

**ADDIS ABABA UNIVERSITY**

**SCHOOL OF GRADUATE STUDIES**

**COLLEGE OF NATURAL AND COMPUTATIONAL SCIENCES**

**SCHOOL OF EARTH SCIENCES**

*Addis Ababa  
University  
(Since 1950)*



**MSC THESIS ENTITLED ON: “DETERMINATION OF GENESIS OF OROGENIC GOLD AND SULFIDE PROSPECTS AT ASHASHIRE WESTERN ETHIOPIA”**

**A THESIS SUBMITTED TO:**

**THE SCHOOL OF GRADUATE STUDIES OF ADDIS ABABA UNIVERSITY IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN EARTH SCIENCES (MINERAL DEPOSIT).**

**By**

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Sep 2020

Addis Ababa, Ethiopia

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This is to certify that the thesis prepared by Sewagegn Yenesew, entitled: “Determination of Genesis of Orogenic Gold and sulfide prospects at Ashashire, Western Ethiopia.” and submitted in partial fulfillment of the requirements for the degree of Master of Science in Mineral Deposit complies with the regulations of the university and meets the accepted standards with respect to originality and quality.

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### DECLARATION

I, the undersigned, hereby declare that the thesis entitled with “Determination of Genesis of Orogenic Gold and Sulfide Prospects at Ashashire, Western Ethiopia.” is my original work carried out under the supervision of Dr. Worash Getaneh and Dr. Mulugeta Alene and has not presented to any university or institution for the award of any degree or diploma program and all sources of materials used for the thesis are duly acknowledged.

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This is to certify that the above declaration made by the candidate is correct to the best of our knowledge and it has been submitted for examination with our approval as university advisors.

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## Abstract

Orogenic gold also known as (“shear zone hosted”, “Mesothermal”, “greenstone-hosted quartz-carbonate vein” deposit). The Ashashire area is also orogenic gold prospect area and source of placer deposit that used as an income source for artisanal gold miners.

The study area is part of Proterozoic terrains that related to the East African Orogeny (EAO), a N–S elongated mega collisional structure stretching from Israel to Madagascar and found between West and East Gondwana. It is located in western Ethiopia in Benishangul Gumuz region at Kurmuk Woreda within the Western Greenstone belt of Precambrian volcano-sedimentary belt, near the Sudan border locally called Ashashire.

Gold is an important commodity of the world. Due to this exploration work in gold including its genesis made worldwide by many scholars and well developed in developed countries. But not well developed in developing countries including Ethiopia. Some reports and exploration works show that Ethiopia is endowed by precious metals including gold in different parts of the country. As a result, the main objective of this research work is to characterize the genesis of the gold and the associated sulfides. To accomplish this objective geological field observation and data analysis including 15 doubly polished and 3 thin section petrographic samples and 20 geochemical samples both for ore and host rock characterization has been conducted. The geochemistry held by fire assay and ICP-MS. The petrographic investigation involves characterization of host rock and ore body. The host rock is mainly composed of greenschist to amphibolite facies metamorphic minerals such as chlorite, carbonate, sericite, amphibole, epidote, and quartz; the ore petrography investigation shows pyrite, pyrrhotite, magnetite, sphalerite, chalcopyrite, galena and gold. The ore microscopic and geochemical analysis indicates that gold mineralization has got strong spatial association with alteration features, such as carbonitization, silicification, sulfidation and sericitization. The concentration of gold increases with sericitized, carbonitized silicified and sulfidized host rocks. The host rock geochemistry Zr vs TiO<sub>2</sub> shows that the tectonic setting lays within volcanic arc setting means that the formation of the deposit is related to subduction related activities. The ore geochemistry result shows the Ashashire area is target area for gold deposit ranges upto 10.3ppm that hosted in chlorite-sericite-carbonate schist in carbonate-quartz veins. The ore components possibly originated from dehydration, decarbonation and devolatilization of hydrated mafic rocks and carbonated rocks during prograde regional metamorphism and precipitates in retrograde conditions. The strong association of gold and carbonate-quartz vein with intense wallrock alteration indicates that gold is precipitated from hydrothermal solutions. The source of solution is still in debating, however the geological, petrographic and geochemistry result of the study indicates that hydrated mafic volcanic rocks and carbonated sedimentary rocks are possible sources.

*Key terms: orogenic gold, hydrothermal process, alteration, sulfide*

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(Sewagegn Yenesew)

## List of Acronyms

AAS: Atomic Absorption Spectrometry

ANS: Arabian Nubian Shield

BIF: Banded Iron Formation

EAO: East African Orogeny

EIGS: Ethiopian Institute of Geological Survey

EMDC: Ethiopian Mineral Development Corporation

GSR: Golden Star Resource

Ltd: Limited

ICP-MS: Inductively Coupled Plasma-Mass Spectrometry

MB: Mozambique Belt

MMAJ: Metal Mining Agency of Japan

PLC: Private Limited Company

UNDP: United Nation Development Program

UTM: Universal Transverse Mercator

TLM: Transmitted Light Microscope

RLM: Reflected Light Microscope

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## CHAPTER –I- INTRODUCTION

### 1.1. General background and Justification

The study area is found in western Ethiopia Benishangul Gumuz region Kurmuk Woreda locally called Ashashire. It is found within the Western Greenstone Belt, a Precambrian volcano-sedimentary belt, near the Sudan border. It is 10km far from Sudan border. The primary target deposit type in the study area is expected to be Orogenic gold (“shear zone hosted”, “Mesothermal”, “greenstone-hosted quartz-carbonate vein” deposit). The area is known and source of income for artisanal gold miners of local peoples.

The Proterozoic terrains in Ethiopia are related to the East African Orogeny (EAO) (Stern, 1994). EAO is a N–S elongated mega collisional structure stretching from Israel to Madagascar. It is found between West and East Gondwana.

There is no sufficient research conducted on gold and sulfide deposits in the western margin of Assosa including Ashashire. But numerous primary gold occurrences have been reported by different agencies and institutions. Among these Metal Mining Agency of Japan (MMAJ, 1974), EMRDC (1982), EIGS (1991), Golden star resources Ltd, (1997), Benzu gold mining Ltd (2013), and currently ASCOM Mining PLC is actively engaged. They have conducted geological, geochemical and structural analysis using stream sediment, trench and borehole samples on gold prospecting targets. The result of these work confirmed the presence of good grade of gold. However, they did not characterize the origin of the mineralization and paragenesis of the minerals. The study of genesis and paragenesis was historically a major step in the scientific understanding of mineral resources. Genesis study focuses on the ore forming processes while paragenesis refers to associations and co-occurrences of minerals in an ore deposit, which can be inferred to have grown or have been present contemporaneously (Ridely, 2013). As a result, the main objective of this research work is to fill the gap mentioned above.

### 1.2. Location and Accessibility of the study area

The study area is located at locality called Ashashire in Kurmuk Woreda Benishangul Gumuz Regional State, Western Ethiopia. It is about 800 km west of the capital, Addis Ababa and 86km from Assosa. It is found west of menghe, north of Assosa and southwest of Sherkole.

It is densely vegetated by small bushes, savanna grass lands, and incense trees, with remnants of tropical rainforests.

Access to the area is via the main paved road from Addis Ababa- Gimbi-Bambasi-Asosa-Kamashi then to Kurmuk or by flying from Addis Ababa to Assosa. There is one paved road that passes to Kurmuk town from Assosa through the Assosa-Komosha-Kurmuk then to Sudan.

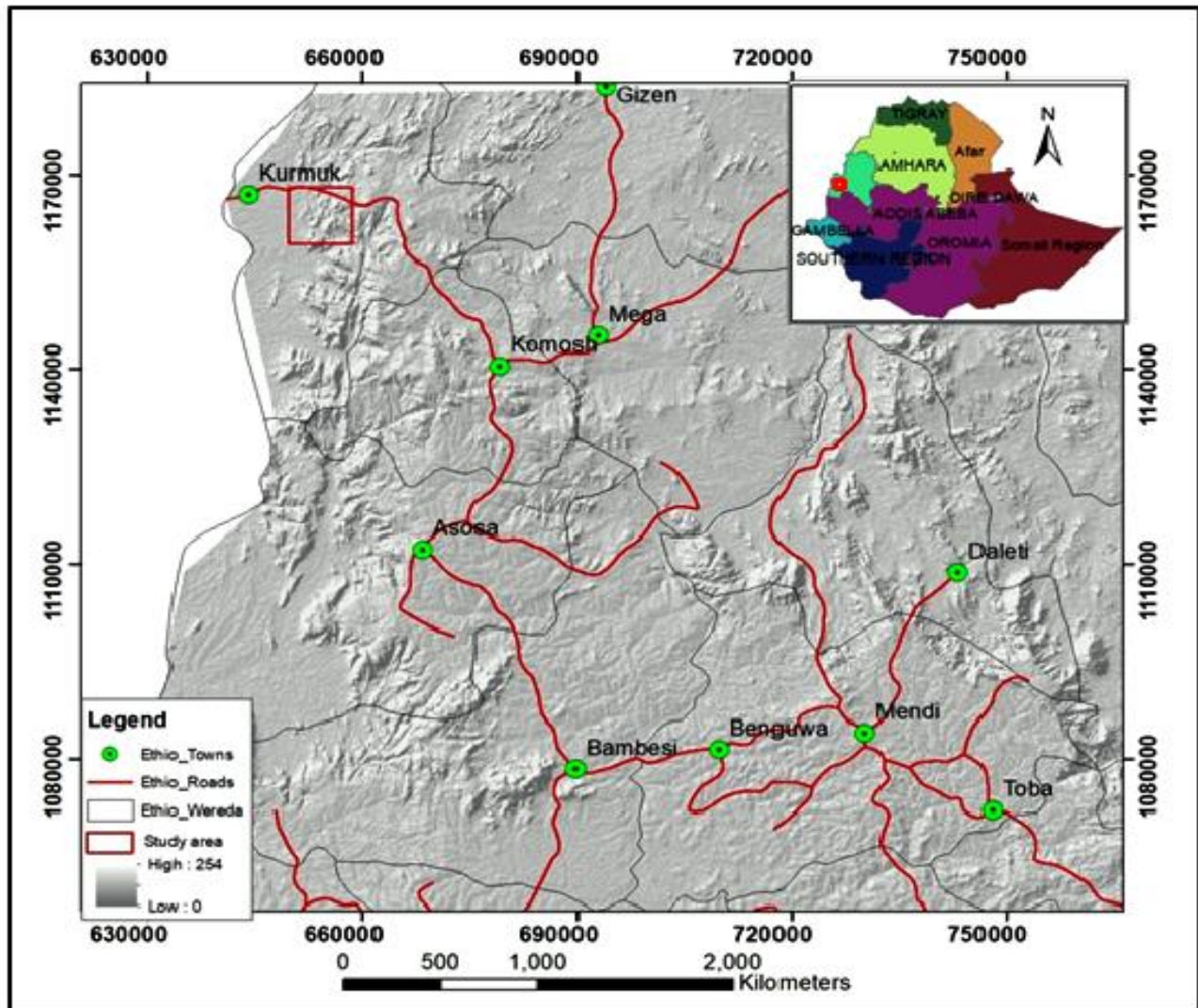


Figure 1.1 Location, Accessibility and Physiographic map of the study area

### 1.3. Physiography of Ashashire

Topographically the study area ranges from approximately ~700m to 1200m above sea level. The center of the Ashashire is situated at approximately Universal Transverse Mercator (UTM) zone (36N). The area is made up of steep slope to flat lands, rugged valleys and mountainous ridges.



*Figure 1.2 Physiography and panoramic view of Ashashire and surroundings*

#### **1.4. Climatic Conditions of the study area**

The region has got arid to semi-arid type of climate. The dry season ranges from end of October to mid-May with a maximum temperature ranging between 40°C to 45°C. The rainy season extends from mid of May to mid of October with maximum rainfall up to 240 mm and the temperature is mostly between 25°C to 37°C.

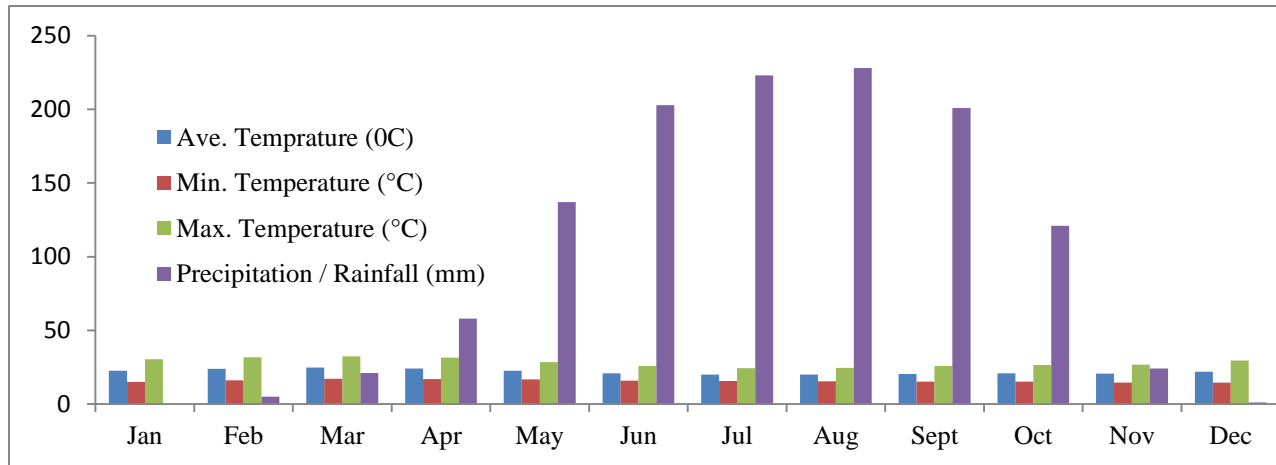


Figure 1.3. The Histogram showing the climatic condition of the study Area.

<https://en.climate-data.org/africa/ethiopia/benishangul-gumuz-1688/>

### 1.5. Previous Works

The Ashashire gold and sulfide mineralization is dominated by Precambrian metasediments and metavolcanics of greenschist facies as reported by (GSR, 1997 and GSE, 1995). These have been intruded by syn to post tectonic intrusives of basic to acidic composition and more recently by Cenozoic basaltic sheeted dykes and sills.

Western Ethiopia greenstone belts has been regionally mapped and evaluated by Fontana (1945).

Huntington Geology and Geophysical Ltd (1967), has conducted photo geological mapping exercise with United Nations Development Program (UNDP). EIGS-UNDP Joint mission also conducted airborne radiometric and magnetic surveys for mineral exploration (UNDP, 1972). The above mentioned scholars and institutions have undertaken stream sediment, soil, grab and pit sampling and regional mapping, diamond drilling to delineate and test the area of interest and mineral occurrences. The Metal Mining Agency of Japan (MMAJ, 1974) further conducted two phases of exploration between 1973 and 1974, to delineate the mineral occurrences and geology of the target areas and carried out a photo geological reconnaissance survey at scale of 1:50,000 to 1:60,000 and geochemical prospecting from stream sediment, pan concentrate, and soil sampling.

The reconnaissance survey incorporates Assosa-Kurmuk-Gizen; Mendi-Tobo and Gorrdana-Billa areas. This survey covered 10,000km<sup>2</sup>, out of which 8000km<sup>2</sup> is in Assosa-Kurmuk-Gizen area which includes the ASCOM mining PLC license area.

According to Ahmed M., 1982, of EIGS completed a program of stream sediment, soil and rock sampling, together with the re-interpretation of historical work between 1980 and 1982. This was

conducted to find areas of interest for follow up work include geological mapping, geophysics, soil, rock and drill core sampling. The EIGS conducted follow up work on their work from their earlier survey between 1982 and 1983, with regional surveys, including soil samples from a number of detailed 100m by 500m grids and rock samples taken from altered or mineralized outcrops to supplement the soil grids and delineate anomalies in Dul area including the Dul Mountain, Azale and Ashashire (Masresha J., 1984).

In 1994, the EIGS began the Dul Gold Exploration Project was undertaken geological mapping, geophysical exploration, 960m of trenching, 446m of pitting and 736.8m of diamond drilling for delineating, evaluating and developing the gold occurrence at Dul Mountain and similar occurrences within the surrounding area (Masresha J., et. al., 1995).

Golden Star Resources Limited Ethiopia Company (GSR) was granted an exclusive Exploration License for the Dul and Menghe license areas covering a total of 1800km<sup>2</sup> in 1995. During the 3 years that they explored these licenses, they drilled diamond drill holes at Dul Mountain, at Menghe Ridge at Azale, and 7 trenches at Ashashire (GSR, 1997). Surface results were not simulated by the drilling. Due to their repeated failure exploring historic targets, GSR undertook a stream sediment sampling program with the aim of defining new targets, during this campaign 4 new targets were outlined (GSR, 1997). Finally relinquished their exploration licenses in Ethiopia in 1998, due to the drastic downturn in gold prices.

Masresha (1999), studies the geological and geochemical conditions for the occurrence of gold in Mount Dul area which is south western extension of Ashashire prospect, shows gold is associated with, pyrite, chalcopyrite, pyrrhotite, scheelite, monazite, magnetite and siderite.

According to Aurigin report in (2015) the Ashashire Main mineralization is open-ended along the strike and down dip. The Company considers that the Ashashire prospect remains the best and the first priority target of the Western Ethiopia project at this stage after taking soil and core samples geochemical analysis taken from number of trenches and drill holes. But the above works not ascertain the genesis and paragenesis of Ashashire primary gold prospect area.

The main objective of the previous exploration work in the areas was to locate areas of interest that deserves further exploration to get an economic placer and primary gold deposit.

## 1.6. Statement of the Problem

Gold is the determinant commodity of the development of a nation and the world. It used in monetary system, and as jewelry. It also increases the relationship between countries in the market system. Due to this exploration work in gold made worldwide by many scholars and well developed in developed countries. But gold exploration is not well developed in developing countries including Ethiopia. Some reports and research works show that Ethiopia is endowed by precious metals including gold in different parts of the country such as in Southern Ethiopia (Ilegademi, Adola), Western Ethiopia (Tulu kapi, Dul) and Northern Ethiopia (Tigray region). However, gold and sulfide occurrences in Western Ethiopia including Ashashire are not well studied scientifically. But numerous primary gold and sulfide occurrences have been reported by Ethiopian mineral resource development committee (EMRDC, 1982), Golden star resources limited, (GSR, 1997), Metal Mining Agency of Japan (MMAJ, 1974), Geological Survey of Ethiopia (GSE, 1991, 1995) and Benu gold mining Ethiopia (BGME, 2013). These reports consists geological, geochemical, structural and geophysical data from the analysis of stream sediment, surface and borehole samples. The main objective of these previous exploration works in the areas was to locate areas of interest that deserves further exploration to get an economic placer and primary gold deposit and to estimate the reserve.

At the current time ASCOM Mining PLC is an actively engaged exploration company in Western Ethiopia at the Ethio-Sudanese boarder Kurmuk Woreda. This Mining PLC has been active in the present research area and they have begun to undergone geological, geochemical, geophysical, and borehole drilling in some of the prospecting areas in 2019. This campany play major role to accomplish this thesis. ASCOM precious metal mining PLC holds an exploration license covering an area of 801km<sup>2</sup> known as Assosa Concession including Ashashire.

Although western Ethiopia particularly Ashashire have been expected potential source of gold resource for future, no efficient studies held on specifically on the characterization of genesis and the paragenesis of the deposit. Previous data collected during exploration work are not systematically treated and interpreted for determination of the origin of the mineralization and paragenesis of minerals. Due to this they have not well defined the characteristics of the host rock, paragenesis and its mineralization. Thus, this research is intended to better understand the origin of ore minerals, establish paragenetic sequence of the ore mineralization based on textural

relationship, and define ore minerals and its host rock, using the geologic, petrographic and geochemical prospecting methods both in field and laboratory observations.

## **1.7. Objectives of the study**

### **1.7.1. General Objective**

The main objective of this research work is to characterize the genesis of the gold and associated sulfides in Ashashire prospect.

### **1.7.2. Specific Objectives**

This work has also its own specific objective which includes preparation of geological map of the study area at a scale of 1:20,000, investigation of the petrography of the ore body and its host rock, determining the paragenesis of the ore deposits and to explain the genesis of the deposit.

## **1.8. Methodology**

To accomplish the above mentioned objectives the following methods and activities are used and accomplished.

### **1.8.1. Literature Review and Secondary Data Collection**

To identify the research problem or gap and the study area deep literature review and data collection has being conducted. Previous data survey and collection including published and un published articles, reports, journals from Advisors, senior students, websites and institutions like Ethiopian institute of geological survey (EIGS) and Ascom Mining Ethiopia PLC. These data includes geological maps, geochemical assay results, lithological data, structural data, and mineralization concepts. Based on this regional geological map and base map has prepared. In addition to this determination on accessibility related to security, analytical methods and instruments, physiography, finance and other costs needed for finalization of the research work has been conducted.

To manipulate and interpret the data softwares has been identified and exercises with these softwares like ArcGIS and ERDAS Image visualizations for map preparation, petrograph, grapher, GCD kit and strater for variation diagram plots and log plots have been identified.

### **1.8.2. Field observation and primary data collection**

The main activity of field observation is field data collection. These data are primary and secondary (from historic bore holes). Among these: taking and recording GPS points of the prospect for mapping of the study area, sectional interpretation and logging of four selected boreholes, petrological description and documentation, geological observations on the alteration type and mineralization style, measuring and recording geological structures, collection of representative core and outcrop samples from both the host rock and mineralized zones for petrographic and geochemical analysis. These samples are taken from well described and logged bore holes and surface outcrops.

### **1.8.3. Sample preparation and Data Analysis**

This work mainly starts from field sample preparation, result reception and result documentation and interpretation. This involves a desktop and laboratory work done after finishing the field work to perform petrographic data analysis using petrographic and ore microscopy, geochemical analysis using ICP-MS for whole rock geochemistry including major, trace and REE element analysis and fire assay for ore geochemistry mainly for Au concentration determination and final documentation, interpretation and presentation. Both petrographic and geochemical samples were collected and prepared from four potential boreholes and sent to Australian laboratory service (ALS). Literature review exists until presentation.

#### **1.8.3.1. Petrographic sample preparation and analysis**

The selected and collected representative core samples were sent to Australian Laboratory Service (ALS) in Australia through Ethiopian ministry of mining for the preparation of 15 doubly polished thin sections. Three thin section samples were prepared from surface exposures in geological survey of Ethiopia. The petrographic investigation held in ore microscopy laboratory, Addis Ababa University and petrographic laboratory in Bahir Dar University.

The prepared doubly polished and thin sections have been analyzed using transmitted and reflected light petrographic and ore microscope respectively. This done to characterize the petrology of the host rock and ore mineralogy, the alteration type and intensity, the paragenesis of the mineralization, the style of mineralization, the structures preserved in the section and its relation with mineralization and determinations of gangue minerals.

### **1.8.3.2. Geochemical data analysis**

Twenty representative selected bulk samples from both the host rock and the mineralized veins were collected from the logged bore holes. These representative samples have been sent to Australia for laboratory analysis of major, trace and rare earth elements after drying, crushing, splitting and pulverizing in Addis Ababa ALS branch. Ore body also has been sampled and analyzed by fire assay AAS (Au-AA25) with detection limit of 0.01-100ppm and whole rock geochemistry for major, trace, and rare earth element analysis via ICP-MS (ME-MS81d) and base metals have been analyzed through ICP-MS (ME-MS81). This laboratory work has been done to characterize the source rock and host rock of gold, its environment of formation and associations with precious and base metals.

