composition of the source rocks and the extent of kaolinization (Olaremu, 2015). The presence of impurities in kaolin could be both organic and inorganic, water soluble and insoluble, crystalline or amorphous, discrete and coatings (Njoka et al., 2015). The common associated impurities of kaolin include; siderite, quartz, feldspar, tourmaline, ilmenite, zircon, mica and pyrite (Ali and Dikko, 2015). Ferruginous and titanoferrous minerals are the most common deleterious and coloring minerals of kaolin that change the color and affects other physical and chemical properties (Ramaswamy and Raghavan, 2011).

A. Types of impurities of kaolin

Identification and examination of the impurities of kaolin using physical, chemical, mineralogical and microscopic techniques is very essential. The investigation and identification of the impurities of kaolin is important to understand the properties and to select suitable processing techniques (Ariffin et al., 2008).

i. Grits

The most common grit components of kaolin are quartz, mica, unaltered feldspar and other coarser and heavy minerals (Ali and Dikko, 2015). The presence of coarser materials (grits) is dominantly related to weathering and alteration conditions of the parent minerals of kaolin (Murray, 2007).

ii. Coloring impurities

The existence of iron in kaolin can be in the form of oxides, hydroxides, oxy hydroxide, sulphides and carbonates along with iron stained quartz/anatase and mica (Olaremu, 2015). The iron impurities (coloring impurities) can also exist in kaolin as either “structural iron” or “free iron”. The removal of structural iron is more laborious, costly and complex as compared to the free iron during the beneficiation of kaolin (Ramaswamy and Raghavan, 2011). The presence of iron (even as low as 0.4%) can affect the colour of the kaolin deposit (Štyriaková et al., 2003).

B. Effect of impurity minerals

The physical and chemical properties of kaolin are affected by undesired ancillary minerals such as quartz, titanoferrous, ferruginous, micaceous and carbonaceous impurities (Olaremu, 2015; Chandrasekhar and Ramaswamy, 2006). The existence of impurities mainly iron bearing minerals affects the color (whiteness) and brightness of kaolin. The coarser impurities (grits) also affect the properties of kaolin such as; abrasiveness, viscosity, plasticity, rheology and structural order (Ramaswamy and Raghavan, 2011; AL-Shameri and Rong, 2009). The impurity minerals hence negatively affect the quality of the commercial product (Kulkarni and Jadhav, 2016). For instance, in the production of high quality materials the iron content in kaolin should be lower than 0.8% (Mandal and Banerjee, 2004). The presence of iron and titanium bearing minerals affect color and brightness whereas, the existence of quartz and feldspar parent minerals affect the abrasiveness of kaolin (Murray, 1999).

2.1.6 Market condition of kaolin

The world kaolin market is unusual and dominated by two large free market economy countries (United States and United Kingdom). The market condition of kaolin is controlled by the quality of product, demand and supply and its distribution. The occurrence of new high-quality kaolin sources and maximizing supply of low-grade materials affect the market of kaolin (Nyakairu et al., 2001). Kaolin has a medium to high unit value and can be internationally traded throughout the industrialized world in its highly refined state (Evans, 1993). The United States, England, Brazil and Australia are the major exporting nations. Most of exported kaolin is particularly with the grade specified for coating paper. Kaolin which is used for ceramics and fillers is usually restricted to regional or local markets. The better-quality kaolin product is required for higher grade industries (paper industries) and can be recycled internationally. The better quality of kaolin makes up most of the tonnage sold and have the highest unit value. Kaolin product characterized by white, bright, fine, smooth and non-abrasive properties is required for higher graded industries and can be traded globally. The increasing of new industrial applications of kaolin makes any promising deposit worthy exploiting, especially in the developing world.

2.2 Mining and processing of minerals

Mining is the world's second oldest industry (next to agriculture) which contributes for the economic growth of a country (Tawiah and Baah, 2011). Mining is the process of digging into the earth for the extraction of valuable materials including metallic minerals, industrial minerals and rocks, energy minerals, and gem minerals (Evans, 1993). The principal life cycles followed by mining industry for the extraction economic minerals are; prospecting, exploration, mine planning, mine development, exploitation, processing, and mine closure and reclamation (Kogel, 2014). The processing of minerals is also required to upgrade the purity or quality of minerals by removing the unwanted gangue minerals associated with the main mineral (Murray, 2007). The choice of processing techniques could be varied with the nature of the required minerals and associated waste materials/impurities.

2.2.1 Mining of kaolin

Kaolin is a type of industrial material resource which is mostly formed at or near the surface conditions. According to Kogel (2014) this resource has almost the same mining life cycles with other earth resources, including coal, industrial minerals, and metals/ precious metals. The geologic investigations and economic analyses to prove the financial feasibility of kaolin deposit are the prior stages conducted before actual mining. As a result, the major economic factors of kaolin industry including; costs of exploration and mine development, stripping, mining and crude clay transport, kaolin processing and drying, final product transport, and energy and water should be considered during feasibility study (Wondafrash Mammo, 2011).

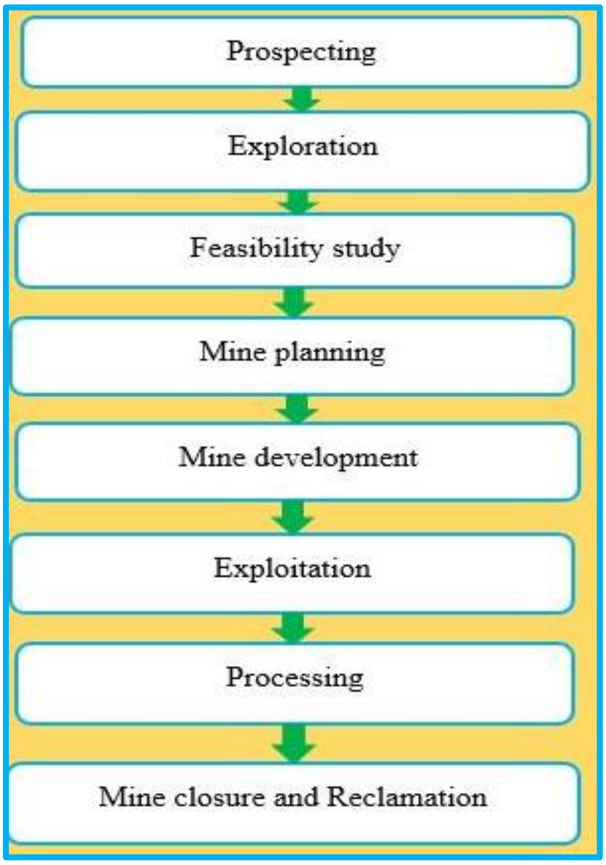


Figure 2.3: *The mining life cycle of kaolin deposits (Kogel, 2014)*

Concerning to mining method, most kaolin deposits around the globe are mined by the surface mining methods. Surface mining method is a cost-effective method and requires fewer workers to produce the same quantity of ore compared to underground mining method (Tawiah and Baah, 2011). Open pit is one of the most common surface mining method used to extract the kaolin deposit. Kaolin can be extracted by hydraulic and dredging surface mining methods. The extraction of kaolin deposit could be performed with the help of various types of equipments including draglines, power shovels, front-end loaders, backhoes, scraper-loaders, and shale planers (https://www3.epa.gov/ttnchie1/ap42/ch11/final/c11s25.pdf).

2.2.2 Processing of kaolin

After proper mining, processing (also called beneficiation) of crude kaolin is required to optimize the higher commercial properties. It is quality upgrading process mainly aimed at removing the abrasive coarse-grained impurities (like feldspar, quartz) and undesirable minerals (like mica, iron oxide). The removal of the undesirable components improves the critical properties of the kaolin product including chemical composition (purity or assay grade), particle size distribution, whiteness and brightness (Wilson, 2004; Kogel, 2014; Refaei et al., 2017). This enhancement of quality adds economic value of kaolin product and is possible that to use as a high-quality raw material in ceramics (porcelain) and paper industries. There are various beneficiation techniques which can reduce the impurity contents and enhance the quality of the product (Roman et al., 2015).

The selection and sequentialisation of processing methods for crude kaolin depends on various factors. The nature (type) and amount of impurities, physical and chemical characteristics of kaolin, access and cost of processing technique, required specification grade (quality) of the product, amount of investment available and the availability of water are some of main factors considered during the selection. After the proper feasibility study of these factors is made, the selection of physical, chemical and biological processing techniques can be possible to remove the impurities and improve the quality of kaolin (Ramaswamy and Raghavan, 2011).

Processing techniques including crushing, grinding, screening, drying, calcining, blunging and extruding can remove the impurity materials (Ajayi and Adefila, 2012; Murray, 2007; Refaei et al., 2017). The magnetic separation (especially super conducting-higher gradient separation), flotation, selective flocculation, sedimentation, chemical and biological leaching methods can also reduce the impurities of kaolin (Qiu-xiang et al., 2011; Raghavan et al., 2000; Roman et al., 2015; Maynard et al., 1969). In general, there are two most important processing methods of kaolin. These are dry and wet processing methods (Murray, 2007).

i. Dry processing method

Dry processing method (also called air-floatation) is low costly, simple (not sophisticated to remove impurities), provide low quality of product and generates huge amounts of dust as compared to the wet processing method. The beneficiated products are produced for low-grade applications. The process does not require water as a beneficiation purpose, rather it employs air classifier for the removal of grit size particles (Kogel, 2014). The selection of dry processing mainly focusses on the properties (quality) of kaolin deposit including the brightness, grit percentage, and particle size distribution to make a particular product. This processing method consists principally of crushing, drying and pulverizing the crude ore prior to air-floating and then removing the impurities and oversized particles (Fig.2.4). The products of dry processing are mainly used in the rubber industry and to some extent for paper filling and to produce fiberglass and sanitary ware (Murray, 2007).

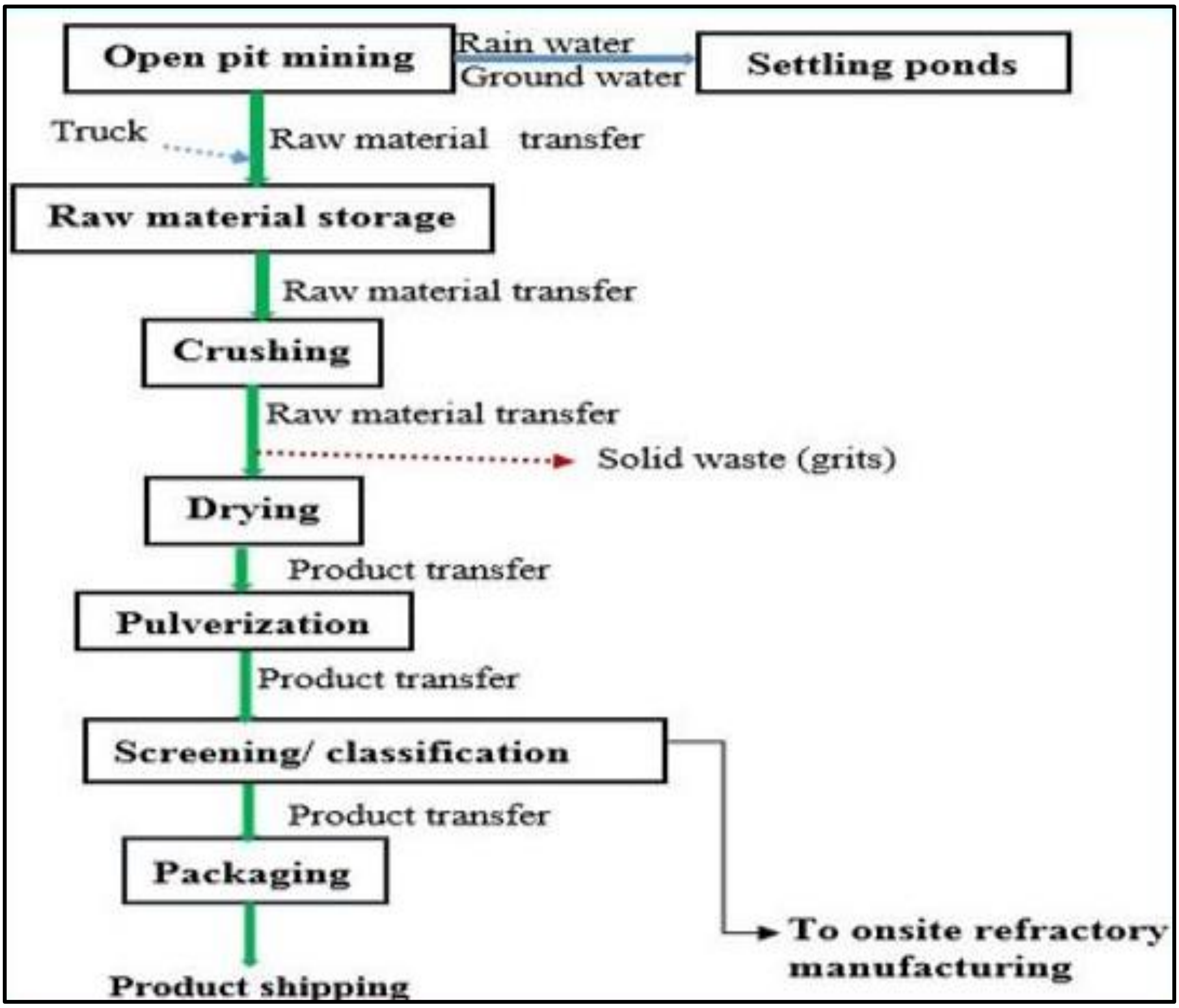


Figure 2.4: *Process flow diagram for kaolin mining and dry processing method (https://www3.epa.gov/ttnchie1/ap42/ch11/final/c11s25.pdf)*

ii. Wet processing method

The second processing method of kaolin is wet processing (also called water-washing) method. This is the most sophisticated and laborious technique adopted for the sake of high-grade materials preparation especially when very low grit contents are required. Wet processing method provides higher purity and enables production of a broader range of particle sizes and shapes (Kogel, 2014). All paper coating-grade kaolins and most filler kaolins are produced using the wet processing method. The wet processing is more effective and water-intensive method that produces higher grades of kaolinite concentrate. Due to its effectiveness, it becomes feasible to process the crude kaolin with lesser quality and higher grit contents (up to 30%) than dry processing method (Murray, 2007). Essentially, the effectiveness of wet processing and use of kaolin in various industrial applications depends on the required commercial properties (Kogel, 2014).

Wet processing method follows a set of procedures and steps to obtain enhanced properties of kaolin product (Fig. 2.5). Once the crude kaolin is mined from the open pit by the excavator, it would be loaded to the storage area found near the processing plant. The crude kaolin (run of mine) is then fed to the processing plant and mixed with water (blunging) to disperse and produce a slurry and vigorously agitated. The purpose of blunging is to disintegrate the crude kaolin into individual kaolin particles by the vibrating drum scrubber/trommel (Ramaswamy and Raghavan, 2010). After the dispersion of crude kaolin in water, the coarse grit materials (> 44µ) started to remove out of the slurry by settling procedures and vibrating screens (Murray, 2007).

The coarse fraction phases of impurities (grits) such as quartz, feldspar, mica, ilmenite, rutile, and pyrite concentrated in kaolin are therefore eliminated by screening. The size classification produces different grades of kaolin with varying particle size distribution. The increase in the finer fraction can result with improved brightness due to the increase in surface area and hence more light scattering sites (Olaremu, 2015). During sizing, the coarser (quartz and mica) and/or denser (ilmenite, rutile etc) impurity minerals get separated from kaolinite mineral. The classification or screening of these coarse-grained particles (grits) are fractionated by wet screening through sluice box or jigs and sedimentation tank or by hydrocyclones (Murray, 2007). The size classification of kaolin slurry using a set of hydrocyclones leads to the enrichment of finer kaolin fractions and the removal of iron and titanium bearing minerals in coarse size ranges (Ramaswamy and Raghavan, 2010).

After degritting of coarser materials, finer material enriched slurry is pumped to the thickener and then filtered and dewatered by means of a filter press, centrifuge, rotary vacuum filter, or tube filter. The filtered and dewatered slurry material is shipped or further processed by drying in apron, rotary, or spray dryers. The moisture content of kaolin is removed in the dryer section due to the elevated temperature (Murray, 2007). Following the drying step, the kaolin may be calcined for further enhancement to be used as filler or refractory material. Various hearth furnaces including flash and rotary calciners are used to calcine kaolin product. The calcination process is carried out to meet the required commercial properties used in various higher quality demanding industries which are not obtained in drying stage. This calcination process can be considered as a third processing method of kaolin and described in detail as a separate sub topic below.

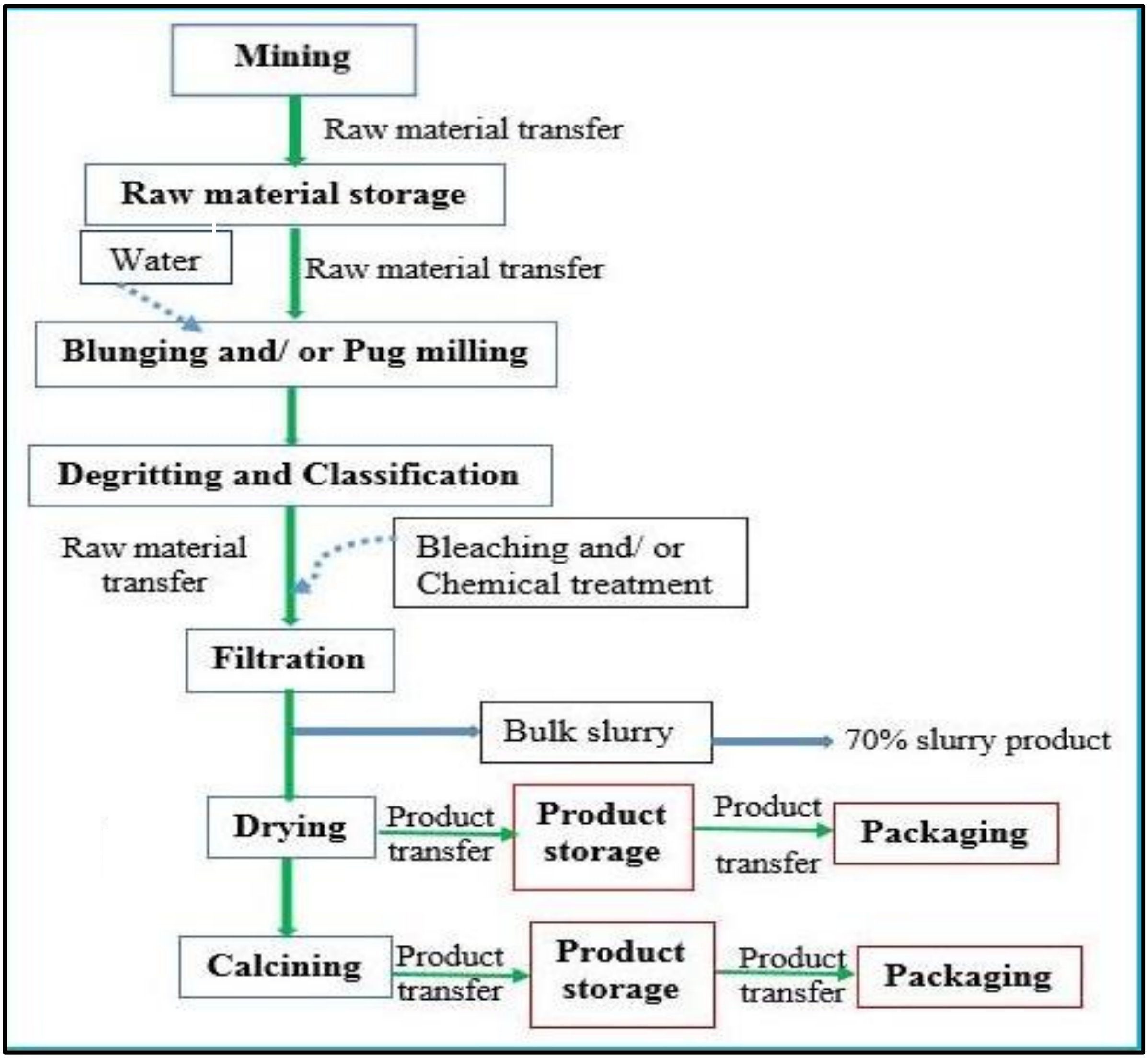


Figure 2.5*: Process flow diagram for wet process kaolin: (https://www3.epa.gov/ttnchie1/ap42/ch11/final/c11s25.pdf)*

iii. Calcination of kaolin products

Depending on the quality specifications, calcination (also called thermal processing) of kaolin products could be conducted. This mechanism is used to enhance the physical and optical properties of kaolin and carried out after the crude kaolin is processed either by dry or wet processing methods (Murray, 2007). Calcination causes a chemical reaction between the alumina and silica in the clay and increases whiteness and hardness, improves electrical properties, and alters the size and shape of the kaolin particle (Ilić et al., 2010). The calcined products could be used in different industries including rubber, cement, ceramics, paint and certain paper applications (Kogel, 2014). The refractory materials are non-metallic materials which have unusual high melting temperatures and can maintain their structural properties at very high temperatures (Chukwudi, 2008). Refractory kaolin can be used for the production of various refractories in metallurgical industry, in power generation, and for the construction of kilns and furnaces (Heckroodt, 1991).

