Addis Ababa University

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School of earth sciences

Genesis of Magmatic Phosphate Mineralization in Gabbro Intrusive rocks of Bikilal-Ghimbi area, Western Ethiopia

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ADDIS ABABA UNIVERSITY, COLLEGE OF NATURAL SCIENCES, SCHOOL OF EARTH SCIENCES

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Declaration

This thesis is my original work and has not been presented for a degree in any other university, and that all sources of material used for the thesis have been duly acknowledged.

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(Tesfa Lemu)

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Acronyms

AFC-Assimilation fractional crystallization

ANS- Arabian Nubian Shield

Ap- Apatite

BPL -Bone phosphate of lime

BPT-Bateman Phosphate Technologies

DAP- Diammonium phosphate

EKIEP- Ethio-Korea iron exploration project

FSU- Former Soviet Union

GVHD- Graft versus host disease

IFDC- International Fertilizer Development Center

IOA -Iron oxide–apatite

IOCG -Iron oxide copper gold

KM –Kilo meter

M.a.s.l- Meter above sea level

MAP-Mono ammonium phosphate

MB- Mozambique belt

Mt- Million tone

NAC-Neutral ammonium citrate solubility

NW-SE-North west- south east

Plg-Plagioclase

PPL-Plane polarized light

REE-Rare Earth elements

ROM- Run of mine

RP- Rock phosphate

TSP- Triple superphosphate

TPL -Triphosphate of lime

USA-United States of America

XPL-Cross polarized light

Abstract

Western Ethiopia is underlain by proterozoic metamorphic belts that form parts of exposed Arabian Nubian shield. The metamorphic belt consists of high-grade biotite gneisses, low-grade volcanogic sediments and mafic ulteramafic complexes. Bikilal-Ghimbi gabbroic intrusive is an elliptical mafic body that intruded into the metamorphic gneissic body during Neoproterozoic time. It consists of olivine gabbro at its center, hornblende gabbro and hornblendite at its periphery. The olivine gabbros are very fresh and un deformed, while hornblende gabbro and hornblendites show slight weathering and with minor deformational structures. The Bikilal-Ghimbi gabbro intrusive has deserved wide attention due to its ore mineralization. Apatite, magnetite and ilmenite mineralization occurs in all this intrusive lithotypes with varying grades. Apatite occurs in the disseminated, lense and lenticular forms. Two main zones of phosphate mineralization, the upper and lower zones, were identified and delineated entirely based on phosphate (P_2O_5) assay values. The strike length of the upper zone is 1600m, while the strike length of the lower zone is 3000m having a thickness of 60m _200m.The mineable reserve of Soji-Bikilal phosphate deposit is estimated to be 181 million tons, at a grade of 3.5% P2O5.

The major element geochemical shows that despite the difference in olivine and hornblende gabbro, there is no chemical contrast between the lithotypes, except for fluid mobile elements suggesting an origin from the same parental magma. Only the perimeter is affected by moderate metasomatism. An estimation of the parental magma composition by using trace element abundance analysia from fresh clinopyroxene and olivine gabbro bulk rock suggests intraplate-type tholiitic magma. The REE element analysis derived from apatite and host rocks show the same magmatic origin for the ores and silicate host rocks. The source of the magma may be linked to mantle degassing or to basic magmas derived by partial melting of the upper mantle.

The ores were formed during magmatism as immiscible liquids which was separated from strongly differentiated magmas, aided by large volatile and alkali elements content. In this magma chamber, the phosphorous and alkali content probably led to the formation of a Fe–F, CO2–H2O–P–Na dominated immiscible melt which separated from a silica-rich melt. The breakdown of this late immiscible phase has resulted in the formation of magnetite–apatite melt and segregation of dense Fe-Ti-(P) rich melts which settled downward in a silicate crystal mush form net-textured and massive Fe-Ti oxide and phosphate ores as part of the cumulate sequence at this Bikilal-Ghimbi region. The immiscible phases of silicate and oxide- phosphates separation, breakdown, crystallization and Segregation might have occurred for more than two episodes resulting in the formation of different ore zones.

The host rocks might have crystallized and segregated from the silicate rich melt which then invaded by the dense Fe-Ti-(P) rich melts which settled downward into a silicate crystal to crystallize and segregate together. The apatite free lithologies were crystallized during the less saturation of the Fe-Ti-(P) immiscible melt phase.

Chapter 1: Introduction

Mineral resources are important natural assets, and it is the nation’s best interest to stimulate a greater understanding of its indigenous wealth. Information on extent, quality and distribution of potential economic minerals is essential for effective and informed decision, which is critical to meet the objectives of nation’s socio-economic development.

Apatite is a term used to describe a group of phosphate minerals with the chemical composition of $Ca_5(PO_4)_3(OH,F,Cl,Br)$. The primary use of apatite is in the manufacture of fertilizer (DAP) which is crucial input for agriculture. This in turn is important to full fill the growing demand for food crops to feed the growing population of the world. Due to the vital need of phosphorus nutrients, the government of Ethiopia was being forced to import the processed phosphate fertilizers from abroad. Ethiopia is doing not only to import chemical fertilizers but also have a program for any opportunity to assess and to develop indigenous phosphate production. Based on this, a project was initiated to assess and locate local phosphate resources, which could be a raw material for fertilizer production.

To meet the above objective, a detail reconnaissance survey was done to locate phosphate rocks provenance. The reconnaissance survey result indicated Bikilal and Melka Arba igneous phosphate deposits to be promising economic potential . Since then Ethiopian Institute of Geological Surveys (EIGS) undertook feasibility study of the phosphate deposit and associated minerals in the Soji-Bikilal. Exploration activities for apatite were conducted since June 1986 at Soji-Gerjo Bikilal area and a phosphate deposit of 181Mt at a grade of 3.5% P_2O_5 was delineated. This phosphate resource is regarded as low grade and high tonnage deposit. And these resources deserve scientific study to further understand its ore genesis.

1.1 Location and accessibility of Ghimbi-Bikilal Area

Ghimbi-Bikilal Area is situated in Western Ethiopia, Oromia National Regional State, Western Wollega zone, Ghimbi Woreda, 441km west of Addis Ababa. It lies between latitudes $9^{0}3^{'}20^{''}$_$9^{0}21^{'}06^{''}$N and longitudes $35^{0}48^{'}03^{''}$ _$35^{0}55^{'}03^{''}$E. The area is accessible by a four- wheel vehicle drive through the asphalted road of 431km from Addis Ababa to

Ghimbi, although the 130km from Gedo to Nekemte is under asphalt upgrading and the detour is not convenient for traffic flow. From Ghimbi to Bikilal is a fairly good 25km dry weather road. The road is full of gullies and erosion cuts at places and farmers at Sariti divert the water from Sariti River for irrigation use which creates obstacles to vehicle driving. So the road needs clearing and culvert construction for the traditional irrigation canal the farmers have constructed.

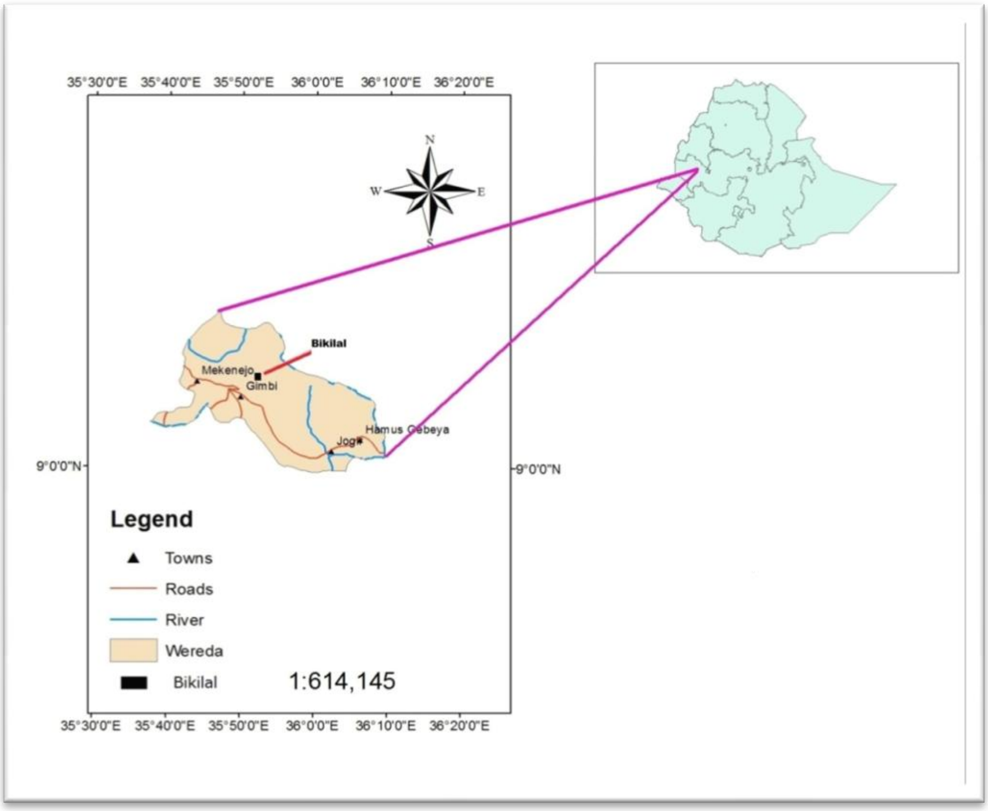

Fig.1.1 ***Location map of the study area***

1.2 Land escape and Topography

The area under study is characterized by rugged topography and mountainous terrain. It constitutes ridges and valleys. Physiographically, it falls on the Western Highland Plateau, the highest elevation is about 2222 meters and the lowest is about 1400 meters m.a.s.l. with local reliefs as high as 500meters.The topography is generally characterized by steeply slopes and rarely gentle and flat.

Distributions of outcrops are irregular and vary from place to place. Most frequently outcrops occur along streambeds characterized by abrupt elevation changes and steep gradient at minor divides and in the upperparts of slopes. Gullies, road cuts, pits and trenches of exploration works are good sites for outcrop exposures. Blocks of substratum (floats) and elluvium usually 1-3 meters thick occasionally reaching 11meters thick cover the greater part of the slopes including the ore zone. In gentle slopes, intense weathering is common such that saprolite is observed in pits and road cuts. Weathering is more intense in the iron ore zone than apatite host rocks. The apatite bearing host rocks are more resistant to weathering as the ore is insoluble in water (Fig1.2).

Fig.1.2 Floats of apatite bearing Hornblede Gabbro (left) and weathered and brecciated top part of massive magnetite bearing Hornblende Gabbro (right)

There are several perennial small springs and streams draining the area with a denderitic pattern. The majority of these streams drain north or eastwards towards the Jejeba river, which in turn flows northwards into the Didesa River. The southwestern part of the study area drains westwards into the Soti River, which also flows northwards into the Didesa. Jejeba and Soti rivers bounded the western and eastern parts of the study area. These rivers are tributaries of Didessa sub-basin of Abay main basin.

1.3 Climate and vegetation

Climatic data was obtained from Ghimbi Meteorological station, located in Ghimbi town. A two year climatic data (2011-2012) was collected and analyzed. Accordingly the mean maximum temperature is 26.5^{0}C (24.2 in July to 29.1^{0}C in March) and mean annual rainfall is 1320.7mm (2.0mm in December and 396.0mm in August). The driest seasons are in December to February, while the highest precipitation occurs during rainy season of June to September.

Three agro-ecological zones characterize the study area: Dega (highland) 20%; Weyena Dega (middle land) 70% and Kola (low land) 10%.

Bikilal lies at the junction of two contrasting avifauna regions, the western Ethiopia low lands and the Western high lands. The Bikilal area is situated between the Didesa low lands to the North and the high lands of Bikilal Mountains at 2222meters. Due to this, within the area there are fauna mixes of high land and low land species. The riverine forest and tall elephant grass bush support a range of species at Bikilal.

The mountain slopes are overgrown by scattered bushes and dense trees at places and elephant grasses. The vegetation cover of the area varies from place to place. Savanna grass, scarce grasses, and long trees with small bushes cover the northern part. The central part is less vegetated and grass covered with long eucalyptus tree and tid, but the southern part, is well vegetated with zigba, tid, eucalyptus tree and small bushes with other varieties.

1.4 Human Activities and Land use

The study area is occupied by villages of Sogi Bikil (Population 1758), Didisa Bikilal (population 1390), Lalisa Bikilal (population 2167), and Garjo Bikilal (population 1,540). The inhabitants of the area are Oromo people, who led their life by crop production and animal breading. The estimated population of the area as of data obtained from Ghimbi Woreda Agricultural Development office is 6,855.

According to the 1997 national census, the rural and urban population of Gimbi Woreda was 112,309 (3892 in urban and 103,631 in rural): 82% of the rural inhabitants are farmers, while 18% are engaged in local and small scale economic activities such as small scale trade, wood work, building construction and the like.

The woreda covers a total of 112,969 hectares of land. Out of these 26,782 hectares is covered by forest, 5,417 ha are covered by grazing land and the rest is covered by crops like coffee, cereal crops etc.

People in the area practice mixed farming, which accounts to 95% of the economic activities of the area. An ox is the integral part of farming systems throughout the woreda and cows produce milk for home consumption and cash income. The people are practicing rain-fed agriculture with small-scale irrigation systems at the stage of beginning.

Most of the lands in the area are cultivated and partly covered by perennial crops such as banana, coffee, avocado and some of it is used for grazing. Land status of the area is suitable for cropping of coffee, sorghum, maize, teff and vegetables. The cropped area covers about 2964 hectares where as the uncropped area is about 2287 hectares. (Data from Ghimbi Woreda agricultural development office)

1.5 Justification of the problem

I came to appreciate the importance of scientific research on the origin and genesis of Bikilal-Ghimbi apatite as the previous works gave attention to mineral exploration, reserve evaluation and beneficiations to economically exploit the resource. However, it is important to consider its magma origin and environment of crystallization to concentrate the apatite as a major phosphate ore which was thought as accessory ones in most igneous rocks.

How apatite mineralization took place within the intrusive igneous rocks of Bikilal area currently needs scientific explanations. The principal goal of this research is therefore to understand the origin and processes that result in concentration of apatite in the intrusive igneous succession in the Bikilal area. The study will compare mineral associations of Bikilal apatite occurrences with that of similar intrusions elsewhere in the world. The modeling of Bikilal apatite origin will contribute to the future detail search works and other prospecting of similar commodities.

1.6 General objective of the study

The genesis model for Ghimbi-Bikilal gabbro intrusive apatite deposit was not studied and none was proposed yet. So the main objective of this work is to propose viable genesis model for the apatite, iron oxide ores associated with Bikila-Ghimbi intrusive gabbro complex.

So this study includes thorough analysis of the origin of apatite and Fe-Ti oxide ores hosted in intrusive rocks and propose the possible genesis of apatite-magnetite-ilmanite mineralization in Bikilal-Ghimbi gabbro intrusive, using petro graphic description, major, trace & rare earth element analysis and propose possible apatite ore genesis model using literature reviews, previously compiled data, and samples that was collected during field work. The petro graphic study is accomplished by thin section analysis under transparent microscopes of apatite and silicates and ilmenite-magnetite ores and their textural relationships with the rock forming minerals is analyzed under reflecting ore microscope. The textural and structural relationships of the ore and gangue minerals will be confirmed by trace element affinity. And the ore genesis modeling will be discussed based on the findings. Besides, it has been intended to establish the geological and geochemical conditions responsible for apatite mineralization.

1.7 Methodology

The study is conducted using knowledge gathered from literature reviews, previous findings, several field sampling and laboratory analyses results, geological mapping and collection and analysis of secondary data. Different books, articles and reports related to this works were referred and relevant ideas and scientific findings were quoted and acknowledged. Samples and data collected during field work were used to prepare the geological maps with modifications of pervious works of the study area. Samples collected were submitted to the Central Laboratory of Geological Survey of Ethiopia for thin and polished section preparations and generation of whole rock geochemical and trace element data. Thin and polished section analysis was done by using transparent and reflecting microscopes of Addis Ababa University, Department of Geology. Graphs, maps and analysis were done by utilizing different software's like arc GIS, Golden surfer, global mapper and petro-graph etc.

1.8 Characteristics of Apatite

Apatite is a term used to describe a group of phosphate minerals with the chemical composition: $Ca_5(PO_4)_3(OH,F,Cl,Br)$. Apatite is an isomorphic hexagonal crystal mineral, which means apatite can exist in many different forms with other minerals as long as the base of apatite calcium (Ca_5) and phosphorus (PO_4) exist together (fig.2.1). As a mineral group, apatite includes hydroxylapatite $Ca_5(PO_4)_3OH$, fluorapatite $Ca_5(PO_4)_3F$, chlorapatite $Ca_5(PO_4)_3Cl$, and bromapatite(Ca_5 $(PO_4)_3Br$). These are the three common forms of apatite that are common in nature and sometimes hard to distinguish from each other. Usually some amounts of both chloride and fluoride are present together**.**

Hydroxyl apatite or hydroxyapatite is so-called due to its hydrogen and oxygen content. It is found in bone mineral and tooth enamel. Fluor apatite, on the other hand, is rich in fluoride ions which are more resistant to acid attack compared to hydroxyl apatite. This can be found in fluoridated water and toothpaste.

Characteristic of apatite mineral is the tolerance of the apatite structure to substitutions. In 1938, McConnell stated that “The structure of apatite seems to be remarkably stable, permitting a number of rather unusual types of substitution and involving a considerable number of ions”. Apatite is able to incorporate half of the elements in the periodic table within its crystal structure. Ca^{2+} is substituted by Na^{+}, K^{+}, Ag^{+}, Mg^{2+}, Sr^{2+}, Ba^{2+}, Cd^{2+}, Mn^{2+}, Zn^{2+}, Bi^{3+}, Sc^{3+}, Y^{3+}, REE^{3+}, U^{4+}, $(PO_4\,)^{3-}$ is substituted by CO_3^{-}, SO_4^{2-}, CrO_4^{2-},F^{3-}, CO^{3-}, OH^{3-}, $AsO^{3-}{}_4$’ VO_4^{3-}, SiO_4^{4-}, F^{-} is substituted by OH^{-}, Cl^{-}, Br^{-}, O^{2-} . Ease of atomic substitution for apatite leaves this mineral open to a wide array of compositions. Substitutions influence many mineral properties, including solubility. For example, F-substitutions will decrease apatite solubility, while CO_3^{2-} substitutions will increase its solubility.

Apatite occurs in crystal forms which may be transparent or translucent. Except for transparent apatite crystals, it is commonly green in color, but also appears as blue, purple, pink, brown, reddish brown, or yellow. Another characteristic which may or may not be present in all apatite crystals is its white streaks which can be noticed only in translucent apatite crystals. The Mohs hardness scale places apatite at 5, that it can just be scratched with a steel knife blade. It is solid but brittle. Apatite has a hexagonal crystal system appearance. The density can range from 3.16 – 3.22. Apatite is a soluble mineral in sulfuric acid, nitrous acid, and hydrochloric acid. It has one poor cleavage on 0001 and fracture is conchoidal and uneven. The luster is vitreous, transparent to translucent with refractive Index of 1.63.

1.9 Nature and Occurrence

Phosphorus occurs in many minerals, of which apatite, $Ca_5(F, Cl, OH)(PO_4)3$, is the most abundant and by far the most important group (Bartels & Gurr 1994).