### **1.8.4. Documentation, Interpretation and presentation of the result**

This is the final stage done after conducting field and laboratory work. The stage involves compiling and processing of the data's obtained from field work and laboratory analysis to accomplish the proposed objective and finally to prepare a document and to produce a geological map. Processing and interpretation of data using softwares and Microsoft offices such as Arc GIS, Petrograph, GCD Ket, Strater, Grapher, Microsoft word, Microsoft excel and Power point.

### **1.9. Materials used**

The geological and other tools that has been used include: Topographic base map at the scale of 1:50,000, satellite images landsat8, geological field kits such as GPS, burton compass, geological hammer, hand lens (20X), polythene plastics bags, etc.

Computation facilities used are computers, required softwares, printing facilities and other computer peripherals. Some of them are laptop, hard disk and flash to store and manage data, geological and geochemical softwares to process and interpret the result. Such softwares are ArcGIS, Goggle Earth Pro, Surfer, rose diagram, GCD Ket, Grapher, strater, Petrograph and Global mapper.

#### **1.10. Beneficiaries of the research out come**

The beneficiates from the result of this research outcome include:

ASCOM Mining PLC and those companies whom practices Gold and sulfide deposit Exploration and Mining uses as a guide for identifying additional prospective areas of gold mineralization, the Academic Communities that interested in Gold and sulfide deposits studies, researchers and Individuals who committed to Gold and sulfides studies, finally, the researcher himself will get logical concepts, deep knowledge through reviewing field investigation and data processing.

## CHAPTER-II- REGIONAL GEOLOGICAL SETTING

### 2.1. INTRODUCTION

The geology of Ethiopia is characterized by Precambrian metamorphic complexes to Quaternary sediments. These include Precambrian metamorphic rocks with their associated syn to post tectonic intrusives, Paleozoic-Mesozoic marine and continental sediments, pre rift to post rift basic to felsic volcanic rocks and undifferentiated Quaternary sediments.

The Precambrian geology of Ethiopia consists of variety of sedimentary, volcanic and intrusive rocks and linear but discontinuous mafic ultramafic rocks which are subjected to low to high degree of metamorphism and deformation.

The formation of the Precambrian basement rocks of Ethiopia is directly or indirectly related to the Arabian Nubian Shield (ANS) in Northern Ethiopia and the Mozambique Belt (MB) in Southern, South Western Ethiopia both of which are related to the development of the East African Orogeny (EAO) (Stern, 1994).

The western Precambrian basement of Ethiopia lies in the western cratonic portion of EAO and it is a transition between the southern portion of East African Orogenic belt (Mozambique belt) and the Arabian Nubian Shield (Stern, 1994).

### 2.2. East African Orogeny (EAO)

The Proterozoic terrains in Ethiopia are related to the East African Orogeny (EAO) (Stern, 1994), a N-S extended mega collisional structure stretching from Israel to Madagascar and produced between West and East Gondwana by the closure of the Mozambique ocean (Fig. 3). It comprises an oceanic domains and crustal materials between the Archean Sahara-Congo-Kalahari Cratons in the west and Neoproterozoic India in the east.

The Mozambique belt includes Precambrian rocks of Southern Kenya, Southern Ethiopia, Eastern Ethiopia, Northern Somalia, and Western Ethiopia to lesser extent Northern Ethiopia (Kazmin et al., 1978, Taddesse Alemu and Tsegaye Abebe, 2007).

EAO consists of deformed and metamorphosed rocks of the ANS in the north and higher grade and more strongly deformed rocks of East Africa and Madagascar in the south.

### 2.1.1. The Mozambique Belt

The Mozambique Belt is the southern extension of the East African Orogen and is a roughly N-S oriented structural zone that formed by the collision of East and West Gondwana (Tenczer *et al.*, 2005). As his explanation 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 and the tectonics related to this event resulted in the formation of thrust propagating onto different Cratons (Tenczer *et al.*, 2005). 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.

According to Braathen *et al.*, 2001; Kazmin *et al.*, 1978; and Tadesse Alemu and Tsegaye Abebe, 2007 the Western Ethiopian shield is part of North-eastern Mozambique Belt.

### 2.1.2. Arabian Nubian Shield (ANS)

The Arabian–Nubian Shield is a juvenile crust (Hargrove *et al.* 2006; Liegeois & Stern, 2010) which was formed during the collision between East and West Gondwana. The Arabian–Nubian Shield ranges from southern Palestine over western Arabia, eastern Egypt and eastern Sudan into Eritrea and Ethiopia.

The Arabian–Nubian Shield is composed of typically low-grade greenschist facies rocks that originated from metasedimentary and metavolcanic rocks that derived from oceanic island-arc volcanism (Stern, 2002; 2008; Stern & Johnson, 2010).

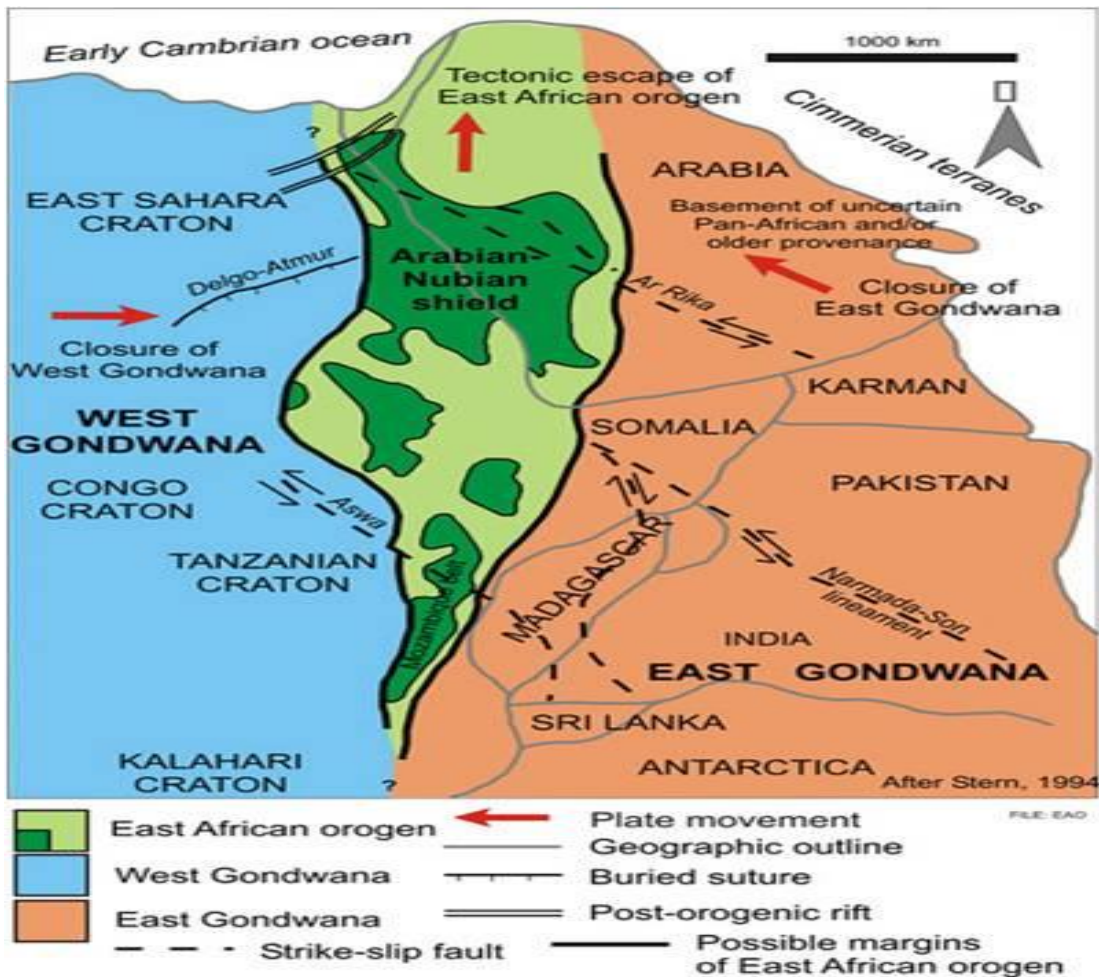


Figure 2. 1. Map of the East African orogeny showing the location of the Arabian-Nubian Shield relative to the Mozambique Belt and adjacent cratonic margins(after Stern, 1994).

## 2.2. The Precambrian geology of Ethiopia

Ethiopia has a varied and multifaceted geological history. The most important geologic terrain for gold prospecting is the Proterozoic crystalline basement which covers about 18% of the country and which hosts nearly all of the known gold occurrences (MoME, 2007).

According to Kazmin (1971), Ethiopian basement rocks are divided into three complexes as Lower, Middle and Upper Complexes and aged as Archean, Upper and Lower Proterozoic respectively by correlating with similar basement rocks of east and north east Africa. Later the basement rocks of Ethiopia were divided into two major blocks (Ayalew et al., 1990; Teklay et al., 1998) as: 1) High grade gneissic and migmatitic terrain exposed in southern and south western Ethiopia (consists of the older lower and middle complex rocks) and this is correlated with the Mozambique Belt (MB), and 2) The younger low grade volcano-sedimentary terrain part of upper

complex rocks which are exposed in northern Ethiopia, younger in age and it is correlated with the Arabian Nubian Shield (ANS). Metavolcanic-metasedimentary sequences exist further to the western Ethiopia near the Sudanese border (Tefera, 1991).

Ethiopian basement rock is composed of two major blocks, in addition to, pre-, syn- and post-tectonic granitoids (Asrat et al., 2001).

These intrusive rocks in Western Ethiopia are grouped according to the degree of deformation and the contact relations with the country rocks as: Pre- to syn kinematics, and late to post kinematics (Ayalew T and Peccerillo, 1998). Based on these scholars Pre-kinematic plutons accounts (830–780 Ma) and volcano-sedimentary units were affected by regional deformation and low-grade metamorphism with E–W shortening event, designated as *D1* by Abraham (1989), resulted in a pervasive, axial plane-parallel foliation, striking NNE-SSW. A later, localized *D2* sinistral-transcurrent phase extended to amphibolite facies in narrow, separate shear zones. The younger age of tectonism is indicated by the 570–540 Ma age of late- to post-kinematic plutons (Ayalew et al., 1990).

The precambrian rocks of Ethiopia are exposed in eastern, western, northern, and southern parts of the country (Asrat et al., 2001) (fig 2.2.).

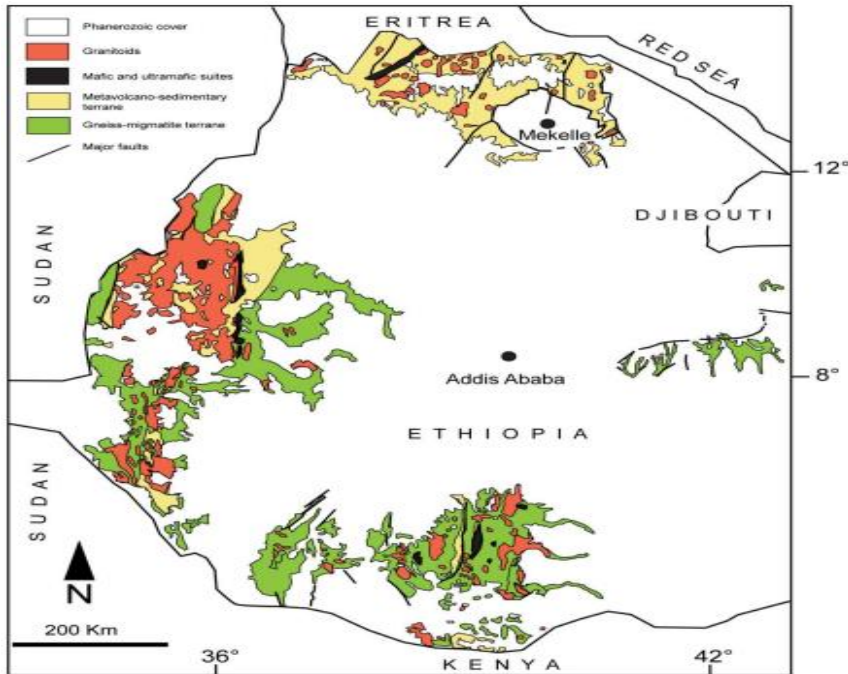


Figure 2. 2. Distribution of the low-grade volcano-sedimentary sequences of the ANS and high-grade gneisses and migmatites of the Mozambique Belt in Ethiopia adopted from (Solomon G., 2009) (modified from Asrat et al., 2001).

### 2.2.1. Geology and Tectonic setting of Western Ethiopia greenstone belts

Precambrian rocks of Western Ethiopia can be broadly subdivided into two contrasting groups, namely the high-grade gneissic terrain and the low-grade volcano-sedimentary terrain. The lithologic boundary between the terrains is tectonic, as marked by ultramylonitic rocks (Abraham, 1989). The high-grade terrain lies west (along the Sudanese border) and the low-grade belt to the east (Kazmin et al., 1979). Granitoid intrusions are also part of the terrains that together form Western Ethiopia's Greenstone Belt (Tsfaye et al., 1999).

The Western Ethiopian greenstone belt has tectonically evolved through different processes beginning early rifting and associated sedimentation followed by subduction and island arc formation, arc-accretion and, finally, continent-continent collision (Kazmin et al., 1979).

The Precambrian geology of Western Ethiopia is part of N–S trending Barka–Tulu dimtu belt which covers a variety of meta-sedimentary and metavolcanic sequences, ultramafic rocks and synkinematic intrusive complexes (Braathen et al., 2001).

### 2.2.1.1. Tulu Dimtu Shear Belt

The Tulu Dimtu Shear Belt is a 200 km wide N–S trending zone in western most Ethiopia near to the Sudanese border. It consists of a volcano-sedimentary sequences lined by higher-grade gneisses, and comprises a 20–30 km thick rocks of ophiolitic affinity (Allen and Tadesse, 2003). The Barka-Tulu Dimtu regional shear zones have interpreted as ophiolite associated sutures, representing the major boundaries that separate arc terrains accreted during amalgamation of eastern and western Gondwana (Stern, 1994; Tadesse & Allen, 2004, 2005).

In the Western Ethiopia shield Tulu Dimtu shear belt is divided into five tectonic domains from east to west are Didesa, Kemashi, Dengi, Sherkole and Daka domains (fig 2.3) (Allen and Tadesse, 2003).

**Didesa Domain:** is found in the eastern part of Tulu Dimtu shear belt covered with polydeformed and metamorphosed gneisses intruded by deformed gabbroic and granitoid bodies and post-kinematic mafic and felsic plutons.

**Kemashi Domain:** is found in the central part of the shear belt that experienced with low-grade metasedimentary and ultramafic-mafic metavolcanic rocks intruded by deformed and undeformed ultramafic-mafic and intermediate plutons.

**Dengi Domain:** is also the central portion of the shear belt covered by low-grade metasedimentary rocks, mafic to felsic metavolcanic rocks and moderate grade gneisses intruded by deformed and undeformed gabbroic to granitoid bodies.

**Sirkole Domain:** is enclosed with alternating sequences of polydeformed and metamorphosed gneisses and low- to moderate-grade metasedimentary rocks and mafic to felsic metavolcanic rocks. In addition it is intruded by deformed and undeformed granitoid plutons. Ashashire exploration area is involved with in this domain.

**Daka Domain:** is the other domain of Tulu Dimtu shear belt at western end part that covered with moderate to high grade polydeformed gneisses, intruded by syn-kinematic granitoids.

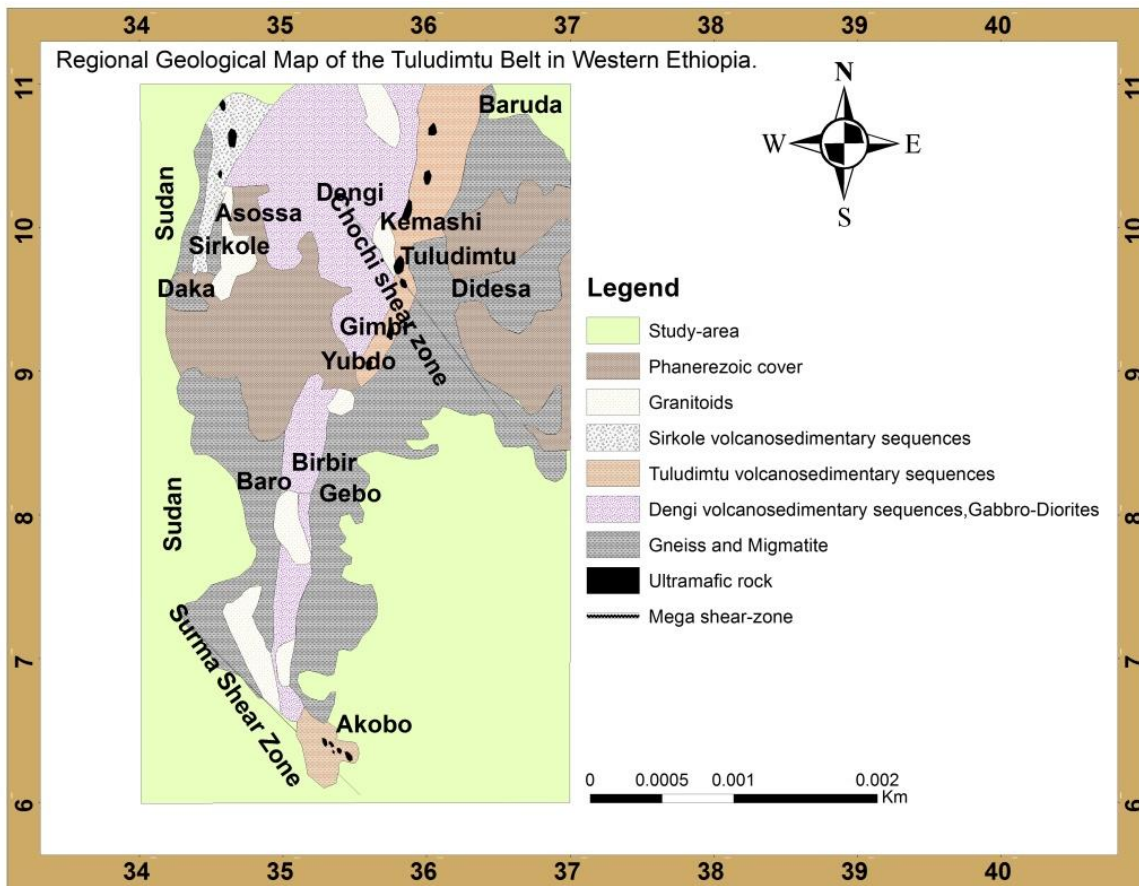


Figure 2. 3. Western Ethiopia Tulu Dimtu shear belt map modified from (Allen and Tadesse, 2003)

## CHAPTER-III-GEOLOGY AND TECTONICS OF GOLD MINERALIZATION

### 3.1. INTRODUCTION

Gold has become a main strategic commodity as petroleum in the ancient and in the present time all over the world. The exploration and study of gold deposit formation has long been examined. It is expected that 75% of world gold commodity is recovered from orogenic gold deposits (Phillips, 2013). Shear hosted gold deposits (Bohlke, 1982) dominantly associated in Precambrian rocks in the mid- to shallow crust (5–15 km depth), at or above the brittle-ductile transition, in compressional settings that facilitate transfer of hot gold-bearing fluids from deeper levels through deep setting thrust faults (Goldfarb et al., 2005; Groves et al., 1998; Phillips and Powell, 2009). Most fertile metamorphic fluids are released over ~500–550 °C, with little fluid released beyond ~550 °C (Tomkins, 2010). These restrictions are consistent with observations that most orogenic gold deposits occur in greenschist to lower amphibolite facies rocks (Groves, 1993).

The formation of vein-type to disseminate or shear hosted gold deposits, broadly categorized under orogenic gold deposits. For 1<sup>st</sup> time the term “orogenic” given and used by (Groves et al., 1998), since these deposits expected to form in accretionary and collisional regions.

Primary Au deposits occurs as Porphyry and associated with high-sulfidation Au-Cu-Ag deposits (Seedorff et al., 2005), classic low-sulfidation Au-Ag deposits (Simmons et al., 2005), low-sulfidation Au deposits hosted on alkalic intrusive complexes (Sillitoe, 2002), Carlin type Au deposits (Cline et al., 2005), Au-rich volcanic hosted massive sulphide deposits (VMS) (Franklin et al., 2005), orogenic Au deposits (Goldfarb et al., 2005), intrusion related Au deposits (Lang et al., 2000) and iron oxide Cu-Au deposits (IOCG) (Williams et al., 2005; Groves et al., 2010).

Orogenic Au deposits are extensive to abundant in parts of most Archaean cratons. The Golden Mile at Kalgoorlie in the Yilgarn Craton of Western Australia (Clout et al., 1990), the Hollinger-McIntyre (Burrows et al., 1993) and Sigma deposit in the Superior Province of Canada (Robert and Brown, 1986), and deposits of the Barberton greenstone belt, South Africa (de Ronde et al., 1992) is some of the larger and best-known examples.

### 3.2. Mineralization and Alterations

The majority of gold and sulfide deposits of the Earth's crust are produced by fluxes of hot aqueous hydrothermal fluids that are efficiently focused within somewhat small volumes of rock (Garofalo and Ridely, 2014). Intrusion-related gold deposits are also a sub-type of orogenic gold mineralization which typically occur within, or adjacent to, intermediate - acidic igneous intrusions (MoME, 2007).

Orogenic gold deposits are also known as Mesothermal gold, gold only, Archean gold, Homestake gold, volcanogenic gold, low sulphide gold quartz veins, Mother lode veins, shear hosted gold associated in space and time with collisional tectonic regimes (Grove., 1998). These deposits are characterized by aqueous complexes with: low salinity, low amounts of  $\text{CH}_2$  and  $\text{N}_2$ , high  $\text{H}_2\text{O}$  and  $\text{CO}_2$  content, near neutral pH, and temperature ranging from 250-350<sup>0</sup>C and pressure between 1 and 3 kbar (Groves et al. 2000).

The dominant alteration minerals in orogenic gold hosted in metamorphosed rocks include: carbonate-sulphide +/- Sericite +/- Chlorite and the elements are Au, Ag, As, Sb, Hg, W, Mo, Te, and B, in different combinations (Pirajno, 2009).

Eventhough the genesis and paragenesis study of ore minerals is the major task in mineral exploration work. The origin of shear hosted or vein-type to disseminated gold deposits, broadly classified as orogenic gold deposits (Groves et al., 1998; Goldfarb et al., 2005) has been remained controversial. The formation processes for orogenic deposits were evaluated in a recent review by Goldfarb and Groves (2015). In recent studies much has been focused on the origin of gold enriched fluids. The majority of evidence favors a metamorphic dehydration and decarbonation source, either from fluids released during metamorphism of sequences deeper in the gold-hosting basins and oceanic rock sequences (Goldfarb and Groves, 2015) or from de-volatilization of the sediment section above a down going subduction slab (Grove et al., 1998; Groves and Santosh, 2015).

The Precambrian geology is taken as an in important source of Orogenic gold and base metal globally (Groves, 2003). The mineralization is mainly associated with, pyrite, chalcopyrite, pyrrhotite, scheelite, monazite, magnetite and siderites (Masresha Bekele, 1999). Most probably orogenic gold deposit hosted in green schist facies terrains is organized by regionally metamorphosed mafic to felsic metavolcanic rocks, komatiites, and volcanoclastic sediments with

some banded iron formation (BIF) of Algoma type and can be hosted by felsic plutonic rocks and locally by porphyries (Worash Getaneh and Solomon Tadesse, 2015).