2.3 Previous works of the area

Southern Ethiopia particularly Adola area has been used as a target area for metalic and industrial mineral resources exploration. Bombawuha kaolin deposit is one of the industrial mineral resources lied at the tip of Adola gold field that has been prospected and explored by many Ethiopian and foreign geologists for many years (Said Mohamed and Sentayehu Zewdie, 2000). Bombawuha kaolin occurrences were initially investigated in 1970 by a group of Chinese geologists (Sabov et al., 1985). Because of the increasing demand of resources for ceramic and refractory raw materials, the prospecting and exploration of kaolin resource was carried out in different parts of the country. Typically, the prospecting and exploration of this economic resources were linked to acidic intrusive rocks (granites and pegmatites) and gneissic rocks (Hailemichael Fentaw and Tibebu Mengistu, 1998).

Most of the EIGS (Ethiopian Institute of Geological Survey) geologists had been carrying out prospecting and preliminary exploration of Bombawuha kaolin deposit since 1981. The first intensive exploration activities had been made from 1983-1984 to investigate the physical and chemical characteristics as well as reserve amount of Bombawuha I and II kaolin deposits (Sabov et al., 1985; Tibebu Mengistu and Hailemichael Fentaw, 2003). The reserve amount of Bombawuha I kaolin deposit was calculated as 132.3 thousand tons of pure kaolin under C1 category, and 158.9 thousand tons under C2 category. Whereas, Bombowoha II kaolin deposit had only C2 categories and its calculated reserve became 39.4 thousand tons. Bombawuha I kaolin deposit had also been recalculated by incorporating additional pitting, trenching and various tests in 1986 to produce a report containing 259.0 thousand tons under C1 category and 247.9 thousand tons under C2 category of both kaolinized pegmatite and granite (Sabov et al., 1986). Here, the reserve of C1 category corresponds more or less to describe indicated or probable reserves whereas C2 category corresponds more or less to inferred or possible reserve of the kaolin deposit respectively.

The EIGS collaboratelly with EMRDC (Ethiopian Mineral Resource Development Corporation) had also conducted an exploration activity for two years (1991-1992) to recalculate Bombawuha-I kaolin deposit. The study had come with reduced reserve quantity (150,015.90 tons under C1 and 75,382.7 tons under C2 categories) derived from both pegmatite and granite rocks (Said Mohamed, 1993). This reserve was considered to be insufficient to supply Tabor ceramic factory and other potential customers for a long period of time. As a result, further prospection and exploration activities became necessary to find other possible kaolin resource around the existing reserves. The exploration activity conducted by EIGS from 1994 to 1995 then met a new kaolin occurrence (i.e. Bombawuha III) within kaolinized pegmatite and kaolinized granite around the existing reserves.

The latest exploration had been made on weathered granite and pegmatites of S-W part of Bombowoha I and Bombowoha III kaolin deposits to investigate the physical and chemical characteristics as well as the reserve amount of the deposit. Accordingly, a total of 2,172,850 tons of pure kaolin is calculated under Cl category and 879,850 tons under C2 category for both deposits (Said Mohamed and Sentayehu Zewdie, 2000). As far as quality is considered, Bombawuha kaolin deposit had been characterized by higher alumina and less impurities content compared to the other kaolin deposit of the country (Tibebu Zewdie and Hailemichael Fentaw, 2003).

Chapter Three

3. Geology

3.1 Regional geology

The Precambrian basement of southern Ethiopia is assumed to form part of the upper Proterozoic orogenic belt of the Arabian- Nubian shield (ANS). The low- grade juvenile arc complexes mainly muscovite and biotite schists are the major greenschist facies rocks of the area. These green schist facies rocks are locally intruded by syn- and post- tectonic granitoids of quartz- feldspar pegmatite and equivalent aplite intrusions (Said Mohamed and Sentayehu Zewdie, 2000; Weldehaymanot, 1995). Basically, southern Precambrian basement comprises Lower complexes (Awata group), Middle complexes (Wadera group) and Upper Proterozoic (Adola group) complexes. The Lower-Middle complexes (Wadera group) and Upper Proterozoic (Adola group) complexes are divided by north to south trending deep seated fault (Kazmin, 1972). The two Precambrian complexes (Wadera and Adola group) are characterised by a variety of rocks. The metamorphosed sandstones, quartzo-feldspathic rocks, and mica schists are recognized under the Wadera group: whereas the Adola group is composed of low grade of ophiolitic rocks, andesitic metavolcanics and associated metasediments, clastic and carbonate sediments, amphibolites, mica schists, quartzite, and quartz-graphite rocks. The Awata group (Lower complex) is characterised by high grade gneiss (Said Mohamed and Sentayehu Zewdie, 2000; Kazmin et al., 1978).

The Wadera group is intruded along the fault by syntectonic granitoid of upper Proterozoic aged granites and granite - gneisses. The intrusion of granitoid and tectonic shifts took place simultaneously and resulted in the formation of open cracks and fissures filled with the post tectonic pegmatite magma. Such an event can be evidenced from the presence of numerous mica-feldspathic veins and veinlets intruding the host gneisses in different directions. The upper proterozoic age of granites and granite-gneisses as well as the latter coming pegmatite rocks became the source of Bombawuha kaolin deposit (Sabov et al., 1985). Tertiary volcanic rocks mainly basalt and some rhyolites are also well exposed towards the north part of the deposit (Said Mohamed and Sentayehu Zewdie, 2000).

In general, different formations that contain different units are found in southern Ethiopia. Aflata formation is the main formation at which the Bombawuha kaolin deposit is hosted. This formation is characterised by the biotite and biotite-hornblende gneiss, mica schist and amphibolite. There are also other formations and units that characterize the southern Ethiopia such as Chakacha formation (amphibolite, plagioclase-chlorite-actinolite schist, phyllite, quartzite), Kenticha formation (mica schist with frequent garnet and staurolite gneiss, amphibolite, graphite schist, marble). On the other hand, a number of units are also exposed in southern Ethiopia such as staurolite; amphibolite; olivine basalt, rare alkaline rhyolite and tuff; serpentinite and biotite granite as shown in Fig.3.1. Since intence deformation has been undergone in the area, different geological structure such as faults, and other micro and macro structures are also expected.

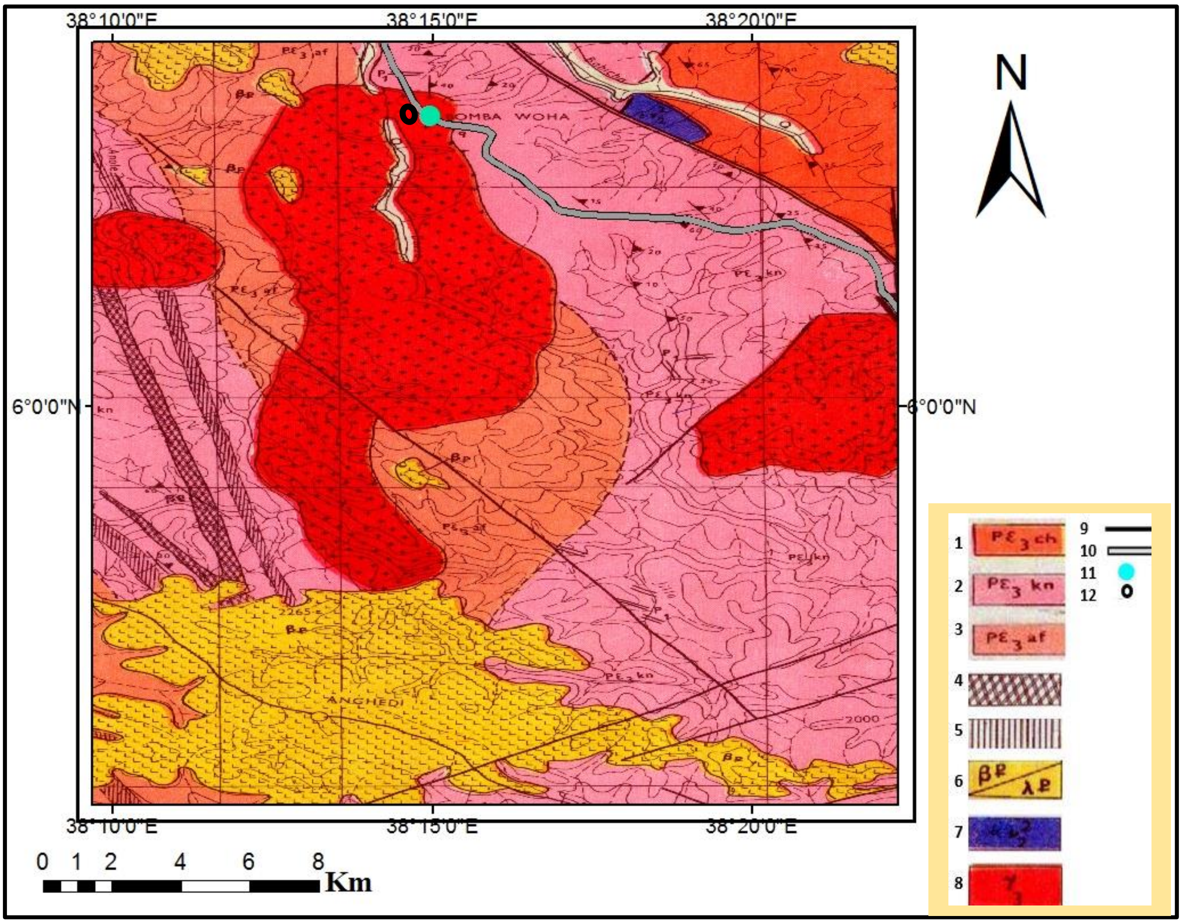


Figure 3.1: *Regional geological map of the area (1) Chakacha formation , Amphibolite, Plagioclase-chlorite-actinolite schist, phyllite, quartzite;(2) Kenticha formation: Mica schist with frequent garnet and staurolite gneiss, amphibolite, graphite schist, marble (3) Aflata formation: Biotite and biotite-hornblende gneiss, mica schist, amphibolite(4) Staurolite (5) Amphibolite (6) Olivine basalt, rare alkaline rhyolite and tuff (7) Serpentinite (8) Biotite granite (9) fault (10) Main road (11) Bombawuha town (12) Bombawuha mining site (adopted from EMRDC, 1982)*

3.2 Local geology

Bombawuha area is characterized by a syn tectonic granitic intrusions that intrudes to the host rock of mica schist. The geology of the deposit and the surrounding area has been described and mapped by Said Mohamed and Sentayehu Zewdie (2000) see Fig.3.5. Before describing the kaolin deposit, it is better to describe the nearby rock, and the parent materials (source rocks) of the kaolin deposit. The mineralogy and texture of the surrounding rocks are described to recognize the mineral contents and textural form of parent minerals. This also helps to understand the interrelationships of the kaolin deposit with the surrounding rocks and their effect on the quality of kaolin deposit. Samples are collected from nearby highly weathered mica schist and granite rocks. The granite rock collected at the base of the mine site and south western of the mine is the major parent (source) rock of the kaolin deposit. Whereas, the mica schist is the host of this source rock collected near the mine sites. These two rocks have different physical and chemical characteristics.

3.2.1 Mica schist

Mica schist is found at the eastern part of the kaolin deposit. This rock is intensively weathered and almost decomposed to reddish lateritic soil. Physically, it can be easily broken as it is hammered and has a red to brown color with a small thread like oriented white veinlets (Fig. 3.2A). The petrographic mineralogy study indicates that, the rock is constituted by the minerals biotite (56%), quartz (16%), opaque-iron oxides (9%), plagioclase (8%), muscovite (5%) and chlorite (6%). Of these listed minerals biotite is the most iron bearing mineral that is the principal deleterious impurity of kaolin. Texturally, this rock is characterized by schistose texture. The constituent minerals themselves show different textural characteristics. The micaceous minerals, mainly biotite and muscovites have similar texture (flaky texture) with different color characteristics while they are observed in the petrographic microscope. Biotite has color of dirty brown to yellowish color (Fig. 3.2B) but muscovite is characterised by colorless or whitish color. The minerals quartz, plagioclase and opaque-oxide minerals are characterised by their anhedral grain shape/texture.

A number of fractures, veins and cross cutting veinlets are observed as major structures that characterize the mica schist rock (Fig.3.2A). The exposure of these fractures, veins and veinlets in this rock unit implies the rock had been subjected to an intensive deformation. The veins and veinlets are formed because of later coming intruded material. The intruded material is altered and decomposed to white kaolin material (i.e. characterised by powdery nature of very soft characteristics) together with the host rock due to surfacial conditions. The rock has also north-south trending foliations. Basically, the petrographic study indicates that mica schist has not a relationship with the kaolin deposit but it is found as a host of the source rocks of the deposit. However, the quality of the nearby (hosted) kaolin deposit may be affected by the iron impurity released from biotite and other iron bearing minerals during decomposition of the host rock by chemical weathering. The released iron impurity can be transported with the help of surface (meteoric) and ground water towards the kaolin deposit.

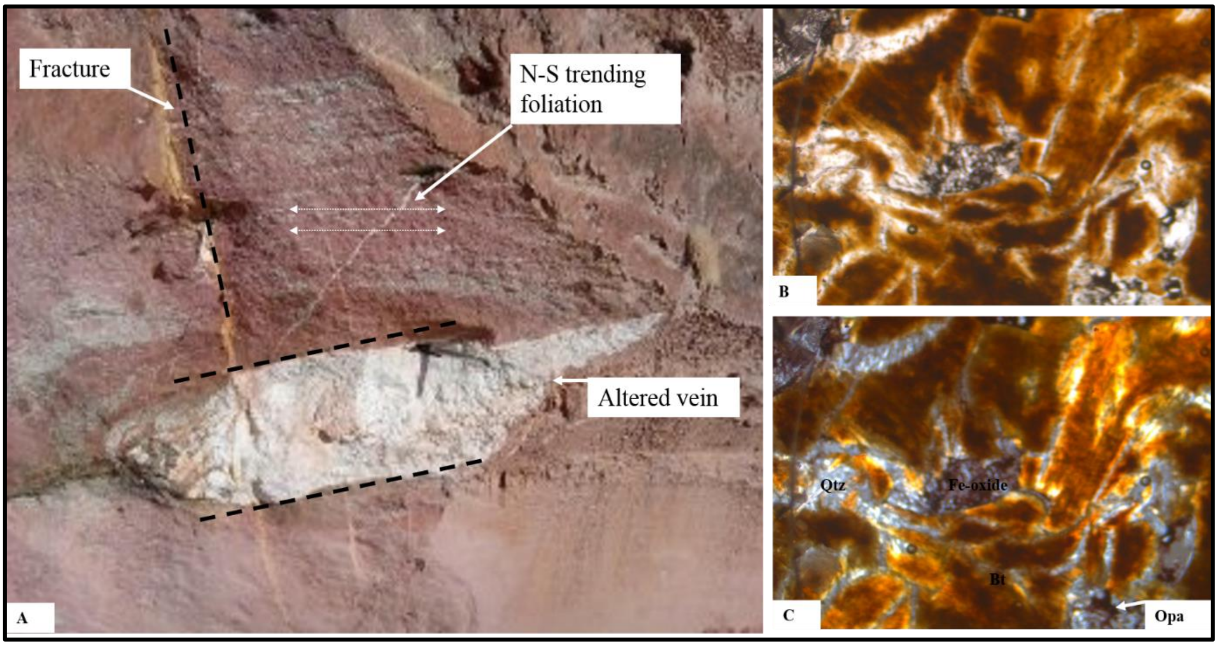


Figure 3.2: *(A) Field photo of decomposed biotite schist rock (BR-1) characterised by red to brown color, schistosity foliation as well as fractures and a hydrothermal vein product. The photos B and C are microphoto pictures of this rock under petrographic microscope in different views; PPL (B) and XPL (C). The included labels stand for; Qtz=Quartz, Bt=Biotite, Opa= Opaque minerals.*

3.2.2 Granite

The granite rock is exposed mainly in the south western part of the kaolin deposit and bottom of the open pit mine. The granite rock is characterised by granular (phaneritic) texture, gray color, soft and friable physical characteristics (Fig. 3.3). The granite rock has also been intruded by the later coming various sizes of pegmatitic vein.

Figure 3.3: *Field photo of granite having gray color and granular texture characteristics sampled at the base of the open pit.*

Mineralogically this rock is composed of quartz (40%), k-feldspar (30%), plagioclase (15%), biotite (11%), muscovite (3%) and other opaque/Fe oxide minerals (1%). However, the pegmatite vein is characterized by coarser minerals of quartz, mica and altered kaolin product. The contained minerals have different physical and optical characteristics. Quartz is colorless under plane polarized light and shows extinction under cross polarized light (Fig. 3.4B). Biotite and muscovite minerals are group of mica that show different optical characteristics. Biotite is characterized by brown to dark brown color and elongated form under both plane polarized light (PPL) and cross polarized light (XPL) (Fig.3.4A and B). Whereas the muscovite mineral become colorless under plane polarized light (PPL) but shows higher order reflectance color when it is observed under cross polarized light (XPL) (Fig. 3.4B). The microcline and plagioclase minerals have also easily distinguishable optical characteristics of 'cross hatched' and 'zebra like' twining respectively under cross polarized light (Fig.3.4D).

