Addis Ababa University
College of Natural Sciences
School of Earth Sciences

GEOLOGY AND GENESIS OF GOLD MINERALIZATION IN KUSHMAGANE AREA, ASSOSA WOREDA, WESTERN ETHIOPIA

A thesis submitted to school of Earth Sciences in partial fulfilment of the requirements for the degree of Master in Mineral Exploration

By Leta Amena

ID. №: GSR/1406/07

Advisor: Dr Worash Getaneh

Co-advisor: Dr Mulugeta Alene

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By: Leta Amena

Approval board:

Dr Balemwal Atnafu______________________________

(Head, School of Earth Sciences)

Dr Worash Getaneh _______________________________

(Advisor)

Dr Mulugeta Alene ________________________________

(Co-advisor)

Prof Gezahegn Yirgu _________________________________

(Examiner)

Dr Zerihun Dawit ___________________________________

(Examiner)

June 24, 2016

Declaration

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

Leta Amena ______________________________ Date _______________

(Student)

Approved by

Dr Worash Getaneh ________________________ Date _______________

(Advisor)

Dr Mulugeta Alene ________________________ Date ________________

(Co-advisor)

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Abstract

Geology of Western Ethiopian Shield is known by volcano-sedimentary terranes, gneissic terranes and ophiolitic rocks intruded by different granitoid bodies. This thesis study generally considered the geology and genesis of gold mineralization in Kushmagane area, a part of Western Ethiopian Shield and involved field investigations and petrographic and whole rock geochemical studies to determine genesis of gold and related processes. Kushmagane is covered by low grade metabasites and metagranitoids metamorphosed at greenschist facies. They consist of quartz veins which are both primary and metamorphic in their origin, the later lacking specific orientation. The metagranitoids are intruded by thin mafic intrusions that are oriented parallel to both regional foliation and the local contacts. They have high silica content (70.40–78.30wt %) and show increase in K_2O and Na_2O and decrease in Al_2O_3, MgO, MnO and Fe_2O with increasing SiO_2 which reflects the crystal fractionation in their evolution. Their REE pattern shows only slight variation between the abundances of LIL and HFS elements which indicates moderate percentage melting of the original material. The low content of Fe and Mg oxides in metagranitoids with their peraluminuous nature indicate crustal contribution. Mafic mineralogy and associated basic volcanic rocks on the other hand, infer mantle source. Therefore, the source for Kushmagane granitoids is likely both basaltic mantle derived parental magma and partial melting of continental crust. Kushmagane metabasites have high concentrations of MgO, Fe_2O_3 and CaO and low concentration of Na_2O and K_2O. Their REE abundance pattern shows nearly parallel trend in a negative general slope. Negative slopes combined with their tholeiitic nature infers that the Kushmagane basalts and andesites originated in the lower enriched mantle reservoir. The flat pattern in metabasalt suggests that the REE abundances in these rocks resulted from phases involving shallow fractionation (e.g., olivine), which do not fractionate the REE. Their tholeiitic nature and abundance of minerals like augite, pigeonite ad hypersthene with minor olivine indicates that the Kushmagane metavolcanics formed as oceanic slab subducted, reached sufficiently hot region and melted to leak into the crust. Gold mineralization in the area, is decorated by presence of sulphides like pyrite, pyrrhotite, chalcopyrite and covellite. Based on observed volcanic arc tectonic setting, ore petrography and alteration types, the mineralization is believed to be orogenic type hosted by metagranitoids and metabasites. The lower Au value in metabasites in the area may reflect that the rocks were also sources for metal and leached by hydrothermal fluids during metamorphism. The probable sources of fluids are proposed to be regional metamorphism of the mafic volcanic rocks, post to syn-tectonic intrusions and/or subducted oceanic crust.

List of Acronyms

Abbreviated Minerals and Rocks

Ab	Albite
Adr	Anderite
Bt	Biotite
Cpx	Clinopyroxene
Cpy	Chalcopyrite
Grt	Garnet
Hbl	Hornblende
Msc	Muscovite
Opx	Orthopyroxene
PGE	Platinum group elements
Plg	Plagioclase
Py	Pyrite
Qtz	Quartz
Bmv	Basic metavolcanic
Mb	Metabasites
Md	Metadiorite
Mg	Metagranite
Mgd	Metagranodiorite
Qv	Quartz vein

Other Abbreviated terms

ICP-MS	Inductively Coupled Plasma– Mass Spectrometry
ICP-AES	Inductively Coupled Plasma–Atomic Absorption Spectrometry
GSE	Geological Survey of Ethiopia
MME	Ministry of Mines and Energy
MoM	Ministry of Mines

Other abbreviated terms (continued)

ANS	Arabian Nubian Shield
MB	Mozambique Belt
EAO	East African Orogeny
EMB	Eastern Mozambique Belt
MORB	Mid Oceanic Basalt
OIB	Oceanic Island Basalt
WES	Western Ethiopian Shield
WEB	Western Ethiopian Belt
WMB	Western Mozambique Belt
CAG	Continental Arc Granitoid
CCG	Continental Collision Granites
ORG	Oceanic Ridge Granitoids
Syn-COLG	Syn-Collisional Granites
VAG	Volcanic Arc Granitoids
WPG	Within Plate Granite
ALS	Australian Laboratory Services
ASI	Alumina Saturation Index
PPL	Plane Polarized Light
RC	Reverse Circulation Drilling
XPL	Crossed Polarized Light

CHAPTER ONE

INTRODUCTION

1.1. Study background

In Ethiopia different geological studies have confirmed presence of different rocks and mineral deposits of different origin, age and evolution. The rocks in the country mainly fall into three broad categories; the Precambrian basement complexes, marine sediments of Mesozoic era and Tertiary volcanics.

The oldest rocks in the country belong to Precambrian era and they are formed before about 600–3000 million years and include various lithological types more or less intensively affected by metamorphism: gneisses, phyllite, quartzite, schists, and granitoids (Getaneh Assefa *et al*., 1981). This Precambrian rocks are originally related to the orogenic event known as Pan-African Orogeny and they particularly belong to the so called Mozambique belt (Kazmin, 1971), which was peneplained during the Paleozoic. Marine sediments of Mesozoic era such as sandstones, limestone, conglomerates, evaporites etc. unconformably cover this Precambrian basement (Getaneh Assefa *et al*., 1981). As a part of East Africa, Ethiopia along with the present Arabian Peninsula faced early Tertiary uplifting and at the end of Oligocene, an important process of break-up initiated, with the formation of three major arms of rift valley structures: the Gulf of Aden, the Red Sea and the East African Rift System (Getaneh *et al*., 1981). The formation of these three arms led to defining of three major lithospheric plates, Nubia, Arabia and Somalia: Arabia and Somalia show relatively diverging movements to Nubian plate and to each other (Barberi *et al*., 1975 as cited in Abbate *et al*, 2015). The eruptions of huge volumes of magma (mainly basaltic) facilitated this plate divergence and is still active now in some parts of the East African Rift System (Barberi *et al*., 1972).

The Precambrian basements host most of the economic metallic mineral deposits that include primary and secondary enriched deposits of gold, platinum, platinum group elements (PGE), nickel, tantalum, base metals, industrial minerals like phosphate, iron ore, gemstones (like ruby, emerald, sapphire, garnet, etc.) and also decorative and dimension stones such as marble, granite and other colored stones (Ministry of Mines and Energy, 2009). Even though many of them including gemstones and industrial minerals remain less developed, the occurrence of these vast categories of rocks and mineral deposits has led to production of different types of resources. The biggest developed mine in the country is that of Southern Ethiopia’s Lega Dembi gold mine and it remains the largest gold mine in the country with total estimated reserve of 82 tons and average annual production of 3.6 tons (Ministry of Mines and Energy, 2009). Other mineral products including platinum from laterite, industrial minerals, gemstones (opal, peridot and other precious stones) and decorative and construction materials are also produced by licensed foreign and local mining companies in the southern, western, central and northern regions of the country (Ministry of Mines and Energy, 2009). There are also some other advanced stage primary gold exploration and development activities in different parts of the country by different foreign and also domestic companies.

1.2. Location and accessibility of the area

A selected study area, Kushmagane is located in Benishangul Gumuz National Regional State, Assosa Woreda (Fig. 1.1). It covers a total area of 3sqkm and it is located at about 775 km from the capital, Addis Ababa and can be accessed via the main road that joins Addis Ababa and Asosa through Addis Ababa-Ambo-Nekemte-Gimbi-Mandi-Assosa. The site is located at about 45km from Assosa town in SW and the road is totally all weather gravel from the town.

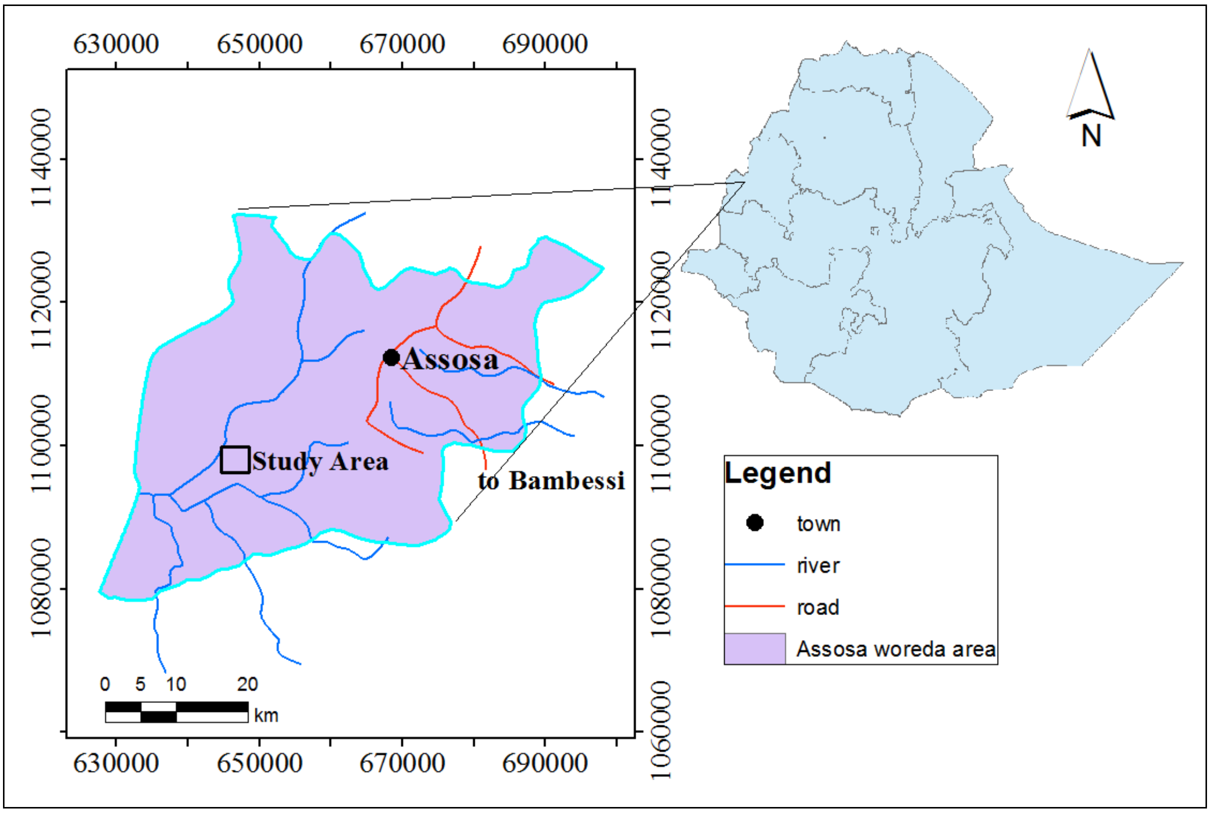


Fig. 1.1. Location map of the study area

1.3. Topography and drainage

Kushmagane and its surroundings, as a part of Western Ethiopian lowland exhibit the general topography of the area which encompasses varied topography ranging from plainly lowland to rocky mountainous terrains. The highest and the lowest elevations in this area are about 1125 meter (Banga Turko) to the south and 576 meter (Belbenjo) (Managem PLC, 2015). At the foot of these Rocky Mountains are plain areas locally dissected by streams that are only scarcely active. Dabus River is the biggest river near to the area and it drains toward northeast to join Blue Nile River.

1.4. Vegetation and climate

The study area lies in a tropical climate, classified as hot and arid region. The mean annual temperature and rainfall of the area is 32^0C and 1000-1400 mm respectively (Managem PLC, 2015). January to April are the warmest months while July to August are the coldest months of the area.

In terms of vegetation, it is strongly covered by grasses and moderately vegetated by different types of forests. The most common vegetation covers are savannah grass, bamboo forest, and deciduous trees. There are also evergreen trees which remain green throughout the year. High rainfalls during summer time yield intense cover of the area by Savannah grasses which even make the area difficult to work on. These very dense and tall grasses along with the trees have been a home to wide range of wild animals like Roan, Antelope, Hyena, Columbus monkey, Patas monkey, Ape, Reed buck, Python, Lion, Pig, Warthog, Porcupine and a variety of birds and reptiles.

1.5. Population and land use

The population in the study area and its surroundings is very sparse. The inhabitants of the area are Mao, Como and Berta people whose Native languages are Maogna, Comogna and Bertegna respectively (Managem PLC, 2015). Most of the Berta people and some of the Como and Mao people can speak Arabic language and follow Islamic religion. Now a day, the scattered settlements and villages of the area are gathered in a group of settlement with the help of the Regional Government. Only limited parts of the area are being used for cultivation by the local people. The life subsistence of the people depends on irrigated and rain feed cultivation, cattle rising, honey bee, placer gold panning and hunting. The main crops they cultivate in the area include: sorghum, maize, groundnuts, cotton, tobacco, oilseed and various fruits including mango, papaya and lemon etc. (Managem PLC, 2015). Although it varies from time to time, malaria infestation period is prevalent during the rainy seasons.

1.6. Previous works

Even though the geology of western Ethiopia is still not well understood, different studies have been conducted in the region from different perspectives. The earlier studies conducted in the area include (Kazmin, 1969 as cited in Tesfaye Kebede *et al.*, 1999; De Wit and Aguma, 1977; Kazmin *et al*, 1978; Senbeto Chewaka, 1980 as cited in Tesfaye Kebede *et al.,* 1999). These studies primarily targeted the Precambrian geology of the area and classified the rocks to either Mozambique belt or ANS. The low grade rocks of the area were categorized in to ANS while the high grades were identified to be part of the Mozambique belt. Furthermore, detailed studies have been conducted in specific parts of the area regarding structures, geochemistry, petrology and tectonic settings. More of these studies state that the Western Ethiopian Shield Studies consists of low to medium grade metavolcanosedimentary rocks, ophiolitic rocks and high grade gneisses and migmatites (Tadesse Alemu and Tsegaye Abebe, 2007; Allen and Gebremedhin Tadesse, 2003; Teklewold Ayalew and Johnson, 2002). Granitoid intrusions intruding into the formers are also part of the area's rocks that together form Western Ethiopia's Greenstone Belt (Tesfaye Kebede *et al*, 1999). Starting from mid 1990s presence of economic minerals was scientifically confirmed and mining activities have been introduced in to different parts of the area (e.g., Solomon Tadesse, 2009).

1.7. Statement of the problem

From the beginning of human history precious metals remained the objects of desire. They have been sought-after for their beauty, their mystic powers and highly esteemed for their value. Since ancient days, men were aware of the value of precious metals as a shield against economic uncertainties at the times of political upheavals. Since the ancient history of human being, the exploration and mining of gold and base metals is significantly increasing due to high demand for them. Similarly, exploration for gold and other minerals in Ethiopia is increasing from time to time. Southern part of the country primarily got attention in beginning times of modern mining processes which is currently being expanded to northern and western parts. Different companies have been dealing with gold, platinum and base metals exploration and production in Western Ethiopia many of them reporting positive results. However, even though the occurrence of the minerals exists in the western greenstone belt, the area remains less studied in terms of genesis of those mineralizations. In Kushmagane area, artisanal miners are collecting quality gold by panning stream sediments. In addition to this, Managem PLC (2015) have reported that they have identified occurrence of gold after preliminary systematic exploration which involved satellite image interpretation, geological mapping at scale of 1:50,000, geochemical sampling (stream sediment, heavy mineral concentration) and rock and chip sampling. However, the area remains unstudied in terms of style of mineralization and genesis of gold and other minerals. Therefore, this study has been designed to map the prospect area at relatively detailed scale than previous maps, to study the mineral paragenesis, wallrock alteration and geochemistry and to identify the probable process of gold genesis.

1.8. Objectives of the study

1.8.1. General objective

This study is generally intended to study geology and genesis of gold mineralization in orogenic metagranitoids and metabasites of Western Ethiopia; a case of Kushmagane area, Assosa Woreda of Benishangul Gumuz region.

1.8.2. Specific objectives

The specific objectives of the study are:

- Producing geological map of the area at scale of 1:10,000
- Determining geochemistry of the host rock
- Identification of style of mineralization (paragenesis, alteration, ore bodies)
- Identifying possible controlling factors of mineralization and
- Determining mode of formation (genesis) of the gold.

1.9. Significance of the research

There are several thousands of known minerals in nature (with estimates ranging from 3,500 to 4,500), but only few of them are considered as ore minerals. Of these, only about a dozen or so are actually enough valuable to be economically important and gold is one of them. In Ethiopia, the consideration given for gold in past years is positive compared with less recognized gemstones, industrial minerals and base metals. Ethiopia is one of the countries that are benefitting from gold exporting. This study has dealt with geology and geochemistry of the area and genesis of the mineralization and hence established the nature of major processes that have been linked with the formation of the gold deposit such as petrogenesis of the source and host rocks and alteration. The study has also identified a possible category under which the area's mineralization falls based on its genesis.

CHAPTER TWO

METHODS AND MATERIALS

2.1. Introduction

Beginning from the initial planning of this thesis work, different materials have been used and different methods have been applied to accomplish it. It all began with reviewing literatures and followed by identification of the problem, setting objectives and methods, and field and post-field works. Field and Post-field works generally involved sample collection and mapping and sample preparations, sample analyses and interpretations respectively and each of them are discussed below.

2.2. Geological mapping and Sample collection

Field works were conducted for fifteen days and involved different activities. The first two days of the field work involved road geology by which the overall geology of the area was outlined. Selected sites like old trenches and boreholes were visited. The other thirteen days were spent on the local geology. Representative samples of the units in the study area were collected both from surface and boreholes. Sampling from test boreholes were done at the same time of drilling to avoid lithological mixing while the RC machine drills. Both mineralized and non-mineralized rock samples were collected for ore microscopy and geochemical analyses. Traverses were selected across the general trend of the rocks in the area along streams which cut and expose the rocks. Measurements on different structures and attitudes of the rocks were made and the geological map of the area is produced at scale of 1:10,000.

2.3. Geochemical Analyses

Ten rock samples, five collected from surface and five collected from test boreholes were washed of weathered surfaces and submitted to ALS geochemical laboratory, Addis Ababa for preparation. Then, the samples were crushed to 70% less than 2mm, riffled to split off 1kg and the splits were pulverized to 75 microns. The pulverized samples were shipped to ALS Services, Loughrea located at Dublin road, Louhrea, Co. Galway, Ireland for whole rock analysis using ME-MS81d, a code given by ALS services PLC to represent combination of ICP-MS and ICP-AES. The ten samples all underwent both ICP-MS and ICP-AES analyses. The results were then interpreted to understand the magma source and to discriminate tectonic setting of the rocks of the area which was further interpreted to understand genesis of gold mineralization.

2.3.1. ICP-MS

This method is a 30 Element Package which uses a minimum sample size of 1g. It involves lithium borate fusion of the sample prior to acid dissolution and provides the most quantitative analysis approach for a broad suite of trace elements. A prepared sample (4.00g) was added to lithium metaborate flux (0.90 g) in a cleaned PTFE microwave sample vessels and mixed well and fused in a furnace at 1000°C for 30 minute. The melt is then cooled for 15 minutes and diluted in 100 mL of 4% HNO_3 or 2% HCl solution so that mineral species including those that are highly refractory are solubilized. The solution is then analysed by inductively coupled plasma mass spectrometry for 30 trace elements including Ba, Ce, Cr, Cs, Dy, Er, Eu, Ga, Gd, Hf, Ho, La, Lu, Nb, Nd, Pr, Rb, Sm, Sn, Sr, Ta, Tb, Th, Tm, U, V, W, Y, Yb and Zr.

2.3.2. ICP-AES

The *ICP-AES* was used to analyse major elements in their oxide forms including SiO2, Al2O3, Fe2O3, CaO, MgO, Na2O, K2O, Cr2O3, TiO2, MnO, P2O5, SrO, BaO. Each of prepared solid samples (2g) was dissolved and mixed with water and sample solution was transformed into an aerosol by a nebuliser. After having been dissolved, the sample is then, topped off with dilute HCl and the solution containing the sample is analysed using inductively coupled plasma-atomic emission spectrometry (ICP-AES).

2.4. Thin and Polished Sections

2.4.1. Preparations

Rock samples collected from field were prepared at thin section laboratory of School of Earth Sciences, Addis Ababa University and Geological Survey of Ethiopia. The fresh parts of the rock samples were cut to slabs of proper size and polished using the diamond grinder until thin sections of approximately 2-12μm thickness are produced. Multiple thin sections were prepared for each units based on the dominance they have in the area.

