ADDIS ABABA UNIVERSITY

SCHOOL OF EARTH SCIENCES

GEOLOGY, MINERALOGY, GEOCHEMISTRY AND GENESIS OF ABIYATA DIATOMITE IN CENTRAL MAIN ETHIOPIAN RIFT

BY

YIRGALEM HUNEGNAW TAYE

ADVISOR: Dr. WORASH GETANEH

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

September, 2021

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Approved by the Examining Committee

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DECLARATION

I the undersigned declare that this thesis is my original work under the supervision of Dr. Worash Getaneh, School of Earth Science Addis Ababa University during the year 2020/21 and has not been presented for any degree in any university, and all the sources of materials used for the thesis have been acknowledged.

Yirgalem Hunegnaw (candidate)

Signature: ______________________

This Thesis has been submitted for examination with my approval as university advisor

Dr. Worash Getaneh (Advisor)

Signature ___________________

Abstract

Abiyata diatomite is situated in Central Main Ethiopian Rift (CMER) on the narrow strip of land dividing the two lakes Abiyata and Shala in the lakes district of the Ethiopian Rift Valley which is about 210 km from Addis Ababa. Geology of the deposit area is composed of Miocene to Quaternary age acidic igneous rocks consisting of pyroclastic tuff, ignimbrite and pumice and lacustrine sediments in which diatomite is hosted.

Diatomite's geological, geochemical, and mineralogical features, as well as its formation, are discussed in this research. To characterize diatomite from Abiyata, chemical, mineralogical, technological, and micro paleontological examinations were conducted on samples collected from outcrops and stream sections.

The XRD characteristic peaks of diatomite demonstrate that it is primarily made up of Opal-A silica, however certain crystalline phases were discovered in adequate amounts. Quartz and feldspar were the predominant crystalline phases, with lesser amounts of calcite, cristobalite, illite, mordinite, wairakite, halloysite, clinoaptilolite, adularia, and tridymite.

From SEM photomicrographs diatomites are primarily formed of benthic freshwater diatom species such as Staurosirella pinnata, Staurosira construens, Pseudostaurosira brevistriata, Epithemia Sorex and surirella pinnata. Diatom species, sedimentary profile sections and mineralogical data suggest that diatomite was deposited in lacustrine-type freshwater shallow lake environment.

Chemical data obtained from 10 diatomite samples show that while silica is the bodybuilding material for diatomite. i.e., Silica (SiO_2), 76.9%; Alumina (Al_2O_3), 3.49%; Sodium Oxide (Na_2O), 1.52%; Potassium Oxide (K_2O), 1.107%; Iron Oxide (Fe_2O_3), 1.1%; Loss on ignition (LOI) 13.7 and other oxides are below 1%.

Studies from technological properties like physical tests, chemistry, and mineralogy and micropaleontology of Abiyata diatomite suggest that calcined diatomite can be used for waste treatment processes in the filter aid industry and as filler material.

Key words: Abiyata, amorphous silica, diatomite, lacustrine, genesis, mineralogy

Acknowledgements

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My sincere and heartfelt gratitude goes to my advisor Dr. Worash Getaneh for his help and guidance to complete my paper. It is a great privilege and honor to work and study under his guidance. He steered me in the right direction whenever I had troubles and problems in the last two years.

The laboratory analysis (XRD, SEM, ICP-AES and Grain size) is done in Czech Republic, university of Charles and Geological survey of Czech Republic. So I would like to express my sincere thanks to Dr. Karle Martinek for his help by facilitating laboratories, Dr. Kristof Verner for financial support, Dr. Viktor Goliáš for XRD analyses, Assoc. prof. Zbynek Engel for grain size analyses Assoc. prof. Ladislav Strnad for geochemistry analyses.

I also like to render my warmest thanks to Mr. Daba Bulto for his presence, support, guidance and valuable suggestions during field work and providing his invaluable time.

I would like to convey my acknowledgement to my colleagues from geological survey of Ethiopia for their advices, comments and suggestions from starting to the end of this thesis work.

The last but not the least my sincerely thanks goes to the administrators of the Negele Arsi Woreda and the community in Abiyata and Shala area for their cooperation during the field work.

List of Acronyms

CMER	Central Main Ethiopian Rift
EARS	East Africa Rift System
GPS	Global Positioning System
GSE	Geological Survey of Ethiopia
ICP-AES	Inductively Coupled plasma Atomic Emission Spectroscopy
JORC	Joint Ore Reserves Committee
LOI	Loss of Ignition
MER	Main Ethiopian Rift
m s l	Mean sea level
NMER	Northern Main Ethiopian Rift
SEM	Scanning Electron Microscope
PPL	Plane Polarized Light
XPL	Cross Polarized Light
PXRD	Powdered X-ray Diffraction

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CHAPTER ONE

INTRODUCTION

1.1.Background

The Main Ethiopian Rift (MER) is about 84km wide and is opening ESE-WNW at a rate of about 2.5mm/yr (Wolfenden et al., 2004). The rift is bordered by large and discontinuous Miocene age normal faults (Tsegaye Abebe et al., 2005).

The MER and its flanks are made of Tertiary to Quaternary volcanics and pyroclastic rocks (Sagri et al., 2008) whereas large areas of the rift floor are covered by upper Quaternary volcano–lacustrine, fluvio–lacustrine, and colluvial deposits.

According to Solomon Tadesse et al. (2003), the MER has a potential for some metallic minerals and many industrial minerals including potash, salt, trona, gypsum, limestone, bentonite, diatomite, pumice and clay. Among the widest range of industrial mineral resources, diatomite is one of the most important industrial mineral resources in the rift. This thesis work tries to investigate one of the diatomite deposits in the central MER near Lake Abiyata. It is suggested that Zway, Langano, Abiyata and Shala lakes were all joined as one huge lake during the pluvial, and diatomaceous earth beds deposited from this giant lake are exposed in the Bulbula and Horacallo river sections (Dubois, 1976).

The deposit of diatomaceous earth between Abiyata and Shala lakes is located 25 km west of the main asphalt from Addis Ababa to Hawassa. There is a relatively good drivable road that continues on to the village of Algae. The terrain where diatomite of Abiyata is located represents a depression which gradually rises to mount Fike on southwest, which rims the lacustrine sediment.

The unique properties of diatomite include: light weight, high porosity, high absorptivity, high purity, multi-shaped, rigidity and inertness. These unique properties make it industrially useful in a variety of ways such as in liquid filtration; as a multi-functional mineral additive; as a carrier for active ingredients and diluents; as aggregate and, as a source of silica (www.ima-eu.org).

It is also raw material for a lot of silicate products. Those diatomite products are mostly consumed in the filter and filling industries. Other purposes of use are as catalyst, in the abrasive industry and filling of pesticides and pharmaceutic products.

Diatomites are of variable purity, although the most commonly used commercial grades contain at least 85% SiO_2, and are used in the manufacture of fillers and filter-aids. The most common impurities are detrital sand and silt, clay, volcanic ash, carbonate and organic material. Impure clayey diatomite containing about 75 % SiO_2, is used to make lightweight refractory bricks; such deposits are referred to in the industry as "moler" (Ibrahim SS, 2012).

This research project was conducted in the MER more specifically in the Central MER with the aim of characterizing the diatomite deposit of the area.

1.2.Geographic Setting of the Study Area

1.2.1. Location and Accessibility

The Abiyata diatomite deposit (Figure 1) is situated in Oromia Regional State, Arsi zone, Arsi Negele Wereda, within the Central MER. It is situated on the narrow strip of land dividing the two lakes Abiyata and Shala in the lakes district of the Ethiopian Rift Valley. The area *is* situated southwest of Lake Abiyata and north of Lake Shala. Distinct landmarks are Lencha Guda and Lencha Tiko, two volcanoes north of the area, and the hillock Billa to the south.

Geographically, the study area is bounded from north to south by latitudes 832450m N and 838700m N, and from west to east by longitudes 446500m E and 453050m E of the map sheet of Hossaina (NB 37-2). The area covers about 40 square kilometers.

The area can be accessed by the road connecting the capital city Addis Ababa with Mojo - Ziway- Shashemene-Hawassa. The Addis Ababa-Hawassa highway lies about 25 kilometers east of the diatomite deposit. The turn-off to the deposit from the highway is at the village of Dole, about 210 kilometers south of Addis Ababa. The dust road (covered in parts with stone chippings) to the diatomite area descends, a few kilometers west of Dole, a north-trending fault scarp to reach the sandy shore of Lake Abiyata in the depression. After crossing the depression, the road rises again and passes over the hilly landscape of Aroressa to enter the area in which the diatomite deposit lies.

To the west and central part of the study area, there are foot trails developed by the local peoples for their day to day activity. This foot trails create additional access to the portion of the study area that is located few kilometers away from the main and gravel roads towards the Algae village.

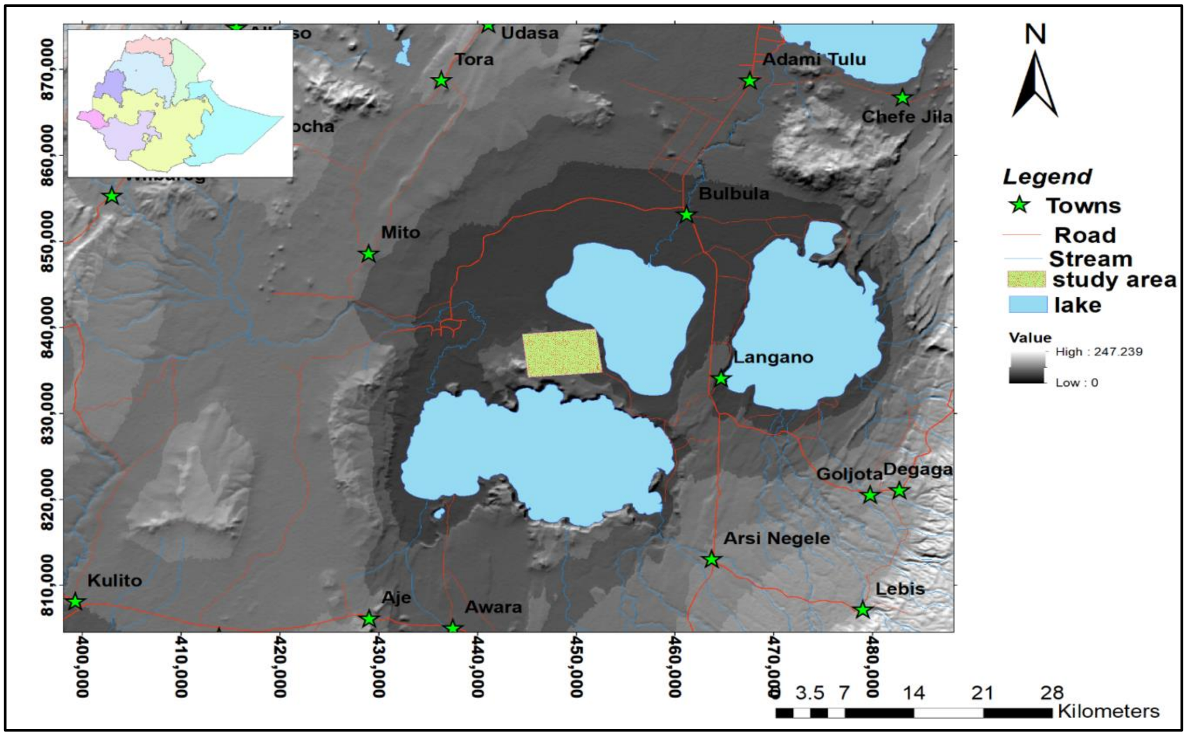


Fig. 1.1 location map of the study area

1.2.2. Physiography and Drainage

The studied area is located in the central part of the MER. The enormous volcanic and tectonic activities that took place in the Quaternary period (Boccaletti et al., 1998) created distinct physiographic groups in the study area identified as the mountain, ridges and cliff blocks bounding the flat caldera floor.

It is characterized by the presence of numerous lakes, calderas and volcanic cones. Lake Shala, Langano, Abiyata, Hawassa and some part of Lake Ziway are found in the central MER, which are surrounded by Pleistocene to Holocene pyroclastics and lake sediments (GSE, 2004).

The area is topographically characterized by the depression zone with steep marginal faults along its edges. The study area is part of an independent basin, called Rift Valley Lakes Basin (RVLB). It is mostly soil covered; relatively narrow depression in which the diatomite occurrence is bounded to the south by the volcanic cone of Billa, to the north by the remnant ignimbritic massif of Lencha Guda, and to the west by the two adjoining ignimbritic mountains of Bilisso and Fike. A canyon which starts in the western part of the area between Fike and Bilisso, cuts through the depression and winds eastwards to Lake Abiyata. The area *is* fairly flat and gently sloping upwards from Billa to Lencha Guda. Small rivers, dry riverbeds in the dry season, have cut deeply (approximately 10 meters) into the landscape.

In the MER, the drainage networks are variable in terms of type, orientation, and density, as they are affected by different factors from place to place. The tectonic activity and lithological variation in the area also partly or wholly control the drainage density and drainage pattern. Within the Rift, the river pattern seems dependent on the rift-wise fractures and faults as well as the main regional slope due to the eastward tilting of the Rift floor. Most of the river channels follow the young lineaments and discharge their water into lakes at the bottom of the rift.

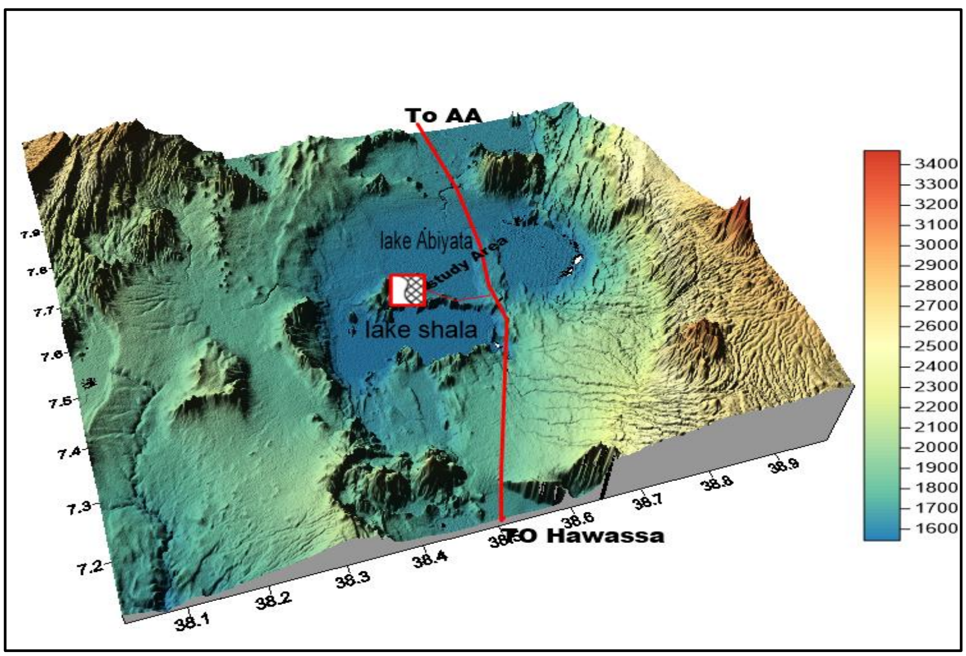


Fig 1.2 Physiographic map of the study are

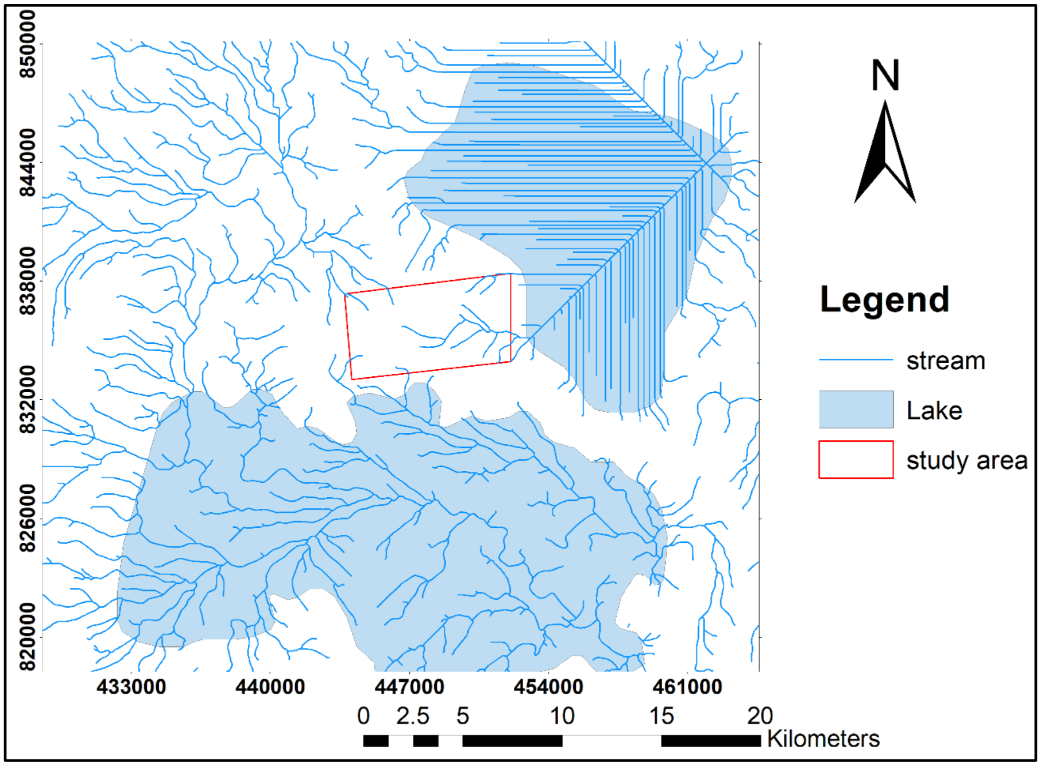


Fig.1.3. Drainage of the study area

1.2.3. Climate and Vegetation

The climate around the study area shows a tropical condition. The climatic condition of the area is mainly expressed by average temperature and average precipitation. According to Climate-Data by NMSA the mean annual temperature is 20.3 ^{o}c at Bulbula Meteorological Station with mild temperature prevailing throughout the year, which is suitable for a wide range of tropical and subtropical crops. Mean monthly air temperature varies from 18.8 ^{o}c in December to 22 ^{o}c in May. The time period from March to June is relatively warmer, when the mean temperature is generally above 21^{o}c. The lake region has two seasons dry (October–February) and rainy (March–September). The rainy season is characterized by a bimodal pattern of rainfall, with a minor rainy period extending from March to May and major rainy period from June to September.

The vegetation distribution is mainly dependent on the climatic condition of the area. As explained above, the climate is characterized by tropical nature. In this type of climate vegetation is scarce and unique types of vegetation are present in the area, which are part of Lakes National Park, consisting mostly of lowly thorny bushes and acacia trees.

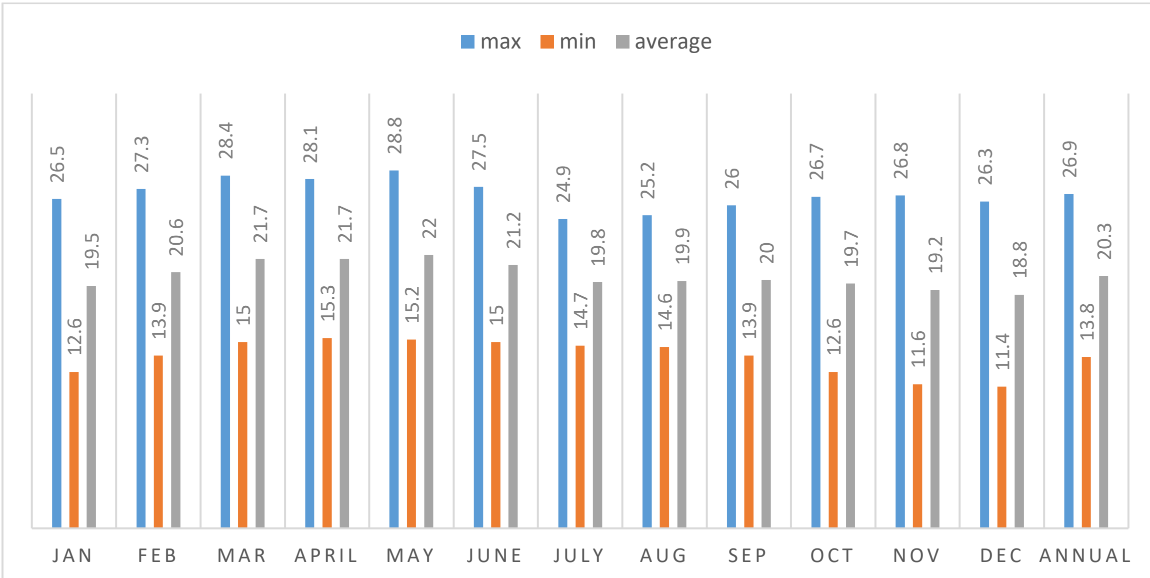


Fig. 1.4.Graph showing the temperature of Bulbula town

1.2.3. Population and Settlement

The local communities living in the project area are settled just at a significant distance in the Keble center and far away about 3-4 km. Settlement is highly dependent on availability of water, farmland and urbanization. Most of the people in the area lead a mixed urban and rural life. Most of the ethnic groups in the area are Oromo with some Amhara and other nations. Generally, the population density of the area is low. As far as religion is concerned, Islam is dominant religion of the people in the area, followed by Orthodox Christians and Protestants. The inhabitant's means of existence is mainly based on cultivation, domestic animal breeding, petty trade and charcoal making are used as subsidiary livelihood sources.

1.3.Statement of the Problem

The MER is an area which is studied a lot. Geological research of MER has been started since early 1970s. Basic geological investigation was conducted during 1970s to ‘80s in order to explore natural resources such as minerals and geothermal spots.

In contrary to this many scientific gaps are visible from economic geology point of view. Limited geological, geochemical and other resources investigation works have been conducted by Geological Survey of Ethiopia on diatomite deposit near Lake Abiyata. However, the work conducted in the area is not enough to assess the genesis, quality and quantity of diatomite deposit in the area.

The origin, geological environment, mineralogical and geochemical studies to elucidate its genesis has not been well studied in detail. On the other hand, the stratigraphical relationship of the ore body with the associated formations is not still well defined and interpreted with respect to the geologic environment.

Following the geological investigations which were performed by the Ethiopian Institute of Geological Surveys on the Abiyata diatomite deposit and in order to exploit and turn to account the diatomite as a raw material for industrial uses, it is necessary to execute subsequent study in the area. However, the essential properties necessarily needed by the industry, such as thermal behavior, mineralogical, morphological, microstructural and textural properties of the Abiyata diatomite have not been studied yet. Hence, the Abiyata diatomite needs to be analyzed and modified to utilize it in industrial applications. Therefore, the current study is motivated by the gap related to mineralogy, technological properties and genesis of the Abiyata diatomite deposit. So this research will thus try to conduct detailed investigations on the possible industrial applications and define the genesis of the deposit.

1.4. Objectives

1.4.1. General Objective

The main aim of this research is to determine the genesis, characterize the quality, estimate the quantity and determine the possible industrial application of Abiyata diatomite deposit.

1.4.2. Specific Objectives

- Investigate the genesis of Abiyata diatomite deposits.
- Delineate and evaluate the size of the diatomite deposits.
- Determine the physical and chemical properties of diatomite and suggest the possible fields of applications.
- Produce geological map of the deposit at a scale of 1:10,000.

1.5. Methodology

The overall activities of the research are divided into three phases; pre-field work, field work and post-field work. During the different phases, a variety of tools has been used, including topographic and geological maps, standard field sampling and measuring tools (GPS, compass, lens and geological hammer), and Arc GIS, global mapper, Stater and google earth softwares.

1.5.1. Field Work and Geological Mapping

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 Diatomite deposit and its surrounding was undertaken. The physical characteristics (such as color, softness, hardness and grain size variation), associated coarse minerals as well as textural and structural features of the diatomite deposit were described. Sampling of both Diatomite and some surrounding rocks (ignimbrite and rhyolite) were also made. The Diatomite samples were collected from both surface outcrops and stream section on the basis of variation in physical characteristics such as color, grain size, and degree of compactness. Afterwards, all of the collected samples were labelled accordingly and put into sampling bags for various subsequent laboratory analyses.

1.5.2. Analytical Methods and Data Analysis

This method defines the petrographic, mineralogical, chemical and physical characteristics of diatomite and describes simple test procedures for determining industrial specifications. After finishing the field work, the collected samples are submitted to laboratory for different analysis. The purpose of these analyses is to get vital information for the characterization of Abiyata diatomite deposit from genesis and quality points of view. These different analyses include; mineralogical (XRD and SEM), geochemical (ICP-MS and ICP-OES), Micropaleontology and Technological tests (grain size distribution, color, PH, bulk density and specific gravity).

a) Mineralogical analysis

This analysis is performed to unveil the minerals present in the diatomite samples and to determine the relative proportion of each mineral in the rocks and the diatomite deposit. The type of silica present in diatomite is a hydrous form of opaline silica which contains between 3-8% structural water (Inglethorpe, 1991).

Several types of opaline silica were defined by Jones et al. (19l7), principally by their different X-ray diffraction (XRD) characteristics. These include opal-C (well-ordered a-cristobalite); opal *CT* (disordered cristobalite/tridymite); and opal A (poorly-ordered, almost amorphous). Diatomite is composed of biogenic opal-A silica which is indicated from XRD analysis by a broad peak. This qualitative and quantitative information of the minerals found in diatomite samples are determined by X-ray Diffractometer (XRD and SEM). The morphology and microstructure of the materials are studied using scanning electron microscopy (SEM) technique. Five representative diatomite samples are selected for this analysis.

b) Geochemical analysis

The prime criterion for judging potential industrial issues is chemical composition. Typical chemical analyses of diatomites used by industry are critical issue. The chemical composition of diatomite is determined with the classical silicate analysis. For example, Theune et al. (1988) define maximum levels for several chemical constituent of filter-aids, diatomites used in filtration and filler applications generally contain >85% silica.

Major and trace elements in sediments are also enriched or depleted by different processes. So, in order to reconstruct the depositional environment, we have to choose several diagnostic elements for interpretation. To depict which elements are depleted or enriched EF (Enrichment Factor) may provide some important information, which are based on element/Al ratios of sediments and average shale (Borchers et al., 2005).

In order to do this and other interpretations ten (10) representative samples were selected for geochemical analysis purpose from the entire collected samples. The samples were taken and collected from different sections. These selected representative samples were sent to geological survey of Czech Republic. The final whole rock chemical composition (major, trace and LOI) analysis of these prepared Diatomite samples were determined using Inductively Coupled Plasma-Atomic Emission Spectroscopy (ICP-AES).

c) Technological tests

This test is aimed at evaluating the suitability of Abiyata Diatomite for different industrial applications. The performed tests are grain size, specific gravity, bulk density, color and PH. In this case six diatomite samples are selected and sent to geological survey of Czech Republic for grain size analysis using hydrometer. Whereas, the specific gravity, bulk density, color and pH of five selected samples were analyzed in Geological survey of Ethiopia and National Soil Testing Center of Ethiopia (NSTCE).

d) Micropaleontology

Micropalaeontological studies of diatom taxonomy can reveal whether a deposit was formed in a freshwater (lacustrine), brackish or marine environment, and whether deposition occurred in deep or shallow water. Diatoms are microfossils and *are* not generally visible to the naked eye although larger diatom**s** may be resolved by a hand lens. Optical or scanning electron microscope (SEM) methods are therefore usually necessary to identify their presence. This method is critical for discriminating the genesis of diatomite depending on the diatoms present in sample weather it is lacustrine or marine deposit.

It is a high-resolution method (conventionally used for detailed petrographic work) capable of providing comprehensive data on the morphology of diatoms and their micropaleontology. The same ten diatomite samples used in mineralogical analysis are given for it. The samples are sent for analysis to Charles university laboratory found in Czech Republic.

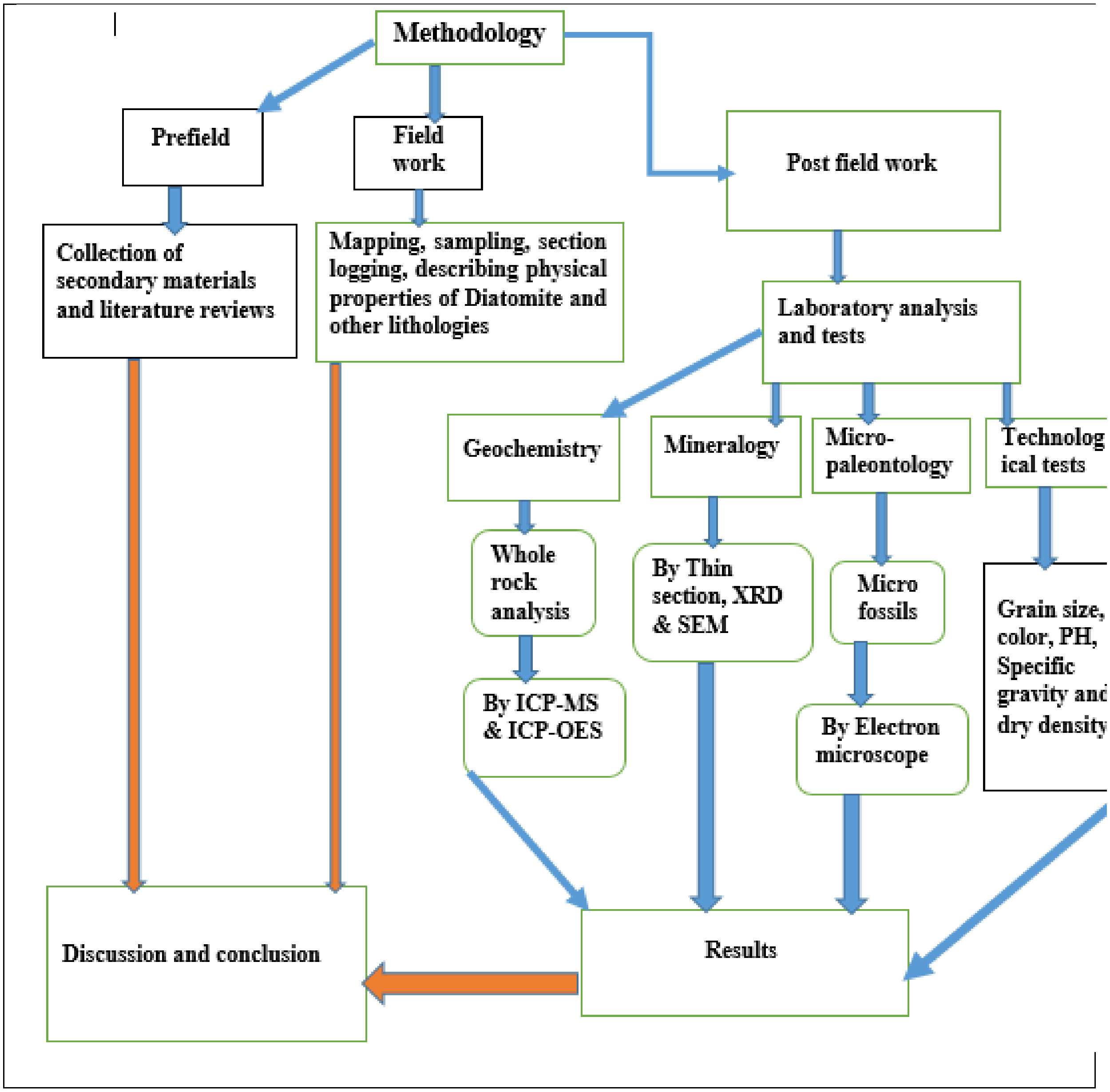


Fig.1.5. Flow chart of methodology

1.6.Research outcome

Abiyata diatomite has not so far been studied in the aspects of genesis. A few is also known on its suitability for different industrial applications. Therefore, this research study will have the following contributions and outcomes.