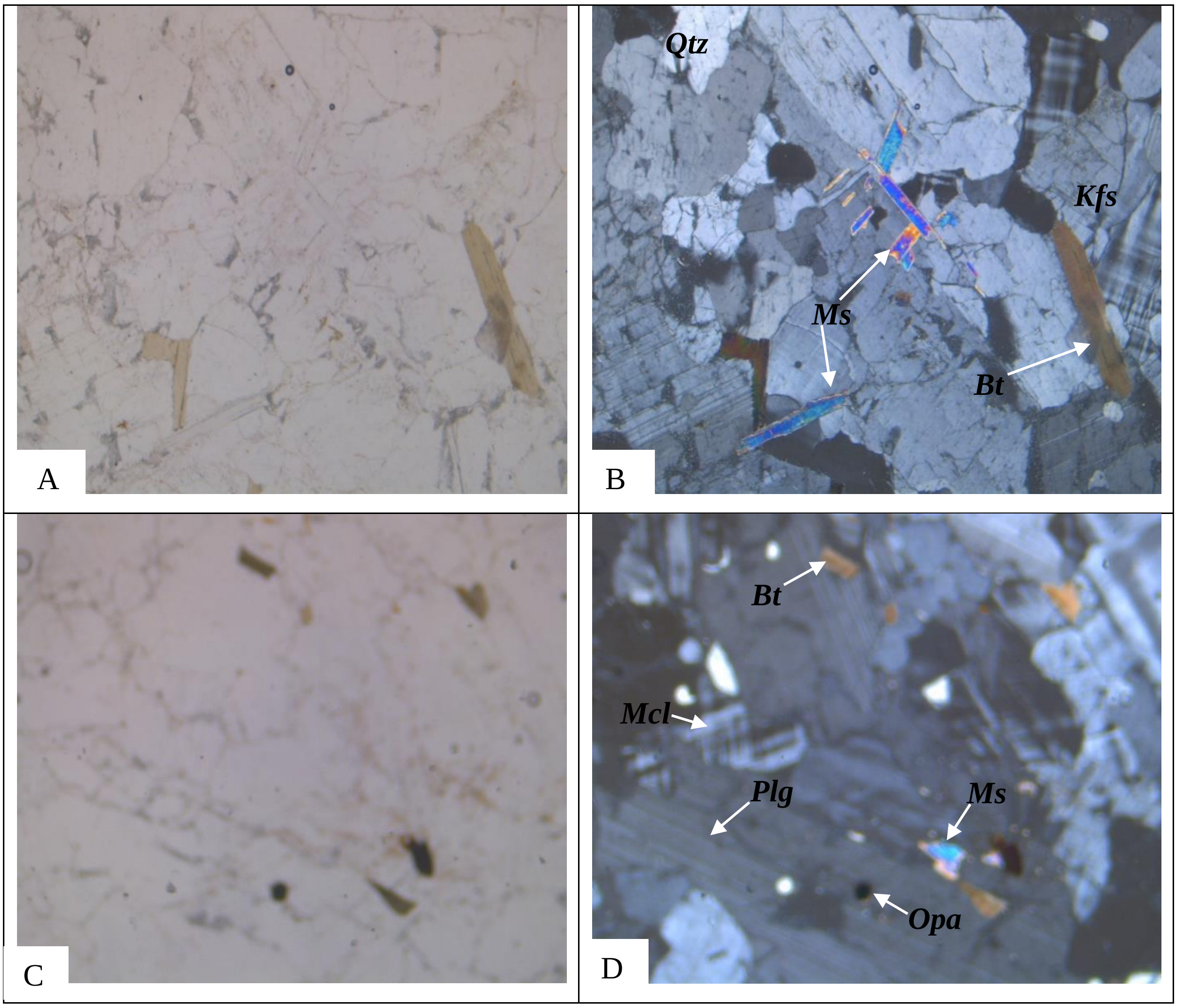


Figure 3.4: *Microphoto of granite under petrographic microscope in different views; PPL (A and C) and XPL (B and D) The labels in the photo stand for; Ms= muscovite, Bt=Biotite, Qtz= quartz, Kfs= K-feldspar, Plg=plagioclase, Mcl=microcline and Opa=opaque minerals*

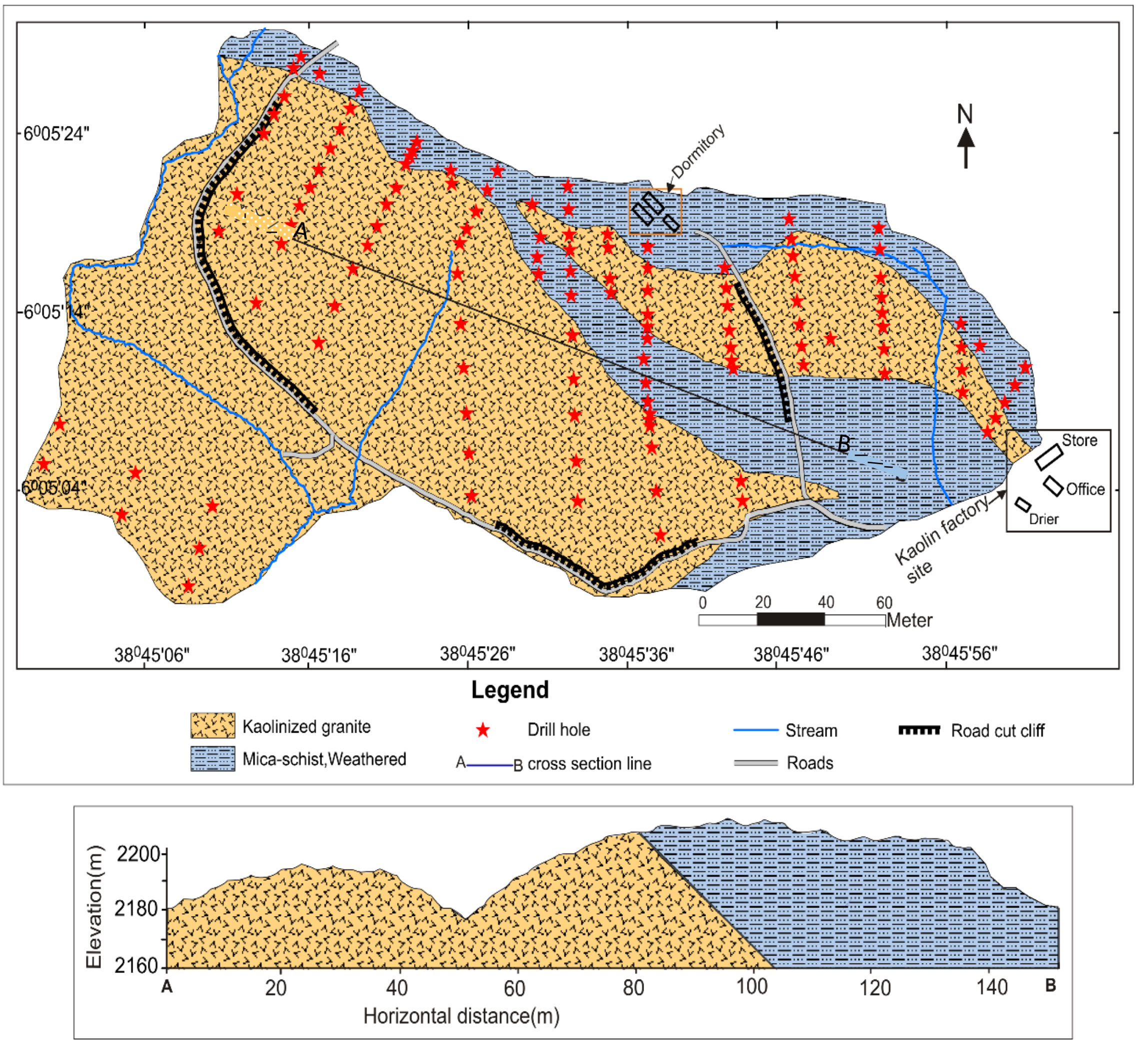


Figure 3.5: *Geological map and cross section of Bombawuha kaolin deposit (after Said Mohamed and Sentayehu Zewdie, 2000)*

3.2.3 Kaolin deposit

The Bombawuha kaolin deposit lies on the northern part of syn to post tectonic intrusion of granitic body which extends to the west and south of the area (Said Mohamed and Sentayehu Zewdie, 2000). The intruded bodies (granite and pegmatite rocks) are source rocks of the kaolin deposit. The mineralogical and textural characteristics of the kaolin deposit is controlled by these parent rock compositions. These two source rocks are identified on the basis of texture, mineral content and physical characteristics. These rocks are kaolinized and have similar mineral content that have different grain size. The resulting kaolin deposit has also similar texture and structure with the unaltered source rock. It has a relict texture which indicates the residual type deposit. The main favorable conditions that facilitate the kaolinization process of the granite and pegmatite rocks are high rainfall, rapid drainage system, fractures, tropical climatic condition, low water table, and sufficient water supply (Nyakairu, 2001 as cited in Murray and Keller, 1993).

Bombawuha kaolin deposit forms a hill like land form and bounded by the main road and local streams. The deposit is characterized by a friable characteristic resulted from the presence of coarser siliceous minerals. The deposit constitutes both primary minerals including quartz, mica and feldspars, and secondary minerals mainly clay minerals. The primary minerals are remained as resistant mineral during weathering process. The deposit has also different physical characteristics. Different colors are observed in the deposit depending on the depth of exposure. The color of the deposit varies from reddish brown upper part to pinkish and becomes gray to white as the depth is increased. The reddish-brown color is basically the overburden material that varies in thickness from the top ridge to the lower slopes of the deposit. The thicker overburden material is found on the top part of the deposit and decreases at the slope sides of the deposit. As the depth of the deposit is increased, the pure gray to white colored kaolin ore is found. Some yellowish brown and pink colors are also observed near the surface and at the contact of mica schist. This color variation is due to the presence of impurities such as iron oxide. During weathering this impurity contaminate the kaolin deposit and affects its properties. The physical characteristics of kaolin ore differ from the overlaid overburden material and underneath unweathered source rock.

The narrow cross-cutting veins and veinlets of kaolinized pegmatite are commonly observed in the fresh and kaolinized granite. These dissecting networks of kaolinized veins and/or veinlets have different size and directions and are exposed mainly at the road cut of the deposit and along the streams. The orientation of most pegmatite veins is nearly north to south. The pegmatitic veins are decomposed in to white and pure kaolin product. The kaolinized pegmatitic veins are also characterised by moderate plasticity, non-abrasive, soft, smooth (powdery feeling) finer grain size. Quartz and mica are the principal impurities (grits) that are found associated with this kaolinized vein. These are coarser minerals and are easily separated from the kaolin product. On the other hand, the kaolinized granite product is characterised by gray to white color, rough, abrasive and non-plastic. It has also friable characteristics because of higher contents of sand sized siliceous minerals.

The mode of kaolin formation may have a considerable impact on the mineralogy, chemistry and morphology of the kaolin clays. It can also dictate the type of mining and beneficiation processes engaged to attain a commercial product for various industrial applications (Bloodworth et al., 1993, Murray, 1991; Ismail et al., 2015). Mode of formation of kaolin deposit can be primary or secondary. Bombawuha kaolin is one of the primary /residual type deposit of the country. According to different literatures (Murray, 1988; Murray and Keller, 1993; Ismail et al., 2014; Hailemichael Fentaw and Tibebu Mengistu, 1998; Kitagawa and Koster, 1991) primary/residual kaolin deposits can be formed in situ by weathering (supergene kaolin), by hydrothermal activity (hypogene kaolin), or in some cases by a combination of the two processes. From these three ways of formations, Bombawuha kaolin deposit belongs to the insitu weathering and hydrothermal alteration of granite and pegmatite parent rocks.

During intense weathering system the primary minerals mainly, feldspar (albite and K-feldspar) will be altered into a kaolinite mineral as shown in the following reactions (Gour et al., 2014).

$2NaAlSi_3O_8 + 2CO_2 + 3H_2O \rightarrow Al_2Si_2O_5(OH)_4 + 2Na^+ + 4SiO_2 + 2HCO_3^-$

Plagioclase (albite) Kaolinite

$2KAlSi_3O_8 + 2CO_2 + 3H_2O \rightarrow Al_2Si_2O_5(OH)_4 + 2K^+ + 2SiO_2 + 2HCO_3^-$

K-feldspar Kaolinite

A kaolinite mineral can also be formed by the hydrolysis process during the alteration of the primary minerals as shown in the following reactions.

$2KAlSi_3O_8 + 2H^+ + H_2O \rightarrow AL_2Si_2O_5\,(OH)_4 + 4SiO_2 + 2K^+$

K-feldspar Kaolinite

$2NaAlSi_3O_8 + H_2O + 2H^+ \rightarrow AL_2Si_2O_5\,(OH)_4 + 4SiO_2 + 2Na^+$

Plagioclase (albite) Kaolinite

The geological setting, chemical and mineralogical composition, textures and structure characteristics of the deposit enables to recognize the deposit type and the process of formation. Chemically, the silica and total alkalies increase with decrease alumina content and clay size fractions with depth. The chemical composition of the deposit is generally characterized by higher siliceous and lower aluminous components (i.e. higher grits). Mineralogically, the kaolinite content decreases down to the depth and increases the contents of feldspar and quartz (grits). It is also observed that the deposit is relatively enriched with the unaltered materials (example feldspar) occupying the lower horizons of the deposit. i.e. degree of kaolinization decreases with increasing depth and the non-weathered parent rock is exposed at the bottom of the deposit. Different features were also observed in the deposit such as grain size distribution, texture, structures/fractures and veins during field work. The texture and structure of the kaolin deposits are similar to their unaltered parent rocks i.e. the deposit retains the texture of the parent rocks. Vertically, the kaolin deposits are in a gradational contact with the parent rocks suggesting that residual (in situ) decomposition. Numerous quartz veins and veinlets and stockworks having different orientation are observed in different parts of the deposit. Due to the intense deformation, the host and/ or source rock is highly fractured. The existence of these fractures allows the parental magma to intrude and the circulation of hydrothermal and meteoric water. It is likely the hydrothermal solution emanating from the pluton, together with that syntectonic activity, is responsible for the formation of kaolin deposits. There are also resistant silicified rocks (quartz enriched) exposed in north east part of the study area. These all features clearly indicate that active hydrothermal activities contribute to the formation of the kaolin deposit.

Chapter Four

4 Description of Mining and Processing of Bombawuha Kaolin Deposit

4.1 Mining of Bombawuha kaolin deposit

The development of mining operation at bombawuha kaolin deposit has been become a source of income and wealth for the country by producing kaolin product for different industries. This mining operation also helps for the local communities by providing job opportunity and other benefits that enables them to lead their life properly. Bombawuha kaolin deposit is a type of surficial deposit and is exploited by using simple open pit mining method. Open pit mining is a type of surface mining method which is employed for the extraction or exploitation of a near-surface mineral deposits (Kogel, 2014). This method is selected by considering the nature of the deposit, overburden thickness (stripping ratio), economic profitability (capital and operating cost) and availability of extracting equipments. The ultimate pit depth of the deposit is governed by the degree of weathering/alteration. Thus, the exploitation of kaolin ore will be stopped when the unaltered source rocks become exposed. The current pit depth of the mine is about 10m. From this the overburden material accounts about 60%. This depth is excavated by two successive benches that have a height of 4 and 6m depending on slope of the land (Fig. 4.1). The purpose of these benches is to provide safety of working place and to avoid dilution effect during the production of kaolin by keeping the stability of the overlying waste material. The slope of benches ranges from 80^0-85^0 and have about 4m bench width. The top of the bench is used as a road (haul) for transporting the mined kaolin to the processing plant.

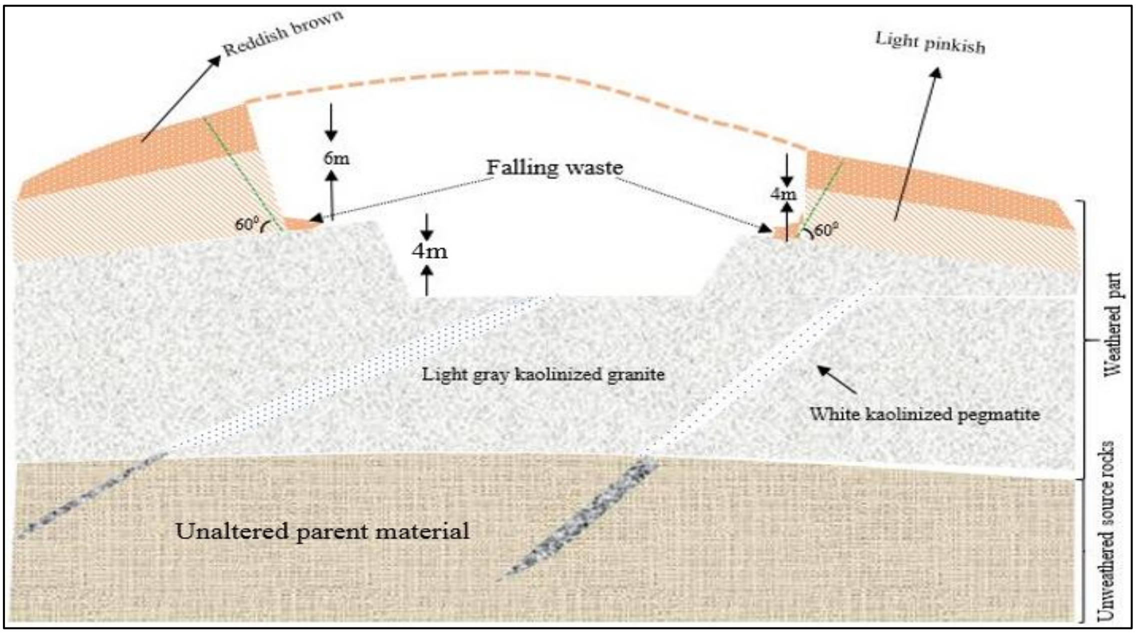


Figure 4.1: *Sketch model of Bombawuha kaolin open pit mine*

Presently, the production of kaolin is carried out by applying the following consecutive mining operation activities (see Fig.4.2).

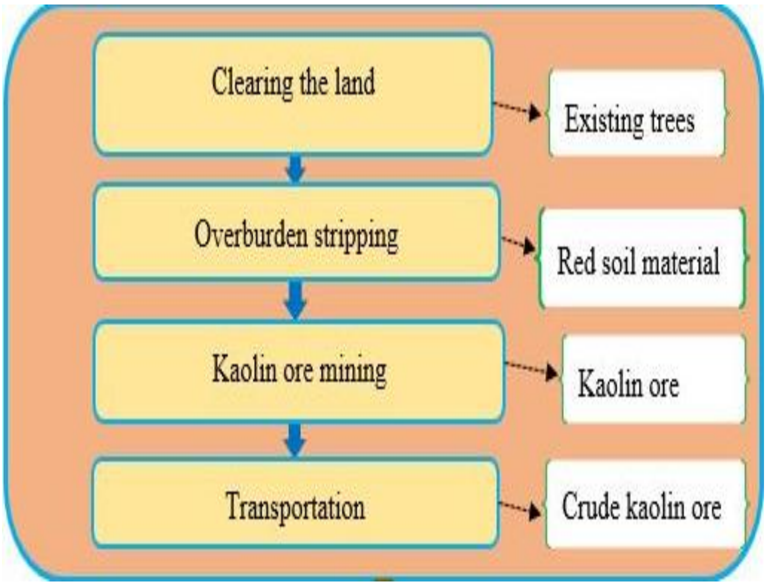


Figure 4.2: *The steps of kaolin mining at Bombawuha kaolin deposit*

4.1.1 Logging and cutting of the forest

Bombawuha kaolin deposit is covered by highly dense and big trees. Removing of trees and clearing of the land are the most preceding activities that helps to start stripping of the overburden material. The big trees of the deposit are removed by a bulldozer and thrown towards the nearby streams.

4.1.2 Removal of overburden material

After the removal of the forest, striping of the overburden waste material is started. This is because the kaolin ore is superficially covered by this reddish brown and light pinkish colored waste material. Thus, its removal is important activity to expose the underneath pure kaolin 'ore'. The overburden material has different physical characteristics from the underneath kaolin ore and also its character varies from top to bottom. The upper most 1-2m part of the overburden material is covered by the black to brown colored plant supporting humous soil material. The color varies from reddish to pinkish towards the kaolin ore.

The thickness of the overburden soil material also varies from place to place depending on the slope of the land. It is thin at the slope face (2-4m) and becomes thicker (4-6m) towards the uppermost part of the ridge. Systematic procedures are not used for the disposition of the overburden material. The thicker (6m) overburden material has been cut at a steep slope face (80^0-85^0). This overlying waste material is characterised by weak geological formation and often failed down in to the ore (Fig.4.1 and 4.3). This causes dilution (contamination) effect and loss of kaolin ore in the crude kaolin production. Due to this reason the quality and quantity of the crude kaolin and the effectiveness of the processing plant could be affected. However, the removal of the overburden material at a successive steps/benches (2-3m) and lower bench angle (45-60^0) can reduce the dilution and ore loss effects. During rainy season the excavated pure kaolin ore can be affected by the red colored waste material coming from the overlying through transportation. The stripping and transportation activities of the overburden material takes place at the same time by a bulldozer. The stripped material is thrown towards the streams found near to the deposit due to lack of stockpiling system.

4.1.3 Mining of kaolin 'ore'

Once the overburden material is relocated, the mining of kaolin ore is started immediately. It is extracted using much the same methods and procedures that were used to remove the overburden waste material. The kaolinized products are characterized by weak, soft and poorly cohesive rheological properties. Due to this reason, drilling and blasting production cycles are not employed during the excavation of the kaolin ore. Thus, it is simply stripped by using mechanical bulldozer. During the extraction of kaolin ore, variations of physical properties of the ore such as color, grain size, softness etc are not considered and the two kaolinized units (pegmatites and granite) are mined together.

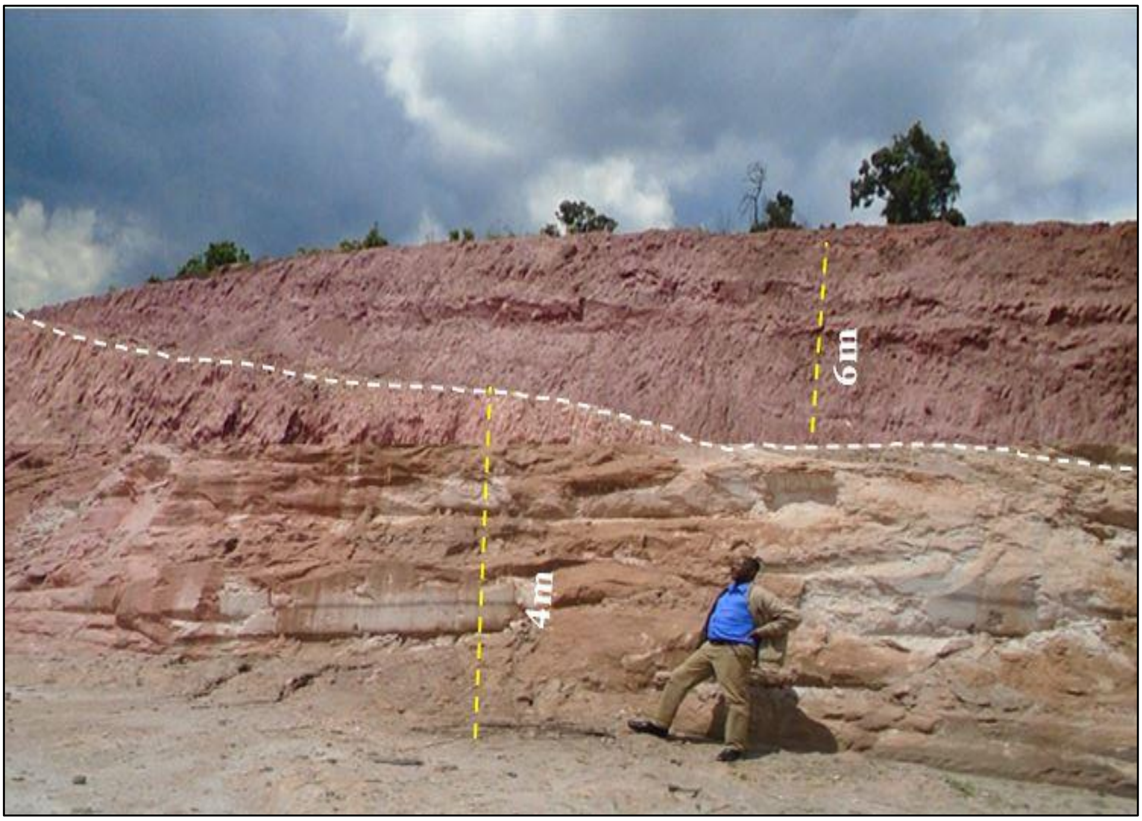


Figure 4.3: *Red to brown colored overburden material and kaolin ore of Bombawuha open pit mine*

4.1.4 Transportation of crude kaolin

After the kaolin ore is mined, it is loaded on the truck and transported to the storage site which is found near to the processing plant. At the storage site the crude kaolin is stocked in two separate heaps until it is processed.