Table.2.1 Main apatite minerals

Mineral	Description
Collophane	Cryptocrystalline apatite
Francolite	Carbonate fluorapatite with 5% carbonate and 1% fluorine
Dahlite	Carbonate hydroxyapatite with 5% carbonate and 2% hydroxide

Hydroxyl apatite composes 70% of bone material in the human body. Hydroxylapatite is the main mineral that tooth enamel and dentin are made of. Hydroxylapatite in tooth enamel is a very rare form because there are a few missing hydroxides. However these hydroxide ions are replaced by carbonate and acid phosphate. Tooth enamel and dentin are the strongest outer layers of the tooth. Hydroxylapatite also help in bone healing. Bones are organic and inorganic. The organic portion of bone has collagen which is a connective tissue. The inorganic portion of bone is composed of hydroxylapatite.

Fig.2.1: Hexagonal apatite crystal (Credited to © 2001 by Göran Axelsso)

Fluorapatite is a naturally occurring calcium phosphate in the form of hydroxyl apatite. Just like Hydroxylapatite this material also makes up the enamel in teeth. Fluorapatite is a harder material than hydroxyl apatite and also helps in protection against tooth decay. Even though Fluorapatite is a harder material than hydroxylapatite it is more resistant to acids (source: http://www.dpi.nsw.gov.au/minerals/geological/industrial-mineral-opportunities).

1.10 Composition, Structure and Associated Minerals

Apatite is widely distributed in all classes of rocks - igneous, sedimentary and metamorphic. It occurs in some igneous rocks as small prismatic crystals, giving lath-shaped longitudinal sections and hexagonal cross-sections. Apatite commonly forms as prismatic crystals, showing the hexagonal cross section and often terminated by bi-pyramidal faces.

There are two major divisions of natural calcium phosphates; they are (1) Apatite, which has a definite chemical composition; and (2) Rock phosphates, such as phosphorite, phosphatic limestone, guano, and bone beds, which are mixed with considerable amounts of impurities and have no definite chemical composition.

1.11 The Main Parameters of Phosphate Characterization

There are several parameters that are used in characterizing phosphate rocks. Among these parameters are:

- Unit-cell a-dimension (a-value), a crystallographic expression of the composition of the apatite composition. The a-cell dimension is expressed in Angstrom ($1Å=10^{-10}$ m).
- Solubility data based on chemical extraction methods, e.g. neutral ammonium citrate solubility (NAC). PO_4/CO_3 ratio as a measure of carbonate substitution in phosphate minerals.
- Surface area (expressed in $m^2 g^{-1}$), and pore size distribution indicating potential reactivity. The calcium phosphate content of phosphate rock is expressed in different world areas by one of the following terms: These commercial terms are widely used and have the following conversion factors:
  - BPL (bone phosphate of lime)
  - TPL (triphosphate of lime)
  - P_2O_5 (phosphorus pentoxide)
  - P (phosphorus – not commonly used)
  - An illustration of relationship between the above terms is:

- 80 % BPL == 80% TPL == 36.6% P_2O_5 == 16% P. Or
- P_20_5 = 0.4576 x BPL
- BPL = 2.1852 x P_20_5
- P = 0.1997 x BPL

For the manufacture of superphosphate, industries generally prefer rock phosphate containing a minimum of 70% BPL; though up to 63-65% BPL is also being consumed. Presence of iron and alumina should be as low as possible as they unnecessarily consume too much of sulfuric acid.

Chapter 2: Literature Review

2.1 Global History and Characteristics of Apatite

Apatite was first discovered in 1788. It was named after the Greek word apatao which means deception or misleading. This is due to its very close similarity and accidental confusion with other minerals such as peridot, beryl, and olivine. It was found to be present in Mexico, Canada, North America, Germany, Russia, Sweden, Iran, Brazil and South Africa (McConnel, 1973).

Apatite is a term used to describe a group of phosphate minerals with the chemical composition: $Ca_5(PO_4)_3(OH,F,Cl,Br)$. As a mineral group, apatite includes hydroxylapatite, fluorapatite, chlorapatite, and bromapatite. The apatite group is a group of similar isomorphous hexagonal phosphate minerals. Since it can be very hard to distinguish between the individual member minerals, and since they may partially replace each other, a distinction between them is rarely made, and they are simply all called "Apatite" by collectors and dealers. It is distributed in all types of rocks: sedimentary, igneous, and metamorphic rocks.

The generally quoted first commercial production of phosphate rock was in England in 1847 (Cathcart, 1980), and mining was undoubtedly by hand methods. Phosphate mining began in the United States in South Carolina in 1867. Platy phosphate rock beds were mined by hand and later by dredges; sorting was mainly by hand (Shepard, 1880).

Phosphate rock deposits were discovered in North and West Africa in the late 1800s. Exploitation of deposits in Algeria and Tunisia began prior to 1900. Production of phosphate rock began at many of the deposits in the North and West Africa region in the early to mid-20lh century.

The most prevalent phosphate minerals in the rocks are species of apatite, i.e. calcium phosphate with quartz, calcite, dolomite, clay and iron oxide as gangue components. Igneous phosphate is often associated with carbonatites and/or alkalic intrusions and is generally low in grade i.e. low concentration of phosphate. The abundance ratio of igneous versus sedimentary rock is 13 to 87. Some 80% of the world phosphate production is derived from sedimentary phosphate deposits.

More than 75% of the global commercially exploited phosphate rock is surface mined, which can take many forms from manual methods to the employment of highly mechanized technologies, with the remainder recovered by underground mining.

2.2 Igneous Apatite Deposits of the world

Apatite ore has diverse families of ore deposits or mineral associations. These are magnetite (hematite), apatite, ilmenite, copper, gold and rare earth elements. The mineralization and occurrences of apatite–iron deposits in maffic ultrabasic intrusive rocks are related in mineral assemblages, host rocks, geological time of emplacement and tectonic environments worldwide. Among the most common World igneous apatite deposits, the following three deposits show some similarities with that of Bikilal Sodji deposit and are shortly described.

1. Kovdor (Russia)

Various apatite-rich rocks occur within the Kovdor alkalic and ultrabasic igneous complex, which is situated in the western part of the Kola Peninsula. The complex has a resource of about 50 percent magnetite and 16 percent apatite (6.6% P_2O_5). Reserves of iron ore have been estimated at about 708 and that of apatite is 113 million metric tons.

The Kovdor massif (Rimskaya-Korsakova, 1964; Ternovoy et al., 1976), is Caledonian, probably Middle Devonian in age. It has a concentrically zoned structure, with an outer belt chiefly of ijolite, an inner semicircular body of melilitic rocks including turjaite, and an ultrabasic core composed of pyroxenites, pyroxene-olivine-rich rocks, and olivinites. These ultrabasic rocks closely resemble the pyroxenites and phoscorites of the Palabora Complex in South Africa. Later intrusive phases consist of apatite-forsterite rocks and magnetite ores (Golovanov et al., 1968).

Apatite-forsterite rocks are concentrated in the southwestern part of the Kovdor Complex at the western end of Kovdoro Lake where, together with the magnetite ores which they enclose, they form an "ore complex". This area is characterized by steeply dipping vertical veins and lenses of variable thickness chiefly in ijolite and pyroxenite and composed essentially of variable amounts of apatite, forsterite, magnetite, calcite, and phlogopite.

2. Kiirunavaara (Sweden)

The iron ores in northern Sweden (such as Kiirunavaara and Malmberget are composed of the assemblage magnetite-hematite-apatite (Frietsch, 1974, 1978, 1980). The ore is characterized by a F apatite with small amounts of CI and OH. The content of P varies from low to high (< 2% P) and the contents of Ti (in sphene or occasionally ilmenite) and S (mostly in pyrite) are low (<0.1%). The ore forms tabular bodies with associated breccias and behaves as an intrusive rock.

According to Cliff et al. (1990) the Kiirunavaara ore was emplaced in a period between 1.88 and 1.90 Ga. U / Pb dating of titanite indicates that the Luossavaara ore has an age of 1.89 Ga (Romer et al., 1994). The ore formation is related to fault lines in a lifting environment, close to the border of the Archean basement (Frietsch1984, 1991). The ore originated by magmatic differentiation as a late phase in the volcanic cycle forming sub-surface injections or surface flows. While the main part of the magma crystallized, the ore remained in solution and was injected as a late, separate phase (Geijer, 1931; Frietsch, 1984; Geijer and Z.dman, 1974).

4. Posht e Badam Block (Iran)

Origin of the iron-apatite deposits of Posht-e-Badam Block Central Iran had been considered as a result of liquid immiscibility and injection or extrusion of ore magmas originated from alkaline/carbonatitic magmas, for many years (Samani, 1988; Förster and Jafarzadeh, 1994; Darvish Zadeh et al., 1996; Daliran and Stosch, 2005).

The field relationships and the overall geological evidence at the Posht-e-Badam Block iron apatite deposits indicate that the rhyolitic to syenitic and gabbroic host rocks are the products of intra-cratonic plutonism and a tensional geological setting (rifting) were roughly synchronous and coeval with mineralization.

The iron-apatite ores of Posht-e-Badam Block were probably formed by magmatic differentiation of an alkaline magma rich in Fe and incompatible elements such as P, REE,Th, U, F and Cl that was derived by partial melting of upper mantle.

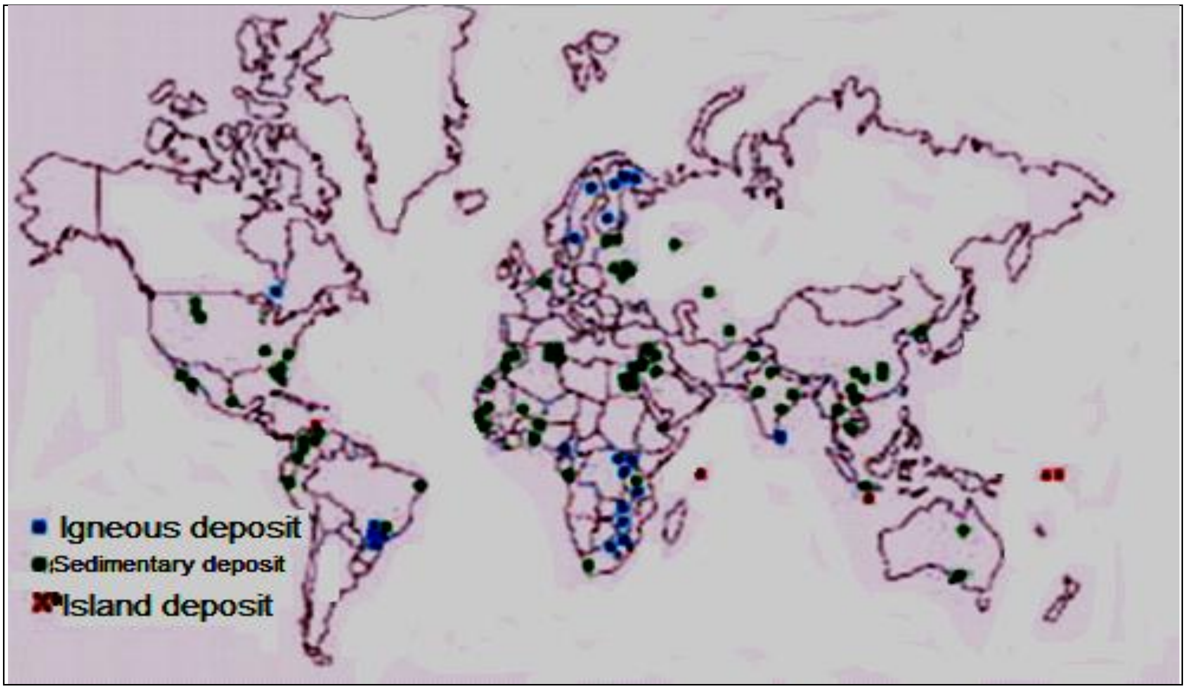

Fig.2.2 Potential economic phosphate deposits of the world, after S.J. VanKauwenbergh, IFDC, 2009)

Table 2.2 Summary of world igneous apatites occurrences after Consult 4, International Bikilal Phosphate Project

S/N	Deposit name	Country	Geological formation	Grade in % P_2O_5	Reserve in Mt
1	Soij Bikilal	Ethiopia	Basic layered gabbro	3.5	181
2	Kiirunavaara:	Sweden	Iron-Phosphate	2.22	-
3	Kovidor	Russia	Apatite Forsterite	4.75	708
4	Posht e Badam Blok	Iran	Mafic	6.2	824

2.3 Importance of igneous phosphate (apatite) deposits

Some soil studies showed that most of Ethiopia’s soils are in deficient of important plant nutrients such as phosphorus, nitrogen and potassium and need applications of chemical fertilizers to increase the fertility of the soils. The low fertility of the soil, which is the main agricultural production constraint, is a problem for existing and future generations of this country whose economy is largely dependent on agriculture. It is also one of the government's challenges to achieve the planned Growth and Transformation plan of agricultural sector which is aimed at boosting agricultural production at the end of the plan period which will be impractical without ample use of fertilizers. Due to the vital need of phosphorus nutrients, the government is forced to import the processed phosphate fertilizers. The government of Ethiopia is doing not only to import chemical fertilizers but also have a program for any opportunity to assess and develop indigenous phosphate resources. One of the efforts so far done is to explore phosphate potentials at Bikilal and Melka Arba igneous phosphate deposits that have a promising economic potential raw material for phosphorus based chemical fertilizer production in Ethiopia.

Based on this, a project was initiated to assess and locate local phosphate resources, which could be a raw material for fertilizer production. Investigations were made on some of the potential resources of phosphate, namely, the Mesozoic-Cenozoic rocks, the Precambrian meta-sedimentary sequences and the intrusive rocks of alkaline basic-ultrabasic rocks from 1984-1986. Consequently, the Bikilal layered gabbro complex had been selected and recommended for prospection and detail investigations. Exploration activities for apatite were conducted since June 1986 at Soji-Gerjo Bikilal area. Since the phosphate indications of the Soji-Gerjo Bikilal area was encouraging, the Ethiopian Institute of Geological Surveys (EIGS) planned to undertake feasibility study of the phosphate deposit and associated minerals in the Soji-Bikilal, which is the northern part of the study area. Accordingly, Robertson Research Minerals Ltd. (RRM) was selected as a potential consultant to carry out the feasibility study. Meanwhile, RRM was bankrupted and Consult 4 International, a South African mine consulting firm, continued the study.

Consequently, successive geological exploration works targeting an area of 4 km^2 with selection of 18 profile lines of 200 m and spacing were cut and a number of pits dug at an interval of 40 m. along the lines. Fifteen trenches were also excavated between the profile lines to confirm the strike continuity of the apatite bearing bodies.

The channel, chip and core samples were analyzed for five oxides (P_2O_5, TiO_2, Fe_2O_3, FeO and V_2O_5). This exploration works reveals grade of 3.5% P_2O_5 and proven reserve of 181Mt phosphate within igneous sources. The near-surface, low-grade high tonage igneous phosphates from Bikilal have been evaluated on their suitability for upgrading through seizing and magnetic separation (Abera 1988, 1994).

Yayu fertilizer factory in the country which is under construction is intended to produce UREA (diamonium nitrate), although the government is not ready to produce DAP (diamonium phosphate) for the time being.

Adding fertilizers to soils and/or plants that are deficient in primary plant nutrient (N-P-K) are vital to have a good plant growth, quality and quantity of plant products. Hence fertilizers are important inputs to increase food crops productivity. In sense of this; apatite is a mineral that is very important raw material source for phosphate fertilizer production and need detail investigation to re-evaluate the deposit for economic exploitation.

2.4 Previous works

Many scholars had done numerous geological investigations on the various aspects of western Ethiopia including the present area of interest. Although, systematic mapping and detailed mineral exploration and prospecting in Western Ethiopia Shield and the whole of Ethiopia started in 1970, early references concerning the geology of the area were given by various authors (e.g., Hess et al., 1932; Cuisinier, 1933;). Desio (1940) made the first attempt to produce a geological map of Wellega area at a scale of 1:2,000,000 and 1:500, 000. He divides the rocks of the area into Lower high-grade gneiss and Upper low-grade sediments separated by unconformity. Mohr (1962) subdivided the rocks of Wellega area as”Catazone" gneiss to the east and” Mesozone" schist to the west in his 1:2,000,000 map of the Horn of Africa.

As part of the search for economic mineral deposits, early photo geological and geophysical studies were conducted by Hunting Geology and Geophysics (1969) who recognized two lithologic units: the gneiss and schist groups. Subsequent workers [e.g., UNDP, 1972; Kazmin (1972, 1975, and 1978); and Kazmin et al., 1978] forwarded a two-fold subdivision of Wellega rocks: Lower and Upper Complex where the former being the oldest and assumed to be of Archean and the latter being the youngest and Neoproterzoic in age.

Senbeto, C., (1980) has conducted geological mapping of part of Ghimbi sheet (NC 36-12) and pointed out the presence of magnetite-hematite ore body closely associated with the gabbro-diorite basic intrusive.

The first real attempt to understand the geology of Bikilal and its iron deposit was made by Ethio-Korean iron ore exploration project (EKIEP), (phase ,I, 1986 and phase II, 1988) and pointed out the occurrence of magnetite-ilmenite deposit with apatite in gabbro anorthosite intrusive, specially localized in horblendite.

Between 1988 and 1993 the Ethio-Canada Agrogeology project funded by the International Development Research Centre (IDRC) investigated the potential of the Bikilal area to provide Phosphate for direct application soil additives. This project was a joint venture between the Ethiopian Institute of Geological Surveys ("EIGS"), the Agricultural Research Institute ("IAR") and the Department of Land Resource Science, University of Guelph, Canada.

This project outlined a resource exceeding 127 million tones of phosphate bearing material with an additional 3 million tones of residual material. The project concluded that the "ore" was amenable to simple beneficiation but that an economically viable process would need to be developed. The study also concluded that the Bikilal "phosphate ore" was unsuitable for direct application.
To locate and assess local phosphate resources in Ethiopia, investigations were made on some of the potential resources of phosphate, namely, the Mesozoic-Cenozoic rocks, the Precambrian meta-sedimentary sequences and the intrusive rocks of alkaline basic-ultrabasic rocks. Consequently, the Bikilal layered gabbro complex has been found to be promising and systematic exploration activities for apatite were conducted since 1986.

In search for agro mineral the Bikilal-Ghimbi intrusive rocks have been systematically explored by Institute of Ethiopian Geological Survey, Consult 4 International, a South African Mining Consulting firm and The Bikilal iron deposit was explored and evaluated in detail by the Ethio-Korean Iron Exploration Project (1984-1987). As a result of successive geological exploration works, a target area of 4 km^2 was selected and 18 profile lines of 200 m. spacing were cut and a number of pits dug at an interval of 40 m. along the lines. Fifteen trenches were also excavated between the profile lines to confirm the strike continuity of the apatite bearing bodies.

The exploration at Bikilal comprises more than 30 diamond drill holes with a combined length of more than 7 km. Extensive pitting and trenching have also been carried out. The channel, chip and core samples were analyzed for five oxides (P_2O_5, TiO_2, Fe_2O_3, FeO and V_2O_5). This exploration works reveals grade of 3.5% P_2O_5 and proven reserve of 181Mt phosphate within igneous sources (Abera, et.al, 1992).

W. B. Woldemichael and J.I.Kimura (2008) compiled the article on the topic “Petrogenesis of the Neoproterzoic Bikilal-Ghimbi gabbro, western Ethiopia” and presented their analysis of detail petrogenesis, whole rock geochemistry, and estimated parental magma types to be of intraplate-type tholiite. They analyzed the olivine gabbro and hornblende gabbro of apatite bearing and apatite free separately and showed their relationship to be of magmatic origin (W. B. Woldemichael and J.I.Kimura, 2008 and the references there in).

W. Mammo Ghebre (2010) published an article on “Geology and Mineralization of Bikilal phosphate deposit, Western Ethiopia, implication and outline of gabbro intrusion to East Africa zone”. In this article again he described petrogenesis of Bikilal- Ghimbi gabbro, the geology, mineralogy and whole rock analysis with its grade implications. They correlated Gabbro intrusion occurrences in Bikilal-Ghimbi of Western Ethiopia with that of East Africa region such as Phalaborwa and Schiel igneous complexes of South-Africa and Sukulu (Uganda) carbonatite and the Villa-Nora (South - Africa) basic – layered – gabbro. Finally, they concluded that all these complexes are of igneous origin and are sources of phosphate deposits of varying grades.