- From the geochemical, mineralogical, morphological, micro paleontological and physical test data of laboratory analysis, we have a better understanding on the genesis and its possible field of application.
- Economic size of diatomite deposit in the area is delineated and evaluated.
- There are a few researches on diatomite deposit in Ethiopia, so this research will be used as a reference for others, who work on such type of deposit.
- Mineralogical assemblage of the deposit was determined and the depositional environment of mineralization interpreted or fills the existing gap of detail information about the mineralization.

1.7.Thesis Overview

The thesis report is intended to have 8 chapters as follows. Chapter one gives general information about the study area, the objectives of the study and methods followed in the research. Chapter two is a review of previous works related with the characteristics, genesis, mineralogy and geological and tectonic setting of Diatomite deposits in general. Chapter three and four deals with the regional geology and tectonic setting and the local lithologic units of the study area as well. In chapter five mineralogical, Micropalaeontological and geochemical data is presented and interpreted. Chapter Six is devoted to technological properties and possible applications of Abiyata Diatomite. Discussion on the genesis of the Abiyata Diatomite deposit is presented and the genetic model of the deposit is illustrated in chapter Seven. Finally, the main conclusion and recommendation is presented in chapter Eight.

1.8.Limitation of the study

The major problem faced during the study was lack of full laboratories in the country. We have neither complete relevant equipment nor experienced man-power to carry out sophisticated industrial usability tests on diatomite in our laboratory. Investigations were confined to the untreated or raw diatomite only. No experiments were carried out on treated diatomite such as drying, grinding, calcining and removal of ferrous materials, nor were investigations carried out on consuming industries. I am therefore highly indebted to team of geologists from the Czech Republic, who took representative samples from collected for relevant analyses. Bulk samples have now been sent to the geological survey of Czech Republic and Charles University to correct these shortcomings of some common laboratory tests.

CHAPTER TWO

2. LITERATURE REVIEW

2.1. Introduction

Diatomite is a chalky, sedimentary rock composed of the skeletal remains of single-celled aquatic water plants called diatoms. The siliceous skeletons become an inorganic mineral in a form of sediment on the bottom of whatever body of water they have inhabited (Wolfram, 1983). They are frequently associated with volcanic activity, with air-fall ash, run-off waters and spring waters providing a source of dissolved silica to replenish that extracted by diatoms (Taliaferro, 1933).

As cited in Schnurrenberger et al. (2003), Merkt et al. (1971) proposed a comprehensive lake sediment classification scheme for use in mapping lacustrine deposits. The proposed classification is based on sediment components readily observable in the field and expands considerably the range of sediment types found in lakes, though primarily concentrating on lacustrine deposits. Conger (1942) hypothesized that the requirements for diatomaceous accumulation are to have (1) conditions favorable for diatom growth, and (2) reduced accumulation of other sedimentary constituents that would dilute the concentration of the siliceous tests of diatoms. Its growth is dependent on many environmental factors such as dissolved silicon availability, phosphorus and nitrogen availability, pH, salinity, and light (Battarbee et al., 2002). The commercial value of diatomite mainly depends on its unique microscopic structure, and also on its chemical inertness, which in turn is measured according to the silica composition of the diatomite.

2.2. Geochemistry and Mineralogy of Diatomite

Diatomite is a powdery mineral composed of the fossilized remains of microscopic single-celled aquatic plants called diatoms. It has been reported (Zhou Kaishang, 1988; Shen Baolin et al., 1987) that the main components of a diatom shell are SiO_2 and H_2O, just like the composition of opals, $SiO2.nH_2O$, formed in the inner cell walls of living diatoms in the earliest period of time. It can be considered a special variety of silica from chemical composition of diatomite is determined with the classical silicate analysis. The characterization from the mineralogical point of view is performed by X-ray diffraction (XRD) and scanning electron microscopy (SEM). According to (Thomas, 1982) Diatomite consists largely of fossilized siliceous (amorphous opaline silica) remains of one-celled aquatic plants called diatoms. It mainly consists of opal-A, which is the amorphous phase making up the original diatoms, while other minerals are quartz, feldspars, calcite, smectite, illite, kaolinite, chlorite, cristobalite, muscovite, etc.

Diatomite is primarily comprised of SiO2, with some other oxides such as Al_2O_3, Fe_2O_3 and CaO, whereas all other major and the trace elements may be present in low concentration. But Goren et al. (2002) have reported the possibility of a change in chemical and phase composition of diatomite after acid leaching.

The chemistry of commercial diatomite deposits is dominated by the siliceous composition of the diatom frustules, which are formed by biologic secretion, or precipitation of amorphous silica (Cummins, 1960; Durham, 1973). Frustules in living diatoms of Holocene age resemble amorphous soluble silica gel, whereas fossil frustules resemble opaline silica and have a lower solubility than younger ones (Kamatani, 1971). Chemical analyses of bulk diatomite samples typically range in SiO2 content from 70 to 90 weight percent and reportedly as high as 97 weight percent in marine deposits (Cummins, 1960; Durham, 1973; Breese, 1994). The quality of a diatomite deposit decreases with greater amount of both clastic particles (silt and clay) and organic matter, which limit the utility of a diatomite in industrial applications.

2.3. Genesis and Geological Setting of Diatomite Deposits

As Barton (1991) states, “Ore deposits belong to the most complex inorganic features of our planet”. If this complexity is represented in several mineralizations overprinting each other but not always yielding valid” (meaningful) parageneses, determining the ore's origin is significantly hampered and must rely on particular mineralogical or geological indicators (single grains may yield substantial information). In order to develop a feeling for the genetic hints frozen in a sample, it is necessary to delineate typical characteristics reflecting particular processes. Diatoms are adapted to wide range of aquatic environments including marine, brackish and fresh waters. The organisms require suitable environmental conditions if they are to flourish including appropriate temperature and photic conditions, narrow salinity and acidity range, and a stable supply of nutrients including silica, nitrogen, phosphorus, iron, oxygen and carbon dioxide. Diatoms inhabit the photic zone depths down to 200m and thrive cold waters in sub-polar and temperate regions. Recent studies have used diatom assemblages as environmental indicators in Quaternary and present-day freshwater lakes (Abella, 1988; Stager, 1988). Since the beginning of the Miocene (Ogg et al., 2016), the most commercially exploited diatomaceous earth deposits are lacustrine in origin.

The first genus and environment classification of diatomite deposit was made by Taliaferro (1933). He describes four different common types of diatomite deposits in the world; ocean diatomite deposit, marsh diatomite deposits, Pleistocene interglacial diatomaceous lake deposits, and lacustrine and marine diatomite deposits associated with Tertiary volcanism (Gurel et al., 2007). Diatoms live in a wide variety of environments from the open ocean to nearshore; and in freshwater rivers, lakes and marshes. Based on their diagnostic floral assemblages and sedimentary associations, ancient diatomites are readily classified into marine and freshwater deposits. Many freshwater and marine deposits are closely associated with volcanism which provides a ready supply of dissolved silica which the diatoms need to construct their skeletons (Taliaferro, 1933; Mulryan, 1942; Williamson, 1966; Kadey, 1983). A rapid expansion in diatom population following the supply of pyroclastic material from an eruption has been recorded in the modern environment (Kurenkov, 1966). Similar responses have been recorded in the stratigraphic record (Abella, 1988). Under favorable environmental conditions diatomite ooze can accumulate very rapidly, perhaps at rates around 1 mm per year (Soper et al., 1922; Gams, 1927).

Freshwater fluvial, lacustrine and paludal diatomaceous deposits are commonly rich in elliptical (pennate), mobile diatoms, (Mathers, *S* J. 1993) which usually occur interbedded with water lain pyroclastics, fine sands, silts, clays and peat. Economic diatomites of this type are sometimes closely associated with bentonite, zeolites and pumice (Mathers, *S* J. 1993**)** whereas marine diatomites are commonly characterized by circular (centric), immobile planktonic forms. Diatomites may be graded into, or be interbedded with, a wide variety of sedimentary lithologies; the commonest are mudrocks, carbonates and waterlain pyroclastics.

It has been discovered that many deposits of diatoms of freshwater origin are comprised substantially of the species Melosora Granulata which, when cleaned of clay impurities, provides a filter aid with superior filtration qualities (Potter, 2000; Sterrenburg et al., 2007). Diatomite composed predominantly of whole diatoms is likely to have accumulated by pelagic sedimentation in a relatively low-energy environment. However, if a large proportion of diatom fragments **is** present this suggest a relatively high-energy environment where attrition resulted from sediment transport and reworking.

The diagram below shows the setting of diatomite deposits in a lake and some of the processes that aided their formation. Rainfall produces streams that carry silica (SiO2) and other nutrients, such as phosphorus (P), into the lake from nearby highlands. Silica also can enter the lake in air-fall ash that was erupted from volcanoes and deposited on the lake's surface. Sunlight provides light for photosynthesis, which enables the diatoms to grow and bloom. After the diatoms bloom and die each year, their silica skeletons settle to the bottom of the lake and form a thin sedimentary layer. Over thousands of years, these layers accumulate to form a diatomite deposit. Diatomite deposits can form both in the shallow (littoral) and deeper (benthic) parts of the lake. Different species of diatoms prefer each environment, and the resulting diatomite deposits in the two locations can differ as a result.

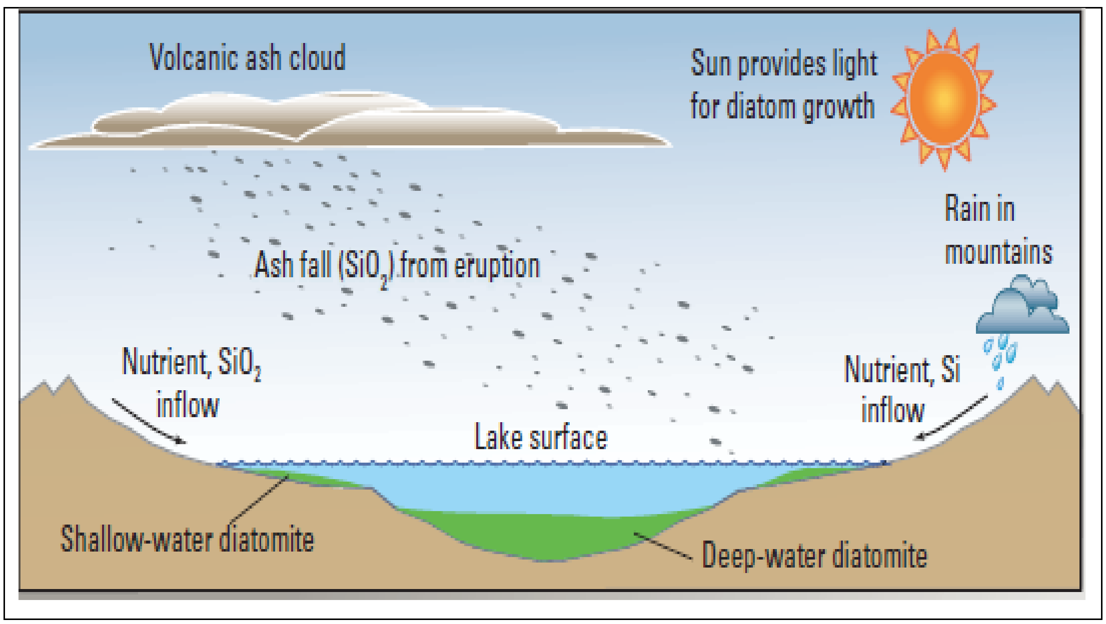


Fig. 2.1 Sedimentological model for accumulation of fresh water diatomite in a caldera lake environment (by USGS at, http://pubs.usgs.gov/fs/2006/3044)

Diatomaceous earth consists of the siliceous remains of microscopic aquatic organisms known as diatoms. Individual diatoms may vary in lengths from 0.005 – 0.4 mm (Nieminen, 1968). They occur in marine and freshwater sedimentary beds and in existing lake and swamp bottoms. The diatom remains must have accumulated under conditions where the deposition of other sediments was temporarily inhibited and where volcanic activity furnished silica-rich water. Diatomite accumulates in areas where the rate of deposition of diatom frustules greatly exceeds that of other sediment components (Berger, 1970; Heath, 1974; Barron, 1987) as cited in Harwood, 2007.

2.4. Exploration, Mining and Processing

2.4.1. Exploration

Exploring and evaluating deposits requires that geology, mining feasibility, and processing feasibility be integrated with the determination of the ore's suitability for the products desired to meet market needs. During the course of these studies, the fundamental elements of an evaluation program must include identification of ore strata and determination of strata mineability (i.e., number, thickness, areal continuity, tonnage potential, and the degree of mining selectivity required). In addition, processing requirements such as the equipment required and the process flow, the determination of economic marketability, and an assessment of logistics, including proximity to utilities, transportation, and work force must be determined. A basic understanding of these elements will benefit the geologist in designing, guiding, and interpreting the sampling program. There are many diatomite deposits in the world but very few that are of high purity with commercial value. As a high priority, the suitability of the diatomite for product/market end uses must be determined.

Although diatomaceous silica is a relatively common sedimentary rock, large economically minable deposits with commercial grades, referred to as diatomite, are uncommon to rare (Harben et al., 1996). Any exploration for diatomite must be based on an understanding of the geological environments in which it can form, and the age of strata which can be expected to contain economic deposits. Literature searches and examination of regional geological maps will help to pin-point potential areas, but preference must always be given to locations closest to the perceived market for the commodity or to coastal port facilities (Mathers, 1993).

To get information on the subsurface geology, prospectors will depend on outcrops, stream beds and rod cuts. Stratigraphic position, geomorphologic features and topographic elevation are also important searching tools. In addition other prospecting tools like geophysical surveys can be used as more sophisticated approaches. Although the physical properties of diatomite could be different from those of the overlaying and underlying, material to reveal its presence geophysical given the right circumstances. It is therefore useful to use geophysics in the exploration of diatomite if the overburden is completely dry, the saturation horizon will not sink below the diatomite layer whilst still leaving the diatomite layer fairly waterlogged.

2.4.2. Mining

The mining and processing of diatomite is delicate and complicated. It requires large processing facilities and heavy earth moving equipment. To minimize costs diatomite is usually mined in open pit, surface mines (although some operations do use underground extraction methods Harben et al., 1996). In surface mining a considerable thickness of earth known as over burden may have to be removed. Once this layer is removed and the purest of the diatomite strata is exposed, it is then cut from the bed with powerful scrapers and stockpiled. It does not need to be blasted as it is soft and friable ore.

Prior to mining, the ore strata are carefully identified in the quarry faces through sampling and evaluation programs that determine and confirm the suitability of each individual stratum. The ore-grade strata can then be rated by quality and carefully segregated from the lower quality waste units using mechanized equipment. Because diatomite is a soft, easily broken sediment, ores are typically dozer ripped or broken from the face by power shovel. Blasting of the ores is neither needed nor possible because of the inherent softness of commercial quality diatomite, its porosity, and its absorptive nature (Harben et al., 1996). The broken material is loaded by front-end loader or belt loader into haul trucks for transport to either the crude storage area or the waste piles.

Depending on the geologic configuration of a deposit, this low-cost, bulk-tonnage mining method generally consists of selectively grading large volumes of ore from exposures of high-grade rock, lifting the select high-grade material with scraper-loaders or loading it onto truck haulers, and transporting to a processing plant (Breese, 1994; Harben et al., 1996). At some deposits where basalt, chert, or other contaminants are interbedded with the diatomite, coarse contaminants must be selectively mined or screened out at the mine site before shipment to the plant.

2.4.3. Processing

Specifications of raw materials for industrial applications become ever more stringent. Under these conditions processing of raw materials based on knowledge of their physical properties to value added grades is indispensable. The quality and the properties of processed diatomite depends on two main factors these are composition and properties of raw diatomite and way and effectiveness of processing.

When chemical and mineral impurities are present in great abundance, alternative terminology is used to describe the sediment (e.g., sandy diatomite, clay-bearing diatomite, diatomaceous marl, and diatomaceous peat) (Jessika et al., 2009). These extraneous materials can affect the properties of the final product, including pH, color, density, and abrasiveness. In such cases, the ore's commercial suitability for some uses will be adversely affected, unless the contaminants can be removed or rendered insoluble through processing. Processing techniques may vary from industry to industry depending on their specification but typically involve crushing, screening, drying and classifying. Calcining may be done to reduce the surface area of the particles and to render most impurities insoluble (Clark, 1978).

The mineral processor must know the up-to-date methods of mineralogical investigation, grain-size distribution, and determination of physical parameters of the mineral.

Crushing and grinding of crude diatomite are accomplished in a series of careful steps designed to preserve the diatom skeletal (frustule) structure, an important attribute of most products. Dolley et al. (2003) present a generalized diagram of a typical diatomite-processing plant, and Harben et al. (1996) briefly described the processes. Where possible, heated air is used to dry and transport diatoms through the beneficiation process, including separation of diatoms from denser and coarser contaminants and classification of diatoms into different sizes. Selected grades of natural diatomite may be calcined in a kiln at 870–1,093°C (Philip et al., 2003). Volatilizing such contaminants as organic matter, CO2, and pore water is necessary to produce a pink granular material. Carbon dioxide and organic-matter contents range from less than 1 to more than 17 weight percent (Cummins, 1960) in some deposits.

Calcining also recrystallizes 40 to 60 weight percent of the silica in the frustules to cristobalite for such specific end uses as special filter grades.

In general, processing costs are lower if H_2O and organic-matter contents, as measured by loss on ignition, are lower (Philip et al., 2003) because less energy is required to remove these contaminants (Benton, 1983). The cost to process some medium-grade lacustrine diatomites, suitable for such lower-end uses as absorbents and fertilizer, can be prohibitive at a loss on ignition as high as 20 weight percent (Breese, 1994) because of the high energy required to volatilize the water and organic matter.

Filtration-grade diatomite is produced from both marine and some lacustrine deposits. However, lower grades of lacustrine deposits generally limit end uses to abrasives, fillers, fertilizer and pesticide, polish, catalyst material, insulating brick, and absorbents (Breese, 1994). The greatest demand for high-grade ore of marine origin is as a filter product, used in processing beer, wine, and liquor, sugars, and pharmaceuticals; however, low-purity marine or lacustrine diatomite with increased contaminant contents may be processed for such lower-end uses (Breese, 1994) as fillers or additives.

2.5. Diatomite Occurrences in Ethiopia

In Ethiopia, clay and lacustrine sediments are found in many parts of the Ethiopian rift valley associated with Tertiary-Quaternary sediments on top of the stratigraphic records. Lacustrine sediments in the Rift Valley are favorable sites for diatomite deposits and the most well-known; occurrences of diatomite in Ethiopia are located in the Rift Valley. The diatomite bearing beds are predominantly of Quaternary formation though Pleistocene diatomites are known to occur near Khora in the region of Mieso.

According to the promotional data compiled by geological survey of Ethiopia (2013), prospecting for diatomite in Ethiopia was done intermittently and experimentally in the past by geological survey of Ethiopia. The first systematic investigation based on drilling was carried out in 1977 to 1979 on a deposit near Lake Abiyata.

Diatomite occurrences are apparently very common in Ethiopia. Large areas of the Rift Valley floor are filled with lacustrine sediments deposited on the bottom of the ancient Pleistocene and Pliocene lake basins. Diatomaceous earth beds deposited from this giant lake are exposed in the Bulbula and Horacallo river sections. Also the Mojo River and its tributaries cut through 10-15 m of light yellow diatomite bearing sediments (Nieminen, 1968).

The Main Ethiopian Rift, due to its wide spread silicic volcanism and lacustrine basins, is the most favorable site for the accumulation of fresh water diatomite deposits. Rift volcanism associated with sediment supply and basin formation, ground water chemistry and hydrothermal activity, caldera collapse and formation of lacustrine basin may provide suitable environment for the formation of diatomite. High level of dissolved silica and abundant nutrient in the lake water give rise to conditions, which favor rapid growth and accumulation of diatomaceous oozes, which compact and dewater to form diatomite.

Good quality diatomite is found in the lake regions of central Ethiopia within the rift floor, but there are also diatomite occurrences on both eastern and western highland of the rift (Sisay Abera, 1994; Amente Abrham et al. (1973) have reported the occurrence of diatomite in Ethiopia like Afdemu-Dire Dawa, Welenchite, near Shashemene and in different parts of the Ethiopian rift.

Lacustrine sediments in the Rift Valley are favorable sites for diatomite deposits, and all the known occurrences of diatomite in Ethiopia are located in the Rift Valley. The acidic pyrociastics and tuff intercalations provided silica for the building of diatom tests, and the tropical climate, with the addition of hot spring water from the active volcanic region, provided warm lake waters in which diatomite flourished (Getachew Niguse, 1976).

Among the several diatomite occurrences and deposits, some of them are potentially exploitable and include Gademotta, Adami Tulu, Chefe Jila and Lake Abiyata lacustrine diatomite deposits. The total resource of high grade from Gademotta, Adami Tulu, Chefe Jila and Lake Abiyata amounts to more than 40mt (Halcrow Group and GIRD 2008.).

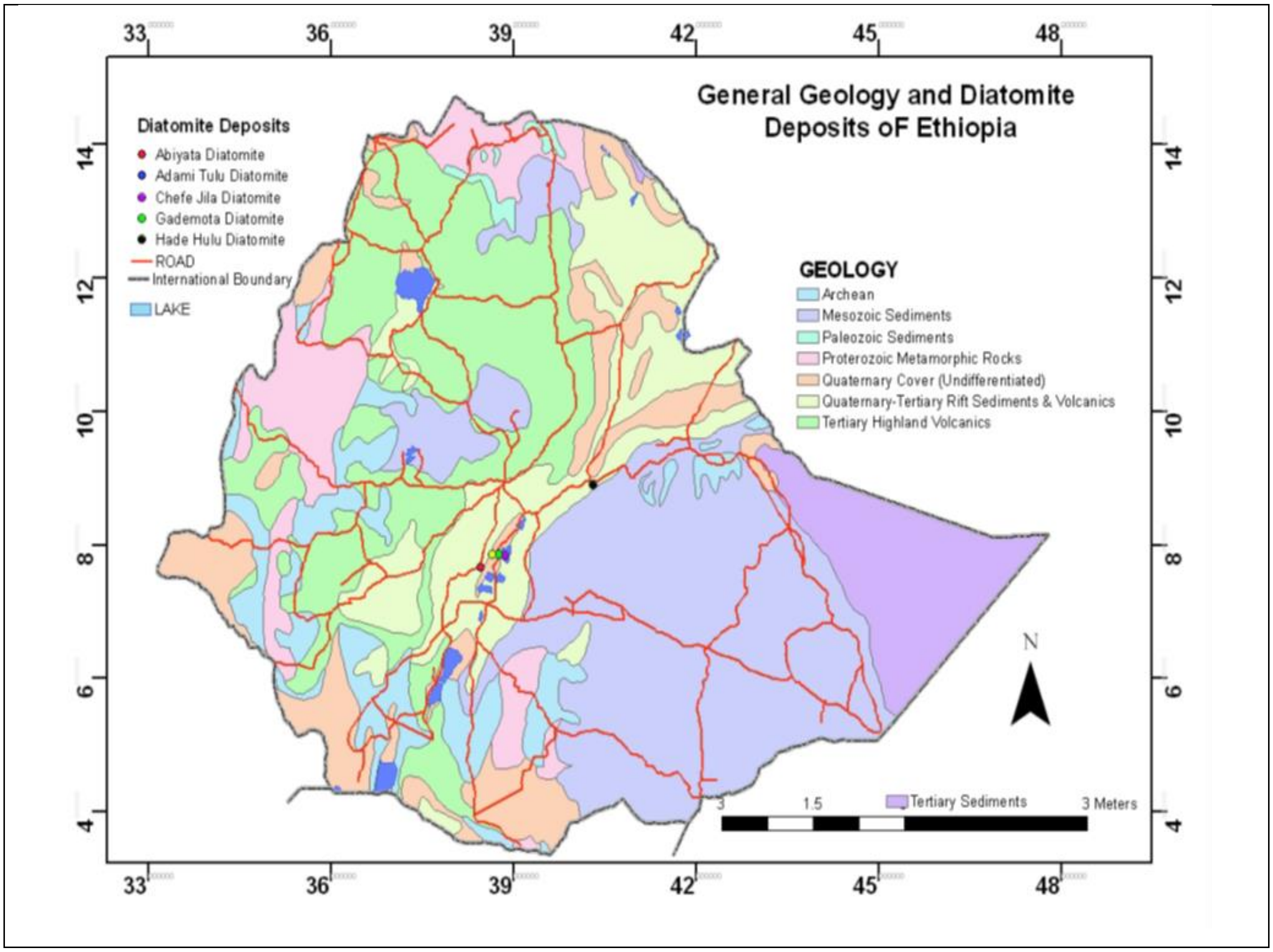


Fig.2.2. Common occurrences and deposits of diatomite in Ethiopia (geological map from GSE)

CHAPTER THREE

3. REGIONAL GEOLOGY AND TECTONIC SETTING OF MAIN ETHIOPIAN RIFT

3.1. Regional Geology

The East African Rift Valley is one of the geologically active areas in the world. In Ethiopia the Rift extends over 1,000km in a NE direction from Kenyan border and covers an area of about 150,000 km^2 that includes the Lakes District (Tigistu Melka et al., 2009).

The Central MER encompasses most of the Lakes Region, up to the Lake Hawassa area and it is bounded by the escarpment of Ethiopian plateau to the west and the Somalian plateau to the east.

Another physiographical feature of this region is that in the north, the rift appears almost symmetric both morphologically and stratigraphically, but to the south it is clearly asymmetrical (said Mohamed et al., 2009). The Debre Zeyt-Nazareth area is represented as a transitional zone between the Ethiopian plateau and the main Ethiopian rift (Seife Michael Berhe et al., 1978). This transitional zone is called Intra Rift complex which includes Upper Miocene - Quaternary products that constitute the floor of the main Ethiopian rift and its successive filling (Tigistu Melka et al., 2009).

Rifting in central MER is younger than 8 ma years and is formed after the formation of northern MER (Tsegaye Abebe et al., 2010). Tertiary to Quaternary volcanics are the only rocks exposed in the MER, apart from minor fluvio-lacustrine sediments, mostly of Quaternary age, that were deposited on the rift floor (Tsegaye Abebe et al., 2010).

An important event in the rift development took place around 10 my ago (Kazmin et al., 1978; Davidson, 1983), and others) by faulting of the pre-rift volcanic succession, Oligocene-Miocene age. Deposits ranging from Miocene-Pliocene to Holocene cover the floor of the rift Valley (Kazmin et al., 1978; Meyer, 1975) and others.

According to Seife Michael Berhe et al. (1978, in the northern part of the MER, two volcano tectonic units are distinguished.

They name the older stratoid unit called the Nazareth group, and have an age of 5-2 myrs according to them and consist mainly of silicic rocks such as alkali and peralkali trachytes, rhyolites, ignimbrites, tuffs and pumice. The younger unit called the Wonji group is Pleistocene-Holocene age and lies with an unconformity on the Nazareth group. It consists of basaltic, silicic and intermediate volcanic rocks and sediments. Beginning with the Nazareth phase, a much stronger volcanic and tectonic activity began with the Wonji fault belt. There were groups of fissures and dikes combined with volcanic rocks, which diagonally crosses the main Ethiopian Rift. It began an evolution from a continental rift to oceanic rift like that in the northern Afar (Pilger and Rasler, 1974).

In the study area lithologies of stratoid silicics, ignimbrites, unwelded tuffs, ash flows, rhyolites and trachytes constitute a considerable portion of the rift escarpments especially in the western part, while in the floor they are unconformably overlapped by younger volcanic of the Dino formation(east of lake Shala where the current study is located)

North of Lake Abiyata, great thickness of late Quaternary lacustrine and fluvial sediments is exposed by the Bulbula River and its tributaries. These sediments have been referred to as the Bulbula Formation by Street (1979) as cited in Gidey Wolde Gabriel (2000).

According to Beshawered 2010 and Kazmin and Seife Michael Berhe (1978), the geology of the MER is grouped in to 3 main lithostratigraphic sequences; pre rift, Syn rift and main rift sequences. In central main Ethiopian rift segment the distribution of such rocks can be seen in the following manner: The stratigraphical framework of the lithologies is described from oldest to youngest below.

3.1.1. Pre-Rift Complexes

Pre rift sequence: are formed before the formation of the MER consisting high grade metamorphic rocks (e.g. biotite gneiss); Mesozoic sedimentary rocks (e.g. Adigrat sand stone, shale and marls) and Kella lime stone) and Oligocene to late Miocene plateau flood basalt (e.g. Aiba-Alajie basalt, Tarmaber-Megezez basalt, Gurage-Anchar basalt and Mekonen formation). They are mostly exposed on the escarpment of the rift.