4.2 Processing of Bombawuha crude kaolin

Both dry and wet processing methods can be used for the purification of crude kaolin. However, the Bombawuha kaolin production uses wet processing method to purify the extracted crude kaolin. The processing method follows a sequence of beneficiation steps for the removal of different size impurities (Fig 4.5). It separates and removes the associated waste materials mainly quartz, mica and iron impurities from the kaolin concentrate and produce the desired particle size distribution of kaolin product (<45µm). The beneficiation unit of the plant has a capacity to produce a kaolin product with 18% moisture content. The process is working on two independent sections. Feeding, washing, classifying and thickening are included in the first section. The other section holds filtering, drying, and stockpiling of the produced kaolin product. The thickener connects the two sections and serves as a storage tank for the kaolin enriched slurry.

4.2.1 Feeding of run of mine

Bombawuha kaolin processing is started by feeding the run of mine (ROM) from the accumulated heaps by a wheel loader in to the feed hopper. The feed hopper is part of the processing plant equipped with a static grid for preventing the big chunks (boulders) of hard rock from entering the plant. From the feed hopper the crude kaolin ore having <150mm is transferred in to the drum scrubber (trommel) with the help of feeder and conveyor belts. These belts rotate continuously in order to transport the crude kaolin until ore feeding is stopped.

4.2.2 Blunging and dispersion of crude kaolin

Washing and dispersion of the crude kaolin takes place in the drum scrubber while it is mixed with water. The drum scrubber is an inclined rotating metal tied by eight rotating tyres. These eight tyres are tied by the belt and keeps the balance of the drum scrubber (Trommel). The drum scrubber vigorously agitates the mixture of crude kaolin and water to form a slurry of kaolin product. The purpose of blunging is to disperse and suspend the fine and light materials from the coarser and heavier materials. The disintegration of abrasive minerals like quartz and undesirable mineral such as mica from kaolin slurry is started. The drum scrubber (Trommel) has two main functions. First, it disintegrates, blunge and disperse the crude kaolin in to under flow and over flow slurry fractions during its rotation. Second, it also helps to transfer the under flow and over flow materials separately at the opposite end members. The inclined positions of the drum scrubber allow to flow the under-flow materials down, and the over flow floated materials at its elevated side. The over flow fractions contain fine and lighter materials of almost totally clay fractions and significant amount of mica which flows in to the sieve bend screen. The under-flow fractions are constituted by denser and coarser grit (sand and gravel sized) materials mainly quartz and micas. These are oversized grit particles removed out of the processing system by vibrating screen as a waste material.

4.2.3 Degritting and size classification

Grit is defined as particles coarser than 325 mesh or 44 µm. Degritting is the removal of coarser impurities (grits) such as quartz, sand, mica, and other heavy minerals from the dispersed kaolin slurry. The incorporated methods which are employed in the processing plant for the removal of grits are vibratory screens, sieve bend, jig also called sand box (drag box), hydrocyclones and mica screen. The disintegrated and fractionated under flow and over flow fractions of the drum scrubber starts to feed the screens. The coarser and denser particles feed the vibrating screen with the help of gravity. These materials are divided in to coarse fractions (>2mm) to be discarded, and a sandy fraction. Two vibrating screens are overlain one over the other which have different opening size (12.5/2.5 mm). At each stage of separation, the coarser materials are thrown as a waste material.

The screened materials then flow from the vibrating screens in to the first hydrocyclone through the pipe line. From the first hydrocyclone the overflow slurry is flown in to the drum scrubber and then to sieve bend whereas the under flow is thrown in to the jigging box. The jigging box separate the coarser and denser particles which are not separated at the vibrating screen and first hydrocyclone. It separates them from the finest and lightest kaolin enriched materials based on their density difference. Here, the coarser materials are also discarded as waste and the over flow slurry is flown in to other finer screen called sieve bend for further processing.

The kaolin concentrates are floated while processing due to their fine particle size and light density. The sieve bend over screen size is discarded as a mica rich fractions whereas, the under size containing the recoverable kaolin is pumped to the second hydrocyclone for the classification at 44µm. The under flow of the cyclones made up of coarse mica and small kaolin concentrate are thrown as a waste due to the absence of the third hydrocyclone. The over flow of the hydrocyclone immediately passes in to a special mica screen where the light trash and the thin flakes of the mica are removed.

The hydrocyclone classification system is the favorable classification method. The hydrocyclones of the processing plant also fractionate and classify the slurry in to various size distributions. The multistage hydrocyclones of the plants classify the coarser and finer concentrate of kaolin. They can also upgrade the quality of the kaolin product by removing the remaining finer waste materials in a repeated cycle.

During washing and sizing processes significant amount of kaolin particles are also lost as observed in the thrown waste materials. This kaolin enriched waste materials (tailings) are utilized by the surrounding people for the cement production. The non-functioning of the third hydrocyclone may cause passing of the finer impurities with the kaolin product enriched slurry. The discarded waste materials/tailings are accumulated and soled for the local people rather than returned back into the mine for the purpose of backfilling. The mica screen under size fraction is the final kaolin product and feeds to the thickener by the gravity.

4.2.4 Thickening of slurry

The thickener of the processing plant is a large circular/round tank (container) at which the kaolin enriched slurry is accumulated (Fig.4.4 and 4.5). The kaolin enriched slurry is held separately to feed into the dewatering section of the plant. At the center of the thickener there is an agitator which rotates very slowly and allows to disperse the kaolin concentrate. The thickener has three main function. These are; to concentrate very diluted kaolin pulp prior to filtration, to clarify the excess water before recycling, and to store the kaolin pulp and allowing independent running of washing and dewatering sections. The thickened slurry is then pumped in to the filter press tank.

4.2.5 Filter pressing of slurry

The clean kaolin enriched slurry is filter pressed for the reduction of moisture content. The purpose of the filter press is to produce dewatered ‘cake like’ kaolin products. After the reduction of moisture, the filtered cakes are discharged continuously in to the underneath cutting unit and dispenser conveyor belt. The dispenser conveyor belt transfers these broken cakes to the conveyor belt for transferring in to the dryer section.

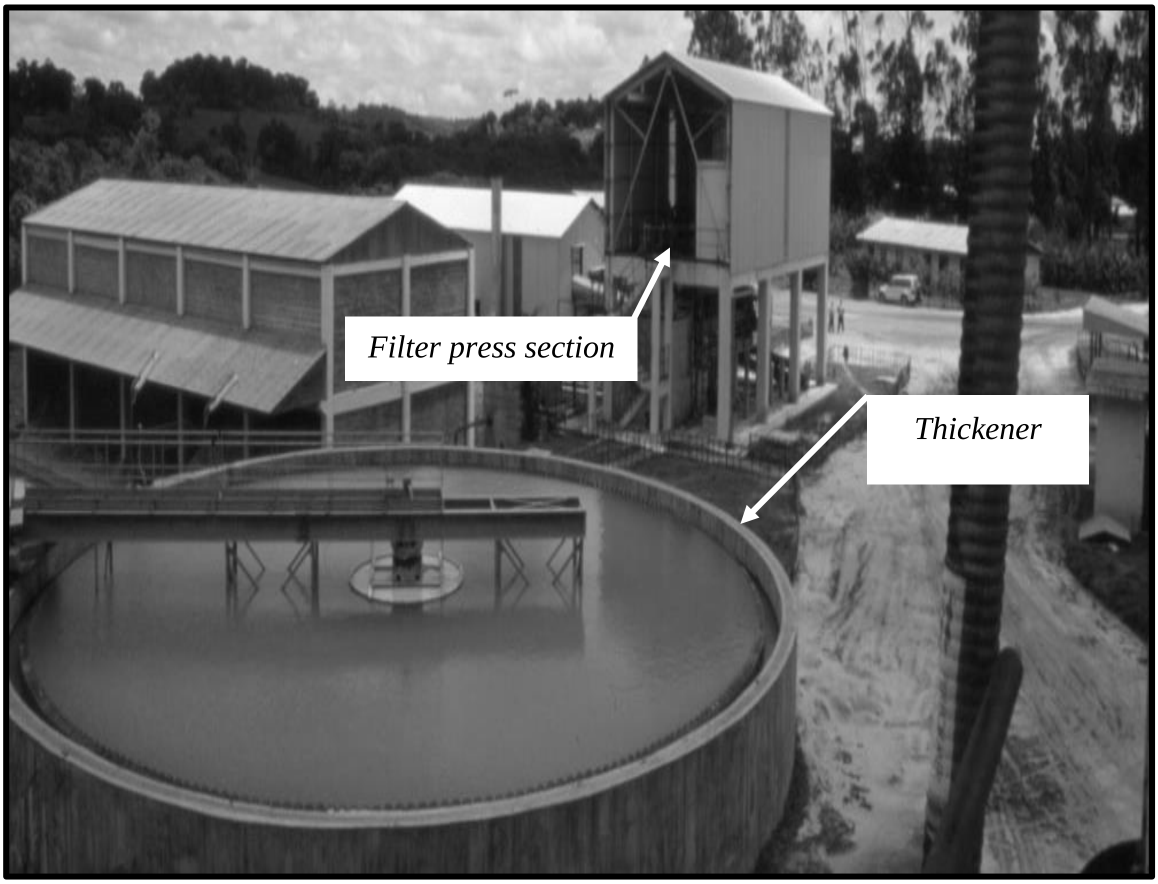


Figure 4.4: *Field photo of thickener and dewatering sections of the plant for kaolin production*

4.2.6 Drying of filter pressed kaolin product

At the extruder the cakes are also dried for further removal of moisture. The final processed kaolin products are discharged using the conveyor belt from the drier section to final stock piling of the products. The kaolin product is packed and dispatched to the customers without pulverization. Tabor Ceramics Factory (TCF) and Melkasa Aluminium Sulfate and Sulphuric Acid Factory (MASSAF) industries are the two main consumers of this processed kaolin product.

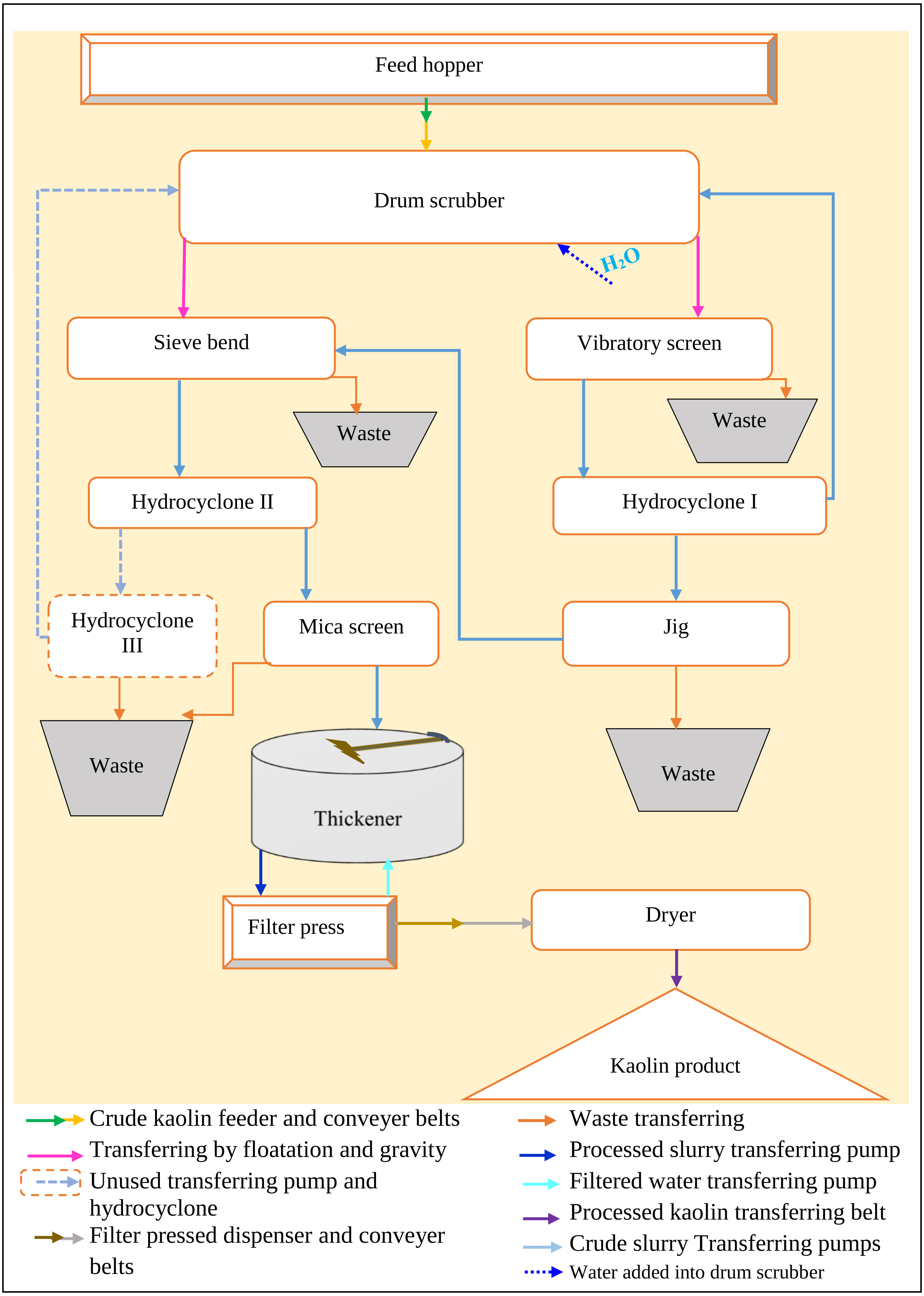


Figure 4.5: *The flow sheet of Bombawuha kaolin processing system*

Chapter Five

5 Properties of Bombawuha kaolin

Different laboratory analyses results are incorporated to assess the quality of Bombawuha kaolin deposit. The physical characteristics including plasticity, grain size distribution, pH, specific gravity and linear shrinkage combined with the chemical and mineralogical composition are the main parameters determined during the laboratory analysis. The characterization of kaolin using physical and chemical analyses also enables to identify the undesirable components of kaolin. The undesirable components are basically considered as impurities. Iron bearing minerals are the main discoloring impurities of kaolin that affect its demand in different industries. The properties of Bombawuha kaolin are described below and evaluated by comparing with the limits fixed by the industrial users and also with the respective properties of better known commercial kaolin deposits.

5.1 Geochemical composition

The inductively coupled plasma atomic emission spectroscopy (ICP-AES) analysis of kaolin samples is intended to find out the concentration of the major and minor oxides in the deposit. This helps to identify major impurities in the kaolin and to determine its quality. The analysis is performed on eight samples that are taken from the slightly altered granite rock, kaolinized deposits, run of mine and processed kaolin products. The results obtained from chemical analysis are given in Table 5.1. The chemical analysis result shows that, Bombawuha kaolin deposit is mainly composed of SiO_2 and Al_2O_3. More than 85% of the bulk composition is constituted by these two oxides. The kaolin deposit is basically derived from granite and pegmatite parent rocks. The samples were also taken from these two kaolinized deposits and their result shows different proportions of chemical characteristics.

The kaolinized granite (BK-1 to BK-4) is the larger deposit characterised by the higher SiO_2 (67.4-70.9%), lower Al_2O_3 (18.1-22.6%) and loss on ignition (LOI) (5.52-9.04%) values. Higher concentrations of K_2O (0.99-3.73%) and Fe_2O_3 (1.18-1.92%) are also observed in this deposit. The presence of TiO_2 in all samples is lower (0.06-0.17%) compared to the Fe_2O_3. Both are coloring impurities of the kaolin deposit and affect the industrial properties of kaolin. The deposit also constitutes lower (<1%) CaO, MgO, MnO and Na_2O components. The slightly weathered source rock (BR-1) of this deposit is also characterised by the higher SiO_2 (72.1%), lower Al_2O_3 (16.3%) and lower LOI (3.85%) values. It has also higher concentrations of K_2O (5.04%) and Fe_2O_3 (1.88%) contents. The presence of chromium and strontium oxides in all samples (kaolinized deposit and parent rock) are below the detection limit. Barium and phosphorous oxides are also contained in all samples in little amount. The barium oxide is moderately high in the slightly weathered rock (BR-1) than the other kaolinized samples. This indicates the degree of kaolinization decreases down to depth. The other kaolinized unit is pegmatite and observed as a vein in the field. As chemical analysis result of this kaolinized unit (BK-5) shows, it has lower SiO_2 (51.5%), higher Al_2O_3 (33.4%) and LOI (11.95%) values compared to kaolinized granite. It is also characterised by lower coloring impurities (Fe_2O_3 and TiO_2), alkalies and alkali earth oxides.

Table 5.1: *Major oxide geochemical composition results of Bombawuha kaolin.*

Oxide (wt. %)	Major oxide composition								
	Rock	Kaolinized granite					Kaolinized pegmatite	Run of mine	Processed kaolin
	BR-1	BK-1	BK-2	BK-3	BK-4	Av. G	BK-5	BM-1	BP-1
SiO_2	72.1	70.9	67.6	66.1	67.4	68	51.5	71.2	45.8
Al_2O_3	16.3	18.1	19.75	20.3	22.6	20.19	33.4	17.95	35.5
Fe_2O_3	1.88	1.89	1.92	1.61	1.18	1.65	1.09	1.88	0.99
CaO	0.15	0.02	0.02	0.02	0.02	0.02	0.01	0.03	0.06
MgO	0.23	0.25	0.26	0.21	0.12	0.21	0.07	0.17	0.12
Na_2O	0.72	0.15	0.06	0.03	0.03	0.07	0.03	0.22	0.05
K_2O	5.04	3.73	1.69	1.12	0.99	1.88	1.53	3.88	1.09
Cr_2O_3	<d.l	<d.l	<d.l	<d.l	<d.l	<d.l	<d.l	<d.l	<d.l
TiO_2	0.13	0.15	0.17	0.12	0.06	0.13	0.03	0.1	0.05
MnO	0.05	0.07	0.09	0.12	0.06	0.09	0.59	0.11	0.06
P_2O_5	0.02	0.02	0.02	0.01	0.01	0.02	0.03	0.03	0.01
SrO	<d.l	<d.l	<d.l	<d.l	<d.l	<d.l	<d.l	<d.l	<d.l
BaO	0.08	0.05	0.03	0.02	0.01	0.03	0.05	0.04	0.02
SiO_2/Al_2O_3	4.42	3.92	3.42	3.26	2.98	3.40	1.54	4.00	1.29
Total	96.7	95.33	91.61	98.64	92.49	94.52	88.32	95.61	83.75
LOI	3.85	5.52	7.88	8.9	9.04	7.84	11.95	5.43	14.7

Note: <d.l; stands for below detection limit

From the above two deposits it is observed that, the higher Al_2O_3 and LOI values are contained in the samples of the deposit that have depleted SiO_2 content. Here, the enrichment and depletion of Al_2O_3 value in the samples define the quality of kaolin. Samples with higher Al_2O_3 and LOI values have higher quality. The kaolinized pegmatite (BK-5) have nearly equivalent values of these oxides with Cornwall kaolin deposit, Georgia kaolin deposit and theoretical/ideal pure kaolin composition. The Cornwall and Georgia kaolin deposits which are found in UK and USA respectively are the most known commercial deposits of the world. These two commercial kaolin deposits and ideal pure kaolin values are used to compare with Bombawuha kaolin deposit (Table 5.2) (Murray and Keller, 1993). The LOI value has a direct relationship with Al_2O_3 and inverse relationship with SiO_2 of the samples. The concentration of TiO_2 is also equivalent to the higher quality kaolin deposits of the world especially with Cornwall (UK) kaolin deposit (0.02%). It is also observed that, the presence of K_2O, SiO_2 content and other fluxing components in both Bombawuha and Cornwall kaolin deposits are similar. This is an indication of both Cornwall and Bombawuha kaolin deposits have similar mode of formation that are a primary/residual type deposit. Not only this, they are also derived from the same parent material i.e. granitic rocks. Whereas, Georgia kaolin deposit is the other higher quality deposit of the world characterised by the higher TiO_2 (1.44%) compared to Bombawuha kaolin deposit. It is a secondary/sedimentary origin kaolin deposit. That is why Georgia kaolin deposit is characterised by the higher TiO_2 and lower quantities of SiO_2, and other alkali and alkali earth components. However, Bombawuha kaolin deposit has higher Fe_2O_3 compared to the two higher quality kaolin deposits.

