ADDIS ABABA UNIVERSITY

COLLEGE OF NATURAL AND COMPUTITIONAL SCIENCES

SCHOOL OF EARTH SCIENCES

PETROGENESIS OF GRANITOID ROCKS OF ASSOSA AREA, WESTERN ETHIOPIA

A thesis submitted to school of Earth sciences in partial fulfillment of the requirements for the degree of Master in Geochemistry

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Abstract

The main objective of this research study to constrain the petrogenesis of granitoid rock of Assosa area. To achieve objective successfully, different research method had been done like: field investigation, petrographic analysis and description and geochemical data analysis and interpretation. Assosa granite rocks dominated by alkali feldspar, plagioclase feldspar and quartz mineral in addition to these the muscovite, biotite, sphene, and hornblend, garnet and opaque mineral occurred. Granitoid rock samples of the area characterized by medium to coarse-grained texture, euhedral to subhedral crystal shape, granular, intergranular texture of opaque mineral(Fe-Ti oxides) and alteration of plagioclase and alkali-feldspar lead to formation of sericite/muscovite and chlorite. An Assosa granitoid rock is categorized under alkali-feldspar granite and syenogranite of plutonic igneous rock classifications on QAP diagram. Scattered data follows and negative trend correlation of some major element versus to SiO_2 indicate the occurrence of fractional crystallization and alteration or mobility elements. It has charactestics of both volcanic arc granitoid (VAG) using trace element tectonic discriminators like: Rb versus Y +Nb and Rb versus Yb + Ta and syn-collisional granitoid (Syn-COLG) Nb versus Y, which resembles subduction zone or island arc environment related granitoid rock formation. The Enrichments of LREE, negative Eu anomaly and slight to moderate flat HREE on Chondrite-normalized and highly deplement of Sr, Ti, P and negative anomaly of Nb and Ta multi variation element pattern diagram indicate common source region and arc-related magmas result from more mafic magmatic source that undergo fractional crystallization. High contents Uranium, Thorium and Potassium in both normalized and variation element diagram and negative anomalies of Nb and Ta indicate that granite of the area are mainly from continental crust of arc-related magmatism. Based on variation diagram of compatible (Sr) versus incompatible (Rb) on log scale representation wide variation in the concentration of Sr but the concentration Rb remain constant. This show that Assosa granite mainly resulted by fractional crystallization of mafic magma related to arc setting.

List of Acronyms

Abbreviated Minerals and Rocks

Ab	Albite
An	Anorthite
Bt	Biotite
Garnet	Gt
Hbl	Hornblend
Kfs	K-feldspar
Ms	Muscovite
Mg	Metagranite
Opq	Opaque
Or	Orthoclase
ORG	Orogenic Ridge Granitoid
Pl	Plagioclase
QAP	Quartz Alkali-feldspar Plagioclase
Qtz	Quartz
QtzVs	Quartz Veins
Spn	Sphene
Syn-COLG	Syn-Collisional Granitoids
XPL	Crossed Polarized Light
ICP-AES	Inductively Coupled Plasma-Atomic Absorption Spectrometry

other abbreviated term used (Continued)

ALS	Australian Laboratory Services
ANS	Arabian Nubian Shield
ASI	Alumina Saturation Index
GSE	Geological Survey of Ethiopia
GPS	Global Positioning System
HREE	Heavy Rare Earth Element
LFSE	Low Field Strength Element
LOI	Loss of Ignition
LREE	Light Rare Earth Element
MB	Mozambique Belt
MER	Main Ethiopian Rift
PPL	Plane Polarized Light
REE	Rare Earth Element
TAS	Total Alkali Silica
UTM	Universal Traverse Mercator
VAG	Volcanic Arc Granitoids
WEB	Western Ethiopian Belt
WES	Western Ethiopian Shield
WPG	Within Plate Granitoids
ICP-MS	Inductively Coupled Plasma-Mass Spectrometry

CHAPTER-ONE

1. INTRODUCTION

1.1 Background

The concept that the chemical characteristics of many igneous rocks reflect the composition of their source regions is widely accepted. This concept has been used in many studies of the petrogenesis of volcanic and plutonic rocks of diverse compositions and sources. Interpretation of the chemical variations within granitoids suites and their relationship to petrogenesis and source rock compositions is still controversial (Soltani, 2000) discussed on his paper of geochemistry and geochronology of I-type granitoid rocks.

The petrogenetic study of an igneous rock or suites of igneous rocks is used to determine the chemical and mineralogical composition of the parent at the time of melting, information parent prior to melting, the extent of partial melting, the temperature and pressure condition during partial melting, and modification of the primary melt composition due to differentiation, and reaction of resulting melts or rocks due to mixing of melts; assimilation, metasomatism, zone refining or late stage residual fluids. The crystalline basement in western Ethiopia contains two major rock groups, high-grade gneisses which are often intensely migmatised, and volcano-sedimentary greenschist assemblages with associated linear belts of ultramafic rocks at Yubdo-Dalatti-Tullu Dimtu (from south to north),as discussed Tesfaye Kebede et al.(1999).

All granites are, in a sense, fractionated rocks, especially ‘high-temperature’ I-type granites because they formed originally from a magma that was completely or largely molten(Chappell et al., 1998).The felsic composition of igneous rocks corresponding to ‘a minimum-melt’ will only result when all restite has been removed and further crystal fractionation continues(Soltani, 2000).

Major element geochemistry reflects the petrogenesis of the three contrasted groups of granitoids. On the basis of Shand's. (1943) and Lacroix's. (1933) chemical classifications, crustal granitoids are calc-alkaline and peraluminous, mixed-origin granitoids are calc-alkaline and metaluminous whereas mantle-derived granitoids are alkaline or peralkaline.

The scarce tholeiitic granites belong to the mantle-derived group, stated by Bernard Barbarin. (1990).Most granitoids of significant volume occur in areas where the continental crust has been thickened by orogeny, either continental arc subduction or collision of sialic masses. The term 'granitoid'is used in the general sense for plutonic rocks ranging in composition from tonalite to alkali feldspar granite with quartz contents between 20 and 60% by volume of the rock. Although granitoids are the most abundant rock types in the continental crust, no single classification scheme has achieved widespread use.

A geochemical classification for granitic rocks, granitoids can be result from differentiation of any hypersthene-normative melt and from partial melting of many rock types Frost et al. (2001). Furthermore, granitic melts may be derived solely from crustal components, may form from evolved mantle-derived melts (Frost et al., 2001). Because of this complexity, petrologists have relied upon geochemical classifications to distinguish between various types of granitoids. Detail and comparative petrological and geochemical study of granites in western Ethiopia (Assosa) appears to be one of the ways to understand the petrogenesis, geochemical characteristics and their relationships of granitods rocks of an area.

1.2 Geographic setting of the study area

1.2.1 Location and Accessibility

Assosa is the capital city of the Benishangul-Gumuz Regional State, which is located 97km east of Ethio-Sudanese border and 667km northwest of Addis Ababa in western Ethiopia. The town is located at a latitude and longitude of 10°04N 34°31E, with an elevation of 1570 meters above sea level. The study area have latitude and longitude of 10º 02' 37.3'-10º 04' 00" N and 34º 31' 00"-34º 33' 24.2" E respectively. It is accessible through the main asphalt road that runs from Addis Ababa -Nekemte to Assosa. The project area located at 3km from Assosa town toward southeast direction which locally known to be Enzi.

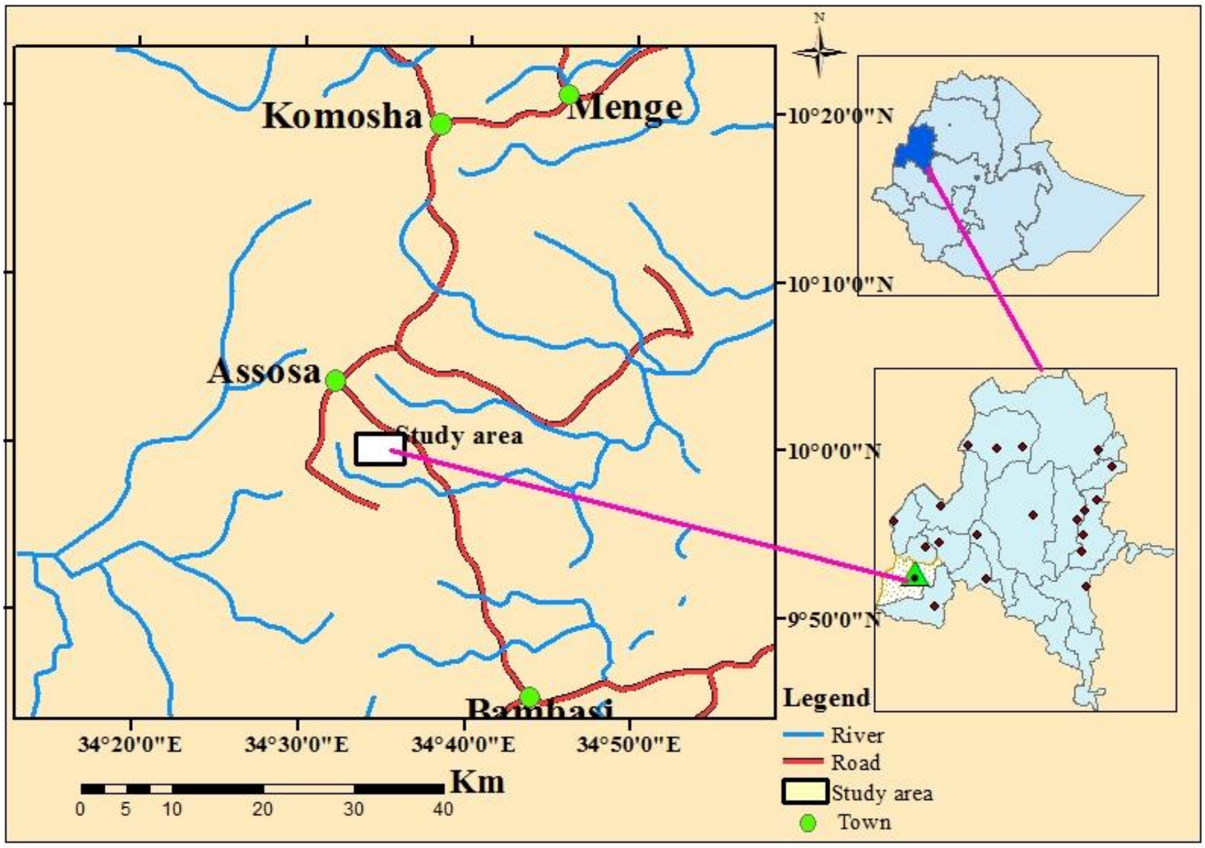


Figure: 1. 1. *Location map of the study area*

1.2.2 Physiography and Drainage

Ethiopia's topography consists of a central high plateau (Ethiopian Plateau) bisected by the Ethiopian segment of the great rift valley into northern and southern highlands and surrounded by lowlands, more extensive on the east and southeast than on the south and west. The plateau varies from 1,500 to 3,000 meters above sea level and features mountainous uplands separated by deep gorges and river valleys, especially in the north. Assosa town has an elevation of 1570m with flatland topographical features. The zone of influence is characterized predominantly by flat to rolling terrain, sloping from a general elevation of around 1600m near Assosa town. The study area is part of the western Ethiopia lowland locally characterized by rugged and mountainous surrounding of town to gentle and flat topography with escarpments and hills at places. There are a number of isolated hills and outcrops rising a few hundred meters above the prevailing elevation of the sloping plateau. The drainage patterns are generally dense, dendritic and sub-parallel. Generally, the streams drain toward southwest and ultimately join the main Mengele 29 which is the tributary of Dabus river. All the streams crossing the study area are intermittent.

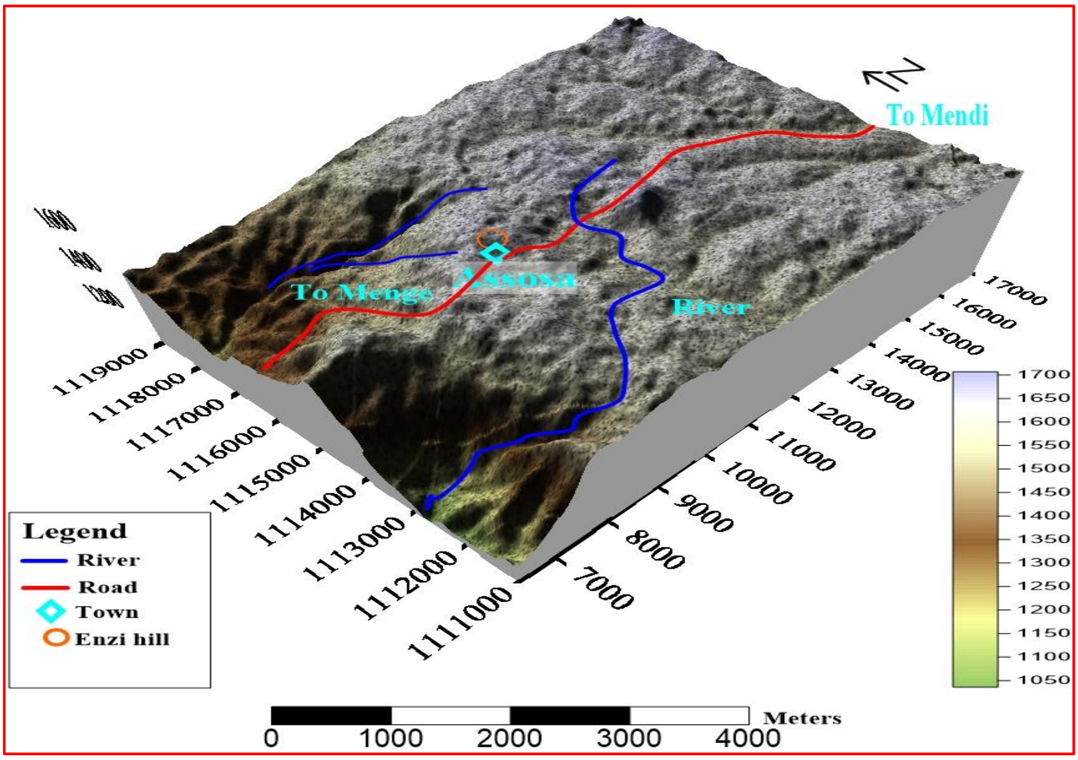


Figure: 1.2 *Physiographic map of study area(using sulphur10 version software).*

1.2.3 Climatic condition and vegetation coverage

1.2.3.1 Climatic conditions

The mean monthly temperature of the Assosa town varies between 18 and 25°C, the annual mean temperature being nearly 22°C, this implies that the temperature condition of the area categorized under tropical or kolla climatic condition. The mean annual rainfall of the town is about 1200mm. The highest rainfall concentration occurs in June, July, August and September. About 75% of the State is classified as "kola" (lowlands) which is below 1500 meters above sea level. The average annual temperature reaches from 20-25°C.The annual rainfall amount ranges from 500-1800mm in the region. The rainy season spreads through May to October. "The average annual rainfall is around 1200mm near Assosa, reducing northwards and westwards down to about 800mm. The rainfall pattern is uni-modal with about 6-7 months dispersion from April to October. The area generally has a relatively high moisture deficit, which is most pronounced close to the Sudanese border and to the north.

Mean maximum temperature and mean minimum temperature data for Assosa stations for the years (2009-2015) are available and mean monthly temperature was computed as described below graphically. The data shows that the lowest temperature occurs in year 2012 and 2014 December and November while the maximum occurs in year 2009 and 2010 during the month of January, February and March. Variation of the mean monthly temperature is high as described below graphically.

Temperature in	**Years**						
	2009	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
Mean maximum temperature (°C)	30.6	30.6	29	30.2	30.5	28.5	30
Mean minimum temperature (°C)	17.1	18.9	16.6	15.8	17.6	16.3	18.1

Table: 1. 1.*Annually mean maximum and minimum temperature value of Assosa town (2009-2015)*

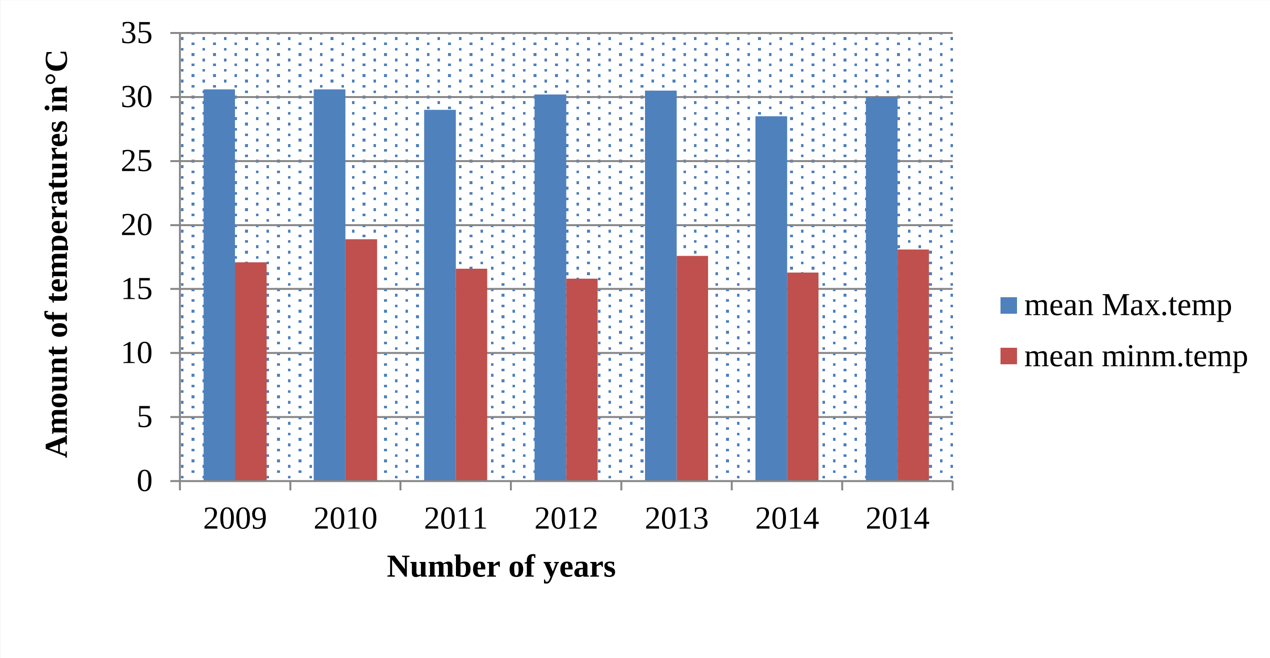


Figure: 1. 3. *Graph of mean maximum and minimum temperature value of Assosa town (2009-2015)*

1.2.3.2 Vegetation coverage

The major part of Benishangul-Gumuz Region is still covered by natural forest vegetation, especially bamboo thicket, broad-leaved deciduous woodlands (Combretum-Terminalia) and Acacia woodlands. Larger areas which have been cleared for crop production are only found around Assosa/Bambessi, Pawe and in some parts of Belo Jegonfoy, Dibate and Bulen where different farmer are more populated. The plant communities in the region are influenced by climatic and edaphic conditions, by fire and by human activities. Under natural conditions, they normally progress into more or less stable climaxes but as the environmental conditions in most cases show some short-term or long-term changes they are always involved in some kind of dynamics. According to (UNECA, 1998), the forest vegetation cover of the region can be classified into eight vegetation types: Dense forests (a type of forest that characterized by a close stand of trees with a more or less continuous canopy rising 7 to 30 m, and a sparse cover of grasses. E.g. Hagenia abyssinica, Juniperus procera, Podocarpus gracilior, Olea africana and Prunus africanus which located in Wonmbera and Dangure woreda*)*, Riverine forests (These type of forest are heterogeneous forests along rivers, characterized mainly by large trees, but also may include bushes and lowland bamboo E.g. Acacia sieberiana, Ficus vasta, Ficus sur, Syzygium guinecnse & Diospryas abyssinica located manily in Metekel zone), Broad-leaved Deciduous Woodlands (Woodlands occurring at altitudes between 300 and 1700m and with a rainfall of 800 to 1400 mm per years. The Dominating species are Terminalia brownii, Combretum molle, Celtis africana, Croton macrostachys, Milletia ferruginea, Ekebergia capensis, Syzygium guineense, and Ficus spp, which located in most part of the region), Acacia Woodland (woodland cover on open land having 5m and upto 20 m height), Bushland (vegetation type is an assemblage of trees and shrubs with a single or layered canopy, usually not exceeding a height of 10 m, e.g. Acacia polycanta, Acacia tortilis & Acacia seyal), Shrubland (vegetation unit is characterized by shrubs usually not higher than 6 m), Boswellia Woodland (vegetation type is mainly confined to the western lowlands of Benishangul-Gumuz. It is often found on poor, shallow soils, steep slopes and in mountainous areas) & Lowland Bamboo (Oxytenanthera abyssinica) Lowland bamboo (Oxytenanthera abyssinica) is a natural forest type of altitude ranges from (700) 1,000 to 1,800 m a.s.l. It requires a minimum annual rainfall of more than 700 mm and grows on poor soils. This located manily southeast of the study area locally known Anbesa chaka. According to (UNECA, 1998) report, the region have bamboo forest of an estimation of total area of 440.000 hectors.