Most recent experimental data on Au aqueous complexes show that complexes are AuOH, AuCl<sub>2</sub>, AuHS and Au(HS)<sub>2</sub> involving different sulfur forms, chloride and alkali metals. These complexes are stable in high temperature, sulfur-rich fluids, vapors and melts can be used to compute Au solubility up to 600 °C and 300 MPa (Pokrovski *et al.*, 2014). These are effective conditions to increase the solubility of Au and may precipitate from these fluids as a result of variation of fluid densities/pressure. The sulfur- and chlorine-bearing fluid would have been able to scavenge metals, and possibly transport to different weaken zones of the crust. Sulfur ligands control the leaching and extraction of Au and base metals from the host rocks. As explained by (Yardley and Cleverley, 2013) the history of releasing reactive metamorphic fluid in metamorphic rocks can be identified into three distinct types of fluid regime. These are during initial prograde metamorphism, fluid is pervasively released by reactions into the grain boundary network and further fluid loss may arise during porosity reduction. These ore fluids have the ability to transport of Au and are also enhanced by the relatively high levels of H<sub>2</sub>S, whereas their ability to transport base metals is limited by the low concentration of chloride. It is primarily the phase relationships in CO<sub>2</sub>-H<sub>2</sub>O-NaCl-H<sub>2</sub>S fluids that lead to gold precipitation and the sources of such fluids may be metamorphic or igneous (Yardley and Cleverley, 2013).

As explained by (Sibson *et al.*, 1988) all orogenic gold ore bodies show strong structural control, often associated with the reverse component of shear hosted in variable green schist facies rocks from volcanic to intrusion and sediments. A metamorphic setting is characterized by brittle, brittle-ductile, and ductile deformation of higher P-T regimes and dominated by ductile deformation (amphibolite facies); brittle-ductile deformation in mid-upper greenschist facies, and lower P-T regime dominated by brittle deformation in lower greenschist facies.

The formation of huge orogenic gold deposit is triggered by thermal effect of mantle (asthenospheric) thermal input and, more significantly, crustal devolatilisation and melting has been recognized as a key driving force (Goldfarb *et al.*, 2001). The presences of mafic, ultramafic intrusive rocks and lamprophyre dykes guide in the associations of ore formation and mantle processes (Rock and Groves, 1988).

### 3.3. Tectonic Setting of Gold Deposits

Different deposit types that formed in significantly different settings at different times, can be put beside closely with, or even directly overprint each other. On the other hand, quite different deposit types may form synchronously but spatially separated within the same broad orogen. Convergent plate boundaries are characterized by various ranges of gold- and base metal deposits (John M. et al., 2012). Thus, the genesis of a major convergent boundary gold deposit of any type can be considered as the combination of three major elements: a fertile upper-mantle source region, a transient remobilization event that extracts gold-enriched magmas and/or fluids from this source region, and favorable lithosphere-scale architecture that allows the focused flux of these magmas/fluids. The enrichment process relates to the addition of gold-enriched, low degree partial melts of asthenospheric mantle to the overlying lithospheric mantle. There may be a very large (>1 Ga) time gap between the enrichment process and the process that extracts those fluids to the upper crust (Grove et al. 2008).

Shear-zone hosted, Mesothermal lode-gold deposits are a major source of world gold production (Woodall, 1988). These gold deposits are most known and their occurrences are related to shear zone-hosted veins within the Neoproterozoic volcano-sedimentary succession of greenschist to amphibolite facies metamorphic rocks as amphibolites, carbonaceous quartz-feldspar-biotite schist, graphitic quartzite, meta-sandstone and conglomerate and the associated basic- ultrabasic intrusions, common in other greenstone belts of different ages (Tadesse et al., 2003).

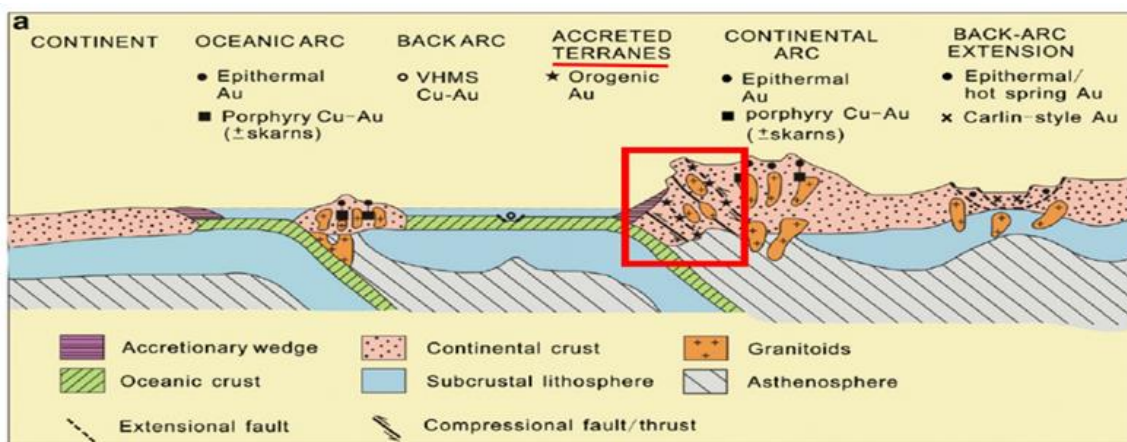


Figure 3. 1. The Mesothermal /orogenic gold deposits in deformed accretionary belts adjacent to continental magmatic arcs (After Grove et al., 1998).

## CHAPTER-IV- GEOLOGY OF THE STUDY AREA

### 4.1. INTRODUCTION

Ashashire area is mainly covered by Arabian Nubian Shield rocks which are regionally metamorphosed to low grade Metavolcano-sedimentary sequences and intruded by felsic to mafic plutonic complexes. These sequences consist of highly to moderately weathered, fractured, altered, crenulated, faulted and metamorphosed units. The overall metamorphic condition of the area is greenschist facies but locally reaches to amphibolite facies. The Ashashire area is specifically covered by metavolcanic to meta-volcaniclastic, metasediment and syn to post orogenic felsic to mafic intrusive rocks. A metavolcanic rock involves amphibolites, green schists (sericite-mica schists, chlorite schist), and ultramafic rocks such as serpentinite, talc schists, and hornblendites. Metasedimentary units also include slate-phyllites, variety of schists, cherts, psammitic rocks, and calcite-quartz veins. The intrusives are felsic to mafic in composition but commonly consists of sheared and chemically weathered (granite).

These low to medium grade metamorphosed rocks has NE-SW trends with local variations and generally shows East-dipping. Abundant quartz veins, chlorite and calcite veins with variable dimension are observed on the out crop as well as core logs levels.

The study area is highly affected by local to regional strike slip faults, shear foliations, micro to macro folds, veins and fractures.

The primary rocks are covered with overburdens of highly to moderately weathered, red coloured (saprolite to saprock) with an average approximate 2.5 meter thickness as observed from the borehole, trenches and outcrops at river cut and road cut exposures. The observed lithologic units are described as follows:

### 4.2. Metasedimentary Rock Units (chlorite-muscovite-carbonate schist)

The metasedimentary rocks in the study are given as a group name for sedimentary origin metamorphic rocks. The metamorphosed sedimentary unit covers dominant portion of the study area mainly in the central and eastern part from Ascom main exploration area (Fig 4.12). These units are slate-phyllite, cherts and variety of schists, such as mica schists, chlorite-muscovite-carbonate schists, carbonate-quartz and chlorite schists. The slate-phyllite unit exposed variably mainly at the eastern portion which is west of the granite unit. This unit shows dull to shiny

appearance, flaky and fissile nature and commonly foliated.

The metasedimentary rock units are highly affected by weathering, nearly N-S foliation and various structures. The quartz vein, granitic dyke and foliation are the common structure in this unit. These rock units have variable thickness throughout the depth of the boreholes and variable extensions on outcrop level. Mostly on average they have a thickness of approximately 20m in borehole and 1km on outcrop level. Metasediment unit is composed of moderately to highly weathered, altered, crenulated, banded and sheared rocks. It breaks easily into thin layers. It experiences variety of alterations such as sulfidation, muscovitization, carbonitization (dolomitization and calcitization) and chloritization. It is difficult to differentiate the two carbonate alterations on visual inspection. But calcite easily fizzes using diluted acid while dolomite only fizzes using strong acid.

The metasedimentary rock units generally have light white to greenish colored with banding and shiny appearance. These rocks are mainly characterized by foliation in mm to cm scale. It is fine grained to coarse grained, generally shows smooth surface to touch.



Figure 4. 1. metasedimentary rock units a) banded silicified sediment (chert) taken from borehole, which is carbonitized and quartz veined sediment b)vertically jointed, crenulated and foliated slate-phyllite sediment c) highly foliated slate-phyllite on road cut exposure d) massive and jointed carbonitized schist

The petrographic investigation shows that the metasedimentary rock unit is dominantly composed of foliated greenschist minerals such as micas, chlorite, quartz and carbonate minerals. From petrographic observation of mica schist in fig 4.2c (TS02) the following minerals were identified and visual estimation is conducted in volume percentage (vol %) as muscovite 45%, chlorite 7%, quartz 20%, amphibole 5%, calcite up to 10%, plagioclase 5% and opaque minerals 7%. Chert dominantly composed of quartz. The microscopic investigation of quartz-carbonate schist consists modally calcite 40%, quartz 25-30%, chlorite 15-20%, sericite 10-15% sometimes up to 30% (TS06), opaque 5-20% and epidote <5%. Carbonate-quartz schist which is composed of 30% carbonate, 40% quartz, 15% chlorite, 5% muscovite, and 6% opaque minerals (TS11).

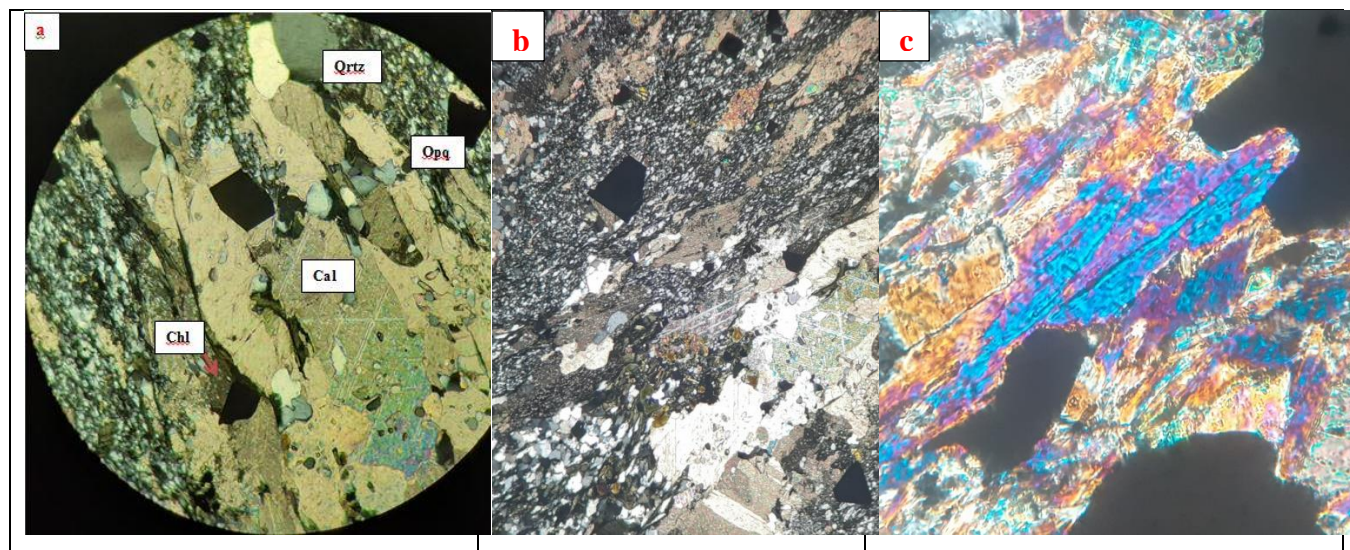


Figure 4. 2. Petrographic view of foliated metasedimentary rock samples a, b) quartz-carbonate schist, c) mica schist (10X).

### 4.3 Metavolcanic rocks

The metamorphosed volcanic rock ranges in composition from ultramafic to mafic. These metamorphosed mafic and ultramafic rocks are metamorphosed to variety of schists. These include muscovite-epidote-chlorite schist, chlorite schist, serpentine-talc schist and talc-chlorite schist. Preferentially the metavolcanics are susceptible to magnet and shows moderately to highly weathered and covers east, western and somewhat central part of the Ashashire Ascom exploration area (fig 4.12). Generally these rocks have fine-to medium-grained texture. They are chiefly

composed of serpentine, sericite, talc, plagioclase, chlorite, carbonate, epidote and quartz signifying that they are metamorphic products of ultramafic to intermediate volcanic rocks.

The outcrop and borehole sample of metamorphosed volcanic rocks shows dark to greenish color. Mostly the rock is moderately to highly sheared, weathered, foliated and deformed. It has various thicknesses dominantly range from a thickness of 5m to 50m from logged borehole throughout the depth and have up to 2 km in outcrop level. This rock unit is characterized by both affric to porphyritic texture. It experiences low to highly brecciation, shearing, weathering and veining. It is massive to foliated and lineated rock. The vein preserved in this rock widens up to 1m thickness. This rock is also moderately to highly affected by variety of alteration chloritization, carbonitization and epidotization in addition to silicification proximal to quartz vein and veinlet. It also shows sercitization, pyritization and sulfide oxidation as minor.

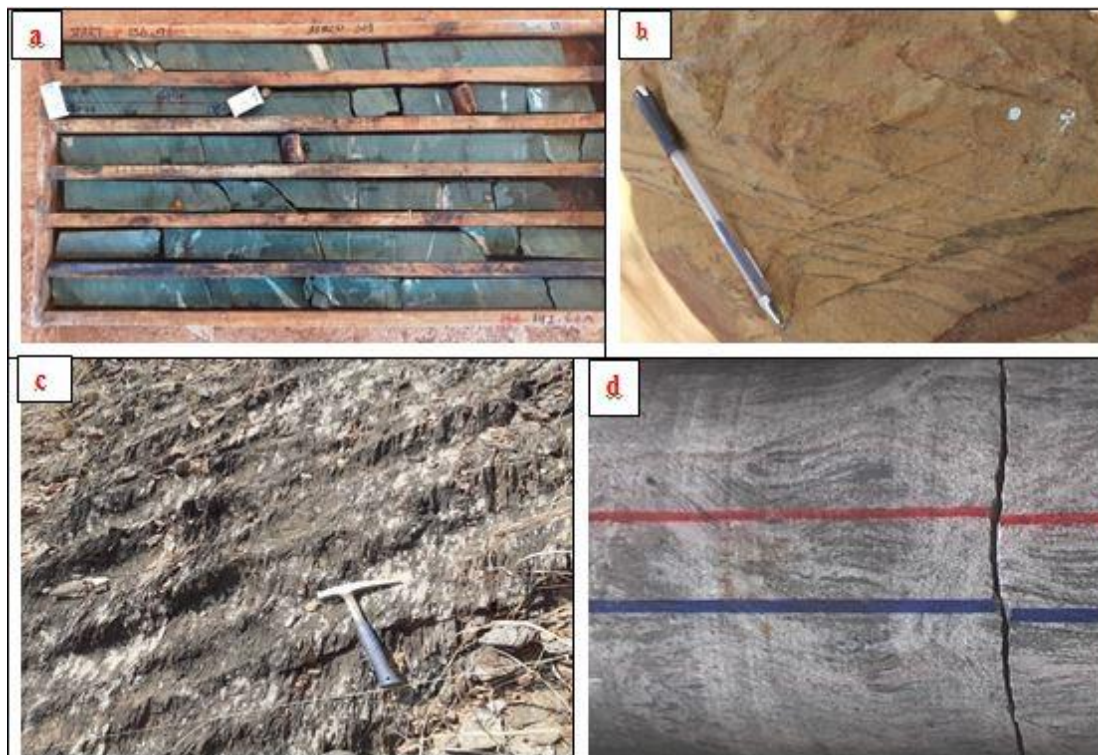


Figure 4. 3. Metavolcanic rocks a) chloritized, sulfidized and carbonitized mafic schist b) epidotized, carbonitized, oxidized and weathered metavolcanic rocks c) sinistral sheared and crenulated chlorite-talc schist d) anastomosing chlorite lineation

To investigate the petrographic properties of the host rock six doubly polished and one thin section were prepared. These are TS01, TS03, TS04, TS05, TS08, TS10, TS12 and PS1. The microscopic

investigation of this rock consists sericite 30-40%, calcite 20-25%, quartz 5-7%, opaque 5-15%, amphibole 10-20% and chlorite 15-30%. PS1 fully composed of talc-serpentine minerals.

The petrographic investigation of sericite-amphibole-chlorite schist consists on average 35% chlorite, 15% amphibole, 5% carbonate, 3% epidote, 10% sericite, 15% quartz and 10-15% opaque minerals (TS03, TS10 and TS12). PS1 which is taken from surface sample composed of 80% serpentine, 15% talc and 3% opaque minerals.

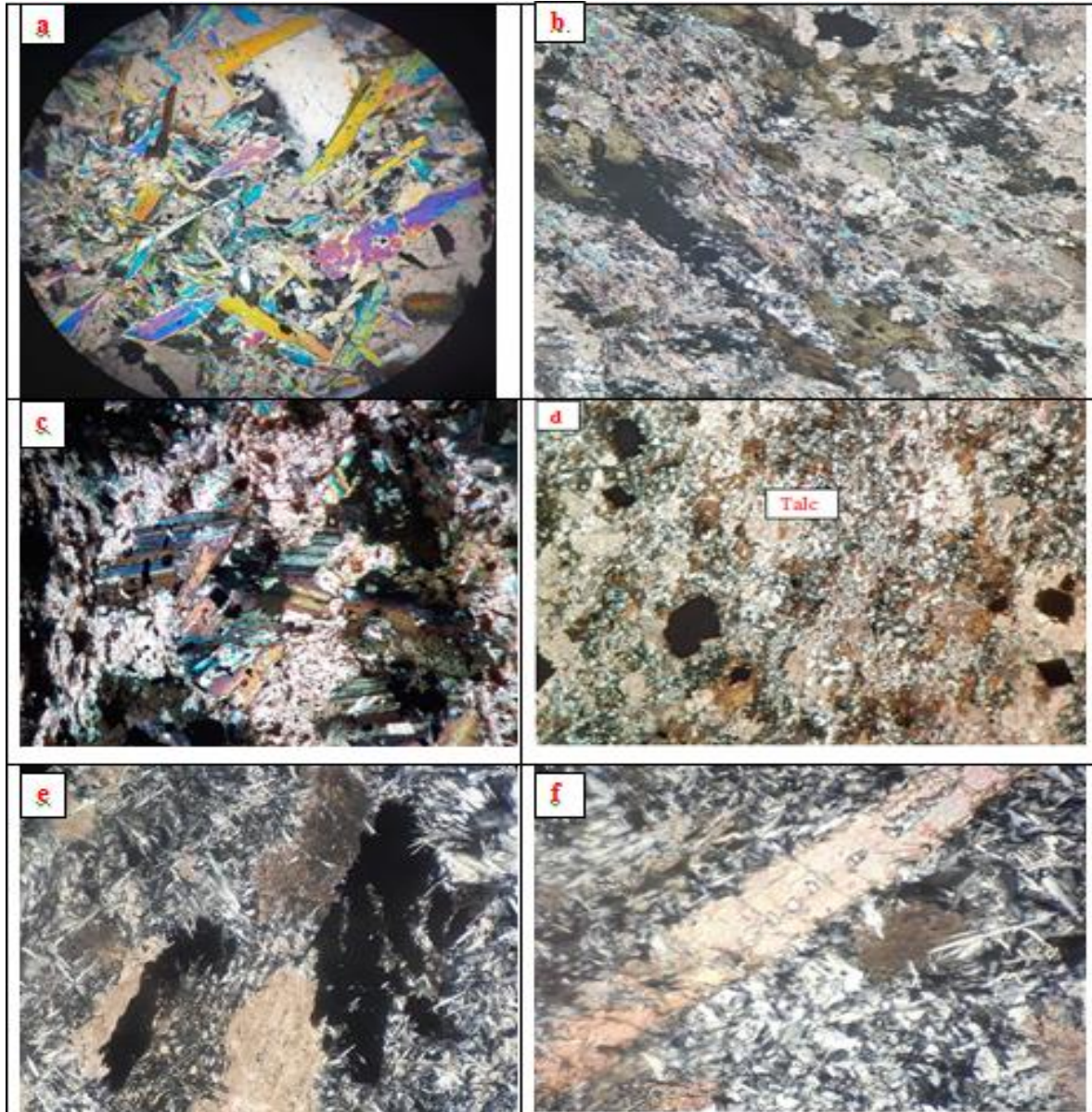


Figure 4. 4. Microscope view of metavolcanics rocks a) carbonate-amphibole schist b)chlorite schist c)chlorite-plagioclase schist (plagioclase phenocrysts), d) talc schist, e and f ) Serpentine-talc schist (4X)

#### 4.4. Chemical Sedimentary rock (Silicified rock)

It is fine grained, hard, massive, and red to light colored rock. Chert shows clastic texture, white strips and somewhat crystalline. Eventhough there is variously colored cherts the field observation confirms the presence of reddish coloured variety. But there is also blackish colored in core sample as seen in (fig 4.5 a, b). This rock shows conchoidal fracture with smooth surface and has sharp broken edges. The silicified rock is crosscut by the intrusions variously. The laboratory result shows that it is mostly composed of quartz no petrographic sample has been taken.

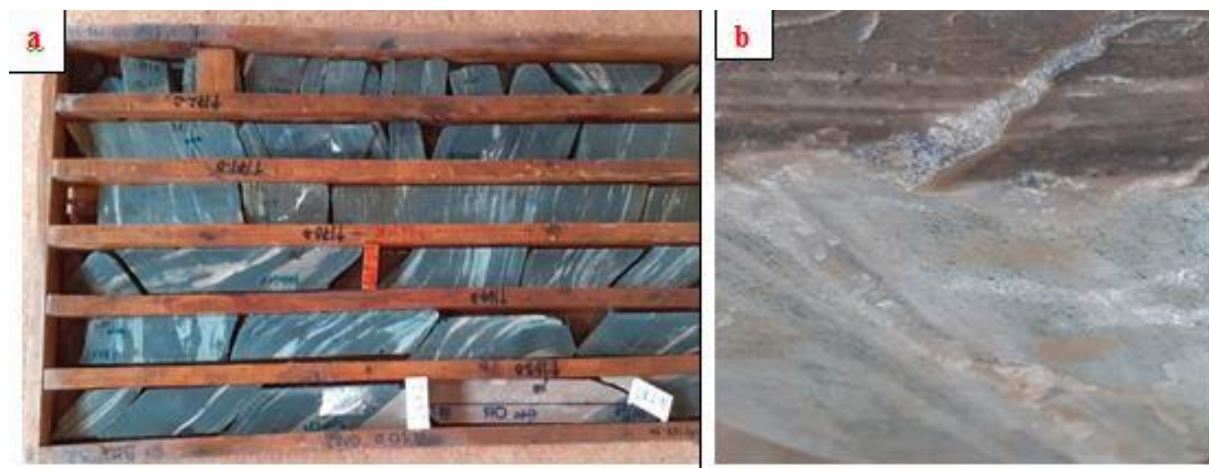


Figure 4. 5. Different variety of chemical sedimentary rocks (cherts) a) chert with white strips and granite intruded from borehole ASRCD009 and b) chert from outcrop at southern part of Ashashire Ascom exploration area but not mappable.