***Table 5.2*:** The geochemical analysis results (%) of Bombawuha kaolin compared to UK, Georgia and theoretically pure kaolin respectively (Murray and Keller, 1993). <d.l stands for below detection limit

Oxides (%)	Kaolinized granite (average)	Kaolinized Pegmatite	UK-Cornwall Kaolin	USA-Georgia Kaolin	Pure kaolin
SiO_2	68	51.5	46.77	45.3	46.6
Al_2O_3	20.19	33.4	37.79	38.38	39.5
Fe_2O_3	1.65	1.09	0.36	0.3	<d.l
TiO_2	0.13	0.03	0.02	1.44	<d.l
CaO	0.02	0.01	0.13	0.05	<d.l
MgO	0.21	0.07	0.24	0.25	<d.l
Na_2O	0.07	0.03	0.05	0.27	<d.l
K_2O	1.89	1.53	1.49	0.44	<d.l
MnO	0.09	0.59	l.d	ld	<d.l
LOI	7.84	11.95	12.97	13.97	13.9
SiO_2/Al_2O_3	3.4	1.54	1.24	1.18	1.18

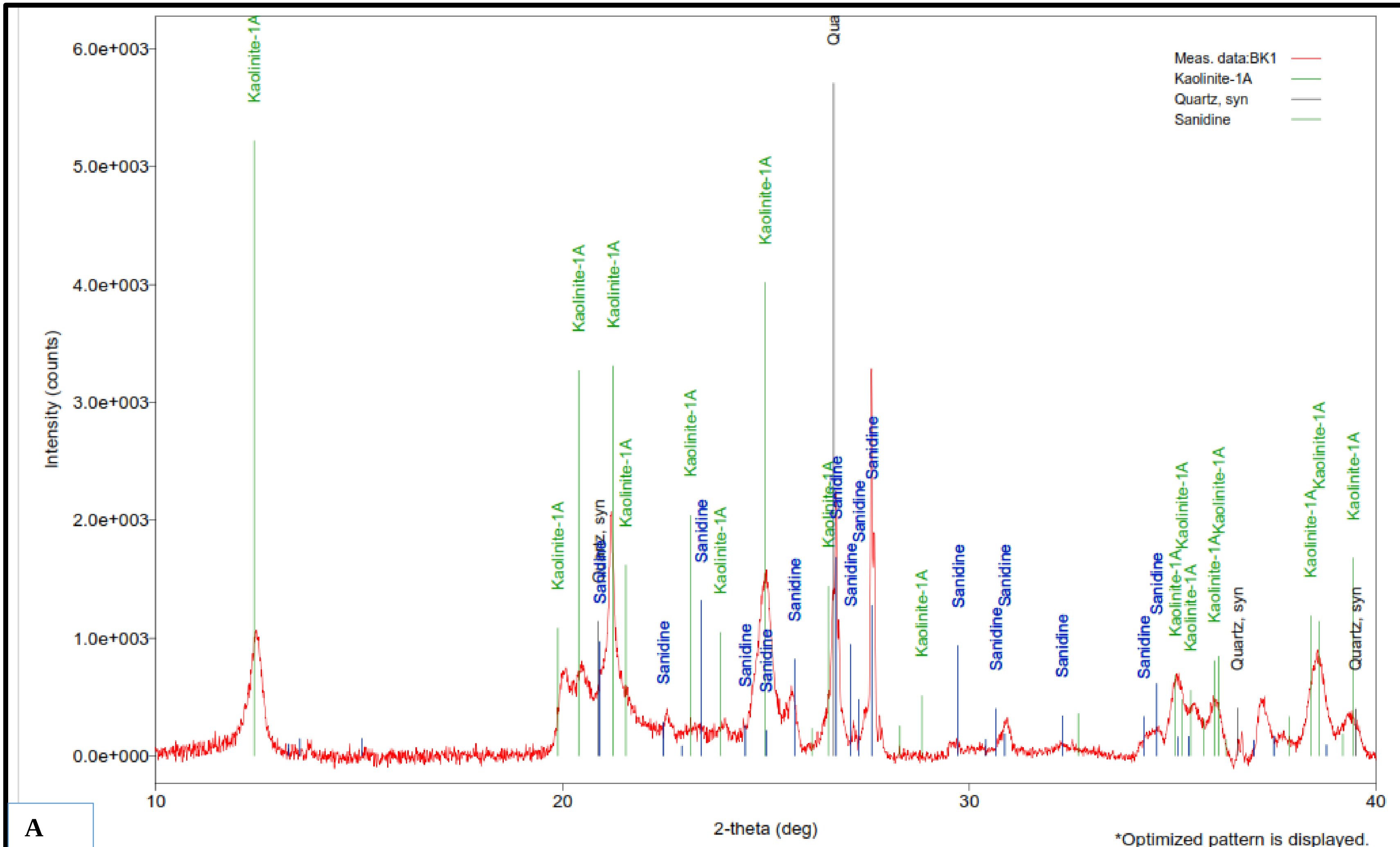
A sample (BM-1) was collected and analyzed from the extracted crude kaolin (run of mine) to examine the degree of dilution. The run of mine (ROM) is characterised by the higher silica (71.2%), lower alumina (17.95%) and LOI (5.43%) values. Significant amount of K_2O and Fe_2O_3 are also contained within the run of mine. The amount of TiO_2, and other alkali and alkali earth oxides are lower (<0.5%). The chemical analysis result of the run of mine (BM-1) is similar with the kaolinized granite (BK-1 to BK-4) deposit and the slightly weathered rock (BR-1). But, its result is so different from the kaolinized pegmatite result value. To determine the effectiveness of the processing plant, a sample was also collected and analyzed from the processed kaolin product. This product (BP-1) shows enhanced chemical properties compared to the other crude kaolin samples. It is characterised by higher alumina (35.5%) and LOI (14.7%), and lower silica values (45.8%) compared to the unprocessed crude kaolin samples.

5.2 Mineralogical composition

The mineralogical composition (XRD) analysis result of Bombawuha kaolin deposit are given in Table 5.3 and Fig. 5.1 to 5.3. The spectra obtained from the analysis are composed of several peaks. Kaolinite and quartz are the major mineral phases that are corresponding to the highest peak detected by the X-ray diffractograms. There are also other minor mineral phases including illite, muscovite, halloysite and other unaltered K-feldspar minerals mainly sanidine and orthoclase. The XRD analysis result shows that, the kaolinized granite (BK-1 and BK-2) and kaolinized pegmatite (BK-5) deposits have different mineralogical characteristics. Kaolinized granite is composed of quartz, kaolinite, k-feldspar (sanidine) and halloysite mineral phases (Fig. 5.1 A and B). The peaks of quartz and kaolinite are superimposed with sanidine and halloysite minerals. Sanidine and orthoclase are polymorph minerals grouped under potassium feldspar group. Kaolinized pegmatite is dominantly composed of kaolinite mineral. But minor illite mineral phases are also detected and that are superimposed with the kaolinite mineral phase (Fig.5.2). Besides these secondary minerals, there are also other coarser and unaltered primary minerals mainly quartz and mica in this kaolinized deposit which are observed in the field. These are easily separable primary minerals of the deposit and have different physical characteristics. The mineral quartz has white/colorless and angular to sub angular form characteristics. The external surface of this mineral is also stained and have a rusty color because of the subordinated mica mineral. The mica mineral is characterized by a flaky texture and the assembled sheets can be easily split from each other. As far as the mineralogical composition of processed kaolin product (BP-1) is observed, it is composed of higher kaolinite mineral phase which corresponds to the highest intensity peak of the XRD pattern (Fig. 5.3). Minor phases of muscovite and orthoclase are also associated with the kaolinite mineral.

Table 5.3: *The mineralogical composition of Bombawuha kaolin deposit*

Sample type	Sample code	Minerals identified	
		Major phases	Minor phases
Kaolinized granite	BK-1	Kaolinite and quartz	Sanidine
	BK-2	Quartz and kaolinite	Halloysite
Kaolinized pegmatite	BK-5	Kaolinite	Illite
Processed kaolin	BP-1	Kaolinite	Muscovite and orthoclase



Intensity (counts)
6.0e+003
5.0e+003
4.0e+003
3.0e+003
2.0e+003
1.0e+003
0.0e+000
10
20
30
40
2-theta (deg)
Meas. data:BK1
Kaolinite-1A
Quartz, syn
Sanidine
Kaolinite-1A
Sanidine
Quartz, syn
*Optimized pattern is displayed.
A

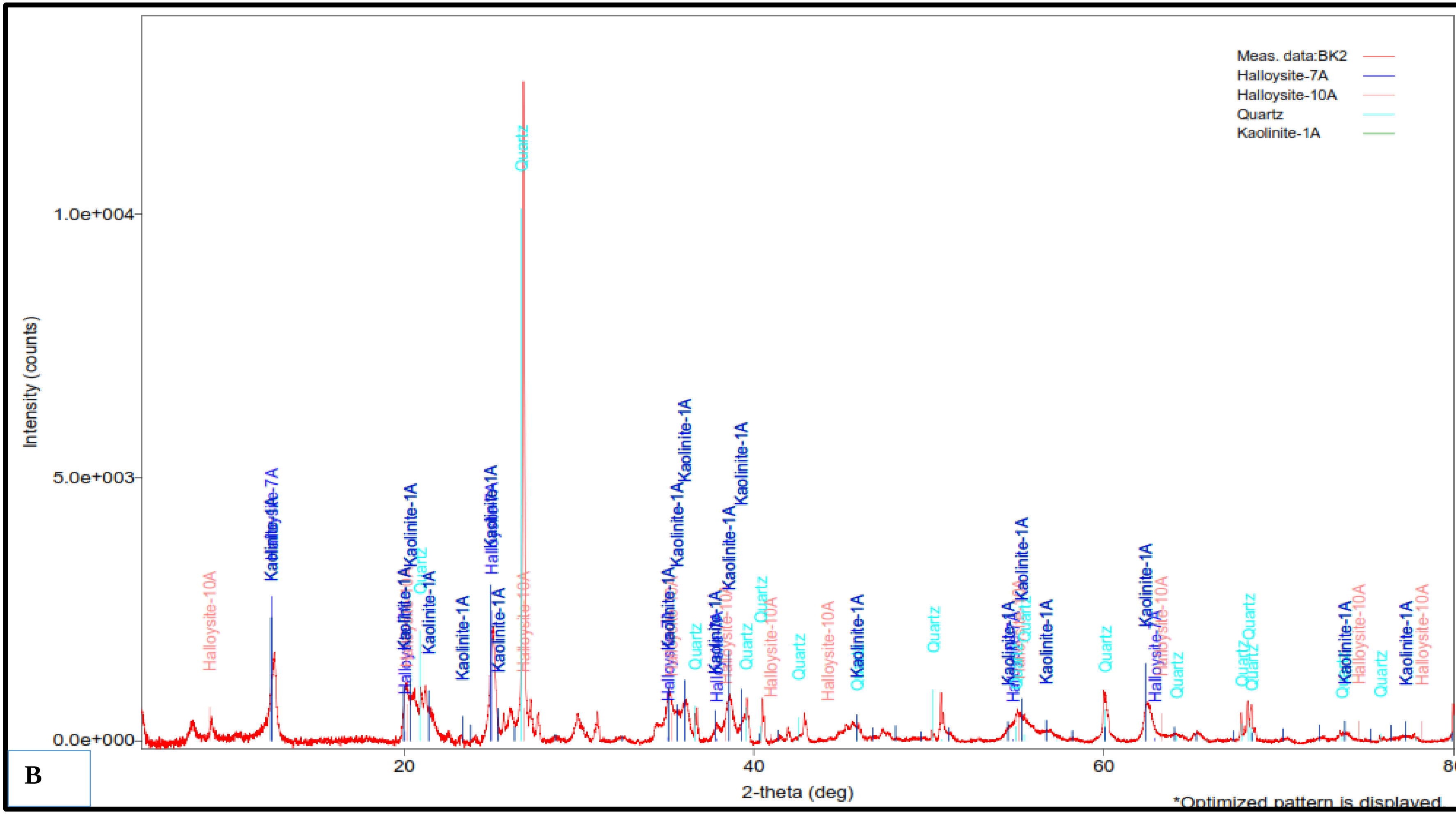


Figure 5.1: *XRD patterns of minerals in kaolinized granite deposit* ***A****(BK-1) and* ***B****(BK-2)*

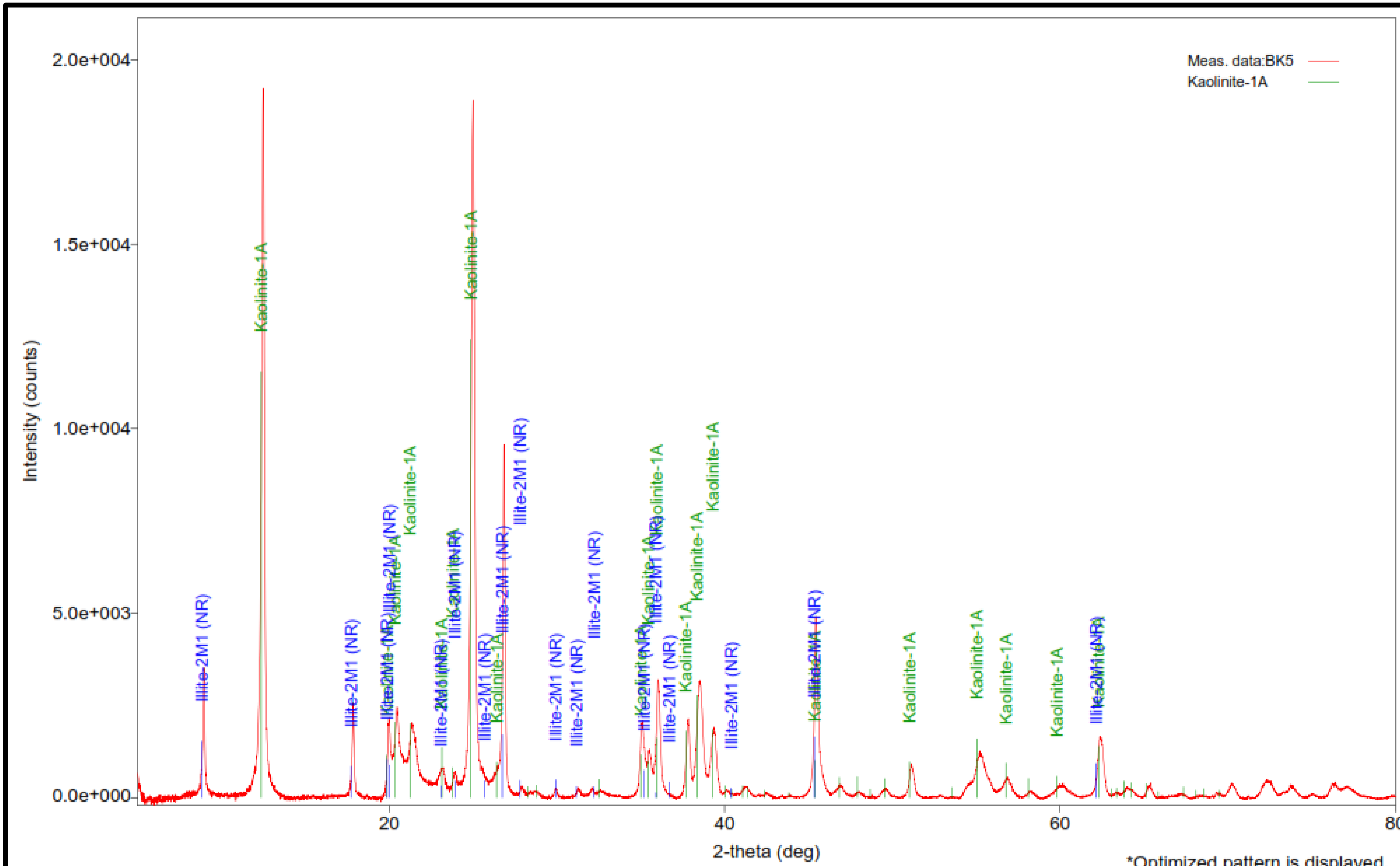


Figure 5.2: *XRD patterns of minerals in the kaolinized pegmatite deposit (BK-5)*

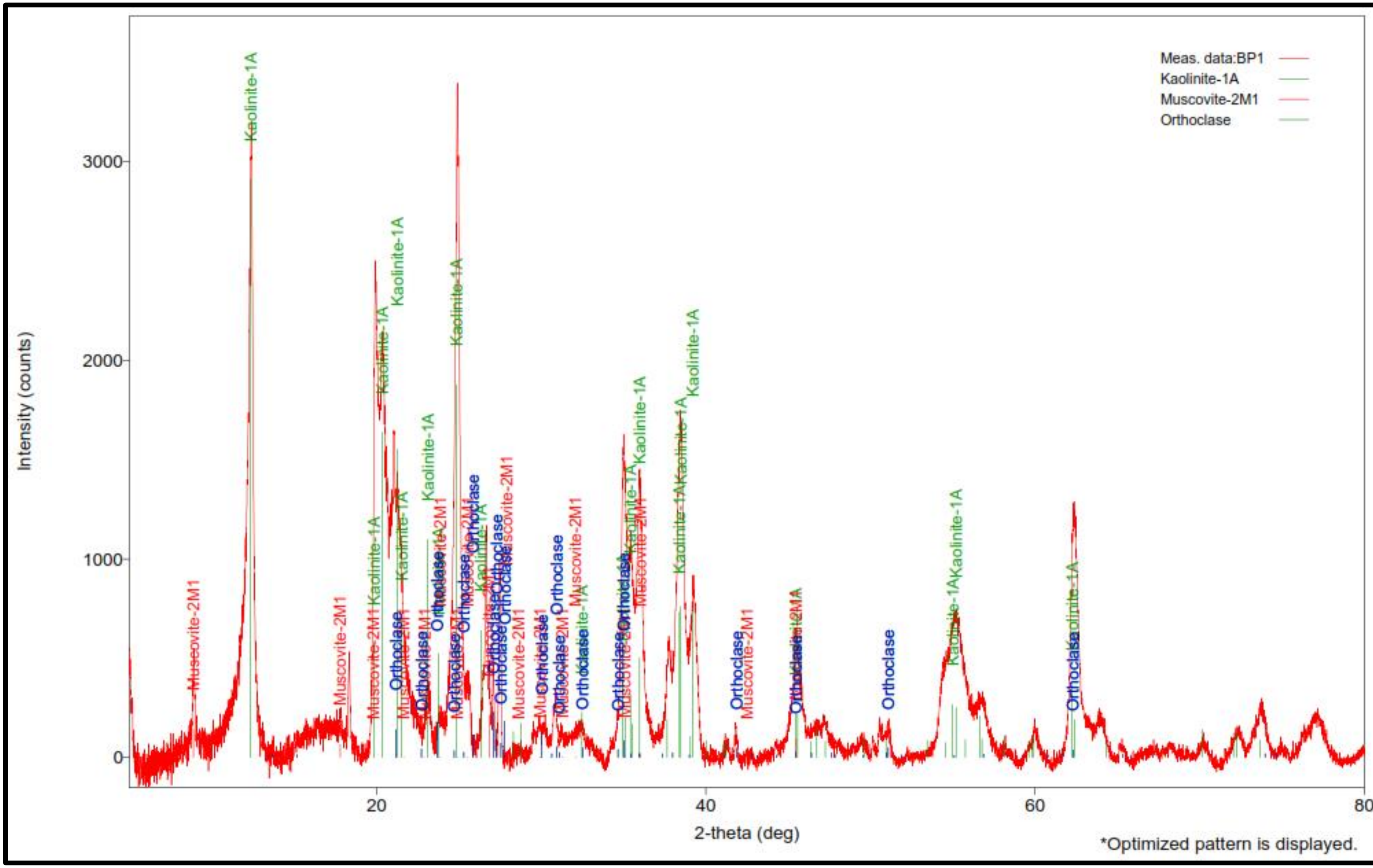


Figure 5.3: *XRD patterns of minerals in the processed kaolin product (BP-1)*

5.3 Physical properties

The physical properties of the deposit are mainly characterized on the basis of the actual site observation and the results obtained from laboratory analysis. Most of the physical characteristics of the deposit depends on degree of kaolinization and its bulk mineralogical and chemical composition (Murray, 2007). They are also related either to size of the individual particles or to the significant contaminant surface charges associated with these particles. The presence of impurity materials (grits and coloring impurities) affect the physical characteristics of kaolin. The following physical properties were determined and described as follows.