3.1.2. Syn-Rift Volcanic Rocks

Synrift volcanism had bimodal character, with predominant acid products and associated basalts (Boccaletti et al., 1999). According to Gidey WoldeGabriel et al. (1990) the age of Synrift igneous rocks is 8 Ma and constitutes upper Miocene-Quaternary products of Nazret pyroclastic rocks of welded to partially welded pyroclastic flows with rhyolitic and trachytic lava domes. The time of formation of the Nazret group is between 9.5 and 3 Ma years (Kazmin and Seife Michael Berhe, 1978). More than 400 m of Nazret pyroclastic rocks have been encountered in deep geothermal exploration well at Aluto volcano (Tsegaye Abebe, 1984; EIGS-ELC, 1985 and others). In addition, Gidey W/Gabriel et al., (1990) reported a thickness of more than 600 m for the Pliocene pyroclastic units in the eastern margin of the rift in the Munesa area.

Another formation of the Nazreth group is the alkaline and per alkaline silicics and ignimbrite formed together and found East of Wando Genet forming the escarp of Hawassa Caldera.

3.1.3. Pliocene-Pleistocene Volcanic Rocks

The most important volcano–tectonic event in the central sector of the MER occurred in Early Pliocene, with the eruption of voluminous flows of rhyolitic ignimbrites and the collapse of very large calderas (Di Paola, 1972; Giday WoldeGabriel et al., 1990). According to Zanettin et al. (1978) and Ebinger et al. (1993) volcanic activity continued up to 11 Ma with eruption of basalts, trachytes and rhyolites. After this phase of volcanic activity the volcanism decreased in the Upper Miocene-Lower Pliocene. Then volcanic activity resumed in the late Pliocene-Early Pleistocene (Zanettin et al., 1978). This activity started with the eruption of Pleistocene ignimbrites (1.6–0.5 Ma; Bonini et al., 2005). Most part of the rift floor especially the surrounding area of Lake Langano, Ziway and Hawassa are covered by Pleistocene-Holocene age lacustrine sediments. They were deposited in a huge lake whose level thousands years before was much higher than at the present. The sediments are mainly represented by sand and silt. They are intercalated with volcanic, mainly ashes and tuffs which in places are extensively developed.

3.1.4. Quaternary Volcanic and Sedimentary Rocks.

The latest volcanism in the Ethiopian Rift is related to the axial extensional zone, referred as the Wonji Fault Belt (Mohr, 1967; Meyer et al. (1975). This event introduced the Wonji series for the volcanic rocks of the rift younger than 1.6 Ma that are related to the Wonji fault belt. The Pleistocene volcanism, however, is not confined to the Wonji Fault Belt only, but that it also occurred in other parts of the rift (Kazmin et al., 1978). On this account they changed Wonji series to Wonji group. The Wonji Group includes the entire rift volcanic formed after the last major event of rift faulting, following the accumulation of the Bofa basalts.

As cited in Caroline et al. (1999) and Street (1979) established three main lithostratigraphic units within the Late Pleistocene-Holocene deposits of the study area. These are stated as follows.

1) The Meki Formation, made up of alluvial and fluvio lacustrine deposits, records the fluctuations in the Meki River base-level.

2) The Bulbula Formation is composed of lacustrine diatomaceous marls and calcareous sands, grading in to and interbedded with thick diatomite units.

3) The Ajewa Formation, in the eastern shore of Lake Shala, (a place where the current study is specifically located) is composed of late Pleistocene and Holocene deep to shallow lacustrine, shore face, alluvial and colluvial deposits.

The lacustrine sediments are mainly represented by sand and silt. The major components of the sediments are volcanic origin, such as pumice and volcanic ash, obsidian, rhyolite and basaltic rock fragments (Tsegaye Abebe et al., 2005; Bevenuti et al., 2002). In the rift floor, interlayering of primary air fall pyroclastic deposits and lacustrine deposits are common. The subaqueous pyroclastic deposits can be identified by reverse graded bedding of pumice layers. The studied deposit (diatomite) occurs associated with these lake sediments.

3.2. Tectonic Setting and Geological History of Main Ethiopia Rift

3.2.1. Tectonic Setting

The MER is composed of northern, central and southern segments. In the Central MER, the rift valley orientation is between N25° and N45° and is characterized by major rift escarpments on both western and eastern margins (Corti, 2009). It is bounded by the Yerer-Tullu-Wellel volcano tectonic lineament to the north and the Goba–Bonga lineament to the south. It is also bounded to the east and west by fault escarpments (some of them with an offset of more than 1500 m) such as the Munesa and Guraghe rift margins

The tectonic setting of the study area falls in the MER. Thus, it's also a part of the great East African rift Miocene-Quaternary intra-continental extensional system composed of several interacting rift segments, from Mozambique to Afar (Ebinger etal 2001, Tsegaye Abebe etal 2007, and Corti 2009). The initiation of this system is thought to be the asthenospheric up welling effects on the thinning lithosphere that can be described by two phases (phenomenon): The uplift of the Arebo-Ethiopian swell and its subsequent dissection by the rift system (Ebinger et al., 2001).The present day tectonic role is majorly governed by the central axial tectonic and silicic-volcanic system commonly known as Wonji fault belt system since the Pleistocene time (Tsegaye Abebe et al., 2007)

African and Arabian rift system has been proposed by different geologists. Justin et al. (1994) predicted the separation rate at the northern end of MER to be 0.5+1cm per year.

According to Ministry of Water Resources (2008), there are some differences in the tectonic liniment of the main Ethiopian Rift; the Eastern escarpment shows, more or less uniform, step faults with important throw while the eastern escarpments is characterized by an abrupt displacement between the plateau and the rift floor in its north western side and in its south western side, the main faults have a small down throw that progressively die out.

The study area forms the central segment of the MER. It is now generally accepted that the initial sagging of the MER began around 15 to 14 million years (Ma) ago. An important event in the rift development took place around 10 my ago (Kazmin et al., 1978; Davidson, 1983) by faulting of the pre-rift volcanic succession, Oligocene-Miocene age. Deposits ranging from Miocene-Pliocene to Holocene cover the floor of the rift valley (Kazmin et al., 1978; Meyer, 1975). A thick succession of stratoid silicics, ignimbrites, unwelded tuffs, ash flows, rhyolite and trachyte flows and domes form large part of the rift floor and also outcrops on the rift escarpments and adjacent plateau margins referred as Nazreth Group (9.5-4 Ma age). In the rift floor, the Nazreth Group is overlain by a sequence of flood basalts of Pliocene age referred as Bofa Basalts 3.5-2 Ma old.

An intense tectonic event occurred in the Pleistocene-Holocene in the main Ethiopian Rift related to the Wonji Fault (Mohr, 1967). With the formation of the Wonji Fault Belt, tectonic movements and volcanic activity produced step-like structures and associated volcanic activity, represented by ignimbrites, basalts and unwedded pyroclastics. The fault zone is straddled by central volcanoes disposed along the axial zone of the Wonji Fault Belt. The main products were rhyolite, trachyte lava flows, pumice, unwedded tuffs, obsidians and pitch stones. The products of the Wonji fault are referred as Wonji Group (Kazmin et al., 1978). Another type of volcanic activity in Wonji Fault Belt was the eruption from fissures of Pleistocene to Recent basalt lava flows. The basalts are controlled by extensional fractures and commonly characterized by fresh aa surface. Chains of scoraceous cones follow the lines of fractures. These basalts are mostly found in the rift floor; south of lake Ziway and lake Shala. Recent flows in many cases follow pre-existing topographic low relief areas.

Although the development of the rift was dominated by volcanic activity, sedimentation also occurred. Wonji Group rocks are intimately associated with lacustrine sediments related to the ancestral lake in the rift floor in the Pleistocene -Holocene times.

Most part of the rift floor especially the surrounding area of Lake Langano, Ziway and Hawassa are covered by Pleistocene-Holocene age lacustrine sediments. They were deposited in a huge lake whose level thousands years before was much higher than at the present. The sediments are mainly represented by sand and silt. They are intercalated with volcanic, mainly ashes and tuffs which in places are extensively developed. Micro-organic deposits (diatomite) occur associated with these lake sediments.

After the process of continental arc assembly and terrain accretion in Neo-Proterozoic followed by uplift, peneplanization and passive continental margin sedimentation in Paleozoic- Mesozoic time, the main geologic and tectonic process in East Africa in Cainozoic era has been continental flood basalt volcanics and rifting (Wolfenden et al., 2004).

Until the early stages of rifting, Asthenospheric up welling effects on the thinning lithosphere had less impact on the magmatic activity (Ebinger et al., 2001).Pre-rift flood basalts dated to 24-23Ma., are evidences to this. Later these magmatic activities changed to transitional flood basalts that represent the formation of rift margin development nearly 10Ma. The Bi-modal Basalt-Rhyolite volcanism proceeded this activity from 7Ma up to now in the Afar basin, meanwhile the beginning of the Ethiopian rift is dated 12Ma.(Tadiwose Chernet et al., 1997).

According to Keranen et al. (2008) the three segments of the main Ethiopian rift has formed sequentially form North east (Afar rift) towards the south west. The Northern Segment (NMER) that links Afar and main Ethiopian Rifts with $N50^0E$ trend is dated 10-11Ma; while the Central Segment (CMER), which covers the "lakes region", has debatable age inferences that range from 5-9Ma; the Southern Segment is dated 18Ma (Baselifew zenebe et al.,2004).

According to Tsegaye Abebe et al. (2007), Quaternary volcanism started 1.6Ma years ago. The ancient relief of the rift floor has been denuded and flattened by deposits of large pluvial lake system (named Oromia Lake by some Authors) along with the occurrence of hyaloclastites. The current crustal extension zone; Wonji Fault Belt, has been attributed the Holocene age.

The Main Ethiopian Rift (MER) is the oblique NE-SW trending plate boundary between Nubia and Somalia that developed above an inherited lithospheric-scale weak zone (Philippon et al., 2013). An intense tectonic event occurred in the Pleistocene-Pliocene in the main Ethiopian Rift related to the Wonji Fault (Mohr, 1967) with the formation of the Wonji Fault Belt, tectonic movements and volcanic activity produced step-like structures and associated volcanic activity, represented by ignimbrites, basalts and unwedded pyroclastics.

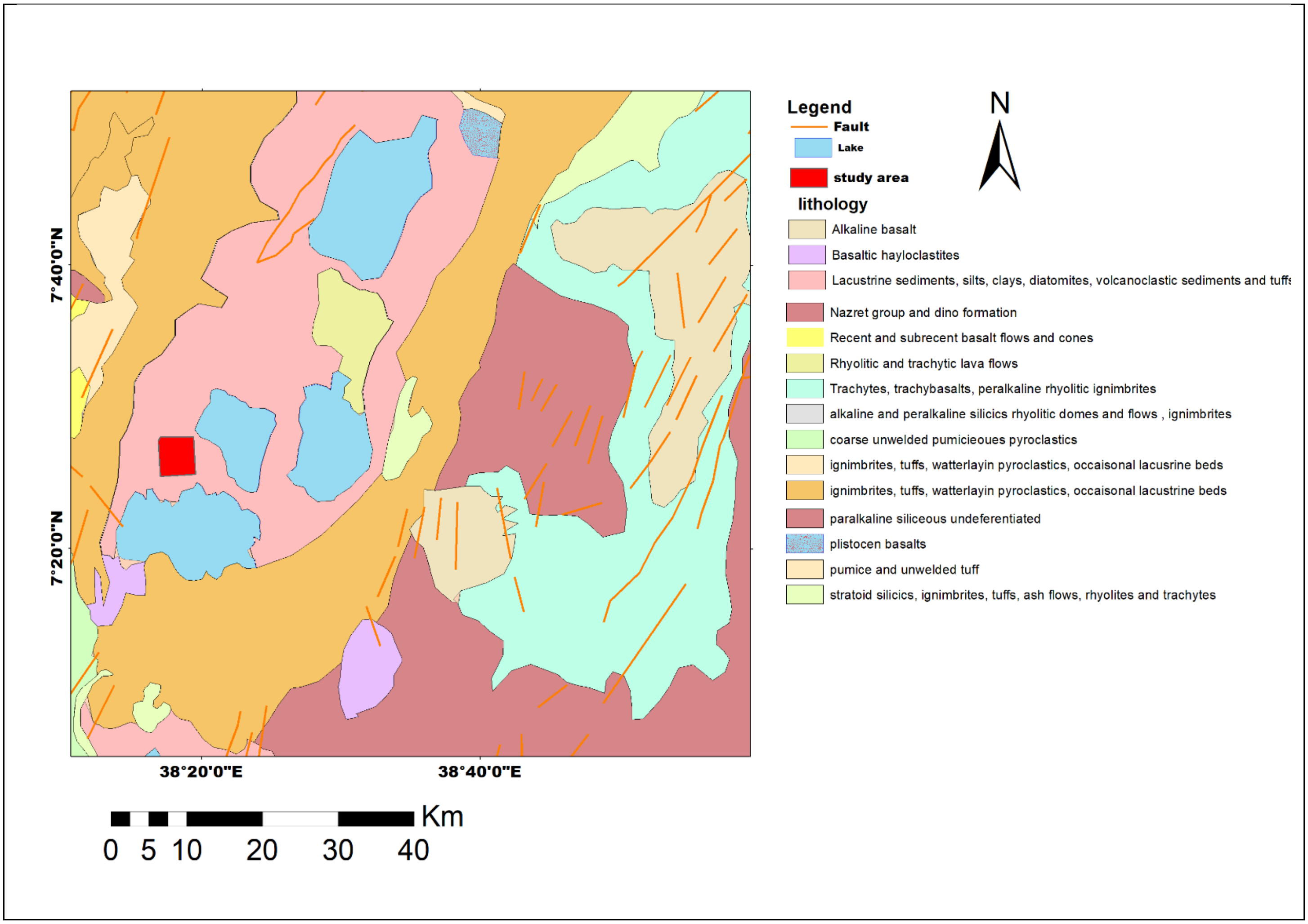


Fig.3.1. Regional geology of the study area after Kazmin and Seife Michael, 1978

3.2.2. Geological History of Main Ethiopia Rift

The Cenozoic geological history of Ethiopia is characterized by massive and voluminous Paleogene mafic and silicic volcanism and domal uplift (Giday WoldeGabriel et al., 2000), Neogene rifting and volcanism, and rift-bound Pliocene–Pleistocene rifting and volcanism (Zanettin et al., 1980). Since the end of the Tertiary period the Ethiopian Rift Valley has been the scene of intense volcanic activity and further minor faulting (*Russel*). Consequently the geological formations are almost entirely volcanic in origin and include both alkaline (basalts) and acidic (rhyolites, ignimbrites, pumices and ash) rock types.

It started to develop during Miocene time, following a broad doming centered on the present Afar depression (Ebinger et al., 2001). During Pliocene and Quaternary, the MER progressively deepened, evolving through a sequence of interacting half-graben segments marking the boundary between the Nubia and Somalia plates (Ebinger et al., 2001 and Corti, 2009). It is limited by discontinuous boundary faults, active from late Miocene and striking between NNE–SSW in the south and NE–SW in the north (Tsegaye Abebe et al., 2007). The youngest part of the MER is the axial zone (Wonji Fault Belt, WFB), mainly formed during the Quaternary time.

Although the studied area is found at the heart of the main Ethiopian rift and the geology is almost exclusively categorized in Cainozoic activity, the presence of older rocks can be seen on rift borders and escarpments. After the process of continental arc assembly and terrain accretion in Neo-Proterozoic followed by uplift, peneplanization and passive continental margin sedimentation in Paleozoic- Mesozoic time, the main geologic and tectonic process in East Africa in Cainozoic era has been continental flood basalt volcanics and rifting (Wolfenden et al., 2004).

Several tectonic events affected Ethiopia prior to the Cenozoic rifting, from collision during the Precambrian to Mesozoic extension (Abbate et al., 2015 and references therein). This long pre-rift history of tectonic events created pre-existing heterogeneities with variable orientation that have controlled the development of the East African Rift System in Ethiopia (Tesfaye Korme et al., 2004). Until the early stages of rifting, asthenospheric up welling effects on the thinning lithosphere had less impact on the magmatic activity (Ebinger et al., 2001). Pre-rift flood basalts dated to 24-23Ma., are evidences to this. Later these magmatic activities changed to transitional flood basalts that represent the formation of rift margin development nearly 10Ma. The Bi-modal Basalt-Rhyolite volcanism proceeded this activity from 7Ma up to now in the Afar basin, meanwhile the beginning of the Ethiopian rift is dated 12Ma.(Tadios Chernet et al.1997). The volcanic products along the MER are characterized by rhyolites, ignimbrites, pyroclastic deposits and basalts (e.g., Giday WoldeGabriel et al., 1990; Hutchison et al., 2016; Fontijn et al., 2018; Siegburg et al., 2018).

According to Caroline et al., (1998) the history of sedimentation in the Ziway, Langano, Abiyata, and Shala lake basins started during the early-Late Pleistocene period and is characterized from this period up to the present-day by a series of climatically controlled rises and falls of lake level.

The flat Abiyata basin depression is bounded to the east by the smooth East Abiyata Border Escarpment, which disappears progressively toward the north, where the Abiyata Main Basin joins Bulbula alluvial plain just north of Lake Abiyata, gravity surveys indicate an abrupt change between a positive anomaly related to intrusion and recent volcanism in the Aluto Caldera, and a strong negative anomaly (Searle et al., 1972).

CHAPTER FOUR

4. GEOLOGY OF ABIYATA DIATOMITE DEPOSIT

Geologically, the study area consists volcanic rocks and lacustrine sediments of Pleistocene and Holocene lacustrine units (Qlp and Qlh) (Hutchison et al., 2016). Lacustrine sediments deposited in the study area are predominantly siltstone, sandstone and diatomite.

According to (Mohr et al., 1980), the oldest outcropping volcanics in the study area are pumice beds dated at about 0.60 Ma and locally the WFB ignimbrite dated at 0.24 Ma. The ignimbrite in the area constitutes the erosional remnant massifs Lencha Guda, Bilisso and Fike mountains, which immediately rim the depression in which the diatomite occur.

The chronostratigraphic data of the CMER presented by (Giday WoldeGabriel et al., 1990) indicate that the geology of Abiyata area is included in, Butajira ignimbrite, Wonji group (pyroclastic rocks volcanoclastic material) and lacustrine sediments ranging in age from Miocene to Quaternary. The diatomite bearing sediments are deposited in Upper Pleistocene within the Lakes Region (Million H/Michael, 1990). The fine-grained, light colored rocks, provably derivatives of pyroclastic eruptions, underlie the lake beds with which the diatomite is associated.

Immediately overlying the fine-grained rock units are grey clayey sediments, especially abundant in the western and southern periphery of the depression. These sediments, which may be originated from the ignimbritic eruptions in the region, are easily attacked by erosion due to their loose nature. They therefore constitute a large portion of the sediments, together with pumice, volcanic ash and breccia.

Trachy basaltic flows from the volcanic cone of Billa underlie the diatomite beds, as seen in the westernmost diatomite exposure in the stream. The basalt does not seem to have had a large areal extent. Between the volcanic cone and the stream a couple of isolated erosional remnants of scoriaceous basalt out crops have been seen.

Due to the original uneven topography of the lake beds, the sediment composition and strata thicknesses vary considerable from place to place. This is intensified by later periodic tectonic movements, the evidence of which are three parallel northwesterly trending faults down throwing eastwards as is it has been shown in geological map below with rather small displacements, especially observable in the western portion of the stream, and frequent changes of the main stream course and the courses of tributary creeks.

The later features have caused partial erosion of the diatomite beds in the extreme western part of the depression and redeposition of the same in the eastern part, not far from Lake Abiyata, thereby causing local lowering of diatomite quality due to admixture of clayey material as seen in physical properties like color, density and roughness.

The lithological units exposed in the studied area are; ignimbrite, pyroclastic ash, and unwelded tuff and pumice. In addition to this, lacustrine sediments are exposed in the studied area and covers large part of the study area and the diatomite is also exposed along the main stream flowing east west direction from the foot of the mount Fike towards Lake Abiyata and in small creeks joining the main stream from the west direction. The description of each unit is given below.

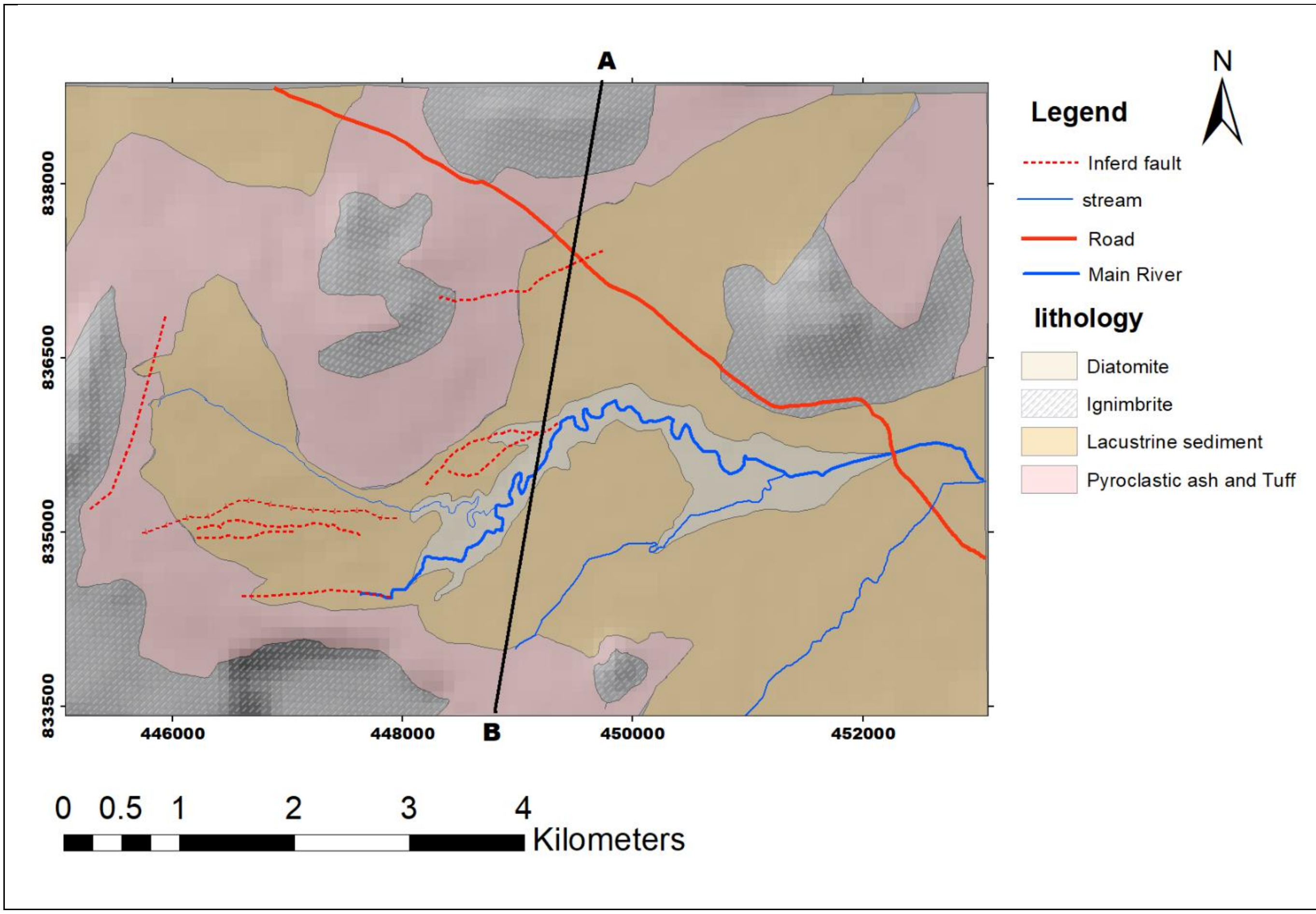


Fig. 3.1 geological map of the study area

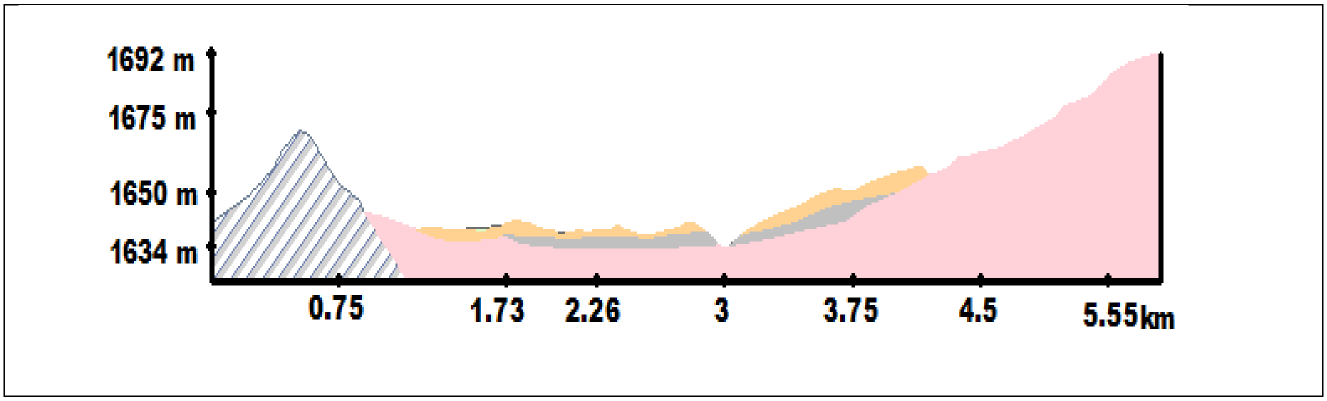


Fig.3.2. Cross section of the geological map

The following general succession was proved by detailed mapping and by river section logging.

A typical section of units was exposed in the northern most gullies northeast of the mapped area. The diatomite layer pinches out to the east and to the south. It is probably in parts eroded by river. There seems to be a continuation of the diatomite to the north. It was probably detected in the in northern part about 2 km north of the diatomite deposit. The so called, whitish tuff, which is slightly compacted, from some areas seems to be identical with the main diatomite layer.

- Dark brown soil horizon or loam soil (in some places volcanic ash and pumice)
- Grey silty clay (lacustrine sediment)
- Intermittent Pumicious pebbly horizon
- Grey sandy clay
- Diatomite bed
- Sandy horizon (often angular grains)
- Sandy clay horizon
- Grey clayey horizon with small sandy bed containing diatomite
- Brownish grey fine-grained clay
- Light grey diatomaceous unit (compacted and fractured)
- Tuff and pumice layer

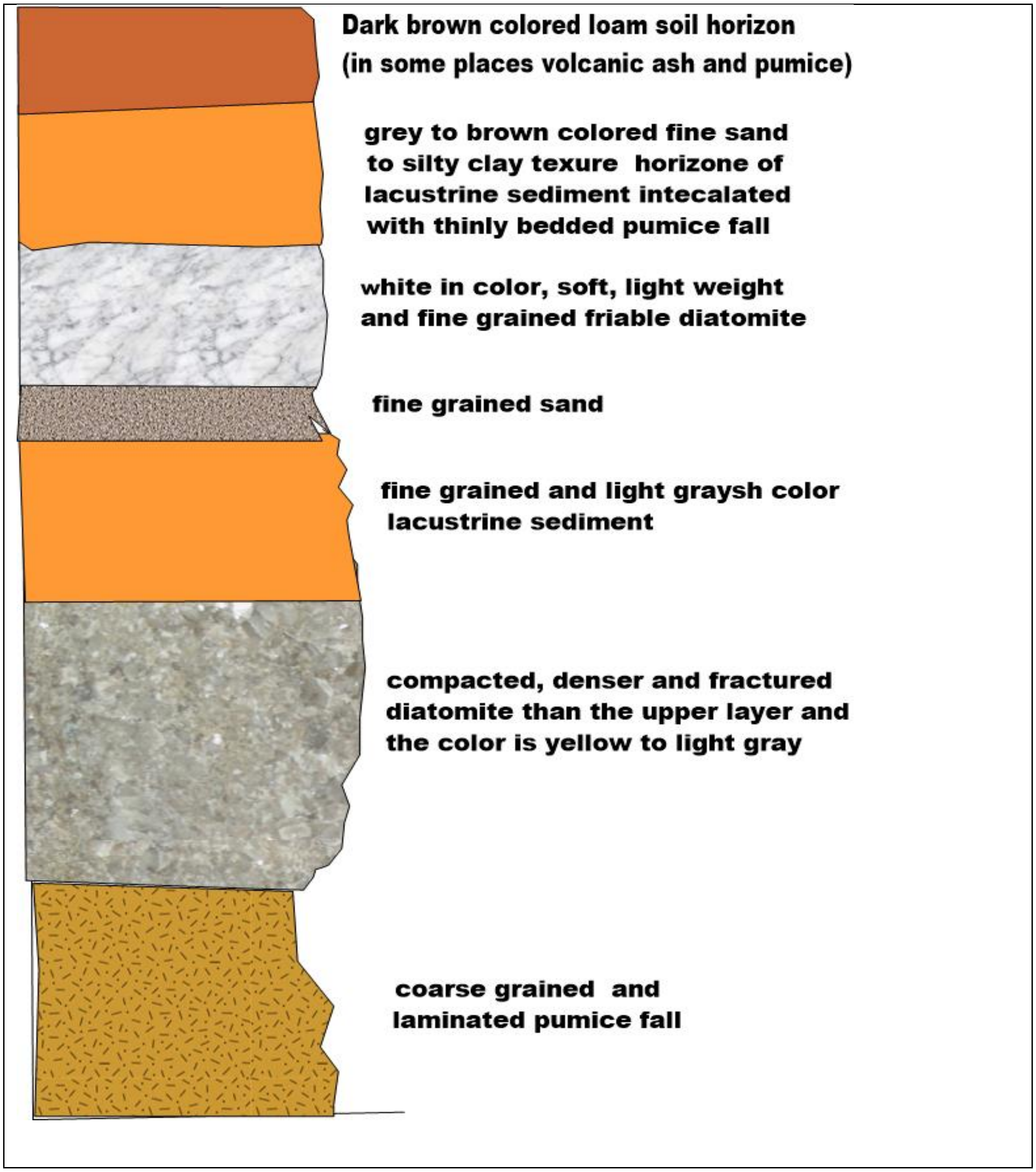


Fig.3.3. *Section showing the exposed part of Abiyata diatomite (not scaled)*

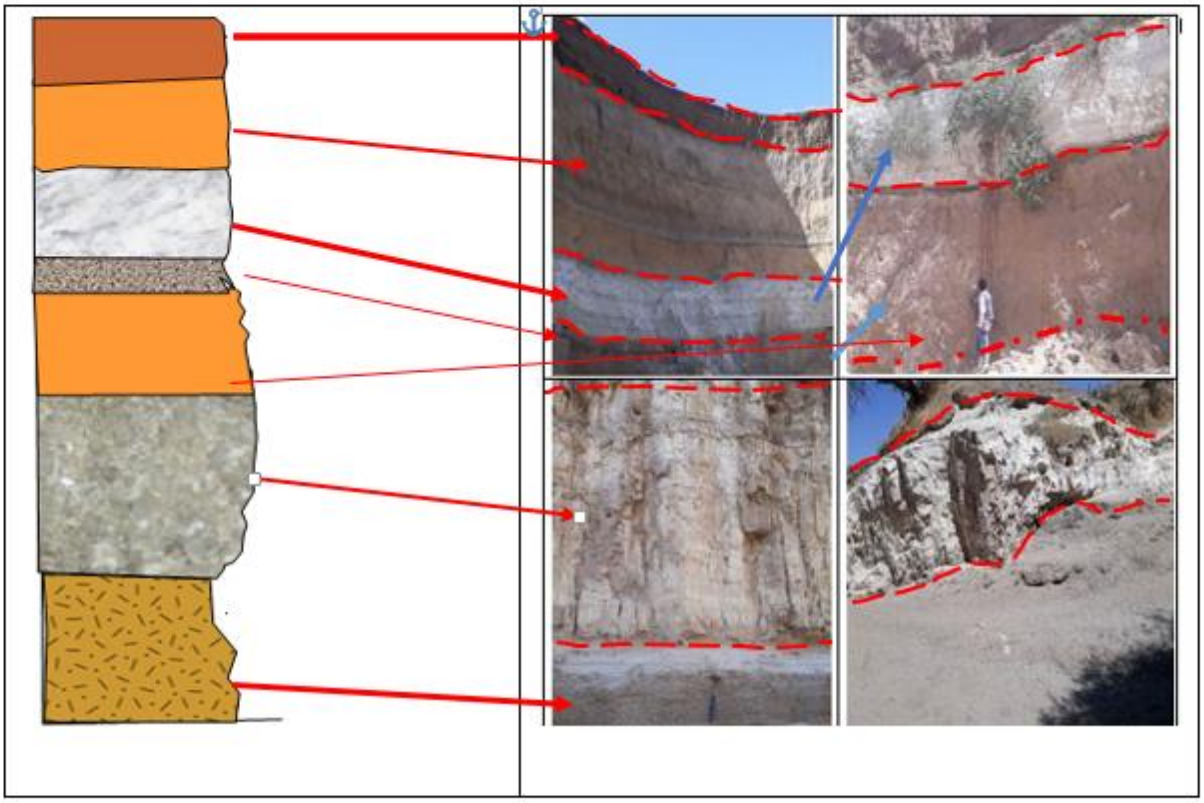


Fig. 3.4.*Section logges with relative photos of the section*

3.1.1. Ignimbrite

The volcano-tectonic evolution of the CMER is punctuated with periods of intense silicic volcanism, characterized by large explosive caldera-forming eruptions and the production of several ignimbrite deposits (Franceschini et al., 2020). The complete sections the ignimbrites are moderately compacted and poorly welded Pumiceous base that grades upward into the densely welded zone before transitioning back into a non-welded Pumiceous top.