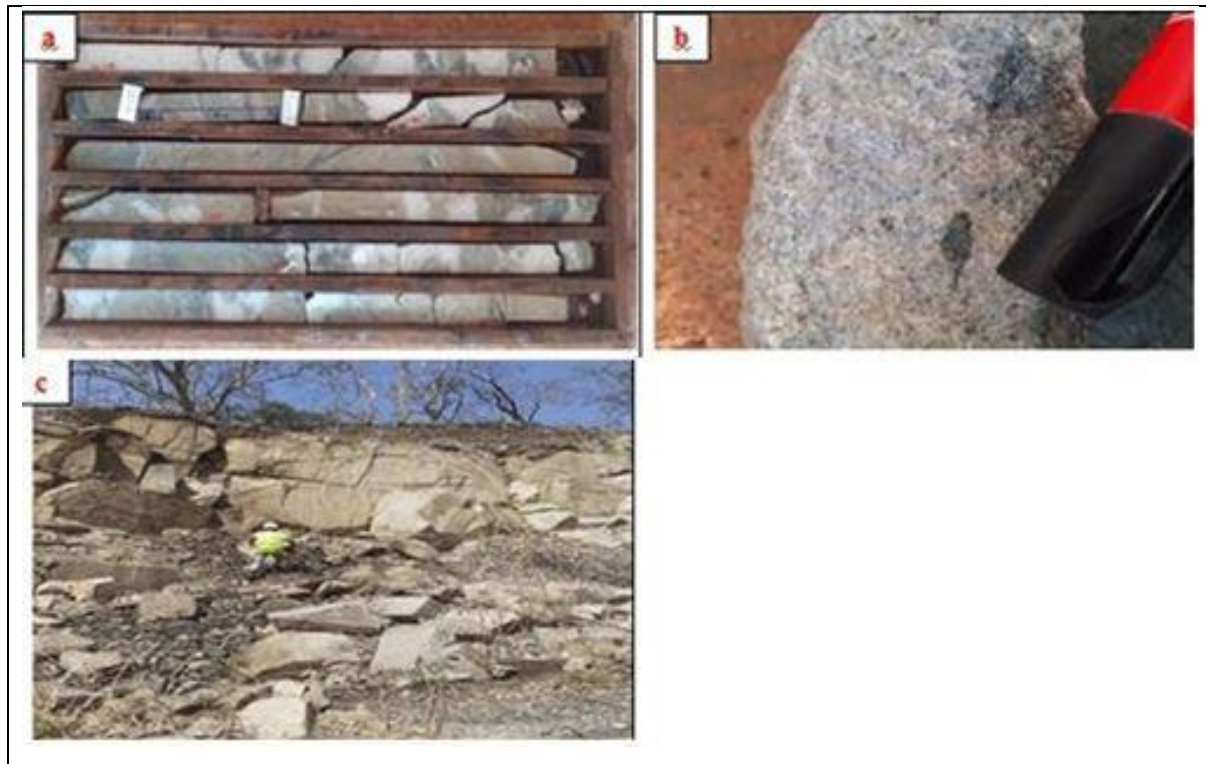
#### 4.5. Intrusion

Most observed intrusive rock is granite and rare mafic intrusives. The granitoid exposed in the western and eastern part of the study area. It also occurs in central part as dykes and intercalation with metasediments. The granite variety frequently shows shearing, consist mafic clasts and highly weathered and changed to kaolinite. It varies from felsic to mafic in composition. It is medium to very coarse grained, pinkish to light colored. The observed intrusion rock is enriched and made up of quartz, k-feldspars, biotite and muscovite. Large phenocrysts of pinkish K-feldspar are mainly observed throughout the rock and color of the rock dominantly taken up again the color of the K-feldspar minerals. The granite intrusion with a variable thickness intrudes almost all rock units. This intrusion shows no shearing, slightly to highly shearing as surrounding host rocks infers that it

is synkinematic (contemporaneous) or shearing effect comes later than host rock formation. It is intruded in various schist rocks such as meta-mafic volcanics and meta-sediments and intercalated with a number of quartz veins.

It is mainly composed of euhedral to subhedral and coarse-grained K-feldspar; subhedral to anhedral, coarse- to medium grained quartz; euhedral, coarse-grained plagioclase, subhedral biotite and less amount of sericite.

Fine-grained granite dikes/sills are light coloured or whitish in color. They attain apparent thicknesses up to 5 m in drill holes. These bodies are usually suffered to intense hydrothermal alteration than the coarse-grained granite rocks. Locally, trace disseminated pyrite have been observed.



*Figure 4. 6. Intrusive bodies a) sheared and veined granite intrusive intruded and intercalated with mafic schist and carbonitized schist taken from borehole ASDD010 b) granite to intermediate intrusive rock with mafic clasts c) jointed and somewhat massive granite intrusive on road cut*

Three samples were taken for petrographic characterization of host rock. Thin section observation of granite consists of 30% sericite (muscovite), 35% quartz, 10% carbonate, 20% plagioclase and 5% opaque fig 4.7 (TS06, PS2, PS3) which is sericite-quartz schist. The petrography of this rock

contains calcite 10%, biotite 5%, quartz 30%, muscovite 25%, altered feldspar (sericite) 26% and opaque minerals 3%.

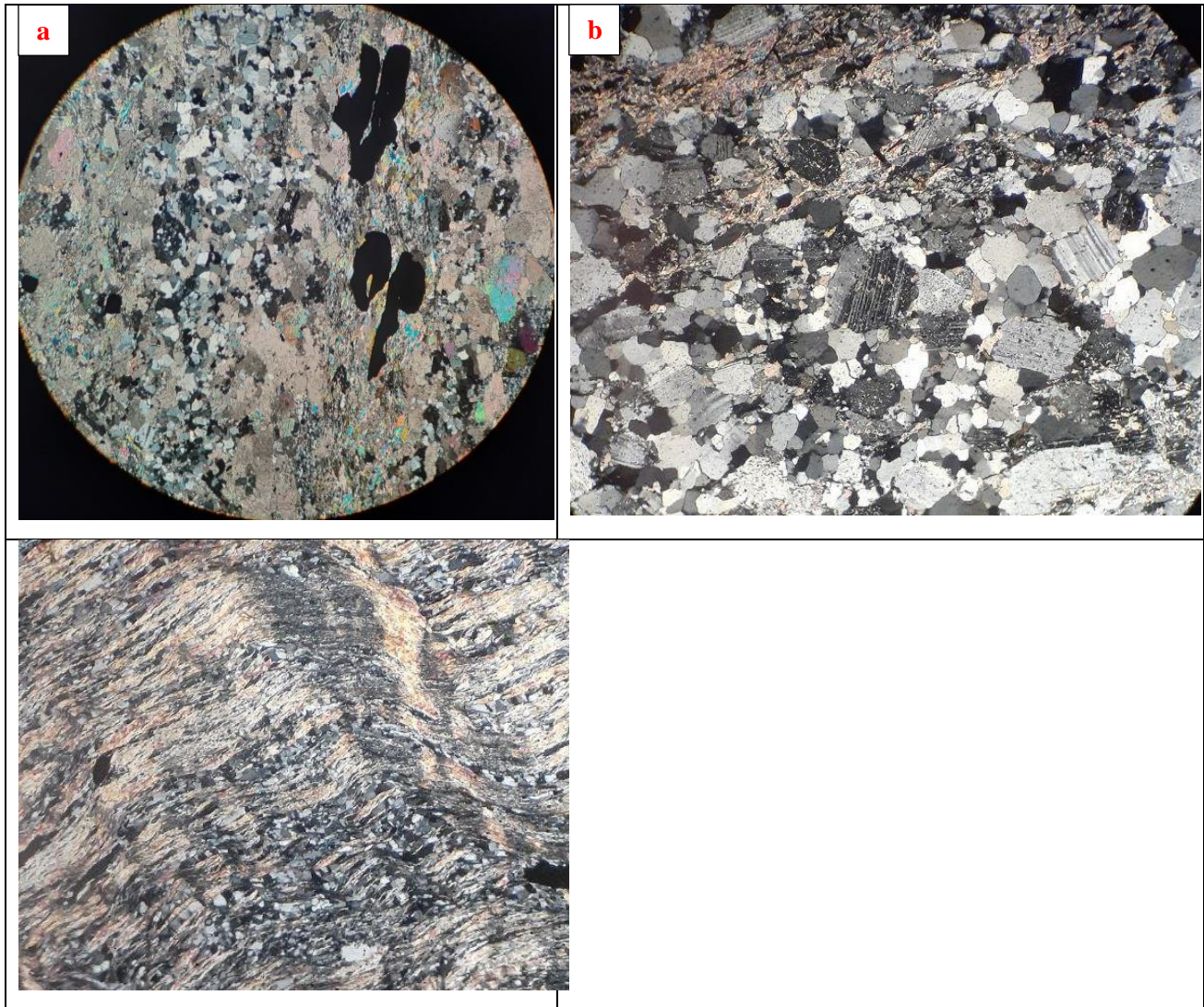
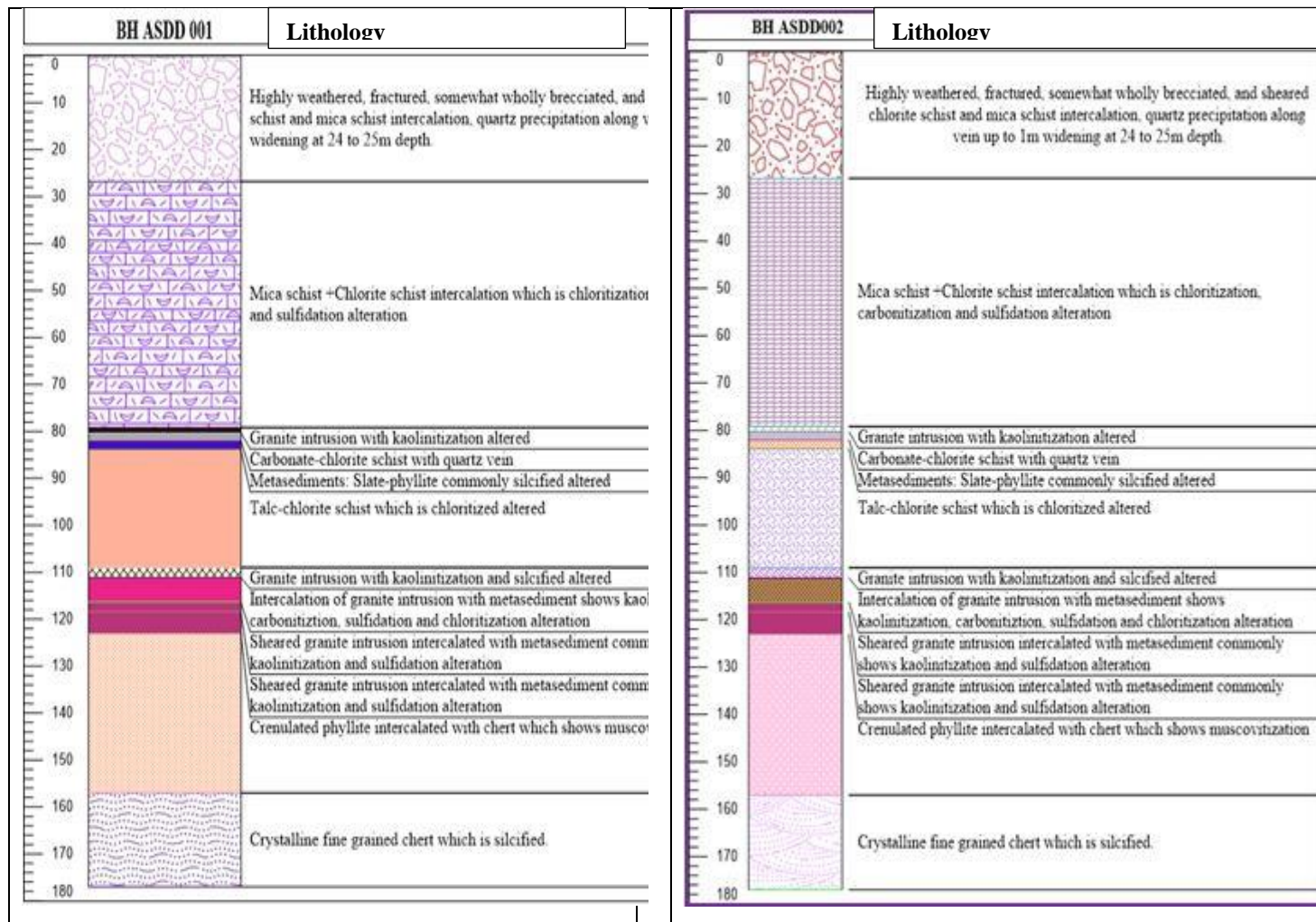


Figure 4. 7. Petrography of intrusive bodies a, c) sheared and foliated granite intrusive b) mafic intrusive



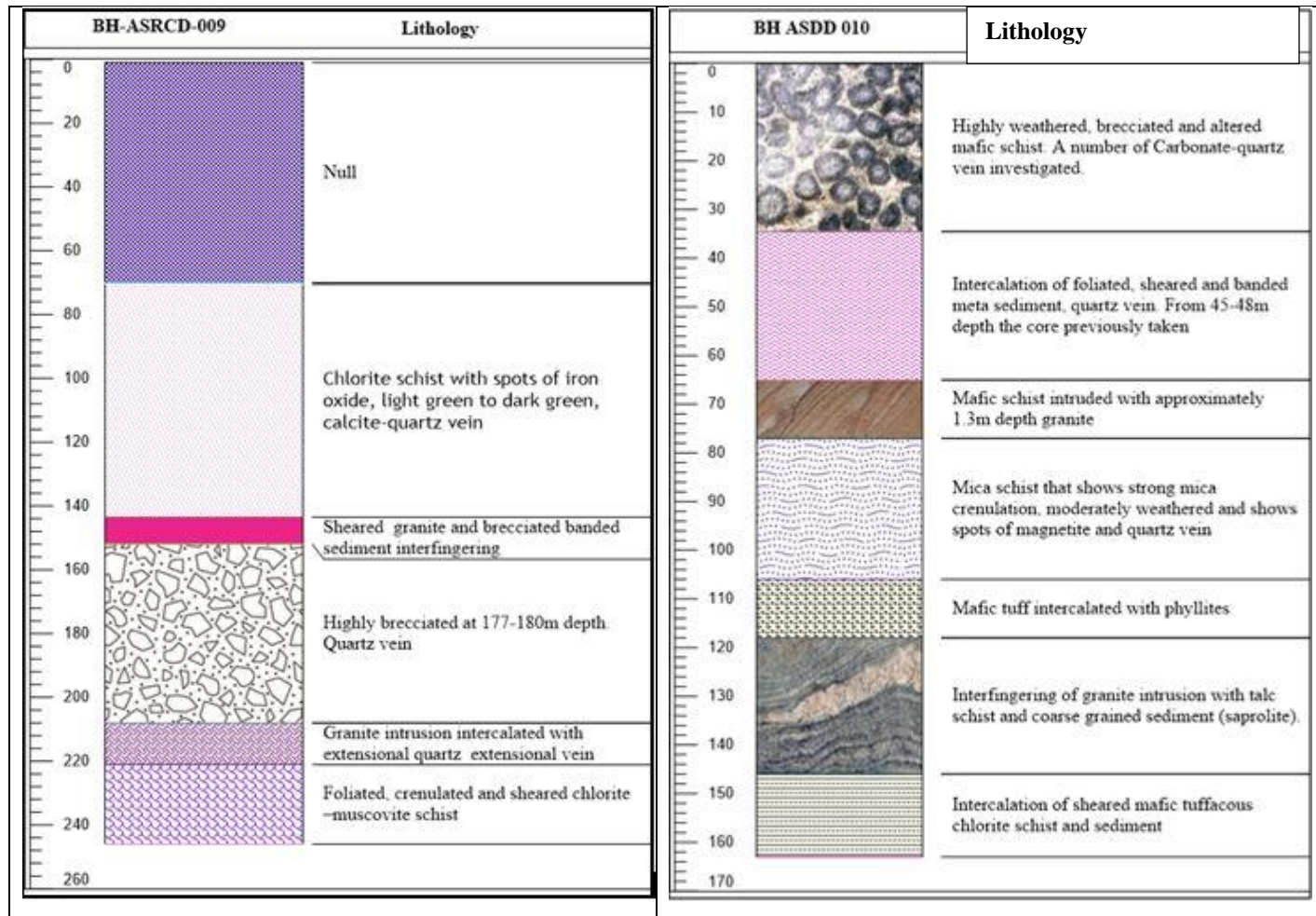


Figure 4. 8. The four selected boreholes description

#### 4.6. Metamorphism and Deformation

The presence of mineralogical and textural change in the study area shows the occurrence of metamorphism. The index minerals that are observed from field investigation are epidote, calcite, albite, chlorite and amphiboles. This shows that the area is affected by Low to medium grade of metamorphism. These phenomena are supported by features preserved in rocks such as alteration due to pressure and/or heat exchange, and changing their appearance entirely as described in section 5.3.

According to view of Ascom exploration geologist, field observation and regional tectonics multiple stage of deformation has happened in the study area. Among these firstly there was E-W Gondwana collision that caused arrangement of host rocks nearly striking N-S parallel to foliation,

Secondly there was granite intrusion following the weakest zone, 3<sup>rd</sup> NNE-SSW sinistral shearing, thrusting and continental scale movement, 4<sup>th</sup> late stage E-W post mineralization faulting, veining and faulting.

According to (Amenti A., 1989), based on his proposed strike slip model defines four phase of deformation (D1-D4) in the western Ethiopia including Dul which is south western extension of Ashashire. D1- is the first phase of deformation that caused NNE trending foliations and affected all low grade greenstone belt rocks. D2- is the second phase deformation which produced steeply plunging s-folds resulted from N-S trending sinistral movements of Sudan and Ethiopia gneissic blocks followed by younger volcanics and sedimentations. D3- is the third event that affected younger volcanics and sediments into low grade metamorphism and folding. D4- is the last stage deformation causing the formation of steeply plunging z-folds which resulted from dextral movements of gneissic continental blocks.

Generally, multiple phases of deformation are recorded in the Western Greenstone Belt including Ashashire. The regional strike of the foliations ranges from NW-SE to N-S and NE-NW. The principal direction of foliation in the region is NE-SW (Benzu Gold Mining, 2013).

#### **4.7. Structural Geology of Ashashire**

The overall trends of rock units is nearly N-S to NNE-SSW that described in rose diagram (fig 4.9) below and dipping mostly towards the east and sometimes to west on the western part of Ashashire. The area is affected by numerous phases of deformations as described in section 4.2 and dominated by low grade green schist facies rocks.

Based on detailed observations of drill cores and fields exposures of road cuttings, stream cuttings and trenches a number of geological structures are investigated. The investigation shows that both ductile and brittle tectonic structures are coexisting in Ashashire. The observed ductile structures include foliations, cleavages, lineations and folds. Besides this, brittle structures include joints, faults, quartz-carbonate veins, chlorite-calcite veins and small brittle ductile shear zones were observed in different parts of the study area with different scale and intensity. These structures are distributed from micro-scale to macro-scale or microscopic to transcrustal level. Furthermore, these structures show different structural styles and morphology. Among these (1) brecciation; (2) stock working and vein sets; (3) laminated veins in shear zones; and (4) predominantly ductile sheared

zones. Such features help to correlated with Yilgarn gold fields of Australia as (Grove et al., 1992).

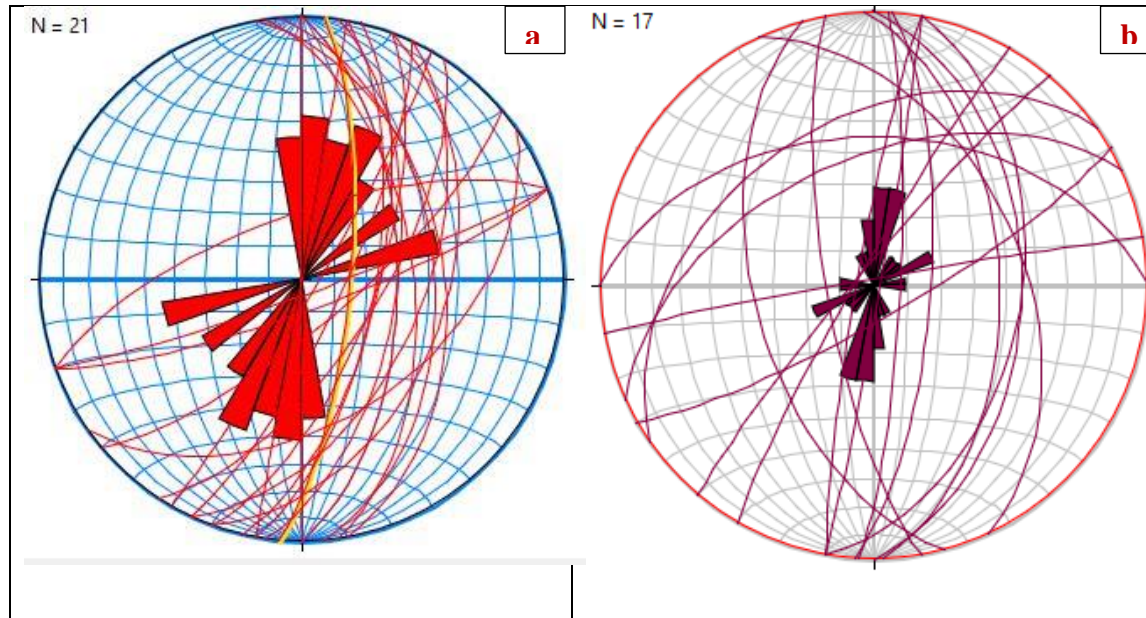


Figure 4. 9. Rose diagram and stereo plot diagrams showing the overall structural conditions that generally striking NNE-SSW to NE-SW. a) foliation orientation b) joint orientation

#### 4.3.1. Foliations

**Foliation:** Ashashire shows variety of deformed morphological characteristics. Among these foliation is a common widely distributed planar fabric with secondary stage that is preserved in almost all rock units except some undeformed intrusives. The geology of Ashashire is mainly affected by well-developed penetrative foliations. The foliations mostly strike  $N50^{\circ}E$  to  $230^{\circ}$  with dip amount 20 to  $60^{\circ}$  E. The preserved foliation is identified by the parallel alignment of micaceous minerals and affects pervasively the metasedimentary rock units including chlorite and mica schists (fig 4.3c).

Foliation at Ashashire is typically defined by platy mineral parallel arrangements mainly chlorite, muscovite or flattened actinolite-tremolite and quartz grains. Foliations in mafic schists (chlorite schist) mainly shows spatial variations in mineral composition and grain size by preferred orientation of elongate and platy mineral grains and aggregates (fig.4.3d ). In some cases it shows lensoid and anastomosing layering. Foliation is a more general term that encompasses cleavage and schistosity.

**Cleavage:** a foliation formed by parallel planes of platy minerals with preferred splitting direction such as mica. Most commonly it is preserved in low-grade micaceous (pelitic) rocks such as slate-phyllites on north eastern portion of the study area. The cleavage can be very planar with somewhat smooth surface. Crenulation cleavage is a common and special kind of cleavage observed in micaceous rocks formed as a result of shortening at a low angle to a pre-existing cleavage. It can be observed micro to macro scale as overprinting on earlier foliation (fig 4.3c).