1.2.4 Population and settlement

Based on figures from the Central Statistical Agency in 2005, Assosa town has an estimated total population of 20,226, of whom 10,929 are men and 9,297 are women. Based on the 2007 Population and Housing Census Report and with 5.5 percent population growth of the city, Assosa has about 35,000 residents of which male and female residents constitute 51.5% and 48.5% of its population respectively. The annual growth rate of Assosa population, however, is expected to rise mostly due to the growing investment activities, rural-urban and urban-urban migration and the establishment of the new public university. There are six large ethnic groups in Assosa town. These are Oromo (41.19%), the Amhara (29.93%), the Berta (17.39%), the Tigray (5.43%), the Sebat Bet Gurage (1.35%), and the Silt'e (1.29%); all other ethnic groups made up 3.42% of the population.

Among these ethnic groups Oromiffa is spoken as a first language by 44.42%, 31.53% spoke Amharic, 15.98% Berta, and 4.43% Tigrinya; the remaining 3.64% spoke all other primary languages reported.

1.3 Problem statement

Since on the proposed project area not any research have been done before, due to that this research project focuses to study petrology, geochemical characteristics and the tectonic environment of granitoid rocks of the specific area through using field data, petrographic data and geochemical analysis data which have not been studied previously.

Some previous work has been focused on type of granitoid rock of western Ethiopia generally, but there is limitations of geochemical data and not specific features of the Assosa area are known, because they have been used only few samples from some part of western Ethiopia (Wallagga), which cannot be the representative for whole western Ethiopia granitoid rock sequences, including the present project. Therefore, the present study aimed to determine the detail local geology, petrographic description and geochemical data of the plutonic province and comparison with other provinces using field geologic data, petrographic data and analysed geochemical data to better understand the geology study area.

1.4 Objectives

1.4.1 General objectives

The general objective of this study is to constrain the petrogenesis of granitoids rock from Assosa area.

1.4.2 Specific objectives

The specific objectives are:-

- To describe the petrography of the granitoid rocks of the area
- To characterize the geochemical signatures
- To demonstrate paleotectonic setting of the area

1.5 Methodology

There was abundance of rock exposures on project area. The overall works of the research are mainly divided into three phases; pre-field work, field work and post-field work. In the pre-field work assessment on literatures about the methods that would be applied and about the study area accessibility, extent etc. are applied. During field work both primary and secondary data collection are carried out and in post-field work collecting, analyzing, synthesizing, presenting and interpreting of data are done. Field investigation and petrographic analysis are the two major methodologies that carried out to meet an objective of research study.

After collecting of data carried out the next step is to analyze those relevant data. Most analyses are done in the laboratory. The samples that collected from the field work are prepared for two purposes. The first purpose is for petrographic study and the second one is for the geochemical analysis. During petrography study thin section preparation and bulk geochemical analysis of representative can be done. Data synthesis involves collecting and integrating different data sets into coherent information for interpretation.

1.5.1 Pre-field work, the activities includes like

- Supervising and the general reconnaissance survey of the research area, assessment on literature data, method applied and collection of information concerning cultural people of the area also studied.

1.5.2 Field work/field investigation

During field work mainly primary data collection is had been done. The main way of collecting the primary data is through means of field work. The main purpose of this field work is to collect representative rock samples, know the distribution of the lithologies in relation to others, observing the general geology of the area, pointing lithological units, descriptions of samples in hand specimens, taking GPS locations of samples and observing physiography and geological structures.

1.5.3 Laboratory and Data analysis

1.5.3.1 Petrographic analysis

12 samples were selected for thin section rock samples are prepared in Geological Surveys of Ethiopia (GSE) Makanisa laboratory branch and sample thin section observation and description undertaken in the Addis-Ababa University School of Earth sciences Petrology laboratory. The thin section samples are selected based on the variety of the composition they have, their colors and their ambiguities to identify while in the field work. The main output of the thin section analysis is modal proportion of minerals they have, grain size texture, and their grain shape. These all information will help lastly to name rocks, rock classification and understanding the magmatic evolution.

1.5.3.2 Geochemical sampling, analysis and data presentation

6 geochemical samples were selected on petrographic bases section. The geochemical sample preparation was done at the Geological Survey of Ethiopia (GSE) Makanisa laboratory. To minimize and remove cross contamination of samples, after crushing and milling every single rock sample, the Jaw crusher and the ball mills are blown by an air compressor and washed out and use quartz rock materials clean to remove any possible contaminant for each sample powdering.

The sample preparation for geochemical analysis includes making a rock powder after removing moisture content of rock through heating crushed rock sample (100°C).During preparation rock sample for geochemical analysis; three main procedures have been followed. The first step is crushing the broken fresh sample in a jaw crusher, the second step is removing the moisture content from crushed rocks at 100°C for 24 hours, and finally the crushed sample will be milled down to micron- size particles in an agate ball automatic milling machine to size of less than 75µm.The powders were sent to ALS services PLC in Ireland for determinations of major and trace element concentration. Major oxide analysis was made by ICP-AES, while trace elements were analysed by both ICP-MS and ICP-AES analytical methods.

1.6 Expected outcome and research relevance

As mentioned in the problem statement in (section 1.3**)** the study area has not been studied in the aspect of petrology and geochemistry and tectonic environment before, therefore this study will be focused to study petrology, geochemical characteristics and the tectonic environment of granitoid rocks of the area which have not studied before by any researcher The main expected research outputs will be:

- Description of granitoids rocks of the area based on petrographic description, geochemical analysis and finally determines the petrogenesis and detail understanding of tectonic environment of the area.
- Finally it provides or support preliminary information for detail exploration of construction material that will be undertaken in the region before and further to overcome the continuity exploration and research studies activity undertaken in the region for the future.

1.7 Previous work

Detail research has been done on the specific area. But a number of research and reports have been done regional wise on western Ethiopia. The analyzed granitoids rock samples of western Ethiopia, Tuppii granite (Wallagga) and SiO_2 contents 72.7 to 75.8 wt. %, and an overall metaluminous character and also show a wide range in concentrations of other major and minor element oxides (Tesfaye kebede et al, 1999). The distributions of these rocks are bimodal with a gap in the range of the intermediates rocks. Based on Shand's. (1947) alumina saturation index (ASI)' the majority of granitoid rocks of the area classified as metaluminous and peralumious with some peralkaline rocks.

In a Chondrite-normalized REE plot, the Tuppii granite discussed by (Tesfaye Kebede and Koeberl, 2002) shows slightly enrichment of LREEs, a pronounced negative Eu anomaly, La_N/Yb_N ratios of 4.8–9.9, and rather flat HREEs, except sample TK055b, which has a relatively flat HREE pattern with a La_N/Yb_N ratio of 18.9.

Tesfaye kebede et al. (1999) have presented on his paper based on field relations, lithological associations and geochemical data indicate that the granitoids rocks of the area classified as VAG are the product of subduction-related magmatism that involves underplating and partial melting of basaltic/gabbroic material. Typically REE patterns of granitoids classified as VAG, during his analysis imply that a source magma that separate from a residue containing hornblend, with preferential fractionation of the HREEs compared to the LREEs (e.g. Gromet and Silver, 1983; Rollinson., 1993).Available evidence suggests that the western Ethiopian Precambrian rocks were affected predominantly by arc magmatism that resulted in the intrusion of plutons, of which granitoid rocks constitute a major part. According to Kazmin. (1978, 1979) the western Ethiopian Precambrian terrane is considered to contain lithological components common to both the Arabian-Nubian Shield (ANS) in the north and the Mozambique Belt in the south. Granitic rocks are used to characterize tectonic settings of emplacement and source characteristics (e.g. Collins et al., 1982; Pearce et al., 1984; Whalen et al., 1987; Eby, 1990, 1992). That helps to understand the Precambrian tectonic and magmatic evolution of the project area. As (Tesfaye Kebede et al., 2002) as demonstrated in his petrogenesis section, the Nd–Sr isotopic and trace element compositions of the Ganjii monzogranite suggest derivation from sub continental lithospheric mantle. The other granitoids (Homa, Tullu Kapii, & Tuppii) may have experienced significant crustal input. The petrogenesis of A- type granitoids of Wollega area western Ethiopia are characterized by inter and intra-unit compositional and textural variations, which reflect their petrogenetic evolution (Tesfaye Kebede et al., 2001).According to him the chemical data from the Homa and Tuppii granites show considerable scatter, probably due to the presence of different plutonic centers with variable chemical compositions. Therefore, to model petrogenetic of the area he focused on the area whose geochemical nature is more uniform. Based on Single-grain zircon Pb/Pb evaporation and conventional U/Pb dating conducted on four granitoids places time constraints on their emplacement and tectonothermal events.

Three granitoid magmatic events were identified at 815 Ma, 700±730 Ma, and 620±625 Ma, which were marked by emplacement of the calc-alkaline Ujjukka granite and granodiorite, the anatectic Suqii-Wagga two-mica granite and the Guttin K-feldspar megacrystic granite, and the anorogenic Ganjii monzogranite, respectively (Tesfaye Kebede et al., 2000). Low isotopic ration of Sr and high isotopic ration of Nd of granitoids suggest they may have been produced by partial melting of mantle-derived material with short crustal residence time, or fractional crystallization of basaltic melt (Asfawossen Asrat et al., 2004).

CHAPTER-TWO

2. REGIONAL GEOLOGICAL SETTING

2.1 Introduction

The western Ethiopian Precambrian terrane is considered to contain lithological components common to both the Arabian-Nubian Shield (ANS) in the north and the Mozambique Belt (MB) in the south (Kazmin et al., 1978, 1979).

The terrain form western and wider branch of the low-grade volcano-sedimentary terrain of the Arabian-Nubian Shield (ANS) bounded both to the east and to the west by the gneissic terrain of the Mozambique Belt (MB).The relation between the Mozambique Belt (MB) and the northern low-grade volcano-sedimentary sequence (ANS) collectively referred to as the East African Orogen, but not well understood as described by stern. (1994). Inherited zircon of Mesoproterozoic age were reported from the different granitic populations in the contrasting low and high-grade terrane indicate a contribution of pre Neoproterozoic crustal material to the source magma of these rocks Kebede et al. (2000, 2001a).The western Ethiopia Precambrian rocks consist of high-grade gneissic terrane and the low-grade volcano-sedimentary sequences.

The lithologies under both terrane are high grade metamorphic gneissic terrains (amphibolite to granulite facies, ortho-gneisses, paragneisses and migmatites) and lower grade metamorphic greenstone / greenschist units to lower amphibolite facies volcano-sedimentary and associated metamorphic-ultramafic assemblages. Both terrains that we described above are intruded by syn and post-orogenic granitoid plutonic intrusives. The terrains are separated by major tectonic features; predominantly early to late Proterozoic thrust and/or shear zones that extend for several kilometres.

According to Geological Survey of Ethiopia (GSE) studied the Precambrian geology of western Ethiopia at different scales (UNDP, 1972; de Wit, 1977b; Kazmin, 1978; Kazmin et al., 1979; Davidson, 1983; Amenti, 1989; Mengesha, 1987; Mengesha and Berhe, 1987; Ayalew and Moore, 1989, Tadesse and Tsegaye, 2000; Solomon and Mulugeta, 2000; Getahun., 2002 as cited in Tadesse Alemu and Tsegaye Abebe,2007).

Accordingly, the Precambrian of western Ethiopia consists of: - (1) high grade gneiss and migmatites, (2) low-grade metavolcano-sedimentary rocks and associated intrusive rocks and, (3) metavolcano-sediments and associated mafic-ultramafic rocks of probable ophiolitic origin(Tadesse Alemu and Tsegaye Abebe,2007). The high-grade gneiss and migmatites referred to as Lower Complex (Kazmin, 1972; UNDP, 1972) are considered as the northern continuation of the Pan-African Mozambique belt. These rocks were regarded as Archean in age mainly on the basis of correlation with similar rocks in east Africa (Kazmin, 1972; Kazmin et al., 1978 as cited in Tadesse Alemu and Tsegaye Abebe, 2007). However according to them, the recent geochronological investigations indicate that the granitoids from the Lower complex fall within the time range of 550 to 810 Ma (Ayalew et al.,1990; Kebede et al., 2000) and some of the granitoids contain inherited zircon as old as 1571±9Ma (Tesfaye Kebede et al., 2000).Which might suggest that the gneiss and migmatites are not juvenile Pan-African terrane but consist of Mesoproterozoic crust that was reworked in the East African Orogen.

The low-grade metavolcano sedimentary rocks referred to as upper complex (Kazmin, 1972; UNDP, 1972) have long been considered as the southern continuation of the Pan-African Arabian- Nubian Shield. Geochronological investigations from plutonic rocks suggest that the age of the low-grade rocks range from ~ 830 to ~ 540 Ma (Ayalew et al., 1990). Based on field, lithologic, geochemical and geochronological evidence the low-grade rocks of western Ethiopia were correlated to the juvenile Pan-African assemblage of northern Ethiopia, Eritrea and the southeastern Sudan. Low-grade metavolcano-sedimentary rocks and associated intrusives outcrop is remarkably persistent and can be traced for the entire length of the Precambrian of western Ethiopia (as cited in Tadesse Alemu and Tsegaye Abebe, 2007).

The abundant plutonic rocks which have a wide compositional range intruded the low-grade belt of Ethiopia (e.g. Ayalew et al., 1990, Gichile and Fyson, 1993, Ayalew and Peccerillo, 1998, Alemu, 1998, Kebede et al.,1999, Tadesse et al., 2000), Eritrea (e.g. Teklay et al., 2000), Red Sea Hills of Sudan (e.g. Almond et al., 1997, Stern and Abdelsalam, 1998), Eastern Desert of Egypt (e.g. Abdel-Rahman, 1995, Moghazi et al., 1998), and Saudi Arabia (e.g. Jackson et al., 1984, Harris et al., 1986) during the Neoproterozoic, indicating the importance of these rocks in the evolutionary history of the region.

Granitoid plutons represent about 60% of the outcrops in the Red Sea Hills of Sudan (Klemenic and Poole, 1988 cited in Tesfaye Kebede and Koeberl, 2002).According to Kazmin et al. (1978) classification the geology of the area into five tectonic zones: (1) an eastern block of high-grade pre-Pan-African rocks; (2) an ophiolite belt; (3) a zone of dioritic/granodioritic batholiths and associated intermediate volcanics; (4) a metavolcanosedimentary belt; and (5) a western block of high-grade pre-Pan-African basement. Northwest of the study area especially along Abay basin and boarder of Sudanese is characterized by high grade terrane and northeast of area is mainly dominated by low grade terrane(as cited in Tesfaye Kebede et al.,1999). The similar relationship is observed that high-grade terrane lies west (along the Sudanese border) and east of the low-grade belt which stated by (Kazmin et al., 1979). As Kazmin et al. (1978) described broadly viewed the major strike-slip movements in the Red Sea fold Belt and Mozambique Belt as suggesting oblique continental collision, implying that similar processes had affected the western Ethiopian Precambrian shield. In the Yubdo area, the southeastern part of the study area, Kazmin et al. (1978) reported a westward, large-scale overthrust, suggesting a subduction zone dipping to the west. Moreover, structural features in the Akobo Domain, southwestern Ethiopia, suggested westward thrusting (Davidson, 1983).Kazmin et al. (1978) further proposed westward subduction for the arc in northern Ethiopia, and eastward subduction for arcs in eastern Ethiopia. The western domain also consists predominantly of gneisses formed from rocks of both supracrustal and plutonic origin and intruded by syntectonic and post-tectonic granitoid plutonic rocks.

2.2 Geology and tectonic Evolution of the Western Ethiopian Shield (WES)

2.2.1 Litho–stratigraphy

According to (Kazmin et al., 1978), western Ethiopia comprises both the low-medium grade metamorphic rocks of Arabian-Nubian Shield (ANS) and the generally high-grade reworked rocks of Mozambique belt (MB). Braathen et al. (2001) also stated that Western Ethiopia shows a division of two Precambrian provinces: Archaean- Paleoproterozoic gneisses in the east, Neoproterozoic and Paleoproterozoic gneisses to the west.

The Precambrian of western region consists of high grade gneiss and migmatite in the east and west and low grade metavolcano-sedimentary rocks in the middle bounded by NNE-SSW trending ophiolitic belts (Tulu Dimtu belt and Assosa-Kurmuk belt) (Tadesse Alemu and Tsegaye Abebe, 2007).As Benzu Gold Mining Ethiopia PLC. (2013) reported the exposed rocks in Western Ethiopia consist primarily of Lower Complex gneisses and migmatite.

These rocks are coarse grained, well foliated and banded, strongly deformed and metamorphosed to amphibolite facies and overlain by the upper complex which consists of metavolcanic and metasedimentary rocks of low grade greenschist to amphibolite facies as described by (Benzu Gold Mining Ethiopia PLC, 2013).The metavolcano-sedimentary lithology includes graphitic phyllite, carbonate schists and marble and Ultrabasic to acidic intrusives related to the Upper complex intrude the Lower Complex (Benzu Gold Mining Ethiopia PLC, 2013).

The lithological boundary between the central low- grade volcanosedirnentary assemblage and the high- grade gneisses to the west and east is tectonic, as marked by shear zones and mylonitic rocks (Abraham,1989).Based on classification made by (Allen and Gebremedhin Tadesse, 2003) and puts the western rocks in to five categories. These are Didessa domain, Daka domain, Kemashi domain, Sirkole domain and Dengi domain.

2.2.1.1 Didessa domain

The domain that differentiated from the adjacent Kemashi domain to the west by distinctive lithological and structural characteristics. The rocks within this domain are moderate grade paragneisses which consist of interlayered biotite- amphibole gneiss, garnet-biotite gneiss and quartzofeldspathic gneiss and ortho-gneisses which consist, banded mafic gneiss. Banded mafic gneisses in ortho gneisses of Didessa domain contain ultramafic bands derived from a layered mafic intrusive body, and very coarse granitoid gneiss and intruded by Neoproterozoic intrusive rocks. Based on the interpretation made by (Allen and Gebremedhin Tadesse, 2003) concluded that this domain is the eastern edge of the Tulu Dimtu belt. Partial melting and deformation events are reported to occur in the Didessa Terrane at ca. 660 Ma (Blades et al., 2015).