In the study area this unit is exposed in three localities eastern forming Lencha Guda, western forming mount Fike and in the southern part of the study area (see geological map). It forms rugged and mountainous terrane dissected by rivers. In all places it is found associated with above listed ridges and it is also exposed by intermittent rivers and in small quarries by local people for fencing and constructing their houses. Mostly, this unit is underlain by pyroclastic ash. In outcrop this unit is massive and hard enough to break it with geological hammer. Massive, green, welded ignimbrites are also exposed in the study area containing abundant pumice fiamme. The deposit is immediately overlain by lacustrine sediments suggesting that it was emplaced in a lake basin (Hutchison et al., 2016). Also, it is compact and light-gray in color.

Fig.3.5. Quarry site exposure of Ignimbrite

Microscopic study of this rock shows hypo-crystalline textures. The typical range of phenocrysts observed in thin section is sanidine, quartz and other alkali feldspar minerals and there are also some opaque minerals. The remaining composition of this rock is constituted by matrix composed of alkali-feldspar, quartz and juvenile materials.

Glass shards were also identified and characterized based on its morphology. It has similar color with quartz and feldspar but typically has a more concave appearance than crystals. Vesicular grains were differentiated from glass shards as glassy particles that contained at least one entire, unbroken vesicle.

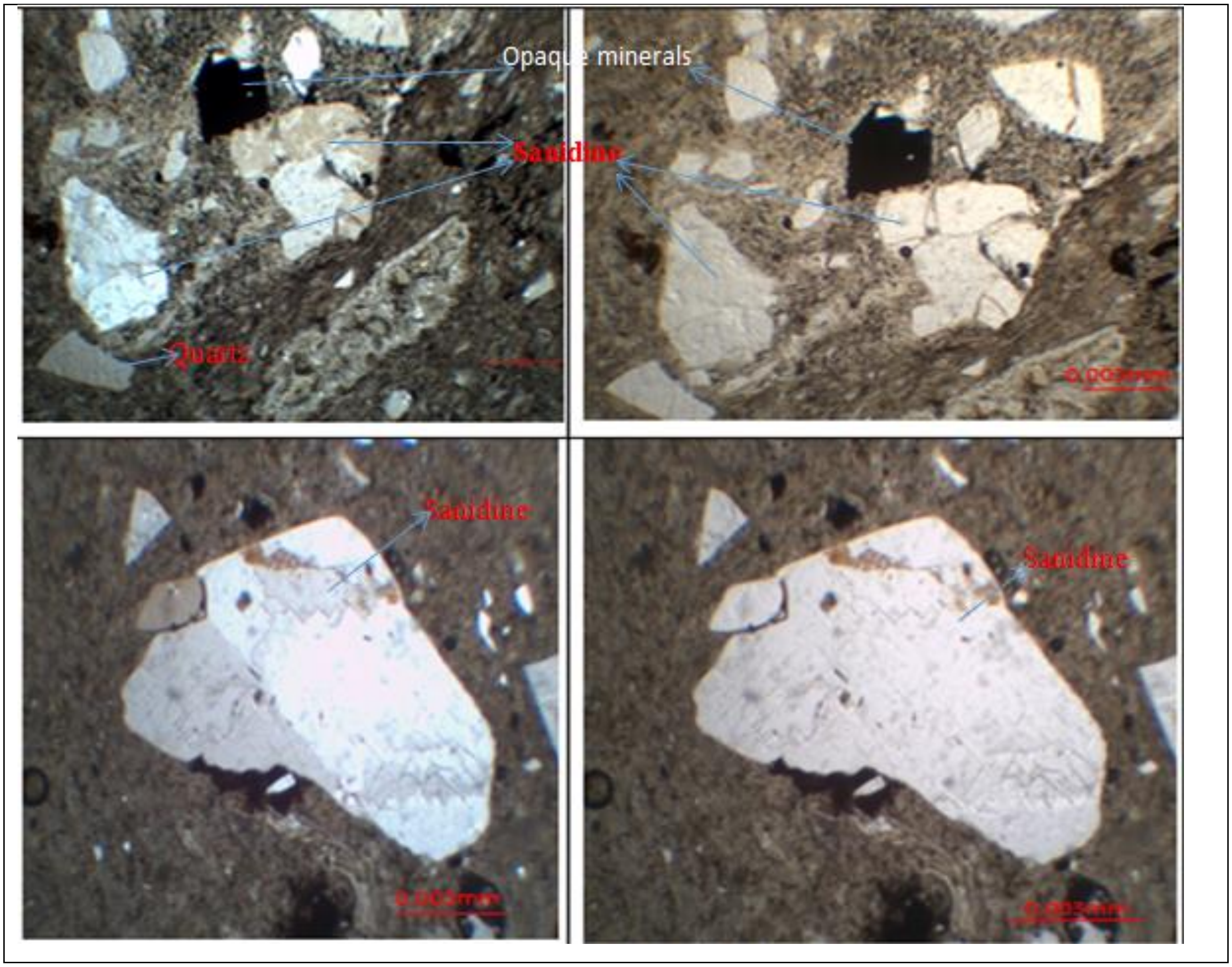


Fig 3.6.Micro photo of ignimbrite under XPL and PPL

3.1.2. Pyroclastic ash, pumice and unwelded tuff

These complex units, which is thick and consisting of air-fall and thin ash-flow tuff, has been mapped as pyroclastic fall and flow deposit. The gray, colored ash-flow tuff is characterized by moderate to dense welding. Most of the pyroclastic units consist of vitric tuff.

This unit, in terms of abundance, is the most dominant lithology of the study area. It's found forming massive mountains, hills and ridges and mostly exposed by creeks joining the main stream. It is mainly composed of fragmented pumice, Pumicious ash and Tuff lenses. In most cases, it is hard to find a clear contact between other units and this unit especially the contact between tuff and pumice is highly localized and un-mappable at the given scale. Hence, it has been mapped as pyroclastic fall and flow as it has been undifferentiated pyroclasts in most places. In upper part, this unit has gradational contact with ignimbrite unite which overlays it. This unit shows light bluish to bluish color when it is fresh and a verity of colors ranging from white to light gray to pinkish gray near alteration zones, in highly weathered surfaces it has brownish, yellowish and reddish color. It usually shows unsorted depositional bedding with occasional fining and coursing up wards textures in some places. At locality, pumice flow deposit containing rhyolite and welded tuff fragments, thin alternation of pumice and blueish gray laminated volcanic sand, and gray tuffs containing white pumice observed in a thickness of 5 to 6m.

The unit also forms a flat plain which is located in the west of Lake Abiyata, Lake Shala and around Alje locality and also distributed as gentle slope from eastern Kuyera to Kofele in the east of Lake Shala. In some stream sections at the base is unwelded, bedded tuff composed of undeformed shards.

The tuffs often referred to as ash in the literature-are rich in pumice, glass shards, and crystals of feldspar. Beds are compositionally uniform across several meters, and their thickness is remarkably consistent for hundreds of meters laterally in the gully sections. Spots of diatomite enclosed in tuff are present in a few exposures.

Unlike Tuff and pumice, ash units are found exposed in large areas in gullies and flat areas. Ash falls usually show a color range between light yellowish gray to light brownish gray. They are usually laminated but they can also form thick beds. Like pumice, the bed thickness and orientation is affected by topography. Sometimes, topographic variation becomes so erratic that ash beds pinch out and return within one exposure. In some parts of the studied area, Ash beds are reworked and welded; this usually occurs in areas where indications of hydrothermal alterations are found. Some pumice beds also contain laminated wavy bands of ash, in which case, the ash beds usually show the same color as pumice beds. It has also been suggested by several previous works that Pumiceous ash units are reworked deposits of paleo-lakes and rivers of Ashes, tuffs and pumice.

Topography also plays significant role in the orientation and thickness of both fall and flow type beds. Pumice clasts found in these units also show variation with respect to the nature of deposition (flow or fall); flow deposits usually become abundant in pumice clasts that have erratic grain distribution (very poor sorting) while fall deposits have less pumice clasts with, more or less, similar sized clasts. Petrographic studies reveal that clasts of pumice and glass, generally 0.02 to 1 mm in size, are fresh and uncompacted.

Fig.3.7. Exposure of pumice fall

4.1.3. Lacustrine sediments

In the rift floor, interlayering of primary air fall pyroclastic deposits and lacustrine deposits are common. Lacustrine sediments intercalated with volcanics mainly ashes and tuffs, which in places are extensively developed and the sequence is shown as volcano sedimentary (Kazmin et al., 1980).

The lacustrine sediments are intercalated with redeposited volcanic ash and tuff. They are mainly represented by sand and silt. The major components of the sediments are volcanic origin, such as pumice and volcanic ash, rhyolite and basaltic rock fragments (Tsegaye Abebe et al., 2005; Bevenuti et al., 2002). These sediments consist mainly of loose and friable silty and sandy ash with fragments of pumice.

They are mostly unbedded and seem to be air deposited and exposed at central and eastern part of the study area covering large part of the study area. The investigated diatomite belongs to this the older lacustrine sequences which are mapped as Ql (Sisay Abera et al.,

1983) consists of thin alternation of Pumiceous sand, silt and mud. In some locality, thin alternation of blueish gray to greenish gray volcanic sand and gray tuffeous silt is observed. In southern side of studied area, light brown silt, grey clay, diatomite and Pumiceous silt are bedding. Generally bedding plains are horizontal.

Fig.3.8. Lacustrine sediment overlaying the bedded pumice

4.1.4. Ore body (Diatomite)

The diatomite is exposed along the east west direction flowing stream joining the lake Abiyata. The exposures are different in color, texture and friability starting from the western most exposure (see geological map). The diatomite exposed at western part is white to yellowish in color, very soft and of very light in weight. At middle exposure the diatomite is also light in color but careful observation shows that the diatomite is in part reworked and an admixture of clayey material is present. The weight is also relatively higher and it is not as soft as western part. Exposure at eastern part hosts a diatomite which is darker than both western and middle. The diatomite there is also harder and heavier than both, and clearly contains much more admixed clay than the first exposures. Since the exposures are confined to the section in the stream and creeks it was difficult to delineate the lateral extent of the diatomite but the bore hole data which was done by geological survey of Ethiopia in 1976 shows the diatomite bed continues both in North and South side of the main stream and it also exposed in small gullies which are crossed by foot trials.

The diatomite deposit of the study area is associated with lacustrine sediments of fine grained, whitish to grayish color, siliceous material composed of the remains of diatoms and reworked materials such as silts, clays and fine sand Pumiceous beds as it is shown in the stream section.

In some areas the layer the diatomite bed from the stream section shows gray silicified diatomite with a platy or prismatic splitting. Which reveal obscured microfossils of diatoms are the most compact and they have become hard rock. This spatial distribution of the field identifiable layer varieties allows selective exploitation of the diatomite with the predictable physical characteristics that define their future use. The vertical thickness of their layers ranges from 2.5 m to 8.5 m as it can be estimated from wall of the river section. The overburden consists of volcanic (Pumiceous) ashes and tuffs, alternating or mixed with lacustrine deposits varying in thickness between 4 and 10 meters. The vertical succession of lacustrine beds in the most of logged sections is more or less similar. There is intercalation of diatomite and other units within section which exposed by river cut. These intercalations form interbedding horizon of 20-30 cm within the lower part of the main layer. The interbeding consists of alternating beds of dark gray,compact sandy and silty textured lacustrine sediments

. *Fig.3.10. River cut and gully side exposure of diatomite*

3.2. Structures

The study area is located in the central part of the NNE – SSW to NE – SW trending Main Ethiopian Rift which belongs to the regional East African Rift System (Ebinger et al., 1996; Bonini et al. 2005). As being part of the main Ethiopian rift, the study area is affected by extensional tectonics. This phenomenon is manifested through different structures like normal faults, ground cracks and fractures.

3.2.1. Faults

These are the most dominant structures in the area. Although they are common features, they are usually difficult to find because they affect unconsolidated lithology (pumice falls and flows); especially minor faults which usually can be found forming book shelf and en-echelon structure often affect one or two beds. On the other hand, major faults are easy to identify but they usually form curved and twisted fault plane. The magnitude of extension formed from these faults seem to be little; usually several centimeters to a meter.

3.2.2. Fissures and Ground cracks

Extensional tectonics coupled with non-cohesive pumice deposit has formed semi-systematic mega fissures and cracks in the study area. This process is facilitated by intermittent rivers which use cracks as channels. Most of these cracks seem to begin from hill foots and ridges (mount Fike and Lencha Guda) and make their way towards Lake Abiyata; fissures also provide direct accesses to deposits. The local minors use these channels to quarry river sand. The general trend of younger fissures and cracks is to East –west direction but most of the cracks lose their original projection because intermittent rivers and flash floods modify them.

3.2.3. Joints and Fractures

Although not common in Pumice fall and flow deposits, joints and fractures affect the indurated units like ignimbrite, reworked material welded tuff and compacted diatomite. Some joints are systematic, depending on the toughness of the unit they affect. In some places joints affecting reworked material are filled by secondary mineral (commonly chalcedony and milky quartz).

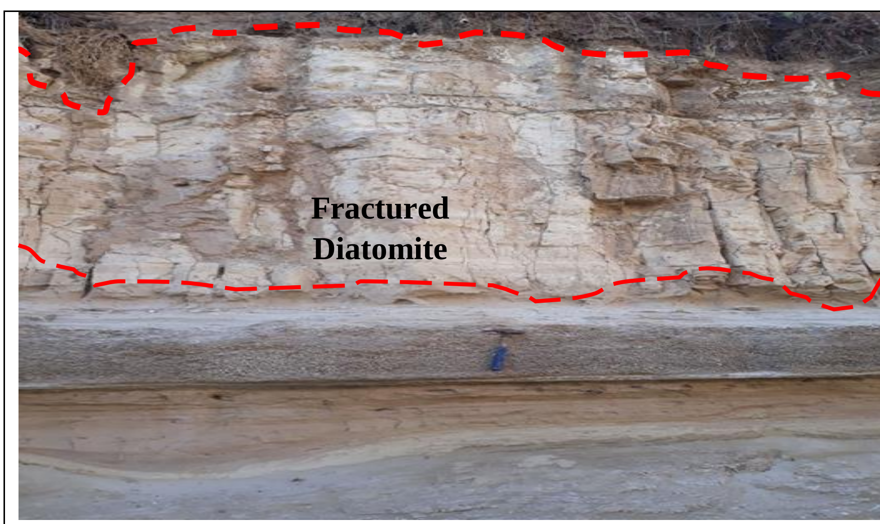


Fig.3.11. Fracture and joint in the compacted diatomite exposure

CHAPTER FIVE

5. MINERALOGY AND GEOCHEMISTRY OF ABIYATA DIATOMITE DEPOSIT

Mineralogical (quantitative and qualitative) and geochemical analysis are the most vital laboratory tests which have been done for the current research work. Powder X-ray diffraction (PXRD) is the most common standard methods of solid matters analysis. It provides information on the sample's phase composition (qualitative and quantitative phase analysis), as well as the crystal structure of the matter (crystal structural analysis). This application is also used at textural analysis. Samples from Abiyata Diatomite deposit were analyzed using ICP-OES and XRD to identify the chemical and mineralogical composition of the diatomite respectively. Diatomite is an amorphous opaline silica, or $SiO2.nH2O$, that forms in freshwater, brackish, and marine regimes that are typically well-illuminated, nutrient-rich environments (Holmes et al., 1989; Bradbury, 1990).

Beside diatom residues, other biogenic matter, secondary minerals, and inorganic sediment, usually clay derived from altered volcanic ash and rock fragment, universally occur in diatomite (Wolen & Duthie, 1999; Owen, 2002).

5.1. Mineralogy

Powder X-ray diffraction (PXRD) data were collected using PANalytical X´Pert Pro diffractometer operating at 40 kV and 30 mA with a secondary monochromator producing CuKα1,2 radiation with X´Celerator detector (X-ray diffraction Laboratory, Institute of Geochemistry, Mineralogy and Mineral Resources, Faculty of Science, Charles University, Prague). For identification of phases the search-match algorithm High-Score with PDF-2 (ICDD) database was used.

Untreated natural diatomite, is mainly composed of amorphous silica (similar to Opal-A) exhibiting a very broad peak in X-ray analysis (Fragoulis et al. 2004; Ibrahim & Selim 2011; Yuan et al. 2004). However other crystalline phases are often present as minor components. Those phases may include quartz, calcite, kaolinite, feldspar, dolomite, cristobalite, and mica (Bakr & Burkitbaev, 2009; Fragoulis et al., 2004; Hadjar et al., 2008; Hassan et al., 1999; Ibrahim & Selim, 2011).

Even though amorphous phase profiles do not have distinct peaks, it can be identified from short-range structural order and chemistry result in (unique et al., 2004).

Diffraction data may be used to identify main crystalline phases from the locations and intensities of well-defined peaks. It can also be used to identify amorphous and poorly-ordered materials by looking the shape and location of large scattering humps (Blake et al., 2012). Crystalline phases have sharp diffraction peaks, whereas amorphous and poorly ordered phases have wide X-ray scattering patterns. It is due to lack of their structural periodicity.

Diffraction patterns containing numerous amorphous phases are difficult to interpret, and distinguish specific phases within the mixture. Diffraction data alone can be problematic. The quantity and composition potential phases of amorphous mixtures are constrained by elemental chemistry (Achilles, 2018).

Diffraction patterns result from the interaction of X-rays with materials in the path of the beam, including mineral phases and poorly crystalline or non-crystalline materials. The structural periodicity of crystalline phases introduces sharp diffraction peaks whereas amorphous and poorly-ordered phases, lacking this periodicity and generate broad X-ray scattering profiles.

From phase patterns it can be concluded that the amorphous profile has significant low-angle intensities, rather than relying on the broadened profiles of crystalline phases. Even though amorphous phase profiles lack prominent peaks, changes in short-range structural order and chemistry result in unique scattering patterns in many amorphous materials (Achilles et al., 2018).

The XRD result of Abiyata diatomite samples indicates the presence of many amorphous phases. However, certain crystalline phases were found in sufficient quantities. The primary crystalline phases were quartz and feldspar, with calcite, cristobalite, illite, mordinite, wairakite, halloysite, clinoaptilolite, adularia, and tridymite as minor components. Crystalline mineral "impurities" in diatomites that have reasonably sharp peaks (Fig.5.1) and semi-quantitative estimation of proportions based on X-ray intensity. The most common mineral components of the diatomites are quartz, cristobalite, feldspar, and smectite. It indicates the significant effect of volcanic activities on these deposits. Mordenite and clinoaptilolite have replaced glass shards and pumice in vitric tuffs that are the products of ash fall-out into a lake basin of late Quaternary age. The mordenite and clinoaptilolite and associated authigenic K-feldspar and Opal-CT represent surface or near-surface manifestations of geothermal activity rather than alteration by diagenesis. It is also evidenced from the morphology of diatoms.

Opal-A is a biogenic amorphous X-ray amorphous silica (Jones and Segnit, 1971). This material produces a distinctive hump on the XRD diffractogram. In upper part of the stratigraphic level there has been no transformation of opal-A to opal-CT or other SiO_2 polymorphs. It implies that the rocks were not exposed to sufficient saline alkaline conditions for the opaline silica to be dissolved (Stamatakis et al., 1989). But the lower stratigraphic level of diatomite has been transformed to porcelain (opal-CT-rich) as a result of diagenetic alterations in a saline-alkaline environment.

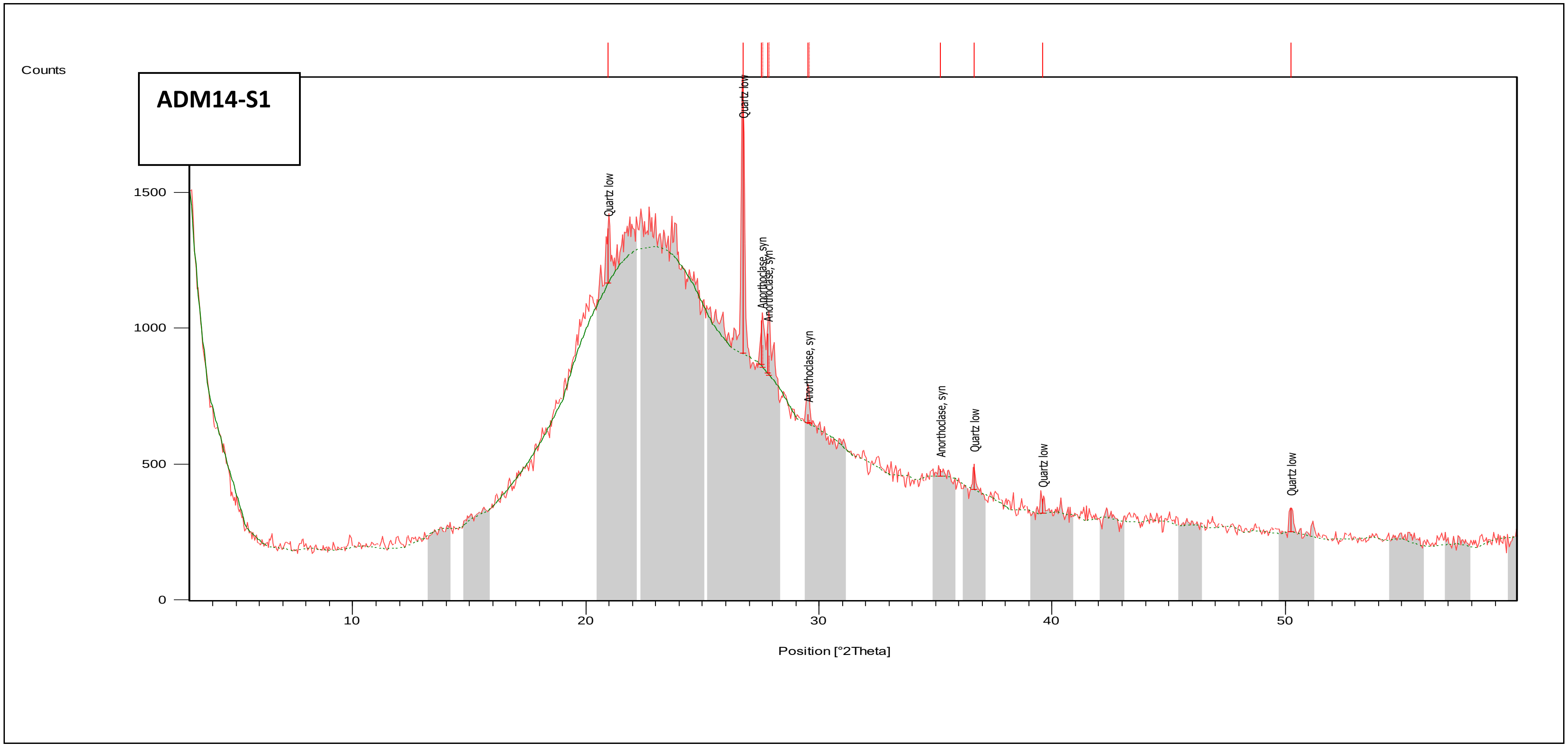
The presence of opal A in the sample is attributed to the appearance of the broad "hump" positioned between 15° and 30° (figure 5.1 A-K). The investigated raw material may be classified as amorphous based on the findings of the XRD examination, while the mineral impurities are represented by a collection peak of small intensities.

As we go down from the top to the bottom of the sections the feldspar content showed a positive relation with clay minerals, especially illite and smectite, which may be an indicator of burial alteration and plagioclase decomposition processes (samples ADM-31, ADM15-S1, ADM14-S2 and ADM14-S3).

The chemical and mineralogical characteristics of diatomite samples were various in different parts of diatomite beds. This suggests the presence of sedimentological variations during the sedimentation of diatomites (calvo et al., 1988). The lower values of crystalline minerals and high values of amorphous minerals (diatomite) have been determined from samples (ADM4-S1, ADM20-S1, ADM22-S1, ADM26 and ADM27). It is categorized as shallow, low-temperature epithermal alteration and "caldera-type zeolitization" because the mordenite clinoaptilolite alteration is closely associated with siliceous sinters and hydrothermal eruption; this is also evidenced by the presence of adularia in the alteration assemblage.

Clinoaptilolite production is evidence of diagenesis of biogenic silica. Clinoaptilolite was found in opal-CT-rich layers usually associated with dense clusters of opal-CT spherulites or dissolved frustules. It is found in cavities and molds in close proximity to opal-CT. Clinoaptilolite, as mentioned above, is frequent in diatomaceous sediments and appear as siliceous frustule replacements and pore fillings, often in close connection with opal-CT.

Silica minerals in the Abiyata diatomite are only quartz and opal with almost no cristobalite and tridymite. Cristobalite and tridymite are post-sedimentary products of opal transformation. Based on this, the degree of lithification for diatomite of Abiyata is set of substage of late digenesis and early protocatagenesis.