Rock samples collected from mineralized zones of the test boreholes were polished at Geological Survey of Ethiopia for ore microscopic analysis. The mineralized rocks which bear sulfides and oxides on their surfaces were desired so that mineralogical alteration and zoning in the mineralization can be understood.

2.4.2. Microscopy

Both ore microscopy and petrographic microscopy studies were conducted at laboratories of School of Earth Sciences, Addis Ababa University. Each rock sample is studied under thin section for its mineralogical make up based on the optical properties of the minerals and the volume percentage of the minerals in the rock is correlated with its geochemistry or geochemistry of samples of its type. For the purpose of ore minerals reflected light microscope was used to identify occurrence of ore minerals, their assemblage and texture. The transmitted light (applied for transparent minerals) and reflected light microscopes (applied for opaque minerals analysis) were Leitz and Nikon Japan 261448 respectively.

CHAPTER THREE

REGIONAL GEOLOGICAL SETTING

3.1. Introduction: The Pan African Orogeny

The term 'Pan-African' was coined by Kennedy (1964) on the basis of an assessment of available Rb-Sr and K-Ar ages in Africa. In Early days the Pan-African was interpreted as a tectono-thermal event of some 500 Ma, during which a number of mobile belts formed surrounding the older cratons (Kröner and Stern, 2004). The concept then extended to the Gondwana continents (Fig. 3.1) and the thermal event was later recognized to constitute the final Part of an orogenic cycle, leading to orogenic belts which are currently interpreted to have resulted from the amalgamation of continental domains during the period of 870 to 550 Ma (Kröner and Stern, 2004). Currently, the term Pan-African is used to describe all Neoproterozoic to early Paleozoic phenomena of tectonic, magmatic, and metamorphic activities related to crust that was once Part of Gondwana.

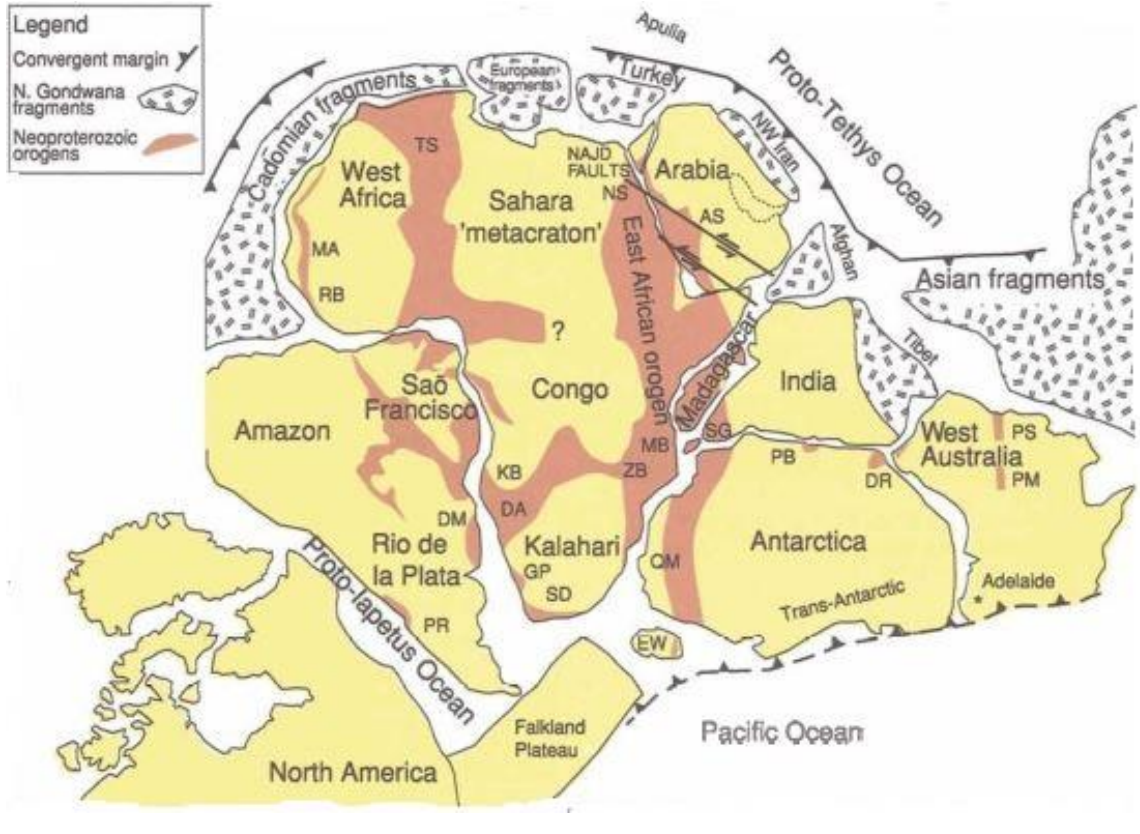


Fig. 3.1. Gondwana at the end of Neoproterozoic time (-540 Ma); the general arrangement of Pan-African belts. AS, Arabian Shield; BR, Brasiliano; DA, Darnara; DM, Dom Feliclano; DR, Denman Darling; EW, Eilsworth-Whitrnore Mountains; GP, Gariep; KB, Kaoko; MA, Mauretanides; MB, Mozarnbique Belt; NS, Nubian Shield; PM, Peterman Ranges; PB, Pryolz Bay; PR, Parnpean Ranges; PS, Paterson; QM, Queen Maud Land; RB, Rokelides; SD, Saldania; SG, Southern Granulite Terrane; TS, Trans- Sahara Belt; WB, West Congo; ZB, Zarnbezi. (Adopted from. Kröner & Stern, 2004).

Generally the Pan-African orogenic cycle was the result of different combined activities. Ocean closure and arc and microcontinent accretion are both parts of Pan-African orogenic cycle along with the final suturing of continental fragments which is responsible for the formation of the supercontinent Gondwana (Kröner and Stern, 2004). Despite early suggestions claiming opening of large Neoproterozoic oceans between different cratons (Fig. 3.1) to be result of breakup of the Rodinia supercontinent some 800-850Ma, current data indicate that the African and South American cratons were never Part of Rodinia (Kröner and Stern, 2004).

A Neoproterozoic crystalline basement ranging from 880 to 550 Ma constitutes the crustal backbone of the Ethiopian region with wide exposures in the southern and western Ethiopia and, to a lesser extent, in the northernmost Ethiopia (Abbate *et al.,* 2015).The Proterozoic terrains in Ethiopia are related to the East African Orogen (Stern 1994), a N–S elongated mega collisional structure stretching from Israel to Madagascar and produced between West and East Gondwana by the closure of the Mozambique ocean (Abbate *et al*., 2015) (Fig. 3.1).

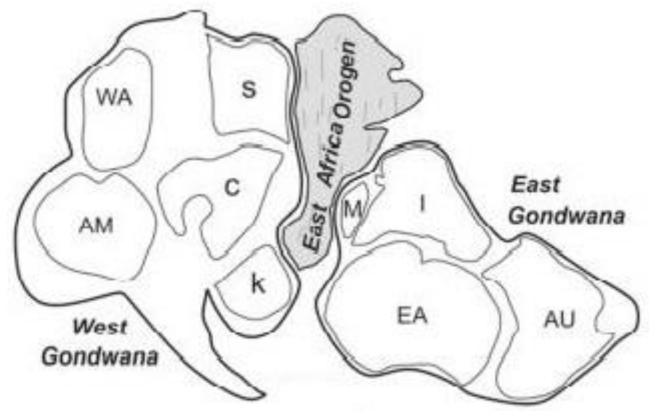


Fig. 3.2. The East Africa Orogen squeezed between West and East Gondwana. WA West African craton; AM Amazo-nian craton; S Sahara craton; C Congo craton; K Kalahari craton; M Madagascar; I India shield; EA-East Antarctic shield; AU Australia craton. Adopted from Meert and Lieberman (2008)

In the north, the East African Orogen constitutes the Arabian–Nubian Shield and in the south the Mozambique Belt. In northern Ethiopia, the Nubian portion of the Shield is prevalent, with dominantly low-grade volcano-sedimentary rocks overlain by metasediments (stromatolitic carbonates and diamictites) associated with “Snowball Earth” (Beyth *et al*., 2003). In southern Ethiopia, the Mozambique Belt exposes abundant amphibolites and granulite facies metamorphic rocks and gneiss terranes (Abbate, 2015).

3.2. The Mozambique Belt

The Mozambique Belt, a part of the Pan African East African Orogen is a roughly N-S oriented mountain range that formed by the collision of East and West Gondwana (Tenczer *et al*., 2005). The cause of this collisional event is believed to be a long-lived subduction system along which island arcs were accreted between 750-500 Ma (Tenczer *et al*., 2005). This study also claims that the tectonics related to this event resulted in the formation of thrust propagating onto different Cratons. The propagation of these thrusts formed a Pan-African metamorphic overprint with a gradient from greenschist facies to high pressure granulite facies in different Cratons in Africa (Tenczer *et al*., 2005). Closure of the oceanic basin occurred at -760 Ma and was followed by the formation of major north trending transcurrent faults at -635 Ma (Abdelsalam and Stern, 1996).

Cutten *et al*. (2006) identified two principal domains in Mozambique Belt namely, Western Mozambique Belt (WMB) and Eastern Granulites (EG). The Western Mozambique Belt (WMB) comprises upper amphibolite facies gneisses with emplacement ages predominantly between 2970 to 2648 Ma (Johnson *et al*., 2003) but also as young as 1837 Ma, and represent reworked rocks of the Tanzania Craton and Usagaran Belt. As yet, no igneous rocks of Pan-African age are identified in Western Mozambique Belt (Cutten *et al*., 2006). On the other hand, the Eastern Granulites (EG) are high-grade, arc-derived lithologies of Pan-African- aged emplacement ages ranging between 841 Ma and 632 Ma (Cutten *et al*., 2006). Both terranes include Neoproterozoic metasedimentary rocks on their lithological make up (Cutten *et al*., 2006).

In its Northeastern branch, the Mozambique belt is largely concealed by Phanerozoic cover and the Precambrian rocks expose only in restricted areas. The areas where the Precambrian rocks are exposed are restricted to the Kenyan and Southern Ethiopian basement, inliers in eastern Ethiopia and southern Somalia and an isolated strip of Precambrian in northern Somalia (Warden and Horkel, 1984). However, different authors (e.g. Braathen *et al*. 2001, Kazmin *et al*., 1978, Taddesse Alemu and Tsegaye Abebe, 2007) added the Western Ethiopian shield to North-eastern part of Mozambique Belt where Precambrian rocks are exposed. Generally, the well-established Precambrian outcrops in this part of the Mozambique belt include Precambrian rocks of Southern Kenya, Southern Ethiopia, Eastern Ethiopia, Northern Somalia, Western Ethiopia and to lesser extent Northern Ethiopia (Kazmin *et al*., 1978, Warden and Horker, 1984, Taddesse Alemu and Tsegaye Abebe, 2007).

3.3. The Arabian-Nubian Shield (ANS)

3.3.1. Origin and Tectonism

The Arabian-Nubian Shield (ANS) in North East Africa and West Arabia is the largest tract of juvenile continental crust originated during Neoproterozoic age and affected by the Pan African orogenic cycle (Patchett and Chase, 2002; Kröner and Stern, 2004, Avigad and Gvirtzman, 2009). It makes up the northern half of the East African Orogen and stretches from southern Israel and Jordan as far as Ethiopia and Yemen, where it makes transition into the Mozambique Belt (Blasband *et al*., 2000; A. Kröner & Stern, 2004).

The ANS is suggested to be a crust that was generated during the formation of smaller terrains of arc and back arc crust within and around the margins of a large oceanic tract known as the Mozambique Ocean, which formed in association with the breakup of Rodina ~ 800–900 Ma (Stern, 1994). Oceanic plateaus are also thought to be accreted (Stein and Goldstein, 1996) and their crustal fragments collided as the Mozambique Ocean closed, forming arc-arc sutures, composite terrains, the ANS and the larger collisional belt known as the East African Orogen (Stern *et al*., 2004; Stern, 1994). In the course of its Neoproterozoic evolution, number of tectono-metamorphic and igneous cycles have processed the ANS; but two major tectono-metamorphic phases were the most prominent (Abdelsalam and Stern, 1996; Johnson and Woldehaimanot, 2003 as cited in Avigad & Gvirtzman, 2009). The first phase, the older phase at around 750 Ma followed the cessation of most island-arc igneous activity and probably pertains to the accretion and assembly of ANS island arcs (Abdelsalam and Stern, 1996; Johnson and Woldehaimanot, 2003 as cited in Avigad and Gvirtzman, 2009). The second phase is subsequent tectono-metamorphic phase which followed a period of reduced igneous activity at around 700 Ma causing thickening of the previously stitched island-arc complexes and formed tight, roughly N–S trending upright folds (Avigad *et al*., 2007 as cited in Avigad and Gvirtzman, 2009).

The Arabian-Nubian Shield was sandwiched between fragments of East and West Gondwanaland as these collided at about 600 Ma (Meert, 2003) to form a supercontinent variously referred to as Greater Gondwanaland (Stern, 1994) or just Gondwanaland. The ANS was subsequently buried by Phanerozoic sediments but has been exposed by uplift and erosion on the flanks of the Red Sea in Oligocene and younger times (Robert *et al*., 2004). A broad region uplifting occurred in association with Cenozoic rifting and formed the Red Sea, exposing a large tract of mostly juvenile Neoproterozoic crust which comprises ANS (Kröner & Stern, 2004).

3.3.2. Litho-stratigraphy

The Arabian–Nubian Shield consists variety of rocks including gneisses, granitoids, various metavolcanic and metasedimentary rocks (Blasband *et al*., 2000). The western margin of ANS is defined by juxtaposition of ophiolite-decorated volcano-sedimentary sequences and juvenile Neoproterozoic arc magmatic terranes with the Eastern Granulite complex of the MB, the

Archean Congo Craton and the Sahara Metacraton (Fritz *et al*., 2013). However, this margin is not defined in the north because it is covered by Mesozoic to Cenozoic sedimentary rocks but it extends along the line of the Nile Valley and crops out in the Keraf arc-continent suture in northern Sudan (Abdelsalam *et al*., 1998 as cited in Fritz *et al*., 2013). Highly deformed mafic-ultramafic bodies also expose within low-grade (ANS) terrains making linear belts which are interpreted as dismembered ophiolitic rocks (*e.g.*, Kazmin *et al*., 1978; Warden *et al*., 1982; Seife Michael Berhe, 1990; Teklewold Ayalew *et al*., 1990; Abdelsalam and Stern, 1996).
Abundant tonalitic to granodioritic plutons stich the ANS terrains together and terrain boundaries are frequently defined by suture zones that are marked by ophiolites (Kröner & Stern, 2004). Most of these ophiolites as identified by Kroner & Stern (2004), have trace element chemical compositions suggesting formation above a convergent plate margin, either as part of a back-arc basin or in a fore arc setting. Its dominantly juvenile nature, relatively low grade of metamorphism and abundance of island-arc rocks and ophiolites make ANS distinct from Mozambique Belt (Kröner & Stern, 2004).

3.4. Geology and Geotectonic Evolution of the Western Ethiopian Shield (WES)

3.4.1. Litho–stratigraphy

Despite scarcity of well-established geological investigations of the relationship between the Neoproterozoic rocks of the Arabian–Nubian shield (ANS) and rocks of the Mozambique belt (MB), different studies (e.g. Kröner, 1985, Vail, 1985, Stern 1994) have confirmed that three types of lithotectonic assemblages: volcano-sedimentary terranes, gneissic terranes and ophiolitic rocks are recognized. 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-Palaeoproterozoic gneisses in the east, Neoproterozoic and Palaeoproterozoic gneisses to the west. The Precambrian of this 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). Benzu Gold Mining Ethiopia PLC, (2013) reported that the exposed rocks in Western Ethiopia consist primarily of Lower Complex gneisses and migmatite. They 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 (Benzu Gold Mining Ethiopia PLC, 2013). The metavolcano-sedimentary lithology include 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).

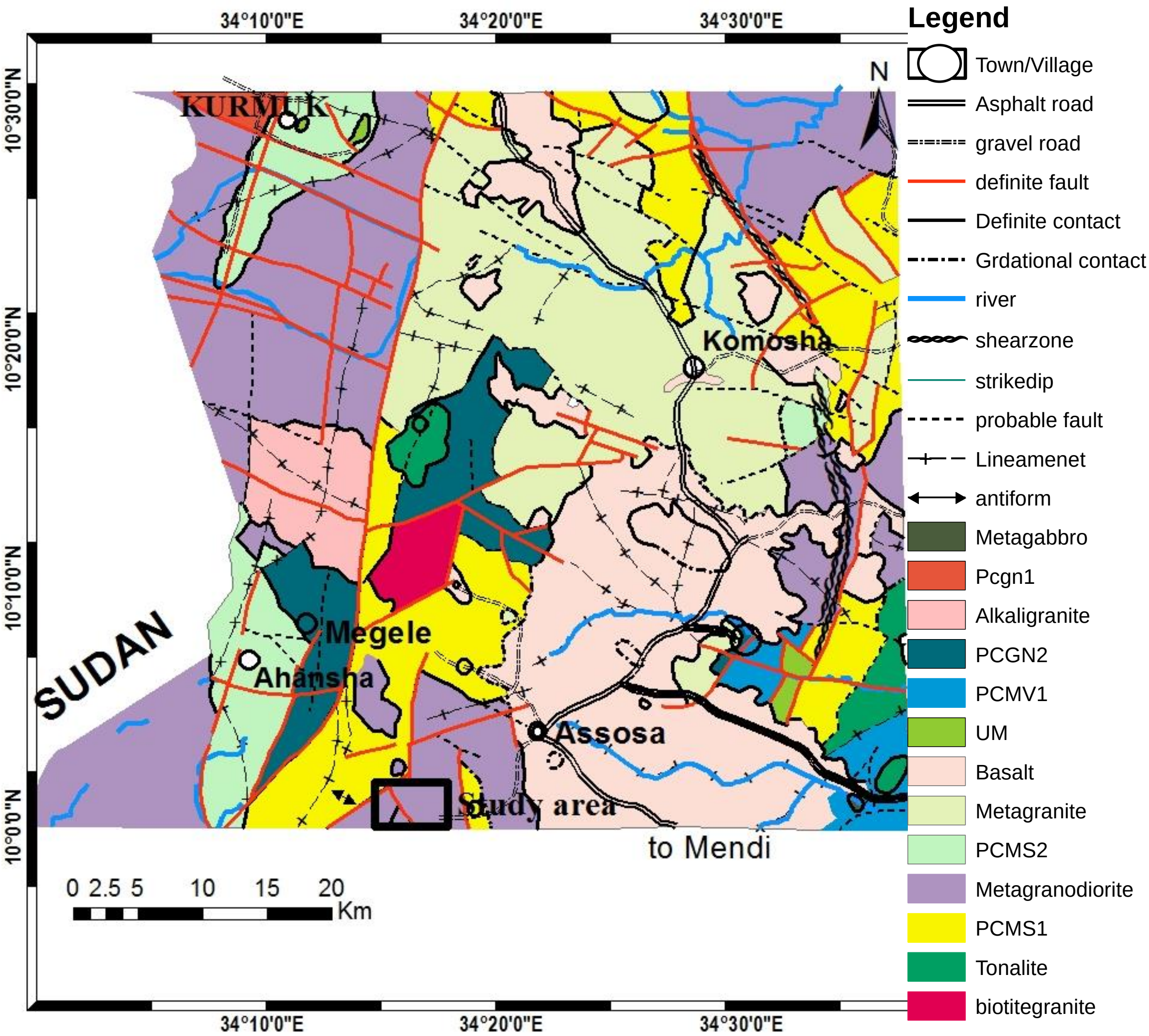


Fig. 3.3. Geologic Map of Kurmuk and Assosa: PCMS1- biotite, graphite and Chlorite schist, quartzite, metasandstone, metaconglomerate and qourtzofeldspathic schist, PCMS2-phyllite and greenschist, minor graphite and talc-schists, quartzite and marble, UM-serpentinite, serpentine-talc and talc-chlorit schists, PCMV1-Amphibolite, lesser quartzite and quartzofeldspathic and graphitic shists, PCGN2-botite and biotite-hornblende gneisses, minor muscovite-biotite schist and quartzofeldspathic gneiss, PCGN1-biotite and biotite-hornblende gneisses, minor amphibolite, granitoid gneiss and migmatite (modified and adopted from Mengesha Tefera and Berhe 1987).

Together, these rocks form the Western Greenstone Belt with predominant lithology including chlorite-graphite-sericite schists, phyllite, quartzite, andesite and rhyolites (Benzu Gold Mining Ethiopia PLC, 2013). Teklewold Ayalew and Johnson (2002), also confirm presence of rocks of varying grades.