2.5 Applications of Apatite

Apatite is a main source of phosphorus that we use today; as a source of phosphoric acid that allows the production of phosphate fertilizer and pure chemicals such as sodium phosphate, mono-calcium phosphate, di-calcium phosphate.

2.5.1 Fertilizer (agricultural input)

DAP (Diammonium Phosphate), MAP (Monoammonium Phosphate) and TSP (Triple superphosphate) are the most commonly traded phosphate fertilizers used for supplying crop with nutrients (P and N). DAP is produced by combining phosphoric acid with ammonia. It contains 18% nitrogen and 46% phosphorus pent oxide. It is widely produced in granular form for direct application as a fertilizer or for blending with other types of fertilizers, and in the non granular form for use in liquid fertilizers. It is stored and transported as a solid at ambient temperatures. The most common grade for MAP is 11% nitrogen and 52% phosphorus pentoxide. This compound is also a component of some dry powder fire extinguishers. TSP is made by reaction in wet-process of phosphoric acid with phosphate rock. Typically it contains 46% P_2O_5. TSP is produced in granular and non-granular form and is used both in fertilizer blends (with potassium and nitrogen fertilizers) and by itself for fertilizer. DAP is the most widely-produced phosphate fertilizer. Production amounts to more than 40 Million tons a year. It is produced in about 20 countries worldwide and consumed in every developed agricultural market. The largest producers are USA, Chinese and Indian companies, who have massive domestic markets to serve. The main producers and exporters are USA, Morocco, Tunisia, Jordan, Russia, Lithuania, Australia and China and is a widely traded fertilizer commodity (source: http://www.icis.com/fertilizers/phosphates/price-reporting-methodology/visited 05/07/2013).

The inputs required to produce one ton of DAP fertilizer are approximately 1.5 to 2 tons of phosphate rock, 0.4 tons of sulfur (S) to dissolve the rock, and 0.2 tons of ammonia (fig.2.4). Changes in the supply or price of any of these inputs will impact DAP prices and availability. The high nutrient content of DAP is helpful in reducing handling, freight, and application costs.

Chemical Reaction (for wet process or acidulation) involved in DAP fertilizer manufacturing from phosphate rock is as follows:

$$Ca_3(PO_4)_2F+3H_2SO_4+2H_2O \rightarrow 3CaSO_4\text{-}2H_2O+2H_3PO_4+HF$$

$$H_3(PO_4)+2NH_3 \rightarrow (NH_4)_2HPO_4$$

The composition of DAP is 18% N, 46% P_2O_5 is (20% P), where as the water solubility (20 ºC) of DAP is 588 g/L at a solution pH of 7.5 to 8.

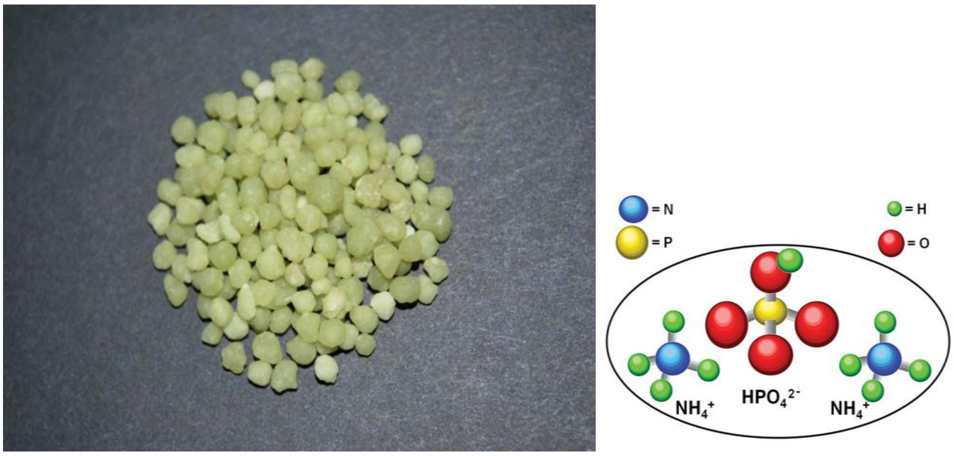

Fig.2.3 Granular DAP grains (left) and their schematic chemical representation (right) /www. ipni.net /

The major use of phosphate is as a fertilizer since it is one of the three major plant nutrients - nitrogen, phosphorus, and potassium. About 90% of the phosphate produced is used in the manufacture of fertilizers, which are available as a wide range of products. There are no known substitutes for the use of phosphates as fertilizers. Today, the annual global production of phosphate is around some 40 million tons of P_2O_5, derived from roughly 140 million tons of rock concentrate. Overall, mineral fertilizers account for approximately 80% of phosphates used worldwide with the balance divided between detergents (12%), animal feeds (5%) and specialty applications (3%), for example, food grade, metal treatment etc.

For general use in the fertilizer industry, phosphate rock or its concentrates preferably have levels of 30% phosphorus pent oxide (P_2O_5), reasonable amounts of calcium carbonate (5%), and <4% combined iron and aluminium oxides. Worldwide, the resources of high-grade ore are declining, and the beneficiation of lower grade ores by washing, flotation and calcining is becoming more widespread.

In addition to phosphate fertilizers for agriculture, phosphorus from rock phosphate is also used in animal feed supplements, food preservatives, anti-corrosion agents, cosmetics, fungicides, ceramics, water treatment and metallurgy.

World fertilizer consumption has increased tenfold since 1930 and almost six fold from approximately 5 million tones of phosphates in 1950 to 30 million tons in 1995. This gives an average annual growth rate of some 4%. However, the global fertilizer consumption growth rate has leveled out, the peak year being 1988 with a total consumption of 37.7 million tons of P_2O_5. Over the last 25 years, farmers in developing countries have increased their overall fertilizer use more than five times and the phosphate use has increased six fold to the present level of 40 million tons. In large parts of the developing countries, there is an insufficient supply of phosphate both in terms of total application and imbalance in the N to P to K ratio. If many of the areas being farmed today were to receive sufficient phosphate to prevent mining of soil reserves, this in itself would substantially increase world demand.

2.5.2 Apatite use as Gemstones

Transparent stones of apatite are used as gems, with chatoyant specimens being referred to as cat’s eye apatite and transparent green stones referred to as asparagus stone. There are also transparent blue stones which are better known as moroxite. While most apatites are found as grains or fragments, large and well-formed apatite crystals have been found in many metamorphic rocks. These became good sources of gem apatites. Most gem apatites are found in Mexico and Brazil in Central and South America, and Burma in Southeast Asia.

Apatite can be cut into gems but the softness of the specimen prevents wide-distribution and it is not as valuable to be considered a gemstone or a mineral specimen. Another reason why apatite is not a popular gemstone is because of its low hardness on the Moho’s scale. Apatite is level 5 of hardness makes the material only useful for earring, brooches, and pendants.

Apatite is also a major source of rare earth elements which are crucial to many industries and technologies. Unlike other minerals that contain rare earth elements, apatite has been found to be non-radioactive. It’s also been found that mining apatite has a minimum impact on the environment, making it a better and more preferable choice over other traditional rare earth ores.

2.5.3 Medical uses of Apatite

Hydroxyl apatite is used medically to replace amputated bone or to even promote bone growth on prosthetic implants. Coral skeletons can actually be heated at high temperatures to create hydroxyl apatite. The high temperatures will burn proteins, and prevents (GVHD). (GVHD) or graft versus host disease is a common disease that may take place during bone marrow transplants. The individual’s immune system receiving the transplant will defend itself. Their antibodies will view the bone marrow as an invader even though it may be the same exact bone type.

2.5.4 Biological functions of Apatite

The primary biological importance of phosphates is as a component of nucleotides, which serve as energy storage within cells (ATP) or when linked together, form the nucleic acids DNA and RNA. The double helix of our DNA is only possible because of the phosphate ester bridge that binds the helix. Besides making biomolecules, phosphorus is also found in bones, whose strength is derived from calcium phosphate, in enamel of mammalian teeth, exoskeleton of insects, and phospholipids (found in all biological membranes). It also functions as buffering agent in maintaining acid base homeostasis in the human body.

2.5.5 Ecological functions of Apatite

Phosphorus is an essential nutrient for plants and animals. Phosphorus is a limiting nutrient for aquatic organisms. Phosphorus forms parts of important life-sustaining molecules that are very common in the biosphere. Phosphorus does not enter the atmosphere, remaining mostly on land and in rock and soil minerals. Phosphates from fertilizers, sewage and detergents can cause pollution in lakes and streams. Enrichment of phosphate can lead to eutrophication of fresh and inshore marine waters, leading to algae blooms.

Phosphorus normally occurs in nature as part of a phosphate ion $(PO_4)^{3-}$, consisting of a P atom and 4 oxygen atoms; the most abundant form is orthophosphate. On land most P is found in rocks and minerals. P rich deposits have generally formed in the ocean or from guano, and over time, geologic processes bring ocean sediments to land. Weathering of rocks and minerals release P in a soluble form where it is taken up by plants and it is transformed into organic compounds. The plants may then be consumed by herbivores. After death, the animal or plant decays, and P is returned to the soil where a large part of the P is transformed into insoluble compounds. Runoff may carry a small part of the P back to the ocean. Generally with time (thousands of years) soils become deficient in P leading to ecosystem retrogression.

2.5.6 Biomedical Application of Apatite

The field of biomedical materials has grown rapidly over the past 20 years and offers solutions to repair defects, correct deformities, replace damaged tissue and provide therapy. This has contributed to the increase in the average lifetime of individuals in developed countries. The market value for biomaterials is of the order of billions of dollars per annum worldwide and is growing as new products offer improved performance or provide new solutions to health problems. Apatite is playing a key role in biomedical implants.

In developing materials used for implantation, consideration must be given to both the influence of the implanted material on the body, and how the body affects the integrity of the material. The body will treat implants as inert, bioactive, or resorbable materials. Generally “inert” materials will evoke a physiological response to form a fibrous capsule, thus, isolating the material from the body. Calcium phosphates fall into the categories of bioactive and resorbable materials. A bioactive material will dissolve slightly, but promote the formation of an apatite layer before interfacing directly with the tissue at the atomic level. Such an implant will provide good stabilization for materials that are subject to mechanical loading. A bioresorbable material will, however, dissolve and allow tissue to grow into any surface irregularities but may not necessarily interface directly with the material (Neo, 1992 and Nancollas and Mohan 1970).

2.6 World Phosphate rock Resources

The USA, North Africa, the USSR and the Pacific islands are the principal phosphate rock producing countries. Most of the countries in Europe and Asia depend upon imports of phosphatic minerals from these countries. The total world reserves of rock phosphate and apatite are estimated at 47,000 million tonnes.

2.7 Potential economic phosphate deposits of the world

A reserve base of 12 phosphate producing countries and their production shows that these countries possess about 90 percent of the world’s phosphate reserves. Based on current extraction rates and economic conditions in the 1990s, more than half of these countries will have exceeded the life of their reserves in less than 20 years.

Sheldon (1987) categorized phosphate reserves and resources according to continents and regions. At first glance, each main continent/region has ample ‘reserves’ of phosphate, with the possible exception of Oceania (391 million tonnes). However, regionally, a few countries, or even one country, may dominate. In North America, the United States of America possesses 84 percent of the reserves. In Europe, the FSU countries possess 99 percent of the reserves. Within Africa, Morocco, South Africa, Algeria, Senegal and Tunisia possess 98 percent of the reserves. The South American reserves lie mainly in Brazil and Peru (97 percent). In Asia, 88 percent of the reserves occur in Iraq, Israel, Jordan and China. Australia possesses 87 percent of the reserves of Oceania.

Table.2.3 World phosphate rock reserves and reserve base (Source: US Bureau of Mines, 2001)

Nº	Country	Reserves	Reserve base
		(1000 tons)	
1	United States of America	1,000,000	4,000,000
2	China	500,000	1,200,000
3	Israel	180,000	180,000
4	Jordan	900,000	1,700,000
5	Morocco and Western Sahara	5,700,000	21,000,000
6	Senegal	150,000	1,000,000
7	South Africa	1,500,000	2,500,000
8	Togo	30,000	60,000
9	Tunisia	100,000	600,000
10	Russian Federation	150,000	1,000,000
11	Other countries	1,200,000	4,000,000
12	World total	12,000,000	37,000,000

2.8 Major world producers of phosphate rocks

The world's top 5 producers are mostly government owned -- include Office Cherifien de Phosphate of Morocco, Mosaic Co (MOS.N) of the U.S.A., FosAgro of Russia and Yuntianhua Group of China.

Annual global production is around 170 million tonnes, while estimated reserves stand at 15 billion tonnes. This means the reserves that can be developed using current technology can be depleted in 90 years, according to data from the U.S. Geological Survey. That compares with 230 year's worth of reserves for potash.

Over 30 countries are currently producing phosphate rock for use in domestic markets and/or international trade.

The world's top 12 producing countries account for nearly 95% of the world's total phosphate production. The three major producing countries, i.e. the USA, China and Morocco, currently produce approximately two thirds of global phosphate production. Of these three major producers, Moroccan reserves account for around 50% of the world total. Morocco is also in the most advantageous situation as its potential reserves and geological *in situ* resources have been estimated to be approximately 60% of total world resources.

The USA and China have between them around 20% of global resources. Current world phosphate rock production capacity is estimated at around 165-195 million tons per annum, or approximately 50 million t/a P_2O_5.

Table 2.4 Top 12 Phosphate rock producing countries (Source: US Bureau of Mines, 2001)

Rank	Country	Production (Tons) 2008
1	China	50,000
2	USA	31,000
3	Morocco	28,000
4	Russia	11,000
5	Tunisia	7,800
6	Brazil	6,000
7	Jordan	5,500
8	Syria	3,700
9	Israel	3,10
10	Egypt	3,000
11	S Africa	2,400
12	Australia	2,300

2.9 Phosphorus availability in the 21st century

High-grade phosphate ores, particularly those containing few contaminants, are being progressively depleted and production costs are increasing. Ingrid Steen, Group Agronomist, Kemira Agro, in Copenhagen, Denmark, examines the outlook for global phosphate rock supply and management of this non-renewable resource.

Today, the annual global production of phosphate is around some 40 million tons of P_2O_5, derived from roughly 140 million tons of rock concentrate. Overall, mineral fertilizers account for approximately 80% of phosphates used worldwide with the balance divided between detergents (12%), animal feeds (5%) and specialty applications (3%), for example, food grade, metal treatment etc.

Considering the dominant role of fertilizers in global phosphate consumption, it is evident that the development of future world phosphate production will be driven by the development of agriculture, which in turn is driven by global population growth and its food requirement. It, therefore, follows that agricultural share in the use of phosphate will increase in the future.

Estimates of world phosphate reserves and availability of exploitable deposits vary greatly and assessments of how long it will take until these reserves are exhausted also vary considerably. Furthermore, it is commonly recognized that the high quality reserves are being depleted expeditiously and that the prevailing management of phosphate, a finite non-renewable source, is not fully in accord with the principles of sustainability.

2.10 Production costs and phosphate availability of 21st century

A number of analyses on production costs for different producing mines and potential mines and deposits have been made. The most significant factors altering the cost situation for recovery and processing of phosphate rock and thus the profitability would be; accessibility of the ore, degree of beneficiation required, capital investment, operating costs and, availability and cost of other resources.

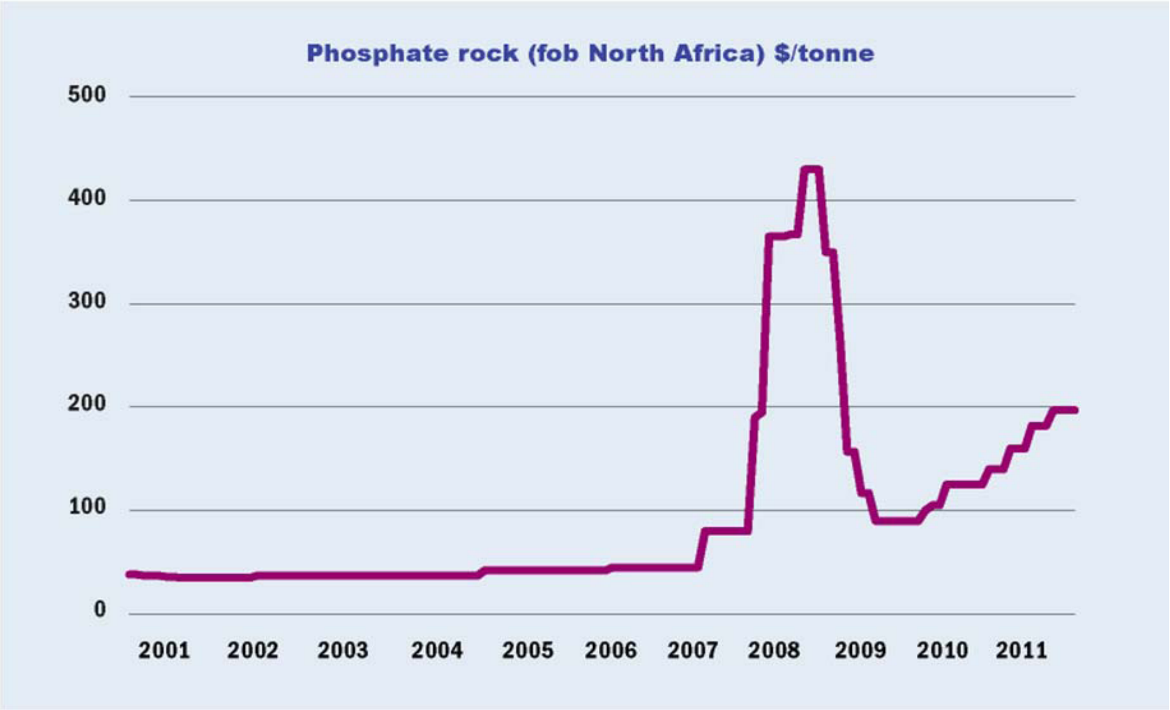

Fig. 2.4 Phosphate rock price trends, source (BC Insight, Mark Evans, UK, 2012)

To illustrate the complexity of these assessments, USGS data is used where reserves are defined as those commercially exploitable at a cost of less than $35/tone. Supposing a cost of around $60/tonne, this would more than double the available commercial phosphate deposits in the USA. It is reasonable to assume a similar situation in other phosphate producing countries, using USGS assumptions. Consequently, with an eventual increase in price for phosphate, a reclassification of some resources to reserves would be the outcome.