#### 4.3.2. Shear Zones

Ashashire is located within Tulu Dimtu shear belt in Sherkole Domain which is Western margin of Ethiopia in Western greenstone belt. Locally there are two shear zones that are found East and West part of the Ashashire main exploration area. Both shear zones show intense shearing but varies by their extensions. In these shear zones the metavolcanic rocks become more brecciated while the metasediments become crenulated and folded. The eastern shear zone is estimated to reach up to 80m and the western shear zone has approximately 70m thickness. These shear zones are identified in relation to the surrounding rocks. Both have variable thickness and commonly characterized by boudinage and mylonite structures. Mylonitized rocks are intercalated with closely spaced secondary filling quartz veins. This is representation of brittle-ductile deformation style. In addition to this, boudinage structures are also preserved (fig 4.10h).

Ashashire prospect is mainly affected by extensional and shortening sinistral and dextral shear structures. The extensional structures trap mineralization while the shortening shear zones are barren. The mineralized quartz veins are expected to be a result of extensional shearing.

#### 4.3.3. Quartz Veins

There are a number of quartz veins. Most of them are dextral extensional shearing effect but there are also left lateral shortening shears are observed (fig 4.10a and b). It strikes nearly N-S and 20-60° NE and sometimes become near horizontal. Generally show smoky to white color and east dipping. The smoky quartz veins are fertile relative to white quartz vein. There are two types of quartz vein primary which is parallel to foliation and secondary which are crosscuts the foliations. The secondary crosscut quartz veins are productive sites of mineralization.

#### 4.3.4. Joints

The geology of Ashashire area is also highly affected by mainly two set of joints that are orthogonal to each other. These joints have generally N-S and nearly E-W trends as discussed in (fig 4.10d).

#### 4.3.5. Dykes

The felsic dykes crosscut almost all geologic unit of Ashashire. But in most cases the carbonitized schist and mafic schists are the main hosts. Compositionally the dykes have granitic and are highly weathered and changed to white colored sediment probably kaolinite.

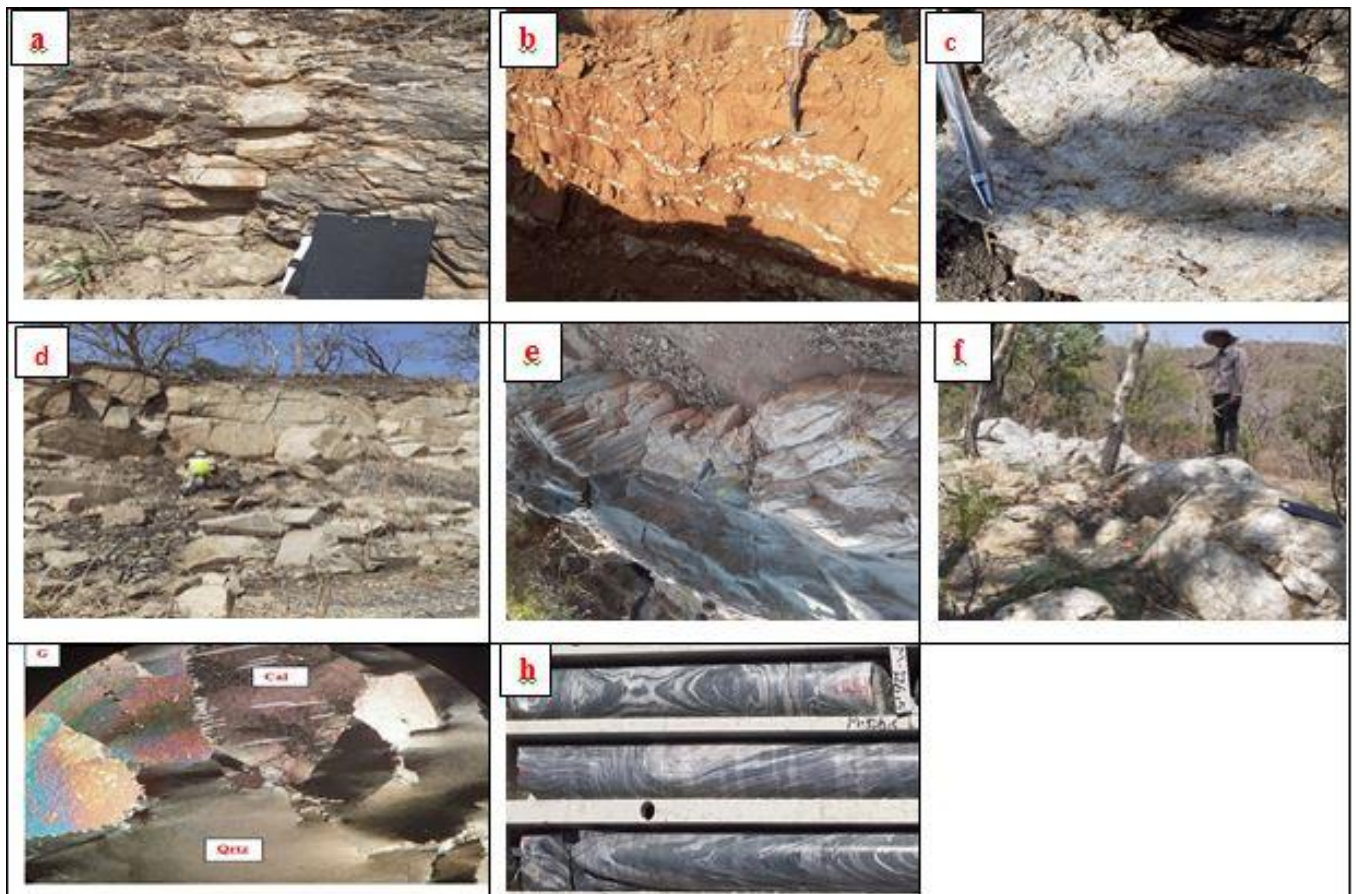


Figure 4. 10. Observed geological structure. A) Shows vertical quartz veining in muscovite-chlorite schist, b) nearly NNE-SSW quartz veining in carbonitization c) foliation in oxidized pyrite-mica schist, d) joints, e) granite dykes, f) flat laying quartz vein, g) deformation twins in carbonates h) boudinage structures in actinolite-tremolite-chlorite schists due to extension respectively.

#### 4.3.6. Folds

Folds are the ductile structure that preserved in micro to macro level mostly in sedimentary origin rocks and metabasalts (fig 4.11a).

#### 4.3.7. Faults

The study area is affected by micro to macro faults that generally control the overall mineralization system. The strike-slip and normal faults are observed (fig 4.11b, c).

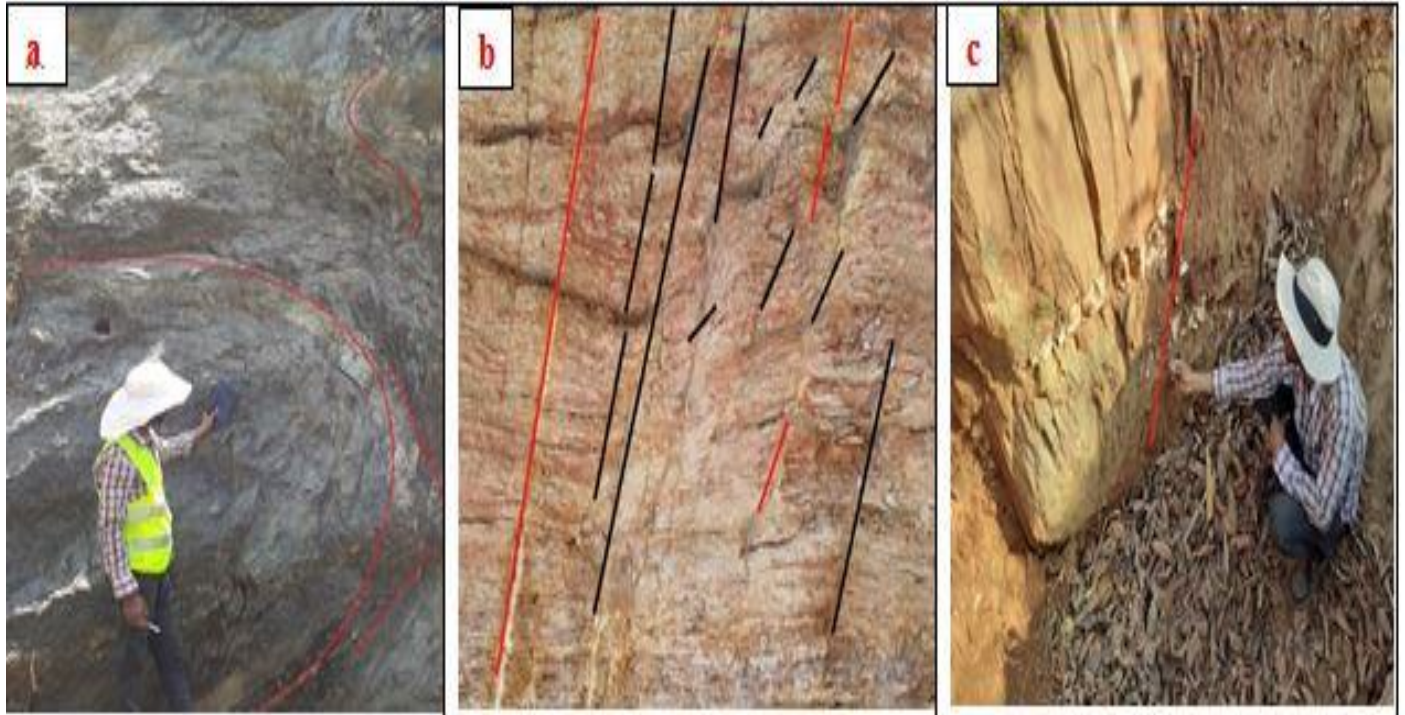


Figure 4. 11. Brittle ductile structures a) recumbent and s-shape folds on mafic schist rocks b) small scale variety oriented dextral strike slip faults on weathered granite c) quartz vein following fractures but seems reverse fault on carbonitized and weathered mafic rock.

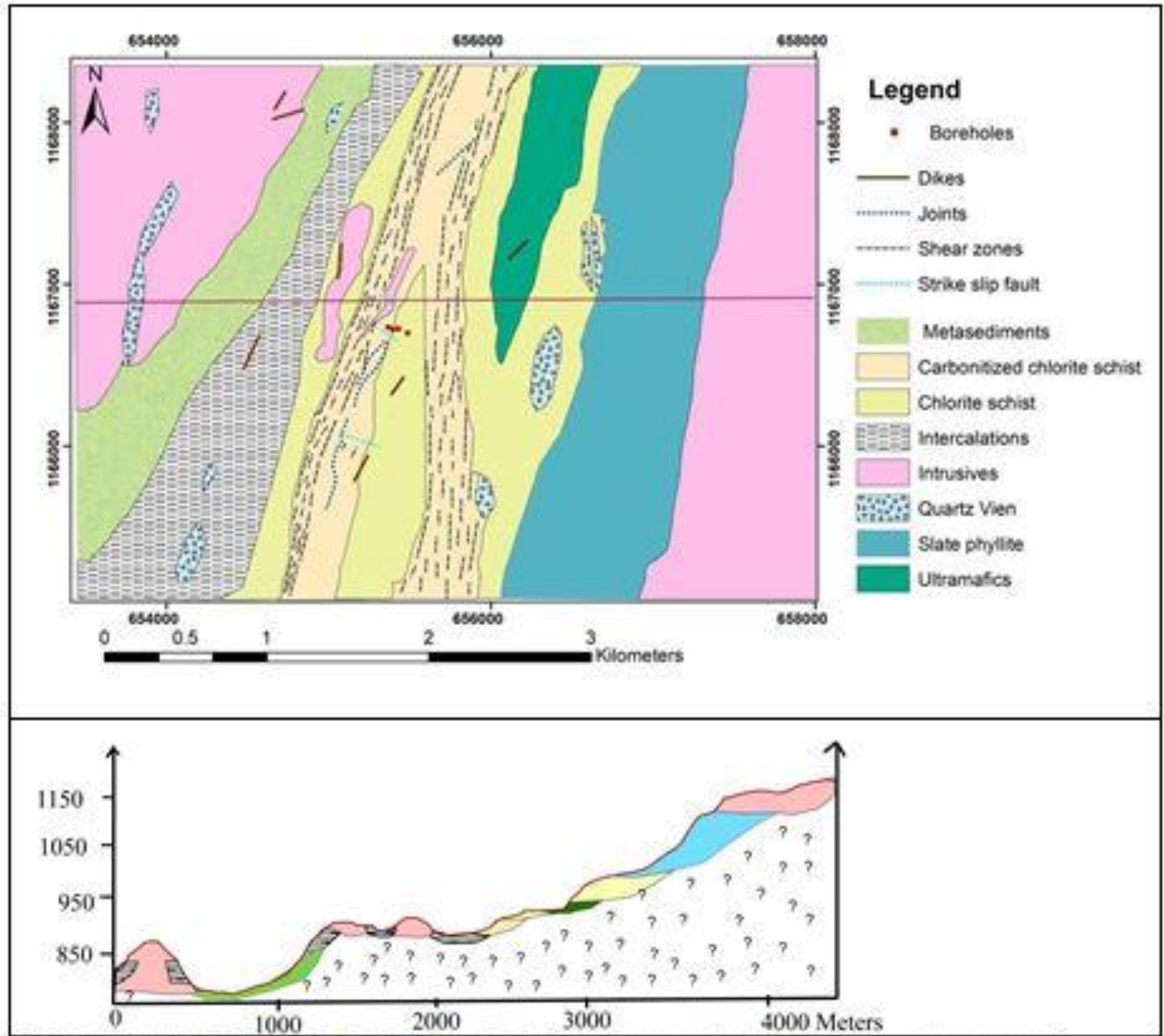


Figure 4. 12. Simplified geological map and cross-sectional view of the study area

## CHAPTER-V-PETROGRAPHY AND WALLROCK ALTERATIONS

### 5.1. Petrography of Host Rocks

Host rock characterization and ore petrographic studies encompass the identification of minerals present in the host rock and ore, their relative abundance, modes of occurrence, structures, textural relationships and modal distribution. Host rock and ore mineralogical identification are guided by identification of color, extinction angle, isotropy/anisotropy, reflectance, birefringence color, cleavage, and shape. In this study ore and ore hosting minerals are identified. Among these whether economic or uneconomic ore minerals including pyrite, magnetite, sphalerite, gold, hematite, pyrrhotite and galena are refractory and easily identified. Under reflected light microscope (RLM) these minerals are bright color and opaque under transmitted light microscope (TLM) i.e. inversely related to calcite, quartz, chlorite, actinolite-tremolite and muscovite minerals that observed under TLM and dull at RLM.

In petrographic description 15 doubly polished thin sections are prepared from four selected historic bore holes. These samples are described in AAU ore petrography laboratory. In this study the host rock mineralogy, alterations, structures and ore minerals are identified. The host rocks are mainly composed of actinolite-tremolite, chlorite, sericite, calcite, biotite, muscovite, epidote and quartz.

**Chlorite:** An index mineral of greenschist facies can easily identified by its pale green to dark green color (fig 5.1a) in transmitted light microscope under PPL and XPL respectively. It occurs as porphyroblast (fig 5.1c). It has basal cleavage and parallel extinction. Occasionally it shows polysynthetic twinning as albite (5.1c). This mineral is most common but commonly preserved in metamorphosed mafic schist rocks that found on central part of the study area mainly eastern and western portion of the Ascom exploration area and at different depths from borehole.

**Actinolite-Tremolite:** This mineral is mainly distinguished by its high relief, radiating feature, prismatic appearance and has low angle of extinction instead of parallel. This commonly observed in mafic schist rocks mainly at TS03 and TS04 (fig 5.1b) thin section sample taken from borehole sample.

**Sericite:** fine grained, greenish and elongated matrix mineral mainly associated with mafic schist rocks such as carbonate-chlorite schist both on outcrop and borehole thin section samples (TS12).

**Calcite:** This also the common mineral mainly identified by its deformation twin and high interference color under XPL but colorless at PPL (fig 5.1c and d). It occurs associated with quartz in veins in out crop and boreholes samples. Calcite under hand specimen fizz when adding an acid. Calcite distinguished by its high birefringence and deformation twinning (fig 5.1g).

**Muscovite:** colorless and multi-colored under PPL and XPL respectively. It is mainly characterized by its foliation and crenulation (fig 5.1 e).

**Quartz:** this mineral abundant mineral commonly shows colorless under PPL and undulose extinction/wave extinction in PPL view of microscope.

**Epidote:** a pale green mineral in hand specimen that mainly associated with mafic schist rocks.

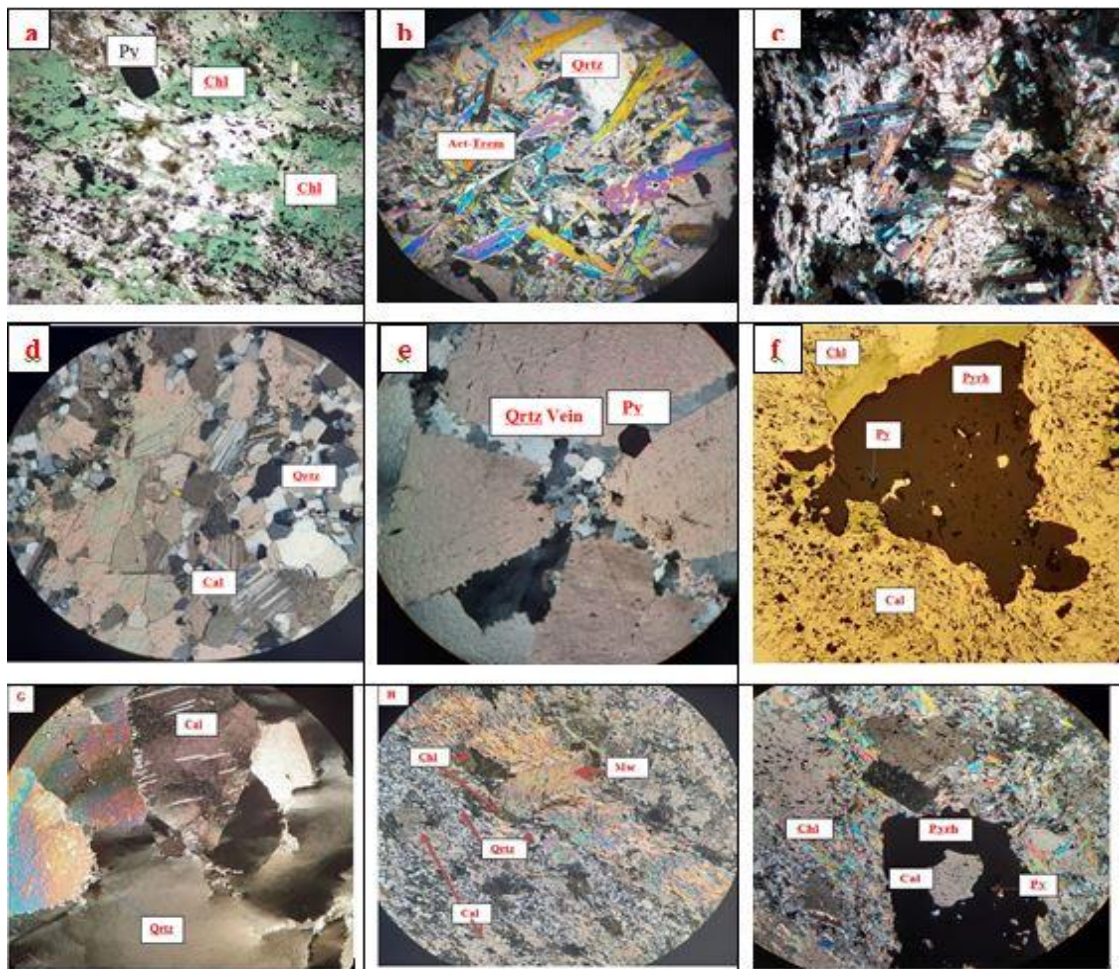


Figure 5. 1. Petrography of host rocks a) chlorite schist b) actinolite-tremolite schist c) porphyroblastic textured and polysynthetic twinning in chlorite schist TS02 d) quartz-carbonate vein with some pyrite minerals in mafic schist e) radiated quartz intergrowth in a vein form on carbonate dominated schist rocks f) pyrite-pyrrhotite ore mineral poikilitic/sieve textured replacement on proximal carbonate-chlorite altered host rock g) deformation twin in calcite h) sheared and crenulated chlorite-quartz-muscovite schist i) sieve texture on pyrrhotite (10X).

## 5.2. Petrography of Ore body

### 5.2.1. Mineralogy

The ore mineralogy consists of mainly sulfide and oxide minerals that include pyrite (Py), pyrrhotite (Pyrh), chalcopyrite (Cpy), galena (Gn), magnetite (Mag), hematite (Hem), and small amount of sphalerite (Sph).

The main gangue minerals in greenstone-hosted quartz-carbonate vein deposits of Ashashire are quartz and carbonates (calcite and dolomite), with variable amounts of muscovite, chlorite, and actinolite-tremolite.

Pyrite is the most common and widespread type of the sulphide minerals in most rocks types as disseminated, stock worked and veined form. Its color is somewhat yellowish and it is preserved in both in metasediments (metapelites) and metabasalts.

**Gold (Au):** a precious metal that is associated mostly with sulfide and oxide minerals. It is bright yellow colored and paragenetically the youngest relative to the coexist minerals. It occurs as dissemination and inclusions in sulfides such as pyrite and pyrrhotite, and as native form in fractures and veins (5.2d).

**Galena (PbS):** this mineral shows three set perfect cleavages visible as triangular pits, high reflectance next to pyrite and isotropic. Some of the minerals which galena is associated are mainly hydrothermal minerals such as sphalerite, pyrite, chalcopyrite and carbonates (dolomite and calcite) and quartz. It is mainly associated with quartz-calcite veins and shear zones. Generally, the mineralization is structurally controlled and mainly hosted in mafic (chlorite) schist and calcite-quartz veins.

**Pyrite (FeS<sub>2</sub>):** is the common and somewhat widespread of the sulphide minerals next to pyrrhotite that are frequently observed both in hand specimen and microscopic level. It is difficult to distinguish pyrite from pyrrhotite in hand specimen. But it can easily identified by their petrographic characteristics. Pyrite is yellowish white to bright white while pyrrhotite is pinkish brown to brown with tarnished surfaces (fig 5.2f). It can be easily distinguished with its yellowish white color to bright white, idiomorphic texture, isotropic and high reflectance nature relative to chalcopyrite under microscope. It occurs as inclusion, dissemination, exsolution/replacement in host rocks and interpreted as the earliest and latest mineral for precipitation (fig 5.2). In hand specimen it has metallic luster and greenish black streak against gold. Pyrite associated with

hydrothermal minerals including chalcopyrite, sphalerite, galena, and pyrrhotite. Paragenetically, pyrite is common from early stage to post stage of crystallization. In some cases it replaces the pyrrhotite and consist gold as inclusion. The mineralization including pyritization occurs mostly as fracture filling and vein filling, in some cases occurs as replacement/ disseminations in host rocks such as muscovite-chlorite-carbonate schist and chlorite schists.

**Chalcopyrite:** chemically it is represented by a chemical formula as  $(\text{CuFS}_2)$  and in this study abbreviated as Cpy. Brassy yellow color, yellowish and low reflectance than pyrite (fig 5.2b). In addition it shows bluish to purplish to greenish tarnish on weathered surfaces against pyrrhotite and pyrite. It is very difficult to identify chalcopyrite from gold but light yellowish than gold. Generally is gold bright yellowish and less abundant than others.

**Hematite:** Chemically it is represented by a chemical formula as  $(\text{Fe}_2\text{O}_3)$  and in this study abbreviated as (Hem). Hematite shows botryoidal appearance and a blood red internal reflection is its main distinguishing features. These deposits occur in enormous masses in Precambrian rocks which are regionally metamorphosed siliceous Fe-rich sedimentary rocks, where residual accumulations of hematite and goethite have developed by leaching of associated silica by natural processes. It occurs in contact metamorphic deposits and as an important phase in some iron-oxide-Cu-Au (IOCG) deposits. It is also found as an alteration mineral in a wide variety of mineralizing environments (Marshall et al., 2004).