2.2.1.2 Kemashi Domain

The Kemashi domain is located northeast of the study area which far approximately 150-180km from the research area. The domain has an approximation of narrow 10-15km wide domain paralleling the trend of Tulu Dimtu belt (Allen and G.Tadesse, 2003). According to these authors Kemashi domain have sequences of metasedimentary rocks of marine origin, mafic to ultramafic metavolcanic and associated plutonic rocks of wide variety make up the domain. The metasedimentary rocks of the Kemashi domain area mainly composed of dark, highly pyritised, pelitic to psammitic schists, intercalated with chert, graphitic phyllite and marble.

2.2.1.3 Dengi Domain

The domain that located between the study area and Kemashi domain toward west direction of Kemashi town. The domain characterized by its wider area and consists of deformed and metamorphosed volcanosedimentary sequences, a coarse-grained Para and ortho-gneissic unit and mafic to felsic intrusive bodies intruding to the later. Its wider extension extended to west of Kemashi domain having 120km wide, Indicates two pulses of magmatism at 850–840 Ma and 780–760 Ma in similar way to Didessa domain (Blades et al., 2015).According to (Allen and Gebremedhin Tadesse,2003) Dengi domain interpreted as a volcanic arc related to the Tuludimtu Ophiolite to the east. The Dengi domain characterized by the presences of intrusive bodies which are more felsic and less deformed gneissic westwards, ranging from intensely deformed gneissic mafic bodies through foliated syn-kinematic granodioritic bodies elongated parallel to the trend of the belt, to more equant, massive, cross-cutting post-kinematic granites.

2.2.1.4 Sirkole domain

Sirkole domain is located west of the study area which far 96km from Assosa town. The domain extends to west toward Sudan boarder in which its western extension limit is unknown. Sirkole domain consists of different N–S elongated blocks of rocks range from small to medium size of blocks of granitoid rock, moderate-grade gneisses only a few km widths.

This domain consists of either medium grade gneisses or metavolcanic rocks intruded by foliated and massive granitoids. There are two major units that make up the areas gneissic lithology. The first one is Tosho gneiss, heterogeneous gneiss which includes undifferentiated complex of biotite-amphibole gneiss and amphibolite and Granitoid gneiss.

2.2.1.5 Daka domain

The Daka domain manily consists of gneissic rocks, which are farther consist of three lithological units. According to (Allen and Gebremedhin Tadesse, 2003) two lithological unit of the area correlated with the two gneissic units of the Sirkole Domain, i.e. the Tosho Gneiss, and the Yangu Granitoid Gneiss. The relationship between these two units is more clearly delineated in this domain. The Tosho gneiss belongs to amphibolite facies and grades from east to west into the granitoid gneiss through a zone of increasing metamorphic grade and migmatisation. The increment in grade of metamorphism of Tosho gneiss towards the west is interpreted to represent formation of Yangu granitoids by anatectic partial melting of the Tosho Gneisses. The others Daka domain’s lithological unit is gneissic unit which is a banded orthopyroxene-bearing granulite facies unit termed Daka Gneiss (Tadesse and Tesfaye, 1999 as cited in Allen and Gebremedhin Tadesse, 2003).

2.3 Precambrian and Phanerozoic Intrusive rocks of the region

2.3.1 Metagabbro

Few isolated gabbroic bodies are found in the central and southern part of the region, mainly intruding the metavolcano-sedimentary units. Generally, the rock unit is dark green to dark gray, medium to very coarse grained. It is mostly massive at the central part with primary igneous mineralogy and texture, and occasionally fairly foliated at the margin. The foliations of the enclosing schists are deflect around some of the gabbroic bodies, suggesting that they are syn or post tectonic. But, some gabbroic rocks intruded the youngest Precambrian units as stated by (Tefera, et al., 1996). Occasionally the gabbroic rocks grade to pyroxene and norite, and at places felsic dykes intrude it.

2.3.2 Metadiorite

The metadiorite is widely exposed in the central and southern part of the region forming small stock to batholiths size complexes, intruding the low-grade metavolcano-sedimentary units. They are generally elongated following the regional structural trend of the surrounding rocks. It is generally light green to dark gray, medium to coarse grained and apparently massive with faint schistosity at the margin, which is defined by preferred orientation of prismatic hornblende and biotite flakes. In places it grades to metatonalite, metaquartzdiorite and metagabbro. The rock commonly shows gradational contact and locally crosscutting relationship with the surrounding metagranitoide and other mafic rocks. The metadiorite intrudes the superacrustal rocks, and close to the contact zone it occasionally contains xenoliths of the host rocks. It frequently contains quartz veins, aplitic, granitic and mafic dykes. The quartz veins/vein lets are deformed. At places pods of migmatitic varieties are present. As described by (Tadesse and Melese, 2001), minor epidotized doloritic dykes are found cross cutting some of the Metadiorite units.

In general Assosa area is characterized by biotite and biotite-hornblende gneiss, amphibolite mafic schists, metasediments and metasediments unit, metagranodioritic rocks, metagranite, alkali olivine basalt which cover most Assosa area Mengesha Tefera.(1991) on the map prepared by geological survey of Ethiopia Berhanu Wondaferew et al., and Mengesha Tefera. (1997).

Among listed unit above the specific study area is mainly dominated by metagranite and alkali olivine basaltic units. Northeast of the study area is mainly dominated by biotite and biotite-hornblende gneiss medium grained, well foliated, grey to dark grey biotite and biotite-hornblende gneisses with well-developed compositional layering underlie areas in the vicinity of Ahansha, north of Kushmangal, northeast of Agubela or southeast of the study area, near Oura village along the Hoha river, and in the easternmost part of the mapped area as mapped by geological survey of Ethiopia (GSE) experts. As the same manner the northeast of the study area is dominated by amphibolite mafic schists of predominantly volcanic origin bounded or enclosed by metagranodiorite, metatonalite and metaquartz diorite. The North, northeast and southwest of the study area is mainly dominated by metasediments and metasediments unit.

In the region there is also phyllite and greenschist, minor graphite and talc schists, quartzite and marble unit the dominant rock types appear to be politic schists and rocks of felsic to mafic volcanic origin, whereas northwest, south and northeast of Assosa town biotite, graphite and chlorite schists, quartzite, metasandstone, metaconglomerate and quartzofeldspathic schist the dominant rock types are of psammitic origin, with minor mafic schists of volcanic origin as discussed by geological survey of Ethiopia experts. The contacts between the two units appear to be of tectonic origin.

Southwest and northeast of Assosa town mainly dominated by metagranodioritic rocks. This unit also contains rocks of granitic, tonalitic and dioritic composition. They usually bear biotite or hornblende. These rocks are grey and medium to coarse grained with well-preserved plutonic texture. Granitic pegmatite, aplitic dykes and quartz veins both parallel to and cutting across the foliation are frequent on the project area. Almost all the study area and surrounding area dominated and covered metagranite rocks which characterized by weakly to strongly foliated metagranite forming small stocks to large batholiths occurs surrounding project area. The small circular gabbroic bodies located just west of Geissan and near the Asosa-Dabus road consist of coarse grained, massive rocks containing mainly hornblende and albite with color index between 40 and 60.One third of the study area is mainly dominated by granitoids rocks especially metagranite the dominant one from other granite types. Southwest and north-west of the study area is covered by these metagranite units that support the dominances of metagranite units over others.

As described on map produced by (Mengesha Tefera, 1997) metaquartz mainly consists of metaquartz diorite; metatonalite and metagranodiorite are found intimately associated in the mapped area and are probably comagmatic in origin. The metaquartz diorite dominate most of the project area in all direction, which have generally dark grey or speckled black-white with color index ranging from 20 to 35, medium to coarse grained, massive to strongly foliated and in places epidotized. The composition ranges from gabbro to granodiorite, quartz diorite being dominant. Both concordant and discordant granitic, aplitic and pegmatitic dykes, quartz veins and veinlets intrude this map unit. These rocks are grey and medium to coarse grained with well-preserved plutonic texture. They range from massive too well foliated. The granitoids cover the north western part of the Ashashire area or northeast of study area and occur as intrusions within serpentinized actinolite schist and feldspathic quartz mica schist. The granitoids include granites, granodiorites and aplites.

The granites are grayish to light pink in colour, coarse grained and the contact with the country rock is marked by quartz-sericite alterations and manganese staining (Benzu Gold Mining Ethiopia PLC, 2013).

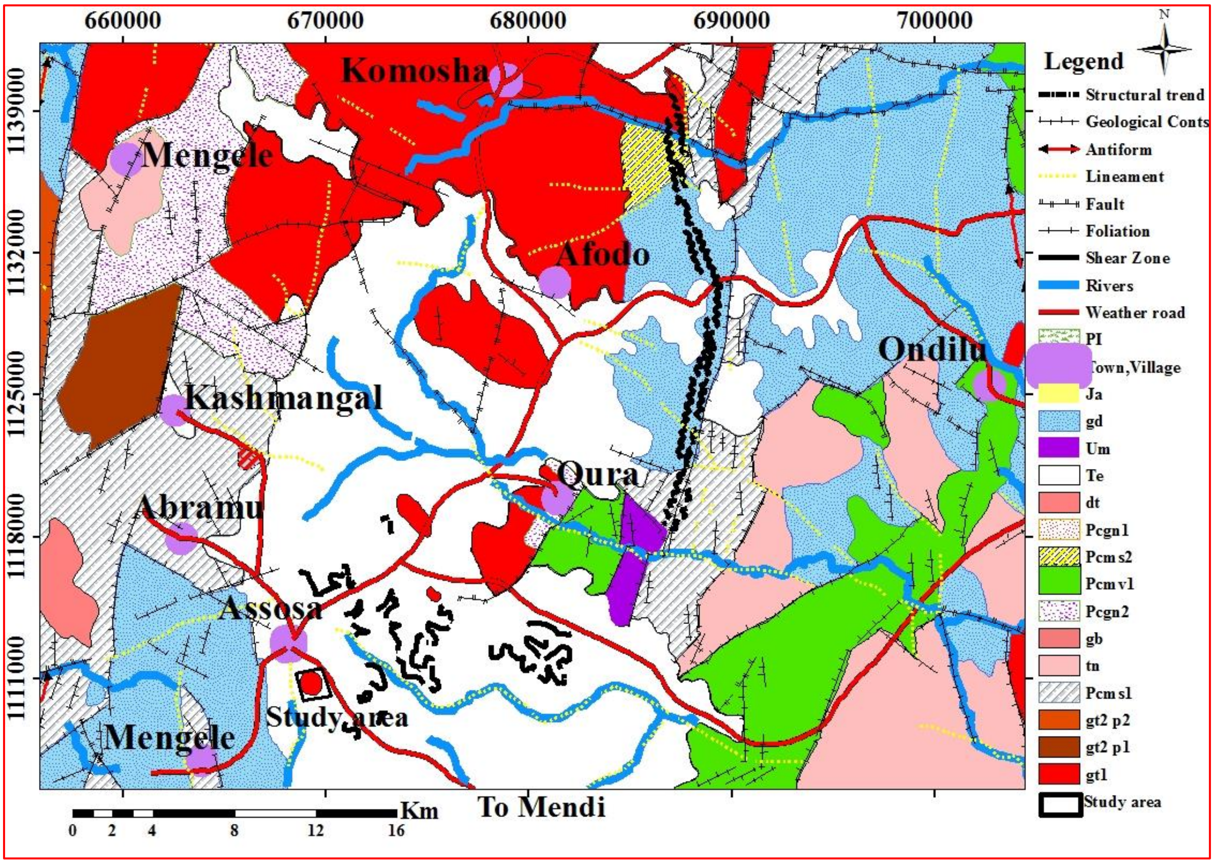


Figure.2.2 ***Geological map of Assosa-Kurmuk area (adopted from Mengesha Tefera, 1997).Where:****gt1-metagranite, gt2p2-alkaligranite, gt2p1-biotitegranite, gd-metagranodiorite, tn-metatonalite, dt-metaquartzdiorite, gb-metagabbro, Pcmr1-calcite and dolomite marbles, Pcmr2-calcite and dolomite marbles, minor biotite, amphibole and chlorite schists and quartzite, Pcms1-biotite,graphite and chlorite schists, quartzite, metasandstone, metaconglomerate and quartzofeldspathic schist, Pcms2-phyllite and greenschist, minor graphite and talc schists, quartzite and marble,Pcmv2-amphibolite and quartzofeldspathic schist, minor graphite, chlorite and biotite schists, quartzite and metaconglomerate,Pcgn1-biotite and hornblend-biotite gneisses, minor amphibolite, granitoid gneiss and migmatite,Pcgn2-biotite and biotite-hornblend gneisses, minor muscovite-biotite schist and quartzofeldspathic gneiss, Um-serpentinite, serpentine-talc and talc-chlorite schists, Ja-sandstone with minor conglomerate, Te-basalt, PI-alkali trachyte and phonolite plugs.*

2.4 Tectonic setting of the region

The WES geotectonically evolved through different processes beginning from early rifting and associated sedimentation followed by subduction and island arc formation, arc-accretion and, finally, continent-continent collision (e.g., Kazmin et al., 1978). The cause for the latter stages, collectively called 'the Pan African orogeny', is believed to be collision of east and west Gondwana (e.g., Stern, 1994) which caused severe E-W crustal shortening (Teklewold Ayalew and Johnson, 2002). The lithological, structural and metamorphic similarities of the gneissic rocks of WES with the basement exposed in further south (in Kenya, Uganda and SE Sudan) infer that the gneissic rocks of WES are a northwards continuation of the Mozambique Belt (Kazmin et al., 1978; Seife Michael Berhe, 1991; Samuel Gichile and Fyson, 1993).Different evidences suggest that bodies within the WES have an intrusive nature (Grenne et al., 1998; Aberra Mogessie et al., 1999 as cited in Teklewold Ayalew and Johnson, 2002). Among the intrusive bodies of WES, A-type granitoids of Wollega area have been identified to include three domains; the Ganji monzogranite, Homa gneissic granite and Tuppi granite as stated by (Tesfaye Kebede and Koeberl, 2003). These granitoid bodies are understood as they either intruded into greenschist facies volcano-sedimentary sequence or emplaced at the contact between low- and high-grade terranes (e.g., Braathen et al., 2001, Tesfaye Kebede and Koeberl, 2003).The granitoid rocks in the area are categorized as pre- to and post-deformation granitoids of within plate and volcanic arc settings. Teklewold Ayalew and Peccerillo, 1998) indicated that pre- to syn-tectonic granitoids appear to be the product of magmatic arc activity (VAG), whereas the other granites fall in the field of within-plate granites (WPG).

CHAPTER-THREE

3. LOCAL GEOLOGY AND PETROGRAPHY OF ASSOSA AREA

3.1 Introduction

The geology of Assosa area consists mainly of tertiary basalts, trachytes and Precambrian rocks. It comprises predominantly outcrops of very old Precambrian rocks, mainly upper complex and syntectonic granitoids. Near Assosa town quaternary sediments, tertiary basalt, and Precambrian rocks are more dominated. The Precambrian rocks in the Assosa area which are composed of granite, gneiss, metagranite, biotite, quartizite, etc. are found underlying the tertiary basalt and the quaternary sediments in the area Benzu gold mining Ethiopia PLC. (2013). These rocks are mainly exposed along the river valleys and some hill sides. Granitoids plutons of the region approximately 70% of outcrop are exposed to surface, along study area the exposure are available to observe and take any measurements.

The reddish brown sandy loam soil in the eastern and northeast part of the town mostly near farmlands and scoraceous basalt of reddish color specially around northeast of town covers most of total coverage of the town. The upper complex overlies the lower complex and consists of metavolcanic and metasedimentary rocks of low grade greenshist to amphibolite facies. The metavolcano-sedimentary lithologies include graphitic phyllite, carbonate schists and marble. Ultrabasic to acidic intrusives related to the upper complex intrude the lower complex and are believed to be related to the tectonic development of the upper complex.

The metagranite rock unit is extensively exposed in the region, forming large batholiths, generally elongated N-S and small ridges. These bodies dominantly intrude the metavolcano-sedimentary units but a few places they intrude the high-grade gneisses. The foliation is marked by preferred orientation of biotite and K-feldspar.

3.2 Petrography and field relation Description

3.2.1 Field relationship description

21 rock samples were collected during field works for both petrographic and geochemical analysis purpose from granitoid rocks of the area for first time. Out of these only twelve representatives rocks samples selected for petrographically description purpose and six rock sample geochemical analysis based on mineralogical and color criteria. Some field relationships and field description are also given in field photographs below from (Figure.3.2.1.a-f, Figure.3.2.1.1.a & b and Figure.3.2.1.2.a & b).

The granitoids rock observed in the study area is classified as alkali granite type during field investigation. These granitoid rock types are further reclassified into different by their color variation; light grey, gray and pinkish granitoid rock in hand specimen classification during field description.

12 rock samples NW(06,08,09,010,011,014,015,017,018,019,020 and 021),which prepared for petrographic examination they have medium to coarse-grained texture. Granitoid rock from an area is manily composed of feldspar group (K-feldspar and plagioclase) and quartz with other accessory minerals that incorporated in small present. The rock unit of area has an average mineral composition of feldspar (plagioclase and K-feldspar), quartz and the minor or accessory (biotite, muscovite, hornblende, opaque, sphene, and chlorite) 60-80%, 23-27% and 1-10% respectively.

The K-feldspar granite(NW-09 & NW-017) from of area is characterized by large phenocryst grain/large crystal shape of pink K-feldspar embedded in a relatively fine-grained groundmass of microcline, plagioclase, quartz, and biotite and accessory minerals (Figure.3.2.1 b & c). This rock is principally composed of alkali feldspar (microcline and orthoclase) with some plagioclase, quartz, and biotite and as minor they contain hornblende, sphene, zircon and opaques. Rock units from Enzi hill (NW-01 and NW-08) mainly contain light dark to dark color K-feldspar and large phenocrysts of feldspars with light to dark color of lamellae of albite plagioclase with minor accessory opaque minerals (Figure.3.2.1.d & e).This rock unit have medium to coarse-grained texture during field hand specimen description.

From filed photography in addition to dark color there is also variety of color due to the presence of some small minerals that incorporated. Field relationship photography of the plagioclase grains (NW-018) occur as porphyroblasts embedded in a fine-grained matrix of quartz, biotite, epidote, clinozoisite and sphene (Figure.3.2.1.f). During field hand specimen description the granitoids unit is mainly linear arrangement plagioclase minerals which have light gray to light white colors with small presence of linear alignments of biotite with light gray to dark color, K-feldspars, quartz with minor's minerals as observed from field photography.