These wide range rocks in WES have been categorized in to different groups using different classification schemes (e.g., Mengesha Tefera and Berhe, 1987; Allen and Gebremedhin Tadesse, 2003). They broadly fall into three groups of lithotectonic units; the Birbir Domain, Geba domain and Baro domain (Teklewold Ayalew and Peccerillo, 1998; Mengesha Tefera and Seife Michael Berhe, 1987 as cited in Teklewold Ayalew and Johnson, 2002). This classification is primarily based on grade of metamorphism and also lithological similarities within the same domain (Teklewold Ayalew and Peccerillo, 1998). According to these authors the Birbir domain encompasses an assemblage of mafic to felsic intrusive and extrusive rocks and mainly volcanogenic sedimentary rocks which are enclosed between the dominantly ortho-gneissic Baro and Geba domains. Monotonous quartzofeldspathic gneisses are reported to be the dominant lithologic units in the easterly Geba domain. This domain is categorized under gneissic terrain encompassing strongly foliated, medium- grained biotite and hornblende-biotite gneisses as predominant rock types (Teklewold Ayalew and Johnson, 2002). The Geba domain also contains very high temperature rocks as some of the gneisses are migmatitic and contain numerous sub-concordant lenses of granitic and pegmatitic material (Teklewold Ayalew and Johnson, 2002). The Baro domain is similarly dominated by the ortho-gneissic biotite gneiss and hornblende gneiss but, in its easterly edge where it makes contact with Birbir domain, it is characterised by para-gneisses.

The other classification is made by Allen and Gebremedhin Tadesse (2003) and puts the rocks in to five categories: Didessa domain, Daka domain, Kemashi domain, Sirkole domain and Dengi domain. This classification discusses the rocks as the following.

3.4.1.1. Didessa Domain

This domain extends from approximately 5km east of Didessa River in Wollega area covering about 70km up to about 25km west of Gimbi town. It is differentiated from the adjacent Kemashi Domain to the west by distinctive lithological and structural characteristics. The rocks within this domain are moderate grade para-gneisses 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. This domain makes a contact with the nearby Kemashi domain which is marked by the N–S trending Chugi Shear Zone, consisting of strongly N–S cleaved phyllonitic rocks derived from the Didesa Gneiss. The interpretation 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 Didesa Terrane at ca. 660 Ma (Blades *et al*, 2015).

3.4.1.2. Kemashi Domain

This is a narrow 10-15km wide domain paralleling the trend of Tulu Dimtu belt. Sequences of metasedimentary rocks of marine origin, mafic to ultramafic metavolcanics and associated plutonic rocks of wide variety make up the domain. The metasedimentary rocks consist of dark, highly pyritised, pelitic to psammitic schists, intercalated with chert, graphitic phyllite and marble.

3.4.1.3. Dengi Domain

The main units characterizing this domain include deformed and metamorphosed volcano-sedimentary sequence, a coarse-grained para- and ortho-gneissic unit and mafic to felsic intrusive bodies intruding to the later. It crops out to the west of the Kemashi Domain and has 120km width and indicate two pulses of magmatism at 850–840 Ma and 780–760 Ma in similar way to Didessa domain (Blades *et al*, 2015). The gneisses and the volcano-sedimentary succession are in tectonic contact across both the N–S Gember Shear Zone and the later crosscutting NW–SE Chochi Shear Zone. The gneissic assemblage consists of biotite-hornblende paragneiss and pelitic gneiss, together with mafic and garnetiferous granitoid orthogneiss. The gneisses are locally migmatised, and the assemblage as a whole is intensely folded and veined. This domain and Kemashi Domain indicate

3.4.1.4. Sirkole domain

The Sirkole Domain was understood to occupy west of Assosa town extending into Sudan, and therefore its western limit is unknown. It consists of different N–S elongated blocks which have 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. The other one is Yangu Granitoid, a large homogeneous anatectic granite gneiss formed by partial melting of the Tosho Gneiss.

The volcano-sedimentary succession encompasses a thick sequence of mafic metavolcanic and interbedded metasedimentary rocks subjected to folding and strong cleavage. The folding and cleavage are primarily strong in graphitic schists. The volcano-sedimentary succession is folded and strongly cleaved with a N–S striking, easterly dipping schistosity, and a mineral stretching lineation plunging gently eastwards. Amphibolite facies assemblages occur in both the gneiss and the volcano-sedimentary successions, the presence of rare kyanite in the graphitic schists reflecting medium to high-pressure conditions.

3.4.1.5. Daka domain

The predominant rocks in this domain are gneissic and they encompass three lithological units (Allen and Gebremedhin Tadesse, 2003). Allen and Tadesse correlated two of the units 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.

Daka Domain's another gneissic unit is a banded orthopyroxene-bearing granulite facies unit termed Daka Gneiss (Tadesse and Tesfaye, 1999 as cited in Allen and Gebremedhin Tadesse, 2003). It crops out in south of the other two units and is in tectonic contact with the other two along the E–W trending Daka River Thrust (Allen and Gebremedhin Tadesse, 2003). This occurrence is significant as granulite facies terranes are rare within the northern part of the EAO. The presence of garnet–clinopyroxene assemblages within the granulite, suggests high-pressure conditions of metamorphism for the Daka Gneiss. Fabrics in the Daka Gneiss, which have an E–W strike and dip gently to moderately southwards, are mylonitic, and related to the formation of the Daka River Thrust.

3.4.2. Origin and tectonic setting

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 (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).

3.4.3. Metamorphism and deformation

Teklewold Ayalew and Johnson (2002) categorised the WES rocks into different metamorphic facies. Accordingly, the metabasites of the region fall into greenschist to lower amphibolite facies in the juvenile ANS domain and mid to upper amphibolite facies in the gneissic domains. The mineral assemblage of metapelites of Birbir domain were interpreted by Teklewold Ayalew (1997) and showed condition of 520^{o}C and 4kbar. On the other hand, the P-T condition of the metapelites in Baro domain was deduced to be 700^{o}c and 7Kbar which marks steep metamorphic gradient among the areas at the transition of the domains. A uniform granitoid composition and lenticular texture over hundreds of square metres of outcrop suggest that the majority of biotite granite and hornblende biotite granite are tonalitic or granodioritic ortho-gneisses. The protolith of rare garnet-bearing and commonly epidotised gneissic rocks are interpreted to be more probably igneous rocks.

Generally, metamorphism in WES occurred in wide range of metamorphic grades beginning from low grades like greenschist facies and lower amphibolite as in Birbir domain to very high grades like upper amphibolite and granulite facies as in Geba and Baro domains (e.g. Teklewold Ayalew and Peccerillo, 1998, Mengesha Tefera and Seife Michael Berhe, 1987). In the higher grade ortho- and para-gneisses and migmatites there is no evidence of primary sedimentary or volcanic features that can be observed on the rocks. The assemblage in high grade gneissic rocks of Baro domain was interpreted by Teklewold Ayalew *et al*., 1990 to be high-grade garnet–sillimanite, garnet–cordierite–gedrite, and biotite–hornblende assemblages which is an indicative of higher amphibolite facies.

Multiple phases of deformation are recorded in the Western Greenstone Belt. The regional strike of the foliations ranges from N-S to NW-SE and NE-NW and the predominant direction of foliation in the region is NE-SW (Benzu Gold Mining Ethiopia PLC, (2013). According to different authors, pre-kinematic plutons (830-780 Ma) and volcanic and sedimentary units were affected by regional deformation and low-grade metamorphism (Braathen *et al*., 2001). Allen and Gebremedhin Tadesse (2005), declared that the structural evolution of Western Ethiopia involved three deformational stages (D_1, D_2, D_3), applied only to the volcano-sedimentary units and represented the Pan African deformation sequence.

The approximately E-W shortening event, designated D_1 in Abraham (1989) is responsible for formation of a penetrative, axial plane-parallel foliation, striking NNE-SSW (Braathen *et al*., 2001). The D_1 deformation event resulted in the overall N–S-striking and steeply E-dipping D_1 foliation which is the most pronounced and penetrative in supracrustal rocks, but is also well developed in marginal parts of the intrusions (Grenne *et al*., 2003). High-strain zones are found along lithological contacts, and also make up the bulk of the kilometer wide Baruda shear belt (Grenne *et al*., 2003). Highly D_1-strained rocks show a stretching lineation that commonly plunges to the east (Grenne *et al*., 2003). A later, localised D_2 sinistral-transcurrent phase reached amphibolite facies in narrow, discrete shear-zones. This deformation event resulted in steepening and tightening of D_1 folds and followed by D_3 which resulted in shearing and faulting of the structures (Braathen *et al*., 2001). The metasedimentary and metavolcanic sequences existing in West Ethiopia's tansect are intruded by plutonic complexes (Tefera, 1991, 1997). These units intruded by plutonic complexes were variably deformed during the main D_1 contractional event and the accompanying metamorphism was generally of greenschist facies but reached lower amphibolite facies locally (Braathen *et al*., 2001). The supracrustal units are intersected by a major D_1 shear-zone referred to here as the Baruda shear-belt. Two narrow D_2 shear-zones are also found in central parts of the transect (Braathen *et al*., 2001).

3.4.4. Economic minerals and rocks resources

Economic minerals occurrence in western Ethiopian shield has been identified in different parts of the area. Kebede H. Belete *et al*. (2002) reported occurrence of several PGM in the disseminated chromites and altered silicates associated with the serpentinized dunite in Yubdo. Gold mineralization is also observed in the area and different companies are currently exploring and mining. Three styles of gold mineralization, i) syenite intrusions related mineralization, ii) skarn gold type mineralisation and iii) fault-shear hosted gold mineralisation in metasediments are recorded in the area (Benzu Gold mining Ethiopia, 2013). Solomon Tadesse (2009) stated four belts in western Ethiopian domain host different economic minerals. The mineralization associated with these belts include primary gold deposits (e.g. Dul, Oda-Godere), the platinum deposit and occurrences (Yubdo and Daletti-Tuludimtu respectively), the iron deposits (Bilikal, Chago, Gadma) and base metals prospects (Abetselo, Kata) of volcanogenic-volcano sedimentary type. Bullock and Morgan (2015) recently reported that they discovered potentially economic graphite-bearing schist units in the Assosa region of western Ethiopia. According to their report, this graphite covers an area of 37 km^2 and is hosted predominantly by quartz-graphitic schist, quartz-feldspar-mica schist and quartzite.

Apart from metallic minerals, the area has been an exploration and mining target for different industrial minerals and rocks. Extensive deposits of marble are found in the Precambrian metamorphic terrain of western Ethiopia and known deposit occur around Daleti, Bulen, Mora, Zigi, Baruda and Mankush. (Heldal,*et al* 1987 as cited in Sentayehu Zewdie, 2011). These deposits form different geo-morphological features and Pink, greenish and sky-blue varieties of them are reported. A variety of igneous rocks, predominantly granites of Proterozoic to Early Paleozoic age, occurring as intrusive bodies within the Precambrian metamorphics of the western Ethiopia are reported to be of dimension stone value (Sentayehu Zewdie 2011). The dimension stone value possessing granites are identified in localities Bure, Anger, Guttin, and Dehan from Wollega and Benishangul areas.

CHAPTER FOUR

GEOLOGY OF KUSHMAGANE AREA

The geology of Kushmagane area is mapped as metagranodiorite in Fig. 3.3. However, it is characterised by exposure of basic/intermediate metavolcanics, metadiorite, metagranite and metagranodiorite marked by mafic intrusions, mesoscopic faults, quartz veins and veinlets. The general trend of the units in this locality is NNE-SSW. The area is studied in terms of lithology, metamorphism and mineralization and the following observation is obtained.

4.1. Litho-stratigraphy

4.1.1. The Metagranodiorite Unit

Metagranodiorite is the most dominant unit in the study area and makes a contact with metabasites which trends about 08^{o} NNE-SSW. It is massive to weakly foliated rock and every of its outcrops in the area physically resembles the other where ever it crops out. It is light to dark grey unit mainly composed of quartz, feldspars, and biotite. Sub-horizontal sills run through it in a direction of almost parallel to contacts and the regional foliation. Around the contact between granodiorite and the mafic volcanic intrusion high degree of silicification and grain size reduction is observed. The unit consists of multiple of quartz veins some of which subjected to mesoscopic faulting. The field observation of this metagranodiorite unit shows presence of plenty visible phenocrysts of quartz (Fig. 4.1).

Fig. 4.1. Metagranodiorite unit in situ picture with quartz vein (left) and sampled hand specimen rock picture(right)

GEOLOGICAL MAP OF KUSHMAGANE AREA; SCALE 1:10,000

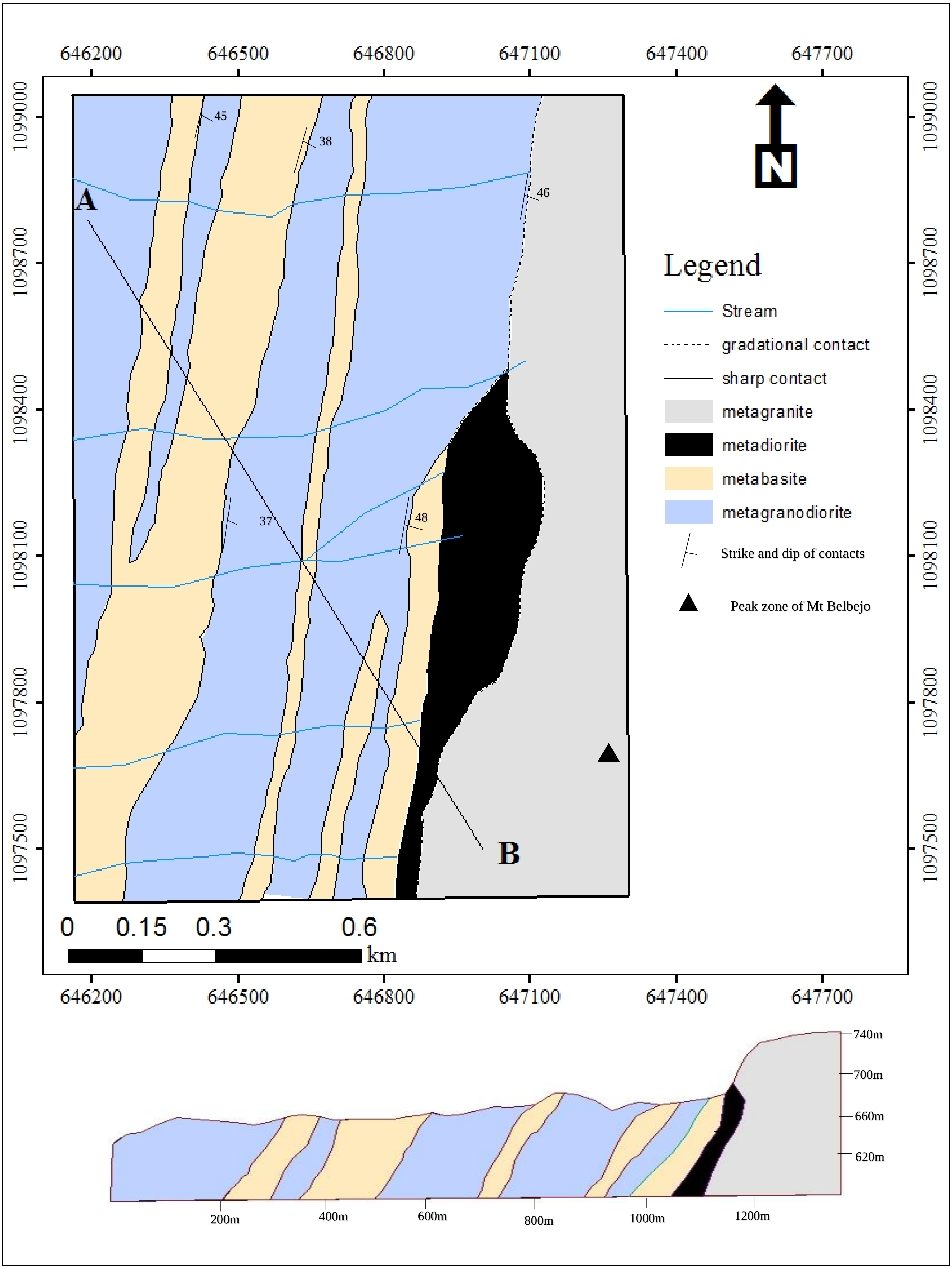


Fig. 4.1.Geologic map of Kushmagane area and its vertically exaggerated cross section. (A—B- profile section selected to include maximum number of lithology, V.E = 2.65x). Elevation data were collected during the fieldwork to compensate the lacking of previously produced topographic map to produce cross section.

Petrography

Petrographic study of representative samples of metagranodiorite rock indicate that the rock is highly dominated by quartz and feldspars. Most of the quartz minerals in the rock show relict concertal texture of intergrown boundaries which infers low grade metamorphism and their resistance to deformation. Among the feldspar minerals, plagioclases dominate the rock with minor orthoclase and microcline. Chlorite, biotite, actinolite, minor hornblende and garnet with opaque minerals also constitute the rock. Sericitization of feldspars which is believed to be result of hydrolysis enhanced by hydrothermal fluids is also observed. Generally, the average modal mineralogical composition (Vol. %) of the samples from this unit is Qtz~30%, Plg~24%, A-spar~9%, Bt~14%, Act~8%, Chl~4% and Hbl~3%, Grt~1% and opaque~7%.

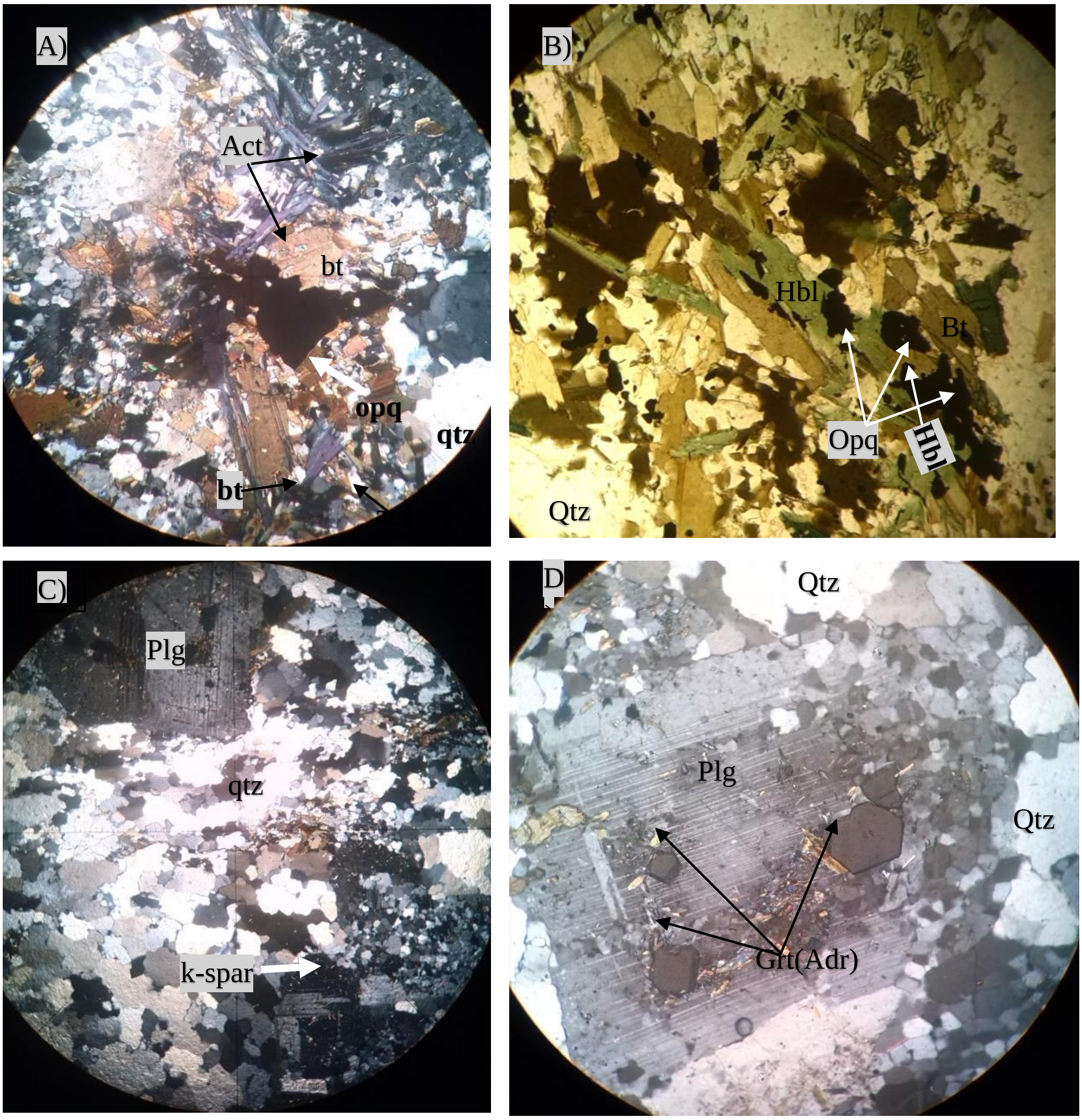


Fig. 4.3. Micro-pictures of metagranodiorite taken under 10X magnification (all under XPL). Fig B shows replacement of hornblende with opaque minerals which is probably result of oxidation.

The anderite shown in Fig. 4.2D is euhedral and bears no fractured surface and it is a post deformation metamorphic mineral.