5.3.1 Colour

Colour is the most quality deterministic characteristics of kaolin. It can determine the suitability of kaolin for various industries. Colour can be determined simply by comparing different kaolin samples 'with naked eye'. However, the Munsell system of color notation enables to record /detect the color of kaolin samples scientifically. The Munsell system allows for direct comparison of clays in the world. Munsell color notations can be used to define the color of kaolin by comparing with the Munsell soil colors. Color has three dimensions hue (a specific color), value (lightness and darkness) and chroma (color intensity/color purity) that clearly describe any color. These components are arranged as hue value/chroma (http://www.envirothonpa.org/documents/munsellcharts.pdf). Hue is indicated by the first letter/letters of the color. Example R stands for Red, YR for Yellow-Red and Y for Yellow.

The determination of color is carried out on the dry kaolin samples in order to avoid the effect of moisture on the whiteness of kaolin. Hence, the colour of Bombawuha crude kaolin samples is characterised by the hue of 10YR (yellow red), value of between 6 and 8 (light gray to white), and a chroma between 1 and 2. From the crude kaolin samples the kaolinized pegmatite shows greater than 8 value (white) and lower chroma (~1) and is denoted as 10YR8/1 Munsell Soil Colour Chart. The processed kaolin product also has a colour value above 8 (white). The kaolinized granite is characterised by the light gray color (10YR6/2) because of the iron impurity.

5.3.2 Grain size distributions

Grain size distribution analysis is also another important parameter to assess the suitability of kaolin in different industries. This is because the physical and optical properties of kaolin depend on the grain size distribution (AL-Shameri and Rong, 2009). The grain size distribution analysis result of Bombawuha kaolin deposit are given in Table 5.4. Bombawuha kaolin deposit is dominantly made up of coarser grain materials (79.9-96.7%). The proportions of clay and silt sized particles of the deposit are very low (3.3-20.1%). The analysis was performed on both the kaolinized granite (BK-1) and pegmatite (BK-5) deposits and their result show different grain size distributions. Kaolinized granite shows higher coarse-grained materials (96.7%) and lower fine particles (3.3%) whereas, the kaolinized pegmatite has lower coarser materials (79.9%) and higher fine particles (20.1%) relatively.

Table 5.4: *The grain size distribution of Bombawuha kaolin deposit*

Sieve size (mm)	Kaolinized granite (BK-1)			Kaolinized pegmatite (BK-5)		
	Retained weight (g)	Retained (%)	Passing (%)	Retained weight (g)	Retained (%)	Passing (%)
4.75	0	0	100	0	0	100
2.36	15.4	7.7	92.3	53.6	26.8	73.2
1.18	38	19.0	73.3	21.6	10.8	62.4
0.6	46	23.0	50.3	22.6	11.3	51.1
0.3	34	17.0	33.3	14.8	7.4	43.7
0.16	28.8	14.4	18.9	12.2	6.1	37.6
0.063	31.2	15.6	3.3	35	17.5	20.1
Pan (<0.063)	6.6	3.3	0	40.2	20.1	0

5.3.3 Plasticity

The plasticity property is a parameter that can affect the quality of kaolin in some industries. It is calculated by taking the arithmetic difference of liquid limit and plastic limit (Atterberg limits). The liquid limit and plastic limit of kaolinized granite (BK-1) becomes difficult to measure because of the presence of higher coarser siliceous materials. As a result, it is considered as non-plastic. Comparatively, the kaolinized pegmatite is enriched with finer particles and its liquid limit and plastic limit becomes 51 and 41 percent respectively. The measured plasticity index of this deposit is also become 10%.

5.3.4 Linear shrinkage

Linear shrinkage is directly related to the amounts of clay minerals and water content. Bombawuha kaolin deposit has lower linear shrinkage value. The shrinkage property of kaolin depends on the grain size distributions. The non-plastic kaolin deposit has lower linear shrinkage value and coarser particle size. The linear shrinkage value of kaolinized granite (BK-1) and kaolinized pegmatite (BK-5) is 0 and 3 percent respectively. The linear shrinkage of kaolinized pegmatite slightly higher than kaolinized granite because of the relative higher finer particles contained in the former deposit. From this it is possible to understand that the higher finer particles (clay) in the kaolin deposit the higher water is absorbed and then the higher the dry linear shrinkage value will be. Therefore, to increase the linear shrinkage value of Bombawuha kaolin deposit reduction of the coarser minerals (grits) is required.

5.3.5 pH

The pH values of Bombawuha kaolin deposit ranges from 6.27-6.37 mol/L. It is near to neutral pH value. These values are a function of coloring impurities such as iron and titanium oxides (Ma and Egleton, 1999). Kaolinized granite (BK-1), kaolinized pegmatite (BK-5) and processed kaolin (BP-1) have 6.27, 6.37 and 6.46 pH values respectively. The pH value of Bombawuha kaolin deposit is almost similar with the ideal pure kaolin pH value (7) (Murray, 2007).

5.3.6 Specific gravity

Bombawuha kaolin deposit has lower specific gravity value (2.53 - 2.65 g/cm^3). Specific gravity depends on coloring impurities such as iron and titanium oxides. Kaolinized granite (BK-1) has slightly higher specific gravity (2.65) than kaolinized pegmatite (BK-5) deposit (2.53). The processed kaolin (BP-1) is also characterised by lower specific gravity value (2.50). From the above statements it is observed that, Bombawuha kaolin deposit has equivalent specific gravity value with the theoretical (ideal) pure kaolin (2.60) (Murray, 2007).

Chapter Six

6. Discussion

6.1 Quality of Bombawuha kaolin deposit

Quality of Bombawuha kaolin deposit depends on a number of geological factors including degree of kaolinization, mineralogical composition of the parent rocks, structure, drainage system and topography of the area. The quality of kaolin is explained in terms of its chemical, mineralogical and physical properties. The chemical composition of Bombawuha kaolin deposit is mainly characterised by higher SiO_2 and lower Al_2O_3 major oxides. The presence of higher SiO_2 and lower Al_2O_3 in kaolin deposit indicate the deposit has higher quartz and lower kaolinite minerals. This is mainly due to incomplete kaolinization (Malu et al., 2013). Figure 6.1 shows the concentration of SiO_2, Al_2O_3 and LOI values in the kaolin deposit sampls (BK-1 to BK-5). The reduction of SiO_2 (SiO_2/Al_2O_3) is observed in the kaolin deposit relative to the bottom granite source rock (BR-1). This is an indication of the mobility of oxide with the higher degree of kaolinization. The depletion of this oxide is compensated by the enrichment of immobile oxide Al_2O_3 (Fig 6.1B). The loss on ignition (LOI) value also becomes higher that indicates the higher alteration phenomena (Fig 6.1D). The higher Al_2O_3 and LOI values of the kaolin deposit compared to the bottom granite rock confirms the higher kaolinite mineral concentration due to the alteration of the primary minerals mainly feldspar.

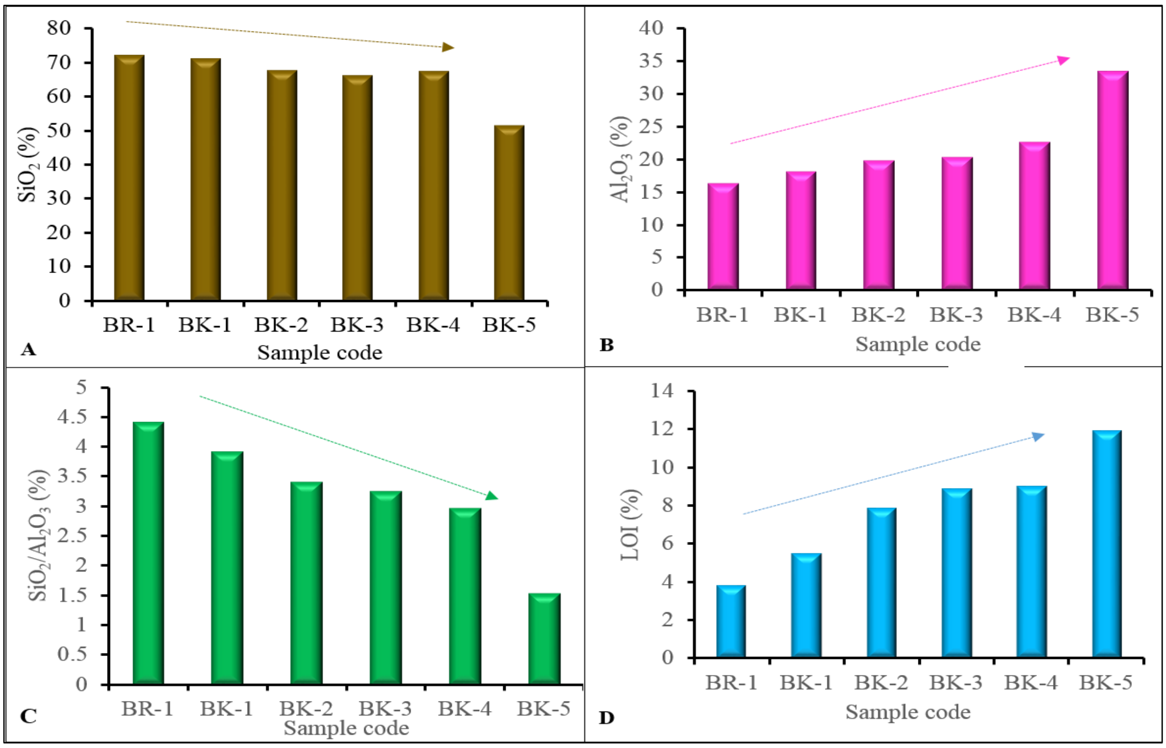


Figure 6.1: *The concentration of (A) SiO_2 (B) Al_2O_3 and (C) SiO_2/Al_2O_3 from the Bottom source rock (BR-1) towards the kaolinized deposit (BK-1 to BK-5) and (D) LOI*

Weathering and hydrothermal processes are the responsible geological processes for the formation of Bombawuha kaolin deposit by altering the granite and pegmatite units. From the two units, the kaolinized pegmatite (BK-5) has better quality due to its lower silica, iron, alkali and alkali earth oxides, and higher alumina and LOI values (Fig. 6.1 and 6.2).

The higher concentration of K_2O in Bombowuha kaolin deposit indicates the presence of feldspar (sanidine and orthoclase) minerals. The presence of higher Fe_2O_3 concentration is mainly due to the decomposition of biotite and illite (Fig. 6.2A). Fe_2O_3 is the most contaminant and deleterious coloring impurity and its presence could affect the suitability of kaolin product for various industries by reducing the optical and refractory properties (Murray, 2007).

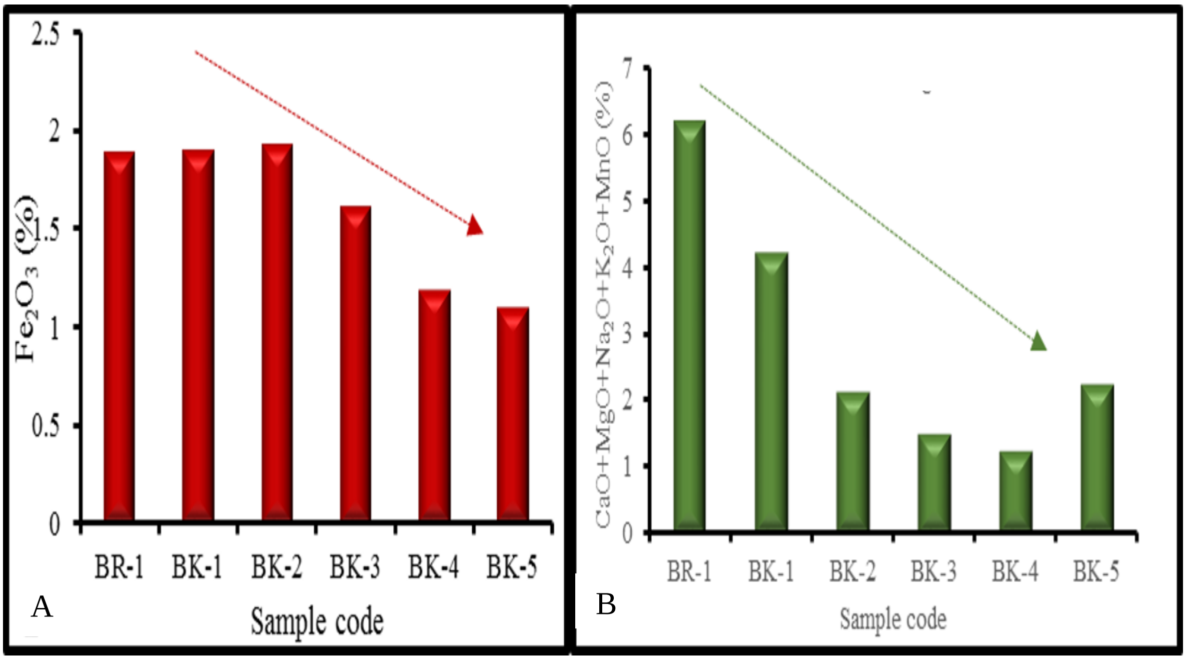


Figure 6.2: *Concentration of (A) Fe_2O_3, and (B) fluxes (K_2O+Na_2O+CaO+MgO +MnO) from the Bottom source rock (BR-1) towards the kaolinized deposit (BK-1 to BK-5)*

The presence of MgO and MnO may be contributed due to the disintegration of biotite (Nyakairu et al., 2001). The lower concentration of Cr_2O_3 and SrO in the deposit indicates the lack of ferromagnesian minerals in the parent material. The existence of minute TiO_2 in the deposit (less than 0.2%) indicates that its lower concentration in the parent rocks (Fig. 6.3). Its effect in the quality of kaolin is insignificant compared to the Georgia kaolin deposit (1.4).

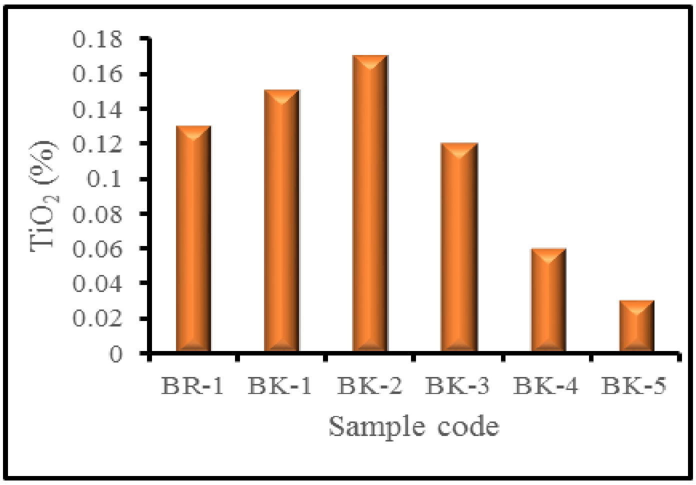


Figure 6.3: *The concentration of TiO_2 from the Bottom source rock (BR-1) towards the kaolinized deposit (BK-1 to BK-5)*

Generally, the enrichment of Al_2O_3, and the reduction of the other oxides indicates the enhancement of quality of kaolin deposit by geological processes (Olusola et al., 2014). From this it is possible to understand that the higher degree of kaolinization has a capacity to leach out the undesirable impurities and enhances the quality of kaolin deposit. The presence of SiO_2, Fe_2O_3, alkali and alkali earth components in kaolin deposit have an effect on the properties of kaolin. These components are higher than the UK and Georgia kaolin deposits and can affect the optical and refractory properties (Siddiqui et al., 2005). The refractoriness property is useful in ceramic production such as floor tiles and bricks (Malu et al., 2013).

As far as the application of kaolin is considered, most kaolin consumer industries need a kaolin product having lower iron content (<1% Fe_2O_3). However, the presence of iron in Bombawuha kaolin deposit exceeds the maximum allowed limit of 1% Fe_2O_3. According to Murray (2007) the presence of iron above the threshold (>1%) in the kaolin deposit adversely affect the commercial properties such as whiteness, brightness and refractoriness. Hence, the paper (coating and filling) and ceramics (white porcelain) industries would be affected.

The unacceptable gray and pinkish colour of Bombawuha kaolin deposit could be due to the presence of higher concentration of iron (>1%) as well as trace amounts of TiO_2 impurities. The iron oxide content of kaolinized pegmatite is lower than the kaolinized granite that confirms the former has higher quality. Generally, Bombawuha kaolin deposit is more siliceous and less aluminous as compared to the higher quality kaolin deposits of UK (Cornwall) and Georgia kaolin deposits, and ideal pure kaolin (Fig. 6.4).

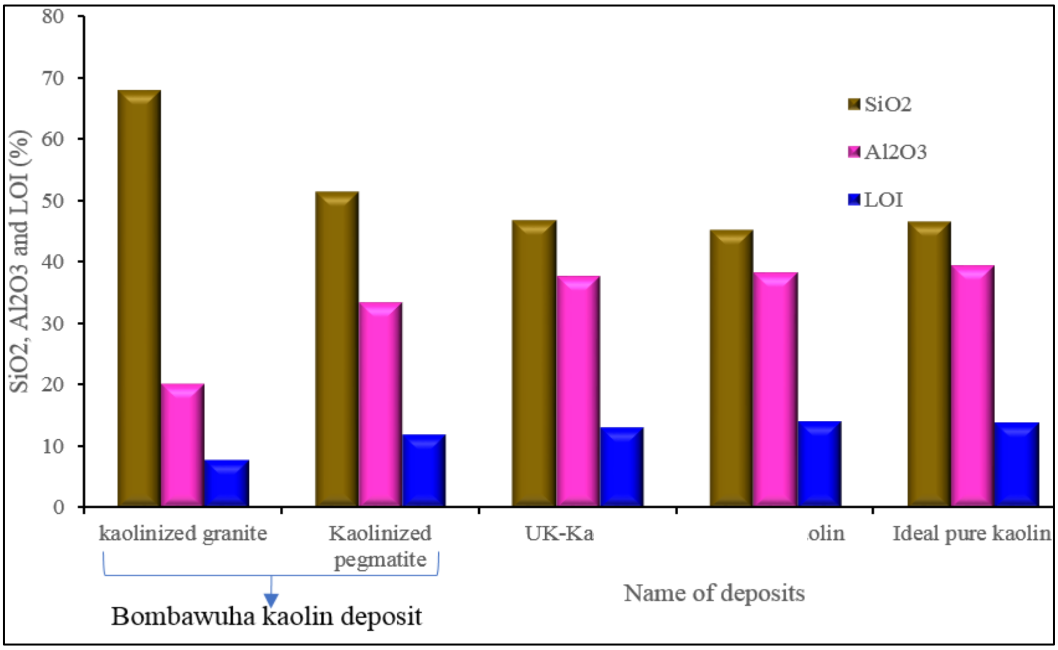


Figure 6.4: *Comparison of; SiO_2, Al_2O_3 and LOI values between Bombawuha kaolin deposit and UK, Georgia and ideal pure kaolins*

The concentration of Fe_2O_3 and K_2O is higher in Bombowuha kaolin than Cornwall and Georgian kaolin (Fig. 6.5)

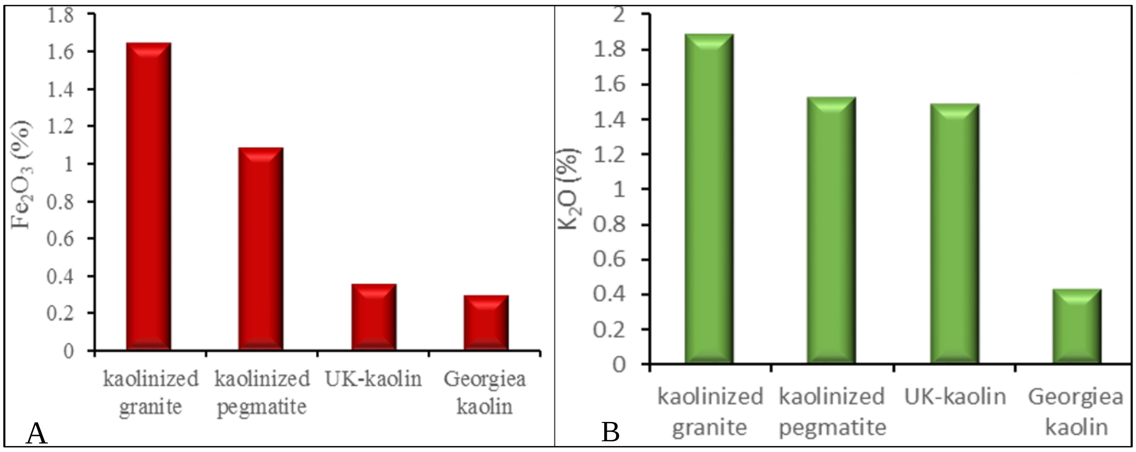


Figure 6.5: *The Comparison of (A) Fe_2O_3 and (B) K_2O contents of Bombawuha with UK and Georgia kaolin deposits*

Besides chemical composition, the mineralogical composition of Bombawuha kaolin deposit is also determined. The mineralogy of the parent rock (granite) which is the major source rock of the kaolin deposit has been studied using petrographic microscope. It is composed of k-feldspar, quartz, plagioclase, biotite, muscovite and opaque (Fe oxide) minerals. The X-Ray Diffraction (XRD) analysis result of the kaolin deposit also shows the presence of kaolinite, quartz, k-feldspar (orthoclase and sanidine), halloysite as well as mica (illite and muscovite). The presence of kaolinite mineral in the kaolin deposit indicates the fractionation/alteration of primary minerals mainly k-feldspar and mica due to surfacial conditions. On the other hand, the existence of primary minerals k-feldspar and mica in the kaolin deposit also clearly indicate the incomplete kaolinization/alteration of the parent rock of the deposit.