Counts
ADM14-S1
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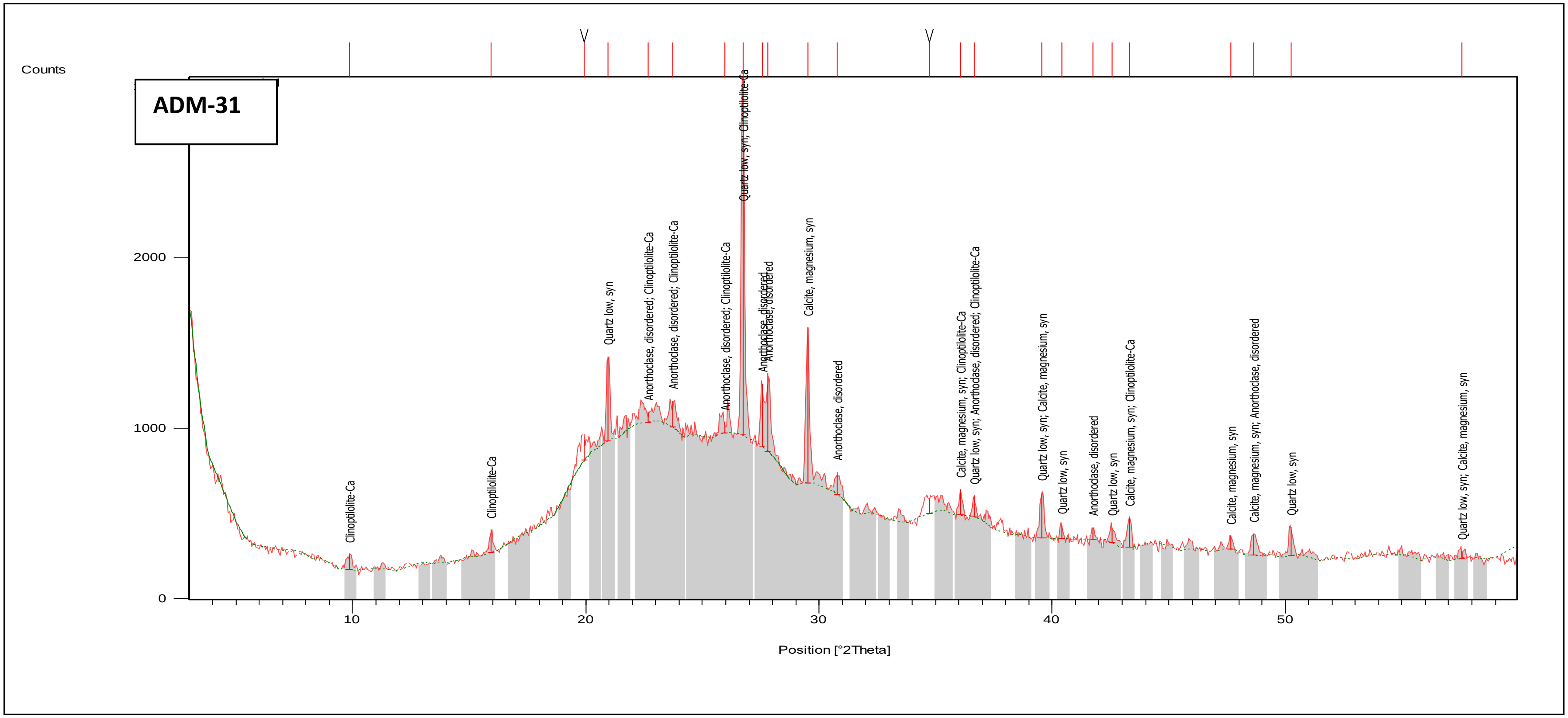
1000
500
0
Quartz low
Quartz low
Anorthoclase, syn
Anorthoclase, syn
Anorthoclase, syn
Anorthoclase, syn
Quartz low
Quartz low
Quartz low
10
20
30
40
50
Position [°2Theta]


ADM-31
Counts
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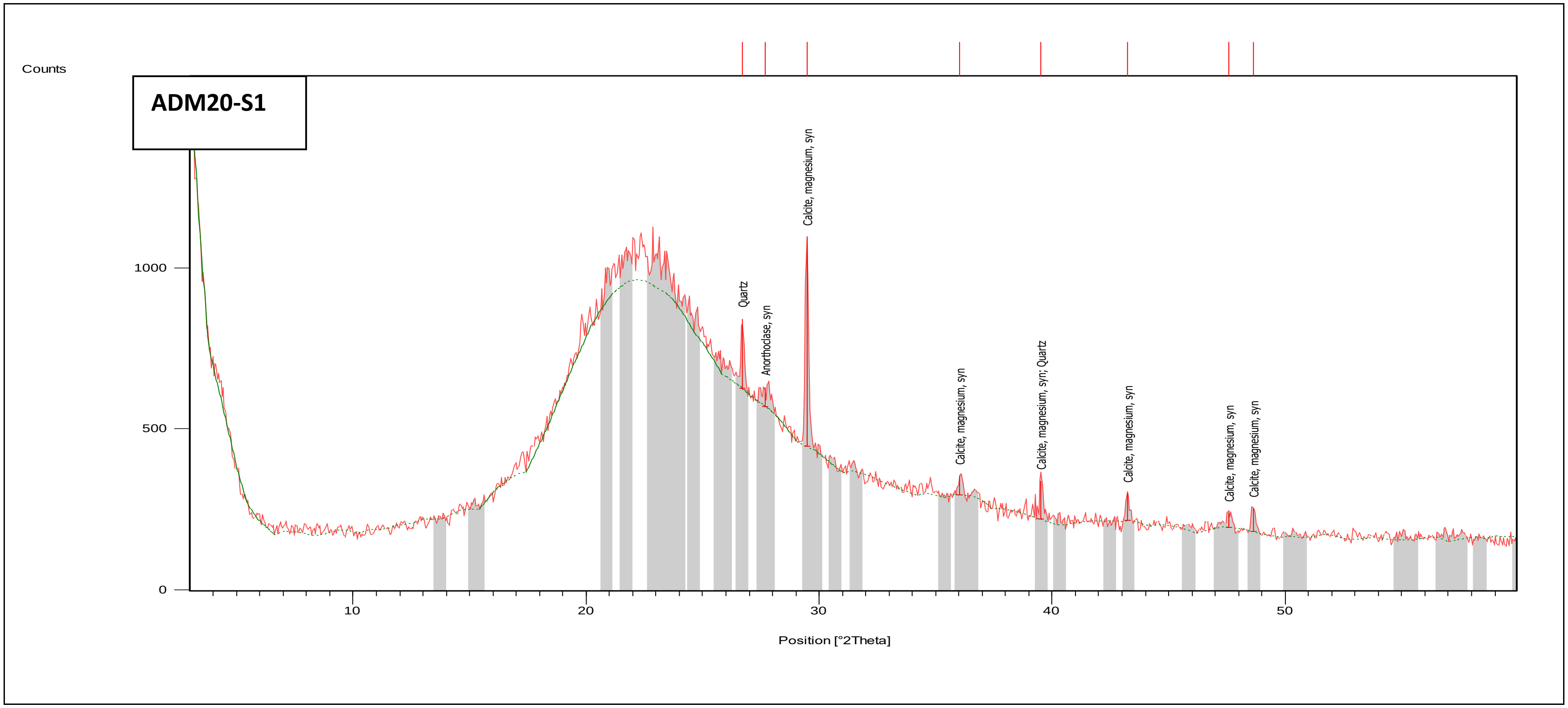
1000
0
10
20
30
40
50
Position [°2Theta]
Clinoptilolite-Ca
Quartz low, syn
Anorthoclase, disordered; Clinoptilolite-Ca
Anorthoclase, disordered; Clinoptilolite-Ca
Anorthoclase, disordered; Clinoptilolite-Ca
Quartz low, syn; Clinoptilolite-Ca
Anorthoclase, disordered
Calcite, magnesium, syn
Calcite, magnesium, syn; Clinoptilolite-Ca
Quartz low, syn; Anorthoclase, disordered; Clinoptilolite-Ca
Quartz low, syn; Calcite, magnesium, syn
Quartz low, syn
Calcite, magnesium, syn; Clinoptilolite-Ca
Calcite, magnesium, syn
Calcite, magnesium, syn; Anorthoclase, disordered
Quartz low, syn; Calcite, magnesium, syn



Counts
ADM20-S1
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500
0
10
20
30
40
50
Position [°2Theta]
Quartz
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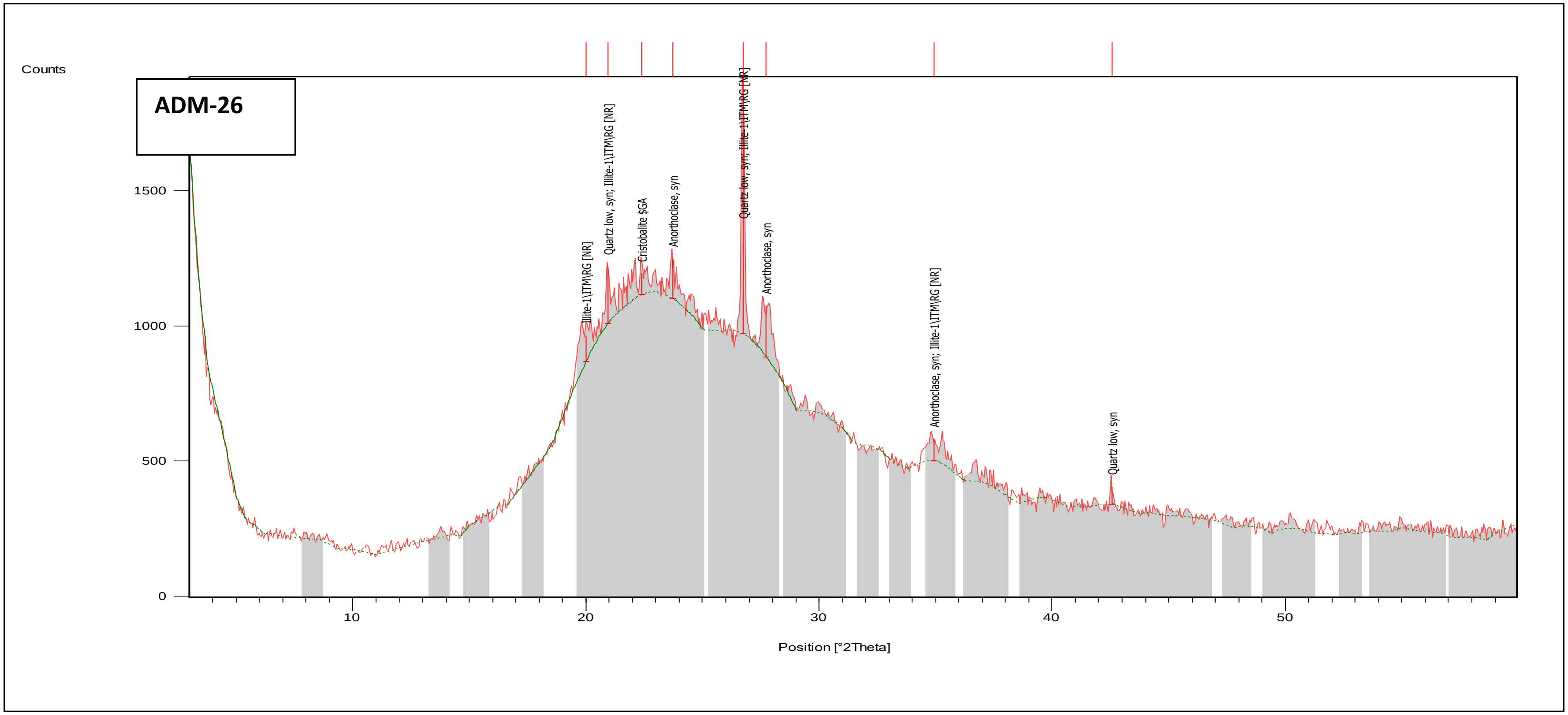
Calcite, magnesium, syn
Calcite, magnesium, syn
Calcite, magnesium, syn; Quartz
Calcite, magnesium, syn
Calcite, magnesium, syn
Calcite, magnesium, syn



Counts
ADM-26
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1000
500
0
10
20
30
40
50
Position [°2Theta]
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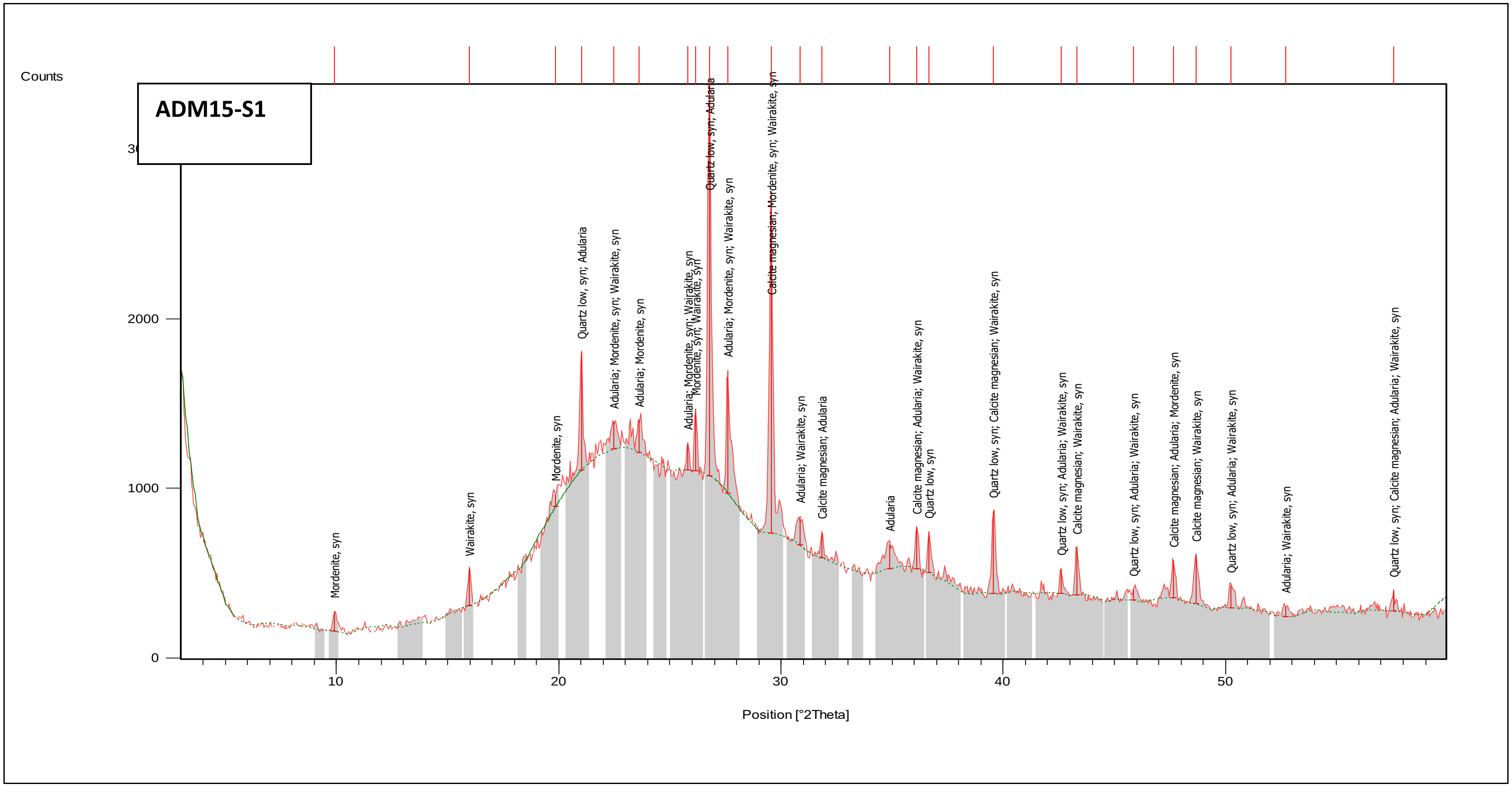
Quartz low, syn; Illite-1\ITM\RG [NR]
Cristobalite $GA
Anorthoclase, syn
Quartz low, syn; Illite-1\ITM\RG [NR]
Anorthoclase, syn
Anorthoclase, syn; Illite-1\ITM\RG [NR]
Quartz low, syn



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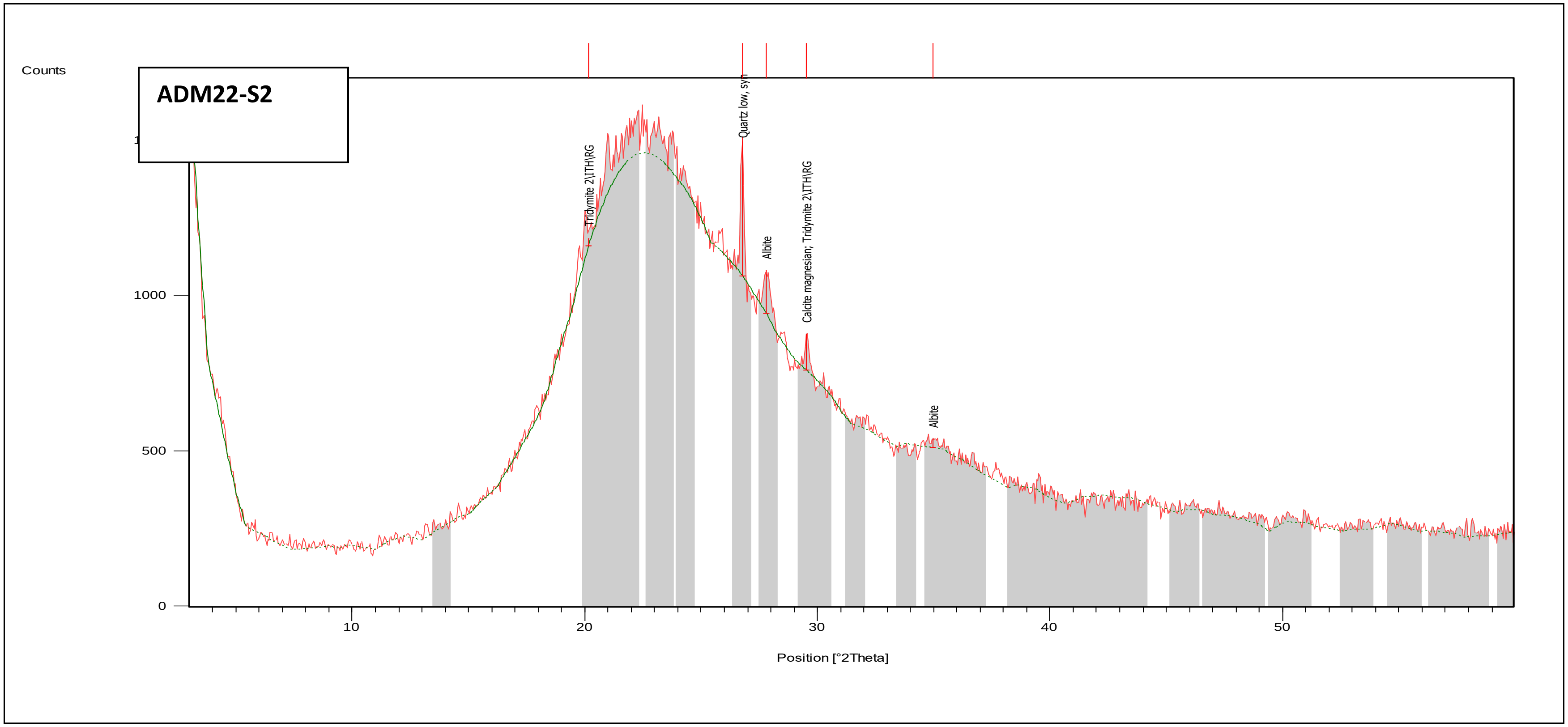
1000
2000
Position [°2Theta]
10
20
30
40
50
Mordenite, syn
Wairakite, syn
Quartz low, syn; Adularia
Quartz low, syn; Adularia
Calcite magnesian; Mordenite, syn; Wairakite, syn
Adularia; Mordenite, syn; Wairakite, syn
Calcite magnesian; Adularia



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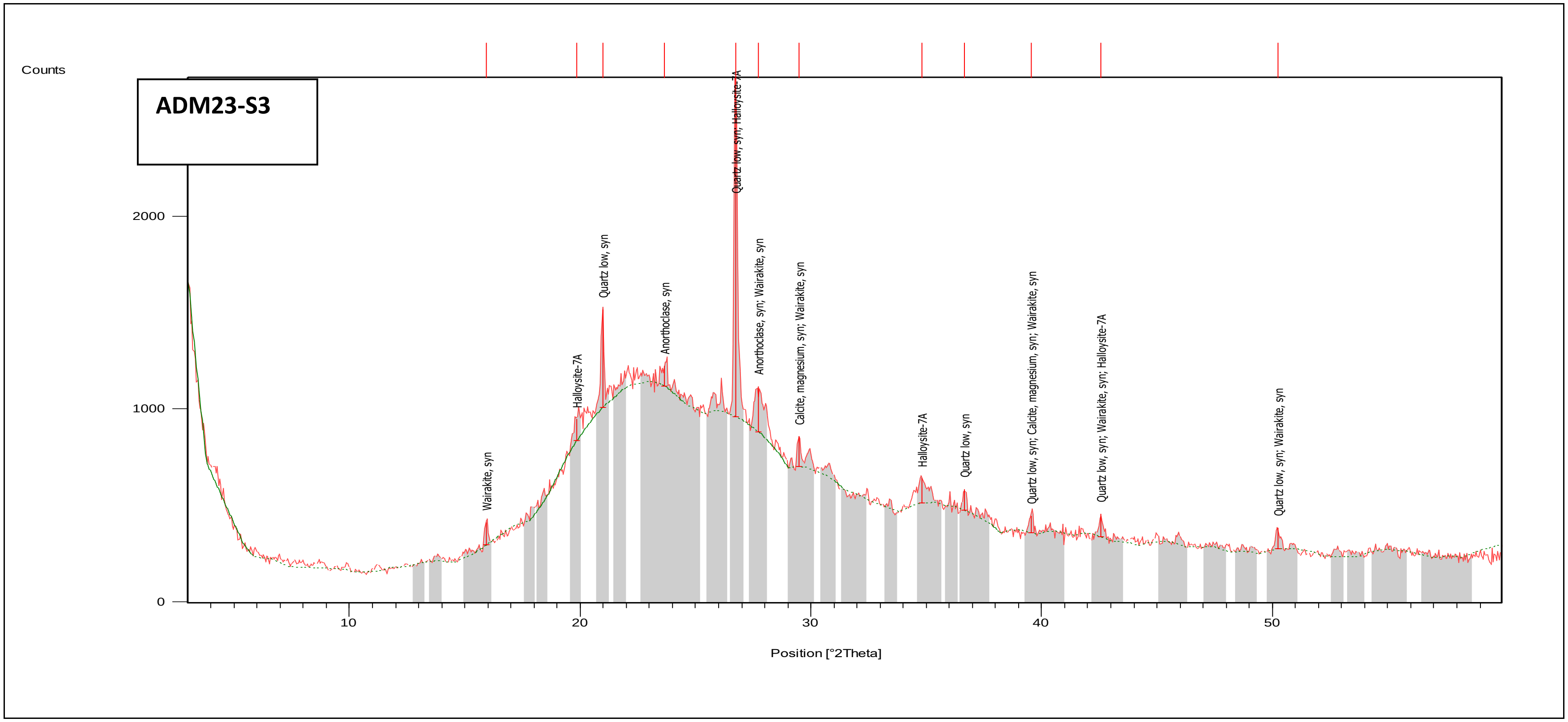
Quartz low, syn
Albite
Calcite magnesian; Tridymite 2\ITH\RG
Albite



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20
30
40
50
Position [°2Theta]
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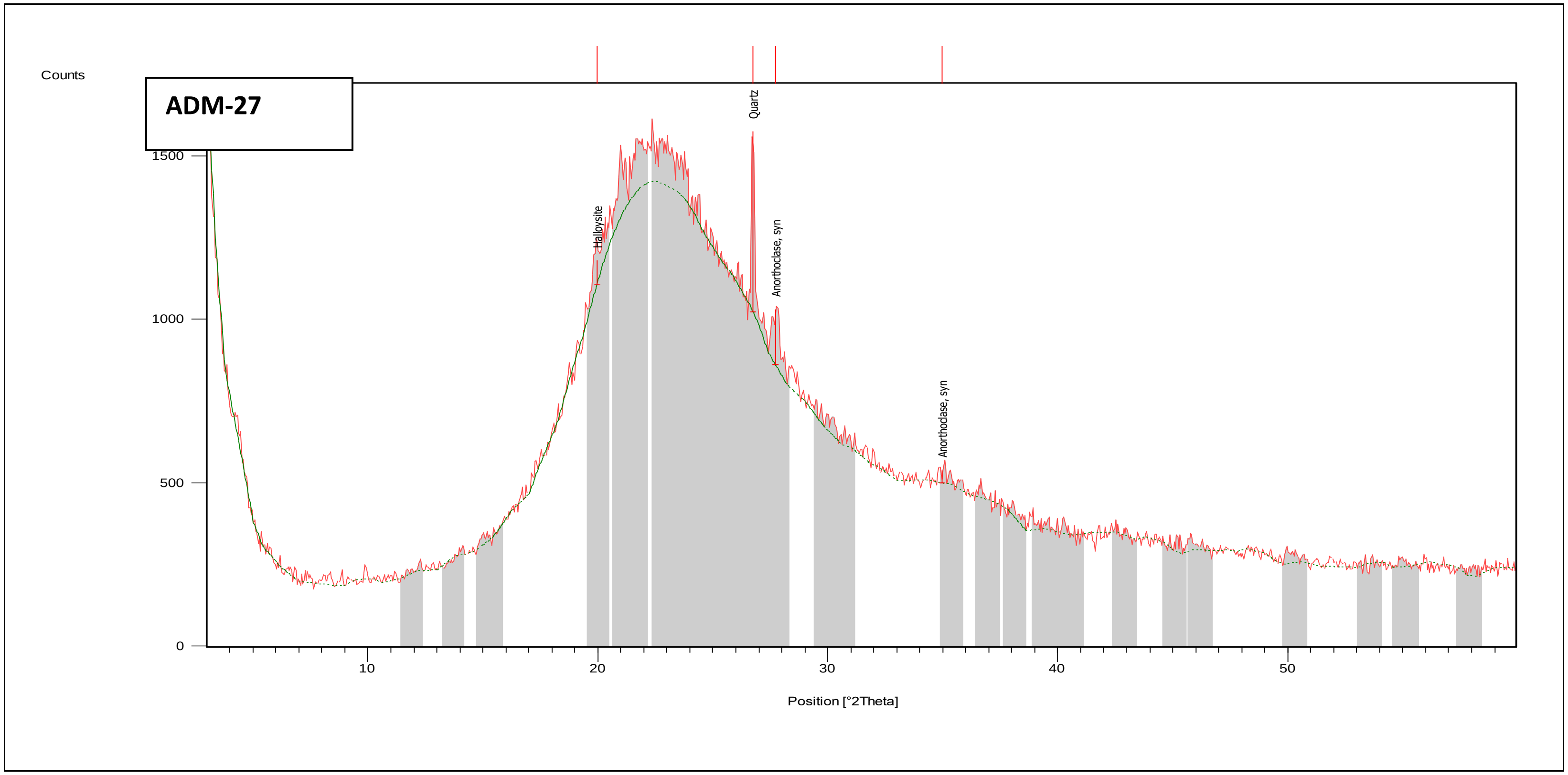
Halloysite-7A
Quartz low, syn
Anorthoclase, syn
Quartz low, syn; Halloysite-7A
Anorthoclase, syn; Wairakite, syn
Calcite, magnesium, syn; Wairakite, syn
Halloysite-7A
Quartz low, syn
Quartz low, syn; Calcite, magnesium, syn; Wairakite, syn
Quartz low, syn; Wairakite, syn; Halloysite-7A
Quartz low, syn; Wairakite, syn



Counts
ADM-27
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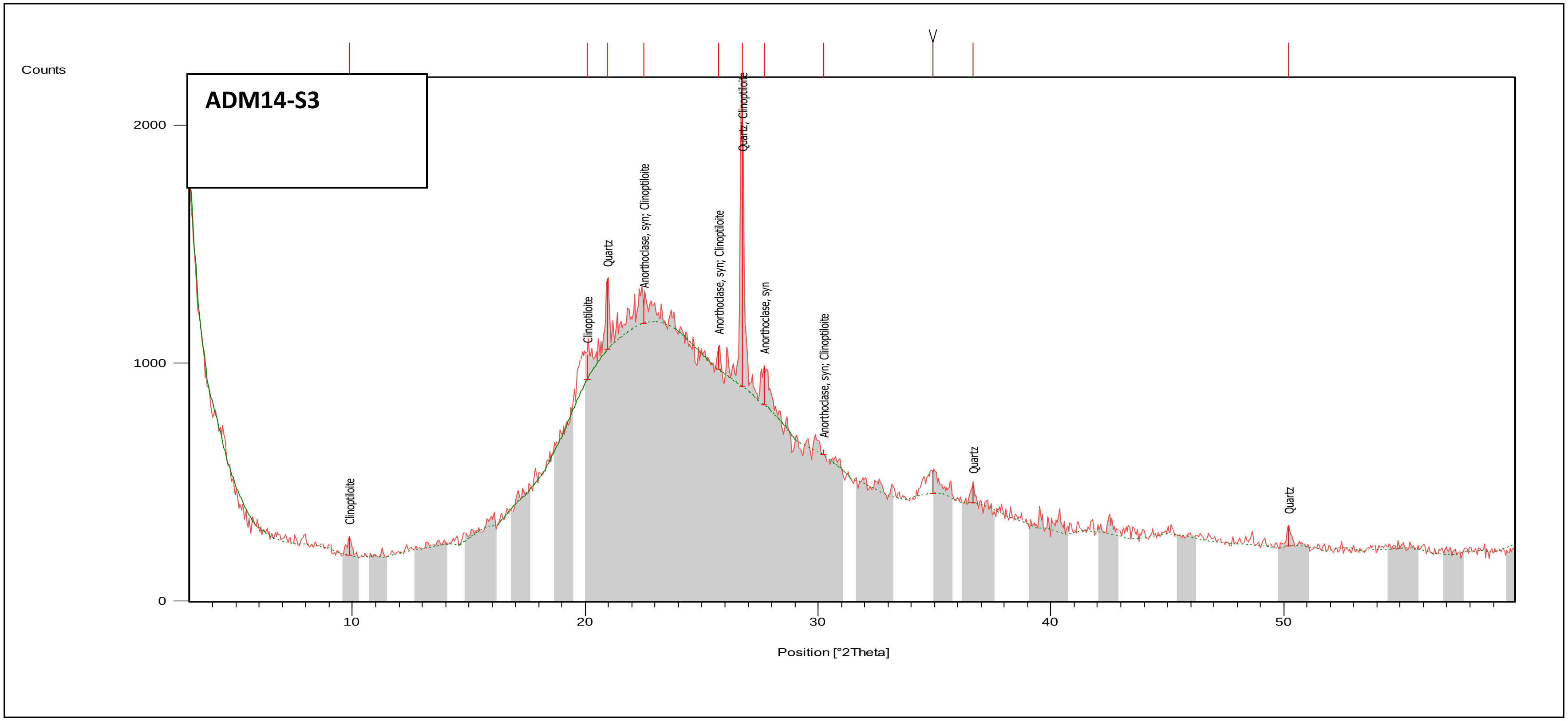
1000
500
0
10
20
30
40
50
Position [°2Theta]
Halloysite
Quartz
Anorthoclase, syn
Anorthoclase, syn



Counts
ADM14-S3
2000
1000
0
10
20
30
40
50
Position [°2Theta]
Clinoptilolite
Quartz
Anorthoclase, syn; Clinoptilolite
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Anorthoclase, syn; Clinoptilolite
Quartz
Quartz