4.1.2. The Basic Metavolcanic Unit

The basic metavolcanic rock is another unit in the area with mappable size at the current scale. It is a greenish dark unit that makes sharp contact with the metagranodiorite and metadiorite where it can be clearly observed. Degrees of chloritization and epidotization are much higher in this unit than in the others with moderate silicification. Silicification is relatively more intensely observed around the quartz veins and veinlets with in itself or where it contacts the intermediate rocks.

This unit is the second largest unit after metagranodiorite in the area. Similar to the others in the area, it also makes contact which trends NE-SW.

Fig. 4.4. Field picture of mafic metavolcanic rock (right part) in sharp contact with meta-granodiorite (left part); mgd-meta-granodiorite.

Petrography

The samples from metabasites show porphyritic texture in a fine grained, holocrystalline matrix under thin section with plagioclases dominating among the phenocrysts. The mineralogy of the rocks is mainly dominated by pyroxenes and plagioclases with minor chlorite, hornblende and opaque minerals. The metabasites in the area are of two different mineralogy. The first units consist of some amount of quartz (~4vol%), the other minerals including albite, chlorite, ortho-pyroxene and no to very rare olivine. The other units have more mafic minerals like ortho-pyroxene, green amphibole, chlorite and epidote than the formers with lesser quartz. In both units there are rare prehnite which is diagnostic for sub-greenschist facies. The mineralogical variation between the metavolcanics indicates presence of parent rocks which were originally andesitic and basaltic.

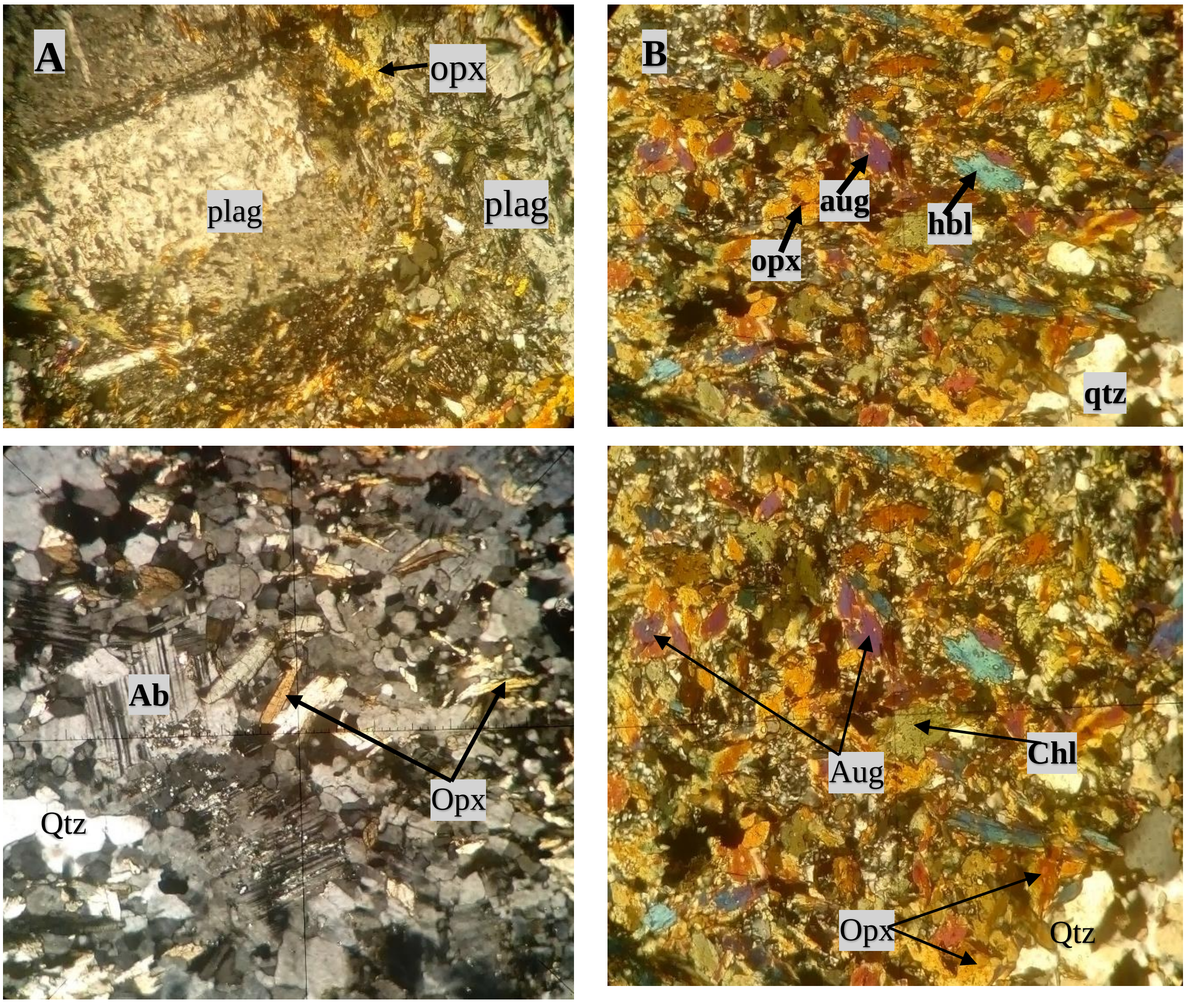


Fig. 4.5. Micro-picture of metabasites taken under 10X magnification. A- A part of metabasalt sample with visible plagioclase phenocryst and recognizable orthopyroxene surrounding it. B- part with more orthopyroxene and augite. Hornblende and quartz are also observed.

4.1.3. Metadiorite

The metadiorite unit in the study area crops out near the Mountain Belbenjo where it makes the foot of the mountain. It appears grey to dark-grey in colour and it is composed of medium to coarse grain minerals with visible quartz, biotite and pyroxene. It makes gradational contacts with metagranite in its eastern and north-eastern part and mafic metavolcanic rock in the western part. In the similar fashion to metagranodiorite, it has been cut by quartz veins and veinlets of different orientation which resulted in intense degree of silicification. Apart from silicification, the rock has also been subjected to chloritization, epidotization, and oxidization. The major oxide mineral in this unit and most of the units in the area is a brownish black- black iron oxide, magnetite. The contact this unit makes with the surrounding rocks strikes almost the same direction with the others, NNE and dips about 48^{o} south-eastward.

Petrography

The metadiorite is the most foliated rock observed in the area and its minerals have been elongated and lack the original shape (almost all the grains are anhedral). The microscopic observation of this unit indicates that the minerals composing it have undergone crenulation. It consists abundant clino- and orthopyroxenes with moderate hornblende and rare biotite. Minor quartz also constitutes the rock.

4.1.4. Metagranite

The Metagranite in the study area dominantly appears light to pinkish grey and crops out within stream cuts. It is made up of medium to coarse grained minerals with commonly visible minerals like quartz, feldspars and micas. Large phenocrysts of pinkish K-feldspar are occasionally observed throughout the rock and colour of the rock dominantly resumed the colour imposed by the K-feldspar. It runs in the same trend with the other rocks in the area (NNE-SSW) and dips 48^{o} south-eastward. The quartz veins featuring throughout the body of this unit have two different orientations and each of them has contributed to silicification of the rock. The metagranite forms relatively higher altitude land forms and makes a contact with the metadiorite and mafic metavolcanic rock in the western and south-western parts respectively. Locally, it has been fractured, weathered and altered. In addition to silicification that is commonly observed in the rock especially, near the quartz veins and veinlets, the rock has also undergone sericitization and kaolinization and epidotization. Similar to metagranodiorite, metagranite consists of fractures of two common orientations oriented NW-SE and and E-W which cross each other at nearly 90^{o}.

Fig. 4.6. Field picture of metagranite, fractured unit(left) and a unit with quartz vein(right).

Petrography

Under plane polarised light most the minerals of samples from this rock appear colourless with only some grey, greenish and opaque minerals showing distinctive colours. Under crossed polar, the thin section indicates presence of multiple minerals including quartz, alkali feldspars, plagioclase, muscovite, opaque minerals, hornblende, garnet, and chlorite.

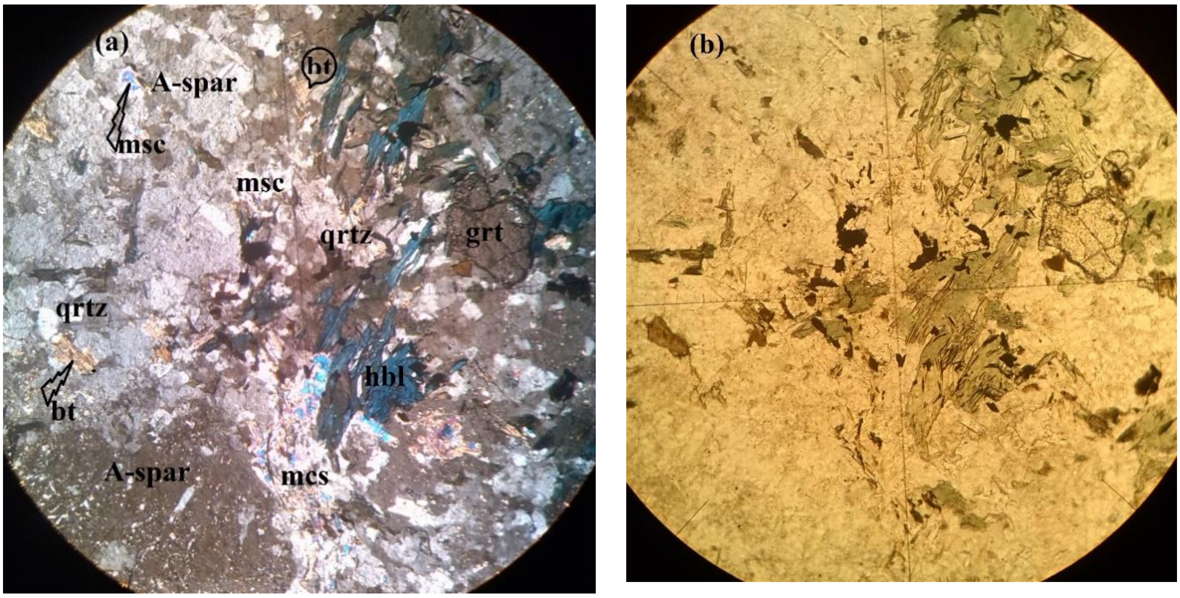


Fig. 4.7. Micro-picture of metagranite

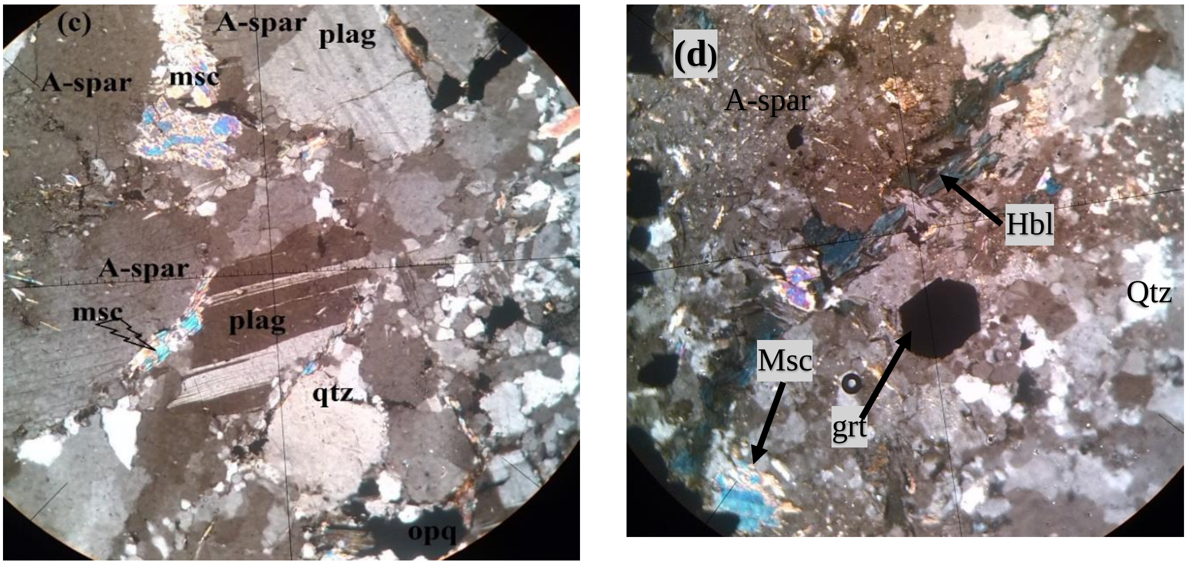


Fig. 4.7. (Continued) (a)-XPL view of part of the sample (b)-the same view of picture (a) under PPL. The alkali feldspar shown in this micro-picture is orthoclase. (c)- Other field of view of metagranite sample showing different minerals. Bt-biotite, msc-muscovite, qtz-quartz, plag-plagioclase feldspar, A-spar, Alkali feldspar, hbl-hornblende, grt-garnet are observed in different views.(taken under 10X magnification).

The most dominating minerals in the rock are feldspars, orthoclase outclassing among them (Fig. 4.7, Appendix 5). The usual simple twinning commonly observed in orthoclase is not as such visible: it simply patches. Some plagioclase (with polysynthetic twins), muscovite and hornblende (with secondary order blue colour under XPL) exist. In some of plagioclase crystals micro fracturing are observed showing inclusion of quartz within the cracked part of the plagioclases. The muscovite in the sample is both primary and secondary. The secondary muscovite is commonly observed in association with the feldspars (at margins of plagioclases or along the fractures within alkali feldspars) inferring replacement of the feldspars by muscovite due to alteration. The hornblende appears greenish to brownish green (right and upper part of the centre of Fig. 4.6b) under PPL and at some of its rim, there are opaque minerals which are probably magnetite that resulted by oxidation of Fe. Very rare sericite with grossular garnet inside it and biotite are other components that constituted the rock. Sericitization is interpreted as a process that involved alteration of k-spar enhanced by presence of hydrothermal fluids. The rarely observed garnet in the rock shows fractures which might have resulted from compressional deformation that resulted in fracturing that is also visible at larger scale in the field. The opaque minerals observed in the rock range between anhedral and euhedral crystal forms with some visible isometric and rhombohedra minerals. The fractured body and occurrence of low grade metamorphic minerals indicate that the garnet in the rocks is primary. However, there are also secondary anderite grossular garnet grains that are characteristics of low grade metamorphism of granitoid biotite.

4.1.5. Quartz Veins (QV)

Quartz veins in the Kushmagane area are distributed through metagranitoids and basic meta-volcanic rocks. They show two general trends; nearly N-S and E-W and most of them are long in their strike direction and possess varying width ranging between 2cm and 30cm. At some localities, the quartz veins of different orientations cross one another and leave the N-S oriented ones displaced (Fig. 4.9). The displacement of these N-S oriented quartz veins when they are cut by the E-W oriented veins infers that the formers are formed earlier. The formation of fractures of the E-W oriented veins resulted in displacement of the N-S oriented quartz veins and later filled with the hydrothermal fluid concentrations.

Fig. 4.8.A) N-S oriented quartz vein in Kushmagane area in metagranodiorite; B) differently oriented quartz veins cross cutting each other in metagranodiorite. N-S QV- North-South oriented quartz vein, E-W QV- East-West oriented quartz vein.

Some of the quartz veins in the area are randomly oriented and lack continuity. These quartz veins are believed to be metamorphic in their origin and precipitated in deformational openings related with metamorphism.

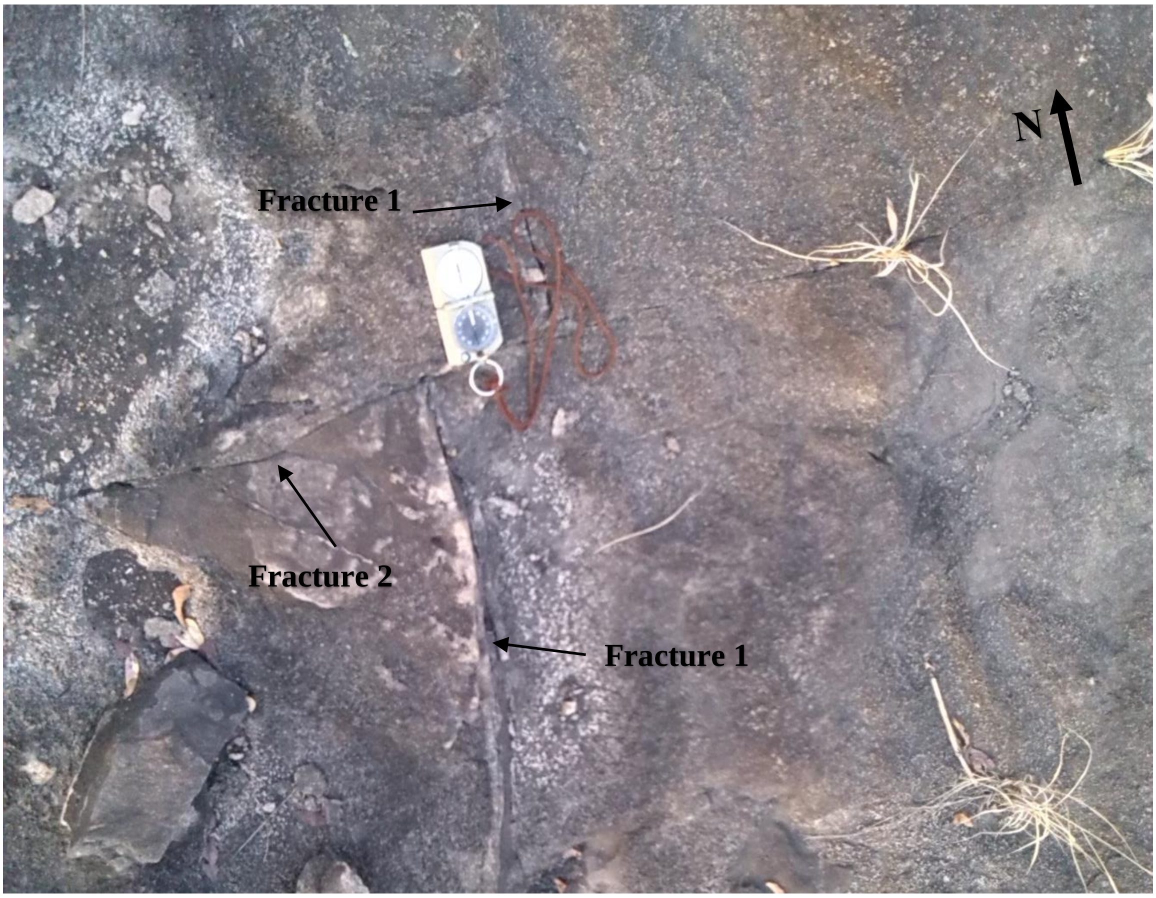


Fig. 4.9. Vein filled fractures crossing each other. The N-S running vein has been faulted while the E-W oriented is continuous.

4.1.6. The Mafic Sills

The mafic (andesitic) intrusive bodies of varying thicknesses which range from 10 to 50cm intrude the metagranodiorite.

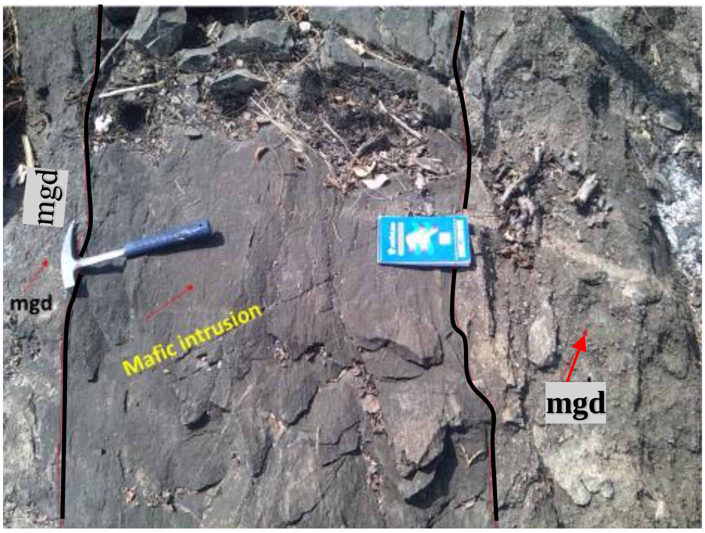


Fig. 4.10 Mafic sills intruding into metagranodiorite unit (mgd-meta granodiorite)

These sills are oriented NE-SW and they are parallel to both the contact between the meta-granodiorite and metavolcanics and the regional foliations. At the boundaries where they become in contact with the country rocks, they have imposed a grain size reduction which is typically visible where the meta-granodiorite is exposed and fresh.

4.2. Metamorphism and Deformation

4.2.1. Metamorphism

The metamorphic process in the study area involved textural and mineralogical modification of both basaltic/andesitic volcanic rocks and the granitoid intrusions. In granitoid rocks, even though the dominance of minerals which can occur in the wide range of temperature and pressure conditions makes it difficult to understand the grade of metamorphism, the field based and petrographic study of the rocks shows that they were subjected to low to medium grade metamorphism. Presence of secondary minerals like minor Prehnite infer that the granitoids underwent low grade metamorphism. Although this Ca-Al silicate minerals is commonly observed in low grade mafic-igneous rocks and greywackes, it is also sometimes observed in low grade quartzo-feldspathic plutonic rocks (Tulloch, 1979). Tulloch (1979) additionally stated that other secondary Ca-A1 silicates including andradite-grossular garnet and epidote are shown to be extremely widespread as low-grade alteration products of granitoid biotite. The other metamorphic mineral that shows metamorphism of the granitoids of Kushmagane is a fibrous actinolite which occurs in association with biotite and other mafic minerals. This mineral is commonly observed in metagranodiorite than in metagranite suggesting it is a product of alteration of mafic minerals.