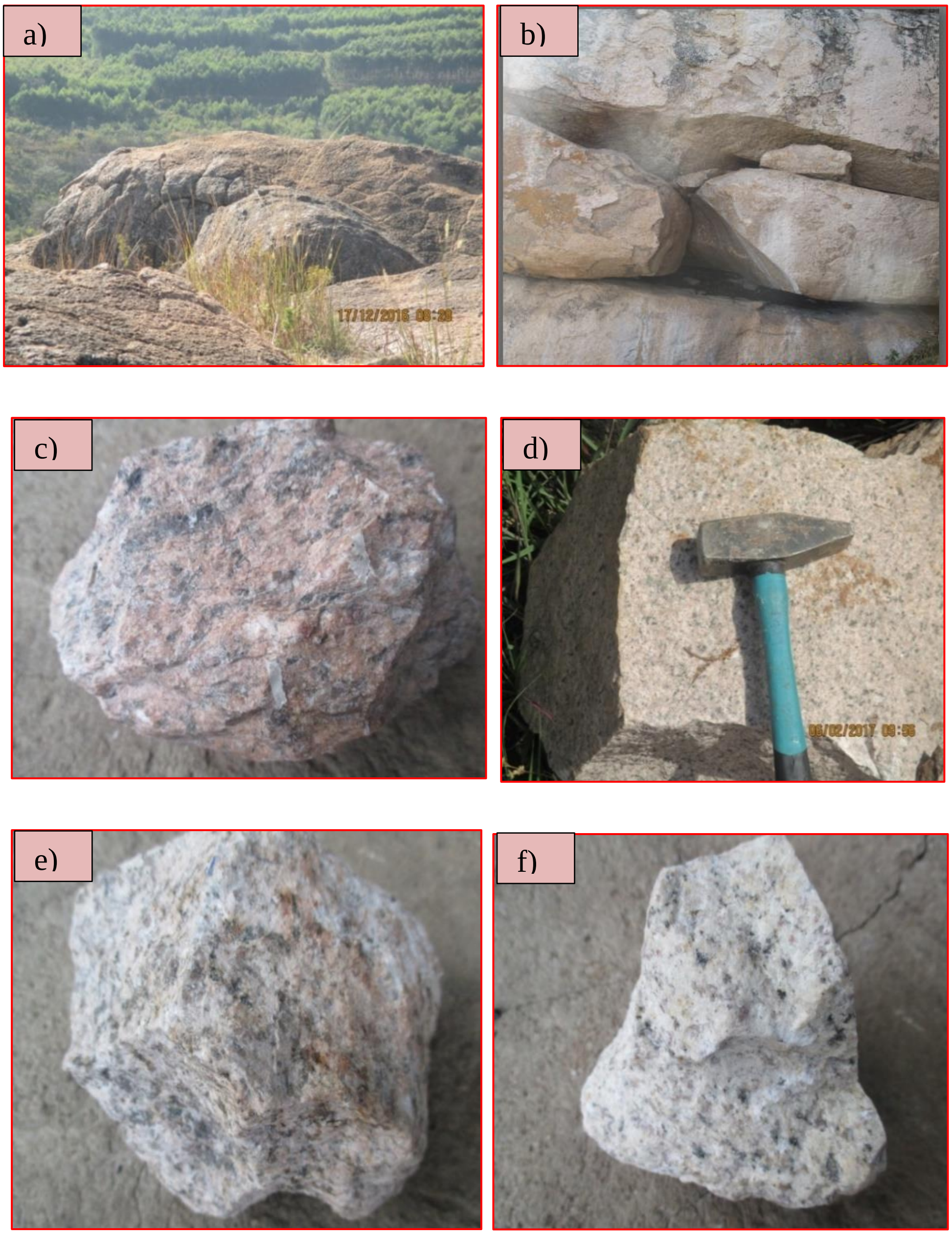


Figure: 3.2.1. *Field photographs of granite rock of Assosa area* ***(a),*** *Massive granitoid rock unit****, (b),*** *both weathered and massive granitoid rock,* ***(c-f).*** *Show major mineral constitute of alkali granite rocks of the area.*

3.2.1.1 Granitoid rock outcrop

Assosa granitoid occurrence is massive, light grey, gray to dark grey, pinkish in color, covering an approximated area of 8-10km^2. It forms morphologically hill and ridges. The granitoid rocks of the study area are mainly dominated by metagranite in which the alkali-feldspar mineral are more commonly dominated than incorporation of others. The abundance of alkali-feldspar mineral results to form the outcrop of alkali-feldspar granite rock of the area. These alkali-feldspar granite rock appear to light to pinkish grey and forming small hill in which the exposures of granitoid rocks (metagranite) form hill or small cliffs. These metagranite unit mainly characterized by having medium to coarse grained minerals with commonly visible minerals like quartz, feldspars (plagioclase, K-feldspar) and mica groups (biotite and muscovite) can be identified in hand specimens during field works. In addition to these listed minerals granitoid rocks of the area incorporated by other accessory or minor's minerals like mica group's sphene, chlorite, hornblende, garnet and opaque minerals. The granitoid rocks of the area show different color variation which reflects their mineralogical composition. The outcrop rocks area characterized by both weathered and massive fresh granitoid rock units. The weathered granitoid rock type is manily exposed to surface and difficult to determine and differentiate between the constituted minerals within rock units and they show variety of colors and fractured easily due to weathering factor applied on, while massive granitoid rock type characterized by its colors of major mineral constituted that can be easily identified during field description.

During field work and petrographic thin section description nearly 60% of the representative samples are dominated by alkali-feldspars mineral groups which form large phenocrysts of pinkish K-feldspar and dark gray to light gray colours of both sodium and potassium rich feldspars respectively which are occasionally observed throughout the rock. The alkali-feldspar granite occurrence of an area has biotite granite composition in small amounts. These plutons are characterized by a complex magmatic development with respect to deformation.

The granite unit of the area is characterized by medium to coarse-grained grain size and leucocratic with light gray to gray color varieties with pinkish colors, hypidiomorphic granular granitoid. The central part of the intrusive is little affected by deformation and looks massive which in turn reflected by the presences of polysynthetic and zoned plagioclase feldspar minerals during petrographic thin section description, whereas the contact zone variably shows foliation. The granitoid mass of the research area and north of Assosa (Komosha granite) has an irregular shape, but south-east and north-west and north-south trending foliation respectively as described below in field photography (Figure.3.2.1.1. a & b).

Most of the flat (gentle) area surrounding the study area north and north-east and south-west of the area is dominated by basaltic rock unit which is very rare exposure. Therefore most of the area was apparently originally covered by tertiary volcanic rocks, but now only remnant caps occur. No isotopic ages are studied before, but these basalts are assumed to be tertiary in age. Most of the flows are thought to be of fissural type. In many places crystalline basement rocks occur at higher elevations than the tertiary basalt flows, for instance between study area and Komosha village, and in the central part of the area along the Abay river. This is due to original topographic relationships in some cases, to fault displacements in others.

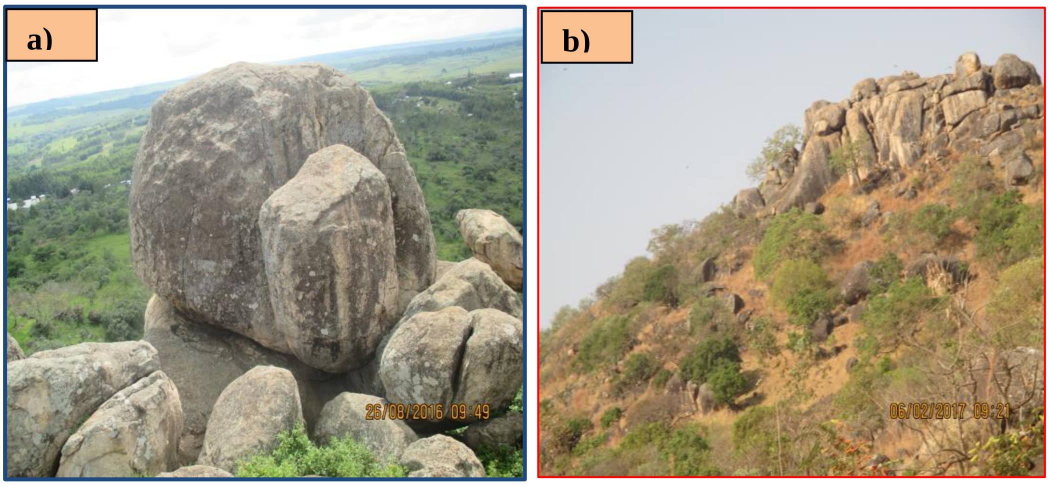


Figure: 3.2.1.1. *Field photographs of granite rock of Assosa area, (Figure **(a)** the irregular shape of granitoid rocks of study area and surrounding rock, **(b)** granitoid rock of the area form hill/ridge.*

3.2.1.2 Quartz Veins (QtzVs) and fracture of an area

Quartz veins of the study area are antitaxial veins; vein formed when the vein material (quartz) is a different composition to that of host rock (granitoid/granite). Therefore quartz veins in the study area are distributed through granitoid rock and they have parallel form. The rock body along the quartz veins is regularly sheared, intensively sericitized, and commonly silicified. The quartz veins in general have smoky to white colour and glassy texture.

The quartz veins of the area have sharp boundaries with the country rock and appear to have exploited structural planes of weakness, such as shearing, jointing and fracturing. These veins often carry pegmatitic patches composed of pink feldspars (orthoclase).These quartz veins which have a trend run from northeast to southwest direction across massive granitoids rock units. Have approximation of up to 2m wide and several meters long.

These quartz veins form a linear line that cross the rock units having trend movements form NEE-SWW direction as described below in (Figure.3.2.1.2a).During field investigation fracture structures of an area terminate by simply dying out (Fig.3.2.1.2b) relative to surrounding rocks. Therefore the fracture pattern of an area looks like mud crack patterns. They are highly curved and irregular fracture surface, in which do not share a common orientation to each other's.

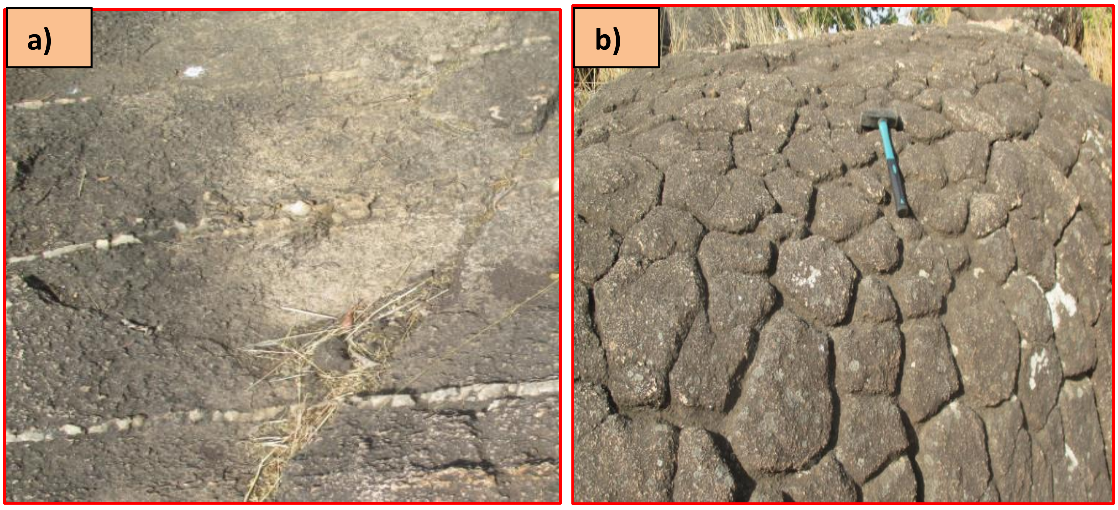


Figure: 3.2.1.2. *Field photographs of quartz veins distributed through granitoid rock units* ***(a)*** *and geologic fracture structure which have orientation like mud crack patterns with irregular surface of the study area* ***(b).***

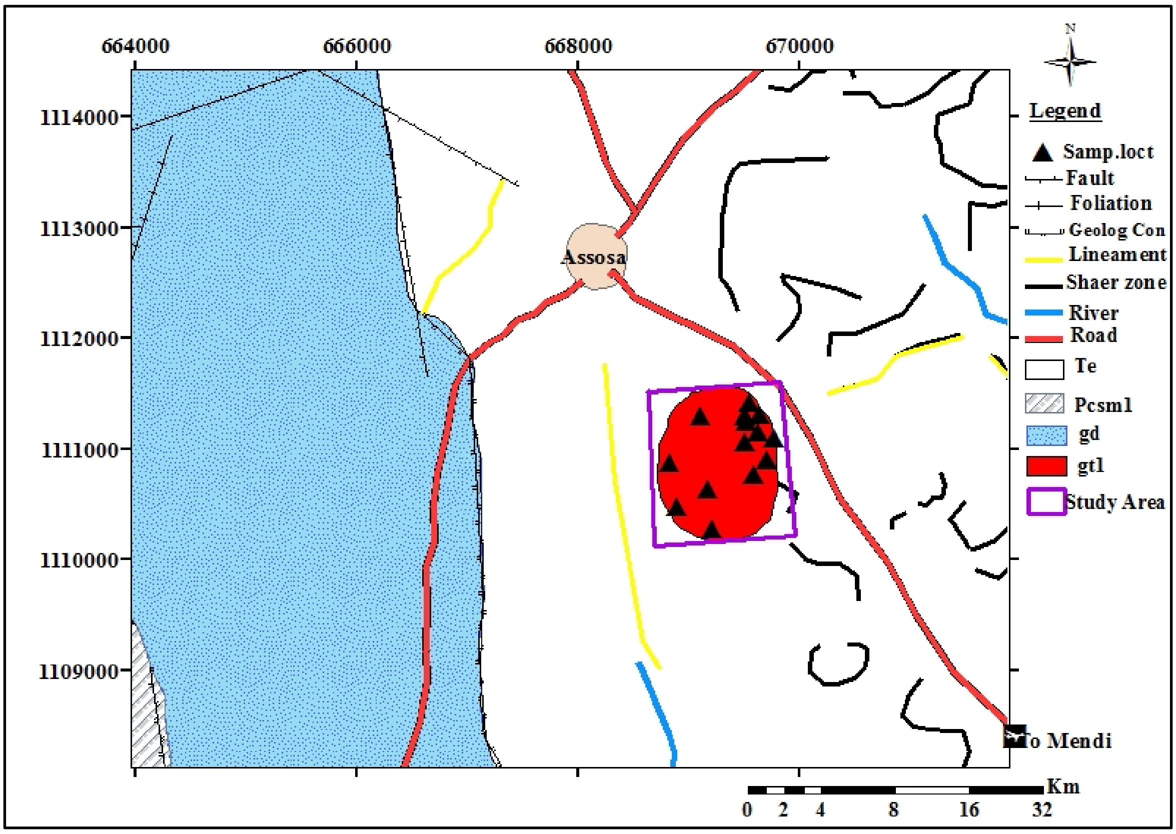


Figure: 3.2.1.3. Location map of representative rock samples (adopted from Mengesha Tefera, 1997).Where: gt1*-metagranite,* ***Te****-basalt,* ***gd****-metagranodiorite, and* ***Pcms1****-biotite,graphite and chlorite schists, quartzite, metasandstone, metaconglomerate and quartzofeldspathic schist. The representative sample includes field sample that collected for hand specimen sample description, petrographic and geochemical analysis.*

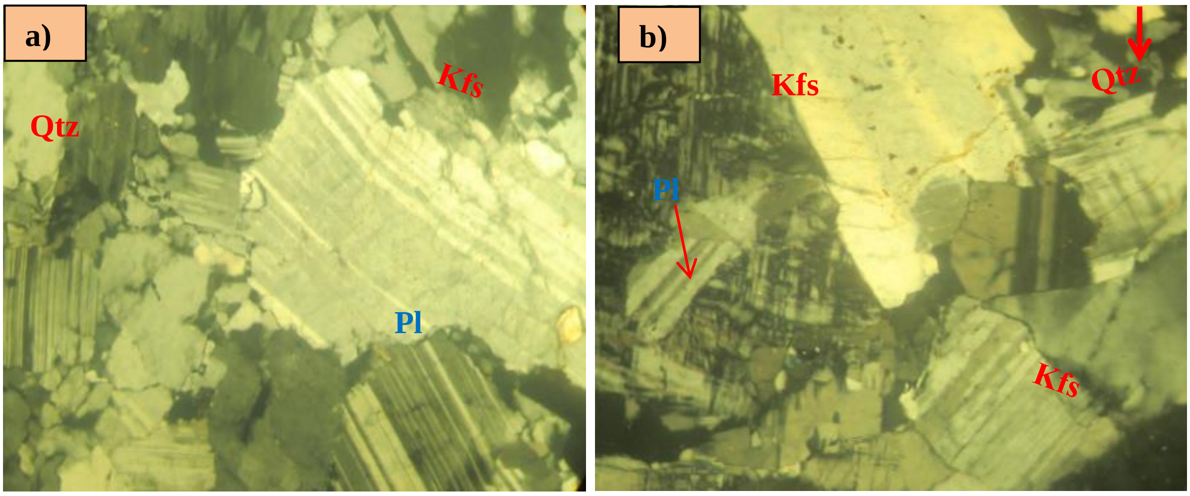
3.2.2 Petrography Description

Sample NW-08 that collected from Enzi hill of granitoids unit which dominated by three major minerals K-feldspars (52%), plagioclase feldspars (13%) and quartz (26%) in addition to these other mineral like accessory/minors minerals Opaque (5%), biotite (3%), muscovite (1%) incorporated in this rock samples. Quartz mineral grain has subhedral to euhedral crystal shape and the feldspar group of mineral show subhedral, euhedral and anhedral crystal shape in which their crystal face is poorly formed or developed while the mica groups (biotite and muscovite grains) flaky and tiny-platy shapes. The large grain size assemblage is both feldspars groups of grain of K-rich and sodium rich feldspars which have dark gray and light gray colours respectively.

The Antiperthitic of Na-rich feldspars (albite) in which the parallel streaks and blebs of Na-rich feldspar within a host of potassium -feldspar (orthoclase or microcline) occurred. The presences of abundant microcline (K-feldspar) in granite rocks suggest that rock equilibrate at a very low temperature in the plutonic environments (Soltani, 2000) discussed on his paper. Due the intergrowth of quartz and alkali-feldspar (granophyric texture) are more abundant in the granitoid rocks of the area, the incorporation of biotite minerals are very less compared to other major granitic minerals(Soltani, 2000).

On this prepared micro photo of thin section plagioclase feldspars show polysynthetic twinning and microcline feldspars tartan twinning (grid patterns) while orthoclase displays Carlsbad twinning. The alkali feldspars have microperthitic texture and the presence of some crack of micro fracture which oriented in different directions can be seen (Figure.3.2.2.1a).

Sample NW-09 collected from locality of Enzi shederia hill of granitoids rock in which the unit is predominated by feldspars mineral groups alkali-feldspars(62%), plagioclase (8%) and quartz (23%) minerals with other accessory minors mineral like the mica groups (biotite-4%) which have sub-parallel alignment, and opaque minerals(3%) (Figure.3.2.2.1b).The overall textures of this rock unit have medium to coarse-grained in which the feldspars grain and the quartz show phenocrysts/large crystal size shape assemblage than relative to others mineral grain. The large phenocrysts of alkali feldspars potassium rich have microperthitic texture. Feldspar, quartz, sphene and opaque (Fe-Ti oxides) mineral grain show the development subhedral-anhedral crystal shape, while the mica group biotite and muscovite mineral grain show an aggregate of containing small flat, almost bendable flakes textures. Intergrowth of dark gray colour potassium rich feldspars within the host of sodium rich feldspar formed, but the intergrowth of these two feldspars has different orientation. K-feldspars (microcline) and plagioclase grain of minerals loss their twin lamellae due to deformation, due to this some grains of this plagioclase mineral the sub-parallel alignments are invisibles.



Figurer: 3.2.2.1.*Micro-photography picture of Assosa granite rock (NW-08(****a), *** *large crystal size of both Kfs and Pl with irregular crystal shape of Qtz minerals), NW-09****(b),*** *light gray to gray color of Kfs with Pl minerals) in 10X magnification under XPL microscope views.*

Sample NW-010 show the dominances of the alkali-feldspars groups of minerals over the other mineral grains. Alkali-feldspar (54%), plagioclase (7%), quartz (27%) with other accessory minerals that constituents in small amounts like opaque minerals (Fe-oxide-5%), sphene(1%), biotite and muscovite (5%)and hornblende(1%).The alkali-feldspar, plagioclase, quartz and hornblend mineral grain have crystal face of anhedral to subhedral, while opaque and sphene mineral grain shows subhedral in which the developments of crystal face are medium ,while the biotite mica groups have flaky grain textures formed.