**Magnetite:** it is abbreviated as (mag) and mainly shows grey to brown color with brownish tint, strongly magnetic, black and dull metallic luster in hand specimen. Magnetite is identified from sphalerite by its slightly brighter and generally browner and against hematite much darker and lacking bluish white tint. It has low concentration and mainly associated with a wide variety of minerals, particularly ilmenite, hematite, pyrrhotite, pyrite, chalcopyrite, sphalerite, and galena. The occurrence of magnetite in Ashashire occurs in oxidized zone skarn deposits and as lamination dissemination with sulphides in shears and veins. Magnetite also occurs as disseminations or veins within alteration haloes.

**Pyrrhotite:** in this study pyrrhotite is abbreviated as (Pyrh). Pyrrhotite the most abundant and characterized by its light yellow to pinkish brown colored ore mineral that associated with most sulfide minerals (fig 5.2b, f). It is easily distinguished by its tarnishing effect on its crystal surface due to exposure to oxygen. This mineral has granular in some cases massive appearance. It has a chemical formula  $\text{Fe}(1-x)\text{S}$ ,  $X=0-0.2$ ) sometimes it consists Ni and Co and forms a chemical

formula  $(Fe, Ni, Co)_{1-x}S$ . Pyrrhotite is unusual in that it maintains a variable iron content, as referred in its odd chemical formula. The variability is formed due to deficiencies of iron in its chemical structure, which is also responsible for its magnetic properties.

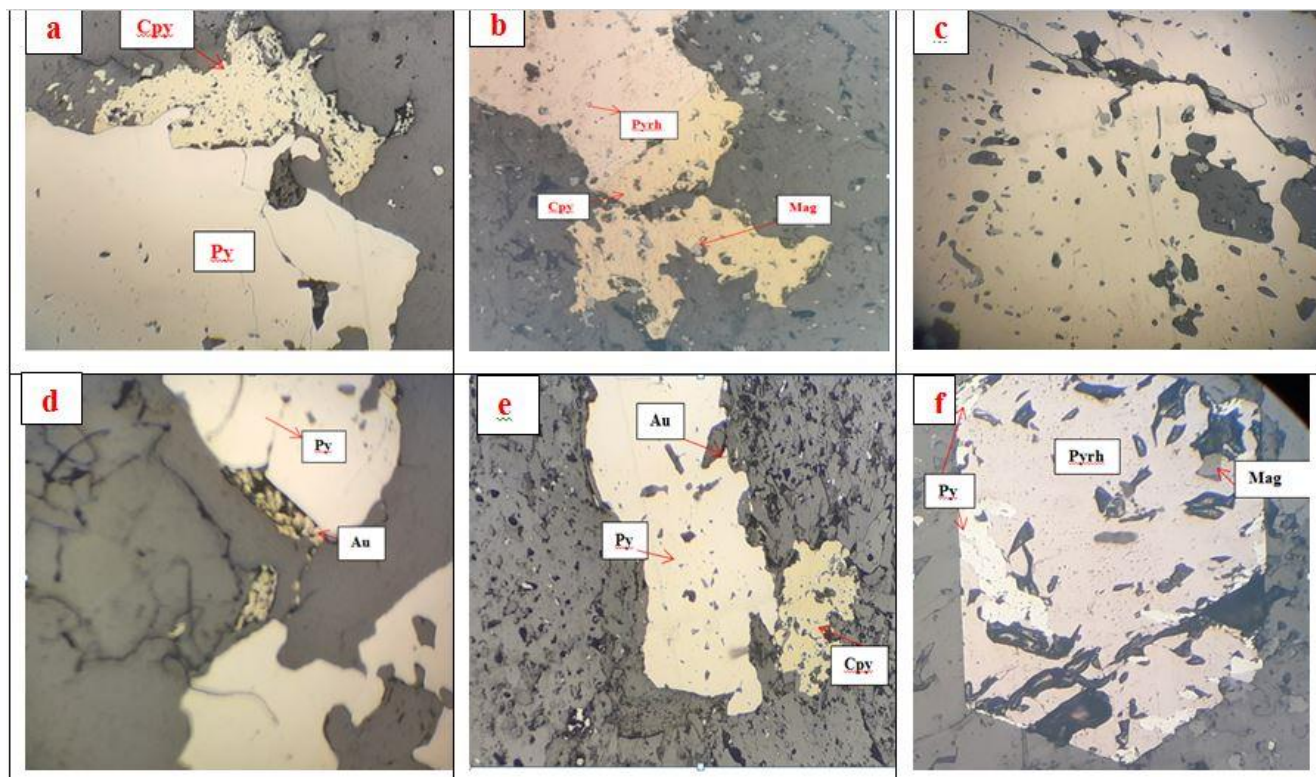


Figure 5. 2. Petrography of ore body a) Pyrite and chalcopyrite replacement and Au replacement on chlorite-carbonate schist rocks, b) Pyrrhotite, chalcopyrite and magnetite replacement in host rocks, c) magnetite filling in fractures and hematite d) gold and pyrite filling on fractures and replacements on quartz and calcite vein e) pyrite and chalcopyrite replacement f) pyrite replacement or exsolution on pyrrhotite with magnification power (10X).

### 5.2.2. Ore Textures

Ore texture identification is a major guidance used in mineral recrystallization sequence determination. The identified minerals show grain boundary penetration to each other equally or unequally, dissemination mostly in the host rock replaced by ore minerals including pyrite, chalcopyrite and pyrrhotite, exsolution of one mineral from the other for example pyrite exsolved from pyrrhotite, mutual grain boundaries mainly equal degrees of penetration example pyrrhotite and chalcopyrite and unequal grain boundary penetration example pyrite and chalcopyrite. Equally interpenetrated grains somewhat difficult to identify its order of formation and needs careful

observations. To avoid this difficulty repeated observations using high power magnification are used. The identical interpenetration of mineral grains, the nonappearance of characteristic first-formed crystals, and the absence of replacement features usually prevent determination of any paragenetic sequence and may indicate simultaneous crystallization of the minerals (Cariag and Vanguhan, 1994).

The textures that mostly observed in minerals are replacement/exsolution, dissemination/ inclusion and fracture (vein) filing mineralization.

Ores precipitated from hydrothermal solutions may be deposited (1) by precipitation in pre-existing open spaces, (2) by replacement, or (3) by a combination of these two processes (Rediley, 2013).

**Poikilitic and porphyritic** texture developments are also common in both ore minerals including oxides and sulfides and also in silicate minerals. Porphyroblastic textured are also observed in mafic schist specially chlorite porphyroblast (fig 5.1c).

A kinematic indicator such as augen structures with strong development of schistosity possibly indicates shearing phenomena. The existence of gold within or a separate grain outside the pyrite and pyrrhotite grains possibly reflects the latest occurrence of gold in the paragenetic sequence. The exsolution of pyrite from pyrrhotite also infers that latest stage crystallization as a result of replacement (fig 5.2f).

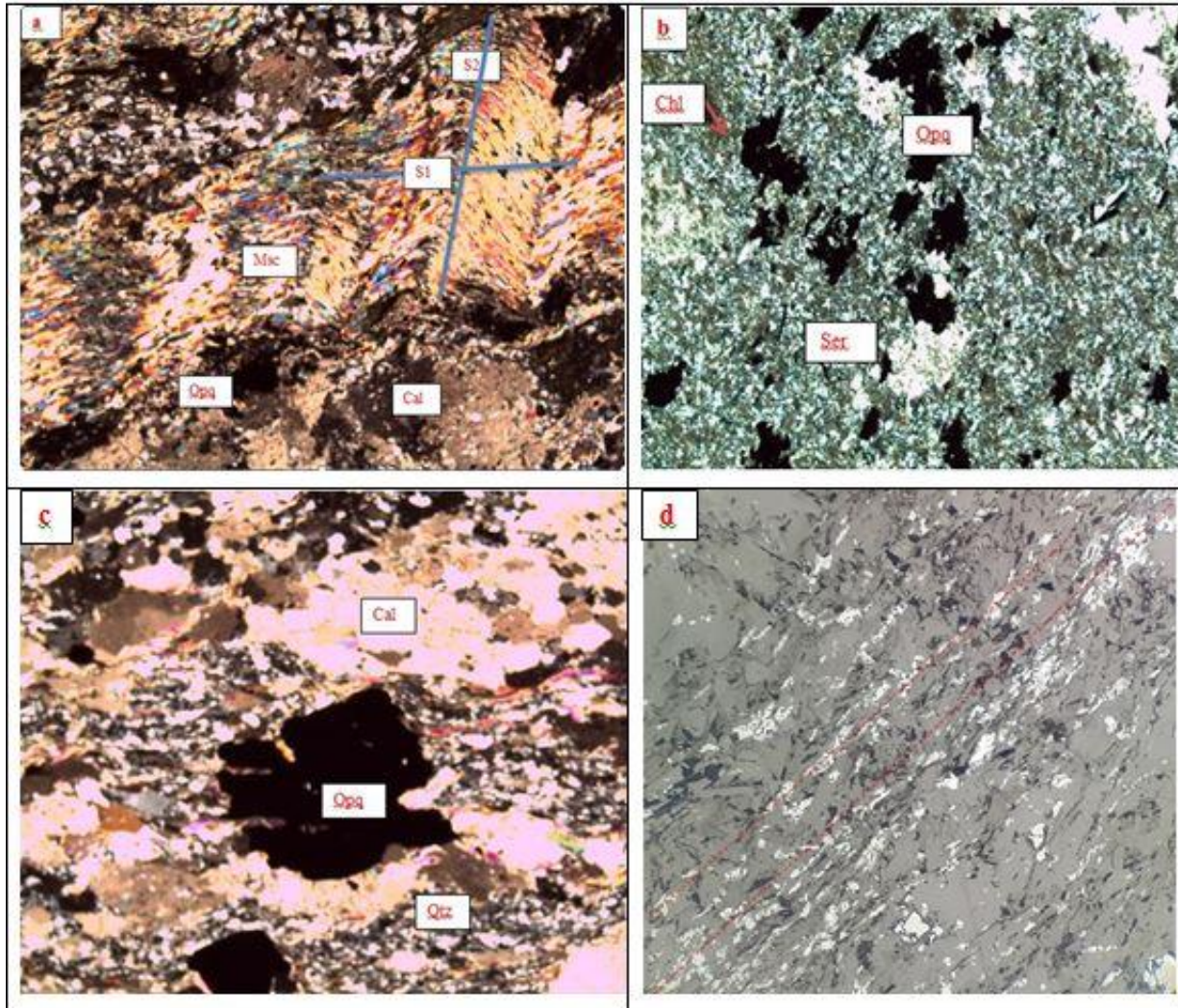


Figure 5. 3. S1-S2 Deformation a) deformation (S1-foliation and S2-crenulation of carbonate-muscovite schist b) chlorite-sericite schist, c) ore minerals replacing host rocks, d) shear hosted mineralization. (10X).

### 5.2.3. Ore Mineral Paragenesis

Textural and crosscutting relationships as mentioned in section 5.2.2 are applied to determine the mineralization sequences of ore minerals. It is difficult to determine the time sequences of ore formations mostly in coarse grained crystals but tried to identify by using low and high magnification power objectives. The shape and grain boundary contact relationships of minerals that are closer to each other are easily observed in some minerals but more complexes in some veins. Pyrite, pyrrhotite, magnetite and galena in most cases show idiomorphic or well crystalized euhedral shape. This infers that the pyrite, pyrrhotite, magnetite and galena formed in the first phase of mineralization and chalcopyrite, sphalerite and hematite most probably crystalized in the later

phase of mineralization. Chalcopyrite, sphalerite, hematite and in some cases pyrite shows subhedral somewhat cusped shape. The presence of pyrite in the two cases shows that pyrite exist in both mineralizing fluids by leaching iron from different host rocks travelling through a system up to the end of transportation and in some cases exsolution from pyrrhotite. The interpenetration of pyrite on pyrrhotite also another case showing later recrystallization of pyrite. Grains with convex faces have been interpreted as forming earlier than those with concave faces (Cirag and Vingham, 1994).

According to textures crosscutting relationships and mineral assemblages four periods or sequences are recognized. The first phase is epidotization and chloritization following regional metamorphism eg. primary calcite and quartz mineralization. The calcite and quartz continues up to phase three due to recrystallization. In phase two ore mineral precipitation such as pyrite, pyrrhotite, sphalerite, galena and others. Phase three includes hydrothermal precipitation and mineralization period that involves gold mineralization, pyritization, and carbonate mineralization. This phase is followed by post mineralization period that dominated by recrystallized carbonate-quartz veins. The fourth phase of mineralization is related to exsolution and replacement of chalcopyrite and pyrrhotite by pyrite (fig 5.4d, f) below.

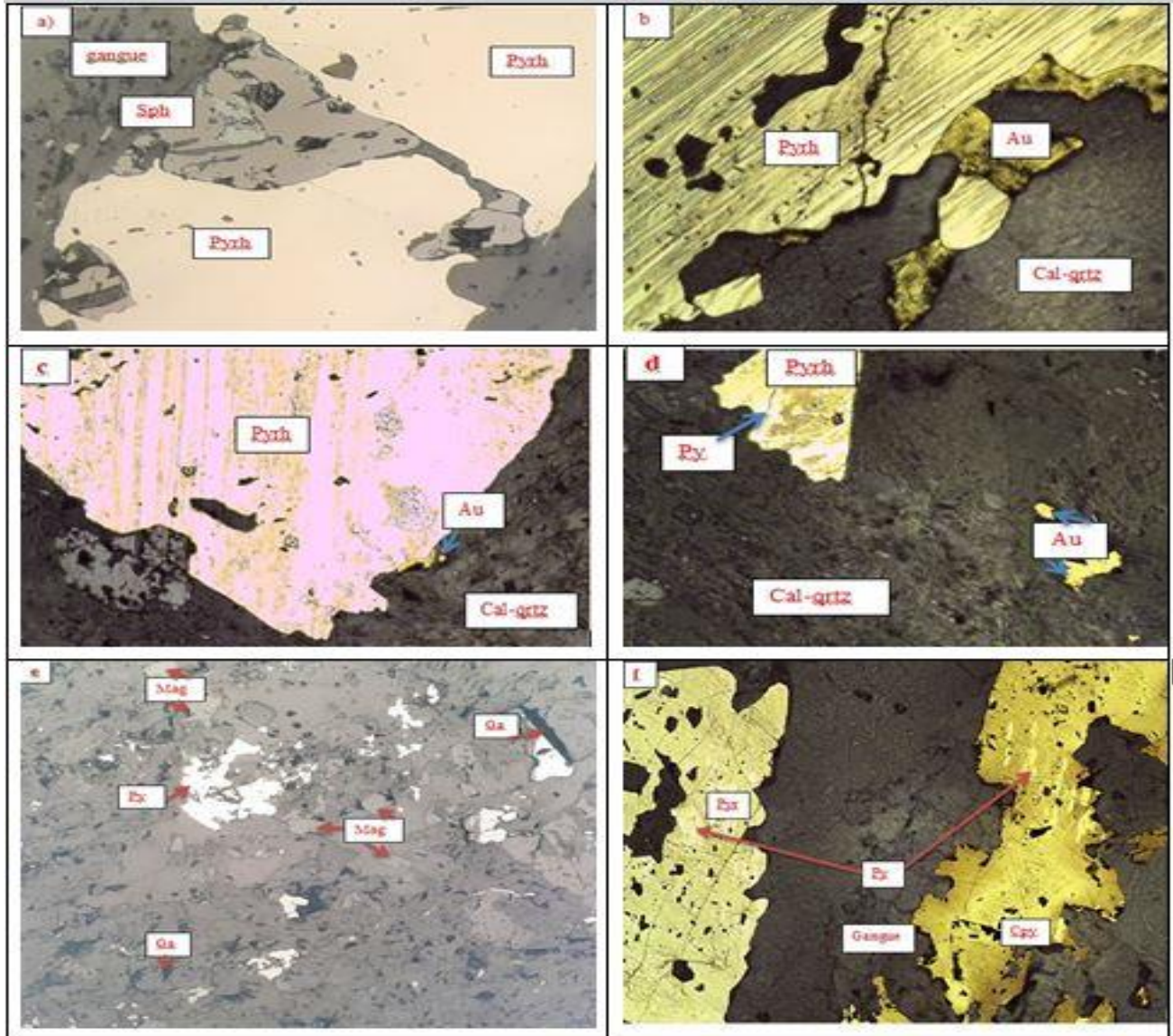


Figure 5. 4. *Paragenetic series and textures of ore minerals* a) sphalerite and pyrrhotite with nearly straight (sharp) boundary (cogenetic), b, c) grains of gold has cusped shape means younger than pyrrhotite both replacing the host rock d) exsolution of pyrite from pyrrhotite and gold disseminated over the host rock e) magnetite, galena and pyrite replacing the host rock without common boundary (nearly equal precipitation) f) exsolution/replacement of pyrite from pyrrhotite and chalcopyrite (10X).

Mineral	Disseminated variety	Hydrothermal calcite-quartz vein hosted variety			Exsolution/ Replacement
		Phase1	Phase 2	Phase3	
Gold					
Pyrite					
Pyrrhotite					
Chalcopyrite					
Sphalerite					
Magnetite					
Calcite					
Quartz					
Chlorite					
Epidote					

Table 1. Paragenetic sequence showing relative temporal relationship between phases of sulfide minerals of the Ashashire mineralization.

### 5.3. Alterations

Gold and sulfide deposits show strong lateral zonation of alteration phases from proximal to distal assemblages on the scales of centimeters to meters. Mineralogical assemblages within the alteration zones and the width of these zones generally vary with surrounding rock type and crustal level. Most commonly viewed mineralization and alterations are carbonates include dolomite or calcite; sulfides include pyrite, pyrrhotite; alkali metasomatism involves sericitization or, less commonly, formation of fuchsite, biotite or K-feldspar and albitization and mafic minerals are highly chloritized and epidotized. In addition to this magnetization and haematization are also observed. The alteration is the result of either infiltration through fractures or by diffusion between grain boundaries.

Major alterations are also chloritization, sulfidation, epidotization, silicification, oxidation and carbonitization. Sulfidation mainly pyritization is extreme in BIF and Fe-rich mafic host rocks and proximal to quartz and calcite veins.

Wallrock alteration in greenschist facies rocks involves the addition of significant amounts of CO<sub>2</sub>, S, K, H<sub>2</sub>O, SiO<sub>2</sub> Na and LILE (Grove et al., 1998).

According to (Evans M., 1987), explanation the alteration of host rock is determined by type of host rock, composition, texture, structure, porosity and permeability. In addition, temperature, pressure, pH and Eh of hydrothermal fluids determine the effectiveness of alteration and mineralization.

As explained by (Yeats and Vanderhor, 1998), in Archean greenstone-hosted deposits the host rock type and metamorphic grade determines the type and intensity of alterations. E.g low grade mafic rocks typically show carbonitization–sericitization-chloritization and sulfidation (pyrite-pyrrhotite) proximal to mineralization, and chlorite-epidote-carbonate alteration distal to the mineralization. In rare case biotite also observed.

In ultramafic host rocks highly magnesian minerals such as talc, serpentine and actinolite-tremolite minerals are observed.

The field and laboratory or petrographic investigation shows different alteration types with various intensities, gold and base metal mineralization are identified. The wall rock alteration includes many processes by which rock-forming minerals are altered due to reactions accompanying the flow of heated aqueous fluids along fractures and grain boundaries.

Commonly alteration follows weak zones such as cracks, fissures, cleavage planes and other surfaces of weakness in rocks. The highly sheared, foliated and fractured nature of host rocks in Ashashire aggravates the intensity of alteration. In addition, the orientation and intensity of the alteration depends on the intensity and orientation of structures and mostly forms a parallel or cross linear and a parallel or cross banded pattern. The parallel patterns occur for instance in mica schists following the foliations. Dominantly and commonly observed alterations are chloritization, silicification, sericitization, sulfidization, oxidation, carbonitization, and epidotization according to their respective discussion below.

### **Chloritization**

Chloritization is the most pervasive and productive alteration type that makes up products of the area's hydrothermal activity (fig 5.5a). It is identified by the development of hydrothermal chlorite mineral. It is more intensively observed in mafic rocks than in the meta-sedimentary and intrusions. The mafic and ultramafic minerals (e.g. Pyroxene and Amphibole) are replaced by chlorite minerals. The field and petrographic study of the mafic metavolcanic rocks showed that even secondary chlorites grown on to the interface of the primary minerals. The presence of chlorine

mineral in metamorphic terrain indicates that the area is affected by low to medium retrograde metamorphism and included in greenschist to amphibolite facies.

### **Silcification**

Field investigation from borehole (5.5d) and outcrop sample supports petrographic investigation shows that silcification is an alteration type that most probably near veins, veinlets generally following weak zones. This alteration is generally manifested by the presence of secondary quartz. It is a widespread with small abundance alteration which is preserved in both meta-sedimentary and meta-mafic volcanic rocks. The intensity and degree of alteration varies one rock type to other rock type based on the proximity and distal nature of the host rock from the veins and nature of host rock. But almost all the rocks have been subjected to this alteration from low degree to high degree of silcification, grade of metamorphism and depth also another parameter.

### **Sercitization**

Sercitization is a rare alteration type in Ashashire dominantly preserved in granite relation to mafic meta-volcanics and meta-sedimentary rocks. It is observed as very finely as fibrous mineral enclosed between grains of harder minerals like quartz and it occasionally encloses hexagonal subhedral minerals. The grains of plagioclase in intrusion 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. Generally, it is indicated by the formation of fine grained sericite mineral.

### **Sulfidization**

Sulfidation is the most pervasive and commonly observed alteration type both in mafic meta-volcanics, meta-sediment and meta-granite in borehole samples. Its appearance in surface rocks is not observed, shows it highly sensitive to oxidation and disappeared easily. Among the common and dominantly observed sulphide alteration is pyritization and is observed in samples taken from test boreholes where there are quartz veins.

### **Carbonitization**

The carbonitization indicated by the presence of calcite and dolomite (Figure 4.3d). This is most frequently observed in both metasedimentary and metavolcanic rocks. The presence calcite

alteration is identified by adding diluted hydrochloric acid. It easily shows fizzing. Dolomitization alteration differentiated by using strong acid compared to calcitization. It can't easily fizzes using dilute acid.

### **Fuchsite Alteration**

This alteration characterized by deep green colored which are chromium rich (CH16 accounts 64ppm) (BGM, 2013) fluid indicators that originate from mantle. Rarely associated with tourmaline (Fig 4.10h).