Prehnite is observed as lenticular to bulbous body within mafic minerals like biotite, secondary chlorite and hornblende in the metagranitoids. Their association with biotite indicates that they are metamorphic products replacing primary biotite according to a reaction, biotite + anorthite + H2O = prehnite + chlorite + K-feldspar titanite + muscovite which was identified by Tulloch (1979). The presence of these minerals in the assemblage is an indication of low temperature metamorphism which is also expected in other parts of the western Ethiopian shield as the area is believed to be collisional and accretion zone. The other feature noticed in the rocks to indicate metamorphism is a quartz texture in which recrystallization affected the original texture in some places. Even though most of the quartz minerals resemble their igneous nature, they have been subjected to deformation and recrystallization which is observed during field work and petrographic studies. Generally, the established mineral assemblages for metagranitoids of Kushmagane are shown below and slightly vary between metagranodiorite and metagranite. The variation of these assemblages is suggested to be a result of variation in mafic components of the original rocks. The metagranodiorites originally had more mafic minerals than metagranites and eventually they are relatively richer in biotite, actinolite and chlorite. On the other hand, the metagranites are products of metamorphism of granite which is relatively richer in alkali feldspars and lack abundant biotite and hornblende. However, the two assemblage are not much different and they share many minerals.

- **Prh + Act** + **Msc** + **Bt** + **Ab**+ **Grt(anderite)** + Hbl + Qtz + kfs
- **Prh** + **Act** + **Msc** + **Ab** + **Grt(anderite)** + Qtz + Kfs

Presence of perhenite (minor), actinolite, albite and biotite in the assemblage reflects that the metamorphism took place in greenschist facies where low temperature- moderate pressure condition existed.

The mafic/andesitic metavolcanics (metabasites) of the area also underwent low to medium grade metamorphic process. The presence of mafic minerals like prehnite which are characteristic of greenschist facies indicates low grade metamorphism. Albite in the mineral assemblage brings the environment to dynamic environment thereby indicating low grade regional metamorphism. The observed general mineral assemblage in the area for metabasites is **chl** + **prh** + **Ab** +**Act** + **Ep** + Opx + augite + qtz + amphiboles.

4.2.2. Structures

Structurally most of the granitoid rocks of the area resemble what is originally observed in their igneous counterparts. However, there are also some secondary structures that are observed in the rocks. Even though no detail structural study is covered in this study, it has been identified that the structures featuring in Kushmagane area include mesoscopic faults, sills, joints, and shear zones. The sills intrude into older metagranodiorite and are oriented parallel to regional foliation and general trend of the rocks as well as the contacts. They make a flat surface sandwiched between bodies of metagranodiorite those once were connected to each other. The other structure in the area is a mesoscopic fault of small size that is distinguished by displacement of key unit, typically the quartz vein. The faults in the study area are observed in different localities and one of them is shown in Fig. 4.11.

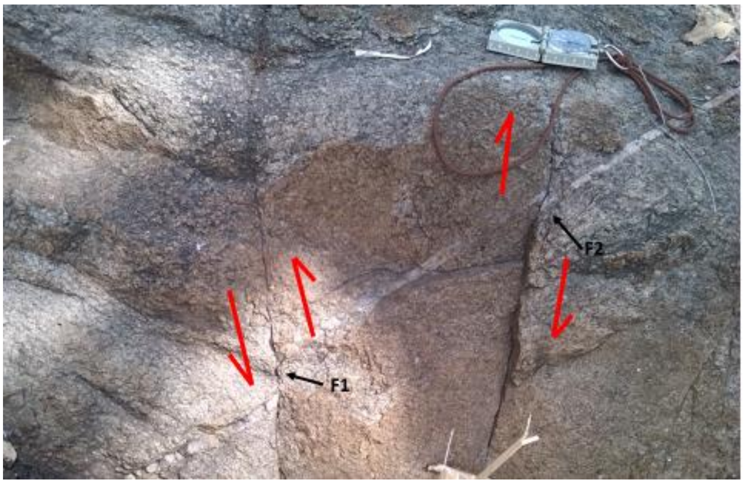


Fig. 4.11. Mesoscopic reverse fault in meta-granite unit. F1 and F2 represent spots to notice dis-placement.

The fault (F1) shown in Fig. 4.11 has a plane which strikes N61^{o}E and dips 55^{o} south-eastward. The other fault observed in metagranodiorite (picture not shown this thesis) displaces the N-S oriented quartz vein of 1–2.5 cm thickness and has about 36^{o} dip amount. The strike of its fault plane is N08^{o}E and it dips south-eastward.

The rocks in the area also show two sets of vertical tectonic joints (Fig. 4.3 left) that cross each other at an acute angle, at very near to 90^{o}. In these orientations both very old mineralized veins and younger non mineralized fractures occur. Tadesse Alemu and Abebe Tsegaye (2007) stated that the structural evolution of WEB is interpreted as result of oblique compression (transpression) stress which led to significant NW -SE directed shortening. The vein filled NE-SW oriented joints are therefore believed to be a result of this stress. Tectonic joints parallel δ_1 direction associated with the development of tectonic structures like folds and locally contain mineral fill which formed at temperatures and fluid pressures found at a depth of several kilometres (Pluijm and Marshak, 2004). Fracturing is observed also at microscopic level in feldspars and it is a sign of low temperature and high strain rate condition which resulted in brittle deformation. In terms of mineralization, fractures that are oriented NE-SW (nearly N-S) are more mineralized than those oriented E-W and they are displaced when they are cut by the later. The orientation of the joints and filled fractures (veins) are plotted on rose diagram and great circles in Fig. 4.12. Note: the NE-SW orientation is also written as N-S because the trend of the features are very close to N-S direction.

Fig. 4.12. Great circles (left) and rose diagrams (right) of orientations of joints and veins in Kushmagane granitoids (all the joints and veins fall in two sets; i. nearly N-S striking, SE dipping and ii. Nearly E-W striking, NW dipping.

CHAPTER FIVE

ALTERATION, WHOLE ROCK GEOCHEMISTRY AND MINERALIZATION

The study on mineralization in Kushmagane area manifests association of different alteration products, uneconomic ore minerals, primary gold mineralization and secondary placer mineralization. Under this chapter mineralogy of the mineralization and related alteration assemblages will be discussed. Furthermore, emphasises will be given to geochemistry of the host rock and processes involved in mineralization will be discussed thereby establishing the genesis of the mineralization.

5.1. Alterations

In the Kushmagane area different alteration types and gold and base metal mineralization are recorded. The identification of alterations was conducted based on field observation and petrographic observation to understand their occurrence and intensity. In the rocks that are exposed to the surface, silicification, chloritization, kaolinitization and epidotization are respectively the most dominant alterations. Sulfidation is also another alteration type that occurs in the rocks of the area but only abundantly visible in depths which range from very close surface to 75m (maximum depth of observation).

5.1.1. Silicification

Silicification is the most dominant alteration type that is observed in the area. It is a pervasive alteration which is observed at the surface and continues with depth even more intensively in intermediate rocks and some parts of mafic metavolcanics. Almost all the rocks have been subjected to this alteration; degree of silicification varying with lithology, distance from veinlets and depth. The metagranodiorite is the most intensively silicified unit as it encompasses majority of the quartz veins and veinlets.

5.1.2. Chloritization

Chloritization is another alteration type that makes up products of the area’s hydrothermal activity. It is more intensively observed in mafic rocks than in the intermediates. The thin section study of the mafic metavolcanic rocks showed that secondary chlorites flown in to the surface of the primary minerals. Chloritization is more or less pervasive in rocks exposed at the surface.

5.1.3. Epidotization

Epidotization is observed almost in all rock units replacing plagioclases. It is commonly observed along sheared zones where the feldspars are ground due to the shearing.

5.1.4. Sericitization

Sericitization is a rare alteration type in the area observed dominantly in granitoids than in the mafic/intermediate rocks. It is observed as very finely ground mineral encapsulated between grains of harder minerals like quartz and it occasionally encloses hexagonal subhedral minerals. The grain boundaries of plagioclases in granitoids dominantly show this feature. Moreover, it is associated with feldspars commonly as replacing unit either inside alkali feldspars or at grain boundaries of the plagioclases.

5.1.5. Sulfidation

Sulfidation is a commonly observed alteration type both in mafic metavolcanics and meta-granitoids. The common sulphide alteration in the area is pyritization and is observed in samples taken from test boreholes where there are quartz veins.

5.1.6. Oxidation

Oxidation in the area is observed both at the depth and on the surface. The surface oxidation mainly resulted in formation of magnetite and it is believed to be an oxidation product of mafic minerals like hornblende that have iron in their chemistry. The petrographic investigation also indicates presence of opaque minerals (e.g., magnetite, also confirmed by physical properties) that appear to replace the hornblendes (Fig.4.2B).

5.2. Whole Rock Geochemistry

The geochemical study of the rocks primarily targeted two dominating units of the area; the metagranodiorite and mafic/andesitic metavolcanics (metabasites). In addition to these rocks, one sample from the metagranite has been included in the analysis. Having the analytical results for these samples, the results are interpreted in terms of both major and trace elements. The primary objective of these interpretations was to determine the protolith and sources of the rocks which in turn helps to understand genesis of the mineralization. Because of high degree of alteration and surface weathering, the SiO_2 content of the rocks has been increased especially for the intermediate rocks. Quartz within all the rocks are results of both primary crystallization and secondary hydrothermal activity. Therefore, during interpretation of the geochemical data, contribution of the alteration has been recognized by comparing with rock petrography.

5.2.1. Major Element Chemistry

The major element distribution of the rocks was determined in the form of oxides and plotted on the variation diagram against the weight percentage of SiO_2 (Fig. 5.1). The samples from granitoid units, WRCS-19, WRCS-20, WRCS-21, WRCS-22, WRCS-23, WRCS-24, WRCS-25 and WRCS26 showed 70.40 to 78.30 SiO2wt% whereas the samples from the metabasites, WRC-27 and WRC-28 have SiO_2wt% of 51.6 and 53.1.

Table 5-1. Major (wt. %) and trace (ppm) element concentrations of samples collected from Kushmagane

	Metagranitoids								Metabasites	
Sample	WRCS-19	WRCS-20	WRCS-21	WRCS-22	WRCS-23	WRCS-24	WRCS-25	WRCS-26	WRCS-27	WRCS-28
Major elements and Cr2O3, SrO and BaO (ICP-AES) (wt. %)										
SiO2	70.5	70.4	71.6	71.4	70.5	70.4	78.3	73.5	53.3	51.6
Al2O3	13.75	13.6	13.55	13.55	13.25	14.05	12.2	12.5	15.4	17.1
Fe2O3	4.06	4.56	4.75	4.54	4.53	4.5	3.44	4.14	11.15	11.35
CaO	2.94	3.51	3.54	3.54	3.42	3.34	1.34	3.26	8.77	11
MgO	0.77	0.72	0.72	0.71	0.69	0.77	0.34	0.53	5.3	5.92
Na2O	5.01	3.91	3.97	3.99	3.88	4.32	4.83	4.23	2.73	1.3
K2O	0.88	0.59	0.6	0.57	0.55	0.58	0.54	0.12	0.14	0.17
Cr2O3	4.06	4.56	4.75	4.54	4.53	4.5	3.44	4.14	11.15	11.35
TiO2	2.94	3.51	3.54	3.54	3.42	3.34	1.34	3.26	8.77	11
MnO	0.77	0.72	0.72	0.71	0.69	0.77	0.34	0.53	5.3	5.92
P2O5	5.01	3.91	3.97	3.99	3.88	4.32	4.83	4.23	2.73	1.3
SrO	0.88	0.59	0.6	0.57	0.55	0.58	0.54	0.12	0.14	0.17
BaO	0.02	0.03	0.03	0.03	0.03	0.03	0.02	0.01	<0.01	0.01
LOI	0.71	0.71	0.63	0.69	0.69	0.23	0.57	0.20	0.75	0.74
Total:	99.03	98.53	99.89	99.52	98.04	98.67	101.88	98.95	98.28	100
Trace Elements (ICP-MS) (ppm)										
Ba	194	262	251	240	236	303	164.5	49	35.7	84.7
Ce	8	11.7	10.7	10.2	10.2	14.6	20.2	27.2	4.7	5.6
Cr	<10	10	10	10	10	20	20	20	50	40
Cs	0.52	0.27	0.29	0.31	0.22	0.84	0.18	<0.01	<0.01	0.04
Dy	2.41	3.16	3.1	2.93	2.94	3.74	6.19	7.39	1.03	1.89
Er	1.67	2.23	1.97	1.84	1.97	2.48	4.04	4.38	0.75	1.32
Eu	0.86	0.71	0.66	0.74	0.66	0.81	0.98	1.04	0.36	0.6
Ga	14.8	18.4	18.4	17.3	17.6	18.6	18.2	18.7	18.7	19.4
Gd	2.35	3	2.65	2.88	2.83	3.55	4.8	6.09	1.03	1.68
Hf	2.6	2.8	2.9	3.5	2.9	3.1	4.8	5.3	0.5	0.9
Ho	0.6	0.68	0.66	0.68	0.64	0.82	1.36	1.53	0.21	0.45
La	3.2	4.7	4.6	4.7	4.8	6.5	7.3	11.3	2.4	2.6
Lu	0.24	0.34	0.34	0.34	0.32	0.41	0.76	0.76	0.12	0.21
Nb	2.6	3.8	3.8	4	3.4	2.9	7.7	7.5	1.4	1
Nd	6.2	9	8.3	7.5	7.6	9.9	13.9	18.7	3.5	4.5
Pr	1.1	1.67	1.52	1.4	1.44	1.97	2.68	3.8	0.68	0.89
Rb	17.2	12.3	12.2	11.2	10.8	11	8.9	1.5	0.6	2.2
Sm	1.86	2.33	2.23	2.44	2.29	2.9	4.06	5.06	1	1.53
Sn	1	2	1	1	1	1	2	2	1	1

Table 5-1 (*continued*)

Sr	177	239	214	210	211	270	88.1	139	199.5	246
Ta	0.2	0.3	0.2	0.1	0.2	0.2	0.4	0.4	0.5	0.7
Tb	0.39	0.52	0.45	0.46	0.43	0.53	0.84	1.04	0.15	0.3
Th	0.52	0.69	0.63	0.61	0.62	0.6	0.9	1.01	0.34	0.28
Tm	0.22	0.3	0.28	0.35	0.29	0.33	0.62	0.67	0.13	0.2
U	0.35	0.29	0.31	0.35	0.35	0.26	0.42	0.43	0.2	0.1
V	22	29	27	29	26	28	9	23	293	258
W	5	6	5	5	5	2	1	2	1	4
Y	13.4	18.9	18.9	18.5	17.4	21.8	35.9	41.8	6.4	12
Yb	1.61	2.01	1.99	1.97	2.13	2.4	4.32	4.77	0.8	1.33
Zr	102	116	104	147	103	118	179	189	17	28

The Harker variation diagrams (Fig. 5.1) show a gap between two different groups of rocks, the metabasites and metagranitoids for each oxide or combination of oxides against SiO_2. All metagranitoids have low MgO, Fe_2O_3, and CaO/total alkali (Na_2O + K_2O) and high Na_2O and K_2O.

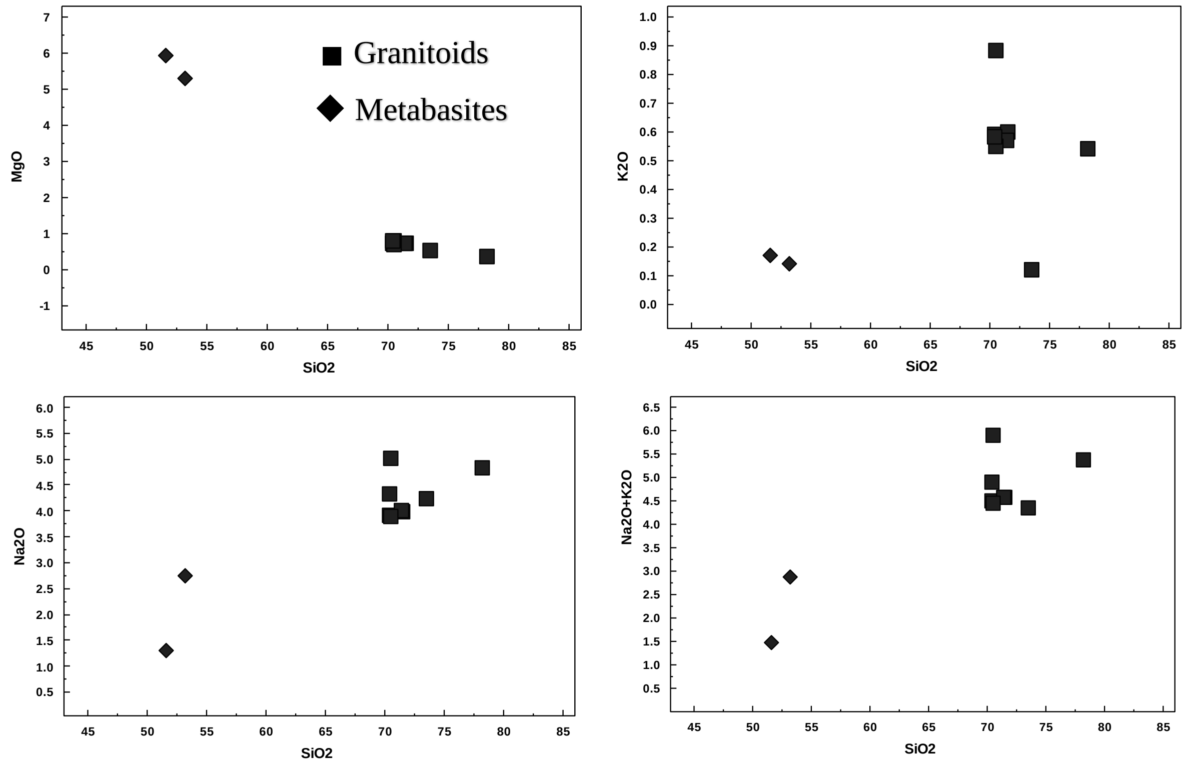


Fig. 5.1. Variation diagrams for selected major elements as a function of SiO_2 wt% for Kushmagane metagranitoids and metabasites. Number of data points seem to be less than number of analysed samples due to overlapping of some samples.

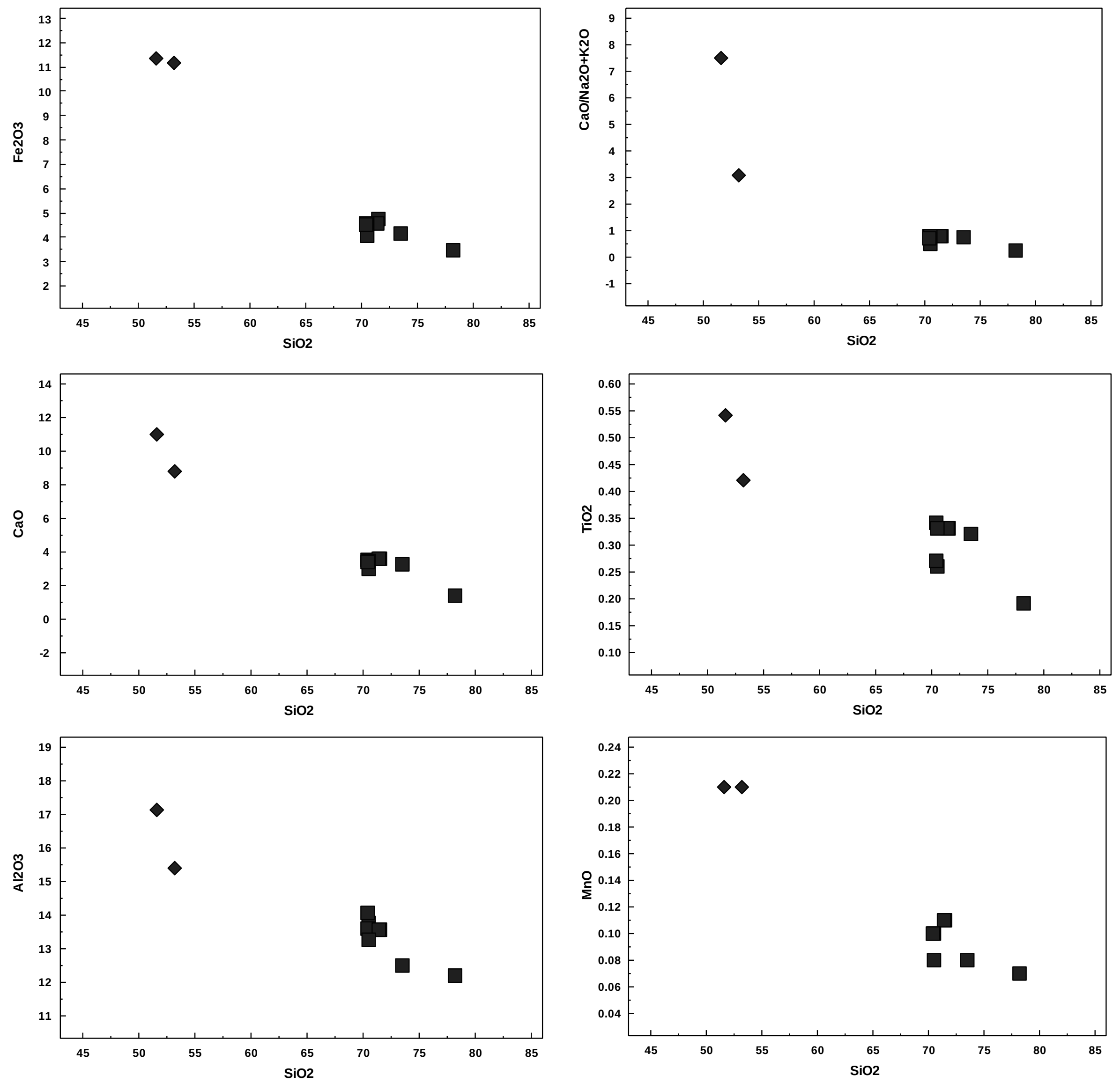


Fig. 5.1 (*continued*)

The trends showing increase in K_2O and Na_2O and decrease in Al_2O_3, MgO, MnO and Fe_2O_3 with increasing SiO_2 may reflect the crystal fractionation process in the evolution of the Kushmagane granitoid intrusions. The obtained geochemical data (Table 5.1) also indicates that the Kushmagane granitoids have more Na_2O than K_2O and therefore they can be categorized as sodic. All of the granitoids have Alumina Saturation Index of greater than one meaning that they are peraluminous. The ASI is calculated according to formula $ASI = \frac{Al2O3}{Na2O+K2O+CaO}$ proposed by Frost *et al*. (2001). The ASI values calculated according to this formula range between 1.557191 and 1.818182 (see appendix 5.3 for all values). The metagranitoids were also plotted on K_2O-SiO_2 (Fig. 5.2) graph and all of them lie in tholeiitic field. This silica saturation characteristic of Kushmagane metagranitoids is also supported by high abundance of quartz observed during petrographic studies.