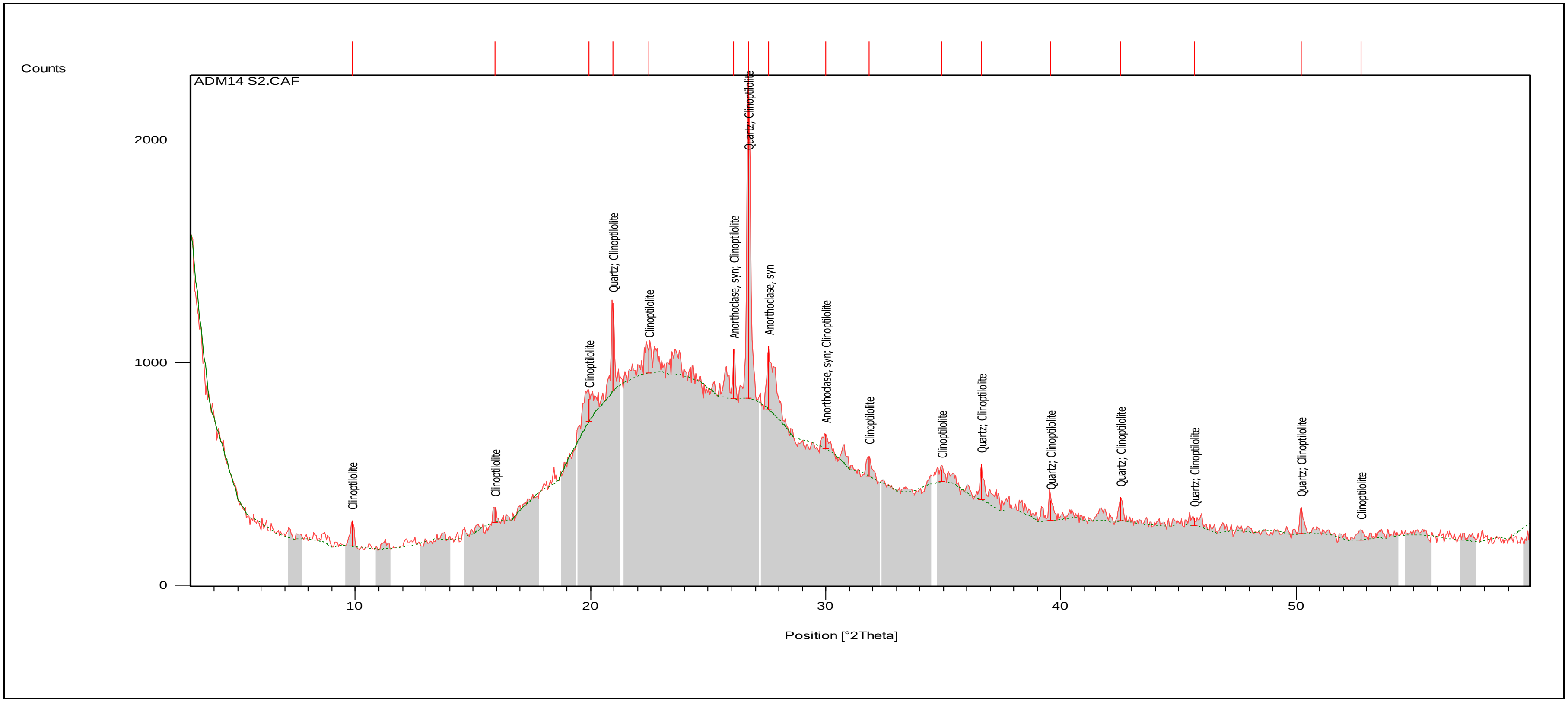


Fig.5.1. XRD patterns of Abiyata diatomite samples

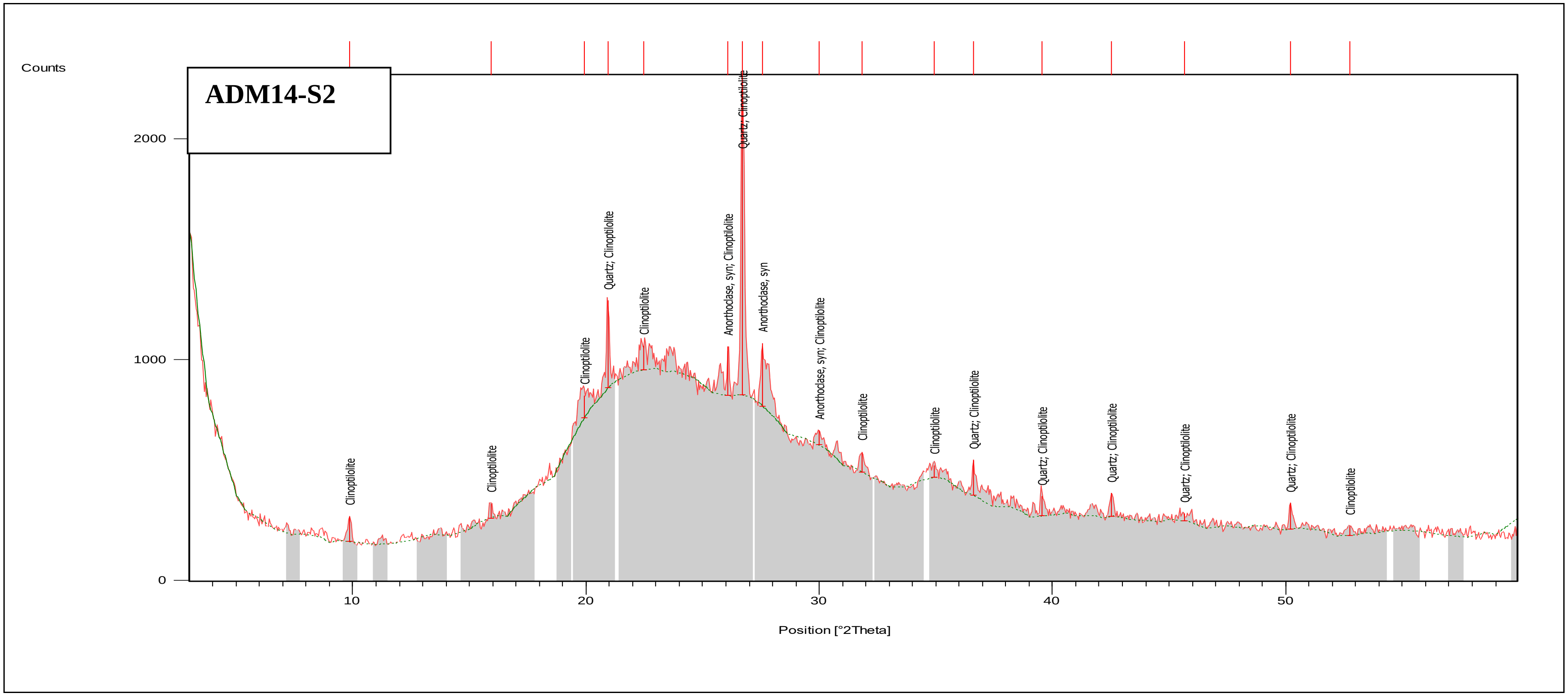


Fig.5.1. XRD patterns of Abiyata diatomite samples

5.2. Diatom Micro-Paleontology

Diatoms are abundant creatures that live in the light zones of continental and marine settings as plankton (floating) and benthic (shallow) species (Bradbury & Krebs 1995). They live in ecological niches that include plant attachment (epiphytic), rock attachment (epilithic), surface mud movement (epipelic), and other habitats (Thomas & Gould 1981).

The diatom assemblage, as viewed via a microscope, not only helps to distinguish marine from freshwater origins, but it also helps to pinpoint the deposition of environment. Like fingerprints, diatom assemblages are unique to each site. These criteria are crucial because diatom assemblages found in marine settings differ significantly from those found in freshwater habitats. As previously stated diatomites have a variety of characteristics and create a variety of effects in the many applications to which they have been used due to structural variations connected to its origin.

The scope of this study does not allow for a detailed paleontological examination of the diatom assemblage. However, for a better understanding of diatomite quality and genesis a basic grasp of the diatom assemblage is desirable, and a basic paleontological description is provided below. The accuracy of diatom identification depends on the procedures of utilization. Morphological study is essential for a high level of taxonomic knowledge and may reveal flaws in identifying individual diatoms.

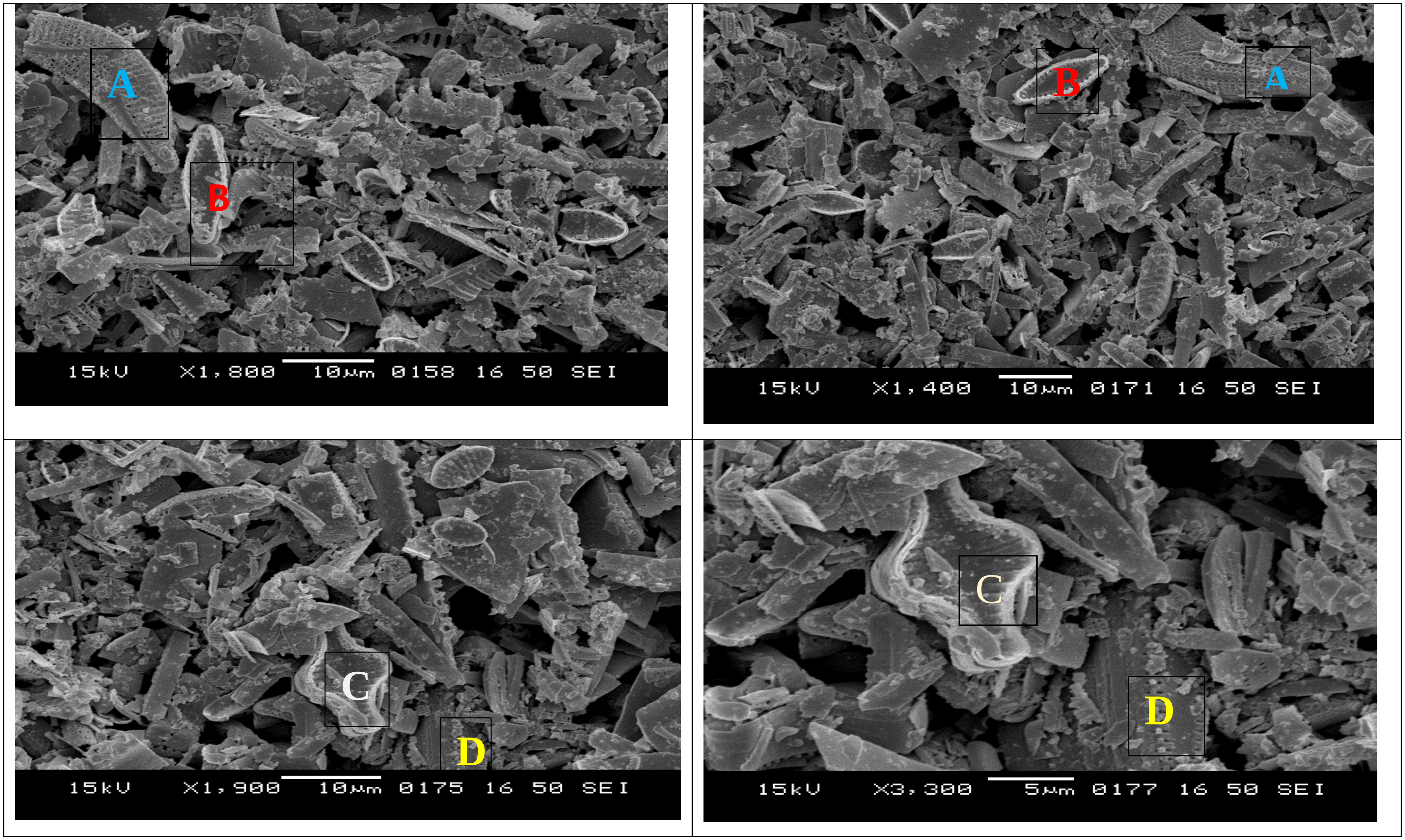
Selected samples were subjected to scanning microscopy using electrons (SEM). This method is beneficial graphic representation of the diatoms' skeletal structure. Most samples from Abiyata are dominated by diatom shapes with a Pennate forms which can be seen in several of the species. The frustules of pennate diatoms are usually elongate and bilaterally symmetrical in valve view. Most of them have a narrow axial area thickened at each end (polar nodule), and the central area usually having a median thickening (central nodule). There are many features present on the surface of the frustule for identification to species level.

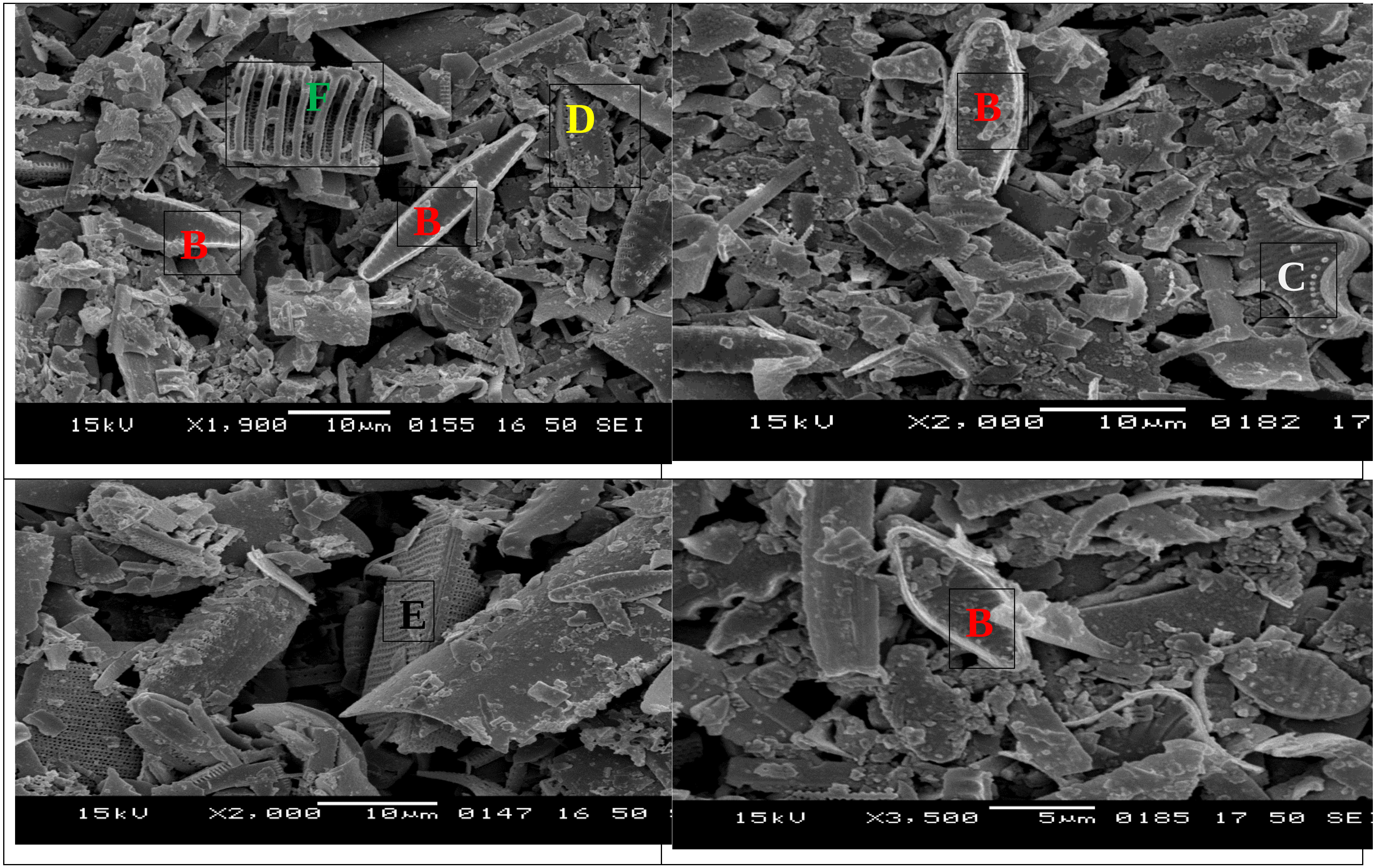
The SEM study of the diatomaceous rocks indicated that the diatom frustules were mostly well preserved, having elliptical and elongated diatoms and ranged in size from 5 to 30 μm (Fig. 5.2). Well-preserved diatom frustules in SEM photomicrographs from the upper stratigraphic level show that diatoms were not exposed to burial diagenesis (Koukouzas, 2007). Broken frustules (mixed with well-preserved frustules) were formed by transportation and redeposition activities in the study area.

Examination of the samples with SEM confirms that the diatomite particles consist of various types of morphologies and species. The diatom assemblages from all sections were dominated by benthic species with limited planktonic species. The predominance of benthic species, together with epiphytic taxa and limited planktonic elements, indicate a shallow, alkaline and mesotrophic freshwater environment (Zalat, 2000). This idea is also supported by the PH analysis result of the samples which are alkaline (9.5 – 11).

The limited identification of diatoms almost all reveals genera and species typical of fresh water assemblages.

The dominant species diatoms from the SEM analyzed samples are Staurosirella pinnata, Staurosira construens, Pseudostaurosira brevistriata and Epithemia sorex. These suggest a shallow-water, seasonally eutrophic, temperate, and alkaline lacustrine environment (Thomas, 1995). Therefore, Abiyata diatomite deposits contain dominant benthic species with fewer amounts of planktonic species. This result supports that the deposit was formed under shallow lake. The high preservation of the diatoms, as shown by SEM studies (Fig.5.2), indicates that no or only partial corrosion occurred following deposition and burial of the diatoms. In addition, the shallow nature of the lakes did not allow dissolution of the diatom frustules. Compaction of diatomite usually gives rise to two stages of diagenesis: opal-A → opal-CT and opal-CT → quartz, but in the case of Abiyata diatomite the second stage is not happened.


A
B
15kV X1,800 10μm 0158 16 50 SEI
B
A
15kV X1,400 10μm 0171 16 50 SEI
C
D
15kV X1,900 10μm 0175 16 50 SEI
C
D
15kV X3,300 5μm 0177 16 50 SEI


F
D
B
B
15kV X1,900 10µm 0155 16 50 SEI
B
C
15kV X2,000 10µm 0182 17
E
15kV X2,000 10µm 0147 16 50
B
15kV X3,500 5µm 0185 17 50 SE

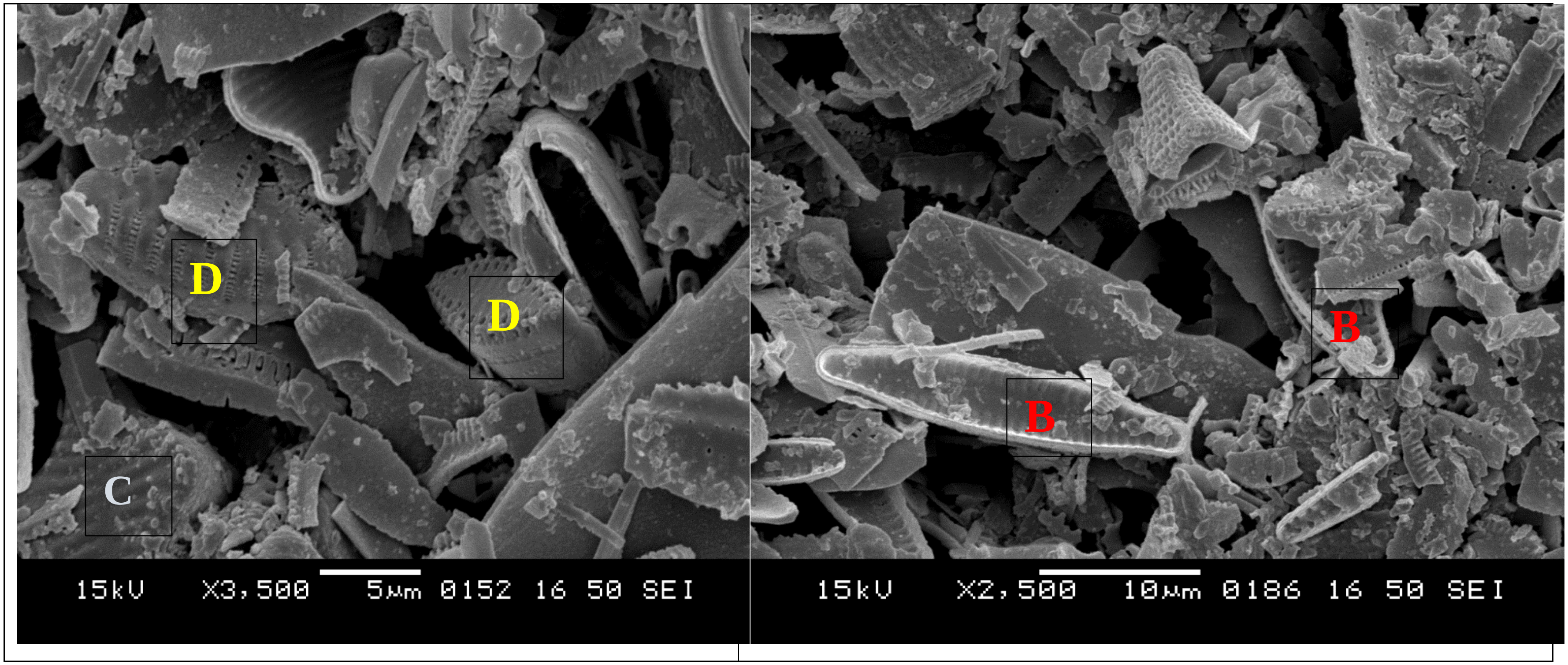


Fig.5.2 SEM photos of diatoms

A= Epithemia sorex, B=Pseudostaurosira brevistriata, C= Staurosira construe, D= Staurosirella pinnata, F=surirella pinnata

E= detail of pore size for platy diatoms

5.3. Geochemistry

The chemistry of commercial diatomite deposits is dominated by the siliceous composition of the diatom frustules, which are formed by biologic secretion, or precipitation, of amorphous silica (Cummins, 1960; Durham, 1973). Based upon a review of the data analysis, the material were composed of a significant amount of quartz contaminated with other oxides as impurities. The major chemical constituent of diatomite is hydrated amorphous silica ($SiO_2.nH_2O$) in addition to secondary components such as alumina (Al_2O_3), iron oxide (Fe_2O_3), calcite (CaO), magnesia (MgO), and other minor inorganic constituents (El-dernawi et al., 2014).

Biogenic siliceous sediments, which are virtually exclusively made up of amorphous silica or opal-A exhibit a radically different geochemical signature (Cressman, 1962).

The geochemical properties of lacustrine sediments are influenced by the chemical composition of local parent materials, the chemical composition of Aeolian sediments, physical and chemical processes in the catchment, and in-lake diagenetic changes (Bleckner et al. 2006; Minyuk et al. 2014). High silica values show that diatomite deposition is related to siliceous minerals (Gurel and Yildiz 2007).

Despite its biogenic origins, silica (SiO2) makes up a significant portion of inorganic lake sediments (Conley et al., 1993; Peinerud, 2000; Cohen, 2003). Because lake sediments contain both biogenic and minerogenic silica it can indicate increased diatom productivity or sediment transit (Brown et al., 2007; Melles et al., 2012).

Total silica concentration in lake sediments is influenced by both biogenic and inorganic silica (Cohen, 2003). Lithogenic silica is found in silicate rocks, a broad group of minerals that make up 90% of the Earth's crust (Nesse, 2011). While silica can be found in aluminum and titanium-bearing minerals, it is also found in quartz (SiO2), which has a bigger grain size than the aluminum and titanium-bearing silicates. In lake water, quartz is relatively durable and resistant to dissolution (Siever, 1962). Under conditions where silica concentrations are controlled by diatom inputs, Si concentrations in lake sediments could be utilized as a proxy for primary production. In lakes with diatoms, the Si/Ti ratio is typically employed to assess the quantity of biogenic silica present (Minyuk et al. 2014).

The chemical analysis of 10 diatomite samples was performed at Geological Survey of Czech Analytical Laboratories (Prague, Czech Republic) using ICP-OES). The chemical composition of the raw material is determined by classical chemical silicate analysis. The content of SiO2 is determined gravimetrically, while the contents of Al2O3, Fe2O3, TiO2, CaO, MgO and MnO are determined by volumetric analysis. The contents of the alkaline oxides K2O and Na2O are determined while using a flame photometer. Loss on ignition (LOI) is determined by thermal treatment of the sample at temperature 1000°C.

In terms of chemical composition, as predicted, the Raw Diatomite (RD) is largely composed of SiO2, with some additional oxides such as Al2O3, Fe2O3 and Na2O. All other oxides are in low quantities, with diatomite rocks are constituted essentially by silica.

The contents of the major oxides of the 10 samples of the Abiyata diatomites are presented in Table 5.1, including the loss on ignition (LOI). The composition of the major element oxide is consistent with that of the whole rock minerals. SiO2 is the most abundant of all oxides and is the bodybuilding material for diatomite, ranging from 62.58% to 84.66% (average 76.4% which is comparable, with some known deposits), the Al2O3 content ranges from 1.52% to 5.16% (average 3.47%), and the CaO content ranges from 0.28% to 1.52% (average: 0.67%).

TFe2O3 represents total iron, including Fe2O3 and FeO, and its content ranges from 0.08% to 3.67% (average: 1.1%). The average MgO content is 0.34% (range: 0.1%–0.56%), the average Na_2O content is 1.59% (range: 0.59–2.5%), and the average K_2O content is 1.1% (range: 0.45–1.9%). In addition the average contents of the other major oxides are less than 1%, i.e., TiO2 (0.17%), P2O5 (0.02%), and MnO (0.05%). And average LOI is 13.7% which ranges from (8.31%-23.63%).

Biogenic silica (BSi) may also dilute the concentrations of other elements (Minyuk et al. 2014). However, Si in lake sediments can also be detrital, derived from mineral material from the catchment (Peinerud, 1997; Peinerud, 2000). It is important to distinguish detrital silica from diatomaceous silica to be able to distinguish between climatic and biologic changes affecting the lake during the time of diatomite deposition. Strong enrichment in silica and depletion in aluminum and titanium suggest the dilution of clastic material by biogenic silica but attempting to distinguish biogenic silica and lithogenic silica using only geochemical data resulted in a variety of possible compositions for the siliceous sediments and is not advisable.

The content of Al_2O_3 changes in the range 1.52–5.16 wt. % and, generally, does not depend on the diatomite variety as it is with the SiO_2 content. Aluminum oxide (Al_2O_3) content in lake sediments is predominantly influenced by detrital, minerogenic inputs, and it is widely employed as a grain size proxy because it is associated with clay-sized material (Clift et al., 2014).

The comparatively high Al_2O_3 content of clastic (detrital) sediments, typically 12–15 %, is a major geochemical feature for lake sediments (Clarke, 1924). But chemical analysis of Abiyata diatomite reveals Al_2O_3 values ranging from 1.52–5.16 wt. % indicating small amount of detrital aluminosilicate minerals suggesting biogenic silica enrichment.

The elevated contents of alumina in some samples (ADM-26 and ADM14-S2) can be explained by higher amounts of clay minerals, which have been identified using the XRD method as illite and smectites. Aluminum is also an element contained in feldspars, orthoclase and albite, the minerals present in minor amounts and in all the samples. Elevated losses on ignition (LOI) are in samples numbered ADM-31, ADM14-S1 and ADM14-S2. They represent the rock varieties with darker colour and both their features (LOI and colour) depend probably upon the presence of a higher amount of the organic substance.

Chemical analysis showed that the results from AES analysis are in good correlation with the results from mineralogical analysis. Samples with high percentage of SiO_2 have also high percentage of silica minerals (opal A and opal-CT).

The chemical analysis confirms the high purity of the raw material and the dominant presence of SiO_2 with about 84.66%. A maximum of 5% Fe_2O_3 is the empirical limit which determines the usability of a diatomite according to some authors. A sample from Abiyata diatomite contains an average of 1.1% Fe_2O_3, which is comparable to the content of Fe in a refined diatomite. Samples ADM20-S1, ADM4-S1, ADM-27 and ADM22-S2 contain less Fe. It is therefore clear that the Fe content of the Abiyata diatomite is very satisfactory. Despite this, it is necessary to find out in which form the Fe compound is present is the raw diatomite. As shown by the analysis of major elements, concentrations of Si and Al in all samples varied from horizon to horizon according to the stratigraphic section and in order to differentiate it I have assigned it as horizon A, B and C from top to bottom respectively. The highest contents of Si and Al were observed in horizon B.

Concentrations of alkali metals (Na, K) were quite low (mean value 1.35%), ranging from 1.4% to 2.6%, and 2.6% to 3.2%, respectively. Potassium content was significantly lower in horizon C 1.9%).

The alkaline earth metal concentrations (Mg, Ca) were uniform, with a mean of 1.4% in both cases. A slight increase of Ca was observed in horizon lower stratigraphic unit. The mean Ti content varied from 0.34% to 0.54%. Contents of biogenic-associated P were lowest in horizon upper stratigraphic units (0.05% to 0.1%), and significantly increased down in the sediment column, with mean values of 0.64% and 0.84% for horizons B and C, respectively.

The OES results show that Fe did not demonstrate important vertical differentiation. In horizons A, B, and C, mean iron concentrations reached 2.01%, 2.18%, and 2.02%, respectively. The Mn content was usually between 0.3% and 0.5%, with Mn/Fe ratios respectively of 0.12, 0.08, and 0.07.

In lake sediments, aluminum and titanium are nearly terrigenous. Al always represents the aluminosilicate mineral in most sediments (Tribovillard et al., 2006). Moreover, Ti usually occurs in clay minerals and heavy minerals (Rangin et al., 1981). During weathering and transportation, the relative abundances of Si, Al, and Ti typically remain unchanged. These results provide evidence that a considerable proportion of silica in the Abiyata diatomite is no detrital.

Table.5.1. Major Element compositions of Abiyata diatomite samples

%wt.	**ADM4-S1**	**ADM-31**	**ADM14-S3**	**ADM14-S2**	**ADM15-S1**	**ADM20-S1**	**ADM22-S2**	**ADM23-S3**	**ADM-26**	**ADM-27**
SiO_2	82.86	62.58	70.04	66.36	75.58	84.66	84.24	77.56	77.26	82.84
TiO_2	0.12	0.26	0.21	0.21	0.20	0.08	0.12	0.24	0.28	0.02
Al_2O_3	2.20	4.66	4.16	5.02	3.80	1.52	2.14	4.07	5.16	2.19
Fe_2O_3	1.13	2.94	2.28	2.98	2.08	0.08	1.32	2.91	3.09	1.29
FeO	0.17	0.20	0.11	0.36	0.07	<0,01	0.13	0.31	0.58	<0,01
MnO	0.03	0.05	0.03	0.07	0.04	0.10	0.02	0.08	0.09	0.02
MgO	0.20	0.56	0.45	0.39	0.41	0.10	0.21	0.46	0.42	0.20
CaO	0.43	1.53	0.33	1.21	0.28	0.28	0.33	1.02	0.87	0.46
Na_2O	1.45	1.95	1.41	2.49	2.50	1.03	1.10	1.53	1.89	0.59
K_2O	0.68	1.37	1.20	1.57	1.37	0.45	0.56	1.41	1.90	0.56
P_2O_5	0.02	0.04	0.02	0.03	0.03	0.01	0.01	0.03	0.02	0.02
LOI	10.32	23.63	19.59	19.13	13.47	11.35	9.55	10.25	8.31	11.43
Total	99.61	99.77	99.83	99.82	99.83	99.66	99.73	99.87	99.87	99.62
H_2O- 105^0C	6.05	19.09	15.39	14.27	8.57	6.30	5.27	5.15	3.42	6.72

The calculation results of the major oxides of the Abiyata diatomite indicate that all samples have high SiO2/Al2O3 ratios (Table 5.1), ranging from 13.42 to 55.69, with an average of 21.88. It is generally believed that the ratio of SiO2/Al2O3 in the average crust is about 3 (Liang et al., 2020) and it has been suggested that if ratio of SiO2/Al2O3 is greater than 3, the portion of SiO2 exceeding Al2O3 can be regarded as biogenic silica (Bostrom et al., 1973). Moreover, in the cross-plot of Si versus Al, almost all the samples of the Abiyata diatomite are located in the area above the Si/Al line (Fig.5.3), showing that they have excess Si, which is indicative of a considerable proportion of biogenic silica. The term "excess siliceous mineral content" (Siex) refers to siliceous minerals other than those found in terrigenous clastic deposits.