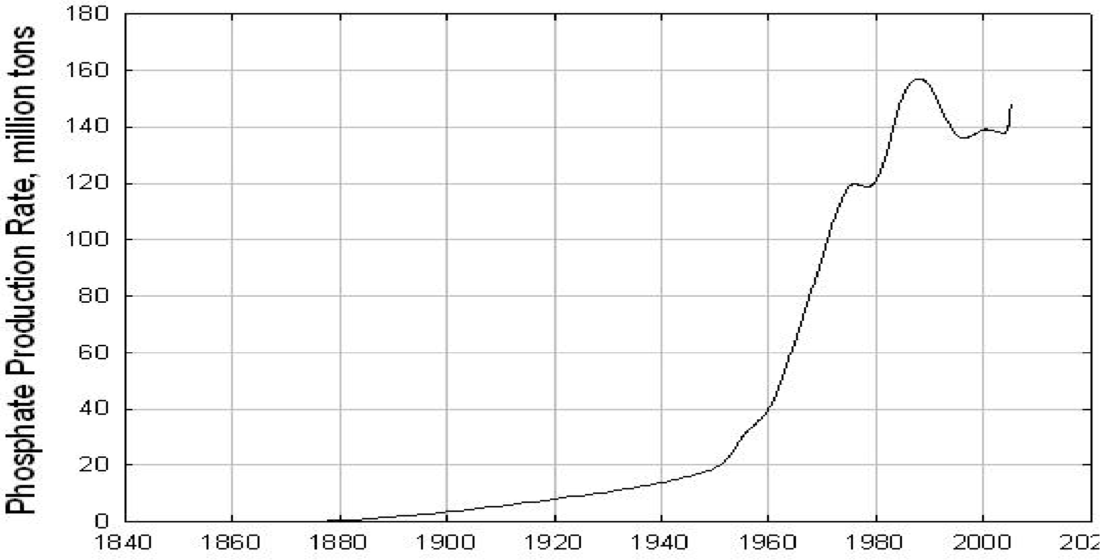

Fig.2.5 World phosphate production rate since 1850 (After A. M. Abouzeid, The journal of ore dressing ® 2007)

2.11 Beneficiation of phosphate ores

The marketable phosphate is usually 30 percent P_2O_5 or higher. The run-of-mine material is mostly of lower grade which needs processing or upgrading. The processing techniques depend on the type of phosphate minerals existing in the ore as well as the associated gangue minerals. Sometimes, simple, inexpensive techniques are enough to produce the required grade. For example, Crushing and screening is used to get rid of the coarse hard siliceous material, and attrition scrubbing and desliming is used to remove the clayey fine fraction. If silica is the main gangue material, single stage or double stage flotation is the conventional mineral processing technique used in this case. If the ore is igneous carbonatitic alkaline or ultra basic phosphate deposit, crushing, grinding, scrubbing, and flotation associated with other steps such as magnetic and or gravity separation is proved to be successful in upgrading this type of ore. The sedimentary phosphate ores having carbonate-apatite (francolite) as the main phosphate mineral and containing carbonates (Calcite and/or dolomite) and / or considerable amount of organic matter represent a challenge in the field of phosphate concentration due to similarity in the physico–chemical properties of surfaces of the constituents of the ore (A. M. Abouzeid,2009).

Beneficiations or ore preparations typically serve to separate and concentrate the mineral values from waste material, remove impurities, or prepare the ore for further refinement. Beneficiation activities generally do not change the mineral values themselves other than by reducing (e.g., crushing or grinding), or enlarging (e.g., pelletizing or briquetting) particle size to facilitate processing. A chemical change in the mineral value does not typically occur in beneficiation. After beneficiation, phosphate rock (concentrate) generally ranges from 26% to about 34% P_2O_5 and up to as much as 42%. Mineral processing operations, in contrast, generally follow beneficiation and serve to change the concentrated mineral value into a more useful chemical form. This is often done by using heat (e.g., smelting) or chemical reactions (e.g., acid digestion, chlorination) to change the chemical composition of the mineral. In contrast to beneficiation operations, processing activities often destroy the physical and chemical structure of the incoming ore or mineral feedstock such that the materials leaving the operation do not closely resemble those that entered the operation.

Because of the increasing demand on phosphate rock for fertilizers, it is becoming more and more common to mine and process low grades of phosphate deposits. The majority of these low grade deposits are of sedimentary phosphates and the rest are of igneous origins. These deposits occur in the form of ore bodies as disseminated, stock work, or vein filling in one or more host rocks or in one thick bed of one or several successive beds intercalated with non-phosphatic materials. Phosphate ores show a wide diversity in the composition of their gangue materials but generally fall into one of the following categories, based on the major associated gangue materials:

- Phosphate ores containing more than one type of the gangue minerals: many of the sedimentary phosphate deposits contain mixtures of undesired constituents. These ores require series of upgrading operations in their flow sheets depending on the type of gangue minerals existing in each ore. This may include, after size reduction, combination of attrition scrubbing, desliming, flotation, gravity separation, and/or calcination. Each flow sheet is to be designed after thorough characterization and testing of a representative sample of the ore under exploitation.
- Igneous and metamorphic phosphate ores: the main gangue materials in these ores are sulfides, magnetite, carbonates (calcite, dolomite, siderite, and ankerite), nepheline syenite, pyroxenite, foskorite, etc. Processing of these ores may include after crushing and grinding, washing, desliming, magnetic separation, and flotation depending on the types of gangue minerals present. However, flotation is a common step in all of them. About 20% of the world's phosphate rock now comes from the mining and beneficiation of igneous deposits, but this percentage will increase as production from sedimentary deposits is being depleted.

2.11.1 Techniques for upgrading phosphate ores

There are several beneficiation techniques for upgrading phosphate ores. The choice of one of these techniques depends on the type of ore as well as the associated gangue minerals. Among these techniques are:

Size reduction and screening: this technique utilizes the differences in differential friability between phosphate minerals and associated gangue and cementing matrix (carbonates, silica, and silicates). In most cases, phosphate minerals are friable while gangue minerals are hard. Here, high percentage of P_2O_5 is lost in the coarse fraction. Air elutriation may be practiced to get rid of the very fine fraction that is rich in clays.

2.11.2. Attrition, scrubbing and classification

This technique is used when the main gangue minerals are clays. Clays are characterized by their fine size, loosely bound grains with the phosphorite pellets. Attrition in water liberates and disperses the clay particles in water and they are removed by desliming and / or classification.

It is also used when the associated gangue minerals are mainly coarse silica or chert chips. In this case, phosphorites are collected from under the screens in a wet process. This may also be practiced to separate a coarse phosphate-rich fraction ahead of a flotation section.

2.11.3 Electrostatic separation

In combination with attrition, desliming, and gravity separation, the electrostatic separation was successful in upgrading phosphate ores by removing silica and /or carbonates, mostly on laboratory scales. However, the low capacity of the electrostatic separators limits their use for large scale production. This technique is used to concentrate phosphate ores of different types.

2.11.4 Magnetic separation

When one of the major gangue constituents is magnetic, magnetic separators are used as one of the steps in the flow-sheet to remove the magnetic constituents. This is mostly used in the beneficiation of igneous phosphate rocks. However, it has also been used for upgrading some sedimentary phosphate ores. The following are examples of plants using magnetic separation in their flow-sheets:

a. The complex igneous phosphate deposit at phalaborwa (South Africa) is upgraded in three stages:

1. Copper flotation
2. Magnetic separation
3. The non-magnetic fraction is subjected to flotation to float apatite. The Run-Of-Mine, ROM, to this plant assayed 7 % P_2O_5, and the phosphate concentrate assay was more than 36 % P_2O_5 at a recovery of 75-80 % P_2O_5.

b. In the Brazil's long established apatite (igneous) beneficiation plants, magnetic separation followed by desliming and flotation are included in the phosphate concentration plants.

c. The dolomitic–pyritic sedimentary phosphate ore of Abu-Tartour phosphate deposit in Egypt is subjected to high intensity magnetic separation, after desliming, to separate the feebly magnetic ankerite.

2.11.5 Flotation

Beneficiation of phosphate ores by flotation has been an important part of the concentration process since the 1920's, when it became possible to recover fine particles of apatite. More than 60% of the marketable phosphate in the world is produced by flotation. This is a common technique for processing siliceous phosphate ores is the anionic-cationic flotation techniques.

Thermal treatment of phosphate ores

More than 10% of the world marketable phosphates are produced by calcination. Traditionally, heat treatment of phosphate ores is defined as heating up the ore to a certain temperature to obtain a product with specific properties. The main objectives behind heating up the ore are:

i) Removing water 120-150^0 C- Drying.
ii) Removing organic matter 650-750^0 C- Calcination.
iii) Dissociation of carbonates 850-1000^{o}C-Calcination.
iv) Removing fluorine up to 1350^{o}C-Defluorination.

Drying, which is a common step in the wet processing of phosphates, is categorized under thermal treatment, but it is not included under the term calcination.

Almost all the heat treatment operations are preceded with ore preparation such as: crushing, grinding, sizing and / or classification, and possibly flotation, to get rid of some of the liberated impurities at one or more of these stages.

Chapter 3: Geology of the study area

3.1 Regional Geology

”Pan-Africa” (Kennedy, 1994) originally referred to the sequences of tectono thermal events at 500 +- 100 Ma, within Africa and Gondwana. However, Kroner (1984), included orogenic events in the period 950-450 Ma, and identified the Arabo-Nubian Shield (ANS) as one of the major orogenic belts formed during Neoproterozoic time. The “Pan-Africa” assembly of Gondwana is thought to be the cause of the East African Orogen, which included the complex intraoceanic and continental margin magmatism and a protracted sequence of tectonothermal events (Stern, 1994). Two major terrains have been identified in the East African orogens. The first is the Juvenile (ie, mantle derived) ANS in the North, where the ANS is dominated by low-grade volcano-sedimentary rocks associated with plutonic rocks and ophiolitic remnants. The second is a tract of older remobilized crust to the south of ANS, known as the Pre-Neoproterozoic Mozambique Belt (MB). This is dominated by high-grade gneisses and migimatites. The East African orogen stretches south from Israel and Jordan through to Tanzania and Antarcatica (Stern, 1994).The transition between the juvenile ANS and MB located within Ethiopia, Sudan, Eritrea, and Somalia.

The Precambrian basement rocks are poly-deformed and metamorphosed high grade gneisses and schists associated with low-grade meta-volcano-sedimentary rocks. They are mainly exposed in the northern, western and southern parts of the country.

The Western Ethiopian Shield (WES) lies near the transition between the ANS and MB, and also lies adjacent to the enigmatic “East Saharan Metacraton”, which consists of older crust that was extensively remobilized during Neoprotozoic time (Abdulsalam, 2002). There has been a limited number on the geochronology of the WES, and those that have been carried out have shown results that are mostly in accordance with models derived for other parts of ANS. Three generation of plutonism have been recognized in WES: 1) “Prekinematic” plutons yield emplacement ages of 814-866Ma); 2) “synkinematic” plutons yield emplacement ages of 700-783Ma and 3) “late to postkinematic” plutons yield emplacement ages of 541-624 Ma (Ayalew, 1990, Kebede, 2001 and Grenne, 2003). Ayyalew and Peccerillo, (1998) suggested that the pre to syn kinematic plutons were subduction related, and were emplaced in intraoceanic island arc environments. Ayyalew and Peccerillo (1998) and Kebede et,al (1999) inferred that “late to post kinematic” plutons possessed geochemical signatures of both subduction-related and intraplate components.

Allen and Tadese (2003) classified and described the N-S trending Tulu Dimtu belt, where the area of this study lies, into five litho tectonic domains. They interpreted the belts as being the effects of collision of orogenic belts formed during the assembly of West Gondwana before the final closure of the Mozambique Ocean. According to this tectonic subdivision, the Bikilal-Ghimbi intrusion lies in the Didesa domain of these five lithotectonic domains. The rocks within the Didesa domain consist of moderate grade paragneisses and orthogneisses intruded by Neopproterozoic intrusive rocks. The paragneisses consists of interlayered boitite amphibole gneiss, garnet-biotite gneiss, quartzitic gneiss, and very coarse granitoid gneiss. The orthogneisses are represented by abanded mafic gneiss containing ultramafic bands, and could have been derived from a layered mafic intrusive body. With the exception of quartizofeldspathic gneiss, which is relatively massive, all are strongly foliated and have abundant refolded folds indicating two or more generations of folds. These rocks have undergone several later brittle deformation episodes, manifested by complex vein arrays filling fracture networks. The gneisses appear to be intruded by a series of weakly deformed igneous rocks, including gabbro, granodiorite, and granite, all of which display a steep N-S foliation, which is concordant with the extension direction of the belt. Few ages are available for the WES gneisses. Johnon et,al (2004) dated 830-785 Ma for the emplacement/ crystallization of the igneous protoliths to the orthogneisses of the WES. The age and affinity of the polydeformed gneisses of the western Ethiopia are still ambiguous and at present no chronological data constrain the ages of western mafic intrusions in Ethiopia (W. B. Woldemichael and J.I.Kimura et,al 2008 and the references there in).

3.2 Local Geology of Bikilal-Ghimbi Area

Several gabbroic intrusions occur within the Western Ethiopian Shield (WES). Based on their occurrence, they are classified as syn, post and late-tectonic varieties. The Bikilal-Ghimbi gabbric intrusion is one of the largest intrusions in the region and is considered to be a syn- to post-tectonic type, based on its apparenly intrusive relationships with the surrounding gneiss (Abraham, 1989 and Alemu and Ababe, 2000, Beshaward 2001; Allen and Tedese 2003).The intrusive underlies an area of about 350 km^2 , and is about 40 km long, with a maximum width of about 14 km in its central part and a minimum width of 2 km in its southern tips. An area of about 70 km2 is underlain by olivine gabbro, where as the remainder mainly consists of hornblende gabbro with layers of hornblendite see fig.5.1. The gabbro defines an elliptical area that is elongated parallel to the N-S foliation of the surrounding gneissic terrain. The contact with gneissic terrain is thought to be an intrusive type, although no child margins or dikes of gabbro within the gneiss are obsereved (Beshaward et, al. 2001).

Layering is a common feature of gabbroic intrusions. Individual layers or layered sequences can vary greatly in thickness, texture, shape, and in their mineralogical and chemical composition (Naslund and Mc Birnery1996); the Bikilal- Ghimbi intrusion is no exception. The olivine gabbro body has no clear layering. However, an intrusive layering is only limited in the periphery, which mostly consists of horblendite and hornblende gabbro, whereas the olivine gabbro cores are apparently massive. Layering/banding features occur in hornblende gabbro. The olivine gabbro shows some variation especially on pyroxene grain size level. Pyroxine crystals as large as 2-3 cm characterize the courser varieties, whereas the equivalent finer varieties contain relatively fine-grained pyroxene (1-5 mm). This textural variation can be considered as textural layering, although clear layering boundaries are not noticeable.

Regionally Western Wollega is underlain by Precambrian rocks composed of gneiss, low grade metamorphic rocks which are further classified as, meta-volcanics, marbles, mafic to felsic plutons, and minor ultramafics, which are intruded by syn to post tectonic granites and gabbro and later covered by tertiary volcanics. The gabbroic plutons are mainly syn-tectonic and a few, including Bikilal gabbroic intrusive are, late to post-tectonic intrusive (Amenti A. 1989).

3.3 **Structure**

The structure described here includes chiefly those within the Precamberian gneiss and intrusive rocks of basic to ultrabasic composition upon which the present investigation has been focused. A brief description of each structure is given below.

Foliation: the map area is characterized by preferred alignment of flaky (biotite) minerals and amphibole crystals and stretching of quartz and feldspars parallel to the main foliation direction. This is well observed in biotite and/or granitic gneiss and poorly observed in hornblende gabbro or hornblendite. In general, the strike of the rocks trends in a north-south and northeast –southwest direction dipping 40°-85° towards east and south east.

Folds: the area shows at least one-phase of deformation or F1-style of deformation. First is the formation of foliation by preferred alignment of flacky (biotite) minerals and second is the folding of the main foliation. The axis of fold is N 80^0E plunging gently towards southwest.

3.4 Stratigraphy of the Soji- Bikilala intrusive gabbro

The Soji-Bikila area is underlain by the major lithological unit's olivine/pyroxene gabbro, hornblende gabbro and hornblendite, and anorthosite see geological & mineralization map (Fig 3.1).

The gabbroic complex is composed of zones/layers of olivine gabbro, leuco-gabbro and hornblende making up the bulk mass. Within the hornblende gabbro, repeated lens-like thin and elongated horizons of hornblendite are found intimately associated with massive and disseminated ilmenite-magnetite bodies, in places with apatite. All units generally dip towards the center of the intrusive with dip angles ranging from 45^0 –75^0.

The Bikilal-Ghimbi Complex consists of apatite-free olivine gabbro, hornblende gabbro, and hornblendite suites and their apatite-bearing equivalents (W. B. Woldemichael and J. I.Kimura et,al. 2008). Descriptions of each litho- stratigraghic units supported by petrological examinations are presented as follows:

3.4.1 Pegmatites

Pegmatites are not out cropped and sampled during this field study. But pegmatitic veins were intersected by drilling in the lower zone during exploration works. They are dull – white and coarse grained with a grain size of 5 – 6mm and composed of quartz,plagioclase and muscovite. The thickness of pegmatite veins intersected is not usually greater than 10m.

3.4.2 Olivine /pyroxene Gabbro

A large mass of olivine gabbro occupies the central portion of Gimbi- Bikilal intrusion. This massive olivine gabbro is surprisingly fresh, and is unaltered except for some minor veins and weathering. Deformation textures are rare and all the crystals are fresh and retained all the original igneous shape. The olivine gabbro is medium to course- grained holocrystalline with a hypidiomorpmic granular gabbric texture, and the modal compositions range from 5-25% olivine, 10-35% clinopyroxine, 30-55% plagioclase, 0-16% apatite and 1-15% ilmenite magnetite. Most of the crystals are subhedral to anhedral, but most of the apatite is euhedral. All the crystals are weakly zoned. This unit is further classified into apatite-bearing and apatite-free olivine gabbro. The olivine gabbro is essentially massive, and contains course pyroxene crystals (2-3cm in size).

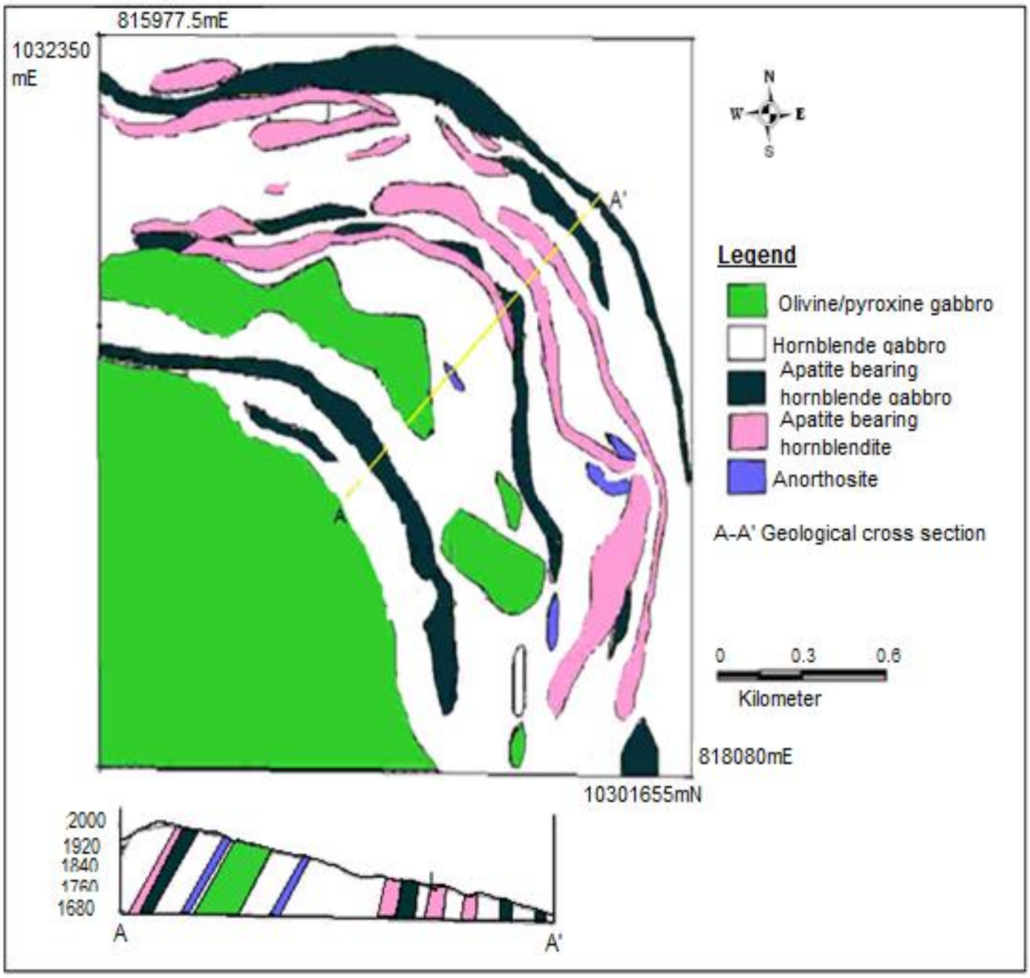

Fig 3.1 Geological map of Soji Bikilal & cross-section A-A' (Modified after Beshawered, 2001)

3.4.3 Hornblende gabbro

The hornblende gabbro is the outer unit and forms a large portion of Gimbi Bikilal gabbro intrusion. The unit makes the melanocratic to leucocratic varieties depending on the plagioclase and hornblende content, and is generally medium to course grained. This unit also hosts hornblendites. The plagioclase and hornblende exhibit a relict to granoblastic texture with accossary ilmenite, apatite and chlorite.