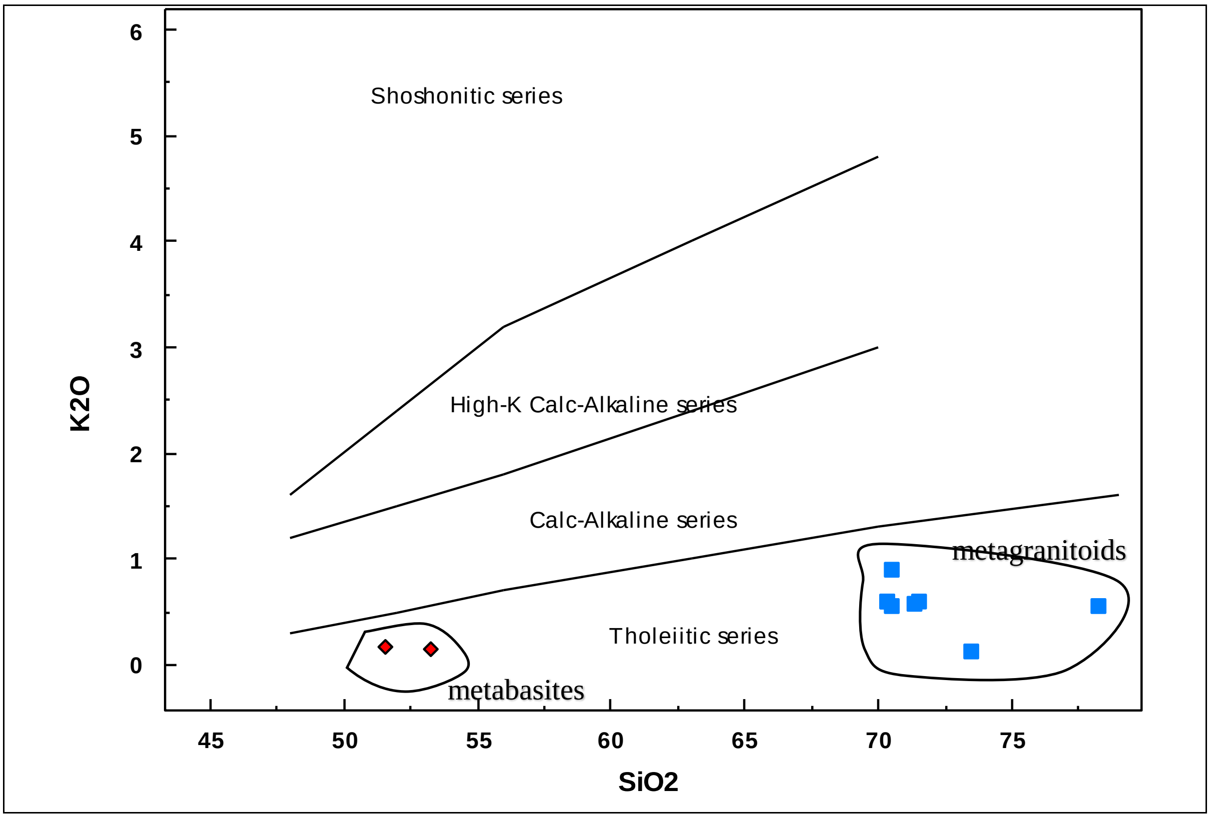


Fig. 5.2. K_2O vs SiO_2 graph for classification of Kushmagane rocks (after Peccerillo and Taylor, 1976) (symbols as in Fig. 5.1).

On the other hand, in mafic/intermediate metavolcanics, the concentration of MgO, Fe_2O_3 and CaO is high while the concentration of alkali oxides (Na_2O and K_2O) is low.

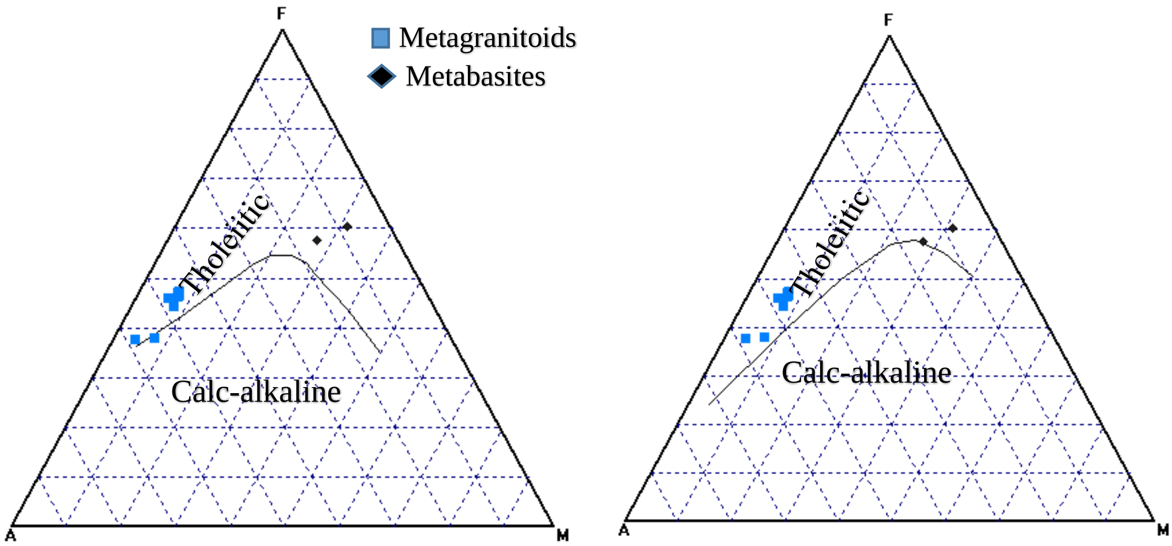


Fig. 5.3. The AFM triangular variation diagram for Kushmagane rocks; A-(alkalis: (Na2O+K2O), F-(FeO+Fe), and M-(MgO) for Kushmagane metagranitoids and metabasites after Kuno, (1968) (left) and Irvine and Baragar (1971) (right).

The AFM variation diagram classification of Kushmagane rocks put them in sub-alkaline field particularly, tholeiitic field. This indicates that the rocks are silica saturated than alkali saturated. Two tholeiitic basalt rock types are recognized according to their degree of silica saturation: Quartz-hypersthene normative (quartz tholeiite) and Olivine-hypersthene normative (olivine tholeiite) (Winter, 2001).The reasonable mineralogical existence of minerals like pyroxene with absence of/or rare olivine in metabasites also indicates that the mafic/intermediate rocks of Kushmagane area are quartz tholeiites.

5.2.2. Trace Element Chemistry

5.2.2.1. Petrogenesis of granitoids

The data of whole rock geochemistry is also interpreted in terms of trace elements to understand the petrogenesis and tectonic setting of both granitoid and the mafic/intermediate rocks by plotting on Chondrite normalized REE pattern and Primordial mantle normalized spider diagram Fig. 5.4A and B respectively.

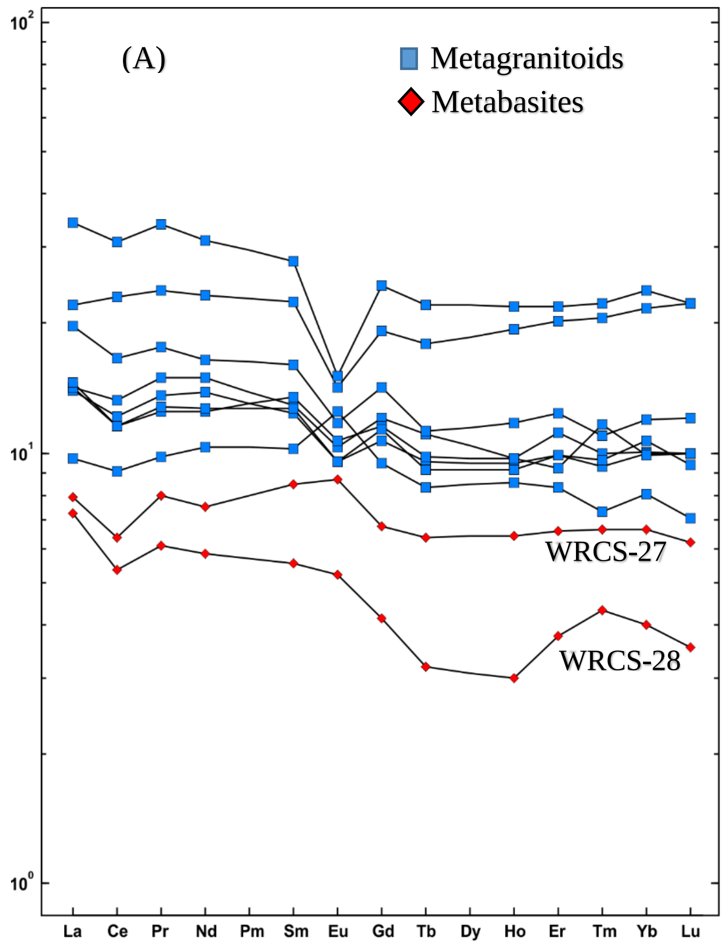
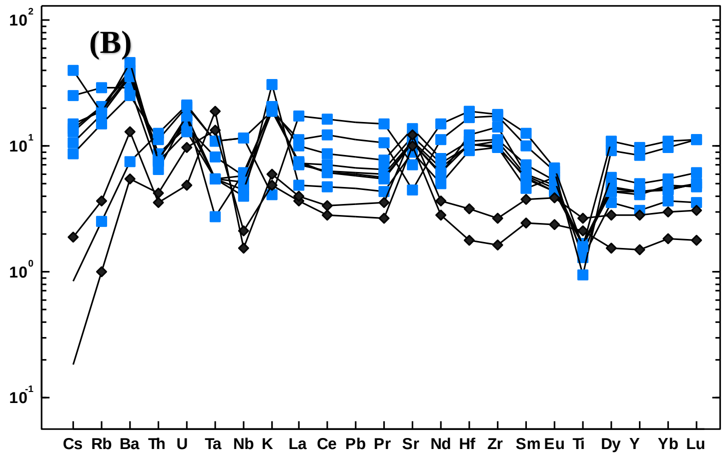


Fig. 5.4. (A)- Chondrite normalized rare earth element patterns for Kushmagane metagranitoids and mafic metavolcanic rocks of the study area, (B) - Primordial mantle normalized spider diagram for Kushmagane metabasites and metagranitoids after McDonough and Sunn (1995).

The slight enrichment in LREE and slight depletion in HRRE of granitoids matches with the general REE pattern of VAG of the other areas (e.g., Ujjuga granitoids of wetern Ethiopia, Tesfaye Kebede *et al.*, 1999). On chondrite normalized REE abundances plot, the Kushmagane granitoid rocks show slightly elevated pattern for light rare earth



elements compared to heavy rare earth elements.

Fig. 5.4. (*Continued*)

They all have moderate to deep negative Eu anomaly except one sample, (WRCS-19) which shows moderate positive Eu anomaly. Because Eu^{2+} is compatible in plagioclase and Potassium feldspar, europium anomalies are chiefly controlled by feldspars (Rollinson, 1993). Thus the negative Eu anomaly in Kushmagane metagranitoids is due to either removal of feldspar from a felsic melt by crystal fractionation or the partial melting of a rock in which feldspar is retained in the source. With high SiO2 contents, the Kushmagane granitoids are more probably formed from evolved magma which involved removal of feldspars. Rollinson (1993) stated that the REE patterns of rocks show high enrichment in LREE and high depletion in HREE when the melting percentage decreases. However, the REE pattern of Kushmagane metagranitoids shows only slight variation between the abundances of LREE and HREE which indicates the moderate to high percentage melting. For arc-related magmas there are two established models related with their petrogenesis. The first model states that arc-related magmas result from basaltic parental magmas that undergo assimilation, fractional crystallization, assimilation-fractional crystallization and storage processes (Grove and Donnelly-Nolan, 1986; Khalaji *et al*. 2007). The other model relates the origin of arc-related magmas to partial melting of continental crusts enhanced by heat from mafic magmas (Roberts and Clemens 1993; Guffanti *et al*. 1996). The Kushmagane metagranitoids have low MgO and Fe_2O_3 contents 0.34-0.77wt% and 3.44-4.75wt% respectively and high SiO2 content 70.40 to 78.30wt%. These values and their tectonic setting (section 5.2.2.4.) suggest that the source for Kushmagane granitoids is likely basaltic parental magma that underwent assimilation-fractional crystallization and storage processes and primary mantle source can't lonely fit with them with such high SiO_2 contents and low MgO. The second model is commonly associated with continental thickening rather than subduction and forms continental collision granites (CCG) which doesn't work for Kushmagane granitoids which are volcanic arc granitoids (VAG) (Fig. 5.6). Large negative Ti anomaly in spider diagram in the granitoid rocks is due to the fractionation of Ti-magnetite. Crests at Ba for granitoids and troughs at Nb and Ta (for metabasites) suggest contamination during fractional crystallization.

5.2.2.2. Petrogenesis of metabasites

The REE abundance pattern of Kushmagane metabasites show nearly parallel trend in a negative general slope. Negative slopes in Fig. 5-4B combined with their tholeiitic nature (Fig. 5.5) infers that the Kushmagane tholeiitic basalts and andesites originated in the lower enriched mantle reservoir. A consistent negative slope in E-MORB and OIBs is deduced as an indicative character for these rocks to originate in the lower enriched mantle reservoir, although very low degrees of partial melting may also produce LREE enriched melts from a primordial or slightly depleted source (Winter, 2001). On the other hand, the parallel pattern in metabasalt (WRCS-27) suggests that the REE abundances in these rocks resulted from phases involving shallow fractionation (e.g., olivine), which do not fractionate the REE. In contrast to metagranitoids, the metabasites show no to slight positive Eu anomaly. The HREE portion of sample WRCS-27 shows relatively flat trend meaning that garnet, which strongly partitions among the HREE, was not in equilibrium with the melt at the time of segregation.

5.2.2.3. Classification of Metabasites based on Tectonic Setting

The mafic/andesitic rocks of Kushmagane are classified as island arc tholeiitic rocks according to both Ti-Zr and Ti-Zr-Sr classifications of Pearce and Cann (1973) (Fig 5.5). This classification is valid with higher Fe_2O_3 compared to MgO given in Table 5.1. Best (2003) suggested tholeiitic and calc-alkaline rocks, collectively called sub-alkaline rocks typify subduction zones, where their composition correlates in a general way with the nature of the crust in the overriding plate. Moreover, abundance of minerals augite and low-Ca pyroxene (pigeonite, hypersthene) with minor olivine also fit into tholeiitic suite. This means the Kushmagane mafic/andesitic metavolcanics formed as oceanic slab subducted, reached sufficiently hot depth and melted then leaked into the crust.

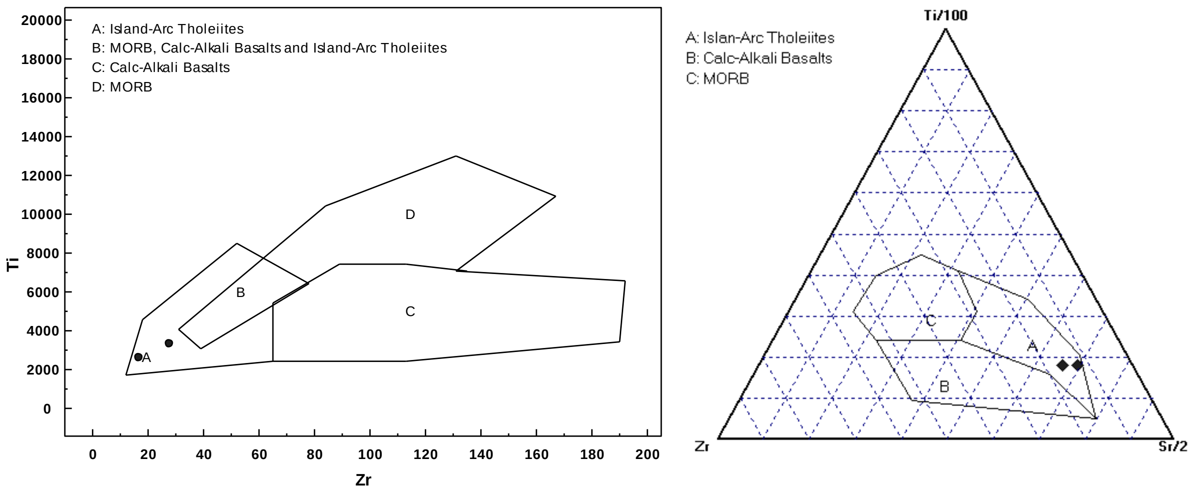


Fig. 5.5. Classification of metabasites based on; (a) Ti-Zr binary diagram and 1973 (b)-Ti-Zr-Sr ternary diagram after Pearce and Cann (1973.)

5.2.2.4. Classification of Granodiorite based on Tectonic Setting

It has been a common trend to classify granitoid rocks based on the tectonic setting. Pitcher (1983, 1993) combined such different classification schemes applied to granitoid rocks and established what the geochemistry, mineralogy and associated volcanic processes would be in each tectonic settings.

Since the rocks in the study area have been subjected to metamorphism, classification and tectonic setting discrimination is based on methods that use immobile elements. In classification of such rock types we have to use diagrams that use high field strength elements such as Ti, Zr, Y, Nb and P which are thought to be relatively immobile in aqueous fluids unless there are high activities of F^- (Rollinson, 1993). Even though it is less known about the stability of these elements at higher metamorphic grades, it has been understood that these elements are stable under conditions of hydrothermal, sea-floor weathering and up to medium metamorphic grades (mid amphibolite facies) (Rollinson, 1993). Regardless of its mobility, Rb has been used on the assumption that the effects of element mobility are much less in granitic rocks than in basic rocks, chiefly because granitic rocks are generally less altered (Rollinson, 1993).

Thus, an integrated chemical classification and classification based on tectonic environment provides us a conceptual framework, which helps to understand the occurrence of granitoids and their genesis (Winter, 2001). In this study, different classification diagrams are used so that the idea about occurrence and geneses of the granitoid rocks can be compared from each diagrams.