### **Oxidation**

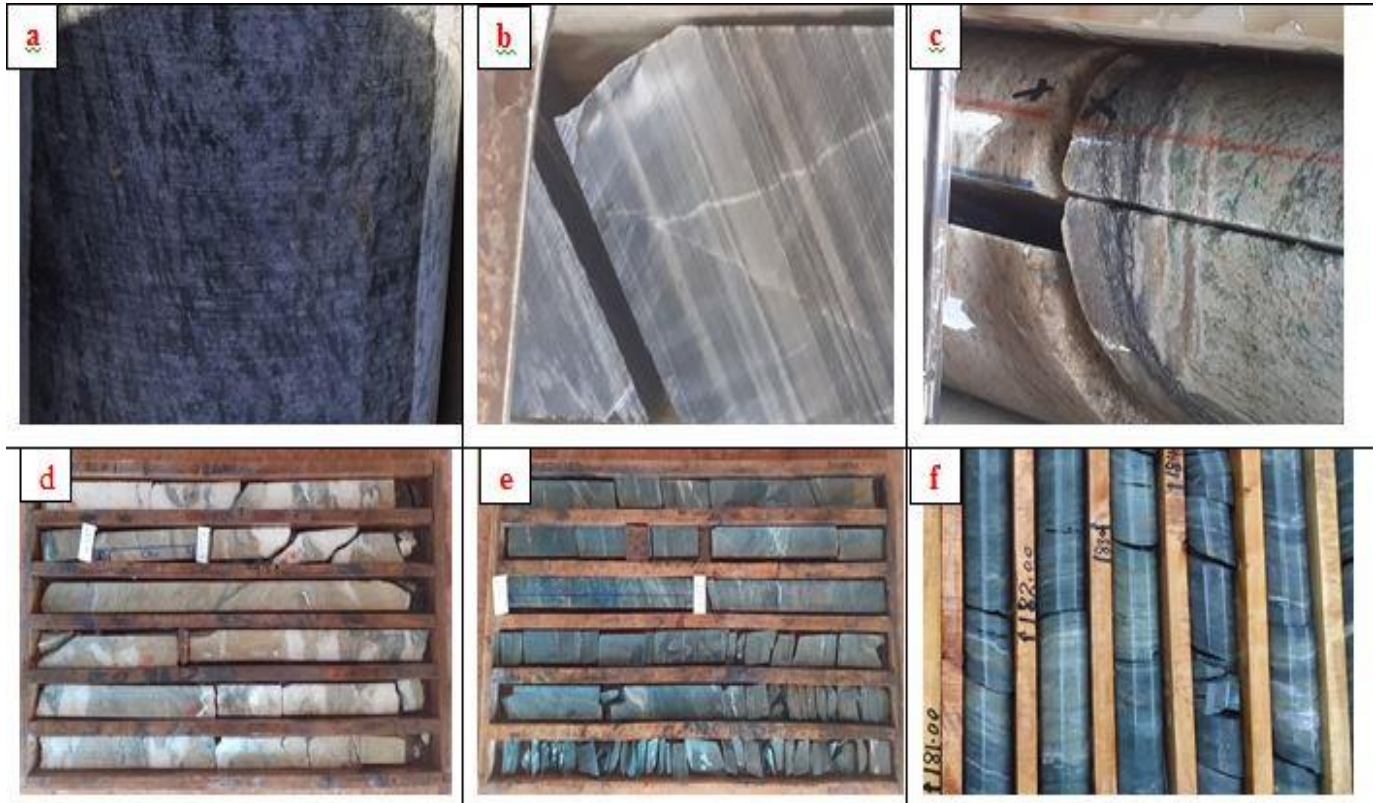
Oxidation in the area is observed both at the depth and on the outcrop level (Figure 4.10c). The surface oxidation mainly resulted in formation of magnetite and it is believed to be an oxidation product of mafic minerals like hornblende that have iron in their chemistry. The petrographic investigation also indicates presence of opaque minerals (e.g., magnetite, also confirmed by physical properties) that appear to replace the hornblendes. Furthermore, oxidation of pyrite is clearly observed. This alteration is manifested by the presence of fine grained red powder which is an iron hydroxide (limonite).

### **Kaolinization**

Kaolinization (Figure 5.5 c) characterized by fine-grained (powder), white clay mineral (kaolin) due to weathering of feldspars with in felsic intrusive rocks and aplitic dykes.

### **Epidotization**

Epidotization (fig 5.5f) is observed almost in all rock units replacing plagioclases. It is commonly observed along sheared zones where the feldspars are crushed due to the shearing and mostly observed far from the mineralization area. It is generally indicated by the presence of epidote that commonly in the form of veins and as laminations cutting across the metavolcanic rocks.



*Figure 5. 5. Different alterations: a) chloritization alteration in hand specimen view of mafic schist b) silicification in chemical sedimentary rocks c) conjugate of amphibole-pyrite, chlorite and alkali-potassic alteration (fuchsite) alterations d) silicification and carbonitization on intercalated metasediment and the felsic intrusion e) oxidation of pyrite on metasediment f)epidotization alteration on mafic schist*

## CHAPTER-VI- GEOCHEMISTRY

### 6.1. Whole rock Geochemistry

#### 6.1.1. Major Element Geochemistry

The major and minor element oxides percentage compositions of Ashashire area are reported in Table 6.1. The host rock shows significant variations in composition as depicted in harker diagram in fig. 6.1. Among these SiO<sub>2</sub> ranges from 40.3 to 66.3%, Al<sub>2</sub>O<sub>3</sub> ranges 9.5 to 15.75%, Fe<sub>2</sub>O<sub>3</sub> ranges from 2.37 to 16.45%, CaO ranges from 2.4 to 12.25%, MgO ranges from 1.24 to 7.56 %, Na<sub>2</sub>O ranges from 0.16 to 5.85%, K<sub>2</sub>O ranges from 0.02 to 2.61 %, Cr<sub>2</sub>O<sub>3</sub> ranges from 0.003 to 0.113%, TiO<sub>2</sub> ranges from 0.19 to 1.94%, MnO ranges from 0.03 to 0.21%, and P<sub>2</sub>O<sub>5</sub> ranges from 0.01 to 0.18% with 3.5 to 18% loss on ignition. The higher value of loss on ignition infers that the rock component has abundant volatile constituents.

Mostly metavolcanic and intrusive rocks of SiO<sub>2</sub> Vs K<sub>2</sub>O and Na<sub>2</sub>O geochemical data clearly shows a positive correlation and shows negative correlation with Al<sub>2</sub>O<sub>3</sub>, CaO, MgO and Fe<sub>2</sub>O<sub>3</sub> fig 6.1. This could infer that normal fractionation of mafic magma to felsic magma.

The mafic meta-volcanics characterized by high concentrations of Al<sub>2</sub>O<sub>3</sub> (9.5 to 15.75 w%), low MgO (1.24 to 7.56 w%), and very low concentrations in oxides of Cr, Mn, Ba and P and Sr (Table 6.1).

Table 6.1. Whole rock major and minor geochemical data in wt% of Ashashire, Western Ethiopia

Sample Type	S. ID	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	CaO	MgO	Na <sub>2</sub> O	K <sub>2</sub> O	Cr <sub>2</sub> O <sub>3</sub>	TiO <sub>2</sub>	MnO	P <sub>2</sub> O <sub>5</sub>	SrO	BaO	Total	LOI
Mafic tuff	CH01	42	11.6	14.45	8.95	4.8	3.14	0.04	0.013	1.94	0.21	0.16	0.02	bdl	96.23	8.91
Meta-Pelite +granite	CH02	55.9	15.75	5.97	5.72	2.71	3.85	1.83	0.006	0.67	0.1	0.18	0.04	0.04	101.77	9
Meta-ultramafic	CH03	40.3	13.3	15.45	8.5	5.64	2.2	0.2	0.019	1.59	0.19	0.11	0.02	bdl	100.87	13.35
Quartz veined-chlorite schist	CH04	65.9	6.65	7.06	5.59	2.82	1.01	0.32	0.01	0.83	0.11	0.05	0.02	bdl	98.38	8.01
Mafic schist	CH05	45	13.25	16.45	12.25	5.23	0.94	0.02	0.018	1.68	0.21	0.13	0.01	bdl	101.48	6.29
Intercalation	CH06	49.7	11.25	9.04	8.87	3.86	1.76	0.74	0.011	0.77	0.17	0.05	0.02	0.01	96.15	9.9
Quartz-calcite vein	CH07	66.3	15	2.37	2.4	1.24	4.63	1.56	0.006	0.19	0.03	0.07	0.05	0.05	98.03	4.13
Meta-ultramafic	CH08	44.3	9.55	6.75	11.35	7.56	0.16	2.61	0.113	0.19	0.13	0.01	0.05	0.04	101	18.19
Chlorite-quartz schist + granite	CH09	61.7	15.5	3.13	4.1	2.46	5.5	1.35	0.014	0.29	0.05	0.16	0.06	0.06	101.03	6.66
Chlorite- schist	CH10	53.5	15.05	12.3	3.88	4.32	5.85	0.13	0.003	0.7	0.17	0.14	0.01	bdl	99.51	3.46

Sample CH08 which taken from sericite-epidote-chlorite schist with high epidotization and some chloritization alteration is distal to calcite-quartz vein accounts highest value of MgO, K<sub>2</sub>O and Cr<sub>2</sub>O<sub>3</sub> with the highest loss on ignition and lowest abundance of Na<sub>2</sub>O, Al<sub>2</sub>O<sub>3</sub>, TiO<sub>2</sub> and P<sub>2</sub>O<sub>5</sub> (Table 6.1).

Figure 6.1 SiO<sub>2</sub> vs major and minor element oxides such as Al<sub>2</sub>O<sub>3</sub>, Na<sub>2</sub>O, K<sub>2</sub>O, P<sub>2</sub>O<sub>5</sub>, CaO, MgO, FeOt, and TiO<sub>2</sub> is plotted. The Al<sub>2</sub>O<sub>3</sub>, Na<sub>2</sub>O, K<sub>2</sub>O, P<sub>2</sub>O<sub>5</sub> shows positive trend and CaO, MgO, FeOt, and TiO<sub>2</sub> shows negative trend with silica. The negative trend between K<sub>2</sub>O and SiO<sub>2</sub> infers crystallization and precipitation of K bearing mineral (feldspars, muscovite and biotite) from the hydrothermal solution. Scatter points for Al<sub>2</sub>O<sub>3</sub>, K<sub>2</sub>O, Na<sub>2</sub>O, TiO<sub>2</sub> and P<sub>2</sub>O are the result of substantial mobility of these oxides during alteration and metamorphism (Alene et al., 2000), but generally show a positive trends.

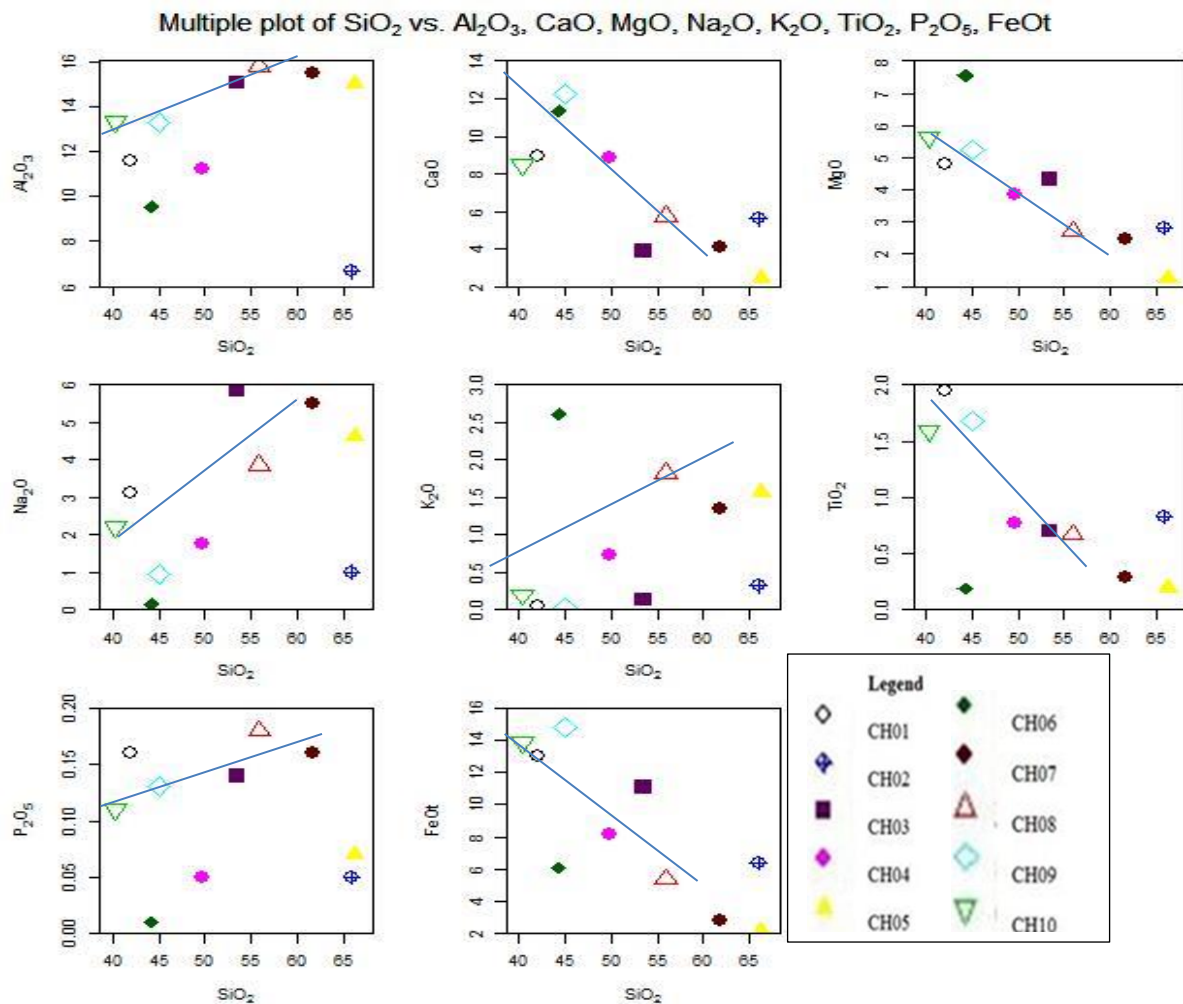


Figure 6. 1. Silica vs. major and minor oxides(w%) scatter plot diagrams

Where CH01(TS01) represents mafic tuff (chlorite schist), CH02 represents sheared muscovite-carbonate-quartz schist (metapelites), CH03 represents Muscovite-amphibole-quartz-carbonate schist (metasediment), CH04 represents epidote- carbonate-chlorite schist (metavolcaniclastic) with quartz vein and granite intrusive, CH05 represents biotite-sericite-carbonate schist (mafic schist), CH06 represents carbonitized-quartz schist, CH07 represents carbonate schist that intercalated with quartz vein and granite, CH08 represents meta-ultramafic (amphibole-chlorite) schist, CH09 represents epidote-chlorite-quartz schist and CH10 represents carbonitized epidote-chlorite schist.

Generally, variation may also be recognized as the derivation from different melts or alteration effects.

### 6.1.2. Trace and REE Geochemistry

The multi-element variation diagram indicates that the geology of the study area is enriched with large ion lithophile elements (LILE) such as Ba, Cs, Th, K, Sr and all samples are depleted in Eu. In addition the graph shows nearly constant trend in high field strength elements (HFSE) such as Sm, Zr, Hf, Y, Tm and others (fig 6.2). The depletion and enrichment infers the compatibility and incompatibility of elements in the hydrothermal solution and magma. The enrichment of LILE is the result of the low degree partial melting of LILE bearing crustal materials while the Eu depletion is due to the fractionation of plagioclase rich magma in magma fractionation series. In addition, the flat trend in HFSE indicates that the source of magma is spinel peridotite mantle instead of garnet peridotite mantle. Since, if they are sourced from garnet peridotite mantle, they show some ups and downs in multi element variation diagram.

Rare earth elements (REEs) play a major role in petrogenetic studies of igneous rocks and most of them show similar geochemical characteristics due their oxidation number of +3 except Eu which can also have  $\text{Eu}^{2+}$ . So, their distribution pattern reflects certain petrogenetic processes (Wilson M., 1997). The spikes, downs, and flat pattern in multielement diagram in (fig. 6. 2), shows very high ratio of the composition of the rock to that of chondrite possibly indicate that the rock is produced by low degree of partial melting. If it were high degree of partial melting, the light REE should have showed lower value and lower ratio due to their compatibility nature when compared to high REEs. Therefore, trace element and REEs geochemistry of Ashashire metabasalts form a zigzag (spike and down) pattern on a chondrite normalized diagram that enriched in large ion lithophile element (LILE), and shows nearly constant (flat) trend in high field strength elements (HFSE), pronounced negative anomaly in Eu, and a spike in K due you to melting of K bearing minerals (fig. 6.2). This pattern is typical of island arc basalts (Sifeta et al., 2005).

Whole rock geochemistry of elements which discussed in fig 6.2 in multielement spider diagram indicate strong positive spikes at Ba, K, Sr and a trough of at Ta. These features are taken to be the typical characteristics of island-arc magmatism (Wilson M., 1997).

The island arc basalts compared to basaltic magma sourced at mid-oceanic ridge and oceanic island have distinct spikes at Sr, K, and Ba, regardless of whether they belong to tholeiitic, calc-alkaline, and shoshonitic magma series (Wilson M., 1997). This fact more confirms that, the metabasalts of Ashashire possibly represents island arc magmatism (fig 6.3).

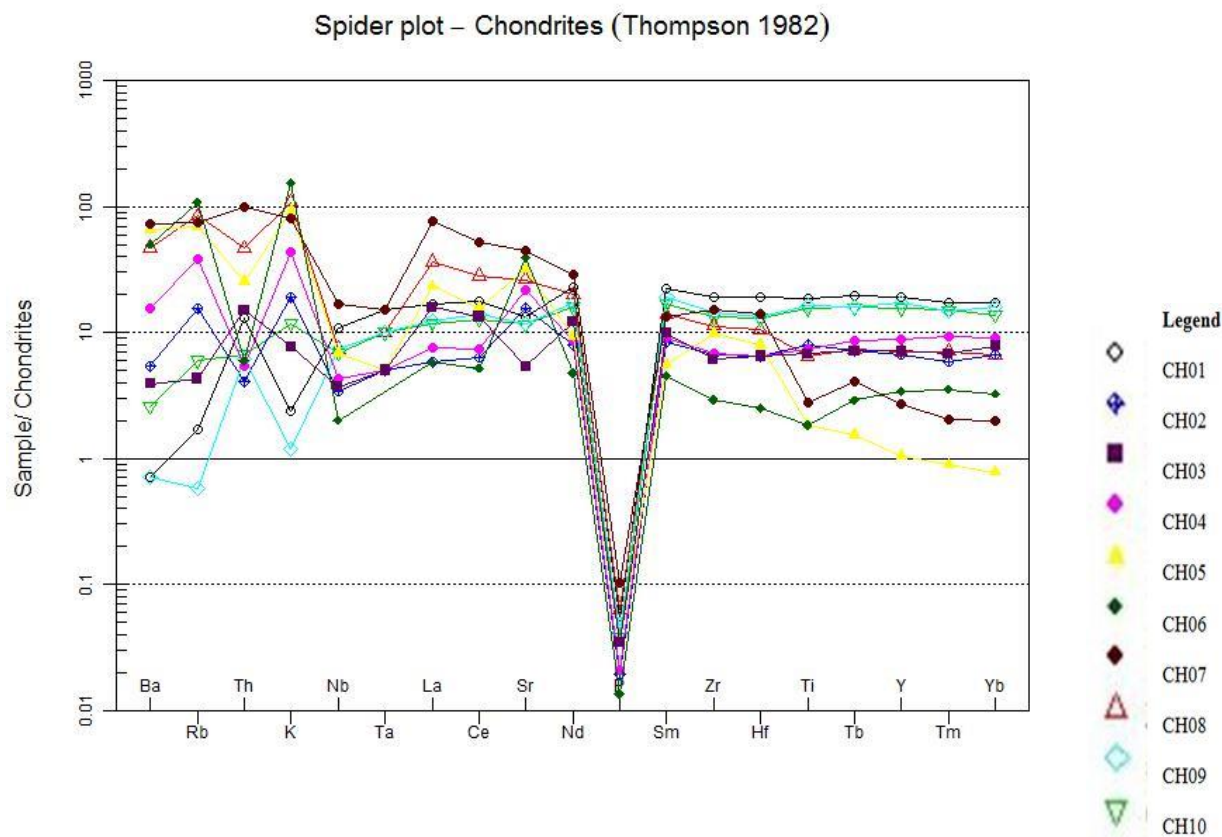


Figure 6. 2. Multielement variation diagram where the sample ID representation is described in figure 6.1. above.

### 6.1.3. Tectonic Setting of the study area

The geochemical result of Zr vs.  $TiO_2$  tectonic plot of Ashashire western Ethiopia geology lies with in volcanic arc setting which is described in (fig 6.3) below and which is similar to the tectonic setting of northern Ethiopia (Alene et al., 2000, Stern, 1994).

The volcanic-arc tectonic setting rocks show petrographic evidence of the presence of regional metamorphic event (Abu-Alam and Hamdy, 2014). It is thought that most lode gold deposits are originated from metamorphic rocks by the dehydration and devolatilisation of basalt and carbonate rocks during metamorphism. Shear hosted gold deposits are closely associated with orogeny and other plate collision events within geologic history. Figure 6.3 discussed below volcanic arc setting shows of the above phenomena that Ashashire gold and sulfide deposit is one component that pass and formed subduction related process of ore formation. Tectonic discrimination diagram drawn

using TiO<sub>2</sub> in (wt%) and Zr in (ppm) for metavolcano-sedimentary rocks suggest as an island arc-tectonic setting. This suggests that the rocks formed in the overlap of MORB to volcanic arc but dominantly as an island arc tectonic setting. The Zr is a petrogenetic indicative mineral due to its alteration mineral as Y, La, Hf, Ta, and Yb (Wood, 1980).

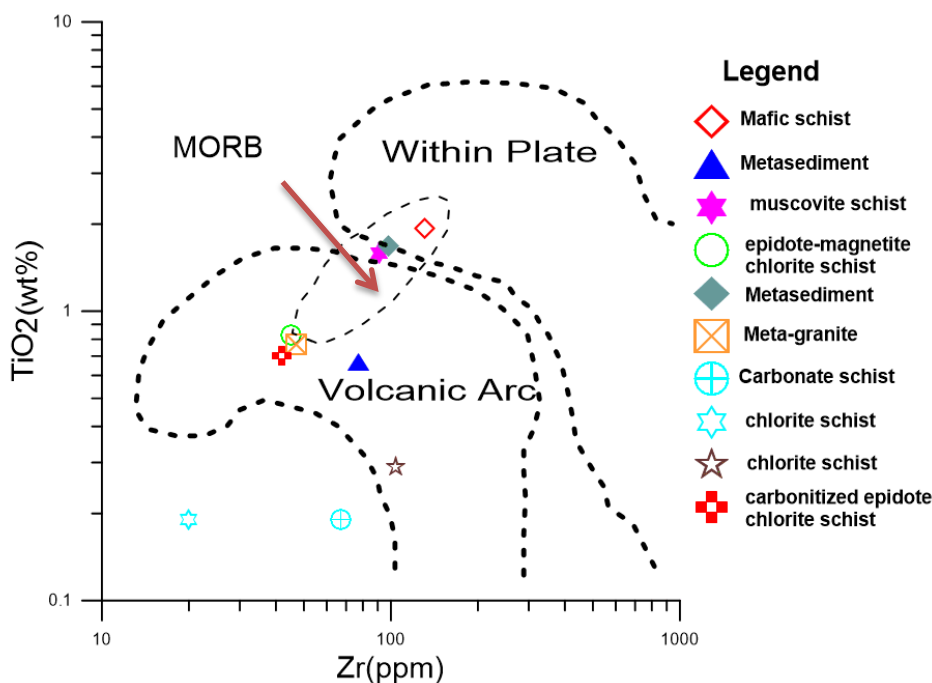


Figure 6. 3. Tectonic setting discrimination diagram of the study area (Pearce, 1980)

## 6.2. Ore Geochemistry

Ten borehole samples from metavolcanic, metavolcaniclastic and metasedimentary lithologies collected mainly from the shear zones and calcite-quartz veins are analyzed for precious and base metals and presented in Table 2 below. Gold value ranges from up to 8.38 ppm with an average value of 2.41ppm, copper values range from 21.5 to 274 ppm with mean of 143.4; zinc range from 18 to 157 ppm with a mean of 91; lead from 0.7 to 3.8 ppm with 2.07 as mean; silver range from 0.01 to 1.83 ppm with a mean of 0.673, Ni ranges from 9.4 to 88.6 with a mean of 64.6 ppm, Co ranges from 6 to 57.8 with an average of 41.2 ppm; and arsenic 0.2 to 31.6 with a mean of 6.65 ppm. Ashashire gold accounts an average grade approximately 2.58g/t from assay results that analyzed by GSR of the seven selected trenches (GSR, 1997).