Hornblende gabbro is the dominant lithological unit in the target area. From apatite mineralization point of view, the unit is sub-divided into apatite free hornblende gabbro and apatite-bearing hornblende gabbro. The apatite-bearing gabbro commonly occurs within the hornblende gabbro mass, and locally regarded as disseminated apatite mineralization. It is generally greenish grey to dark greenish grey in hand samples.

Coarser and finer varieties of the unit are observed; generally medium grained with an average grain size of 3-4mm. It is characterized by leucocratic to melanocratic varieties and composed of plagioclase, hornblende and variable amounts of ilmenite and sulphides with rare apatite grains.

As the unit is the outermost one, several inclusions of diorite, migmatite and amphibolite; dikes of microgranite and pegmatite veins are observed. Petrological examination of the specimens showed the following composition: 50-70% plagioclase, 25-40% hornblende, 5-10% opaque minerals (ilmenite + magnetite), with a dominant subhedral – anhedral texture.

3.4.4 Hornblendite

The hornblendite is fine to medium grained texture phanertic to massive texture. The hornblende grains are subhedral to anhedral, and show slight schistosity. Uralitization is prominent with rare traces of unaltered zones of pyroxene cores. The hornblendite is subdivided into apatite bearing and apatite free groups. The modal composition of hornblendite ranges from 60-90% hornblende, 5-30% ilmenite-magnetite, 0-9% plagioclase, and 0-20% apatite. The hornbledite is hosted within the hornblende gabbro.

3.4.5 Anorthosite

The unit is encountered as patches within the hornblende gabbro unit, at the eastern side of the olivine/ pyroxene gabbro and it is the least extensive of all units. It is dull-white and fine- to medium- grained. It is usually composed of plagioclase up to 90% and hornblende makes up the rest.

Chapter 4: Apatite Deposite of Bikilal area

4.1 Mineral Exploration Activities of Ethiopia (GSE)

Mineral resources are important natural assets, and it is the nation's best interest to stimulate a greater understanding of its indigenous wealth. Information on extent, quality and distribution of potential economic minerals is essential for effective and informed decision, which is critical to meet the objectives of nation's socio-economic development.

To fulfill the above objectives, the Geological Survey of Ethiopia (GSE) was established in 1968 as a national institution responsible for geological mapping, ground geophysical surveys, mineral exploration and evaluation, as well as geotechnical and hydrogeological, and geothermal activities. In addition to these, the survey collects archives and disseminates earth science information to create earth-resource awareness among the population. Based on these backgrounds, the GSE had conducted and has continue to conduct several prospecting and exploration works to assess and locate indigenous phosphate and iron resources in different parts of the country using conventional methods.

In 1985 exentensive sdudies were conducted by GSE to assess for phosporite –bearing formations and apatite-bearing formations in Eastern and Southern parts of Ethiopia. At that time first priority was given to geological formations of lower metamorphic complex, Hamanlei series of carbonate composition (Jurasic in age), Mustahil series of terrigenous-carbopnate composition(Early Cretaceous in age), Auradu series of terrigeneous-cherty-carbonate composition (Paleocene-Early Eocene in age). The survey was carried out by the study of drill core from oil wildcats and hydrogeological wells sunk by the Soviet Petrolium exploration Expendition (SPEE). In the lower metamorphic complex only calcite veins were identified as commercial interest of the area. But the calcite veins are not apatite-bearing. All the sedimentary beds did not show potential economic phosphorite deposit according to this survey and igneous apatite took attention of GSE.

4.2 Important Mineral Deposits of Ethoiopia

The geological formation in Ethiopia ranges in age from Precambrian to recent. The Phanerozoic sedimentary and volcanic rocks cover most part of the central high lands, rift valley and eastern lowlands of Ethiopia. The Precamberian metamorphic rocks, which consist of low-grade volcano sedimentary metamorphic rocks and high grade geiss and schists outcrop only in the northern, western and southern parts of the country. The most important economic minerals that are found in Ethiopia can be grouped into metallic minerals, industrial minerals, and energy resources.

The metallic minerals- which are hosted mainly in the Basements rocks include various occurrences of gold (Adola), platinium (Yubdo), rare earth elements, columbo-tantalites, copper, lead, zinc, iron, and nickel. Base-metal indications are also present in Mesozoic sediments.

The industrial minerals such as feldspars, marble, granite, talk, graphite, kyanite, mica, kaolin and quartz are mostly found in Precambrian rocks. The construction materials are hosted in Tertiary to Quaternary volcanics and sediments. Chemical raw materials of salt, sulphur and potash are mainly found in the Afar depression. Igneous phosphate which is mainly hosted in the Bikilal gabbroc rocks is associated with iron-titanium minerals and it is the most promising potential for phosphate resources. The known reserve of apatite-magnetite- ilmenite deposits is 181 Mt containing 3.5% P_2O_5, and 6% TiO_2 (Consult 4 International, 2002).

The energy resources which include coal and oil shale, are found within Senozoic volcanic for example, the Yayu coal (SW of Ethiopia) have a thickness 4-25m and about 121 Mt of coal.

4.3 Mineral Resources of Bikilal-Ghimbi Area

4.3.1 Apatite-magnetite-ilmenite deposits

The most common mineral deposits occurring in the area are apatite- magnetite-ilmenite and rare sulfides. The type of the apatite is hydrxylfluor-apatite Varity (IFDC, 1987).The apatite- magnetite-ilmenite deposits are genetically intimately associated with the crystallization and intrusion history of the Bikilal layered gabbro intrusive. Fe-Ti-oxide-apatite association is common to gabbroic intrusive complex in the world. The ore deposit is syn-genetic segregated late magmatic type that is associated with a basic magma. As a result of this, the mineralized bodies are localized and restricted in a certain complex that is in basic petro graphical zone. The mineralized rocks are composed of amphibole, chlorite, plagioclase, apatite, magnetite and ilmenite. From textural and mineralogical relationship point of view, beneficiation is possible by using grinding, magnetic separation and floatation methods.

The Fe-Ti-P mineralization occurs as lenses and hosted in amphibole gabbros. The nature of the contact between mineralized lenses and the host rocks is not very clear. In some places, the contacts are gradational but in some places are abrupt. Further detailed studies were conducted at Soji-Bikilal area, which is part of Soji-Gerjo Bikilal that covers 4.5 km^2 in order to delineate more apatite-bearing ore bodies and finally the mineable reserve were estimated to be 181 Mt at 3.6% P_2O_5 and 6.0 % TiO_2 (Consult 4 International, 2002).

Detailed studies on the extent and volume of iron ores revealed that the tonnage of iron deposit is 57.8 Mt of indicated and inferred reserves. The average grade of the total iron is 41.65% (23.29% Magnetite iron), 0.36% P_2O_5, 0.77% S, 16.72% $Tio_{2,}$ and 0.24% $V_2O_{5.}$

4.3.2 Apatite

Apatite occurs as euhedral to subhedral elongate prismatic grains, probably formed early in the crystallization sequence. There is an intimate association between apatite and the oxide minerals, ilmenite and magnetite which either partially or entirely enclose euhedral apatite grains.

It is hosted mostly in hornblendites, hornblende gabbro and occurs as apatite-ilmenite-magnetite- tremolite actinolite disseminated ores. Mostly the highest percentage of apatite mineralization is found in hornblendites and in melanocratic- hornblende gabbro, usually containing up to 15% apatite. There are generally two groups of size and shape of apatite crystals namely, long and thin (prismatic) and short and stumpy. Grain size varies between 0.14 and 0.31mm.The apatite is of hydroxyfluor- apatite type with 40.05- 41.52% P_2O_5 content (Sisay Abera., 1992).

The refined geological and mineralization map of Soji-Bikilal shows two layers of upper and lower zones of apatite mineralization. The strike length of the upper zone is 1600 m. The thickness of the upper and lower layers of phosphate mineralization’s are 30m and 40m respectively, separated by a 35m barren zone (W. Mammo et,al.2010*)*. In the middle of the strike extent, the zone splits into two with the inner layer being up to 100m thick and the outer layer up to 200m thick, separated by a 60m barren zone.

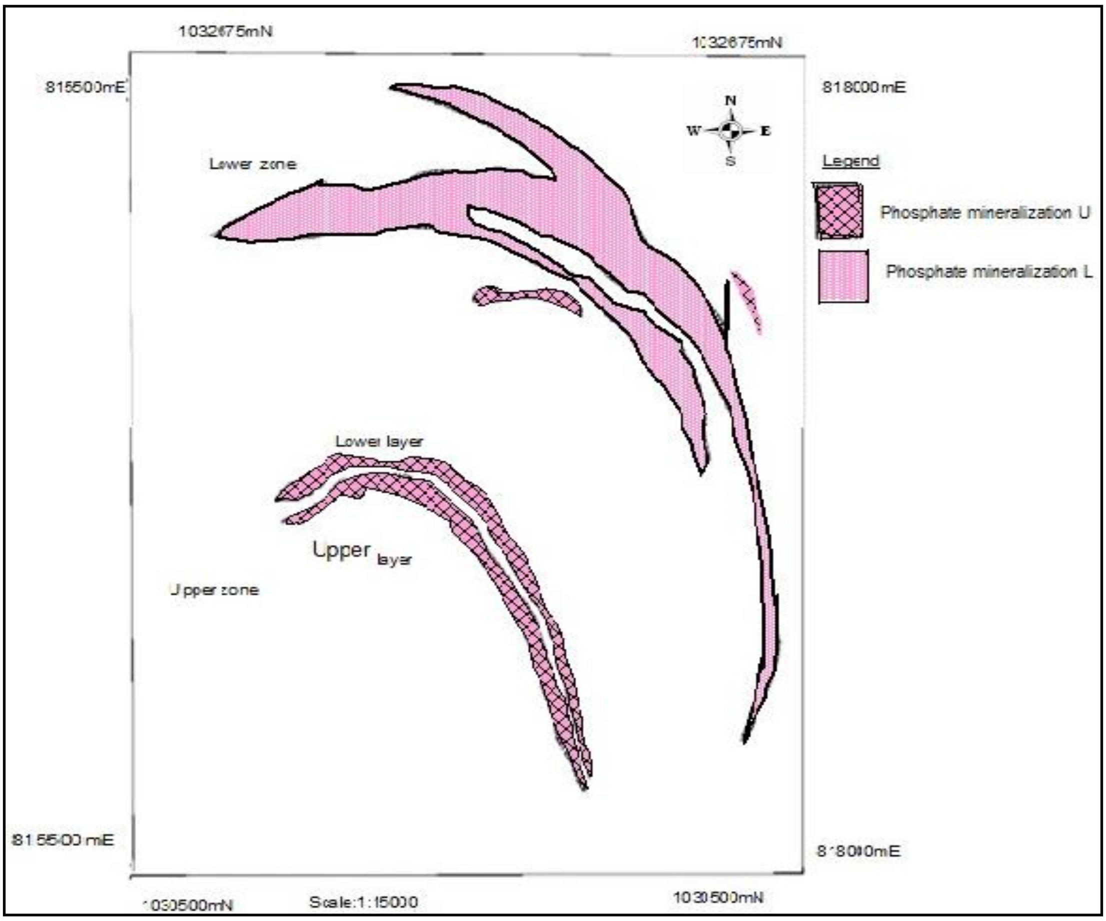

Fig.4.1 phosphate mineralization map of Soji Bikilal (modified after Beshawered, 2001)

The strike length of the lower zone is 3000m having a thickness of 60m ─200m (Fig.4.1). In the upper zone layers, the phosphate grade over the thickness of the layers is fairly consistent with occasional high grade patches and low grade patches. Overall, the mean grades of the upper and lower layers of the upper zone are 2.35% P_2O_5 and 2.62% P_2O_5 respectively.

In the lower zone, the phosphate grades are generally higher. The northern part of the lower zone is the best mineralized part of the deposit with phosphate grades averaging 3.7% over a width of 160m. The main phosphate distribution is normal with an excess of low values. The mean grade of this zone is 2.78% P_2O_5 (W. Mammo et,al, 2010).

4.3.3 Magnetite-ilmenite

Although the proportion of ilmenite and magnetite is not well established, they are commonly associated with the lithologies of the area. They are mostly hosted in the apatite-magnetite-ilmenite-tremolite-actinolite disseminated ore, hornblende gabbro, and some olivine/hornblebde gabbro.

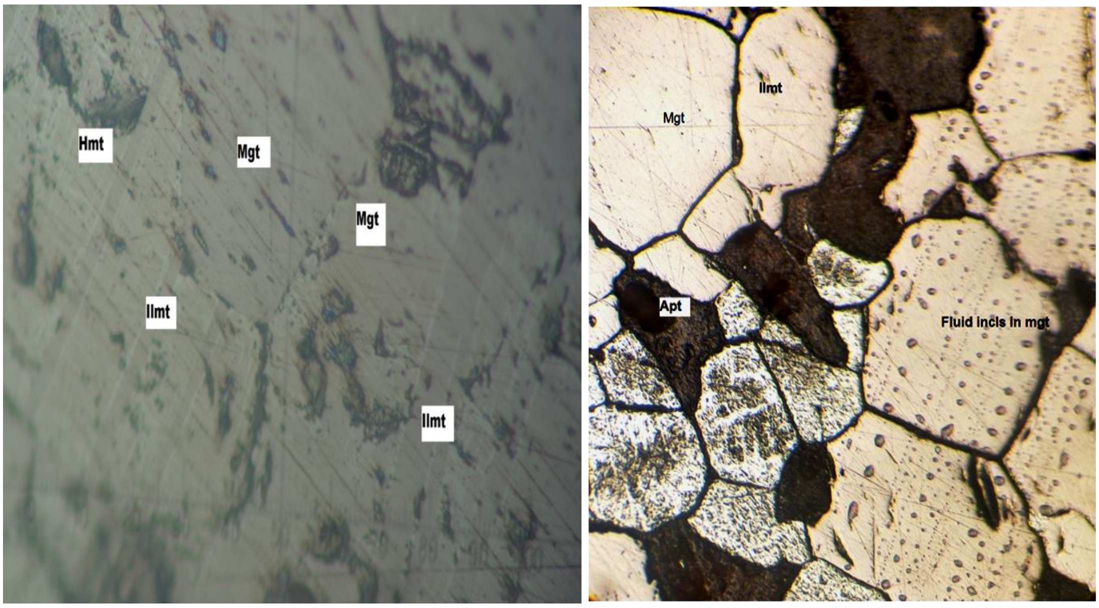

Fig.4.2 photomicrograph showing exsolution lamellae of ilmenite (Ilmt) and hematite (Hmt) within magnetite (left) and photomicrograph of ilmenite, magnetite and apatite forming net textures with the oxides ore and silicates.

Table 4.1 Summary of Petrographic descrtpion of Ghimbi-Bikilal gabbro intrusive with modal compositions of constituent minerals

No	Thin section Samples	Description and modal compositions
1	BS-2 Rock type (lithology) is hornblende gabbro	Equigranular phenocrists of plagioclase crystals constitutes 60-80% of the total field of views. Subhedral to anhedral grains of olivine occupy 5% in the groundmass of slightly altered hornblende. Opaque minerals constitute 5% of the mineral aggregates. All the opaque minerals show simultaneous crystallizations and segregations.
2	BS 24G Lithology Olivine gabbro	Contains elongate prisimatic plagioclase crystals (45%) and subhedral pyroxenes (38%) in the ground mass of slightly altered clinopyroxenes. Olivine occupies about 15% and opaque minerals about 5% of the total field of views.
3	BS 16A Lithology is Apatite bearing hornblendite	It is almost opaque minerals which would be magnetite ilmenite. Apatite crystals of this section constitute about 15% of the total field of views. Massive magnetite dominates every field views. Patches of hornblende constitutes about 10%.
4	BS 20 Lithology is Apatite bearing hornblendite	Shows almost opaque minerals with vein filling of elongate prismatic apatite crystals of elongate structures. The opaque (ore) minerals form net textures with each other and hornblende which occupy about 12% of every field of views.
5	BS 24A Apatite bearing hornblendite	Equigranular subhedral grains of hornblende form ground mass constituting 60% while anhedral to subhedral apatite grains occupies about 10% and opaque minerals occupying about 5% of the total. Plagioclase constitutes about 15-18% with hypidio-xenoblastic texture.
6	BS 16 Olivine gabbro	Dominated by elongate prismatic anhedral to subhedral crystals of plagioclase. Plagioclase constitutes 65%, olivine 15%, pyroxenes 30% and hornblende 20%.