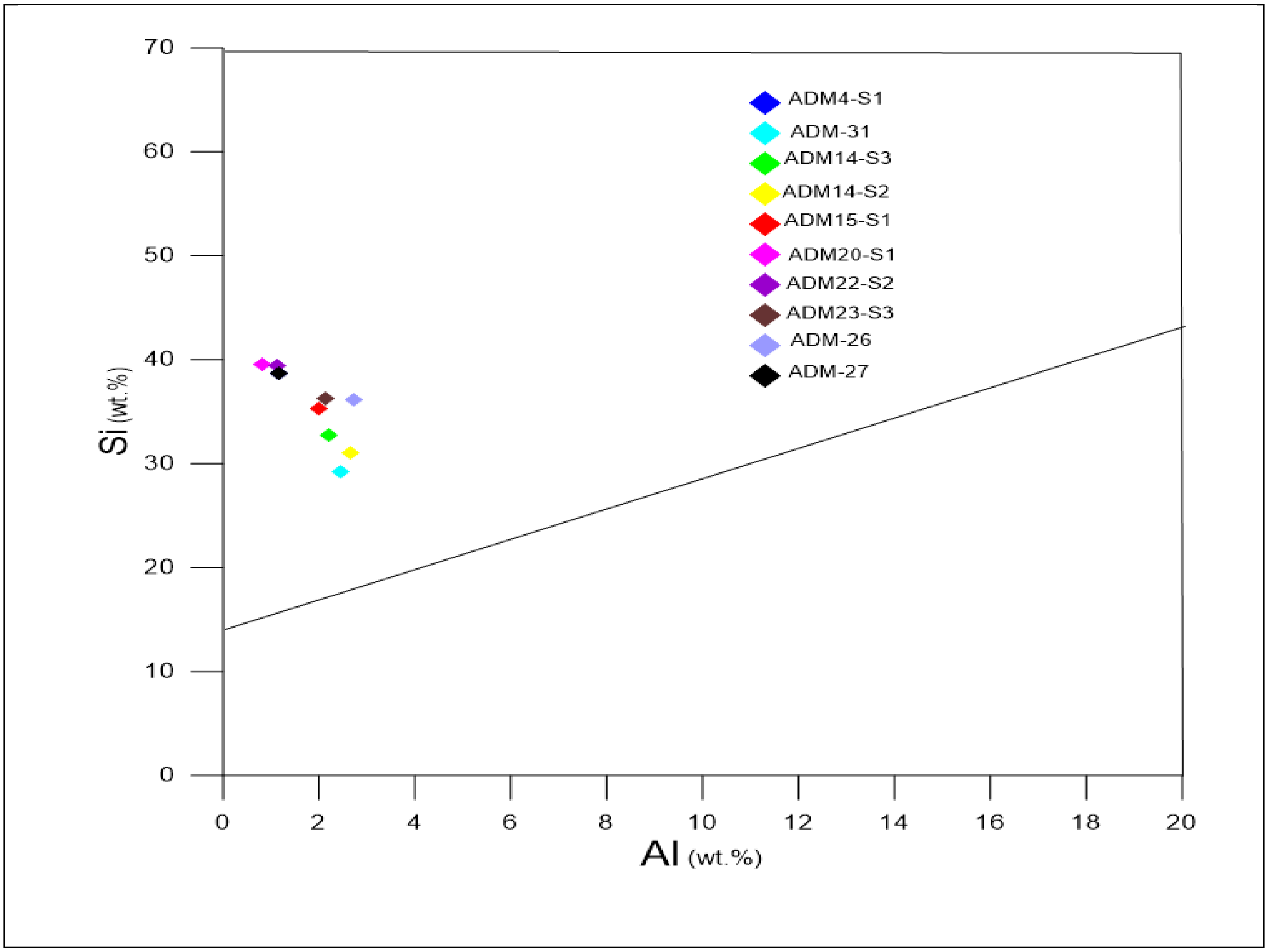


Fig. 5.3 Si vs Al showing silica excess and silica deficit zone after (Peinerud, 2000)

CHAPTER SIX

6. PHYSICAL PROPERTIES AND POSSIBLE APPLICATIONS OF ABIYATA DIATOMITE

6.1. Introduction

Diatomites have different rock-forming diatom compositions and mineral and organic impurities. The chemical and physicomechanical properties and fields of application depend on sedimentation conditions and age of the deposit (Demidov and Shelekhova, 2006).

It is utilized in a wide range of industrial applications because of its high porosity, low density porous and permeable structure, chemical resistance, high purity, high specific surface area, absorptive capacity, and absorbent characteristics (Ediz et al., 2010)

The testing techniques that are used to assess and standardize diatomite powders and aggregates are similar to those used to evaluate and standardize other industrial minerals. Pure diatomite has white color but it is more frequently buff to gray in certain areas and only rarely black. It is also chalky, soft, friable, extremely finely porous, or very low in density (floating on water until saturated), and the frustules are chemically inert in most liquids and gases. Diatomite has a low heat conductivity and a high fusion point due to its large pore capacity.

High-grade diatomite's physical and chemical characteristics make it ideal for a variety of specialized applications. Although both types of deposits provide filter grades, other end applications include fillers, additives, absorbents, and abrasives (http://pubs.usgs.gov/bul/b2209-d/), the highest quality diatomites, mostly from marine sources, are used in filtration (http://pubs.usgs.gov/bul/b2209-d/).

6.2. Physical Properties

According to Inglethorpe (1993), diatomite has a unique combination of physical and chemical qualities (high porosity, high permeability, tiny particle size, large surface area, low thermal conductivity, and chemical inertness) that make it appropriate for a wide range of industrial applications.

The quality of diatomite resources is usually determined by a laboratory examination of its physical characteristics. High pure diatomite is characterized in a unique manner by high permeability (0.1-10 mD) and porosity 35-65% (Murer and Mobil, 2000) and tiny particle area, poor thermal conductiveness and density (Hassan et al., 1999); (Gao et al., 2005). During field investigation, information may be obtained that can be utilized to classify the relative quality of diatomite for industrial application.

Various experiments were carried out in order to identify the physicochemical properties and regions of application of diatomite from the research area.

6.2.1. Grain size distribution

Different substances are incorporated into or absorbed on mineral matter in an aquatic environment, depending on physical, chemical, and biological processes that can modify the sediment texture**.**

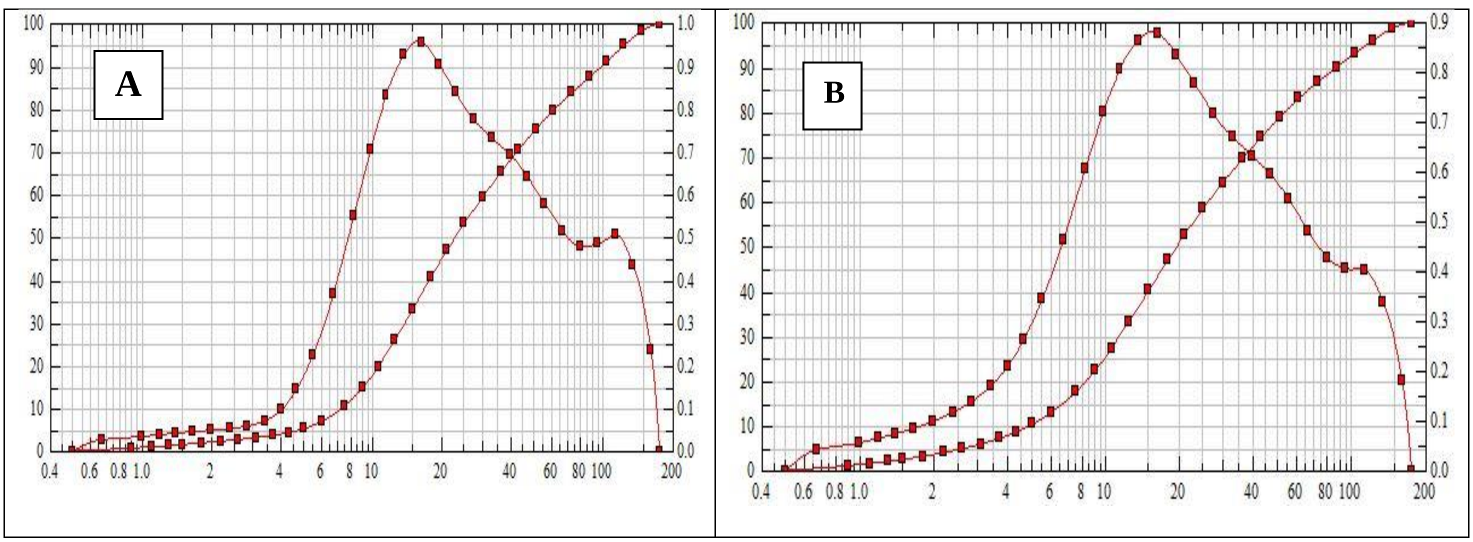
The general dimensions of the particles in a sediment or rock (such as average diameter or volume) based on the assumption that the particles are spheres or that the measurements may be represented as diameters of comparable spheres. It is typically assessed by sieving, calculating settling velocities, or measuring areas of microscopic pictures" (AGI, 1980).

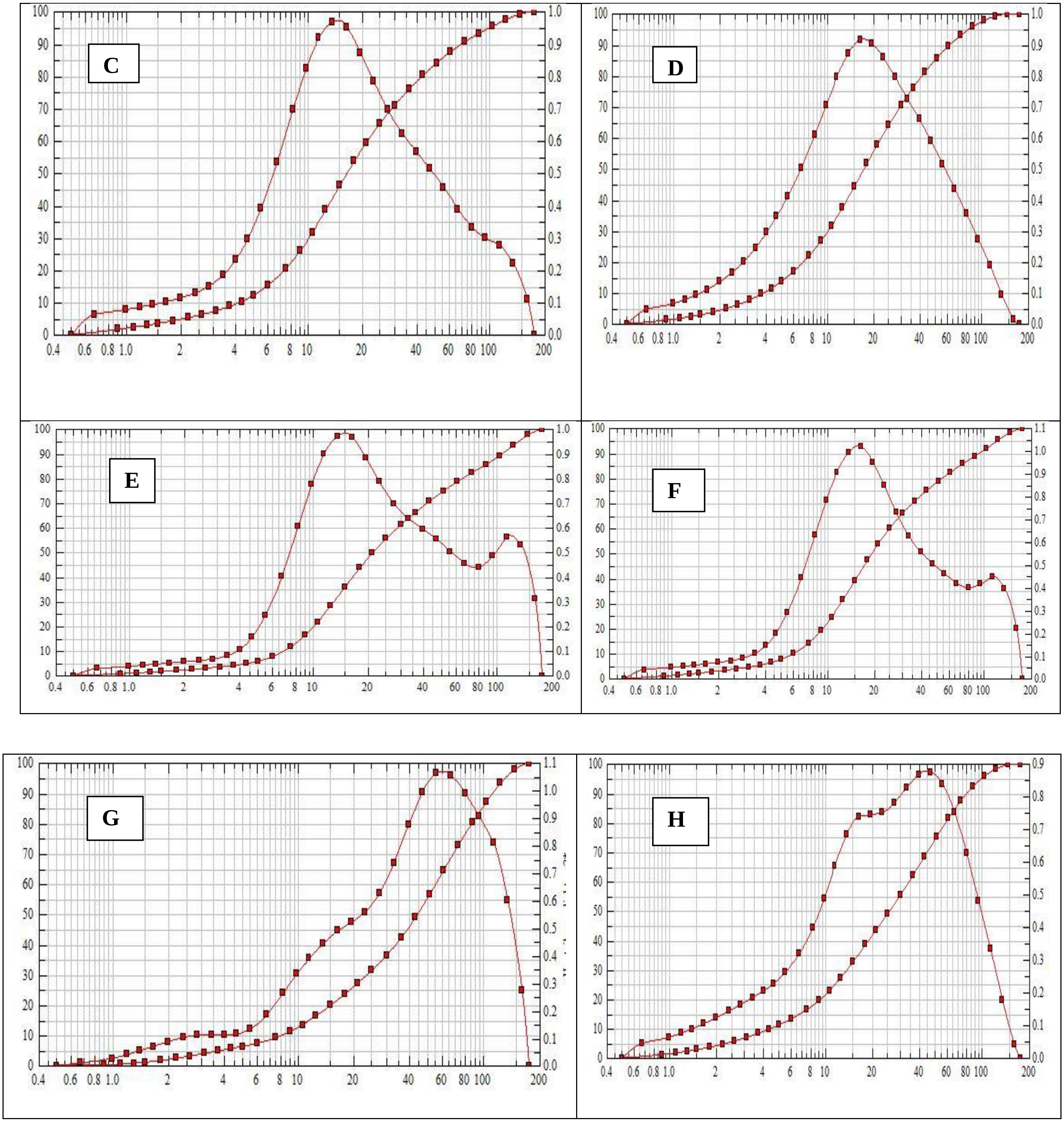
The grain-size distribution of samples was determined with the HELOS/KF-MAGIC (Sympatec, Germany) laser diffraction analyzer. Samples were dispersed in distilled water and ultrasonic bath for 30 sec prior measurements. The measurements were performed at constant temperature (25°C) conditions using the R3 optical module with the measuring range of 0.5-175 μm.

One of the main characteristics of diatomites is their particle-size distribution. The particle size distribution of Abiyata diatomite contains high percentage of clay and silt size particles (>75%) that are passing through 63 μm sieve. From the results it is evident that granulometrically samples strongly differ from each other. Important intervals of the grain size distribution curve are shown below (fig.6.1). Because the organic component and accessible salts tend to bind the diatom skeletons together, determining grain-size categorization of raw diatomite is difficult. Treatment with H_2O_2 and thermic separation of the organic component result in a shift towards tiny grain sizes, thus the results are merely orientative.

I tried to select contrasting samples, but it is very homogeneous and most samples has bimodal distribution with main peaks between 10 and 30 micrometers and with secondary peak around 100 microns (larger linear bioclasts seen on SEM pictures) ADM23-S3 (G) and ADM-26(D) samples are different showing unimodal distribution with main peak between 40 and 70 micrometers.

The smaller average grainsize diatomite is better for the filler-aid purposes. The studied diatomites are very fine that are composed of very fine sand and silt/clay fractions, with 100 % particles passing through 175µm sieve. Results emphasizes that all most all samples of diatomite are very fine (practically clayey). This is confirmed by the investigation of finely disperse particles of the initial diatomite samples using a laser analyzer. However, the predominant particle sizes in the sample are between 10 and 50 µm, as is indicated by the strongest peaks (Fig. 6.1*)*.




C
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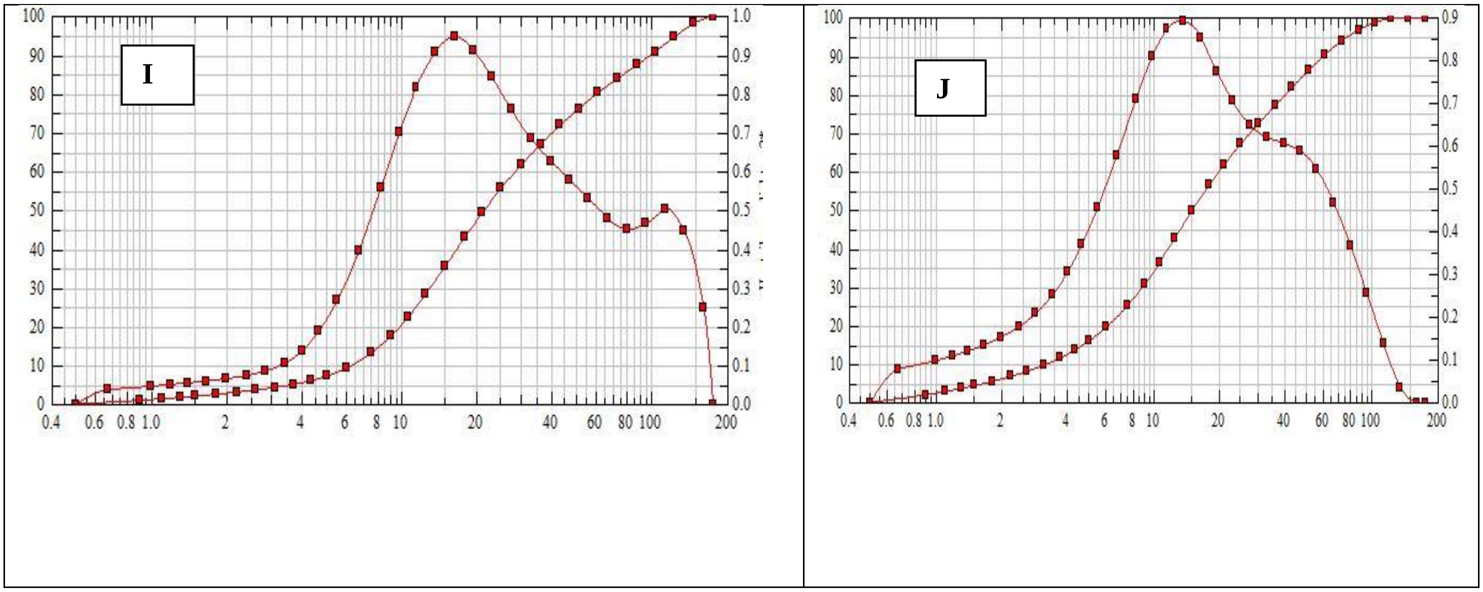

Fig.6.1. Particle size distribution curve of the Abiyata diatomite (x-axis size in um, left y-axis intensity and right y axis distribution frequency).

6.2.2. Colour

The blackness and whiteness of diatomite depend on the presence and absence of impurities. The color of pure diatomite is white or near white, but possible impurities found with it may darken the color. Such impurities may be other aquatic fossils such as sponge residues, sand, clay, volcanic ash, mineral aerosols, calcium carbonate, magnesium carbonate, soluble salts and organic matters.

According to Christidis (2013), color has three characteristics: hue (the primary color that corresponds to a wavelength), saturation (also known as purity or chroma) (the density of color), and value (the brightness, lightness, or whiteness of the color) (the light intensity or visual lightness of a colour). Those descriptive components are usually written in the following order: hue value/chroma, hue value/chroma.

Hue is represented by designating the base spectral color or wavelength (Red, Yellow, Blue, or somewhere in the middle, such as Yellow, Red, etc.) and each hue symbol, color preceded by the digits 0-10. The value of an object's brightness and darkness varies from 0 (black) to 10 (white) (white).

On the Munsell Color Chart, chroma represents the color intensity, saturation, or relative strength of color on a scale of 0 to 8. Diatomite has a range of colors including; white, yellowish gray, light gray, dark gray, and brownish gray. The brown diatomite color is due to organic residues embedded in it (Ivanov & Belyakov, 2008).

Using the procedures described above, five diatomite samples were chosen for color analysis. The color identification was performed at central Ethiopian Geological Survey laboratory. The Munsell Soil Color Chart is used for preliminary color evaluation. The Munsell color chart was compared to a powder of diatomite samples mixed with distilled water. The following colors have been identified as a result of this. Munsell Color diagram names for samples ADM15-S1 and ADM14-S3 are hue 2.5 year Pale yellow 7/4 and 7/3, respectively, whereas ADM4-S1 is hue 10 yr light gray 7/2 and hue 5 yr pink 8/3.

For clay minerals used in the filler business, color is one of the most essential criteria to consider (Murray, 2006). It is measured across the visible spectrum, which is around 400 to 700nm. Because of the existence of organic matter, redox conditions that are influenced by moisture, and local environmental variables, the color of soil can change.

In the manufacture of white pigment, paper, and ceramics, whiteness is a key parameter. However, some industries do not have a crucial color criterion. For example white color is less significance for the manufacturing of refractories and diatomite with a bad color is also used in the rubber sector (MNDR, 1989). The majority of Abiyata diatomite has a pale yellowish color and may be utilized in most industrial applications that do not need precise beneficiations.

6.2.3. Bulk density and specific gravity

Generally, loose, porous and those rich in organic matter soils have lower bulk density. Sandy soils have relatively high bulk density than silt and clay soils. Since its total pore space in sands is less than that of silt or clay soils. Finer-textured soils, such as silt and clay loams, that have good structure have higher pore space and lower bulk density compared to sandy soils.

The bulk density of clay minerals plays an important role in its economic value when fired (as a refractory, filler, coater, absorbent, etc.). Determination of bulk density also afforded a simple means of rapidly assessing the relative purity of the diatomites. Theoretically "pure" diatomites will have a much lower bulk density than those which contain a higher proportion of mineral impurities. Complex diatom skeletons are composed of low density amorphous silica and therefore have a high void volume when packed. Crystalline minerals are relatively dense and form solid particles with simple shapes which have a high packing density. The relationship between bulk density and diatomite is, however, complicated by the influence of particle-size distribution.

Bulk density typically increases with depth since subsurface layers have reduced organic matter, aggregation, and root penetration compared to surface layers. Subsurface layers are also subject to the compacting by the weight of the soil above them and decrease its porosity. The wetting and drying of diatomite has also effect on the bulk density of diatomite in the area as we have seen some difference from laboratory results.

In this study bulk density was calculated by measurement of the volume occupied by a known weight of diatomite following a controlled compaction procedure.

Measuring the bulk density of diatomite samples are essential to determine the specific field of applications of the deposit. Some industries such as cement and insulation brick industries are needed light diatomite while other industries may use heavy diatomite.

6.3. Possible Fields of Applications and development opportunities

Diatomite is a multifunctional industrial mineral, having commercial interest in the food, agricultural and the construction sectors and also in environmental applications. It is one of the natural raw materials required by contemporary technology and they have a wide range of applications, including filtering, filling, and insulating materials, as well as structural materials. The most common application of high-quality diatomite is as a filtration medium because of their honeycomb structure. Because naturally occurring fossilized remnants of diatoms have intrinsic filtering properties. The outstanding physical and chemical properties of diatomite are the reasons for its long use in commercial applications. Beside that diatomite has been used as building materials, filtration media, soil additives, abrasives and for controlling of insects and parasites. Nowadays diatomite is produced on a large-scale with a number of commercial grades for different applications.

The commercial value of diatomite is primarily determined by its distinctive microscopic structure, as well as its chemical inertness, which is determined by the diatomite's silica content. The results of the completed laboratory investigations (grain size, density, chemical and mineralogical composition) enable a broad and adequate assessment of the quality. Diatomite has been the workhorse of food and beverage production for over a century. Almost every grocery store aisle includes a product that has been filtered with diatomite. Diatomites derived from pure pennat and coarse diatom genus and species are recommended for filtering applications (Uygun, 2001).

Most industrial applications require further treatments and modifications of diatomite but certain industries are used raw diatomite without any beneficiation. Frequently, the organic material and other contaminants need to be removed via suitable cleaning procedures to prepare the frustules for some applications and also for further surface modifications.

Processed diatomite has a unique particle structure and chemical stability that makes it ideal for situations where no other type of silica may be used. The usage as a filter assist is the most common of these uses, accounting for more than half of its present consumption. It is actively exploited and used as a raw material for filtration of fluids, pesticides, thermal treatment, paper and rubber filling, natural water purification, and other applications due to its unique diatom structure, low bulk density, high absorptive capacity, high surface area, and relatively low abrasion.

The factors that affect the ultimate properties of processed diatomite products are complex and interrelated; they include the fundamental composition and nature of the diatomite crude ore as well as each of the handling and processing steps that follow mining. Thus, the quality of mill and kiln production can vary, and the implementation of quality and process control procedures is required to ensure that uniform products of acceptable quality are produced.

High filtering rates are possible with coarse particles with a consistent particle shape, but fine contaminants will remain in the filtrate. Christensen et al., 2001; El-Shafey et al., 2004 found that diatomaceous earths commonly contain a mixture of substantially undamaged frustules and a fraction of shattered frustules. Despite the fact that there are thousands of species of diatoms, saltwater diatoms are often favored as a source of filter assist materials since the main contaminant in saltwater diatom deposits is sand or grit, which is easily removed. Clay, on the other hand, is a major contaminant in fresh water deposits that has proved difficult and expensive to remove. Furthermore, the great variety of particle forms found in marine diatoms has been thought to provide the most efficient filter media (Breese, 1994).

Depending on sedimentation conditions and age, diatomites contain distinct rock-forming diatom compositions, mineral and organic impurities, and therefore different chemical and physicomechanical properties and application sectors. Diatomite can be employed as a "pre-coat" or a "body feed" in a filtering process, depending on the nature of the material to be filtered. For optimal performance, the shape and size of the filter aid particles are important considerations. Purity, whiteness, fine grain structure, high porosity, lightness (weight), chemical resistance, capacity to insulate heat, sound, and electricity, and high absorption characteristics are required in diatomites used as filler material, and should include a minimum of 70-80 percent SiO2 (Mete,1982). Furthermore, the economic value of a certain diatomite bed can be predicted based on those components' ratios, thus determine the possible costs for mining and processing to get the final product with a silica content higher than 80%, suitable for applications. The more silica present in the diatomite ore, the higher is its economic value.

Because most industrial minerals are consumed in bulk, their tonnage can be considered as one of the main factors that could prevent a resource from being converted into a reserve. Depending on the present information the tonnage of Abiyata diatomite is sufficient for its use in industrial applications requiring bulk amount. Thus, from tonnage point of view the major markets could be those industries that require large amount diatomite. These industries are mainly filter, filler (in rubber, paper, paint and plastic), glass and pharmaceuticals.

Taking into considerations all limitations on the remaining physical property tests and required beneficiation processes, some possible fields of applications could be recommended. In Abiyata diatomite “modifying factors” (see Fig. 7.4) that are related to mining, processing, environmental and infrastructure can be considered as an opportunity to develop the resource. It is near to main asphalt road from Addis Ababa – shashemene and can be accessed by gravel road that runs from Negele Arsi town to the deposit site.

As discussed before, diatomite has been used for a long time as building materials, thermal insulators, and abrasives. During the last centuries, the true nature of the diatomite has been revealed leading to a large scale production that continuously increased over time.

The fineness of particle sizes and the acceptable ranges of mineralogical and geochemical compositions make Abiyata diatomite useful to various industries. But its value as a filter media would probably be low due to the preponderance of small size diatoms as it has been determined by grain size analysis.

Because of the impurities and somewhat broken composition this material should be satisfactory for normal uses except filter media. It should be fair for filler, absorbent and entirely satisfactory for lightweight aggregates due to its low bulk density. Because of its high content of silica, this material is particularly suitable for lime-silicate insulation powders.

Moreover, the skeletal of diatomite (diatom secretion), microscopically viewed, have quite complex structure with numerous fine microscopic pores, cavities and channels and therefore, well proprietor a large specific surface area and high adsorption capacity.

Table 6.1 Comparison on chemical composition of diatomite with different deposits in the world

Sample	SiO2	Al2O3	Fe2O3	TiO2	Na2O	K2O	CaO	MgO	LOI	Reference
China	82.95	5.75	1.41	0.69	0.06	0.06	0.24	0.21	7.93	*2
Turkey	76.5	7.25	3.85	0.5	0.45	0.85	-	-	0.43	*2
Egypt	83.6	4.24	1.07	-	-	-	6.17	-	4.86	*2
Algeria	72.1	5.3	3.8	0.37	0.65	0.54	7.2	2.6	7.44	*2
Jordan	72.5	11.42	5.81	-	7.21	0.69	1.48	0.25	0.64	*2
Mexico	70.38	13.52	3.37	-	0.17	0.3	0.66	0.42	11.18	*2
Morocco	72	7.3	4.3	-	1.8	1.2	10	1	2.4	*1
Hungary	77.68	4.14	3.23	-	0.12	0.39	1.09	1.98	11.23	*1
Romania	75	9.8	3.85	-	0.5	1.34	0.7	1.98	6.91	*1
Ethiopia	79.6	3.49	1.1	0.17	1.52	1.107	0.674	0.34	13.7	This work

***1**: Diatomites referenced in Stamatakis et al., 2003

***2**: Diatomites referenced in Angela et al., 2012

Comparing the results with different diatomites from Hungary, Romania (Stamatakis et al., 2003) and China, Turkey, Egypt, Morocco, Jordan, Mexico and Algeria (Angela et al., 2012) it’s verified that there aren`t a big differences, but the SiO_2 percentage is a quite higher in our samples than some deposits meaning that these samples are more pure. In this case, it is important because the final application of the diatomite will be like an additive in construction materials.

Due to its sufficient physical and chemical properties this material should also be suitable for use as light-weight mineral filler in the powder form after general refining processes. The small grain size and the friability of diatomaceous rocks contribute to the high specific area of the respective blended cements, which in turn is responsible for the drastic increase of the water demand. The material of this deposit should also be suitable as filler provided that it is calcined with the addition of small amount of an alkaline flux. The pH values of Abiyata diatomite deposit ranges from 9.92-11.2. It is near to alkaline pH value. The pH value of Abiyata deposit is almost similar with the ideal lacustrine deposit diatomite pH value. Since it is not acidic it is also needs safety in easily reactive areas.

Processed diatomite possesses an unusual particulate structure and chemical stability that lends itself to applications not filled by any other form of silica. Foremost among these applications is its use as a filter aid, which accounts for over half of its current consumption.

The cost to process some medium-grade lacustrine diatomites, suitable for such lower-end uses as absorbents and fertilizer, can be prohibitive at a loss on ignition as high as 20 weight percent (Breese, 1994) because of the high energy required to volatilize the water and organic matter.

CHAPTER SEVEN

7. RESULT AND DISCUSSION

7.1. Genesis of Abiyata Diatomite Deposit

In the sediments of lakes and other aquatic environments, many forms of biogenic remnants accumulate, ranging from siliceous algae to carbonate precipitates. Diatoms are a type of unicellular algae that form a siliceous test or frustule. They are an ecologically and bio geochemically significant group of organisms in aquatic settings, and they are frequently preserved in lake or marine sediments. The fossilized remnants of diatoms can produce diatomite when they collect in high quantities in sediments. Diatomite may originate in freshwater and marine environment where a large population of diatoms lives and their remains accumulate (Boggs, 2009).