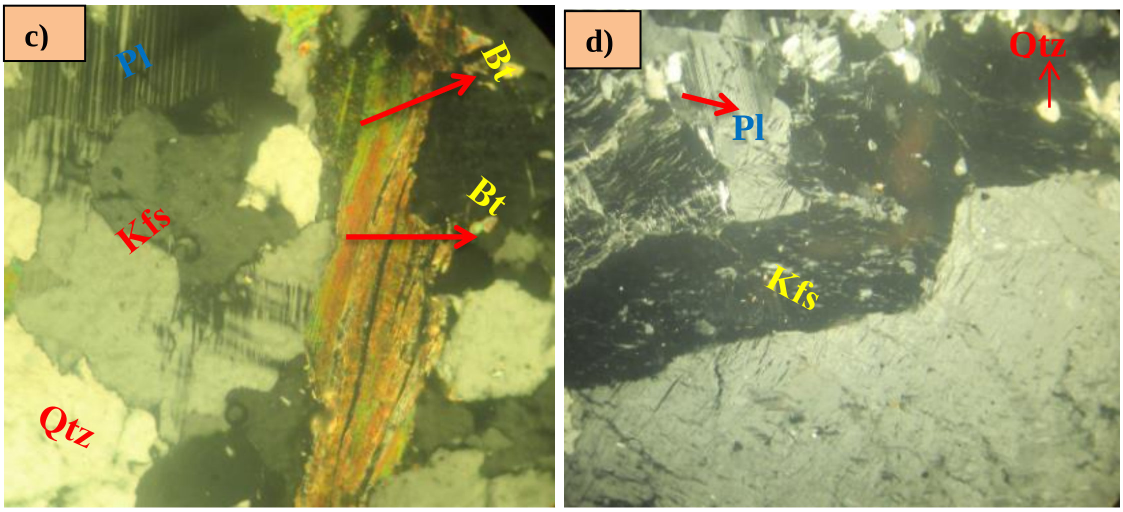
In this representative rock sample plagioclase, orthoclase and microcline of feldspar show polysynthetic, Carlsbad and tartan twinning respectively. Perthite of parallel streaks and blebs of Na-rich feldspar (albite) within a host of potassium-feldspar (orthoclase or microcline) is formed. Granophyric quartz-alkali feldspar intergrowth of quartz and alkali feldspars occurs and the quartz minerals show recrystallization and elongated shape of muscovite mineral grain rarely shows very pale pink or green to light green and biotite of pink, light to light greenish brown under XPL microscope views (Figure.3.2.2.2c).

Sample NW-015 are the representative granitoid rock sample that taken from study area for both petrography and geochemistry purpose. Granitoid rock unit consists grain of alkali-feldspar (58%) and plagioclase (12%) and quartz mineral grain (23%) and in addition to these major granitoids mineral constituents other accessory minerals includes biotite groups (4%) and opaque (Fe-oxide-3%) and the sphene constituent as trace minerals (Figure.3.2.2.2d).

The grain size shape of the three major constitute mineral K-feldspar,palgioclase and quartz including opaque and sphene has anhedral to subhedral crystal shape, while the biotite mica grain group characterized by flaky grain textures.

The large crystal shape/phenocrysts of feldspars (both Na & K-rich) which small cracks of micro fractures occurred. Alkali-feldspars and plagioclase feldspar grain groups' loss their lamellae twin due to deformation and they remain dark to light gray colours in which sub-parallel of alignments are invisible too observe.

The feldspar groups range from light gray to dark gray colour with medium to coarse-grained textures. The microcline K-feldspar part has tartan twin can be crossed by light colours of sodium rich albite minerals and exsolution of plagioclase feldspars within the host of K-feldspars occurred. Quartz grains which show slightly interference colour ranged from small to medium irregular crystal shape and they characterized by the presence of small cracks of micro fractures. Very less in amount of mica group and opaque grain are present in this representative thin section sample.



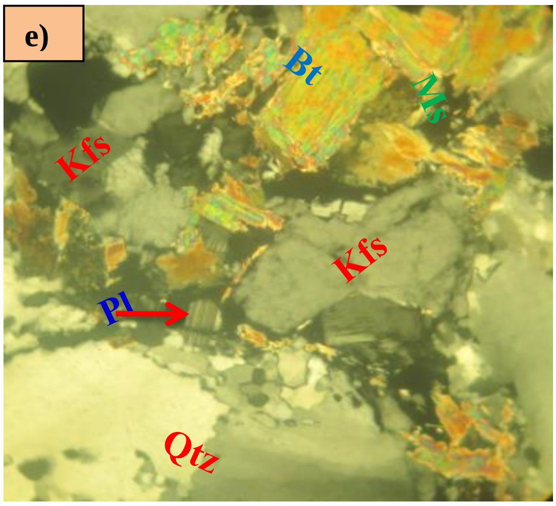
Figurer: 3.2.2.2.*Micro-photography picture of Assosa granite rock NW-010****(c),*** *dominance Kfs with Qtz with some elongated shape of biotite minerals),NW-015****(d),*** *Carlsbad twinning of Ort feldspar have light gray to dark gray color) in 10X magnification under XPL microscope views.*

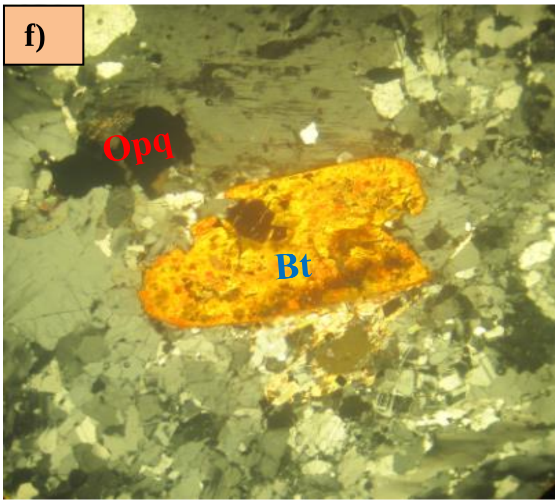
Sample NW-019 prepared thin section consists alkali-feldspar(50%),plagioclase (13%),quartz (29%) and accessory mineral like biotite and muscovite (5%),opaque(2%) and hornblende (1%).The overall mineral grains show medium to coarse-grained textures. Alkali-feldspar and plagioclase mineral grain has anhedral to subhedral crystal shape, while the biotite mica grains show flaky textures. Large crystal shape/phenocrysts of quartz grain with slightly interference colours (cloudy colors) than feldspar groups show subhedral to euhedral crystal face. In light gray alkali feldspars the resorbed quartz is occurred which form graphic texture of quartz grain. In dark colored K-rich feldspars grain small to medium sized cracks of micro fracture occurred. Polysynthetic or multiple twinning plagioclases while K-rich feldspars microcline exhibits tartan twinning.

Some grain of alkali and plagioclase feldspar loss their twin lamellae due to action deformation. Biotite and muscovite grain group show sub-parallel alignment which perfect alignment. Biotite mica group show yellowish colour while muscovite slightly pale pink or green to light green under XPL microscope views but under PPL muscovite looks colorless while biotite brown and yellowish brown and both of them show small to elongated crystal face with flaky texture(Figure.3.2.2.3e) .

Sample NW-020 are that collected from granite of Enzi shederia area, which consist of alkali-feldspar mineral group with modal percentage of (58%), plagioclase (12%), quartz (25%), biotite (3%), opaque mineral like (Fe-oxide-1%), while muscovite grain group and chlorite is incorporate as accessory or trace minerals.

The three dominant mineral grain and opaque groups characterized by development of crystal face of anhedral crystal in which the crystal face medium poorly developed, while biotite and chlorite has flaky and muscovite has tiny-platy grain texture. Grain size distribution of thin section the phenocrysts assemblage is alkali-feldspar grain which characterized by tartan twin (microcline) and Carlsbad twin (orthoclase) while the plagioclase feldspars has polysynthetic or multiple twinning. Some alkali and plagioclase feldspar grain twin lamellae losses due to deformation therefore the probability to see albite lamellae is less in some case. On quartz mineral grains randomly orientated small crack of micro fracture occurred. Large phenocryst or large crystal shape of biotite yellowish brown colours (Figure.3.2.2.3f) have flaky grain texture and irregular crystal shape.





Figurer: 3.2.2.3.*Micro-photography picture of Assosa granite rock NW-019****(e),*** *white to cloudy Qtz, dark gray & alternative band color of Pl minerals with some Bt) and NW-020****(f),*** *large crystal shape of Bt with other minerals like gray color of Kfs, white color of Qtz with dark color of Opq minerals)) in 10X magnification under XPL microscope views.*

The granitoid rocks of Assosa area can be named based on the modal mineral composition obtained by point counting, during petrographic thin section description were then plotted on QAP diagram. Therefore based on modal mineral composition of rock thin section analysis the granitoid rocks of the study grouped under alkali-feldspar granite and syenogranite rock granite rock group. On thin section description of mineralogical point counting the granitoid rock of an area is almost all samples fall under alkali-feldspar granite and syenogranite rock type on QAP plutonic rock classification. From thin section observation and description the rock sample of an area is manily dominated by alkali feldspar, quartz and plagioclase minerals in addition to these three major minerals the incorporation of mineral like biotite, muscovite, opaque minerals area involved in small amount and other accessory or trace minerals like sphene, chlorite and hornblende are also incorporated in very small amount.

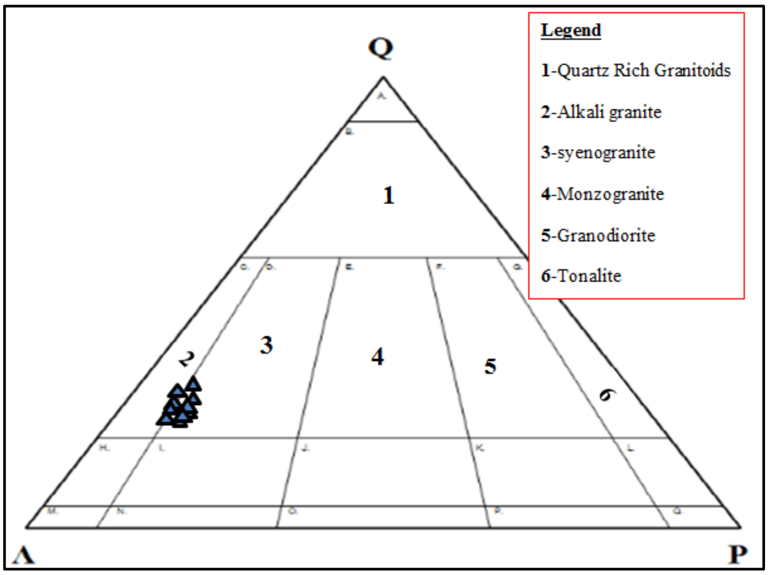


***Figure: 3.3. QAP** diagram of Assosa granite rocks based on the modal composition of major granitoid rock minerals Quartz (Q), Alkali-feldspars (A) and plagioclase feldspar (P).*

CHAPTER-FOUR

4. GEOCHEMISTRY OF ASSOSA GRANITOID ROCK

4.1 Introduction

Geochemistry with integration of petrographic data analysis used to address the geochemical signature, petrographic analysis result, paleotectonic environments of an area. Major element geochemistry used to evaluate magmatic evolution, while trace and rare earth element analysis, can be used to determine source suite of cumulate or to evaluating the composition of magma sources such as the mantle and lower crust, the behaviors of each trace elements magmatic evolution and to trace geodynamic setting of the granitoid rocks. Trace element geochemistry are used to model processes of melting (equilibrium and fractional) and crystallization (equilibrium and fractional).Trace element allows to estimate of the trace composition of the parent melted, the minerals in the residue at the time of removal of the melt, the sequence of minerals involved in differentiation, and along with the initial isotope ratios will allow an estimate of the extent of mixing or reactions with other melts or rocks.

4.2 Major element Geochemistry

By Definition major element are elements which their concentration is usually greater than 1%wt. Major element are elements which are predominant in any rocks and their concentration is expressed as wt% in oxides form. These major elements includes Si, Al, Fe, Mg, Ca, Na, and K and with their oxides SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, Na_2O, and K_2O respectively. The main application of these major elements for rock classification and for construction of variation diagram in turn used to know evolution of magma to characterize source composition cumulates compositions and liquid evolution trends. The major element geochemical data of all samples that were collected from the study area is used in oxide form. They plot on the Harker diagram against to wt% of SiO_2. Analyzed geochemical result of granitoid rock of area includes: - NW-09, NW-010, NW-014, NW-018, NW-019 and NW-021 showed that 73.9, 73.9, 75.2, 75.8, 75.7 and 75.8 SiO_2 wt% respectively.

Samples	NW-09	NW-010	NW-014	NW-019	NW-018	NW-021
SiO2	73.9	73.9	75.2	75.7	75.8	75.8
TiO2	0.19	0.21	0.16	0.17	0.15	0.06
Al_2O_3	13.40	13.50	13.35	13.30	13.25	13.60
Fe_2O_3	2.01	2.39	1.75	1.96	2.00	1.57
MnO	0.03	0.05	0.03	0.02	0.05	0.03
MgO	0.14	0.19	0.12	0.01	0.08	0.07
CaO	0.46	0.45	0.49	0.24	0.55	0.03
Na_2O	4.57	4.38	4.58	4.25	4.76	4.64
K_2O	4.67	4.79	4.49	4.79	4.30	4.56
P2O5	0.06	0.03	0.01	0.01	<0.01	<0.01
LOI	0.45	0.50	0.29	0.31	0.63	0.53
Total	**100.01**	**100.5**	**100.57**	**100.92**	**101.63**	**100.93**

Table: 4.2. *Major element geochemistry of analysis geochemical results of Assosa granite rocks.*

Major element Harker diagram shows two major trends. These trends can be observed plotting the major oxide against silica concentration on Harker diagram. On plotted Harker diagram many major oxides versus SiO_2 (Fe_2O_3, TiO_2, Cr_2O_3, K_2O and Na_2O) (Fig.4.1a-j**)** show scattered data follows, this occurred due to presence of crystals. K_2O and Na_2O causes, these two major oxides show scattered trend versus to SiO_2, this may implies that small alteration of feldspars and plagioclases or the richness of the granite rocks with alkali-feldspar and biotite or due to contamination of magma forming the rocks (NAZEMI et al., 2015)(Figure.4.2.1.a & b). Concentration of K_2O is variable that range from (4.3-4.79wt %), that characteristics of subduction-related granite in continental margin settings (Grigoriev and Pshenichny, 1998; Rottura et al., 1998). The low content of Na_2O (4.25wt %) in alkali-feldspar granite of area implies that presence of lower content of plagioclase and absence of hornblend, while the abundance of K-feldspar enriched the rock with (K_2O=4.79wt %)(Figure.4.2.1.a).

Higher content of Na_2O (4.76wt %) indicate that Na has not been removed from the source rocks (Figure.4.2.1.b).

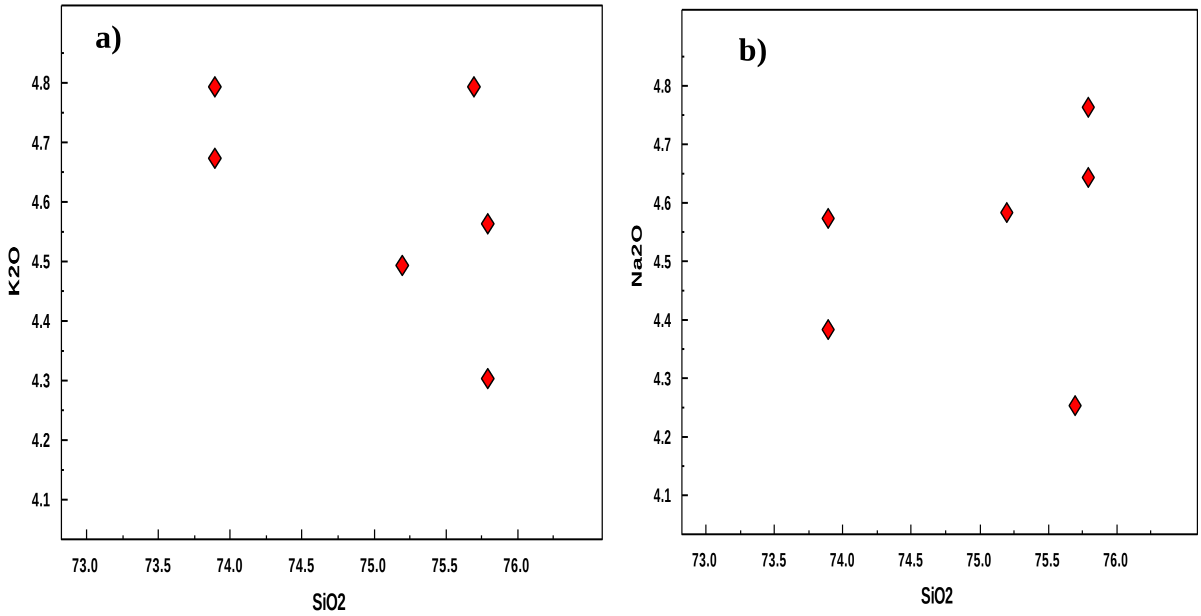


Figure: 4.2.1. *Harker diagram of major oxide versus silica,* ***(a)*** *K_2O versus SiO_2* ***(b)*** *Na_2O versus SiO_2, show scattered data follows and their concentration is expressed as wt%.*

The major oxides like Al_2O_3, CaO, MgO and P_2O_5 and trace element Sr and Ba show negative correlation trends against SiO_2, due to fractional crystallization during magmatic evolution (Figure.4.2.2.a-f).

The overall major elements on Harker diagram plot that show negative trend correlation respect to SiO_2 indicate the granitic rocks are likely the result of fractional crystallization during magmatic evolution supported by separation of apatite and mafic mineral during crystallization. Fractionation minerals like apatite and ilmenite were indicated by the presence of the declination in concentration of TiO_2 and P_2O_5 with increased in SiO_2 concentration (Adi et al, 2012). Reduction of TiO_2, P_2O_5 against SiO_2 in granitoid rocks, indicated by the reduction of apatite and biotite and titanite minerals during differentiation of rocks (Figure.4.2.2.d & e). The decline of CaO versus to SiO_2 indicates due to crystal fractionation of plagioclase and calcic amphibole minerals (Figure.4.2.2.b).

The value of P_2O_5 range from (0.01-0.06wt%) is occurred in granitoid rock sample of an area, which is mostly dominated by quartz and K-feldspar, consistent with the lower solubility of P in more felsic and lower temperature granite melts (Harrison and Watson,1984;chappell et al,1998). Low concentration of P_2O_5 in relation to SiO_2 which show negative correlation trend indicates the presence of abundant apatite crystals within the rock (Figure.4.2.2.d).