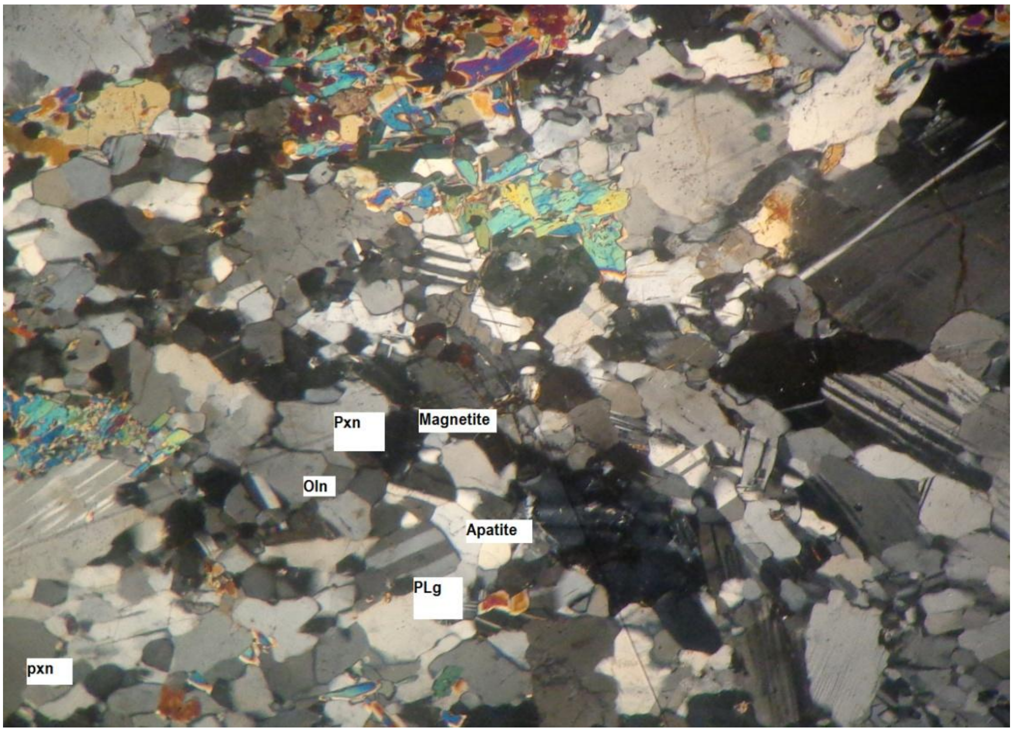

Fig .4.3 Photomicrograph showing typical net textures in hornblende gabbro

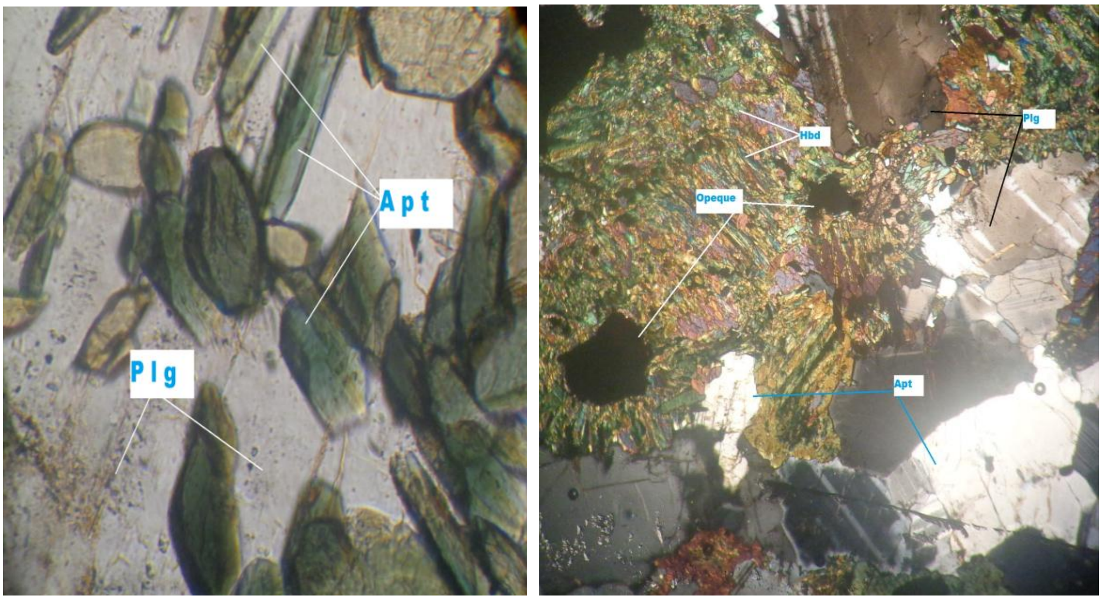

Fig 4.4 Photomicrograph of typical prismatic apatite crystals within plg XPL, 20X (left) and typical apatite mineralization in hornblendite XPL 4X (right)

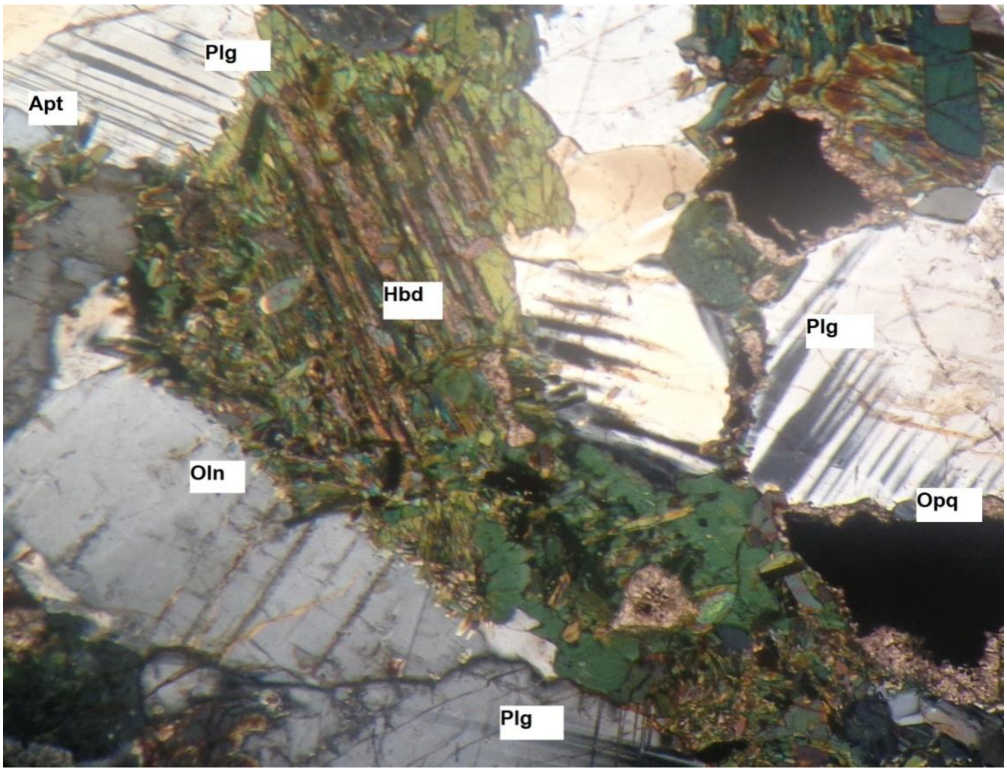

Fig *4.5 Photomicrogragh showing anhedral plagioclase and olivine crystals in olivine gabbro XPL 4X*

4.4 Beneficiation of Soji Bikilal apatite deposits

The beneficiation process proposed by (CONSULT 4 International) in their report of feasibility study was as follows.

1. The run of mine ore is crushed in four stages of dry crushing to 100% finer than 0.3mm as the test work did not show that a size fraction of especially poor grade could be achieved, irrespective of the selectivity, type or severity of the crushing process. As it was not possible to produce a poor size fraction which could be discarded as a coarse reject, the entire ROM was crushed to the target size of 0.3mm. Four distinct stages of crushing are recommended to ensure that the phosphate is not over crushed; too great proportion of the phosphate value is lost to the fine rejects.
2. The crushed phosphate ore is classified in the order of 45µm with an air classifier. According to the mass balance for the beneficiation, some 45% of the ore is discarded as fines reject containing 39% of the P_20_5.

3. The deslimed size fraction of between 300 and 45µm is consequently subjected to two stages of dry magnetic separation, achieving significant upgrading. In fact, a concentrate assaying in the region of 33% P_20_5 is produced at 38% recovery of P_20_5.

The magnetic separation steps enriched the phosphate from 4.9% to 33% P_20_5 while retaining some 79% P_20_5 recovery during the separation, an extremely selective operation.

The reasons behind the dry beneficiation process flow sheet are given below as opposed to a flotation process:

1. The dry beneficiation route succeeded in achieving merchant grade concentrate at - 5% weight recovery. It is doubtful whether improved metallurgical performance could be achieved via a wet process as the dry process is considered less expensive and extremely effective.
2. When the choice is available between wet or dry routes, i.e. both can produce merchant grade - one should invariably select the dry route, as it is less expensive in terms of investment and capital costs. There is no need to construct a large water supply and management system, thickening operations, filtration equipment etc.
3. The phosphate is extremely low grade (3 to 5%*)* and to concentrate the ore to *>30%* P_20_5 an enrichment factor of at least 15 (assuming 7% weight recovery) is necessary. At ROM costs in the region of US$2.70/ton, the beneficiation has to be both effective and reasonably priced.
4. The project site is remote and water is only available at an elevation 1000metres below the processing plant site making it an expensive commodity.
5. Based on extensive experience in phosphate processing, Bateman believed that flotation could be developed for this particular ore type successfully and would probably be capable of ensuring production of merchant grade concentrate. The incorporation of flotation would be at least an order of magnitude more expensive than the effective dry route. Flotation based beneficiation was not studied as a result of this rationale.

Chapter 5: Major, Trace and Ree geochemistry of Ghimbi-Bikilal

5.1 Major element geochemistry

The major element bulk geochemistry of the Bikilal-Ghimbi gabrro is derived from 10 samples collected during field investigation and generated by the Centeral Laboratory of Geological Survey of Ethiopia. The geochemical data are presented in table 5.1.

Table 5.1 Whole Rock Analysis Result

Sample name	BS 24A	BS 2	BS 16A	BS 20	BS 24G	BS 16	BS 24B	BS 24E	BS 25	BS 17
SiO_2	47.66	46.07	47.23	48.2	47.68	45.74	52.99	49.95	47.55	47.88
TiO_2	0.7	2.07	0.87	0.38	0.38	1.36	0.65	1.21	0.66	1.99
Al_2O_3	16.79	18.55	16.35	17.65	17.54	16.34	19.43	16.35	15.89	13.83
Fe_2O_3	9.73	12.94	10.68	8.25	8.74	12.14	5.09	10.06	6.84	14.05
MnO	0.14	0.14	0.15	0.12	0.12	0.16	0.11	0.17	0.11	0.31
MgO	9.59	6.03	10.3	10.09	10.54	9.61	3.92	6.5	11.45	7.1
CaO	12.5	10.11	11.95	12.96	12.7	11.56	12.49	11.79	15.31	11.35
Na_2O	2.22	3.25	2.26	2.1	1.89	2.25	3.7	2.69	1.24	2.51
K_2O	0.06	0.17	0.05	0.04	0.04	0.09	0.19	0.72	0.11	0.17
P_2O_5	0.01	0.03	0.01	0.01	0.01	0.02	0.07	0.19	0.03	0.16
Total	99.4	99.36	99.85	99.8	99.64	99.27	98.64	99.63	99.19	99.35

Silica contents of samples of the intrusive bodies range from 45.74 to 52.99 wt. % and K_2O from 0.04 to 0.72 wt %.Na_2O range from 1.24 to 3.7wt%. The Na_2O+K_2O versus SiO_2 classification diagram of Cox, et, al. (1979), as modified for plutonic rocks by Wilson (1989), the Bikilal-Ghimbi gabrro plots almost entirely in basic to ultrabasic magma series field, and has a gabrroic composition(fig 5.1). On the basis of the Irvine and Baragar (1971) classification scheme (Fig.5.2), all samples are sub-alkaline belonging to the calc-alkaline series, all fall in the high to medium-K calc-alkaline field and are potassic in the An–Ab–Or diagram of Irvine and Baragar (1971).

The silica content of the apatite-free gabbros and hornblendites shows a wide range from 45 to 55 wt %(W. B. Woldemichael and J. I. Kimura et al 2008).The apatite bearing subsets all plots out of range on the diagram due to their low silica content (25-45wt %). This is due to the effect of apatite concentration, which results in an abundance of P_2O_5 of up to 8 wt %. Although rock types range from fresh olivine gabrro to uralitized hornblende to hornblendites, overall the Bikilal-Ghimbi samples fall in a narrow compositional range (W. B. Woldemichael and J. I. Kimura et al 2008).

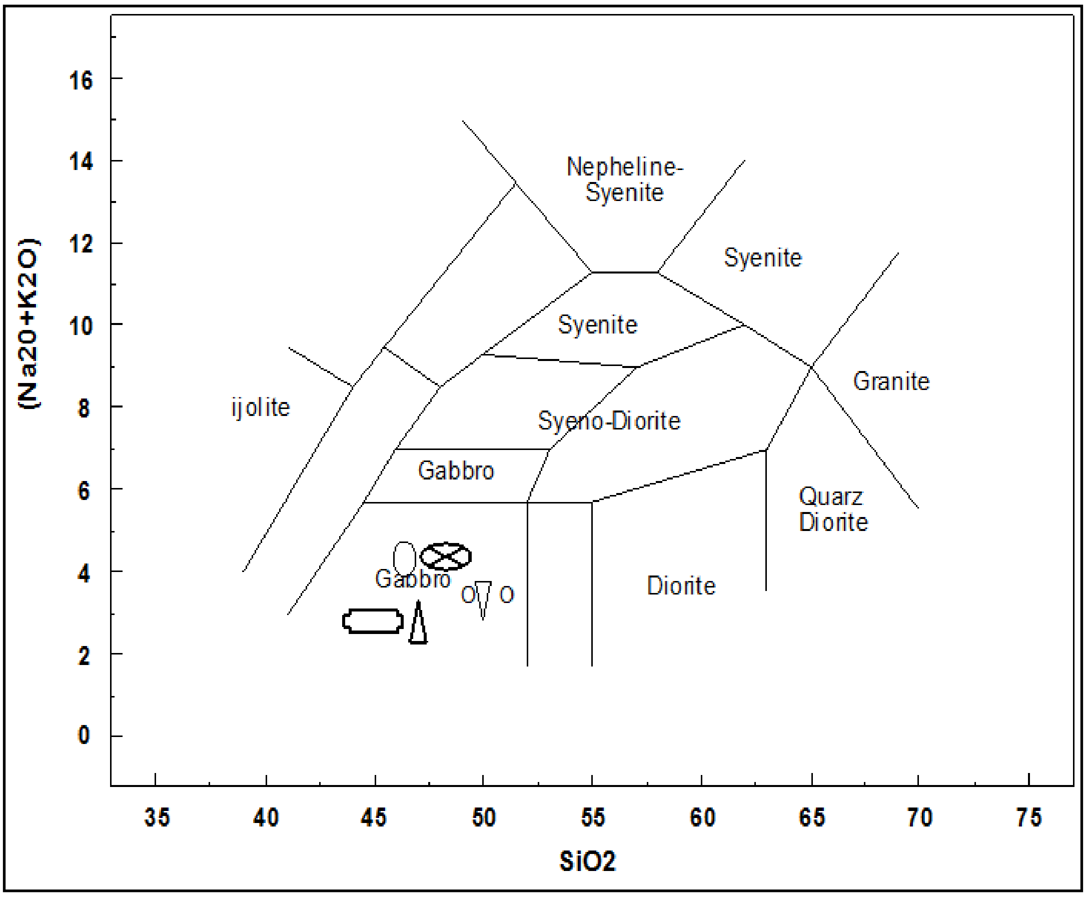

Fig 5.1 TAS classification for rocks of the study area, after (cox.et al.1979 adopted for plutons by Wilson, 1989).

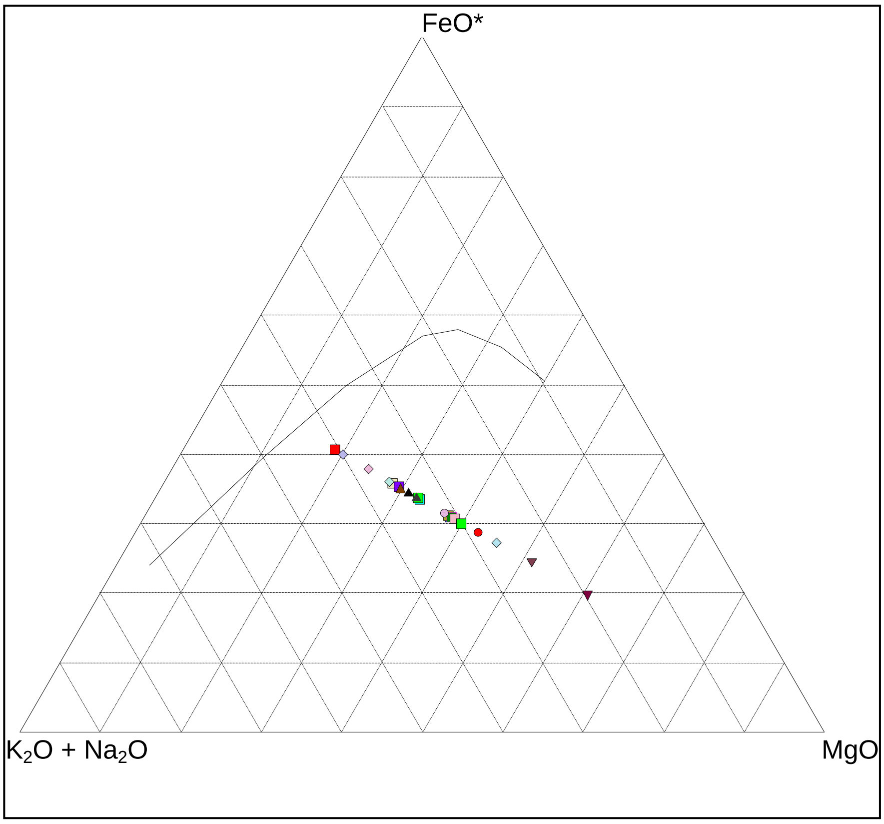

Fig.5.2 An AFM classification diagram for the Bikilal-Ghimbi gabbro showing cal-alkaline trends according to the boundary between the two fields, as proposed by Kuno (1968), showing the trend proposed by Irvine and Bargar (1971).

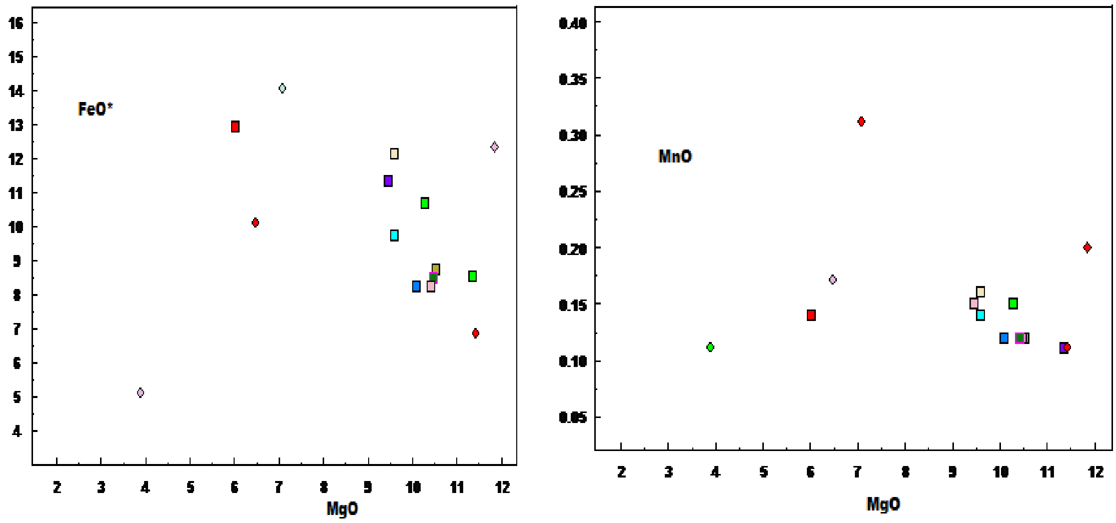

Fig 5.3 Major element MgO variation diagrams for Bikilal-Ghimbi gabbro showing no clear correlation with FeO and MnO.

No significant correlations are observed in variation grams of FeO and MnO against MgO in the Bikilal Ghimbi gabrro. The AFM triangular plot shows Fe enrichment trend for the apatite bearing subset. The boundary proposed by Kuno, 1968, reveals only both tholeiitic and calc-alkaline trend, where as only a subalkaline trend is observed according to the boundary proposed by Irvine and Baragar (1971). The MgO content of the Bikilal-Ghimbi gabrro intrusive ranges from 3.92wt%-11.45 wt %. The MgO abundance overlaps between rock suites, irrespective of the apatite content (W. B. Woldemichael and J. I. Kimura et al 2008).

5.2 Trace and Rare Earth Element Geochemistry

Unfortunately trace element analysis was not done for samples collected during this field investigation due to lack of some reagents at the Central laboratory of Geological survey of Ethiopia. Nicely generated trace element data for same area was obtained from W. B. Woldemichael and J. I. Kimura et al 2008. This Trace and REE data was partly presented in table 5.2 and part of the discussion is made based on this data.

Variations of trace elements also provides additional in sight in to the sources and major processes that controlled the nature of the volcanic products. The relative abundances of trace elements are used to identify the minerals that were present during melting or fractional crystallization. The Bikilal-Ghimbi gabbro intrusive shows slight depletion in compatible elements e.g. Ni 25-268ppm and Cr 27-475ppm.