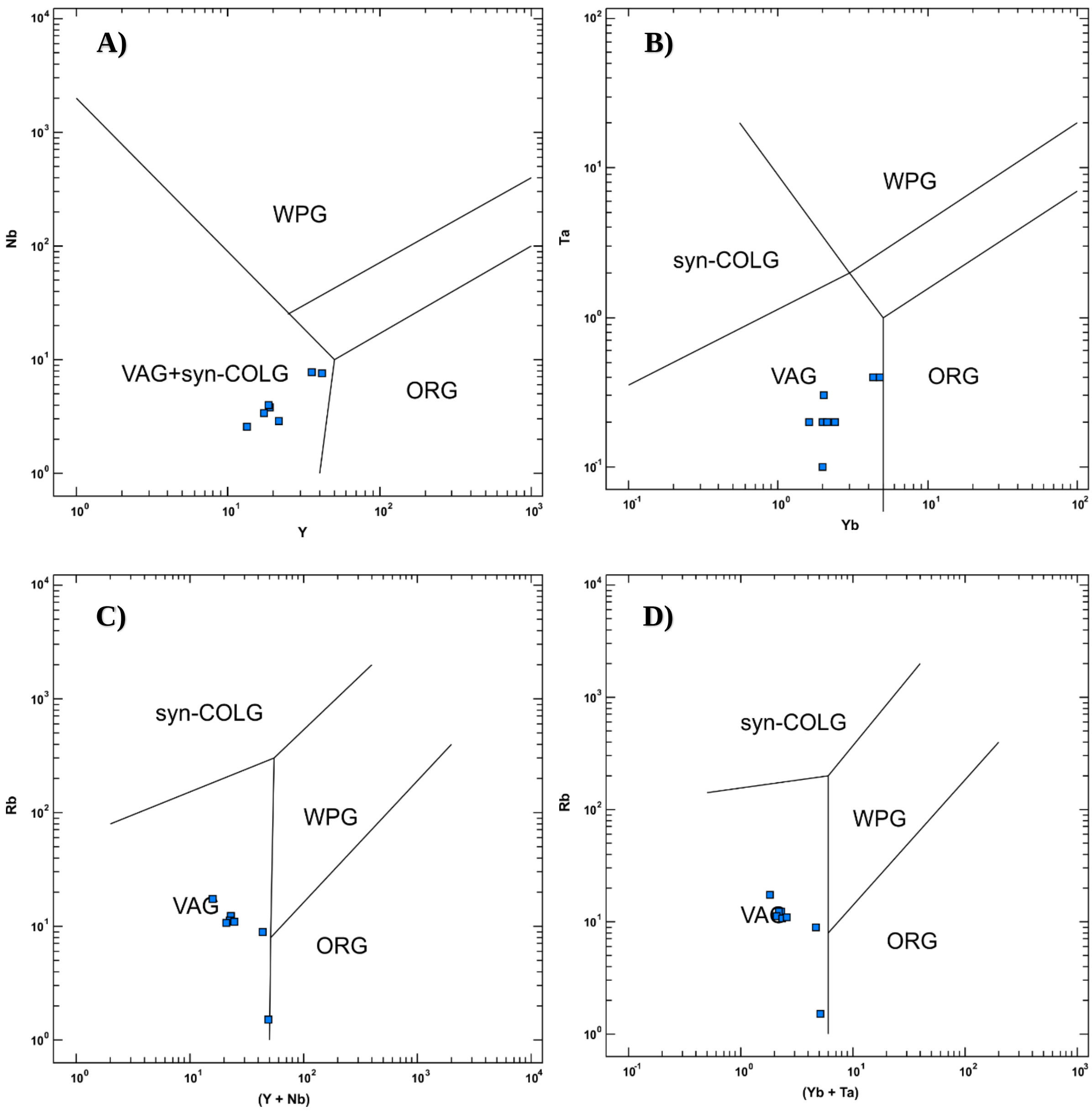


Fig. 5.6. Trace element tectonic setting discrimination diagrams of the granitoid rocks of Kushmagane. Syn-COLG: syn-collision granite; VAG: volcanic arc granite; WPG: within-plate granite, ORG: ocean ridge granite. Concentrations of the elements are in ppm. (A) Y–Nb binary diagram and (B) (Y+Nb)–Rb, (C) Rb versus Y+Nb, (D) Rb–(Yb+Ta) after Pearce et al., 1984. (Symbols as in Fig. 5.1).

According to all above tectonic discrimination diagrams (except diagram C, where one sample lies on boarder of volcanic arc and oceanic ridge settings), all the granitoids of the area lie in VAG of Pearce *et al*. (1984 as cited in Winter, 2001). Except the encratonic alkaline granitoids which exclusively originate in upper mantle, no other granitoids originate exclusively in the continental crust or in the upper mantle (Lameyre *et al*, 1982 as cited in Barbarin, 1990). Barbarin (1990) also stated that the majority of the orogenic granitoids originate at the crust-mantle interface and involve crust and mantle-derived component, the relative proportions varying in the different 'hybrid' granitoids. The formation of such granitoids (granodiorite, tonalite, granite) is believed to be associated with crystal fractionation of parental basaltic magma and partial melting of mantle-derived mafic underplate. This setting involves melting mechanism which results from subduction generated energy, transfer of fluids and dissolved species from slab to wedge which in turn result in melting of wedge and transfer of heat upward (Winter, 2001). Pitcher (1993) stated granitoids of such characteristics form in active continental margins.

5.3. Mineralization in Kushmagane

5.3.1. Placer gold

A placer gold in Kushmagane is wide spread throughout the seasonal streams of the area where the local peoples mine from by panning. It has been an economically dependable for the local peoples. The placer mining activity by local people is commonly done near the quartz veins which are believed to be the site for deposition of the gold. This means that the placer deposit in the area is secondary product of the primary orogenic/shear hosted gold mineralization.

5.3.2. Primary Mineralization (Anomaly results from Exploration activities)

Due to the fact that the analytical methods used for whole rock geochemistry don't cover Au, gold is not observed in the analyses. However, soil geochemical data, trench data and test borehole data have been adopted from Managem PLC and presented in Table 5.2, Fig. 5.7 and Table 5.3. Managem PLC has been conducting an exploration program for gold and base metals in the area for last four years and has done chemical analyses on soil samples, trench floor samples and test borehole samples. 1021 soil samples analysis indicates that 752 samples have Au concentration of equal to or greater than 2ppb increasing up to 88ppb for one sample.

Table 5-2. Summarized soil geochemical data on Au concentration (data adopted from Managem PLC, 2013)

Au concentration (ppb)	<2	2-10	11-30	30-40	>40
Number of samples with the value	269	725	23	2	2

Analysis of trench samples plotted on the following map (Fig. 5.7) shows Au consentration (ppb) of samples collected from floor of the trenches. According to this Fig. the samples have very wide range of Au concentration, from less than 1ppb to 874ppb. The rocks were also sampled from test boreholes and show slight positiive anomlies of gold. These values are summarized and shown in Table 5.3. Eventhough the results are not as high as the currently estimated cut off grade for gold, most of the results show values beyond clark value.

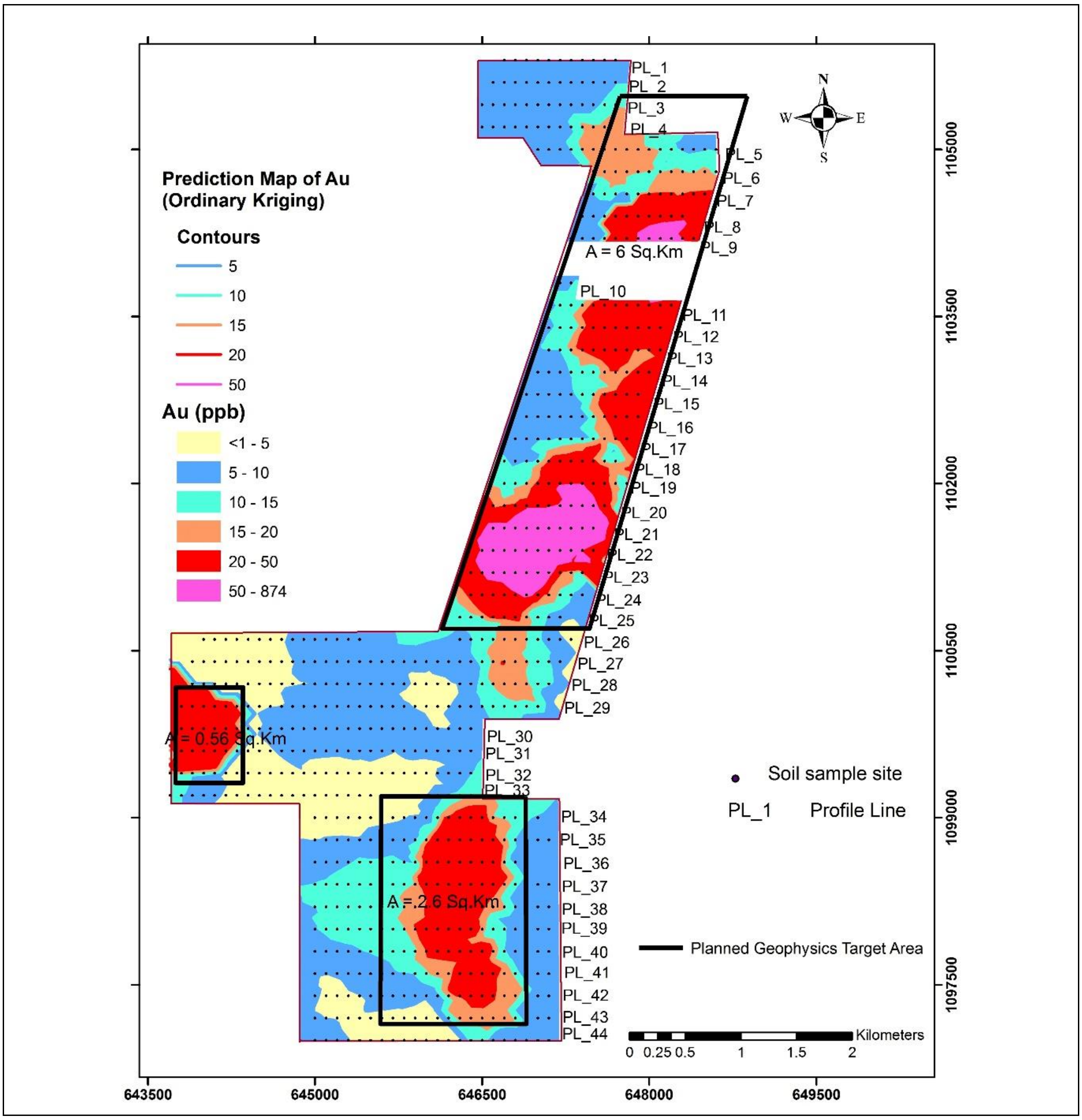


Fig. 5.7. Kushmagane soil and trench geochemical map for gold (adopted from Managem PLC, 2015).

According to values presented in Table 5.3, relatively higher Au values are observed in metagranodiorite where the quartz veins are associated.

Table 5-3. Summarized gold values for rocks sampled from test boreholes (data adopted from Managem PLC, 2016).

Samples	Bore hole Code	Rock type	Au (ppm)	Depth of sampling (m)	Lat.	Lon.
001588	WRC-23	Mgd+qv	0.54	3	646285	1097788
001594	WRC-23	Mgd+qv	0.41	8	646285	1097788
001597, 001598, 001599, 001600, 001601	WRC-23	Mgd	<1	11–15	646285	1097788
001430	WRCS20	Mb	0.02	20	646301	1098449
001561	WRC-22	Mgd+qv	0.04	34	646441	1097597
001571	WRC-22	Mb	0.01	42	646441	1097597
001572	WRC-22	Mb	0.01	43	646441	1097597
001404	WRC-21	Mb	0.01	17	646234	1098097

5.3.3. Ore geology

5.3.3.1. Host rock

Geochemical analyses in Kushmagane indicates both basic metavolcanics and metagranitoids have gold concentration beyond the crustal background values. The associated sulphides also exist in both of the two especially along fractures that are connected to the contacts between the two. These indicate that the mineralization in the area is hosted in both the metabasites and metagranitoids.

5.3.3.2. Mineralogy of the Mineralization and ore textures

Au mineralization in Kushmagane is decorated with presences of sulphides typically pyrite and Pyrrhotite being the most dominant sulphides. In above topic it has been indicated that both the metabasites and metagranitoids have Au concentrations beyond crustal values. As a result, in this thesis study, samples from both of the rocks are collected and analysed for both whole rock geochemistry and petrography (ore microscopy and thin section studies). The ore petrographic study and field investigations show that sulphides like pyrite, pyrrhotite, chalcopyrite and covellite are present in the area. Magnetite is among ore minerals resulted by oxidation of mafic minerals. Below are the most common ore minerals, associated alteration products and gangue minerals that are observed in association with the mineralization. These minerals have grain sizes ranging between as big grains as those visible to naked eye and microscopic grains.

Precious and base metals:

The geochemical analysis of soils and rocks of the area by Managem PLC indicates presence of precious metals and base metals like Ag, Pb, Zn, and Cu. This is an indicator of concentration of these metals in rocks of the area either as native or their ore mineral forms. The occurrence of these metals is discussed as below from both geochemical and ore microscopy analyses as well as field observations.

Pyrite:

Pyrite crystals are observed in field beginning from test boreholes as shallow as 15m up to 75m (the maximum depth of observation) disappearing at different depth levels between this range. Polished section examination entails its occurrence as anhedral to subhedral crystals with brassy yellow luster in plane polarised light. Nearly cubic pyrite crystals were deposited in fractures, vesicles and veins and as disseminations in the groundmass (lower part of plate B designated cubpy). This indicates that the pyrite is of two different generations. The deformed pyrite crystals (e.g., hdpy in plate A) are believed to be formed earlier so that the deformational features are observed on them.

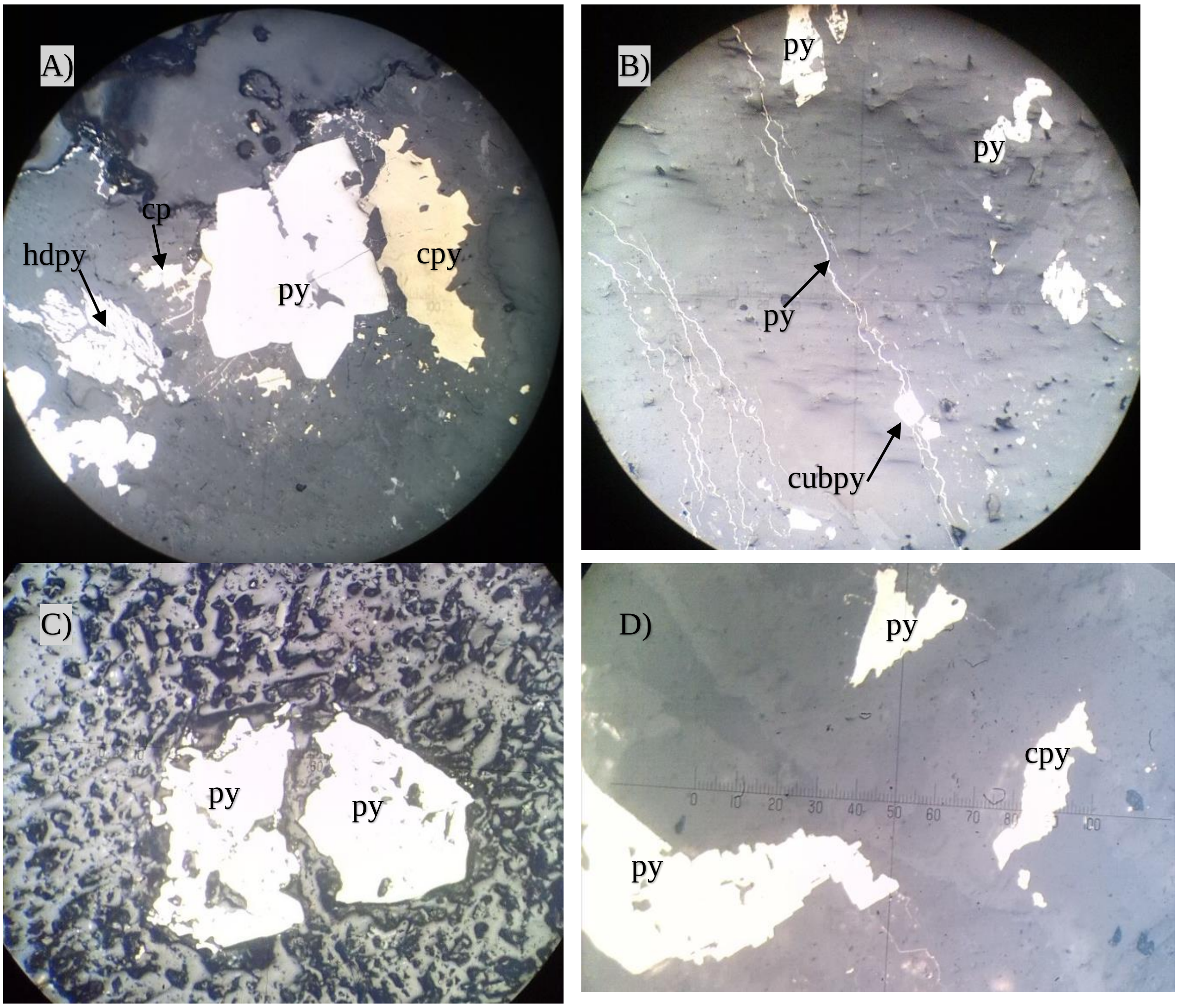


Fig. 5.8. Micro-picture of Kushmagane sulphides and oxides; under 10X magnification (XPL).

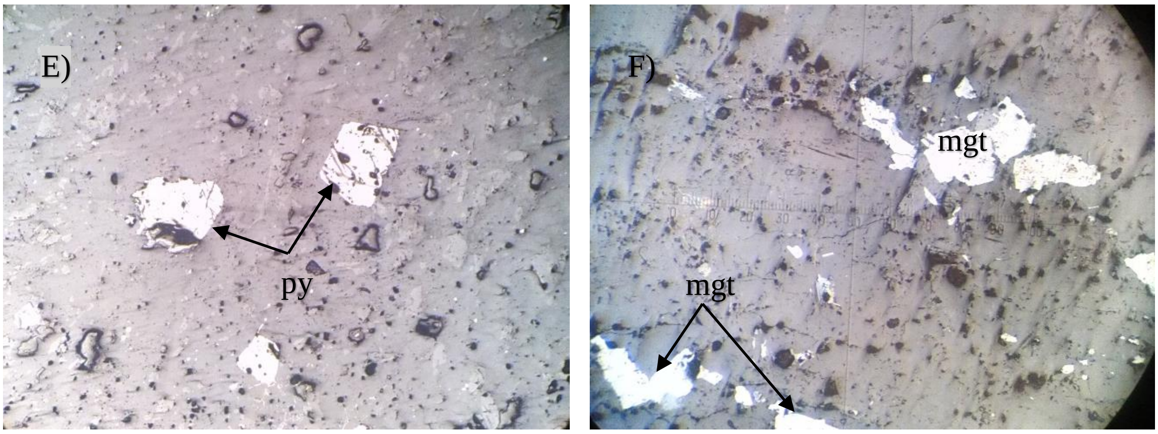


Fig. 5.8 (Continued)

The occurrence of these minerals is distributed throughout the rocks from mafic composition to granitoids and from surface to deeper boreholes. The above pictures represent ore minerals observed in polished section both from mafic rocks and granitoids as well as both from borehole and surface. The cubic crystals of this mineral are believed to be second generation as they exhibit only small deformational features. Most of euhedral pyrites are observed as fine grains disseminated through the gangue minerals.

Pyrrhotite: The presence of this sulphide was observed in the field during borehole sampling. It occurs as anhedral to subhedral grains and distributed within both mafic metavolcanics and meta-granitoids.

Covellite: Covellite is observed in a polished section whose sample is collected from surface. It appears bluish in the polished sample.

Magnetite: Magnetite is an ore mineral that is observed both on the surface and at depths. Almost all of the rocks in the area has been oxidized changing the Fe in their mafic minerals in to magnetite. The field based magnetic test, thin section and polished section studies also suggest presence of this mineral. In thin section analysis it appears opaque and fails to provide any diagnostic feature of itself. However, association of opaque minerals with hornblende infers alteration of the mafic mineral into magnetite. Gangue minerals observed in association with the ore minerals are dominantly quartz and feldspars.

5.3.3.3. Ore Mineral paragenesis

Based on textures, deformational features and cross cutting relationships, the paragenetic evolution of Kushmagane sulphides has been established. The ore mineral paragenesis is presented in Fig. 5.9. The presence of two textural characteristics infers that the sulfide mineralization in the area took place at least at two stages. Sulphides of Stage-I mineralization have undergone deformation and show no or very less preservation of primary habit. Moreover, they exhibit fractured surfaces which are implemented due to stresses. The stage-II sulphides fill in cracks of gangues or stage-I sulphides and show subhedral to euhedral habits reflecting they were formed after deformation event that imposed fracturing on stage-I sulphides. The summary of formation of these sulphides and oxides is presented in Fig. 5.9.

Mineral	Primary mineralization		Secondary Mineralization
	Stage-I	Stage-II	
Pyrite	———	———	
Chalcopyrite	———	———	
Pyrrhotite	———	———	
Magnetite			———
Covellite			———

Fig. 5.9. Ore mineral paragenesis of Kushmagane gold mineralization.

5.3.4. Genesis of the Mineralization

According to interpretation of data obtained in different ways mentioned in chapter 2, the gold mineralization in the area is related with quartz veins resulted from hydrothermal processes in volcanic arc setting. It is highly associated with metamorphosed granitoid rocks and also mafic rocks where they make contact with the formers. Thus, the gold mineralization in Kushmagane area can be categorized as low-sulphide gold–quartz vein. Low-sulphide gold-quartz veins, also orogenic veins are greenstone-hosted gold or mesothermal quartz veins consisting gold in massive to wispy nature along with multiple persistent quartz veins that are hosted mainly in regionally metamorphosed rocks (Drew, 2003). The veins commonly are present in fault and joint systems that are produced by regional compression locally cutting granitic rocks and their ages generally are post-metamorphism (https://pubs.usgs.gov/of/2007/1214/PDF).