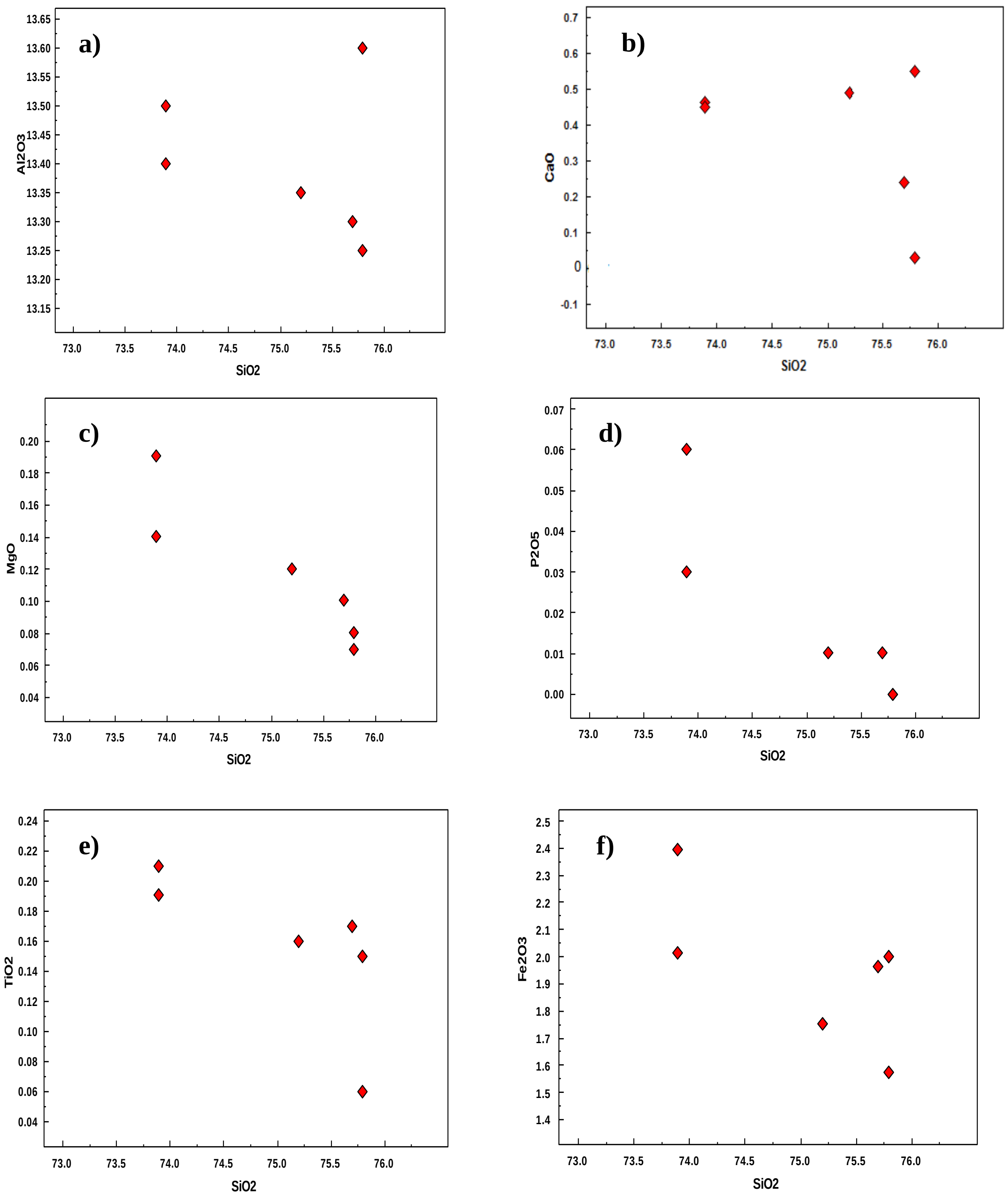


Figure: 4.2.2.*Harker diagram of major oxide versus silica (Figure (****c, d & e****), show that negative trend correlation against silica i.e. as the concentration of silica increase concentration these major oxide decline and as their concentration increases concentration of silica decline), while Figure* ***(a, b & f),*** *show some scattered data with negative trend correlation with silica. In whole figure representation all major oxide expressed as* ***wt%.***

In the case of Al_2O_3 versus SiO_2 it show two trends one trend occurred the trend that run up to curve which indicate that absence of crystallization while beyond curve (inflection) that indicate presence of sequences of crystallization, therefore in Al_2O_3 (13.25-13.6wt%) case does not exhibit a strong variation. Higher content of Al_2O_3 in granitoid rocks of the area is characterized by due to the enrichment of rock samples by mineral like plagioclase, amphibole and biotite (Fig.4.2.2.a).

As SiO_2 increase concentration of Ba elements decrease within the alkali-feldspar granite, which indicates that granitoid rock of the area contains more abundant of K-feldspar and less amount of biotite (Fig.4.2.3.a).The low contents of Ba is obsrved in alkali-feldspar granite of an area, that indicate the low content in biotite minerals but high SiO_2 and modal contents of K-feldspars, while the depletion of Ti and P reflect fractination of apatite and illemnite (Fe-Ti oxides) and depletion of Sr from granitoid (alkali-feldspar granite),refelcts that the fractionation of plagioclase (Soltani,2000).A large fraction of Ba was partitioned into K-feldspars crystals and the precipitation of K-feldspar crystals from the melt of the alkali feldspar granite resulted in Ba content falling sharply in the remaining melt, consistent with fractional crystallization processes (e.g. Wyborn et al., 1987; Chappell et al.,1998.,Wyborn, 1998).

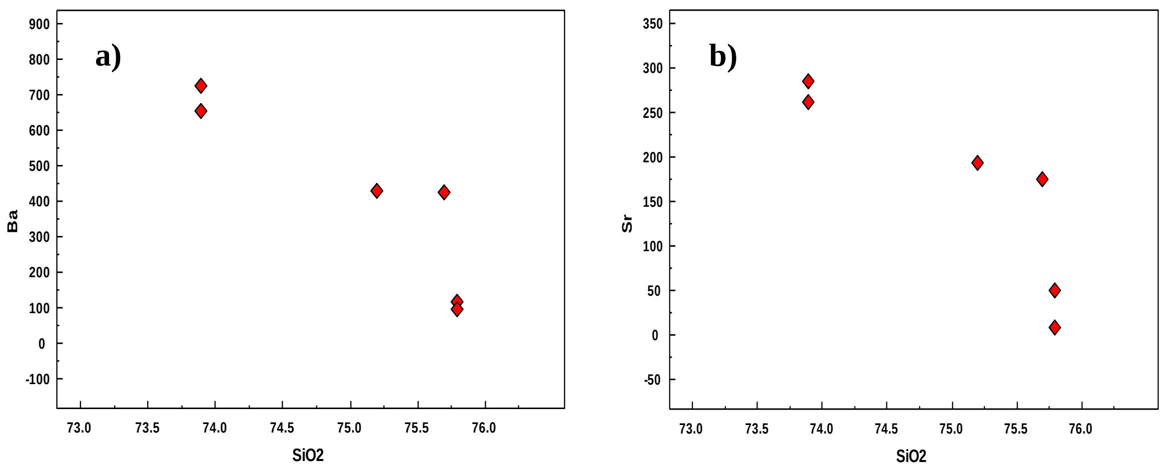


Figure: 4.2.3.*Variation diagram between selected trace element versus silica (Figure* ***(a & b),*** *show that negative trend correlation between silica and selected trace elements of both Ba and Sr, in both case as concentration of silica decrease concentration of these trace element (Ba & Sr) increase).Concentration of trace element (Ba &Sr) expressed as ppm and while concentration of silica expressed as wt%.*

4.3 Trace element Geochemistry

Trace elements are elements in which their concentration is usually < 0.1%.They are elements that constitute in a small fraction in rocks and their concentration can be expressed as parts per million (ppm) or more rarely by parts per billion (ppb).These analysed trace elements includes Cs, Rb, Ba, Sr, Pb, Sc, Y, Th, U, Pb, Zr, Hf, Ti, Nb, Ta, La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, and Lu.

	NW-09	NW-010	NW-014	NW-019	NW-018	NW-021
Ti	0.07	0.11	0.07	0.07	0.08	0.07
Rb	119.5	117	96.8	121	141	160.5
Sr	261	285	192.5	173.5	49.8	6.7
Y	17.9	27.4	29.5	8.7	15.7	6
Zr	400	403	234	337	344	477
Nb	29.1	20.5	17.4	22.4	29.3	8.5
Cs	1.03	1.08	0.51	0.92	1.17	1.08
Ba	651	722	427	421	115.5	93.9
La	80.6	129	91.2	50.5	39	45.3
Ce	165.5	227	164	129	84.5	41.9
Pr	20.4	27.6	19.6	10.75	9.93	6.84
Nd	63.9	86	63.7	29.2	30.6	17.2
Sm	10.45	13.15	9.93	3.95	5.07	1.72
Eu	1.46	1.88	1.57	0.58	0.71	0.22
Gd	5.47	7.52	7.22	1.94	3.28	0.9
Tb	0.73	1.01	1.01	0.3	0.47	0.12
Dy	3.54	5.17	5.45	1.67	2.7	0.73
Ho	0.64	0.87	1.01	0.29	0.54	0.18
Er	1.8	2.31	2.8	0.89	1.5	0.6
Tm	0.28	0.34	0.4	0.16	0.22	0.12
Yb	1.79	1.83	2.37	1.04	1.63	0.88
Lu	0.32	0.28	0.32	0.18	0.26	0.17
Hf	9.3	8.7	5.5	7.6	9	9.9
Ta	2.4	1.9	1.3	1.6	2.3	0.6
Pb	24	27	26	23	22	2
Th	23.3	18.45	19.8	19.95	26.8	17.75
U	7.02	5.94	3.91	8.24	7.49	3.41

$(Sm)_N$	68.3	86	64.9	25.8	33.1	11.2
$(Gd)_N$	26.6	36.6	35.1	9.4	16	4.4
$(Eu)_N$	25.2	32.4	27.1	10	12.2	3.8
$(La/Yb)_N$	32.4	50.4	27.7	34.9	17.1	36.7
Eu/Eu*	0.59	0.58	0.57	0.64	0.53	0.54

Table: 4.3. *Trace element geochemistry of analysis geochemical results of Assosa granite rocks.*

The main objectives of analysis of these trace elements are for identification of source rock and determination or to trace paleo tectonic environment of granitoid rocks of area.

The rare earth element (REE) pattern of the Assosa granite rock which have enrichment in LREE, small to moderate Eu negative anomaly and flat HREE (holmium to lutetium) trend may show similar trend to post-Archean granitic rocks distinctive feature of contemporary upper continental crust. On multi element variation diagram pattern there is lowest contents of Ba,Cs,Ta and Nb and depletion of Sr, P and Ti can be ocurred (Figure..4.3.1).

Small to modrate negative anomaly of Ti and P are chracterized by the low modal content of apatite, biotite and Fe-Ti oxides (illemenite),while the large negative anomaly of Sr compared to other trace element is due to the low modal contents of plagioclase minerals in granite and stable phase of plagioclase in the remaining liquids during melting (NAZEMI et al., 2015) and deplement of Sr and negative Eu anomlay indicate that the presence of continuous fractionation of plagioclase during differentiation (Figure.4.3.1 & 4.3.2).Zig zag feature that observed on the multi-varation element plotted diagram show the crustal contamination of granite (Wilson,1989 as cited in NAZEMI et al., 2015).SiO_2 and Nb show negative correlation to each other's demonstrate that fractional crystallization during the formation of the granitoid rocks. In addition to Nb trace elements like Zr, Sr and Rb with SiO_2 show negative correlation, this may imply that fractional crystallization occurred during the formation of the granitic rocks (Adi et al., 2012).

High contents of trace-elements like Uranium, Thorium and Potassium in both normalized and variation element diagram and negative anomalies of Nb and Ta indicate that granite of the area are mainly from continental crust.Deplements of Nb and Ti on REE patterns have a geochemical indication of for the involvment of subduction-type enviroment (Hill et al.,1992;Whalen et al., 1996; Ajaji et al.,1998;Soesoo,2000).

The Nb and Ta negative anomalies trace tectonic discriminator most ganite rock sample support the arc-related magmatic origin, that indicate the product of subduction related zone as (Figure.4.3.1) and on chondrite-normalized that show enrchiment of LREE and slight deplement to flat patterrns of HREE (Figure.4.3.2). Nb and Ta negative anomaly more prominet in the depleted island arc theoliites (pearce and peate, 1995) and subduction related magmatism (feature of primitive oceanic arc lava) resulted due to different processes in diffeent magmatic sources.

The depletion Nb may be ocurred due to fractionation titanate minerals and negative anomalies of Nb and Ta and the high Pb content of granite of the area is characterized by low Nb/La,Ta/La and Ce/Pb is relative to the oceanic crust and the upper mantle.

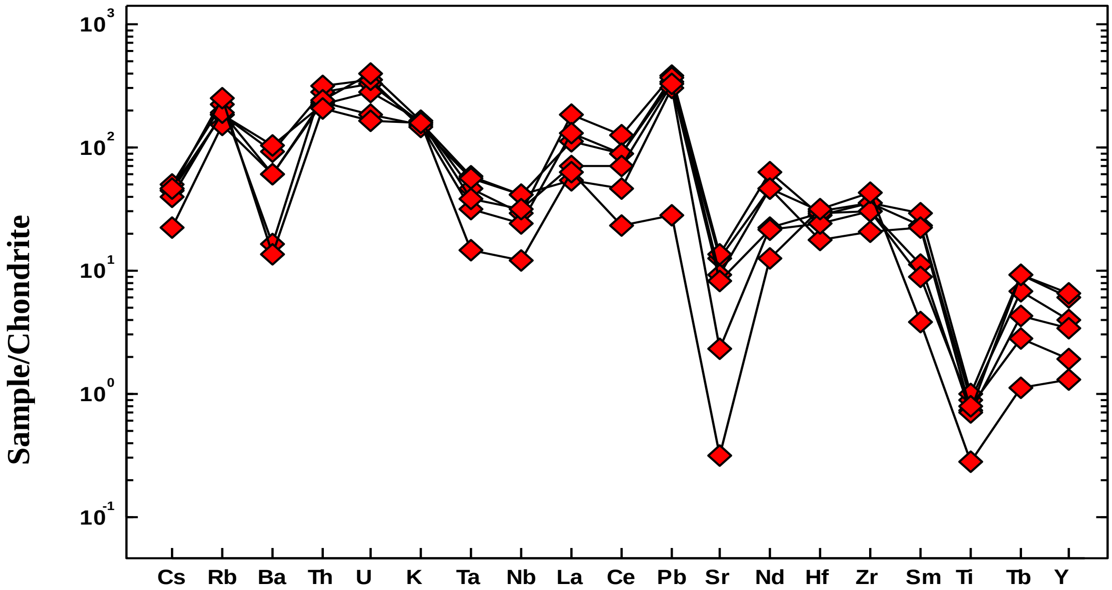


Figure: 4.3.1. *Multi element variation diagram of granitoid rocks of the area, Primordial mantle-McDonough et al., (1992)*

Assosa granite rock formed by different processes in different magamtic suites,which are the featrure of granite suites of average crustal composition supported by negative anomalious value of Nb,Ta and Ti elements. In addition to that their anomalies values may also be generated during intracrustal melting and magma differentiation, and evidene for tectonic setting of crust generation.

The enrichment of incompatible element concentration particularly high La/Yb and low Nb/La of the coeval basaltic rocks, suggest that the rock derivation primary from enriched domains within the subcontinetal mantle lithosphere, rather than the asthenosphere (Turner, 1996).The high contents of Rb trace elements are obsreved that refelcets,the rock sample low modal content of biotite mineral and high contents of felsic minerals like K-feldspar,which refelect the source rock is acidic origin.The high content of Th in alkali-feldspar granite from multi element variation diagram may be explained by the presences of minerals like:zircon,titanite and apataite.

On Chondrite-normalized REE patterns Assosa granite show the enrichments of light rare earth elements (LREE) and slight to flat arrangments of heavey rare earth elements (HREE) with slightly to moderate negative anomaly Eu diagram (Figure.4.3.2).The enrchiment of LREE are showed by ($(La/Yb)_N$ ratio =50.4) with relatively flat HREE and the negative Eu anomaly is showed by the value of (Eu/Eu*=0.64), with Eu anomaly range from (0.53-0.64). Calculated Eu anomaly for analyzed sample lies within the negative Eu anomaly, in which the ratio of Eu/Eu* is less than 1.0 indicate a negative anomaly (Rollinson, 1983). As (Adi et al., 2012) presented on his paper, a granitoid rocks that show behaviors of the enrichment LREE and relatively flat HREE patterns with slightly depleted and negative Eu anomaly which confirm that arc-related origin and strongly granitic rocks are product of subduction zone, resembles the upper continental composition were generated from source materials with abundant plagioclase.

From the analyzed sample Assosa granite of show more or less similar REE pattern parallel patterns with small Eu anomaly, suggesting the involvement of a fractionation processes in the origin of granitoid rocks of the area (Tesfaye Kebede and Koeberl, 2002).Therefore enrichment of LREE and negative Eu anomaly of granitoid of Assosa suggesting that melts were generated from source materials with abundant plagioclase.

From this variation patterns of rare earth elements pattern (both LREE & HREE), the granitoid rocks of an area belongs to active marginal arc environments that support tectonic setting of an area. The higher enrichment of LREE compared to HREE is indicate charactestics of the magmatism of the subduction zone (Winter, 2001).

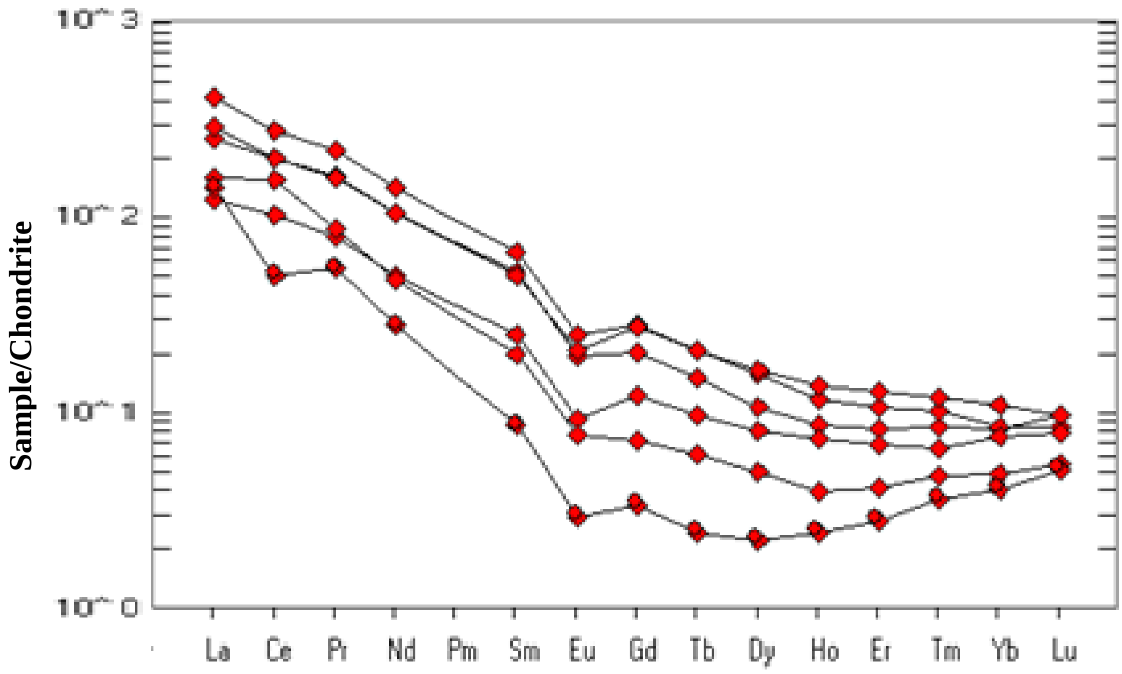


***Figure: 4.3.2.** Chondrite-normalized REE patterns diagram of granitoid rocks of the area, After COND-Sun & McDonough (1989)*

The higher strontium concentration value variation relative to rubidium concentration value on incompatible versus compatible element plotted diagram implies that the involvements of fractional crystallization arc-related more mafic magmatism of mantle derived material during rock formation. Incompatible element variations in magmas and magmatic rocks are mainly related to variation in degree of melting, while the compatible elements are indicators of the extent of fractional crystallization. The pronounced negative Eu anomaly indicates the importance of plagioclase and/or K-feldspar in the fractionating phases or in the residual mineralogy in case of an anatectic origin (Cullers and Graf, 1984).