They are enriched in incompatible elements. Various bi variate variation diagrams i.e. trace elements vs. MgO wt percentage were plotted. Selected trace elements plot against MgO are shown in (Fig 5.4). With this Rb,Y, V, and Zr, shows a decreasing trend.

The fractionation of alkali – feldspars will lead to the removal of Rb from the liquid melt. Therefore a decrease in Rb with increasing SiO_2 indicates feldspar fractionation.

Sr preferentially enters the plagioclase structure or other Ca bearing phases and shows a negative correlation. There for Sr fall is attributable to removal of feldspar and apatite. V similar to TiO_2 its fall is related to Fe –Ti oxide fractionation.

Table 5.2 REE element analysis of the Bikilal -Ghimbi intrusive (pmm)
Data Source (W. B. Woldemichael and J. I. Kimura 2008)

Sample No	TCH 23	BG 07	BG 11	BG 12	BG 16	5128	BG 35	5125	6104	6102
La	1.23	1.27	1.3	1.08	1.12	2.05	2.49	15.3	17.3	10.8
Ce	3	3.24	2.87	2.88	2.79	4.87	5.8	42	45.9	28.6
Pr	0.51	0.54	0.45	0.53	0.48	0.81	0.92	6.87	7.12	4.3
Nd	2.59	2.88	2.41	3.11	2.63	4.33	4.68	37.5	37.1	22.7
Sm	0.79	0.96	0.72	1.15	0.89	1.35	1.37	9.29	9.2	5.34
Eu	0.52	0.78	0.86	0.83	0.67	1.41	0.61	4.2	4.34	3.04
Gd	0.93	1.31	0.86	1.64	1.17	1.59	1.65	10.8	9.67	5.83
Tb	0.14	0.21	0.13	0.26	0.18	0.24	0.26	1.33	1.23	0.72
Dy	0.84	1.33	0.77	1.65	1.15	1.41	1.58	7.34	6.85	4.01
Ho	0.16	0.26	0.15	0.33	0.22	0.27	0.31	1.31	1.19	0.69
Rer	0.38	0.67	0.36	0.83	0.58	0.66	0.82	2.99	2.7	1.57
Tm	0.055	0.093	0.05	0.126	0.081	0.095	0.115	0.365	0.335	0.192
Yb	0.332	0.6	0.309	0.801	0.51	0.558	0.718	1.989	1.849	1.039
Lu	0.047	0.087	0.047	0.117	0.075	0.084	0.106	0.274	0.261	0.139

Trace elements are correlated with MgO and the variation among them is seen (Fig.5.4). The Ba, Sr, and Ga contents correlate negatively with MgO, and the chemical variation between the apatite –free and apatite bearing samples is similar, whereas in the trends for other trace elements, the apatite-free and apatite-bearing gabbros are more distinict. The apatite-free olivine gabbro shows clear correlations than the hornblende did, whose data tend to be scattered. The incompatible trace elements Y correlate positively with MgO in the apatite-bearing subset, its abundance is elevated due to the concentration of rare earth elements (REE) yttrium in the apatite (W. B. Woldemichael and J.I. Kimura et al 2008 and the references there in). The decrease in Ni content with decreasing MgO content suggests an olivine fractionation. The low Sr and Ni contents of the apatite bearing samples can’t be accounted for by apatite and Fe- Ti oxide concentration alone, suggesting a depletion of these elements in the magma.

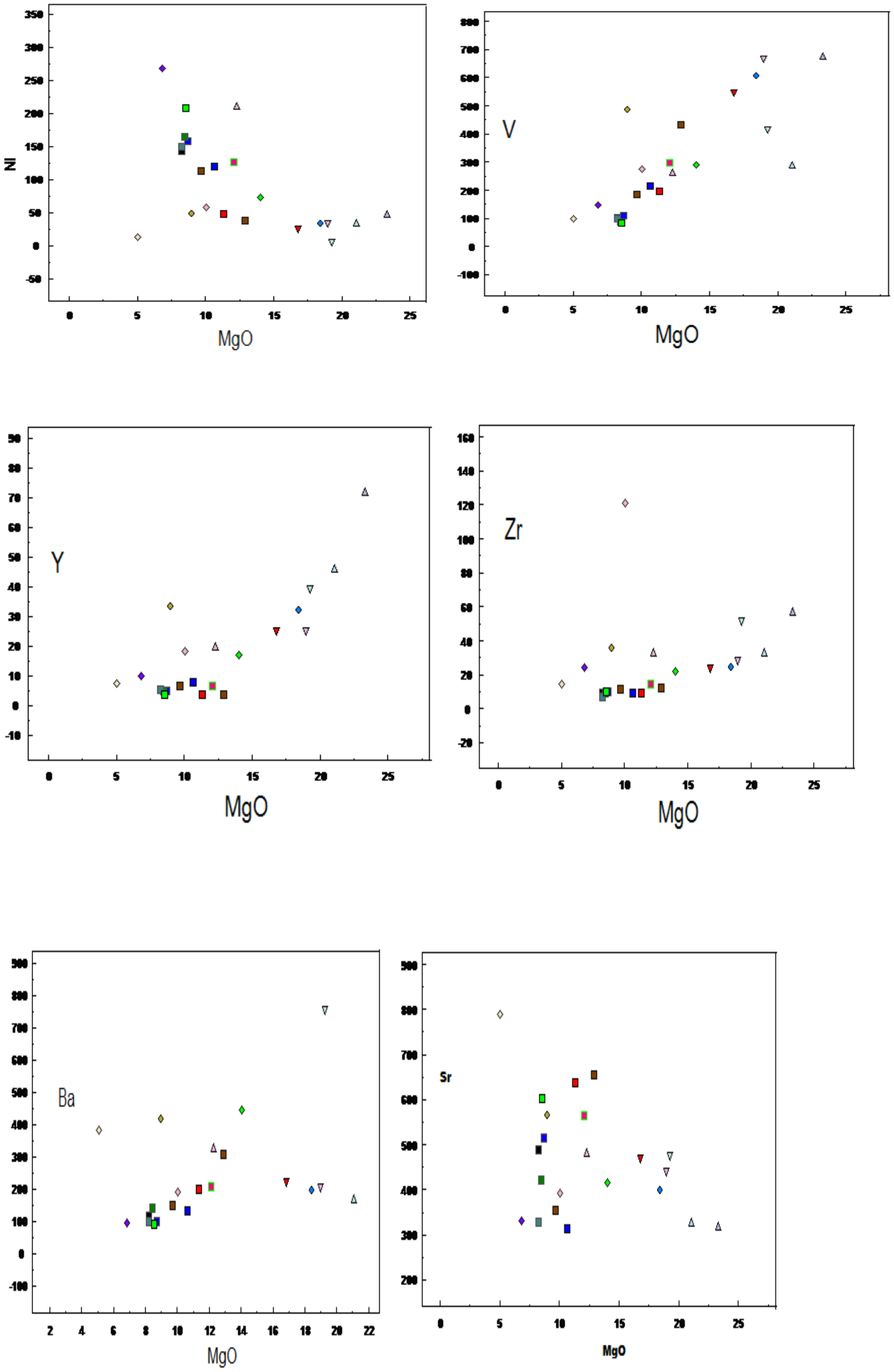

Fig5.4. Trace element vs MgO variation diagrams for the Bikilal-Ghimbi gabbro

Apatites from Ghimbi-Bikilal gabbro intrusive ores have moderate concentration of REE and show a common pattern of moderate LREE/HREE fractionation and positive Eu anomaly (fig.5.5). Moderate to steep LREE/HREE fractionation is a common characteristic of magmatic apatites connected with alkaline and maffic rocks. Different magma compositions give rise to different characteristic of REE patterns (Hess, 1989, and Wilson 1991). Strong LREE/HREE fractionation is connected with alkaline rocks and HREE>LREE distribution is connected with ultramafic rocks. Most of the apatite bearing iron ores are associated with calc-alkaline magmas with LREE/HREE fractionation varying from moderate to steep (R.Frietsch,J-A.Perdahl,1995). Eu enrichment indicates plagioclase accumulation.

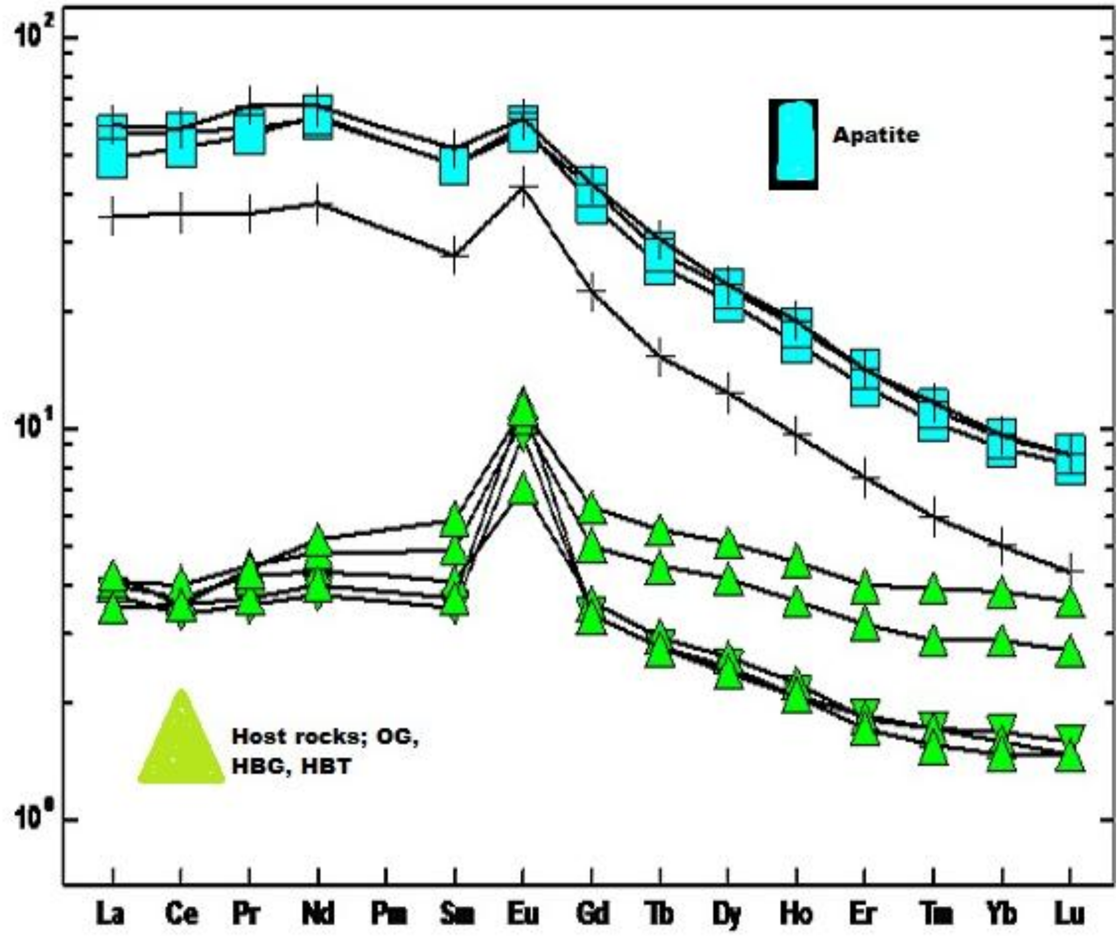

Fig 5.5 Condrite normalized REE diagram of Apatite bearing host rocks OG, HBG and HBT of Ghimbi-Bikilal intrusive rocks (Data for Bikilal from W. B. Woldemichael and J.I. *Kimura et al, 2008; and Chonrite values from Boynton 1984)*

Apatite in phosphorites (such as the Paleoproterozoic Palang deposit in northern Sweden) has a different composition (< 1000 ppm REE with Ce depletion) which excludes a sedimentary origin of the Kiruna apatite (fig.5.7). Ce deficiency, characterizing marine apatites and is not seen in igneous apatites (Laajoki, 1975; Altschuler, 1980).

According to Taylor and McLennan (1985), REE distribution patterns depend on the bulk REE composition in the parent magma. Most of the apatite-bearing iron ores are associated with alkaline to sub-alkaline magmas with a LREE/HREE fractionation varying from moderate to steep (Frietsch, 1995). REE patterns in iron-apatite ores of Bikilal-Ghimbi intrusive gabbro shows similar pattern with that of Kiruna in Sweden(fig. 5; Frietsch et al., 1995; Harlov et al., 2002), Avnik in Turkey (Helvaci, 1984; Aral, 1986), El Laco in Chile (Frutos et al., 1990), Abovjan in Russia (Frietsch et al., 1995) and Iron Spring in USA (Frietsch et al., 1995). All the above iron ores have a magmatic origin with varying apatite ore genesis (magmatic melt, hydrothermal to liquid immiscibility or the combinations of them). It can be concluded that the REE distribution in apatite magnetite ores are related to the composition and source of enclosing host rocks.

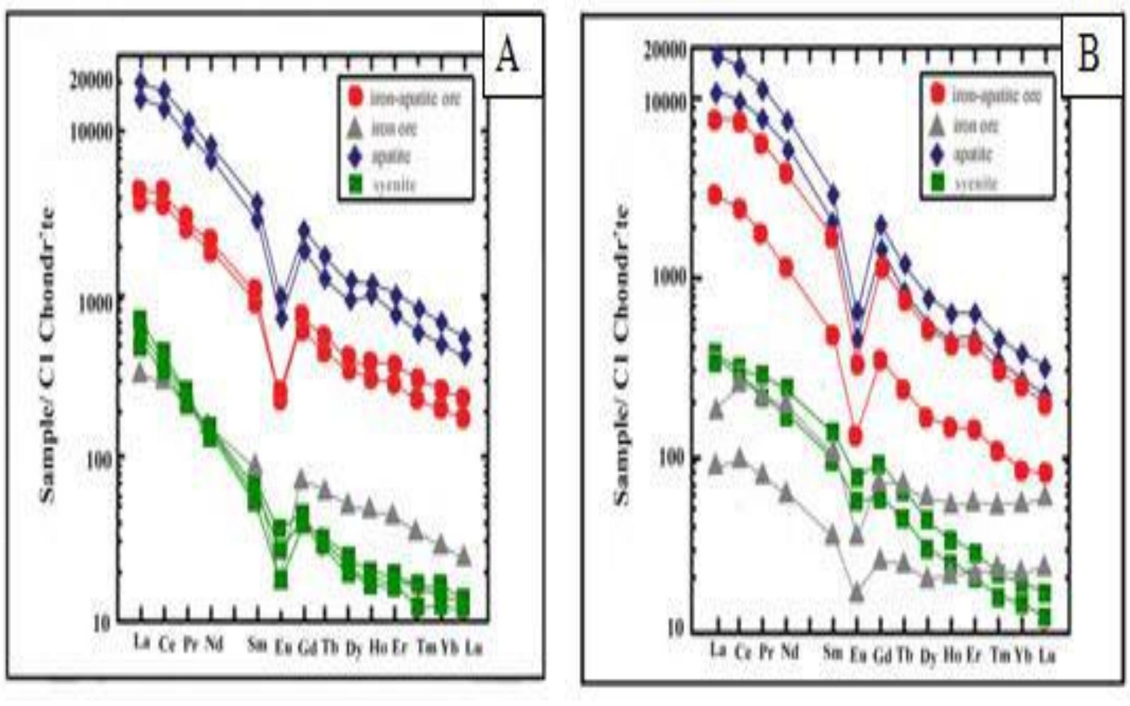

Fig 5.6 Chondrite-normalized REE pattern for apatites, apatite- bearing iron ores, iron ores and syenitic and gabbroic intrusions adjacent to them from Posht-e-Badam Block iron-apatite ores (A: north Esfordi, B: Lakeh- 3 Siah)

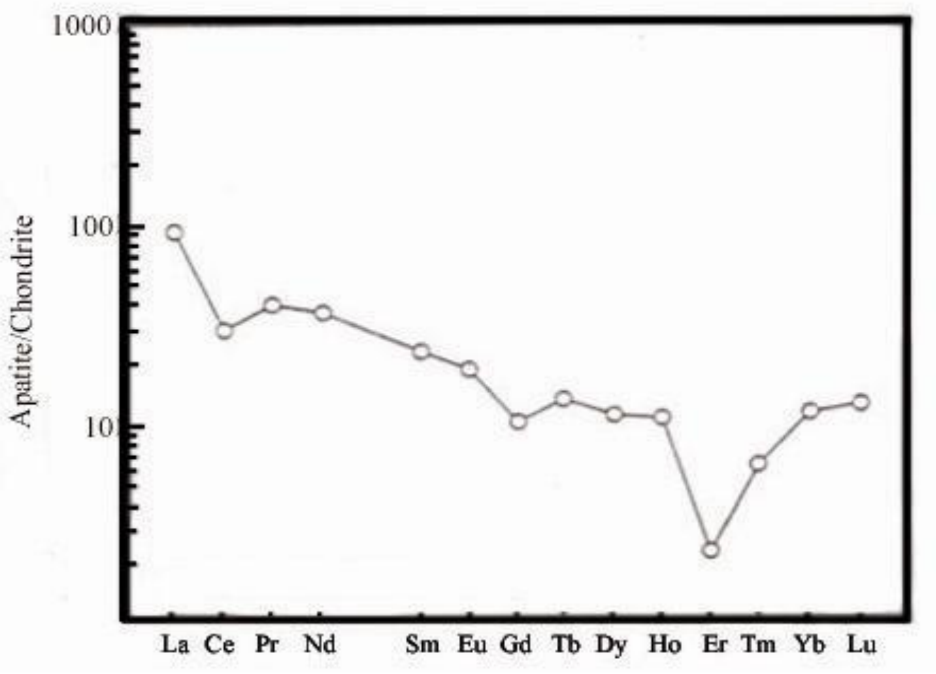

Fig.5.7 Chondrite-normalized REE pattern for apatites from phosphorites (Frietsch, 1995).Typical REE pattern for sedimentary phosphorite.

Chapter 6: Genesis of apatite in igneous rocks

6.1 General

Iron oxide–apatite deposits, recently referred to as “IOA” (Daliran, 2010; Williams, 2010) as well as the “P-rich iron oxide deposits” (Groves, 2010), are spatially and temporally excluded from iron oxide copper gold (IOCG) deposits (Groves *et al*., 2010; Williams, 2010). Iron oxide–apatite deposits occur in magmatic terrains of Proterozoic to Cenozoic ages. The Kiruna-type deposits show a common association with evolved felsic intrusions, although the nature of the relationship between intrusions and these deposits is an area of substantial argument (Hitzman, 2000; Barton& Johnson, 2004; Williams *et al*., 2005; Daliran *et al*., 2010). Examples of this type of deposits occur in Kiruna, Sweden (Harlov *et al*., 2002), Missouri, USA (Snyder, 1969), Chile (Bookstrom, 1977; Nyström , 2008), and the Bafq district of Iran (Forster & Jafarzadeh, 1994; Daliran, 2002; Daliran *et al*., 2007, 2010; Jami, 2007).

Fe-Ti-Oxide-apatite association is common to gabbroic intrusive complex in the world. Magmatic Fe, Ti oxides and P ores are commonly associated with or hosted in mafic intrusions of Proterozoic anorthosite complexes (Bateman, 1951; Lister, 1966; Force, 1991). Field evidence shows that these kind of ores occur either as disseminated oxides in homogeneous silicate rocks, or as veins, lenses or layers of massive Fe, Ti oxides_apatite (i.e. nelsonite) that are in sharp contact with their host rocks (e.g. Willemse, 1969; Duchesne, 1999). The origin of these ores has been controversial partly as a result of such diversity. Two attractive but contrasting models proposed for their formation include sorting of Fe,Ti oxide crystals from magmas (Emslie, 1975; Ashwal, 1978; Duchesne, 1999; Charlier et al., 2006), and accumulation of oxide melts that resulted from immiscible separation in magmas (Lister1966; Kolker, 1982; Force, 1991; von Gruenewaldt, 1993).