The presence of quartz and other minor unaltered mineral phases are the impurity minerals of the kaolin deposit. Quartz, k-feldspar and mica minerals contribute to the grittness of the kaolin deposit that affects the properties of kaolin such as decrease the plasticity and shrinkage properties of kaolin. They also affect the abrasiveness, and other optical and rheological properties of kaolin (AL-Shameri and Rong, 2009). The halloysite crystal which has unique shape (tube like) is originated from plagioclase and k-feldspar during kaolinization of granite rock. Halloysite mineral is transformed to the kaolinite mineral during weathering process. The presence of halloysite indicates the incomplete kaolinization and affects the properties of kaolin such as increase the viscosity and lower the dispersion properties (causes the reflocculating effect), lower the opacity which are the most required properties in the paper industries (Siddiqui et al., 2005).

Specifically, kaolinized pegmatite has higher concentration of kaolinite than the kaolinized granite. This indicates the higher quality characteristics of kaolinized pegmatite. The mineral illite is derived from mica during weathering and alteration processes. Its small proportion is also an indication of incomplete weathering or alteration of mica minerals. The presence of mica (biotite and illite minerals) becomes a source of iron impurity during kaolinization process (Ali and Dikko, 2015).

In addition to chemical and mineralogical composition, the physical characteristics can also help to evaluate the quality of Bombawuha kaolin deposit. Different physical properties were analyzed and are discussed here. The kaolin deposit shows color variation. The color variation of the kaolin deposit is resulted due to the presence of colouring impurities (mainly iron). The presence of minute iron bearing minerals may paint the kaolin deposit during weathering process. As a result, the color of kaolin varies from light gray to white. The kaolinized pegmatite is whiter than kaolinized granite. This indicates the lower contents of iron impurity is contained in kaolinized pegmatite than kaolinized granite. Bombawuha kaolin deposit is also dominantly characterised by coarser materials (Fig. 6.6). The higher coarser grains (grits) of the deposit is mainly due to the presence coarser minerals such as quartz, mica and feldspars. Grits are resulted from the incomplete kaolinization (Nyakairu et al., 2001). These grits affect the grain size distribution, plasticity and linear shrinkage values of the deposit.

According to Murray (2007) the higher grits also affect the most favorable commercial properties of kaolin such as brightness, opacity, glossy, viscosity, abrasiveness and smoothness which are required in paper and ceramics production. Evans (1993) stated that a kaolin material having the highest quality is characterised by fine grain size distributions (i.e. > 90% of the particles have less than 2μm). For example, a kaolin with grain-size distribution range of 75-94% and 25-48% that have less than 2μm is required as a filling and coating agent of paper production respectively (Bloodworth et al., 1989).

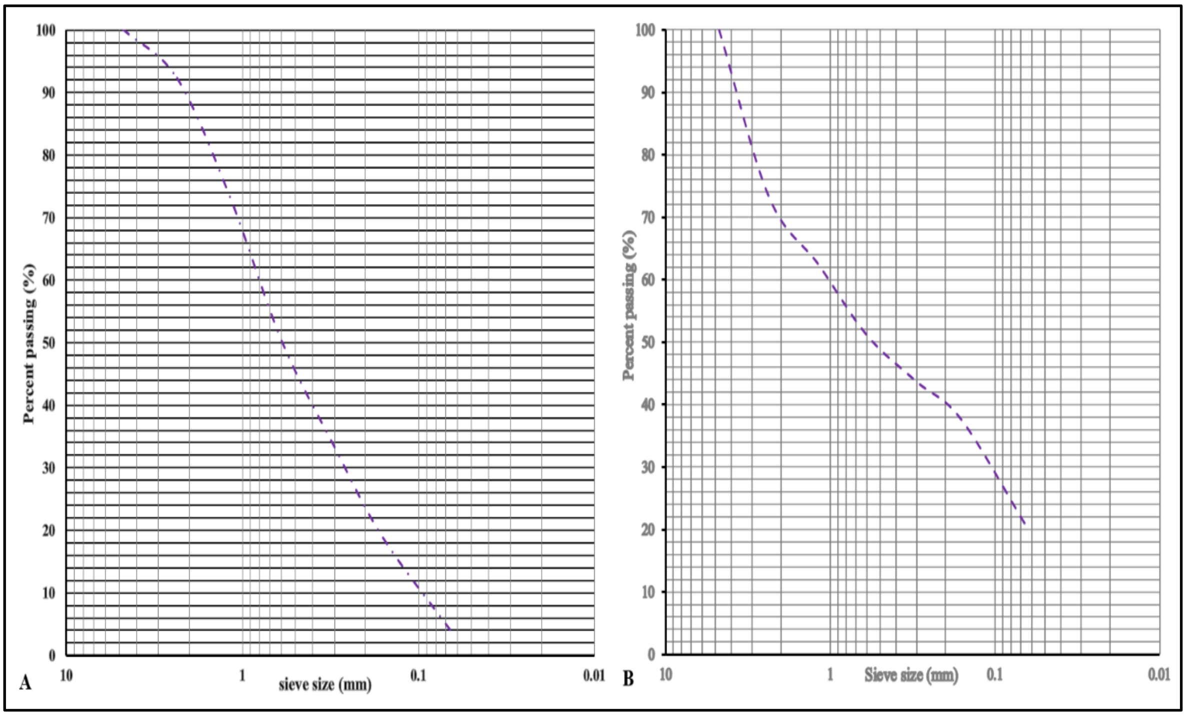


Figure 6.6: *The grain size distribution of Bombawuha kaolin deposit. (A) kaolinized granite), (B) kaolinized pegmatite*

The plasticity and linear shrinkage properties of kaolin are also essential properties in the production of ceramics. These properties are affected by the grain size distribution characteristics. Bombawuha kaolin deposit is characterised by a slightly plastic to non-plastic property and lower (0-3) linear shrinkage values. This is due to the presence of higher silica and silica enriched minerals (grits) such as quartz, mica and feldspar. Plasticity and linear shrinkage properties are increased by removing the coarser (mica and quartz) minerals (Siddiqui et al., 2005). Kaolinized pegmatite is slightly plastic and has higher linear shrinkage value compared to the kaolinized granite. This is because kaolinized pegmatite has higher finer fractions/clay (20.1%) than kaolinized granite (3.3%).

The variation of pH and specific gravity values of kaolin indicates the presence of impurities mainly iron and titanium oxides (Ahmedin, 2007). However, the variation of pH (6.27-6.37) and specific gravity (2.53-2.65) values of Bombawuha kaolin deposit are very low compared to the ideal pure kaolin's pH (7) and specific gravity values (2.60) (Murray, 2007). According to Miranda-Trevino (2013) the presence of iron impurity in kaolin causes a decreasing of pH and increasing of specific gravity values respectively. Thus, insignificant variation of pH and specific gravity values from the ideal kaolin indicates that the presence of iron and titanium impurities are very small to decrease the pH and increase the specific gravity values of Bombawuha kaolin.

6.2 Impurities of Bombawuha kaolin deposit

Impurities are the undesirable minerals or elements/oxides that are constituted within the kaolin deposit as an extra component associated with the main and economical mineral or element/oxide in this case alumina/kaolinite. Quartz and mica (biotite and muscovite) are the major impurities of Bombawuha kaolin deposit. Minor impurities of unaltered feldspar (orthoclase and sanidine), halloysite and illite are also contained within the deposit.

These impurities can be grouped in to primary (quartz, mica and feldspar) and secondary (halloysite and illite) minerals. Based on their effect on the deposit they can also be grouped as grits and colouring minerals. Grits are the impurities that constitute unaltered coarser minerals associated with the kaolin product. Quartz, mica and minor amounts of unaltered feldspar are the main grits of kaolin deposit. These impurities affect the commercial properties of kaolin such as grain size distribution, plasticity, abrasiveness, smoothness and shrinkage of kaolin (Murray, 1999).

The colouring impurities are also the other undesirable components which mainly affect the color of kaolin and other physical and optical properties of kaolin. Fe_2O_3 and TiO_2 are the most coloring impurities which have negative impact on the properties of kaolin and can inhibit its end use in various industries. Bombawuha kaolin deposit is characterized by higher iron (>1%) and lower titanium (<0.2%) coloring impurities. From these two coloring impurities, iron (Fe_2O_3) is the most considerable impurity of the deposit. This impurity is released due to the decomposition of micaceous minerals (biotite and illite).

6.3 Production techniques of Bombawuha kaolin deposit

Quality of kaolin can be affected by the executed mining and processing techniques. The procedures followed in the extraction of kaolin deposit is not similar with the other hard rock surfacial mineral deposits. Mining of Bombawuha kaolin deposit is operated using simple open pit mining method. It does not follow drilling and blasting production cycles because of weak /lower strength/ rheological properties resulted from weathering and alteration effect. Thus, the exploitation of the kaolin ore is started after the removal of the overlying barren waste material.

Currently the weak and thick (4-6m) overlying material is removed at one step with the face angle range of 80-85^0 (nearly vertical) till the underneath kaolin ore is exposed. However, the failurity of waste material from the overburden in to the ore is observed. This is because the thicker overlying waste material that have very steep face angle is removed continuously without technical step. The waste material failed from the overburden may cause dilution and ore loss effect. During rainy season the waste material is also overlaid on to the kaolin ore by the runoff water derived waste due to the absence of diversion system. This also hinders the production rate of the ore and disturb working place during exploitation. The stripping of over lying waste material step by step at lower face angle (45-60^0) can reduce the failurity of waste material in to the underneath kaolin ore.

A sample was collected from the accumulated run of mine (feed) for chemical composition analysis. The result shows higher SiO_2 (71.2%), lower Al_2O_3 (17.95%) and LOI (5.43%) values. Fe_2O_3 (1.88%), alkali and alkali earth oxides are also high (4.3%). Generally, the chemical composition of the run of mine is more equivalent to the composition of kaolinized granite than the kaolinized pegmatite (Fig. 6.7). This indicates the quality of the exploited kaolin ore (run of mine) is predominantly similar to the kaolinized granite (lower quality than kaolinized pegmatite). The unkaolinised source rock may also contaminate (dilute) during the exploitation of the kaolin ore/ i.e. Unwise mining technique/.

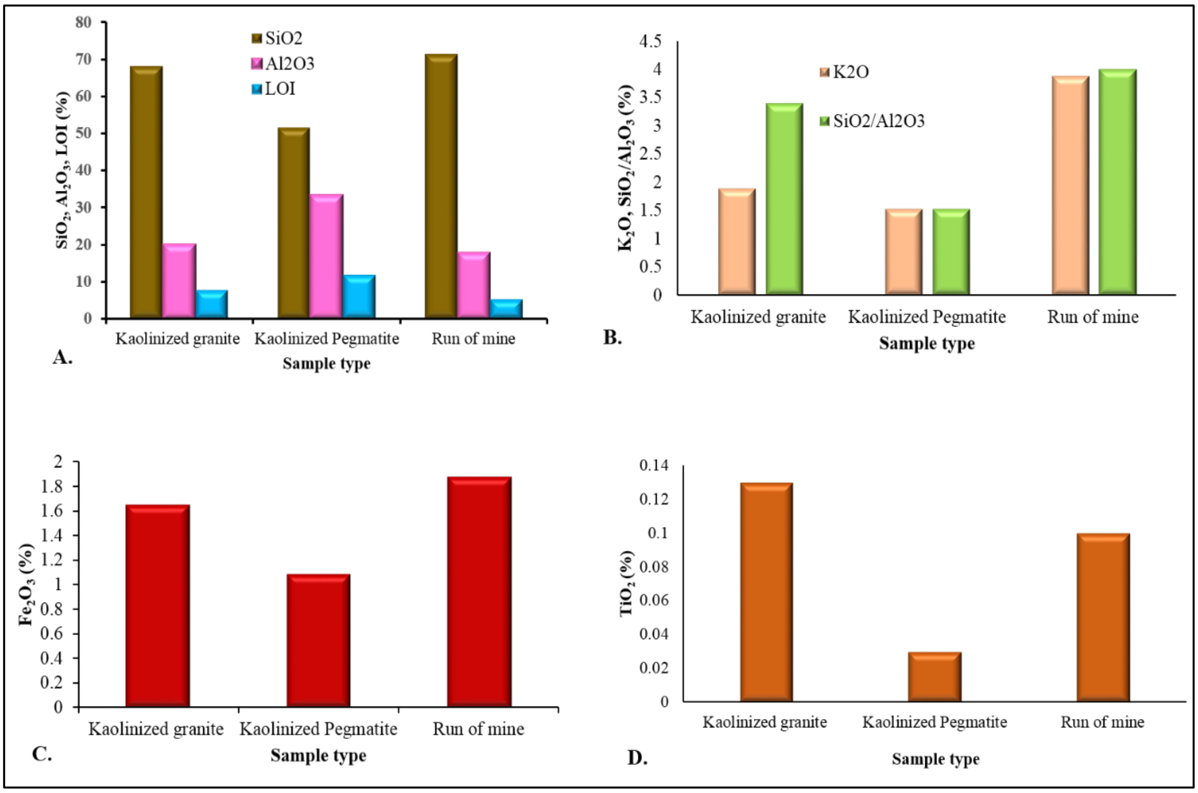


Figure 6.7: *The concentration of oxides in the run of mine as compared to kaolinized granite and kaolinized pegmatite*

6.4 Quality of processed kaolin and effectiveness of wet processing method

The quality of processed kaolin product mainly depends on the quality of crude kaolin and efficiency of processing techniques. Bombawuha crude kaolin is processed using wet processing method for the reduction/removal of the undesirable impurities. This processing method upgrades and compromises the quality of kaolin product by removing the available impurities (grits and coloring impurities). It enhances the properties of kaolin product such as grain size distribution, plasticity, linear shrinkage, brightness, viscosity and other commercial properties (Murray, 1999). The efficiency of this wet processing method/system is measured by the properties of the processed kaolin products.

Table 6 1: *The enhancement of chemical properties and effectiveness of wet processing*

Oxides (%)	Before processing	After processing	Enhancement and effectiveness of wet processing %
SiO_2	71.20	45.80	-36
Al_2O_3	17.95	35.50	+98
Fe_2O_3	1.88	0.99	-47
TiO_2	0.10	0.05	-50
Fluxes ($CaO+MgO+Na_2O+K_2O$)	4.30	1.32	-69
SiO_2/Al_2O_3	4.00	1.29	-68
LOI	5.43	14.70	+171

Note: The negative (-) and positive (+) signs indicate that percent of decreasing and increasing of chemical components by the processing system respectively

The wet processing system of Bombawuha significantly reduce the SiO_2 content of kaolin from 71.2% to 45.8% by 36%. The reduction of SiO_2 clearly indicates the removal of quartz and other silica enriched minerals. Similarly, the Al_2O_3 and LOI values are increased from 17.95% and 5.43% to 35.5% and 14.7% respectively. The wet processing system has also a capacity to produce kaolin products having a high alumina yield up to 35.5% which is maximized by 98% from its crude state. The LOI value is also enhanced about three times from its crude state. This indicates the increasing of kaolinite concentrate (finer particle) due to the removal of associated impurity minerals (mainly coarser minerals). Increasing of the concentration of kaolinite mineral is directly related with the enhancement of refractoriness property of kaolin (Mandal and Banerjee, 2004).

The lowering of silica and increasing of alumina concentrations indicate that the wet processing system clearly reduces the coarser and abrasive silicate impurities (grits) of kaolin. Here it is possible to understand that, the coarser components can be easily separated in the course of processing by screening or settling procedures. The removal of these coarser impurities (grits) mainly quartz, feldspar and mica also indicate the improvements of physical parameters of kaolin including grain size distribution, brightness, viscosity, plasticity, linear shrinkage, color, abrasiveness, smoothness, fineness (Murray, 2007).

The SiO_2/Al_2O_3 is also reduced properly by 68% due to the enhancement of the alumina and reduction of the siliceous minerals mainly quartz. The wet processing method also reduces the flux components (alkalies and alkali earth oxides) effectively from 4.30% to 1.32% by 69%. The decreasing of these fluxes indicates significant removal of mica and k-feldspar minerals. The reduction of the flux components enhances the refractory properties of kaolin product (Mandal and Banerjee, 2004).

The concentration of Fe_2O_3 is also reduced from 1.88% to 0.99% by 47% due to the application of processing. Almost half (0.89%) of the Fe_2O_3 content is reduced from the crude kaolin state. The lowering of Fe_2O_3 indicates the elimination of Fe-oxide impurities or iron bearing minerals during washing and screening. The other coloring impurity i.e. TiO_2 is also reduced by 50% from the crude state. The reduction of these two coloring impurities (Fe_2O_3 and TiO_2) clearly enhances the optical properties of kaolin such as whiteness and brightness (Murray, 2007).

Generally, the processed kaolin product (BP-1) has higher quality compared to the unprocessed crude kaolin. This is because, the increasing of Al_2O_3 and LOI values, and reduction of SiO_2, Fe_2O_3, TiO_2, and alkalies (Na, K) and alkali earth (Ca, Mg) oxides (see Fig. 6.8). It also infers that the removal of grits and iron bearing minerals mainly mica. This is an indication of overall quality enhancement by the processing system.

However, about 0.99% iron impurity is still contained in the processed kaolin products. This indicates either the iron impurity has ultrafine size (as fine as the clay minerals) or may exist as a structural iron of kaolinite mineral which have been incorporated during kaolinization and needs complex processing method for its removal (Ali and Dikko, 2015; Ramaswamy and Raghavan, 2011).

The presence of Fe_2O_3 more than 0.8% causes negative impact on the properties of kaolin such as whiteness, brightness and refractoriness. These properties are basic for the productions of paper and fine ceramics (white porcelain) (Mandal and Banerjee, 2004; Zegeye et al., 2013; Murray, 2007; Wilson, 2004). This implies the requirement of further processing in order to reduce the iron impurity below 0.8% and to upgrade the quality of kaolin products.