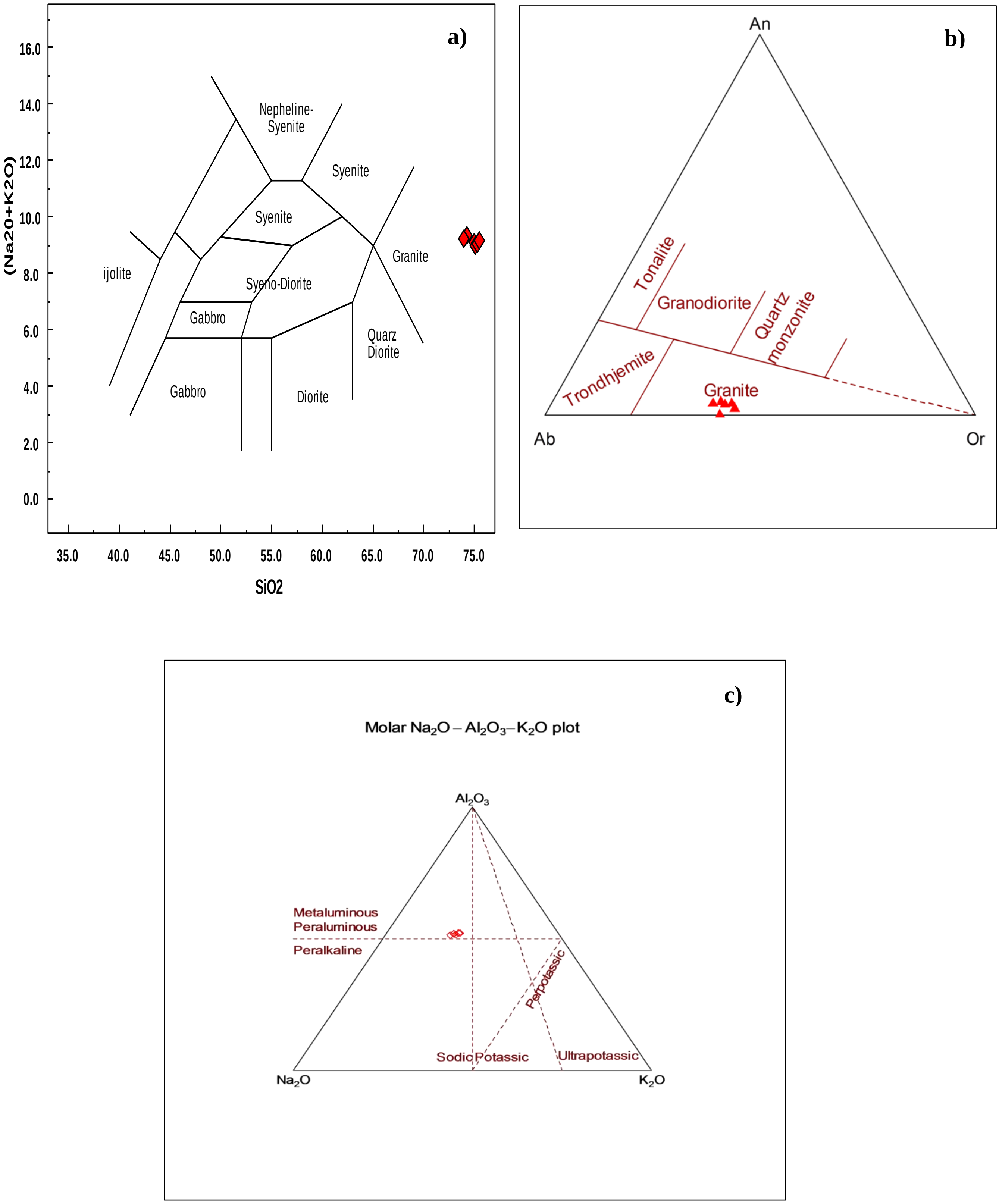
4.4 Classification of Assosa granite rocks

Based on general chemical plutonic rock classification of TAS diagram, (After Cox-Bell-Pank, 1979) the plutonic rocks of an area of whole analyzed samples fall on felsic granite plutonic rock with silica content ranges from 73.9-75.8 wt% SiO_2 (Figure.4.4.a).

The granite rock of an area has an overall of both metaluminous and peraluminous based on (Shand, 1943) and grouped under highly potassium calcic- alkaline series as plotted on (Figure.4.4.c & d).Potassium-rich calcic-alkaline hybrids may be produced by injection of mantle-derived magmas into thick continental crust during the period of relaxation and uplift that follows a collision event. These often indicate the change from a compressional to an extensional regime (Barbarian, 1990). In A/CNK (mole ($Al_2O_3/CaO+Na_2O+K_2O$)) and A/NK (mole (Al_2O_3/Na_2O+K_2O) classification diagram (after Shand, 1943), almost all analyzed rock samples were plotted into peraluminous categories (ASI=0.98-1.00), except one sample plotted on metaluminous and one sample exactly in the transition between metaluminous and peralumious classification categories. Therefore Assosa granite rocks range from slightly metaluminous to relatively moderate peraluminous (Figure.4.4.c).

The presences of biotite, hornblend, magnetite, apatite and zircon minerals in small amount rarely suggest that there is some metaluminous source of the rocks. The peraluminous suite have ASI>1.0, while the metaluminous characterized by having ASI<1.0.The presences of micas and the accessory minerals in the rock, which related to source magma and condition of melting happened in both case (ASI>1.0 and ASI<1.0) (Nyarko et al., 2012).

In the normative Ab-An-Or granite rock classification diagram of (O'Connor,1965) plotted the analyzed whole rock samples fall in the field of granite rocks, in the area boundary between albite (Ab) and orthoclase (Or) (Figure.4.4.b).This type of classification applied to felsic rocks with more than 10% normative quartz (Rollison,1993). According to K_2O against SiO_2 diagram (Peccerillo and Taylor, 1976) the granitoid rock of study area fall within the calc-alkaline range and have highly potassium contents. In general the whole rock sample analysis that indicated peraluminous (except one sample metaluminous, that indicate the dominance of CNK over Al) and the calc-alkaline series with dominance of potassium rich feldspars nature of the rocks.


a)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
(Na2O+K2O)
35.0
40.0
45.0
50.0
55.0
60.0
65.0
70.0
75.0
SiO2
Nepheline-
Syenite
Syenite
Syenite
Granite
ijolite
Syeno-Diorite
Gabbro
Quarz
Diorite
Gabbro
Diorite
b)
An
Ab
Or
Tonalite
Granodiorite
Quartz
monzonite
Trondhjemite
Granite
c)
Molar Na2O – Al2O3–K2O plot
Al2O3
Metaluminous
Peraluminous
Peralkaline
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Ultrapotassic
Na2O
K2O

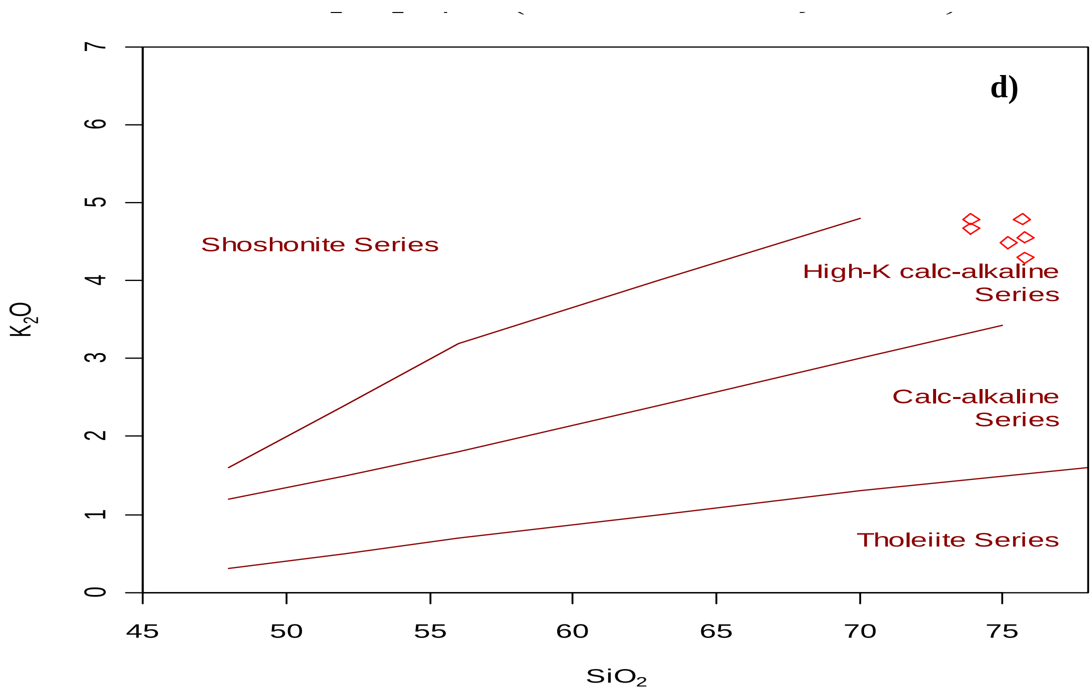

*Figure: 4.4. Chemical classification of plutonic granitoid rocks of the study area based on TAS or Total Alkali-silica. (After Cox Bell-Pank, 1979)***(a),** *granite rock classification using Ab-An-Or plot (O'Connor 1965) diagram* **(b),** *molar Na2O –Al2O3-K2O plot diagram***(c)** *and granitoid rock classification based SiO_2 –K_2O plot diagram (Peccerillo and Taylor, 1976)***(d).**

4.5 Tectonic setting of area

By definition a tectonic classification relates chemical and intrusive style of granitoids to periods of orogenic cycles or periods of extension. As discussed by different authors like (e.g. Collins et al., 1982; Pearce et al., 1984; Whalen et al., 1987; Eby, 1990, 1992 as cited in Tesfaye Kebede et al.,1999) granitic rocks are used to characterize tectonic settings of emplacement and source characteristics. While understanding of tectonic setting of the area help to understand the Precambrian tectonic and magmatic evolution of the area. Recently besides A-type granitoid of the western Ethiopia as (Tesfaye Kebede et al.,1999, 2001b) discussed granitoid of western Ethiopia (Wallagga) characterized by volcanic arc granitoids (VAG) and syn-collisional leucocratic granite (Syn-COLG).

Assosa granite has characterized by metaluminous-peraluminous varieties of granites, which suggest that generation from crust that experienced continent-continent collision or island arc magmatism (Tesfaye kebede and Koeberl, 2000).

From our geochemical data result Assosa granite rocks have a chemical charactestics of both volcanic arc granitoid (VAG) and syn-collisional granitoid (Syn-COLG) as described on (Figure.4.5.a-c). Using Rb versus (Y+Nb) (Figure.4.5.a), Rb versus (Yb+Ta) (Figure.4.5.b) and Nb versus Y (Figure.4.5.c), trace element tectonic discrimination all samples confirm the arc volcanic related origin (VAG) and some samples in (Figure.4.5.c) characterized by an association of both volcanic arc granitoid (VAG) and Syn-collisional granitoid (Syn-COLG).In both tectonic setting the granitoid rocks of Assosa area are product of processes associated with subduction zone or island arc environments. From multi element variation diagram plotted the enrichment in LREE and slightly depletion in HREE, especially in the case of Nb and Ta trace tectonic discriminator most sample support the arc-related origin, that indicate (suggest) the granite rock are the product of subduction related zone. The enrichment of moderate to high incompatible trace element of Assosa granites suggesting that the continental crust has been an important role in their magma genesis (Soltani, 2000). In addition to tectonic setting discrimination plotted diagram (Figure.4.5.a-c), granite rock classification using different method (Figure.4.4. c, d & e), Assosa granite rock have both crustal and mixed (crust + mantle) origin which in turn supported by the peralumious (peralumious intrusive granitoids) and metaluminous (calcic-alkaline rock, potassium calcic-alkaline granitoid (high K & low Ca)) nature of the rock.

The presence of small calcic-alkaline (low K & high Ca) have subduction zone nature, while the high K-calcic-alkaline rocks has collisional tectonic setting, in which both tectonic setting classified as orogenic granite origins. Therefore granite rocks of an area found on the subduction oceanic plate into continental plate. The analyzed of all six geochemical samples lies within both volcanic arc granitoid (VAG) and syn-collisional granitoid (Syn-COLG) tectonic setting. Modeling of partial melting and fractional crystallization is having not been done due to the absence of any recorded data on parent magma which has not been studied before around the study and surrounding area.

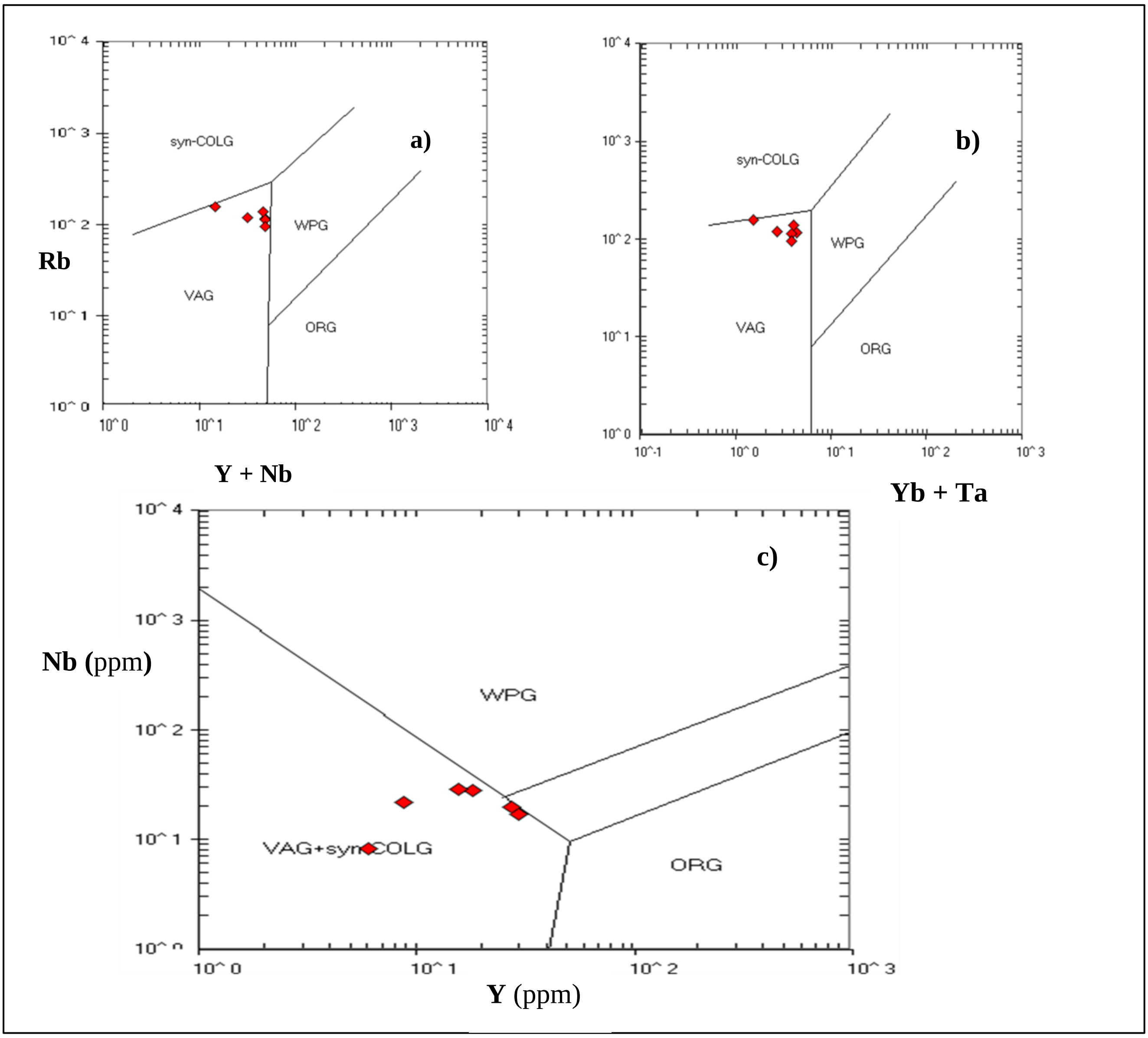

Figure: 4.5.*Tectonic discrimination diagram of Assosa granitoid rocks (after Pearce et al., 1984)* ***(a),*** *using Rb versus Y+Nb****, (b),*** *Rb versus Yb+Ta and* ***(c),*** *Nb versus Y* trace element tectonic discriminator *in which VAG: Volcanic Arc Granitoid, Syn-COLG: Syn-Collisional Granitoid, WPG: Within Plate Granitoid and ORG: Orogenic Granitoid rocks and concentration these trace element expressed as ppm (part per million).*

4.6 Petrogenesis

The granite rock of the area has both compositional and textural variations, which constrain their petrogenetic or magmatic evolution. The analysed geochemical data result of Assosa granite on plotted Harker diagram (Figure.(4.2.1.a & b and 4.2.2 a, b & f)), show considerably scattered data for major oxide against SiO_2, while some major oxides show the negative trend against SiO_2, both trend occurred probably due to the contribution of different plutonic activity with variable chemical composition of the rocks. The negative trend or curved/inflation trends of major elements against SiO_2 on Harker variation diagram plotted indicate the granite rocks are likely to be the result of fractional crystallization arc-related magmatism from more mafic magma of mantle derived during magmatic evolution supported by separation of apatite and mafic mineral during crystallization. Fractionation of these mineral in turn reflected by the depletion of rare earth element like Sr, Ti, P, & Ba on multi-element variation diagram samples of Assosa granites, this may occurred due to the varying in the proportion of crystallizing phases, such variation expected to be occurrences of variation in a crystalline magma (Tesfaye Kebede et al., 2000).From the composition of major and trace elements trend understand that the Assosa granitoid derived by fractional crystallization of common magmatic sources.

Enrichments of Th reflect that there is large contribution of a crustal component in the genesis of granite rocks of the area (Figure.4.3.1).Negative anomaly of Nb and Ta and positive value of Pb indicate that granite rock of the area is arc-derived magmatism or mantle derived material which later contaminated by crustal materials and deplement of Nb and Ta trace element with enrichment of LREE and slight (deplement) to moderate flat HREE pattern indicates the granite of the area resembles from the continental crust composition. High content of Pb and low content/negative anomaly of Nb and Ta behaviors of oceanic crust and upper mantle.Their anoamlies value (Nb,Ta and Ti),indicate that granite rock of the area resulted from different magmatic suites of different process, which are granite feature of average crustal composition and negative anomalies value generated during intracrustal melting and magma differentiation, and evidene for tectonic setting of crust generation.

Practically, on the Chondrite-normalized REE patterns the granite samples of an area show enrichment light rare earth element (LREE) and flat higher rare earth element (HREE), with Eu negative anomalies. This may suggest common or analogous magma sources and crystallizing phases and such REE pattern related to arc-relating granite origin and associated with subduction zone, which resembles the granitoid of the area is may be from continental composition were plagioclase more abundant and mantle derived composition of mafic magma.