A unique feature of Fe,Ti oxide-apatite ores and associated intrusive rocks is their magmatic origin. They underwent slow cooling in crustal magma chambers, a process that modifies both the original composition and textures of the oxide minerals present in them (Frost & Lindsley, 1991, 1992).This leads to a loss of magmatic information that is critical in the understanding of the origin of these ores (Downloaded from http://petrology.oxfordjournals.org/ at Addis Ababa University Libraries on April 16, 2013).

According to Frietsch and Perdahl (1995) most of the apatite-bearing iron ores are associated with calcalkaline magmas with a LREE/HREE fractionation varying from moderate to steep. The apatites of the volcanogenic magnetite–apatite ores of the Kiruna type mainly show similar REE patterns with some variation in the total content and the LREE/HREE fractionation varying from moderate to steep (Frietsch & Perdahl, 1995). Europium depletion results from Eu distribution into Ca-plagioclase in the early stage of crystal differentiation. In the apatite of many Kiruna type iron ores (namely Avnik, Bafq, E1 Laco and Abovjan), the total content of REE is high with pronounced negative Eu anomalies (Daliran, 2002).

The source magma for the gabbroic intrusive may be formed from sulphur- poor fluid melts that was enriched in Fe, P and REE (Daliran and Stosch (2005). The source of these fluids may be linked to mantle degassing or to carbonatite magmas as is suggested by Samani (1998). Hauck (1990) states that alkaline magma is the ultimate source of iron-rich melts, which he suggests to have been derived from it by liquid immiscibility.

Phosphorous is incompatible in the mantle mineralogy and during partial melting will be quickly concentrated in the melt (Hugh R.Rollinson et.al 1993). The magmatic model that explains the formation of these types of deposits from high temperature, volatile-rich iron oxide and P melts, mainly based on textural magmatic features dendritic magnetite igneous structures, and the relation between the ores and their host rocks with El Laco as the most spectacular example. Chemical data from magnetite and apatite is also used to support the model (Frietsch and Perdahl, 1995; Naslund et al., 2002; Nyström and Henríquez, 1994). Broman et al. (1999) interpreted fluid inclusion data from pyroxene and apatite at El Laco to have formed from a late-magmatic remnant fluid gradually becoming lower in temperature and salinity.

6.2 Genesis of Apatite in Bikilal-Ghimbi gabbro intrusive rocks

The Bikilal-Ghimbi intrusive apatite is much more related to that of iron oxide, apatite deposits of Posht-e-Badam Block (central Iran) age wise. The Ghimbi –Bikilal emplacement ages is 541-624 Ma (Ayalew, 1990, Kebede, 2001 and Grenne, 2003). Posht-e-Badam Block has been formed 539 and 527 Ma and was concluded to be of magmatic origin.

Apatites from iron ores of the Posht-e-Badam Block are commonly fluor-apatite (Borumandi, 1973; Darvishzadeh, 1982). A similar feature is observed in the apatites from Kiruna-type ores (Parak, 1985). This feature is typical for the igneous apatites such as those from the Skeargaard intrusion, which show high F/Cl ratios (Brown and Peckett, 1977). That of Bikilal-Ghimbi gabbro intrusive apatite is hydrxylfluor-apatite. The fluor-apatite content of igneous apatite seems to be spatially and temporally related.

Petrogragraphic study of bulk rock samples both surfacial and underground indicated that the host rocks of apatite, ilmenite-magnetite constitutes gabbric body. The intrusive gabbro is partitioned into olivine gabbro, hornblende gabbro and hornblendite litholgies. Although the grade of ores differ from lithology to lithology and from surface to sub surface they occur in all lithologies indicating that they are of the same magmatic source. W. B. Woldemichael and J.I Kimura et, al 2008, showed and analyzed apatite bearing and apatite free olivine, apatite bearing and apatite free hornblende gabbro and apatite bearing and apatite free hornblendite in their petrographic work of the area. This indicates that there were episodes of apatite bearing eruptions and zone of mineralization and/or non conducive environments for ore depositions. The source magma for the gabbroic intrusive may be formed from sulphur- poor fluid melts that was enriched in Fe, P and REE (Daliran and Stosch (2005).

From the literatures and analytical point of views it is practical to test against the following hypothetical genesis model for apatite, magnetite, ilmenite ores in Bikilal-Ghimbi gabbro intrusives.

6.2.1 Liquid Immiscibility

Magmatic melt processes for the genesis of Bikilal-Gimbi gabbro apatite, ilmenite, and magnetite ore deposit applies depending on the existing data. The field observations, petrological and whole rock chemical analyses all show their magmatic origin. The REE patterns for apatite and host rocks of Bikilal-Gimbi gabbro intrusive confirm same magmatic origin. The REE patterns of the Bikilal –Ghimbi gabbro intrusive rocks show a common origin of the oxide and phosphate ores and the gabbroic host rocks (Fig.5.3). The host rocks are crystallized from the tholiitic to sub-alkaline parental magmas in an intraplate continental arc tectonic setting (W. B. Woldemichael and J. I. Kimura et al 2008).

Fe-Ti-oxides and P mineralization is common to gabbric intrusive complexes in the world. The origin of Fe–Ti oxides and P in ferro basaltic magma can generally be accepted to be magmatic, with liquid immiscibility between silicate magma and iron-titanium phosphorous- oxide magma, small percent partial melting of Fe and P-rich crustal rocks, or extreme crystal fractionation is the most commonly cited processes (Philpotts, 1967; Kolker, 1982; Barton & Johnson, 1996; Naslund, et al., 2000). When the Bikila- Ghimbi intrusive Fe-Ti oxides and P ores were assessed for involvement of immiscible geochemical processes, some signatures are determined. The samples are examined optically for evidence of textures such as ocelli, globular structures, spheroidal bodies (Ferguson, 1964; Sorensen et al., 2003), ovoid bodies and net texture are observed. Observed net texture structures of oxide and phosphate ores and silicates in Bikilal-Ghimbi gabbro are clear indicatives of crystallizations from immiscible magmas (Fig 4.3). The globular textures of minor sulfide (oxide) disseminations in the Skaergaard and Sudbury intrusions have been considered a diagnostic evidence of sulfide immiscibility (Wager, Hawley 1962). Similar minor sulfides (oxides) are indicated in Bikilal-Ghimbi gabbro intrusive which is an additional evidence of liquid immiscibility for its magmatic activity.

Another useful criterion for recognizing sulfide immiscibility in silicates is the depletion of chalcophile elements (eg. Ni, Cu) in the resulting igneous rocks, because chalcophile elements are strongly partitioned into the sulfide phase. Bikilal-Ghimbi gabbro intrusive shows its chalcophile elements depleted and this can be a clear evidence of liquid immiscibility.

Occurrence of Cr-poor titanomagnetite, granular ilmenite and apatite as clusters in the net-textured ores may have formed from Fe-Ti-(P) rich melts. Similarly Fe-Ti-(P) rich melts were immiscible in silicate magmas incongruent to the formation of magmatic sulfide ores and that immiscibility occurred because of oversaturation of Fe, Ti and P during the crystallization of silicate minerals. The segregation of dense Fe-Ti-(P) rich melts behaved like a heavy mineral that settled downward in a silicate crystal mush to form a net-textured and massive Fe-Ti oxide ores as part of the cumulate sequence (www.minersoc.org).

The settling out of the heavier sulfides and oxides result in the peculiar net-textured ores often found in many of the deposits (ww.cps-amu.org/sf/notes/b3-3-2.htm). In the magma chamber, the phosphorous and alkali content probably led to the formation of a Fe–F, CO_2–H_2O–P–Na dominated immiscible melt which separated from a silica-rich melt.

The role of other volatile constituents such as CO_2 and F is also important in this process (Weidner 1982). The presence of hydroxyl fluor-apatite and hydrous minerals (amphiboles) also suggests high F and H_2O content. Both experimental and theoretical analyses of the behavior of volatile-rich magma systems stress the important role liquid immiscibility may play (Kolker 1982).

It means that segregation of the magma were done within the crustal depth and wasn't complete. Silicate portion formed gabbroic intrusions and oxide-phosphate melt ascent to upper parts within the magma chamber.

The breakdown of this late immiscible phase has resulted in the formation of magnetite–apatite melt, which behaved intrusively at Bikilal-Ghimbi area into the N-S trending shear belt of Gneissic body. The immiscible phases of silicate and oxide- phosphates separation, breakdown and crystallization might have occurred for more than two episodes. This has resulted in occurrence of different ore zones which were identified as upper and lower zones of apatite ore mineralization in which case the lower zone was identified to be more p-rich. This might have accounted for the higher density of ore carrying immiscible fluid than the silicate melt.

The intrusion of the separated iron-oxide, phosphorus melt depends upon depth of separation, volatile content, and finally presence or absence of favorable tectonic and structural conditions seem preconditions for Bikilal-Ghimbi gabbro intrusive and apaptite-oxide ores in it.

6.2.2 Hydrothermal Alteration

Ghimbi Bikilal apatite, magnetite and ilmenite mineralizations need to be tested against hydrothermal alteration hypothesis. From the field observation, breciation of out crop rocks and weathering and alteration of lithologies are very minimal except in hornblendites at places. Moderate weathering prevails at the top most part of hornbelendites where massive magnetite ore occurs (fig.1.2). This is related with less resistance of magnetite to weathering. Olivine gabbro was repeatedly reported to be surprisingly of very fresh. The secondary minerals reported are actinolite and chlorite which may be formed during eruption episodes due to volatile fluids. No actinolization and K-feldspar alteration are observed around the ore and form metasomatic aureoles (halos) around the ore veins. This was only seen at places where hornbledite is in contact with the eastern gneiss limited to the periphery.

The hydrothermal alteration can be tested with element mobility in the crystallization of the melt. Element mobility describes the chemical changes which takes place in rocks after its formation, usually through interaction with a fluid. The mobility of major elements is controlled by three main factors: the stability and composition of the minerals in the unaltered rocks, the stability and composition of the minerals in the alteration product, and the composition, temperature and volume of the fluid phase.

Hydrothermal alteration around the iron oxide–apatite mineralization and the host rock can be detected from microscopic textural analysis. Minor alterations of pyroxenes to amphibole are observed in thin section analysis. And trace alteration of magnetite to hematite was observed in reflecting ore microscope. When the proportions of ore minerals are analyzed, hematite content is very minimal indicating low or no hydrothermal processes taking place in the ore genesis. Larger quantities of specular hematite are in all probability due mostly to hydrothermal or metamorphic activity (Rahmdor P., 1980). In

Bikilal- Ghimbi gabbro intrusive hematite ore is negligible which constrain less or no hydrothermal alteration.

The role of other volatile constituents such as CO_2 and F is also important in this process (Weidner, 1982).The presence of hydroxylfluor-apatite and hydrous minerals (amphiboles) also suggest some F and H_2O content. At places some pyroxenes are altered to amphiboles. These are indications of hydrothermal processes that took place after the mineral segregation. Secondary minerals like hematite are very rare. Sodium, aluminum feldspars are not far beyond the normative percentages. But these findings are not sufficient enough to conclude that ore genesis of Bikilal-Gimbi apatite ore to be of hydrothermal, although these have some additional impacts in crystal growth of magnetite-apatite minerals and alteration of magnetite to hematite.

In hydrothermal alteration significant secondary minerals are observed. In case of Ghimbi-Bikilal gabbro intrusive no significant secondary minerals are reported. But some uralitization of pyroxene to hornblende were observed (W.B. Woldemichael and J. I. Kimura et,al 2008) and this can be associated with late stage hydrothermal recrystallization (Deer et, al 1992). W.B. Woldemichael and J.I.Kumara et, al 2008) nicely sampled individual representative clinopyroxene and olivine and analyzed rim and core conditions and draw the conclusions above.

The most common mineralization occurring in the area is apatite, magnetite- ilmenite and rare sulfides. The type of apatite is hydxy-fluor apatite. The apatite magnetite- ilmenite ore and iron ore of Bikilal deposit are genetically intimately associated with crystallization and intrusion history of Bikilal layered gabbro intrusive.

Chapter 7: Summary and Discussion

The apatite bearing intrusive gabbroic rocks at Ghimbi-Bikilal are formed as the result of basic magmatic intrusion of tholiitic parental magma type. The REE patterns of the Bikilal –Ghimbi gabbro intrusive rocks show a common origin of the oxides, phosphate ores and the gabbroic host rocks (Fig 5.5). The host rocks are crystallized from the alkaline to sub-alkaline magmas.

The source of these fluids may be linked to mantle degassing or to carbonatite magmas as is suggested by Samani (1998). Hauck (1990) states that alkaline magma is the ultimate source of iron-rich melts, which he suggests to have been derived from it by liquid immiscibility and of sulphur-poor fluid source that was enriched in Fe, P and REE. According to Maaloe and Aoki, et al, 1977, most of the P_2O_5 reside in the lower mantle and the remaining in the upper mantle. The source of this magma seems the partial melting of the upper mantle. The magma has undergone several fractionation and crystallization followed by liquid immiscibility as evidenced by the textural studies, REE signatures and petrographic indications. I.e., the ores and silicates segregated into cumulate of the study area show net textures among their anhedral crystal grains and the Eu enrichment is due to plagioclase accumulations during magmatic processes. The iron-apatite ores of Bikilal-Ghimbi gabbro was probably formed by magmatic differentiation of an alkaline magma rich in Fe and incompatible elements such as P, REE, Th, U and F that were derived by partial melting of the upper mantle. Deep seated faults caused ascending of parent magma and emplacement in the upper parts of the crust. This fault may be related with N-S trending of Didessa shear belt as the gabbroic intrusive body is in line with this belt.

In the magma chamber, the phosphorous and alkali content probably led to the formation of a Fe–F, CO_2–H_2O–P–Na dominated immiscible melt which is separated from a silica-rich melt.

The phosphorous content and the so-called alkali-iron effect (Guilbert and Park 1997) fluxed the immiscible melt and kept iron in solution at temperatures significantly lower than the melting point of magnetite at rather shallow depth (Moore and Modaberi 2003). The role of other volatile constituents such as CO_2 and F is also important in this process (Weidner 1982). The presence of hydroxyfluor-apatite and hydrous minerals (amphiboles) also suggests high F and H_2O content. Both experimental and theoretical analyses of the behavior of volatile-rich magma systems stress the important role liquid immiscibility may play (Kolker 1982).In some places, immiscible portions of phosphates, oxides and silicates can be seen within another portion.

It means that segregation of the magma were done within the crustal depth and wasn’t complete. Silicate portion formed gabbroic intrusions and oxide-phosphate melt ascent to upper parts within the magma chamber.

The breakdown of this late immiscible phase has resulted in the formation of magnetite–apatite melt, which behaved intrusively at Bikilal-Ghimbi area into the N-S trending shear belt of gneissic body. The immiscible phases of silicate and oxide- phosphates separation, breakdown and crystallization might have occurred for more than two episodes. This has resulted in different ore zones which were identified as upper and lower zones of apatite ore mineralization in which case the lower zone was identified to be more p-rich. This may account for the higher density of ore carrying immiscible fluid than the silicate melt.

The intrusion of the separated iron-titnium-oxide, phosphorus melt depends upon depth of separation, volatile content, and finally presence or absence of favorable tectonic and structural conditions seem preconditions for Bikilal-Ghimbi gabbro intrusive and apaptite-oxide ores in it.

Presence of volatiles led to the minor alteration, breciation and metasomatism of country rocks at the peripheral of Eastern part of the study area. The segregation of dense Fe-Ti-(P) rich melts behaved like a heavy mineral that settled downward in a silicate crystal mush to form net-textured and massive Fe-Ti oxide ores as part of the cumulate sequence (www.minersoc.org), while the phosphate crystallize and settle lately with the silicates especially in plagioclase. Most of the high concentration of REEs was probably partitioned as F-REE complexes in the fluorine-dominated fluid generated during volatile exsolution. The majority of the REEs are contained in apatite as apatite has a tolerace to accomodate even half of the elements in the periodic table. Although the ore genesis is attributed to many magmatic processes, it is proposed that liquid immisciblity played a great role in the genesis of apatite in Bikilal- Ghimbi gabbroic intrusive rocks.

Chapter 8: Conclusions and Recommendations

8.1 Conclusions

The origins of phosphorus, iron oxide magmas have been controversial, but increasing evidence exists to support an origin through the breakdown of oxidized intermediate silicate magmas into a pair of immiscible melts.

The petrographic study of the Bikilal-Ghimbi gabbro intrusive shows an affinity to alkaline to sub-alkaline magmas. The REE patterns of the Bikilal –Ghimbi gabbro intrusive rocks show a common origin of the oxide and phosphate ores and the gabbroic host rocks (Fig 5.5). The host rocks are crystallized from the alkaline to sub-alkaline magmas. A probable source for this ore forming magmatic process was partial melting of mantle rocks and/or mantle degassing.

Alkaline magma is the ultimate source of iron-rich melts, with sulphur-poor fluid source that was enriched in Fe, P and REE derived from it by liquid immiscibility.

It is proposed that the Fe-Ti-(P) rich melts were immiscible in silicate magmas similar to the formation of magmatic sulfide ores and that immiscibility occurred because of oversaturation of Fe, Ti and P during the crystallization of silicate minerals.

Iron-apatite ores of the Bikilal-Ghimbi gabbro intrusive has comparable REE patterns that demonstrate a similar origin and processes in their genesis with the host gabbro intrusive of Neoproterzoic age. The ores were formed during magmatism as immiscible liquids which separated from the strongly differentiated magmas, aided by large volatile and alkali elements content.

In summary, it may be concluded that following the establishment of late Proterozoic tensional orogeny in the Bikila-Ghimbi area and the onset of ultramafic magmatism followed by segregation of dense Fe-Ti-(P) rich melts which settled downward in a silicate crystal mush form net-textured and massive Fe-Ti oxide and phosphate ores as part of the cumulate sequence at this region. In view of the ore bodies, neither of the hypotheses alone can be held responsible for the formation of them. Therefore, it is suggested here that the separation of an iron oxide melt and silicate melt as immiscibility and the breakdown of this late immiscible phase has resulted in the formation of magnetite–apatite melt, which behaved intrusively at Bikilal-Ghimbi area into the N-S trending shear belt of gneissic country rocks.

Therefore among the ore genesis models proposed, liquid immiscibility played a great role in the genesis of apatite in Bikilal- Ghimbi gabbroic intrusive rocks.

8.2 Recommendations

1. The hydrothermal solution involved in the ore forming processes was not identified whether juvenile or meteoric.
2. The age of Bikilal-Ghimbi gabbro intrusive and gneissic country rocks need to be clearly identified by isotopic studies.
3. 3.The share of each of liquid immiscibility and magma fractionation as well as hydrothermal fluid processes in the genesis of apatite need to be clearly investigated with additional isotopic studies.
4. The economic viability of the ore minerals should be evaluated together rather than separate evaluation of agro mineral at one time and iron at another and ilmenite resource totally unconsidered.
5. For apatite resource to be exploited economically, the feasibility should be revised against the current market rates and floatation need to be considered in its beneficiation process as nearly half of it is lost through fine eject.
6. It may be worth considering the recovery of ilmenite from these deposits as additional economic mineral for use in the pigment industry.
7. Infrastructures which were main traits for iron- apatite ore exploitations of the study area were electricity (power), road and water. Now sufficient power is available at Ghimbi town sub-station, road is under construction by URAP (universal road access program) and it is easy to develop the nearby water sources from Jejeba and Soti rivers by construction of river intake structures or weir for ore processing purpose.

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