Massive accumulations of fossil diatom frustules have been observed in multiple lakes situated in silica-rich environments, especially in volcanic and hydrothermally active areas. In these settings, the high dissolved silicon concentrations promote the growth of diatoms (Wallace, 2003). However, high diatom concentrations in sediment also have been observed in lakes with no volcanic or hydrothermal influence. Lakes of Northern Sweden (Frings et al., 2014) and Lough Neagh, Ireland (Plunkett et al., 2004) are the best examples of it. High biogenic silica accumulations were occurred in oceanic environment such as equatorial Pacific Ocean. Such silica accumulation were got from diatoms grow by feeding continental siliceous dust and nutrients brought by upwelling. Similarly, cold-water regions, such as the productive Antarctic convergence zones have sufficient nutrient, dissolved silicon and diatom-rich sediments (Flower et al., 2013).

The prerequisite for a large number of these microorganisms in the environment is a photic zone rich in nutrients. Except in the warmest and most hypersaline waters, diatoms may be found in all waterways. They are common in marine and freshwater phytoplankton and phytobenthos, regardless of latitude (Hustedt, 1930; Pentecost, 1984). Taliaferro (1933) was the first person to classify diatomite deposits. The author classified it into four types based on the genesis of the deposit. Those include, Ocean diatomite sediments, Marsh diatomite sediments, Pleistocene interglacial diatomaceous lake sediments, and lacustrine and marine diatomite sediments connected to volcanism. The presence of diatoms in an unknown deposit indicates that it was formed in either one of two environments. As a result, it's not surprising that one of the most important criteria for deposit categorization is whether the deposit is marine or freshwater origin. Some researchers have been added to the previously stated settings, whether the sediments are formed a contemporary lake, marsh, or bog (Durham, 1973).

The availability of nutrients has a great influence on the evolution, diversification, and increased productivity of both marine and nonmarine diatoms (Falkowski et al., 2004; Kidder et al., 2005). This may also have been contributed to the turnover of temperate non-marine planktonic diatoms near the middle/late Miocene boundary. The major nutrients necessary for diatom production are phosphate, nitrate and silica (Round et al., 1990). Among these, silica may have been especially important because its availability has varied greatly.

Conger (1942) was proposed that diatomaceous accumulation requires favorable circumstances for diatom development and reduction in the accumulation of other sedimentary components that would dilute the concentration of diatom siliceous tests. Many environmental variables influence diatom development, including dissolved silicon availability, phosphate and nitrogen availability, pH, salinity, and light (Battarbee et al., 2002). Temperature and pH affect diatom preservation. Biogenic silica dissolves more quickly when pH (>8) and temperature rise (Alexander et al., 1954).

During the Miocene, prolific volcanism provided nutrients derived from the chemical breakdown of silicic ash-falls to lacustrine settings along with producing lava flows. Those products were blocked rivers and streams creating water bodies later variably infilled by continued eruptive activity (Wallace, 2003). Theses volcanic ash may result in algal blooming and floristic alteration (Owen, 2002). Additionally, volcanic ash may supply phosphorus for diatoms (Kociolek, 1989).

Herbert (1968) was focused on the link between diatomite accumulations and small, basalt-lava obstructed, shallow lacustrine systems with topographically depressed landscapes or localized drainage. He also identified diatomite associated with earlier lava flows or near the foot of important volcanic sequences at early stages of eruptive activity. Interestingly many shallow freshwater diatom deposits are closely associated with geological formation rich in abundant dissolved silica for diatom growth. Hence, locations where these diatomites have formed are often associated with characteristic geological formations of basalts, tephra, and other volcanic rocks that are rich in silica. The common association of lacustrine diatomites with volcanic rocks may simply reflect excellent preserving capacity because of increased resistance to erosion and the slowing of dissolution of biogenic opaline silica (Barron, 1987). Even so, the role of volcanic ash as an important source of silica but its source for lake diatoms is undoubted.

The above geological formation is mainly found in the rift areas. Therefore, the Main Ethiopian Rift is the most suitable site for the formation of fresh water diatomite deposits due to its widespread silicic volcanism and lacustrine basins. Dissolved silica is the mandatory item for the diatom life cycle to flourish. Large diatomite deposits need abundant dissolved silica. Therefore, rift volcanism, which is linked to sediment supply and basin development, ground water chemistry and hydrothermal activity, caldera collapse, and the formation of a lacustrine basin, may create an ideal environment for diatomite production in the area.

The presence of high levels of dissolved silica and nutrients in lake water creates circumstances that encourage fast development and accumulation of diatomaceous oozes, which compress and dewater to produce diatomite. Volcanism have been played a primarily role in supplying source materials that were easily eroded and carried into the lake. The presence of several pure tuff bands suggests that ash fell directly into the lake water. In the case of Abiyata this activity is evidenced by the occurrence of large masses of pyro-clastic materials and numerous tuff and pumice intercalated diatomite deposit as seen from the river section.

Alteration of volcanic sediments provided the main source of nutrients for diatom growth (Holmes et al., 1989). This occurred within a global context where early Miocene upsurges in grass-dominated ecosystems provided vast quantities of such nutrients as silica and phosphorous that spurred world-wide expansion of diatomite growth associated with continental lakes (Kidder & Gierlowski-Kordesch. 2005). Therefore the diatomite deposit of the area is mainly associated with the alteration of such volcanic rocks and pyroclastic ash. Because diatom frustules (the diatoms' retained amorphous cell walls) are entirely made of silica, the diatoms require dissolved silica in the water to thrive. The diatomite deposits in Abiyata required a lot of silica. The presence of high alkalinity enhances the dissolution of biogenic silica. The laboratory test result of Abiyata diatomite samples has an alkaline PH range of (9.92-11.00). Therefore, such environment facilitates dissolution of the silicon and water enriched by silicon, which acts useful for the development of the diatomite. Thus, dissolution of diatoms in the upper parts of intervals indicates repeated shifts toward greater alkalinity and lower lake levels, which were likely driven by enhanced evaporation and/or decreased freshwater input to the lake associated with increased aridity.

Micropalaeontological studies of diatom taxa can reveal whether a deposit was formed in a freshwater, brackish or marine environment and whether deposition occurred in deep or shallow water. According to Inglethorpe (1993), elliptical (pennate), mobile diatoms are often found interbedded with waterlain pyroclastics, fine sands, silts, clays, and peat in freshwater fluvial, lacustrine, and paludal diatomaceous deposits. This form of economic diatomite is sometimes found alongside bentonites, zeolites, and pumice. Marine diatomite deposits, on the other hand, are found in the ocean. The diatom photomicrographs of SEM data from Abiyata diatomite deposit reveal the presence of abundant elliptical and elongated diatoms. Benthic species such as Staurosirella pinnata, Staurosira construens, Pseudostaurosira brevistriata and Epithemia sorex are dominated the Abiyata diatomite deposit (Fig. 5.2 A-F). However, the SEM result of Abiyata diatomite indicates the presence of few planktonic species. The presence of such abundant benthic species, epiphytic taxa, and minimal planktonic components imply a shallow, alkaline mesotrophic freshwater lacustrine environment (Zalat, 2000).

The XRD analysis result of Abiyata diatomite samples indicates the presence of zeolite minerals like clinoaptilolite, mordenite, warkiarite and alterd pyroclastic minerals like albite and illite. Therefore the presence of such zeolite and pyroclastic minerals is an evidence for fresh water lacustrine diatomite genesis.

Despite the fact that lacustrine sediments are complex mixes of components, a number of investigations can be performed to determine their geochemical origins (Smol, 2002). In addition to Micropalaeontological analyses a number of chemical index design characteristics were used to reconstruct the sedimentation conditions. For example Ti to Al ratio has been used as an indicator of sediment provenance and degree of sediment alteration (Minyuk et al., 2014; Young and Nesbitt, 1998). Young and Nesbitt (1998) suggest that sediments derived from slightly to moderately altered source material have chemical index of alteration (CIA <80). Here, strong chemical alteration may mobilize aluminum into lower sections of a source material profile, causing to increase Ti/Al ratio in altered sediments. In addition to that, the concentration of Al and Ti are used to determine the origin of the deposit. Both Al and Ti are immobile in most sedimentary environment and there are enriched in sedimentary formations (Oksuz, 2011 and reference there in). Ti is highly immobile in hydrothermal solutions and is indicative of clastic input (Shah and Khan, 1999; Sasmaz et al., 2013 as cited in Kahrezehi et al., 2015). Their concentration could tell us whether the source silica is biogenic, detrital or hydrothermal during mineralization. The average concentration of Al and Ti in Abiyata diatomite deposit is low, 3.49 % and 0.17% respectively. Thus, clastic (detrital) contribution during mineralization seems minimal.

Adachi et al. (1986); employed the Al-Fe-Mn triangulation approach to assess whether siliceous minerals are hydrothermal or biogenic in origin. Normal terrigenous clastic deposits, hydrothermal silicon and biogenic-silicon under unusual circumstances are the two types of silicon sources. These are hydrothermal and non-hydrothermal. The hydrothermal origin of silica is rich in Iron (Fe), while non hydrothermal origin is rich in aluminum (A). The ternary diagram on (Fig--) indicates that all of the samples are failed on non-hydrothermal origin.

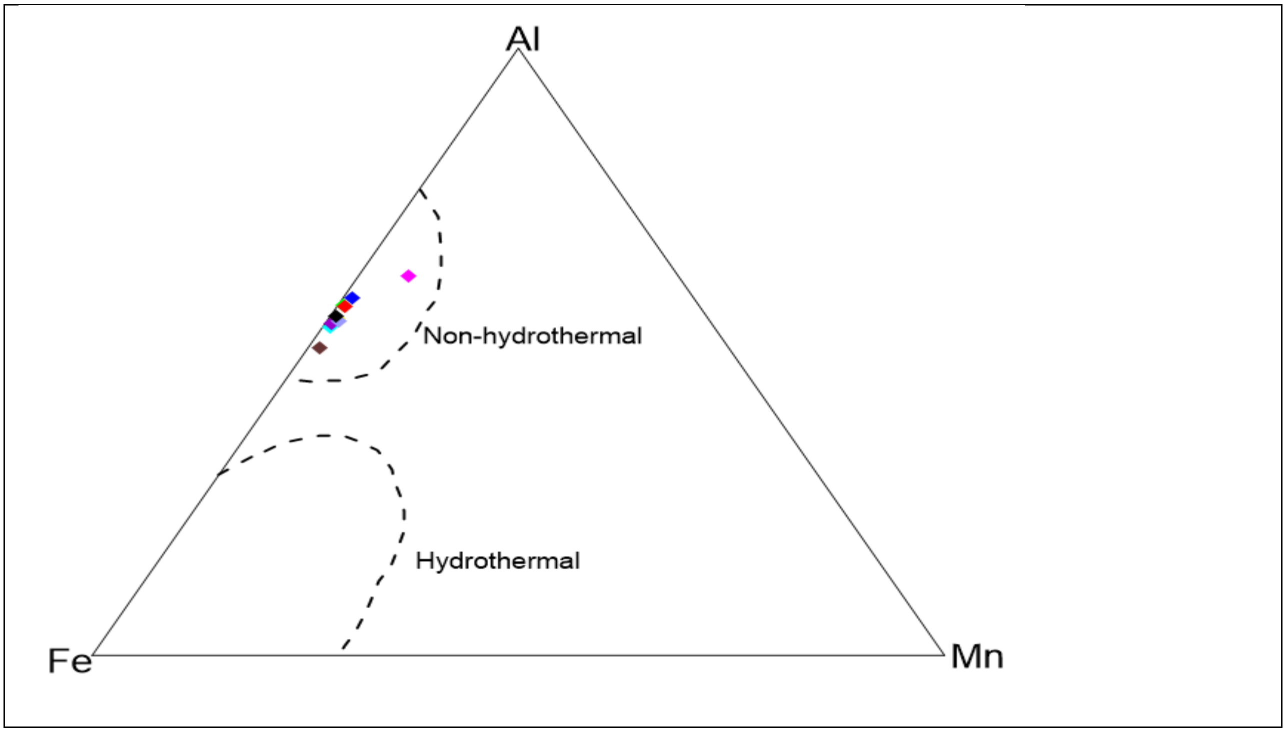

Fig.7.1. Ternary diagram used to show the origin of silica deposit after (Adachi et al., 1986)

7.2. Grade and Quality of Diatomite

The grade and quality of diatomites are determined from the mineralogical, chemical and physical tests result. Therefore a total of 10 diatomite samples were taken from different section for further laboratory analysis. Beside that field observations can be used to get a rough notion of quality. Color is the most easily recognizable characteristic. The higher a diatomite's brightens is the more appealing its potential as filler. Block density is another feature that is visible in the field. A low block density indicates the absence of contaminating materials such as sand and clay. Block density reflects the diatom type and degree of consolidation. The chemical analysis of the diatomite is useful in a general way to determine the relative purity of the deposit. But it is not an effective criterion for predicting the performance of the material for most applications (Kadey, 1975). High silica content is a good indication that a deposit is pure but does not mean that the deposit is of commercial grade. Properties that can be used to detect the performance of the material for different uses must be determined in a testing laboratory. Properties that must be determined are weight, wet density, screen size, brightness, abrasion, water absorption, filtration flow rate, clarity, porosity, pH, and resistivity. Other specialized tests are needed when a sample is being considered for a specific use. Most of these tests are well known; however, some are proprietary.

Commercial diatomite products are offered in a great variety of grades. Principal factors are the size, shape, overall arrangement and proportions of the various types of frustule. The above factors are affected the filtration rate, product clarity, and absorption capacity of the deposit. In addition to that the contents of silica and the presence of impurities, such as certain minerals and chemicals (especially iron, a major impurity), clay, sand, and organic matter affect the quality and grade of the deposit. Several additional specifications are made for certain applications, such as brightness/whiteness and abrasive hardness. Reduction in the content of free crystalline silica is required by some environmental regulations, particularly for calcined products.

Amorphous silica, a constituent of the diatom frustule, is the main component of diatomite, although variable quantities of other materials (metal oxides, clays, salts (mainly carbonates) and organic matter) may also be present. Chemical precipitation and atmospheric contact, together with the prevailing environmental conditions, are determinant factors in the nature and importance of the impurity content of a deposit (Mendioroz et al., 1989).

The quality of diatomite is also determined from the shape and size of diatom valves, proportion and type of impurities and degree of consolidation and alteration. It is reflected in chemical composition, physical properties, and mineral composition.

The chemical composition of Abiyata diatomite is compared with diatomites from (Turkey, Egypt, Algeria, Jordan, Mexico, Morocco, Suizhou, China, Caldiran lake van basin east Anatolia Turkey) see table 6.1. The SiO_2 percentage of Abiyata diatomite is a quite higher than other deposit. These results suggest that the diatomite deposit of the area is high grade. In this case, it is important because the final application of the diatomite will be like an additive in different industrial materials. The chemical composition of the raw sample from Abiyata diatomite deposit is only slightly below the standards of filter aid quality. The contents of Al_2O_3, Fe_2O_3 and CaO are slightly above the permissible limits. Therefore such deposit needs certain beneficiation to enhance the quality of the deposit.

Low density diatomite is essential for many industrial applications. Therefore, diatomite deposits must be only moderately compacted and free from the effects of diagenesis, chemical alteration or metamorphism. Therefore economic deposits are only found in strata of late Tertiary or Quaternary age where there is no deep burial and metamorphism. Conger (1942) suggested that uplift and exposure under good drainage conditions are important factors for the removal of organic material and formation of pure deposits this is ideal for deep marine diatomite deposits. Generally, the sedimentation conditions, age of diatomites, contain distinct rock-forming diatom compositions, mineral composition, organic impurities, the chemical and physicomechanical properties affect the possible field of application (Demidov and Shelekhova, 2006).

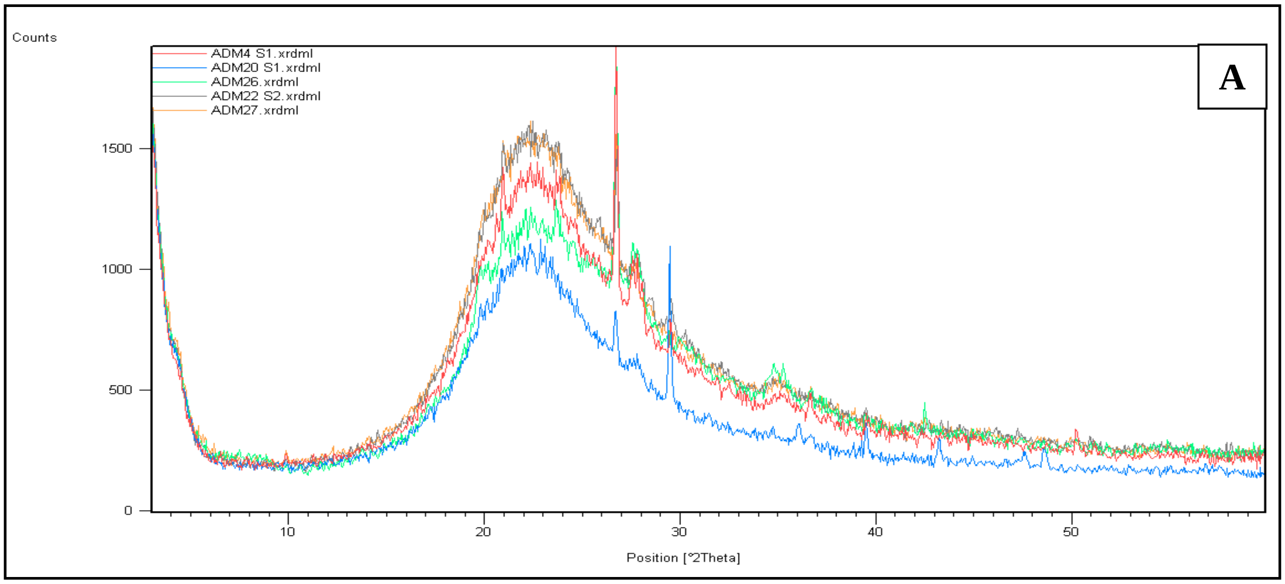

Fig.7.2. XRD result of diatomite with less crystalline minerals.

It can be observed that diagram A (samples ADM4-S1,ADM20-S1,ADM-26, ADM22-S2 and ADM-27)contains about 90% diatomite (broad humped peak) with a negligible amount of impurities i.e. crystalline mineral (sharp peaks in XRD), and diagram B contain around 75% diatoms with 20-25% quartz and other crystalline minerals which are impurities in the case of diatomite.

The composition of bulk sample that was compiled for technological testing from section is also represented by the average of these ten samples. The quality of the diatomite from the sample site (ADM20-S1) is only marginally greater than the deposit's overall quality, as indicated in table 5.1. The average silica concentration of 76.9 % is below the filter aid quality standard of 85 percent. The highest SiO_2 concentration of 84.66% in sample ADM20-S1 from section suggests that there is very minor quality fluctuation.

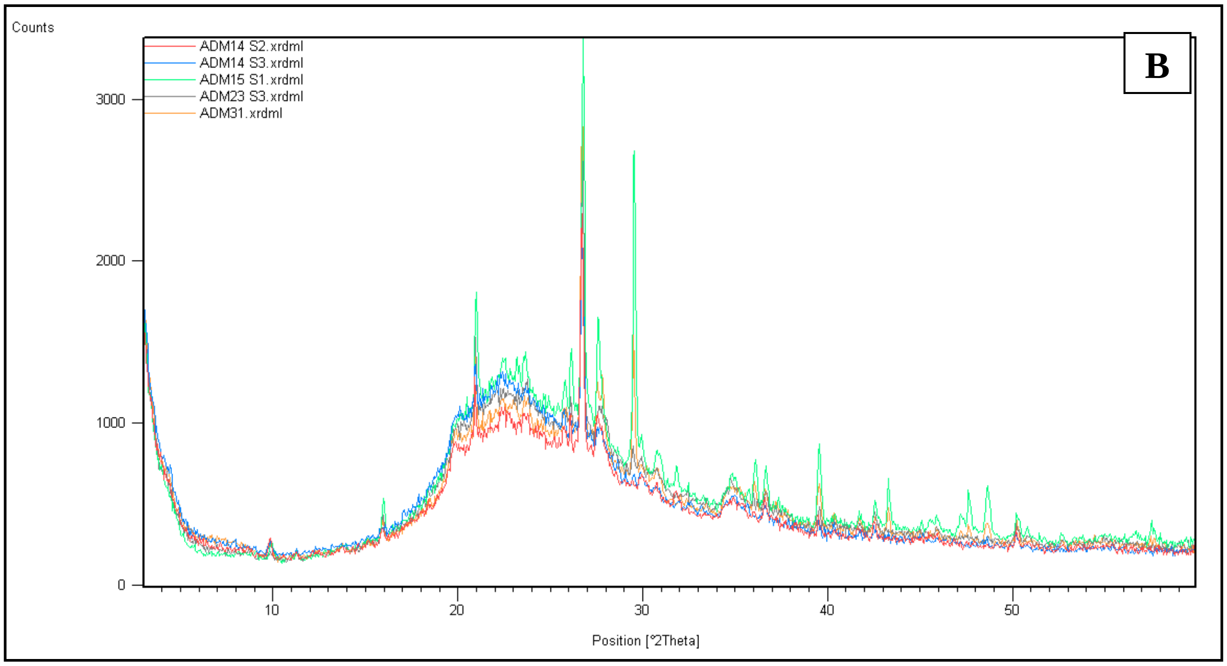

Fig.7.3. XRD result of diatomite with more crystalline minerals.

7.3. Resource Estimation

The criteria for estimating industrial mineral resources are based on (Ehinola et al., 2009) equation. The resource is calculated using the formula, Resource = A x Th x ρ**,** Where 'A' is area calculated from the plan geological map of ore body, 'Th' is average thickness from section logging and 'ρ' is bulk density from the laboratory result.

Based on the results of the detailed geological mapping and results of surveyed sections and gullies it is possible to evaluate the resources of two delineated areas. Resource block I encloses the area bound by the mapped outcrop of the diatomite. Reserve block II follows to the east where the diatomite is covered by pumice gravel and where it was proved by test bore holes from (GSE, 1976).

The surface area was measured from the geological map. The resource potential of the diatomite deposit is estimated conventionally using the geological map of the deposit by field observations and thickness measurements of the exposed deposit. As mentioned in the previous section, the thickness of the deposit is not constant. Thus, the calculation considers this variation and weighted average thickness of the deposit is used. Additionally, the total area is further divided in to two blocks (block 1 and block 2) considering thickness variations.

Tonnage of block 1 = area 1* Thickness * density

= 1111084m^2 * 4. 5 m* 0.42 g/cm^3

= 2,099,948 ton

Tonnage of block 2 = area 2* Thickness * density

= 496424m^2 * 3.8 m * 0.42 g/cm^3

= 792,292 ton

Total tonnage = (2,099,948 + 792,292) ton

=2,892,240 ton

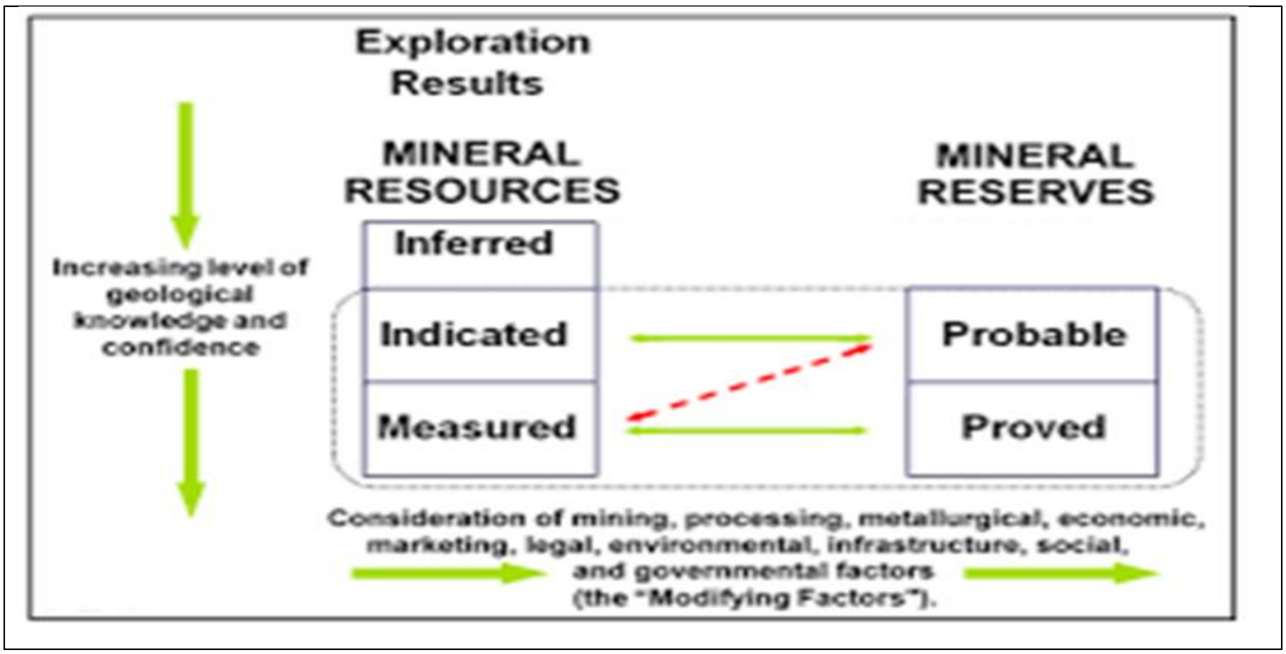

Fig.7.4. *Classification scheme for mineral reserves and resources* (Jorc, 2012)

Considering the level of geological knowledge and confidence this resource is classified under indicated mineral resource based on (Jorc, 2012). This classification is made because the number of data points used to estimate is small and no drilling data at fixed base line and profile line is available to know the lateral and vertical extension of the deposit. It is estimated using only field observations and some laboratory tests. Mineral resources are transformed to ore reserves in accordance with principles such as those diagrammatically presented in (Fig 7.4). The transformation of resource to reserve is depend on a numbers of factors such as degree of geological, geochemical, geophysical and remote sensing studies. Beside that there are also other non-geological factors that control it. Assuming the quality of the ore, free from gangue minerals, and considering the modifying factors listed by the JORC Code, 2012 (Fig.) this resources could be transformed from resource level to reserve level with additional data generated from drilling.

CHAPTER EIGHT

8. CONCLUSION AND RECOMMENDATION

8.1. Conclusion

The goal of this research was to determine the mineralogy, geochemistry, genesis, grade and quality of the Abiyata diatomite deposit and to indicate the possible fields of application. This work is the first to give a comprehensive characterization of Abiyata diatomite. From detail geological, geochemical, mineralogical, paleontological, morphological and textural works of Abiyata diatomite the following conclusions have been given.

- The geological study of the area indicates the presence of lacustrine sediment, pumice, pyroclastic ash, ignimbrites and unwelded tuff. Rhyolitic glass alteration is prevalent in buried tuff deposits as seen in PXRD.
- The Results of PXRD analysis of the diatomite (Fig.5.1 A-J) depicts amorphous behavior of the sample manifested by the appearance of one complex “hump” widely positioned between 15 and 30° (2θ) with the maximum peaking around the 25°. Beside that there are also other crystalline phase’s impurities, which are quartz, cristobalite, feldspar, calcite, illite and zeolite minerals (clinoaptilolite, mordenite, wairakite) and low temperature hydrothermal minerals like adularia.
- The microscopic studies (SEM) and the XRD analysis of the Abiyata diatomite sample showed that the sample was high grade diatomite composed of diatomaceous skeletons (frustules) containing minor amounts of other crystalline minerals (impurities).
- The results obtained from the chemical composition of diatomite, indicate material with high purity, with a dominant presence of SiO_2 (76.9%), while the presence of the remaining oxides are small and best suit for different industrial applications.
- Based on the detailed examination of the sample the crude diatomite represents a weakly diagenesis, soft loose rock with a white to greyish white color; it has a low bulk density (0.42g/cm^3).
- The fossil diatom assemblages are mainly comprised of freshwater, epipelic, mesotrophic, mesosaprophic and alkaline forms. The flora is dominated by benthic species with very low abundance of planktonic species (Figs. 5.2 A-F). These

characteristics of diatom species suggest the freshwater and the genesis of the diatomite is associated with the volcanic activity in the area, and the increase of silica within the water, provided the conditions required for the development of the diatoms.

- Generally, from the genera and species of the deposit, the elevation of the deposit which is found 1, 600 meters above sea level that indicate young in age and the deposit is found in within terrestrial volcanic sequences strengthen Abiyata diatomites are thought to be entirely lacustrine in origin.

- The mineralogical and chemical examinations of diatomite samples indicates the presence of optimum concentration of SiO_2, Al_2O_3, Fe_2O_3 and TiO_2 and best suit for different industrial applications. Beside those physical tests like particle size, pH, bulk density and specific gravity revealed its application in industries like filtering, filler (in paper, rubber, plastic and paint), ceramics, pharmaceuticals and cosmetics.
- Following the conventional approach (area, thickness and bulk density) a total of 2,892,240 tons of Diatomite resource have been estimated under indicated mineral resource category.

8.2. Recommendation

- The diatomite deposit potential of the area is good and applicable for various industrial applications. But it needs further geological, geochemical, geophysical, physical and mineralogical works to assess its uses and resource potential of the area and its surroundings.
- More laboratory testing and evaluation of the diatomite like thermogravimetric analysis (TGA) and the differential thermal analysis (DTA) of diatomite are recommended and other important technological property tests should be carried out to strengthen the industrial applications listed in this work and to further elucidate and recommend other industrial applications.
- Full. Species identification will also be useful in reconstructing the environment of deposit.
- Geophysical method of exploration is recommended to delineate the areal extent of the buried diatomite and to know 3D view of the deposit. A logical follow-up to this work would be electrical-resistivity soundings to determine the depth and the low mean bulk

density (0.42 g/cm3) immediately suggests high-precision gravity surveys as a mapping tool for buried deposits (Durham, 1973) because the expected bulk density of the over laying and under laying lithologies show a large density contrast for the target.

- The resource estimation technique followed for this study is conventional and it considers only estimated thickness from section logging and area from geological map. Thus, further drilling should be carried out to better visualize the deposit in three dimensions and scaling up to a reserve level.

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