The geochemical analysis data result plotted using the trace element tectonic discriminator indicate almost all representative samples plotted within volcanic-arc granitoid (VAG) and syn-collisional granitoid (Syn-COLG),which indicates the granite rocks of the area formed associated with subduction zone. Assosa granite rock accounted for fractional crystallization processes as plotted on (Figure.4.6.c) using incompatible versus compatible (Rb versus Sr) trace elements. The high content of Sr against Rb plotted diagram may imply that plagioclase was incorporated into the melt (Asfawossen Asrat et al., 2004),while depleted or low value of Sr suggest that Assosa granitoid may generated by extensive fractional crystallization from mantle-derived mafic magmas. The variation of Sr concentration value with nearly constant Rb concentration value may reflect the presence of fractional crystallization that control Assosa granite rock formation (Figure.4.6.c & d). Genesis of low content of Sr (6.7 & 49.8 & ppm) it may involve small degree of partial melting of underplated basaltic material to produce the least-differentiated silicic magma, which mostly undergo high to moderate of fractional crystallization to generate the most evolved silicic rocks (Dereje Ayalew et al., 2002).Positive correlation trend observed between Sr and the Eu contents suggest fractionation of plagioclase, which suggest accumulation of plagioclase within the granite rock samples (JUNG et al., 1999) (Figure.4.6.b). Source material of Assosa granitoid rock is from peralumious and potassium rich, which supported by fractionation of minerals and highly K-calc-alkaline and the peralumious nature of the rock (Figure.4.4.c & e).The alkaline granite nature of the area generated by extensive fractional crystallization mantle-derived mafic magma.

Assosa granite show negative anomaly Nb, Ta and positive Pb. This are typical of continental crust arc magmatism, which suggest that Assosa granite may be formed either by partial melting of the continental crust or by fractional crystallization of mafic magma related to arc magmatic setting. To differentiate partial melting from fractional crystallization we use variation diagram of compatible element (Sr) versus incompatible element (Rb) on log scale (Figure.4.6.d).As shown in the (Figure.4.6.d) there is wide variation in the concentration of Sr but the concentration of Rb remain constant. This show that Assosa granite mainly resulted by fractional crystallization of mafic magma related to arc setting.

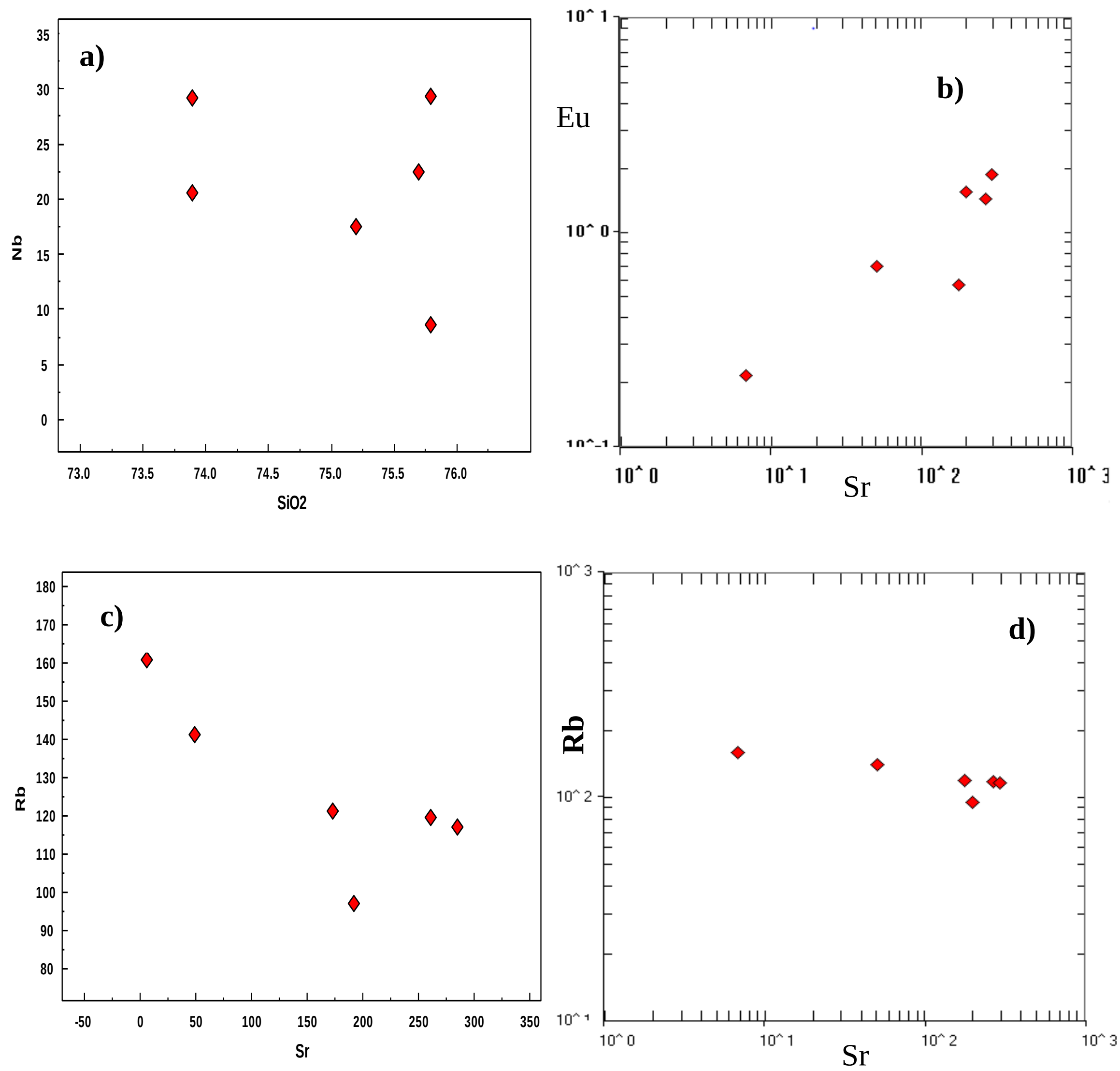

Figure: 4.6. *Variation diagram of granitoid rocks of area between selected trace elements* ***(a),*** *Nb versus* SiO_2*,* ***(b),*** *Eu versus Sr,* ***(c)*** *and* ***(d)*** *Rb versus Sr. Trace element concentration expressed as ppm (part per million).*

CHAPTER-FIVE

5. CONCLUSIONS AND RECOMMENDATION

5.1 Conclusions

- The strong relationship between field relation, petrographic relation and geochemical data of major and trace element composition plotted data diagram, indicate that Assosa granite rock originated from orogenic tectonic setting (collision and subduction zone).
- The low concentration of Sr in Assosa granite related to the generation of the source magma from plagioclase deficiency/poor rock and stable phase of plagioclase in the remaining liquids.
- Negative Eu anomalies value (Eu/Eu*=0.53-0.64), may explained that the behaviors of source material or the occurrence of plagioclase residue during melting.
- Enrichment of trace like: U, Th and K and negative anomalies of Nb and Ta and positive Pb suggest that the granite rocks of the area are manily from continental crust were subduction related magmatism and mantle derived source of more mafic magmatic materials.
- The granite of the area have calc-alkaline series nature which dominated by highly potassium rich feldspars and the K-feldspar minerals group mainly have microperthitic texture with euhedral to subhedral crystal shape and intergranular texture of opaque (Fe-Ti oxides) mineral also incorporated in small amount.
- The alkali feldspar granite of the area manily explained as high SiO_2 and modal alkali feldspar and low content of biotite minerals.
- Assosa granite rocks have peralumious behaviors in which their alumina saturation index range (ASI=0.98-1.00) indicate the granite rocks of the area peralumious nature and potassium rich source except one sample lies at transition boundary between metaluminous and peralumious rocks.
- The Enrichments of LREE, negative Eu anomaly and slight to nearly flat HREE on Chondrite-normalized and deplement of Sr, Ti, P and negative anomaly of Nb and Ta on spider diagram indicate Assosa granite rocks have common magmatic source region.

- Geochemical signature and the mineralogical charactestics Assosa granite from western Ethiopian Precambrian associated with volcanic arc granite and syn-collisional granite which reflect were generated and emplaced along the subduction zone. In addition field relation and geochemical analyzed data indicate that the granitoid rocks of Assosa area classified as volcanic arc granitoid (VAG) using Rb versus Y+Nb, Rb versus Yb +Ta and Syn-collisional granitoid (Syn-COLG) using Nb versus Y, which are the product of subduction-related magmatism.
- Due to lack of any recorded data concerning parent magma of an area partial melting and fractional crystallization model for granitoid rock of the area had not been modeled. Therefore Fractional crystallization processes that control the formation of granite rocks of the area is simply implemented from the fractionation of minerals on plotted Harker diagram of major oxide against SiO_2, using trace elements plotted diagram and tectonic environment discriminator granitoid rock of the area.
- Assosa granite show negative anomaly Nb, Ta and positive Pb. This are typical of continental crust arc magmatism, which suggest that Assosa granite may be formed either by partial melting of the continental crust or by fractional crystallization of mafic magma related to arc magmatic setting.
- Based on variation diagram of compatible (Sr) versus incompatible (Rb) on log scale representation wide variation in the concentration of Sr but the concentration of Rb remain constant. This show that Assosa granite mainly resulted by fractional crystallization of mafic magma related to arc setting.
- The typical behavior of negative anomaly of Nb and Ta and positive anomalies of Pb, may indicate arc-related magmatism of crustal material undergo low to moderate partial melting and mantle derived material(later contaminated)from more mafic magmatic sources by moderate to high fractional crystallization processes.

5.2 Recommendation

- For better understanding of the petrogenetic of Assosa granitoid rocks, more geochemical data analysis including trace element and isotopic data are required to implement and the petrogenetic and tectonic setting deduction made from the major elements of the granitoid rocks.
- Detailed follow-up on exploration and investigations of granitoid rocks of the region are recommended to performed in order to understand granitoid rock resource of the region including study area.
- The research studies targeted in very small area coverage of sampling, which has not real representative of granitoid rocks of the area and region as whole, the research studies, recommended that wider area coverage through producing of large scale geological map to better understanding of genesis of granitoid rock of the area and related geological phenomena.
- Lastly the research studies recommend researcher for future research opportunity will be carried out within the region that enriched with enormous construction raw material/dimension stone including granitoid rock of the area with other metallic and native mineral found within the region.

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APPENDIXES

Appendix-1. Field description of granitoid rocks of the Assosa area.

Sample Name	Geographic location (**UTM**)		Characteristics (mineral constituents, color, texture & others)
	Northing	Easting	
NW-06	1111308	669643	The sample characterized by fine to medium grain texture. Qtz grain show fine to medium to coarse grained texture with whitish color, presence of small mica groups (Biotite & Muscovite) with black to colorless are occurred. The granitoid sample is dominated by pinkish colors.
NW-07	1111243	669515	The sample have medium to coarse grain textures. They mainly dominated by three major granite minerals Qtz, Kfs and Pl with the presence of other minerals as accessory or minor.
NW-08	1111057	669504	Sample dominated by black color of Bt & Pl mineral grain, light shiny luster of Ms with colorless, Qtz (colorless), while the feldspar grain group characterized by pinkish to light grey colors. The sample have medium to coarse grain textures.
NW-09	1110772	669590	pink color of Kfs & whitish color of Pl, medium to coarse grain Qtz, black to brown Bt & colorless Ms (silvery shine).The overall sample is dominated by pinkish color with colorless Qtz is observed.
NW-010	1111102	669770	Light to grey color of Qtz crystals, black Bt & Ms whitish color, pink to grey color large phenocrysts of Kfs is occurred. The overall texture of sample show fine to medium grained texture.
NW-011	1111160	669629	The sample consist in major mineral like: Qtz, feldspar (A-feldspars, Pl), Bt & Ms which have Colorless, pinkish to light grey, whitish, black to dark & colorless color respectively. The overall texture of rock sample is medium to coarse grained texture; large pinkish phenocrysts of A-feldspar can be observed. The rock sample show mixture of different colors due to incorporation of different minerals.
NW-012	1110898	669704	The sample mainly consist Qtz, feldspar (A-feldspars, Pl), Bt & Ms which have Colorless, pinkish to light grey, whitish, black to dark & colorless color respectively.

NW-014	1111422	669543	The granitoid rock sample dominated by pinkish color of A-feldspars over the others. Bt mineral that characterized by dark to dark brown shiny flaks (luster) & colorless of Ms (silvery shine), Qtz (looks glassy colorless) that makes differ from Ms, small amount of Hbl (amphibole) have dark brown color is observed.
NW-015	1111298	669508	Bt & Ms mineral are show dark shiny flake & silvery crystal respectively. Large phenocrysts of pinkish(Kfs) & white to light gray color of Pl.
NW-017	1110622	6699	Large crystal of Pl (black) and Kfs (pinkish) color is observed. Qtz grain fine to medium grained with colorless or whitish. Bt show black to dark color & Ms (white shiny luster).and medium to coarse grained texture.
NW-018	1111081	670487	This sample characterized by colorless of Ms, Pl & Qtz, but Ms differ from them by it shiny property. While Bt have black to dark color. Small incorporate of Hbl (dark green) is observed.
NW-019	1111124	670238	Gray to pinkish Kfs, dark to gray color of Pl, large crystal of Bt, small sized crystal of shiny Ms, whitish color of Qtz. Sample consist of mixture of different colors due the presence of many and have medium texture and irregular shape.
NW-020	1111532	670153	This sample characterized by small sized of nearly uniform size of all incorporated mineral like: highly pinkish color of Kfs, gray to dark color of crystal of Pl, shiny behavior of whitish Ms and black color of Bt minerals which has charactestics of easily scratched by hand. Texture of medium to coarse grained and irregular crystal shape.
NW-021	1111191	670609	Crystal of gray to dark color of Pl, small to medium sized pinkish Kfs, light to luster reflectance of Ms(shiny luster) and small sized black Bt, whitish color glassy Qtz. The sample has medium to coarse grained texture of irregular to sub angular crystal shape.
Note: The granitoid rock sample of the area have medium to coarse grain texture, characterized by mixture of colors due to the incorporation of different minerals (Kfs, Qtz, Ms, Bt, Hbl etc.),which reflect their different mineralogical composition. The large crystal of pinkish color of Kfs mineral and anhedral crystal shape of Qtz mineral are dominant of the rest mineral grains. The collected rock sample of the area mainly has charactestics of irregular shape.			

Appendix-2. Petrographic description of minerals of granitoid rock of the area.

Phase name		Mode (%)	Characteristics		
			Color	Shape	Texture
Kfs	Microcline	54-67	Light white to light gray	Euhedral-subhedral	Micro-perthitic texture formed (inclusion of Pl, Qtz within Kfs) and cross hatched and tartan twin is common to all.
	Orthoclase		Light to dark gray	Euhedral-subhedral	Show Carlsbad twin and with the incorporation of other plagioclase (albite) minerals.
Plagioclase (albite) feldspar		8-14	Light white to alternative band color	Euhedral-Subhedral, some anhedral and Elongated	Anti-perthitic of parallel streaks & blebs (albite) occurred within Kfs (both orthoclase & microcline).
Quartz		25-32	Light white, cloudy color	Euhedral-subhedral, some anhedral and sharp Irregular shape	Granophyric (intergrowth with Kfs) and graphic texture (micro-fracture) and granular texture.
Biotite		2-5	Mixture of pink, light greenish brown	Subhedral-anhedral	Flaky to tiny platy texture are common.
Muscovite			Pale pink, green to light green	elongated shape and subhedral -anhedral	Flaky to tiny platy texture are common.
Others(Opq, Hbl, Sphene, Chl)		1-5	Black both under PPL & XPL	Hypidio/anhedral,euhedral-suhedral	Medium to fine grained texture and intergranular of Opq mineral are common.
Note: The representative rock sample of the area of prepared thin section sample mainly characterized by granular, intergranular and medium to coarse grained texture, perthitic texture of Kfs from (micro perthitic-medium sized perthitic), euhedral to subhedral crystal shape more commonly observed in thin					

section and granophyric or graphic texture also observed in some case.

Appendix-3. Modal mineral composition of representative rock samples.

Sample name	**Mineral name and their modal (%)**					
	Quartz **(Qtz)**	K-feldspar **(Kfs)**	Plagioclase **(Pl)**	Biotite **(Bt)**	Muscovite **(Ms)**	Opaque **(Opq)**
NW-06	28	54	11	3	1	2
NW-08	26	52	13	3	1	5
NW-09	23	62	8	4	Trace	3
NW-010	27	54	7	5	Trace	5
NW-011	25	55	7	4	5	3
NW-014	29	52	10	4	Trace	4
NW-015	23	58	12	4	Trace	3
NW-017	24	61	9	2	Trace	4
NW-018	25	58	8	4	2	3
NW-019	31	53	9	3	2	2
NW-020	28	58	12	3	Trace	2
NW-021	23	57	13	2	3	2
Note: The representative rock samples of granitoid rocks of the area has modal mineral described on (Appendix-3) in addition to these others mineral like (Spn 1% to trace, Chl as trace and Hbl 1% to trace) have mineral percentage range from 1% to trace incorporated.						

Appendix-4 Recalculated modal percentage of major granitoid rock minerals.

Sample Name	Quartz (Q)	Alkali-feldspar (A)	Plagioclase(P)
NW-06	30.1	58.1	11.8
NW-08	28.6	57.1	14.3
NW-09	24.7	66.7	8.6
NW-010	30.6	61.4	8
NW-011	28.8	63.2	8
NW-014	31.9	57.1	11
NW-015	24.7	62.4	12.9
NW-017	25.5	64.9	9.6
NW-018	27.5	63.7	8.8
NW-019	31.5	54.3	14.2

NW-020	26.3	61.1	12.6
NW-021	24.7	61.3	14
Note: Granitoid rocks of the area manily dominated by three major minerals alkali-feldspar mineral which account to be 54.3-66.7%, quartz 24.7-31.9% and plagioclase feldspar 8-14.2% modal percentage.			

Appendix-5 Alumina Saturation Index (ASI) of Assosa granitoids (ASI= mol%

$$\left(\frac{Al2O3}{CaO+Na2O+K2O}\right))$$

Sample name		Al_2O_3	CaO	Na_2O		K_2O		ASI
NW-09		13.40	0.46	4.57		4.67		0.995~1.0
NW-010		13.50	0.45	4.38		4.79		1.00
NW-014		13.35	0.49	4.58		4.49		1.00
NW-018		13.25	0.55	4.76		4.30		0.98~1.0
NW-019		13.30	0.24	4.25		4.79		1.00
NW-021		13.60	0.03	4.64		4.56		1.00
Note: The granitoid rocks of the area have ASI range value from 1.3814-1.4734								

Appendix-6. Trace element geochemistry analysis geochemical results.

Samples	NW-09	NW-010	NW-014	NW-019	NW-018	NW-021
Li	10	10	10	10	20	20
Sc	3	3	1	1	2	1
V	6	7	<5	6	<5	<5
Cr	170	20	140	10	280	180
Co	<1	<1	<1	<1	<1	<1
Ni	30	10	25	6	27	28
Cu	23	8	6	6	3	3
Zn	50	31	57	29	96	69
Ga	21.9	21.6	20.6	20.2	23.9	23.7
Ge	<5	<5	<5	<5	<5	<5
As	0.6	1.5	0.5	0.8	0.8	0.2
Se	0.5	0.7	0.9	0.3	0.3	<0.2
Mo	9	2	1	2	1	2
Ag	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Cd	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
In	0.03	0.034	0.018	0.023	0.035	0.015
Sn	2	2	2	2.07	2	1
Sb	0.11	0.25	0.07	0.19	0.07	0.06
Te	0.02	<0.01	<0.01	0.01	<0.01	<0.01
W	2	<1	1	<1	2	2
Re	0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Hg	0.007	<0.005	<0.005	<0.005	<0.005	<0.005
Bi	0.08	0.08	0.03	0.04	0.06	0.02
C	0.02	<0.02	0.01	0.01	0.01	0.08
S	<0.01	<0.01	<0.01	<0.01	0.05	<0.01