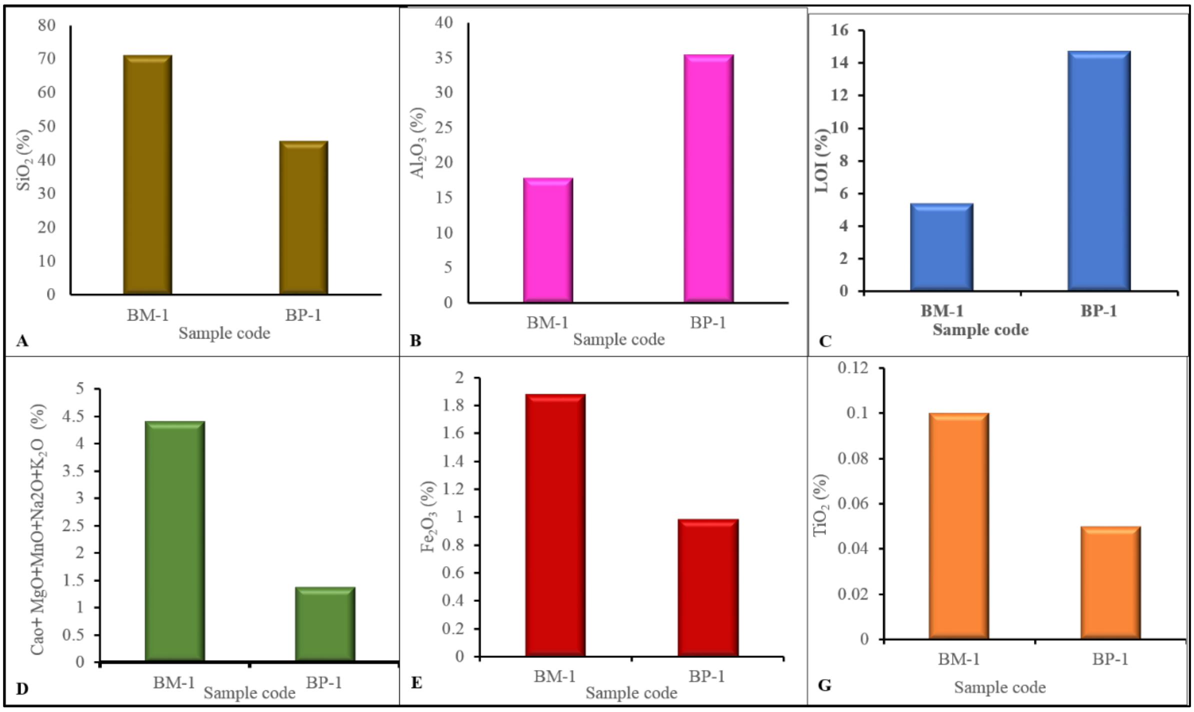


Figure 6 8: *The major oxide concentrations of the run of mine (BM-1) and processed kaolin (BP-1)*

As far as the mineralogy of processed kaolin (BP-1) is considered, it is characterised by higher concentration of kaolinite due to the removal of grit materials such as quartz, feldspar and mica. The presence of orthoclase and muscovite impurities indicates their fine and ultrafine size which passes through the screens and hydrocyclones of the processing plant. The other probability is linked to dilution effect due to unwise mining of kaolin ore. This happens during the extraction of kaolin ore, the unkaolinised rocks may be incorporated and causes to increase the amount of impurities and reduce the effectiveness of the processing system. The presence of these fine impurities may affect the physical and chemical properties of kaolin for industrial use. The presence of coarser and sharp-edged quartz and mica minerals in the crude kaolin may affect/tear apart the processing screens and allow the extra impurities to pass through the screens. The processed kaolin product is also characterised by higher pH and lower specific gravity values that are more equivalent with the ideal pure kaolin values due to the removal of coloring impurities. Its color is also whiter than the crude kaolin. This clearly shows the lowering of colour imparting minerals mainly iron bearing minerals by the processing system

In the field the processing plant of kaolin was observed to understand the constraints that hinder quality of kaolin product. The processing components including screens and hydrocyclones are old and the impurity can be passed to the kaolin product. In addition to this, three hydrocyclones are available in the processing system but recently the third hydrocyclone is not functional. The presence of iron (0.99% as Fe_2O_3) and minute abrasive silicate minerals including orthoclase and muscovite in the processed kaolin product may be due to the non-functioning of the third hydrocyclone of the processing system. Transitory of these impurities may hinder the processed kaolin product to fit with the specification of higher quality demanding industries. Thus, the incorporation of the third hydrocyclone enables to reduce the undesirable trace impurities and enhances the quality of the processed kaolin. It also helps to avoid the ore loss, to increase quantity of the clay product, to upgrade the fineness properties, and to enhance the overall quality of kaolin products by enhancing the alumina/ kaolinite concentrate.

6.5 Quality enhancement techniques of Bombawuha kaolin product

Depending on different literature analysis, the higher iron impurity in the processed kaolin product can also be removed by other additional suitable processing techniques. There are different physical and chemical processing methods that can remove this impurity (González et al., 2007). Magnetic separation (especially high gradient or super conducting magnetic separation), flocculation, froth floatation (ultra-flotation), microbial, and chemical leaching and dispersants are the common iron impurity removal techniques (Refaei et al., 2017). However, the choice depends on the type and quantities of impurities, the cost of processing techniques, economy, technology, environmental effect, and maximum required quality of the product for industries (Zegeye et al., 2013). The addition of leaching and dispersant chemicals can remove the iron impurity effectively except their economic implementation and environmental impact (Qiu-xiang et al., 2011).

6.5.1 Magnetic separation method

Magnetic separation technique (mainly high gradient magnetic separation) is the most suitable processing technique for the removal of iron impurity (Hailemichael Fentaw and Tibebu Mengistu, 1998; Raghavan et al., 2000). Because it is effective, have lower cost (compared to leaching and dispersant chemicals), have not environmental impact, produces a bright, white and value-added kaolin product. This processing technique of kaolin handles 75% of the world white porcelain and paper productions (Refaei et al., 2017). Therefore, it is possible to use this technique by accompanying further investigation on its economic and technical feasibility. It is assumed that, the magnetic method combined with the existing washing, screening and gravity separation methods can reduce the iron impurity and enhance the properties including color (whiteness), brightness, and refractoriness (Ramaswamy and Raghavan, 2011).

6.5.2 Effectiveness of magnetic separation method in upgrading the quality of kaolin product (case studies)

i. Egyptian kaolin

The Egyptian kaolin deposit is located mainly in two localities namely in Aswan and Sinai. Even though their origin is obscure, they were most probably formed by surface geological process associated with transportation and deposition. These kaolin's satisfy the local demand for filler, paper and ceramic industries for the past 50 years, however in comparison to the current standard, the Egyptian kaolin is failed under low grade. This is due to detection of impurities mainly iron oxide and titanium oxide within it. These impurities affect the brightness of kaolin and decrease its demand for paper and ceramic industries.

In order to upgrade the quality of kaolin, magnetic separation method was employed. Before the crude kaolin is introduced in to the separator, complete chemical analysis of the kaolin sample was performed using X -Ray Fluorescent (XRF). As the result of analysis shows, the crude kaolin sample has relatively high amount of TiO_2 (3.19%) and Fe_2O_3 (1.69%). The crushed crude kaolin is added in to the magnetic separator to avoid these impurities. Since iron and titanium are highly prone to magnetic attraction they are decreased effectively as the crude kaolin passed through this separator. Finally, the concentration of iron and titanium oxides decrease by 55.6% and 77.8% from the crude kaolin and becomes 0.75% and 0.71% respectively (see Fig. 6.9). Due to the removal of these impurity oxides the brightness value became increased (75.21%). From this case study it is concluded that magnetic method is an effective means of removing iron and titanium from the kaolin and enhance its brightness (Refaei et al., 2017).

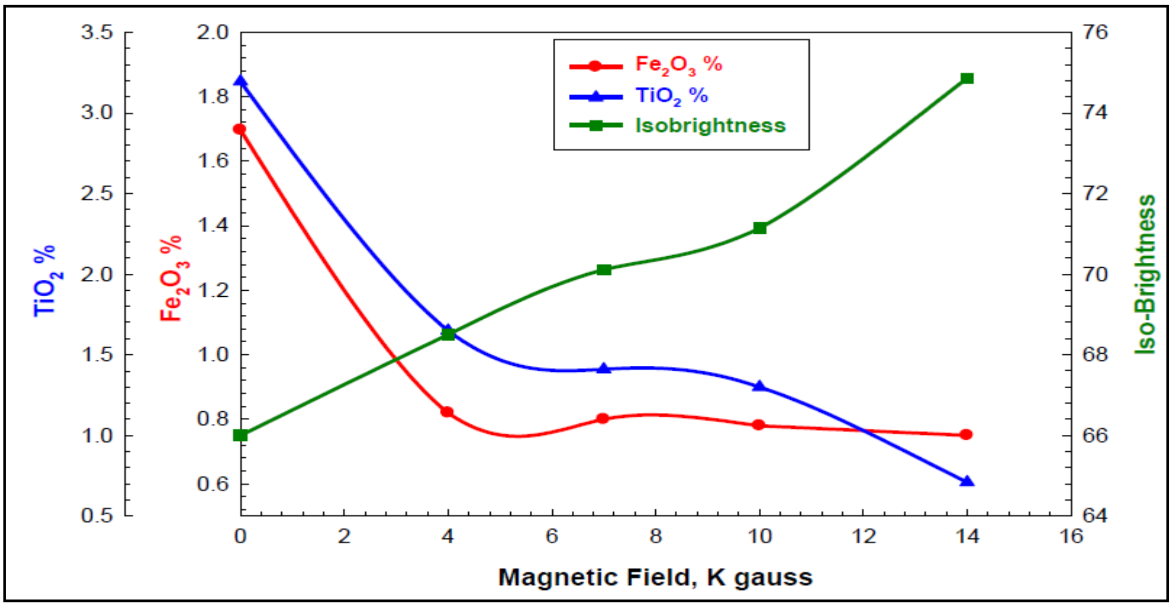


Figure 6.9: *Product grade as a function of magnetic field strength (adopted from Refaei et al., 2017)*

ii. Western India kaolin

According to Raghavan et al. (2000) India has substantial kaolin deposits at which most of them are not exploited because of absence of modern processing. Superconducting High Gradient Magnetic Separation (SC-HGMS) is a standard operation in most of the modern kaolin processing plants elsewhere in the world. This method is also tested in India for the removal of coloring impurities (Fe_2O_3 and TiO_2). The kaolin having 0.36% Fe_2O_3 and 1.6% TiO_2 is fed to this processing method. After processing the Fe_2O_3 and TiO_2 impurities are reduced by 58% and 12% and become 0.15% and 1.4% respectively.

6.6 Industrial suitability

Every industry that consume kaolin as an ingredient for the formulation of any products, has to meet a set of standard specifications. The suitability of Bombawuha kaolin deposit for different industries is measured by its chemical, mineralogical and physical properties compared to the standard specifications of the industries. Essentially, the specifications of kaolin depend on the purpose for what industry it will be used. The suitability of Bombawuha kaolin deposit for various industries is mainly affected by particle size distribution and coloring impurity. Because, the frequent coarser minerals (grits) like quartz, feldspar and mica as well as iron impurities are contained and affects the properties of kaolin such as color, plasticity, grain size distribution, shrinkage and other optical properties.

As far as the industrial use of kaolin is considered, the properties of Bombawuha kaolin deposit does not fit to the specifications of most industries. The colour of kaolin is the most important properties for various industries. Bombawuha crude kaolin has light gray color and may affect for paper and fine ceramics (white porcelain) productions. But it can satisfy for the industries which does not require white color as a parameter. When the grain size distribution of Bombawuha kaolin deposit is considered, it does not satisfy for most higher quality demanding industries. Because it is dominated by the higher coarser materials (>80%) and lower finer particles (3-20%).

The plasticity of Bombawuha kaolin deposit does not fit with the standard specifications of tableware and porcelain (10-30%) (Iyasara et al.,2014). But it can be used for the production of materials that require <10% plasticity value such as bricks, pipes, tiles and pottery. The pH value of Bombawuha kaolin deposit (6.27-6.37) can fit the specifications of paper industry as filler (5–7.5) and coating (6.5–7.5), and paint industry as extenders (4.5-9.5) (Siddiqui et al., 2005). The kaolinized pegmatite (BK-5) has higher Al_2O_3 (33.4%) and lower SiO_2 (51.5%) and iron oxide (1.09%) compared to the kaolinized granite. Relatively, it also has higher finer particles (20%<0.063mm). Thus, its chemical and physical properties are nearest to the specified values of the industries (Table 6.2).

As far as the processed kaolin is considered, it is characterised by lower SiO_2 (45.8%), lower Fe_2O_3 (0.99%) and higher Al_2O_3 (35.5%). The kaolinite mineral is also high with slight orthoclase and muscovite minerals. Physically, it is also characterised by higher finer particles. More than 90% of the products have <45µm grain size. Due to the lowering of iron impurity, the color is also enhanced and become white. As a result, Bombawuha processed kaolin is suitable for the production of ceramics (bricks, pottery, floor and wall tiles), paint filer, plastic and rubber filer (Siddiqui et al., 2005). Slight enhancement of alumina (>35%) and reduction of iron (<0.9%) is required for the higher grade demanding industries such as porcelain and paper production. This helps to enhance the refractory, brightness and whiteness properties of kaolin (Murray, 2007).

Table 6.2: Chemical composition of Bombawuha processed kaolin product and standard specifications of industries

Oxides (%)	Bombawuha Processed kaolin	Standard specifications of industries							
		Paper coating	Paper filler	Porcelain	Ceramics	Refractory bricks	Paint	Rubber	Plastics
SiO_2	45.8	47.8	48.7	48	47-48	51-70	45-48	44-47	44-47
Al_2O_3	35.5	37 **x**	36 **x**	37 **x**	35.1-37	25-44	37-38	37-39	37-39
Fe_2O_3	0.99	0.58 **x**	0.82 **x**	0.6 **x**	0.6-1	0.5-2.4	0.6-1.1	0.05-1.5	0.3-1.7
TiO_2	0.05	0.03	0.05	0.1	0.02-0.1	0.1-2.8	05-1.4	0-1.4	0.05-1.4
CaO+ MgO+ Na_2O+ K_2O	1.32	1.76	2.53	2.03	1.2-2.7	1.1-4.8	1.2–2.7	-	-
LOI	14.7	13.1	11.9	12.4	11-12.5	-	13.8-14	13.5-4.5	13.5-14.5

Note: - Paper coating, Paper filler and Porcelain (Olusola, 2014); Ceramics, Paint, Rubber, Plastics (Siddiqui et al., 2005). **'x'** indicates the need of improvement of Bombawuha kaolin product.

Chapter Seven

7. Conclusion and Recommendations

7.1 Conclusion

Bombawuha kaolin deposit is a primary/residual type deposit which is derived from granite and pegmatite parent rocks by weathering and hydrothermal processes. The field investigation combined with physical, chemical and mineralogical analyses result indicate that the deposit is characterised with light gray to white color, highly abrasive, lower plasticity, lower linear shrinkage and higher grits compared to the industrial specifications and other commercial kaolin deposits. The presence of higher amounts of grits (coarser impurities such as quartz, mica, and feldspar), coloring impurities (mainly iron oxides and other small amounts of fluxing components) lead to lower the quality of kaolin deposit.

Bombawuha kaolin deposit is constituted by higher silica and iron, and lower alumina, LOI and titanium. The color variation of the deposit comes due to the presence of coloring impurities mainly iron. Quartz and kaolinite are the major minerals of the deposit with minor amounts of mica (muscovite and illite), feldspar (sanidine and orthoclase) and halloysite minerals. The presence of higher quartz combined with minor mica and trace feldspar minerals leads the deposit to be highly gritty, increase abrasiveness, decrease plasticity and linear shrinkage properties.

From the two sources of the deposit, kaolinized pegmatite has improved physical, chemical and mineralogical properties (higher quality) than kaolinized granite. Kaolinized pegmatite has white color, moderate grain size distribution, moderate plasticity, lower silica, higher alumina, higher kaolinite, lower iron and titanium impurities. On the other hand, kaolinized granite has higher grits and iron impurities. It also has light gray color, higher silica, lower plasticity, lower linear shrinkage and finer particles.

The mining/open pit method produces a crude kaolin having similar properties with the kaolin deposit. The run of mine (crude kaolin at the feed) is characterised by higher silica and iron oxide impurities, and lower contents of alumina and LOI values. As far as the Bombawuha kaolin processing system is observed, the employed wet processing method include mechanical washing and screening system. It is effective for the removal of coarser materials (grits; such as quartz and mica). The processing technique enhanced the quality of kaolin product by increasing the alumina content, lowering the silica and iron content. According to the analysis result Bombawuha processed kaolin product can fit for many industrial applications including ceramics (wall and floor tile, sanitary ware, bricks), paint, rubber and cement. It can also be used for the paper industry as a filler after the enhancement of the alumina and reduction of iron content using the required extra processing techniques.

7.2 Recommendations

- In this research work, it was tried to assess the physical, chemical and mineralogical characteristics of the kaolin deposit. It is recommended that to incorporate brightness, viscosity and firing properties of kaolin to increase the certainty of the study.
- Based on the laboratory analysis result, the kaolinized granite and pegmatite shows different physical and chemical characteristics. The kaolinized pegmatite is characterised by higher quality compared to the host kaolinized granite. Therefore, it is required to add further investigations on its economic and technical feasibility to use selective mining.
- The mining activity gives an attention only to the ore of kaolin, but there are also other industrial minerals mainly quartz and mica which are considered as by products. It is important to undertake further investigation on the economic feasibility of these minerals to be used in different industries.
- As the researcher observed, some parts of the processing plant (hydrocyclone) are not working. Due to this reason, there is loss of kaolin ore and incorporation of undesirable impurities to the product. Therefore, it is recommended to include the detached parts of the processing plant to enhance the quality and quantity of the clay product.
- The overburden waste material is thrown to the side of the streams. During rainy season it is degraded and eroded down the slope by gravity. This kaolinized waste material may has a capacity to degrade and lower the fertility of the soil for the agricultural purpose. Hence, it is better to protect and reuse as back filling material to the excavated open pit mine.
- In the study area the forest is extensively removed because of the introduction of kaolin mining. However, after the extraction there is no reforestation activity. So, the mined cites should be recovered by plantation to sustain healthy environment.

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Appendix I: The Chemical composition of Bombawuha kaolin compared with other kaolin deposits of the world (%)

	Ethiopia (Bombawuha) kaolin deposit		Botswana	USA	Pakistan	UK
Oxides (%)	Kaolinized granite	Kaolinized pegmatite	Makoro	Georgia kaolin	Shah Dheri	Cornwall kaolin
SiO_2	68	51.5	51.1	45.3	45.3	46.77
Al_2O_3	20.20	33.4	32	38.44	36.8	37.79
Fe_2O_3	1.65	1.09	1.8	0.3	0.8	0.36
TiO_2	0.13	0.03	1.5	1.44	0.5	0.02
CaO	0.02	0.01	0.02	0.05	2	0.13
MgO	0.21	0.07	0.1	0.25	0.5	0.24
Na_2O	0.07	0.03	0.1	0.27	1	0.05
K_2O	1.89	1.53	0.06	0.44	0.2	1.49
LOI	7.84	11.95	13.32	14	12.90	12.97

Makoro (Ekosse, 2001), Georgia kaolin (Murray and Keller, 1993), Shah Dheri (Siddiqui et al., 2005), Cornwall kaolin (Murray and Keller, 1993)

Appendix II: The industrial specifications of kaolin for different industrial application (after Siddiqui et al., 2005)

Mineral Content	Paper Coating	Paper Filler	Ceramics	Paint filler	Rubber filler	Plastics filler
Kaolinite	93–99%	95–90%	_	_	High	High
Mica	7–10%	5–10%	_	_	_	_
Physical properties						
Brightness (cps)	90–92%	82–85%	75–90%	76–90%	70–92%	70–92%
Viscosity	66–70%	_	_	_	_	_
<63 µm fraction	_	_	100%	_	-	_
<10 µm fraction	100%	85–97%	80-96%	70–99%	-	22-80%
<2 µm fraction	89-92%	60–80%	40-70%	15–70%	20–80%	17–90%
pH	6.5–7.5	5–7.5	_	4.5–9.5	4.5-5.5	_

Appendix III Applications of Kaolin (adopted from Murray, 1999)

Paper coating	Adhesives	Medicincs	Foundaries
Paper filler	Bleaching	Food additives	Floor tiles
Ceramics raw material	Cement	Catalyst preparations	Textiles
Extender paint	Fertilizers	Adsorbents	Crayons
Filler in rubber	Plasters	Porcelain enamels	Linoleum
Filler in plastics	Filter aids	Detergents	Chemicals
Extender in ink	Cosmotics	Pastes	Water purification
Insectisides	Roofing granules	Sizing	Wall tiles

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Thesis Chapters	Test I		Test II		Test III		Test IV		Test V		Test		Avge	
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Abstract	100	0	100	0	100	0	100	0	100	0	100	0	100	0
Introductory chapter	100	0	98	2	100	0	98	2	100	0	98	2	99	1
Literature review	97	3	100	0	99	1	100	0	99	1	95	5	98.5	1.5
Methodology	100	0	100	0	100	0	100	0	100	0	100	0	100	0
Result and discussion	100	0	100	0	100	0	100	0	100	0	100	0	100	0
Conclusion	100	0	100	0	100	0	100	0	100	0	100	0	100	0
Overall thesis	97	3	98	2	99	1	98	2	99	1	93	7	97.5	2.5

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