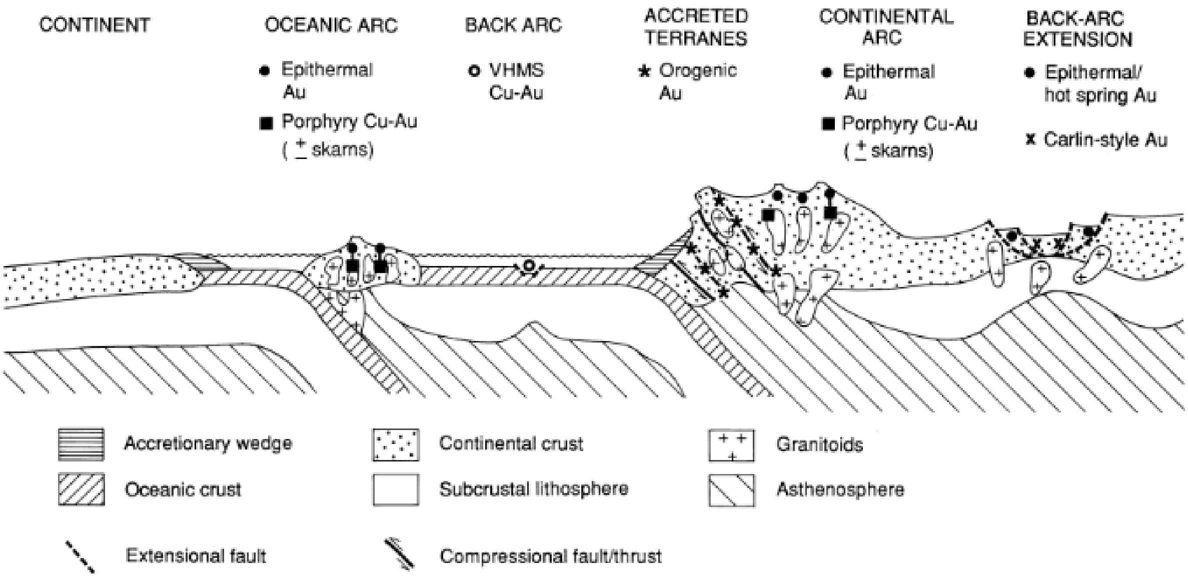


Fig. 5.10. Tectonic settings of gold-rich epigenetic mineral deposits (adopted from Groves et al., 1998). Epithermal veins and gold-rich porphyry and skarn deposits, form in the shallow <5 km parts of both island and continental arcs in compressional through extensional regimes. The epithermal veins, as well as the sedimentary rock-hosted type Carlin ores, also are emplaced in shallow regions of back-arc crustal thinning and extension. In contrast to the so-called 'mesothermal' gold ores termed orogenic gold on this diagram are emplaced during compressional to transpressional regimes and throughout much of the upper crust, in deformed accretionary belts adjacent to continental magmatic arcs. Note that both the lateral and vertical scale of the arcs and accreted terranes have been exaggerated to allow the gold deposits to be shown in terms of both spatial position and relative depth of formation.

The study area lies in a continental arc subjected to shearing and fracturing of granitoid intrusions and mafic metavolcanics due to compressional stresses. Studies suggested structural and geological variations in Western Ethiopia's ophiolitic belts are results of successive collisions of juvenile island arcs and continental arcs (Vail, 1985; Berhe, 1990; Stern, 1994; Abdelesalam and Stem, 1996). Therefore, the gold mineralization in Kushmagane is related to continental arc granitoids resulted from melting introduced by subduction of the oceanic crust and surrounding metabasites. Fig. 5.9 demonstrates the tectonic setting of different deposit types along with commonly associated rock types. Accordingly the orogenic gold deposits are formed in volcanic arc settings where there are either deformed granitoid intrusions or the surrounding volcanic rocks. This also fits with Kushmagane gold mineralization and other deposits that can be associated with these settings and rock types include epithermal Au-deposits and skarn deposits. The less carbonitization observed in the area denies the probability for the mineralization to be skarn type. The orogenic gold deposits in greenschist facies terranes are typified by quartz-dominant vein systems with ≤3–5% sulphide minerals mainly Fe-and As-bearing sulphides and <5–15% carbonate minerals (Grooves *et al.*, 1998). The spatial and temporal occurrence of mesothermal gold deposits is consistent to deformational processes at convergent plates regardless of whether they are hosted in Archean or Proterozoic greenstone belts or Proterozoic and Phanerozoic sedimentary rock sequences (Barley and Groves, 1992). Integration of these concepts with current observations entails that the mineralization took place in regionally metamorphosed pre- to syn-deformational granitoids s as well as the associated mafic rock.

5.3.4.1. Sources of metals

The source of gold and other metals in volcanic arc setting has been a debating topic for researchers. Different studies (e.g., Bierlein and Craw, 2008; Willman *et al*., 2010) suggest that mafic metamorphic rocks are the principal sources of metals in orogenic deposits. Goldfarb *et al*. (2001) also generalizes in most instances, the ore forming fluids for orogenic gold deposits are metamorphic in origin and that fluid generations leach and transport Au and others during the transition of metabasites from greenschist to amphibolite facies. The Kushmagane metabasites are also metamorphosed to greenschist facies and they are probable sources of metals providing to the surrounding rocks by dehydration process during prograde metamorphism. As they provide Au to the surrounding rocks during metamorphism, metabasaltic rocks face depletion in their Au concentration (Pitcairn *et al*. (2006a). Additionally, Pitcairn *et al*. (2015) showed that metabasaltic rocks undergo a significant mass loss of Au between greenschist and amphibolite facies. Thus, the lower Au concentration of metabasites compared to metagranitoids (Table 5.3) is probably due to removal of Au form the formers. However, some samples from the metabasalt and metaandesite rocks of Kushmagane still show greater Au values than what was set by Pitcairn *et al*. (2015) in greenschist facies (0.0008ppm). This may indicate that the protoliths of these rocks had higher Au contents or the leaching was not intense to remove much of Au from them. Moreover, it may be because these rocks also acted as host rocks accumulating the metals in their fracture zones. In contrast to this, Pitcairn *et al*. (2015) suggest that metasedimentary rocks are much more suitable source rocks for fluids and metals in orogenic gold deposits than metabasaltic rocks as they are mobile mobile during metamorphism of all elements commonly enriched in this style of deposit. However, no metasedimentary rocks are observed during this thesis study and the idea of considering them as sources is not presented.

5.3.4.2. Sources of fluids

No gold deposits are formed in a simple way and require some extensive natural processes by which they get a value beyond crustal background. Therefore, other thing that needs to be discussed is the source and condition of fluids that contributed to gold mineralization. There are different sources of fluids that are proposed as carriers of economic metals either in ionic form of themselves or as components attached to anions in the solutions. Major sources in these settings include magmatic fluid and fluids from metamorphosed mafic rocks. Dube and Gosselin (2007) suggest that the greenstone-hosted quartz carbonate vein deposits (orogenic deposits) are related to metamorphic fluids from accretionary processes and generated by prograde metamorphism and thermal re-equilibration of subducted volcano-sedimentary terranes. On the other hand, Hart (2005) stated granitoid intrusions are common features of orogenic belts and are an obvious fluid source for any proximal gold occurrence. Earlier under this topic, it has been discussed that the mineralization is formed in fractures resulted due to compressional or transpressional stresses in metamorphosed pre- to syn-deformational granitoids and surrounding metabasites. However, presence of fractured zones yielding pressure drop is not enough for concentration of metals from the fluids. Zhu *et al*. (2011) suggested that a pressure drop alone would not cause the fluids to enter the two-phase field and needs a pressure decrease combined with a drop in temperature below ~300^{o}C. Gold mineralization in most shear zones is post-peak metamorphism and involves a multi-stage alteration event accompanied by gold mineralization through continuous fluid flow over a long period of time (Zhu *et al*., 2011).

Without fluid inclusion data analysis, it may be difficult to reveal what the exact source of the fluids is. However, with available geochemical data, rock and ore petrography and field studies, the fluid source probability is thus either metamorphic or magmatic. The current study identified the rocks in the area underwent low grade metamorphism which thereby generated metamorphic fluids which also produced veins of metamorphic origin. Tesfaye Kebede *et al*. (1999) identified that the western Ethiopia consists of plutonic rocks of variable composition and age intruding the basement rocks, particularly the low-grade volcano- sedimentary sequence. In this studies pre-, syn- and post-tectonic plutonic suites dominated by granites and granodiorites with some tonalite, diorites and gabbroids were identified. The current study suggests that fluids from the post- and syn- tectonic granitoids have contributed to mineralization of earlier formed pre- to syn-tectonic granitoids and metavolcanic rocks of the area. This quartz vein related orogenic mineralization has also generated secondary alluvial placer gold deposits in the area from which the artisanal miners used to mine a gold for long time. The deposit is structurally controlled accumulating along the structural zone where the quartz veins run through.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusions

Geology of Kushmagane area is covered by metavolcanics and metagranitoids sparsely intruded by mafic sills. These rocks are marked by quartz veins and veinlets of two common orientations, N–S and E–W. The N-S oriented quartz veins are parallel to the general trend of the rocks in the area and are cut by E-W oriented veins. They are displaced along the plane through which the E–W veins run while the later remain continuous. This indicates that there are at least two generations of quartz veins and, the N–S oriented ones are older as they are modified by the E–W oriented veins. These N-S, identified to be older quartz veins are the mineralized veins along which artisanal miners mine and Managem PLC got relatively higher anomalies. Metagranodiorite, the most dominant unit in the area is intruded by mafic sills which parallel both the regional foliation and contacts. The grain size reduction observed at the contact between the sills and metagranodiorite indicates that the mafic intrusion are formed after the granodiorite.

The metamorphic process in the area has imposed textural and mineralogical modification of both metabasites and metagranitoids. The metabasites show two mineralogical characteristics which is indicative of metamorphism of andesitic and basaltic rocks. The mineralogy observed in metabasalts is more enriched in mafic minerals than the andesitic metavolcanics while the quartz volume percentage is lesser. They consist of plagioclase phenocrysts with quartz and no olivine or (rare olivine only in metabasalts) in groundmass. These combined with their tholeiitic nature from chemical data interpretation shows that the Kushmagane metabasites are quartz-tholeiitic. Generally they consist metamorphic minerals like minor prehnite, chlorite, and actinolite which are diagnostic of greenschist facies. Existence of albite in the assemblage additionally indicates low grade regional metamorphism.

All the granitoids have ASI value of greater than one meaning that they are peraluminuous. This, combined with their identified tectonic setting (VAG) and mineralogy indicates that they are formed in active continental margins from basaltic parental magma of mantle source and partial melting of mantle derived mafic underplate and other crustal materials. On the other hand, Kushmagane metabasites show nearly parallel flat REE pattern in a negative general slope. Moreover, they are classified as island arc tholeiites and these data together indicate they originated in the lower enriched mantle reservoir. The flat pattern in metabasalt (WRC-28) suggests that the REE abundances in these rocks resulted from phases involving shallow fractionation (e.g., olivine), which do not fractionate the REE.

The gold mineralization in Kushmagane area is associated with both metabasites and meta-granitoids in the area. Anomalies have been observed both in the metagranitoids and mafic metavolcanics indicating both of the rocks probably hosted the gold. However, the lower Au concentrations of the metabasites may be a clue to indicate that these rocks are source of the gold and are leached during metamorphism. The mineralization is decorated with presences of different primary and secondary ore minerals including pyrite, pyrrhotite, covellite and magnetite. The gold mineralization is believed to be orogenic type (mesothermal) which is deposited in compressional/ tranpressional fractures and shear zones resulted in syn- to pre-deformational metagranitoids and metabasites in which the formers intruded. This mineralization is accompanied by fluids whose source is suggested to be the metamorphism of mafic rocks in the surrounding area granitoid intrusions and/or the subducted oceanic crust.

6.2. Recommendation

This study mainly covered the geology and genesis of gold mineralization in Kushmagane area where particularly indicated on the local geological map. It involved petrographic analysis for both rock and ore studies and whole rock geochemical analyses. Thus, identification of the geneses of the mineralization was based on these analyses which may face ambiguity on exact determination of source of the fluids and the mineralization. Structural relationship of the mineralization with the host rocks needs detailed structural investigations and age determinations which are not implemented in the current thesis study. Therefore, for more understanding of the source of the fluids and structural controls, fluid inclusion and isotope studies have to be implemented in the further studies. Most of the samples collected for ore petrography were RC samples broken in to small sizes which were not able to show sulphides on bigger rock surfaces. Therefore, further studies may consider drill core samples for more understanding of sulphides distributions, textures and replacement features. To cover more features in the area in the map, geologic maps of greater scales have to be produced so that the structural and lithological features are better understood. The current study only targeted very narrow area in terms of both mapping and sampling and may not represent the wide variety of rocks, structures and processes of the western Ethiopian Shield. Consequently, larger areas have to be covered to better understand these phenomena. Furthermore, it has been a long time since the local people began gold production from placer deposits near the local streams. Therefore, data on gold deposits in the area needs to be updated and presented to mining companies/organizations so that better mineralization zones can be identified and mined.

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Appendices

Appendix 1. Location and description of sampling for samples used for geochemical analyses

Sample	X-Coordinate	Y-Coordinate	Description of sampling
WRCS-19	0646364m	1098835m	Granodiorite rock sampled from borehole of 49m
WRCS-20	646475m	1101105m	Granodiorite rock sampled from borehole of 30m
WRCS-21	646475m	1101105m	Granodiorite rock sampled from borehole of depth 45m
WRCS-22	646475m	1101105m	Granodiorite rock sampled from borehole of depth 49m
WRCS-23	646475m	1101105m	Granodiorite rock sampled from borehole of depth 51m
WRCS-24	0646279	1098449	Granodiorite rock sampled from surface exposure
WRCS-25	0647029	1098329	Granodiorite rock sampled from surface exposure
WRCS-26	0646756	1098186	Granite rock sampled from surface exposure
WRCS-27	0646340	1098819	Metabasite rock Sampled from surface exposure
WRCS-28	0646425	1098396	Metabasite rock Sampled from surface exposure

Appendix 2. Location and description of samples used for petrography

Sample	X-Coordinate	Y-Coordinate	Description of sampling
M1	0646279	1098449	Fresh sample of the rock identified on the filed as metagranodiorite was sampled from the surface.
M2	0646259	1098400	Fresh sample of the rock identified on the filed as metagranodiorite was sampled from the surface.
M3	0646757	1098224	Fresh sample of the rock identified on the filed as metagranodiorite was sampled from the surface.
WRCS-24	0646884	1098894	Fresh sample of the rock identified on the filed as metagranodiorite was sampled from the surface.
M7	0646200	1097440	Silicified sample of metabasites was sampled from surface
B21A	0647005	1098076	Fresh sample of foliated metadiorite was sampled from surface
M8	0646425	1098396	Fresh sample of metabasites was sampled from surface.
WRCS-27	0646340	1098819	Silicified sample of metabasites was sampled from surface
M9R	0646375	1098988	Chloritized, silicified sample of metabasites similar to M9 was sampled from surface.

Appendix 3. Petrographic description of some of the sampled rocks.

Granodiorite Samples (after identification by field and petrographic investigations)		
No.	Sample code	Description
1	M1	This sample represents a rock which generally possesses subhedral, medium to coarse grains of quartz (~35vol %), plagioclase (~26%), and alkali feldspars (~11%). Subhedral to euhedral grains of opaque minerals (~3%), and biotite (~15%), perhenite(~5%), fibrous actinolite (~4%), secondary chlorite (~1%), hornblende (~3%), garnet (~1%) are present in the rock. Perhenite is observed replacing mafic minerals.
2	M2	This sample resembles sample M1 both in overall textural and mineralogical make up. Quartz and feldspars are the most dominating minerals. The estimated volume per cents of the minerals in the rock are Qtz~32%, Plg~25%, A-spar~10%, Bt~15%, Act~7%, Chl~3% and Hbl~8%.
3	M3	Sub-granular
4	M4	The principal mineral constituents are quartz~30%, plagioclase~25%, alkali feldspar (orthoclase +microcline)~10% and biotite~15%, with subordinate anderite garnet ~1%, hornblende~3%, actinolite~5%, Chlorite~5 and opaque minerals~6%. Plagioclase is partially altered to sericite

5	M1R	This sample represents medium to coarse grained rock and consists of plagioclase phenocrysts. Two types of garnet are recognized: the first group are deformed and are relict where the other group are low grade anderite garnet. The general modal composition (vol.%) of the minerals is estimated to be quartz~30%, plagioclase~25%, alkali feldspar (orthoclase +microcline)~9% and biotite~16%, with subordinate anderite garnet ~3%, hornblende~3%, actinolite~5%, Chlorite~4 and opaque minerals~5%.
Metagranite samples (after identification by field and petrographic investigations)		
6	M5	Medium to coarse grains of Qtz-30%, A-spar-30%, plg-7%, msc-15%, opaque-8%, hbl-6%, grt-1%, Bt-3% make the rock. Very rare biotite is also present. The grains have euhedral to anhedral shapes and some of their original characteristics have been modified. Muscovite is observed as primary mineral as well as alteration product in association with feldspars. The simple twinning in orthoclase is not as such visible: it simply patches. Some plagioclase exist with polysynthetic twins. Rare sericite with grt inside it exists and it is probably resulted from alteration of k-spar with presence of hydrothermal fluids. The plagioclase within the sample shows fracturing and inclusion of quartz within the cracked part.
7	M6	Medium to coarse grains of Qtz-31%, A-spar-29%, plg-7%, msc-12%, opaque-8%, hbl-6%, grt-1%, Prh-3%, Bt-3% make the rock.
8	M6R	Similar to the above samples this one is also constituted from medium to coarse grains of Qtz-33%, A-spar-31%, plg-8%, msc-11%, opaque-9%, hbl-6%, grt-2%, make the rock.
Metabasite samples		
9	M7	This sample represents a mafic rock with mineralogical make up of Pyroxenes (augite + clinopyroxene)~30%, Chlorite~11%, plagioclase~28%, quartz~5%, biotite~7%, Act~10%, Opq~7% and rare hornblende and olivine. The pyroxenes are of igneous origin and remained unchanged due to low grade metamorphism in the area. Hbl; shows visible simple twinning and occasionally lies between plagioclase crystals which show polysynthetic twinning. There are also number of opaque minerals with in the thin section. Most of the opaque minerals are anhedral with very rare euhedral minerals.
10	M8	Porphyritic texture with phenocrysts of plagioclase around which different minerals occur as groundmass. Some pyroxenes also exist as phenocrysts. Opaque minerals of smaller size than plagioclase and pyroxene also occur as phenocrysts. Generally the sample is constituted from plagioclase~29%, quartz~5%, biotite~5%, Act~10%, pyroxenes~28%, Chlorite~11%, Opq~8%, prh~4%.
11	M9	This sample is similar to samples M7 and M8 but, consists more quartz. In a similar fashion to these minerals, it consists of phenocrysts of plagioclases which make~75% of total phenocrysts. The mineralogy of the rock is generally plagioclase~30%, quartz~10%, biotite~6%, Act~10%, pyroxenes~20%, Chlorite~11%, Opq~9%, prh~4%.
Metadiorite samples		
12	M10	This sample represents a rock with crenulated foliation. Generally, the minerals have been elongated and lack the original shape (almost all the grains are anhedral). The volume per cent of the minerals is estimated as, plagioclase~36%, pyroxenes~13%, quartz~19%, amphiboles~8, biotite~5%, chlorite~5%, Act~7%, Ep~5%, Opq~2%.

		The presence of abundant quartz is an indication that protolith of this rock was quartz diorite.
13	M10R	Medium sized grains of plagioclase~36%, pyroxenes~10%, quartz~19%, amphiboles~5, biotite~6%, chlorite~6%, Act~8%, Ep~8%, Opq~2% constitute the rock. The crenulation of foliation in above sample is also observed.
14	B21A	The mineralogy of the rock includes both mafic and felsic minerals the mafic ones being the most dominants. (35%, pyroxenes~11%, quartz~14%, amphiboles~6, biotite~6%, chlorite~7%, Act~8%, Ep~8%, Opq~5%,). Most of the crystals are anhedral, and little crenulation is observed.

Appendix 4. ASI value of Kushmagane granitoids (ASI=$\frac{Al2O3}{Na2O+K2O+CaO}$)

	Oxides				
Sample	Al2O3	CaO	Na2O	K2O	ASI
WRCS-19	13.75	2.94	5.01	0.88	1.557191
WRCS-20	13.6	3.51	3.91	0.59	1.697878
WRCS-21	13.55	3.54	3.97	0.6	1.670777
WRCS-22	13.55	3.54	3.99	0.57	1.67284
WRCS-23	13.25	3.42	3.88	0.55	1.687898
WRCS-24	14.05	3.34	4.32	0.58	1.705097
WRCS-25	12.2	1.34	4.83	0.54	1.818182
WRCS-26	12.5	3.26	4.23	0.12	1.642576