The veins are filled dominantly by quartz, carbonate, pyrite and chlorite, with minor amounts of muscovite, sericite, epidote, amphibole and native gold, pyrrhotite and chalcopyrite which generally comprises less than 10 vol. % of the veins. The ores are gold-rich with (Au:Ag = 1.5:1 to 9.6:1) and have high concentrations of As, and Mo, with very low base metal concentrations. Bi shows direct relationship with Au ([appendix 3](#)), but Co, Cu, Pb, Zn and others are inflected relationship. In most cases gold mineralized veins which Au > 0.5 ppm are highly affected and hosted in carbonate-quartz veins.

The spatial association of Co and Ni with gold possibly due to the interaction of the mineralizing fluid with the wall rock.

A decreasing trend in TiO<sub>2</sub> with respect to SiO<sub>2</sub>, suggesting that one or both of titanomagnetite and titanite also crystallized early fractionation phase of magma series.

Table.6.2. Precious and Base Metal Concentration in ppm at Ashashire, Western Ethiopia.

Fire Assay (Au-AA25) and IC-PMS (ME-MS41) Method for Precious and base metal assay result in ppm															
Hole ID	Rock Type	Sample ID	Au1	Au2	Ag	Au2/Ag	Cu	Pb	As	Co	Cr	Mo	Ni	Sn	Zn
ASDD002	<i>Carbonate-chlorite schist</i>	CH11	5.04	4.36	1.83	2.38251	232	2.8	12	57.8	50	0.08	73.9	bdl	141
ASDD002	<i>Mafic schist</i>	CH12	2.49	2.04	0.55	3.70909	92.6	2.3	31.6	50.4	17	0.28	59.8	bdl	72
ASDD002	<i>muscovite-chlorite schist</i>	CH13	6.76	2.4	0.25	9.6	21.5	3.8	3.6	35.6	41	0.84	161.5	bdl	55
ASDD010	<i>Granite intrusive with quartz-calcite vein</i>	CH14	2.72	1.87	0.98	1.90816	274	3.5	7.9	73.2	59	0.25	88.6	bdl	157
ASRCD009	<i>Chlorite-sericite schist</i>	CH15	2.99	1.59	0.46	3.45652	245	1.7	1.2	42.3	41	0.65	52.8	bdl	98
ASRCD009	<i>Brecciated chlorite-sericite-carbonate schist</i>	CH16	10.3	8.38	1	8.38	56.6	2.4	1	25.7	7	0.28	30.6	bdl	56
ASRCD009	<i>Granite with recrystallized quartz vein</i>	CH17	8.81	0.06	0.04	1.5	24.7	0.7	0.2	6	3	0.12	9.4	bdl	18
ASDD010	<i>Surface oxidized material</i>	CH18	0.1	0.02	0.01	2	199	0.9	1.8	55.5	94	0.14	64.7	0.2	123
ASDD001	<i>Oxidized surface material</i>	CH19	2.38	0.98	1.57	0.6242	232	1.7	6.2	48.9	57	0.82	71.9	0.2	133
ASDD001	<i>Banded and weathered chert.</i>	CH20	0.07	bdl	0.04	Bdl	56.5	0.9	1	16.5		0.23	32.4	bdl	53

Table 1. The precious and base metal concentrations results using ICP-MS and Fire assay method. Where Au1 is gold concentration using fire assay and Au2 represents gold concentration from ICP-MS. Where 'nd' not defined.

*Where CH11 represents carbonate-chlorite schist, CH12 (mafic schist) represents amphibole-chlorite-carbonate hosted calcite-quartz vein, CH13 represents sheared muscovite-chlorite schist that host carbonate-quartz vein, CH14 represents sheared granite intrusive with quartz-calcite vein, CH15 represents chlorite-sericite (mafic) schist, CH16 represents brecciated chlorite-sericite-carbonate schist with carbonate-quartz vein, CH17 represents sheared granite with recrystallized quartz vein, CH18 represents weathered and brecciated surface oxidized material, CH19 represents highly oxidized surface material, CH20 represents highly banded and weathered chert.*

## CHAPTER-VII- MINERALIZATION

### 7.1. Gold and Sulfide Mineralization

The morphology of minerals in Ashashire gold mineralization indicates that the deposit is structurally controlled. As a result knowledge on the structural condition of the study area is critical to have information on mineralization style of ore deposit. It gives a guide to how the mineralizing fluid originates, transports, interacts with country rock and form a deposit. A detailed field observation from boreholes and out crop samples shows that the mineralization of Ashashire gold and sulfide mineralization is highly controlled by micro to macro NNE-SSW trending with 60 to 70° dipping geological structures hosted between nearly NNE-SSW trending shear zones.

The petrographic observation also confirms that these structures control the overall ore formation process from transportation to preservation. The mineralization and its morphology are dependent on the path that the hydrothermal fluid transports. The metamorphic hydrothermal minerals such as calcite+chlorite+sericite+actinolite-tremolite+muscovite+epidote+quartz mineral assemblage in host rock following the carbonate-quartz veins and shearings infers that the hydrothermal gold and sulfide mineralization is preserved with shear hosted carbonitized mafic schist commonly chlorite-calcite-quartz veins possibly by diffusion of ore constituents through dehydration of hydrated metavolcano-sedimentary rocks during greenschist to amphibolite facies regional metamorphism. The gold in the calcite-quartz veins and in some chlorite veins occurs within quartz or within, or marginal to pyrite or pyrrhotite sulfide minerals. Gold occurs as native form in the form of inclusions/disseminations in metal sulfides such as pyrite, pyrrhotite and calcite-quartz veins surrounded by intense proximal chlorite-carbonate-pyrite hydrothermal alteration minerals and distal alteration minerals such as epidote, chlorite and quartz.

The gold and base metal sulfides don't show clear relationship interms of concentration from geochemistry investigations generally <0.3% Cu (Table 2). The concentration of base metals is not much economic and abundant in Ashashire. The deposit becomes gold only instead of gold and base metal sulfide deposit, but with some content of base metals.

Gold-sulfide mineralization is associated with brecciation and fracturing of the metavolcano sedimentary rocks and related furginized zones, close to sulfidized, carbonitized and chloritized alteration zones that hosted in shear zones and related quartz veins. Mineralized veins in Ashashire orogenic gold and sulfide prospects are generally chlorite-carbonate-quartz-dominated structurally

controlled i.e. generally shear hosted or veined. The host rocks have also minor content of amphibolite facies minerals, typically actinolite or tremolite, and limited content of sulfide minerals which is less than 10%. The associated minerals have variety textures for instance, pyrite, magnetite and pyrrhotite grains show euhedral shape and while in most cases quartz grains show interlocking-granular texture; this infers that the granular texture is the result of recrystallization of grains during metamorphism.

Gold is hosted in chlorite-sericite-carbonate rocks of carbonate-quartz veins and in the adjacent most strongly altered wall-rock, commonly as inclusions in hydrothermal greenschist facies and sulfide minerals mostly in pyrite and pyrrhotite. Sulfide minerals are the most common component of both ore and alteration haloes. Pyrrhotite is the dominant sulfide in most ores, and typically coexists with pyrite and oxides (magnetite). Rarely base metal bearing sulfides including chalcopyrite, sphalerite, and galena are associated mineral assemblages.

In most field and laboratory investigations gold rich carbonate-quartz veins are characterized by the occurrence of visible pyrite+pyrrhotite +magnetite± chalcopyrite ± sphalerite ± galena ± hematite mineralization. The distribution of pyrite and pyrrhotite varies throughout the mineralized veins, with pyrrhotite being the most abundant ore mineral at a nearly constant concentration of about 40-60% of all sulphide phases among the ore mineral assemblages, and commonly associated with pyrite, sphalerite, chalcopyrite and magnetite. The pyrite and pyrrhotite minerals are highly susceptible to weathering and easily oxidized or tarnished. Mixtures of chlorite, sericite, muscovite and carbonates are usually associated with disseminated sulphides in the mineralized quartz veins.

According to Benu Gold mining Ethiopia report in 2013, three styles of gold mineralization observed in western greenstone belts, i) syenite intrusions related mineralization, ii) skarn gold type mineralization and iii) fault-shear hosted gold mineralization in metasediments are recorded in the area. The field and laboratory investigation confirms that Ashashire gold mineralization focused on mainly in the rim of calcite-quartz veins on shear zones in chlorite-carbonate schist rocks. Some granite sample geochemistry also shows that the gold mineralization is also associated with intrusives.

Ashashire gold accounts an average grade approximately 2.58g/t from assay results that analyzed by GSR of the seven selected trenches. While the fire assay result from Benu Gold Mining recorded up to 64ppm. Similarly, the fire assay geochemical result of this study record shows gold concentration ranging <0.02 to 10.3 ppm and on average approximately reaches to 4.17ppm with

(n=10). The lowest concentration in this study recorded in sample (CH20) which is hosted in silicified rock while the highest anomaly of Au is recorded in sample (CH16) which is chlorite-sericite-carbonate rocks which is dominated by carbonate-quartz veins. It also associated with potassic altered mainly fuchsite alteration and crenulated meta-sedimentary rocks. At the same time ICPMS detects the concentrations of Au below detection limit (0.02ppm) and 8.38ppm in CH20 and CH16 respectively of the same sample as discussed above. It occurs as inclusion in pyrite and pyrrhotite.

The Au/Ag ratio value most consistently  $>1$ , typically ranges in 0.624–9.6. Enrichment or depletion of Ca, Fe, Mn or Mg is non-existent. Alteration mineral assemblages, alteration indices based on CO<sub>2</sub> and K, and pathfinder elements enriched in the deposits can be used in defining exploration targets and vectors to ore in bedrock (Juhani et al., 2011).

There are numerous visible old mining pits in Ashashire area and surroundings. Most peoples of the western Ethiopia including the Kurmuk Woreda communities are participating in artisanal gold mining following the river channels. This shows that placer gold typically sourced from orogenic lode-gold deposits. For many of the great placer districts, for instance the enormous circum-Pacific placer fields of the California foothills belt, Russian Far East, and central Victoria (Goldfarb et al., 1998.)

## **7.2. Genesis of Mineralization**

Genesis study is a critical parameter in mineral deposit exploration. The genesis shows how minerals are formed in a certain geologic conditions. It involves what will be the possible sources and host rocks of metals and hydrothermal fluids. This topic also focuses on characterization of possible sources, host rocks and associations of gold and sulfides and the conditions for the precipitations will discussed below.

### **7.2.1. Sources of Metals**

Gold is widely distributed throughout most geological materials with very low concentration background level (Boyle, 1987). The widely distributed gold needs a very wide variety of geological processes to form an economic ore deposit. Among gold concentrating geological processes hydrothermal process is the most common and fertile process for most world class orogenic gold deposits. The alterations discussed in chapter five are the result of hydrothermal processes. The preservation of orogenic gold and minor sulfide mineralization in Ashashire that

confined in shear zone, is related to the action of hydrothermal fluids produced due to thrusting, regional deformations (faulting and folding), shearing and/or emplacement of younger intrusive rocks (Mahmoud M. and El-Sawy K., 2009). The association of gold mineralization to fractures, shear zone and alterations of silicification, chloritization, sericitization and carbonization with low to medium grade metamorphic conditions shows that the ore forming fluids are possibly related to metamorphic process operating in the temperature ranges of about 300°C (Ridley, 2013). Most orogenic gold deposits are possibly sourced from metamorphic rocks by the dehydration and decarbonation of metavolcano sedimentary rocks during metamorphism. The occurrence of hydrated metamorphic minerals (fig 5.1) such as chlorite, tremolite-amphibolite and carbonate minerals (calcite and dolomite) infers that these rocks will be the possible source materials for gold and sulfide metals and hydrothermal fluids generation. This is also confirmed by scholars as metamorphism of hydrated mafic (Wilson et al., 2013) and a sedimentary rock (Tomkins, 2010) appears to be the best source for gold, ligands and fluid production.

Orogenic gold deposits are typically formed during late stages of the deformational metamorphic-magmatic history of the evolving orogen, syn-kinematic with at least one main penetrative deformation stage of the host rocks (Goldfarb et al., 2001 and Groves et al., 1998, 2003). In the case of Ashashire gold and sulfide mineralization confined to greenschist to amphibolite facies metamorphic rocks that hosted in carbonitized, chloritized and silicified rocks as in syn to post kinematic fractures and calcite-quartz vein fillings.

The highest grade concentration of Ashashire gold nearly accounts 10.3ppm from fire assay Table 2. The mineralizing components possibly sourced from both metavolcano-sedimentary rocks commonly hydrated and carbonated varieties for example basalts and marine sediments that metamorphosed to pyritic-chlorite-sericite-carbonate schist. The host rock is also enriched by pyrrhotite, pyrite and magnetite. Pyrite enriched carbonaceous sedimentary rocks can easily generate more fertile fluids than mafic rocks (Tomkins, 2010). This can be explained by gold precipitation as a result of chemical reactions between an H<sub>2</sub>S-bearing aqueous fluid and wall rock (Ridley, 2013) as the fluid moves from high potential of fluid pressure to the precipitation zone which is reduced fluid pressure or discontinuities. The mineralized rocks are highly affected by quartz veins and hydrothermal alterations such as pyritization, sericitization, carbonization and chloritization. In most cases sulfidation and carbonization associated with the mineralization while

chloritization alteration affects most rocks but the petrographic and field investigation of this alteration is not always related to gold mineralization.

The mineralized veins and shear zones commonly surrounded by chlorite-carbonate-sulfide strong proximal and chlorite-epidote distal hydrothermally altered metavolcano-sedimentary rocks (figure 5.2) in chapter five. The host rocks are mainly replaced by secondary hydrothermal gangue and ore minerals including chlorite, calcite, quartz, actinolite-tremolite and epidote minerals. In addition small amounts ore minerals as chalcopyrite, galena, pyrite, pyrrhotite, magnetite, hematite and sphalerite minerals also precipitated and replace the host rocks. These mineralizations are structure controlled and characterized by moderately to steeply easterly dipping and sometimes flattened laminated fault and vein fill carbonate quartz veins in brittle-ductile shear zones and faults, with or without extensional veins and breccia. The nature of the host rock determines the extent whether (extensional or compressional) of mineralized carbonate-quartz veins. The highly altered, fractured and veined rocks are susceptible and exposed to largely extended veins with multiple stages of mineral growth. In the case of the gold enriched veins in highly deformed and metamorphosed volcanics and sediments, it is widely thought that the gold may have been derived from the surrounding rocks and may have been concentrated by circulating fluids during metamorphism (Fyfe and Henley, 1973).

In the world, Archean greenstone belts (Neoproterozoic) volcano-sedimentary succession of greenschist to amphibolite facies metamorphic rocks well-endowed with orogenic Au mineralization. The source of the Au is likely to be the abundant mafic-ultramafic greenstone sequence terrains, whereas the abundance of Au lodes may be linked to accretionary fluid events. Because it needs periods of continental growth (Goldfarb et al., 2001)

The N-S trending shear zones may create favorable condition for deep seated hydrothermal fluids to leach elements including gold and boron from the wall rock and precipitate them in veins (Dekisissa, 2000). The Ashashire gold and sulfide mineralization hosted between the two nearly NNE-SSW trending shear zones described in figure 4.7 and occurs as disseminations/ replacements in carbonitized mafic rocks and fracture filling in veins and shear zones. Small amounts, however, are found in the gold-bearing pyrites, pyrrhotite and magnetite as inclusions and generally associated with pyrite, magnetite and pyrrhotite and a little with galena and chalcopyrite of sulphide minerals. The ore bodies prospect concentration are highly complicated but commonly on weak

zones mainly with post tectonic fractures (calcite-quartz veins) and shear zones. They represent fracture fillings (pyrite, pyrrhotite, chalcopyrite, galena, sphalerite and oxides of iron) and associated with some wall-rock alterations in the contact zone of the host rock units. The distribution of the primary gold deposits and occurrences is structurally controlled (calcite-quartz vein or highly fractured and sheared zones (Moharram et al., 1970).

The generations of hydrothermal minerals including gold involve several crustal processes such as ocean floor spreading and deposition of sediments followed by subduction, greenschist to amphibolite facies metamorphism and intrusion of granites (Berhe, 1990 and Worku and Schandelmeier, 1996).

As a general the Ashashire gold precipitation possibly resulted from three causes 1) loss of sulfide (H<sub>2</sub>S) from hydrothermal fluid, 2) By acidification this may cause the formation of traps due to dissolution of carbonaceous metasedimentary rocks due to the interaction with acidic hydrothermal fluid. This may also cause change in fluid chemistry and hydrogen fugacity. 3) Due to reduction of the physiochemical conditions of hydrothermal fluid as it's flowing towards the earth surface following deep seated fractures as discussed by (Ridely, 2013).

### 7.2.2. Sources of Fluids

The natural occurrence of various lithologic units and structural complexity such as various varieties of schists, thrusting, shearing effect and the hydrothermal alteration due to hot water and host rock interaction makes the area more complex to characterize the source of ore metals and transporting fluids. But the fluid inclusion study indicates that the fluid is low salinity with maximum of 4.9% NaCl equivalent and H<sub>2</sub>O-CO<sub>2</sub> fluid (Dekisissa and Koeberl, 2002). The study area is tectonically complex, metamorphosed and hydrothermally altered. Metal and alteration source hydrothermal fluids probably originating from dehydration and decarbonation of hydrated and carbonated volcano sedimentary rocks such as chlorite-sericite-carbonate schists. Dehydration and decarbonation reactions during metamorphism produce substantial volumes of metamorphic water in the mid- and lower-crust (Grove et al., 1998). Mafic rocks produce metamorphic low-salinity fluids containing H<sub>2</sub>O, H<sub>2</sub>S and CO<sub>2</sub>, and for this reason they promote Au-S complexing and the formation of gold-only lode deposits (Grove et al., 2000).

The study area is covered with metamorphosed volcano-sedimentary rocks which are highly deformed and complex even the mineralized veins are also deformed this infers that there was a

movement or deformation syn to post mineralization. Movement along structures may be critical process at the depth of orogenic deposits to generate permeability for hydrothermal fluid (Ridely, 2013). The hydrothermal fluid flows starts to precipitate along discontinuities such as deep seated fractures (faults), veins and shear zones that are vertically to steeply plunging and somewhat continuous. The continuity of discontinuities infers that the fluid transports long distance travel. This weakness on the surface becomes steeply plunging to near horizontal and generally quartz veined and somewhat mineralized.

In Ashashire gold and sulfide exploration area a numerous syn to post granitic intrusions is preserved figure 4.6 in chapter four. This granite intrusion creates heterogeneous stress and causes inhomogeneous strain to surrounding metavolcano-sedimentary sequences. This heterogeneous stress causes fracturing, brecciation and veining. As a result, the samples taken from contact zones between granitic intrusions and metavolcano-sedimentary sequences shows economically mineralized zones and become common sites of ore-fluid infiltration and gold precipitation in most prospects and deposits including Ashashire.

Hydrothermal fluid and hostrock interaction produces sulfur-rich fluids with distinctly reducing Eh, which would easily transporting gold bi-sulphide complexes (e.g. Borg et al., 1990).

Most metamorphic hot fluids have low salinities and low concentrations of reduced sulfur. Fluids of this nature are generally concerned in the formation of orogenic gold deposits, which represent a very important category of gold deposit types (Phillips et al., 1994).

Metamorphic dehydration of seafloor rocks is a viable mechanism for producing abundant aqueous-carbonic and low-salinity fluids at the metamorphic transition of greenschist to amphibolite facies in subduction zones (Worku and Schandelmeier, 1996). The metamorphic model, with fluids being produced at depth under prograde greenschist-to-amphibolite facies metamorphic conditions and depositing orogenic gold ores in a retrograde P–T environment typically near the brittle–ductile transition, fluids produced in these grades are dominated compositionally by H<sub>2</sub>O, CO<sub>2</sub>, and CH<sub>4</sub> in approximately that order of abundance (Grove et al., 1998). The volatiles H<sub>2</sub>O, CH<sub>4</sub>, CO<sub>2</sub> and sulfur species, are produced as metamorphic fluids during prograde reactions of this type. Hydrothermal fluids, which resulted from dehydration and decarbonation in metamorphic area is expected to be an important for the orogenic gold mineralization including Ashashire. These fluids must be concentrated into weak zones as shear zones and veins to be generate economic deposit. The mineralized zones in Ashashire such as the calcite-quartz veins are developed as fracture filling

(fault and joints) or shear veins (result of brittle ductile deformation). In most cases deep crustal fluids appear to easily follow pre-existing zones of weakness with higher permeability compared to the surrounding altered metamorphic rocks. The majority of evidence that favors the metamorphic source fluids will released from, either during metamorphism of sequences deeper in the gold-hosting basins and oceanic rock sequences (Goldfarb and Groves, 2015) or from de-volatilization of the sediment section above a down going subduction slab (Grove et al., 1998; Groves and Santosh, 2015). In this zone the metamorphic reactions may liberate observed minerals components such as gold, sulfides, quartz, carbonates and oxides that focus in veins and faults, from the deforming rocks as discussed in chapter five.

## CHAPTER-VIII- CONCLUSION AND RECOMMENDATION

### 8.1 Conclusions

As summary of metamorphic hydrothermal environments the ore fluids are possibly released during prograde greenschist to amphibolite facies metamorphism. Hydrothermal ore minerals including orogenic gold are precipitated in retrograde physicochemical conditions near brittle-ductile transition zone. This is demonstrated by many geological, petrographical and geochemical evidences (e.g. Ashashire this study). The alterations, mineralogical, and textural evidence also suggests that Ashashire orogenic gold ores have been deposited from complex hydrothermal solutions. Many geological processes are applied in the formation of this deposit and structures in the rocks were important in localizing ores and in the movement of fluids.

Visible gold grains in the petrographic investigation is hosted in chlorite-carbonate-quartz veins that put on in (chlorite-sericite-carbonate) schist in carbonate-quartz veins which is adjacent to strongly altered wall-rocks, and sometimes as inclusions in sulfide minerals mostly in pyrite and pyrrhotite. Sulfide minerals are the most common component of both ore and alteration haloes and form typically takes nearly <10% of the whole rock. Pyrrhotite is the dominant sulfide in most ores, and typically coexists with pyrite and oxides (magnetite and hematite). Rarely metallic sulfides including chalcopyrite, sphalerite, hematite and galena are associated mineral assemblages.

The study area is affected by a number of hydrothermal alterations. These alterations include sulfidation, carbonitization, silicification, kaolinitization, sericitization, chloritization and epidotization due to formation of (pyrite, pyrrhotite), (calcite, dolomite), quartz, kaoline, sericite, chlorite, and epidote respectively.

The main ore mineralogy includes pyrite, pyrrhotite, chalcopyrite, galena, sphalerite, magnetite and minor hematite. Paragenically, these minerals shows complex stage of mineralization and difficult to differentiate their sequence but their morphology, texture and grain boundary relationship infers that the oxide minerals (magnetite and hematite) and in some cases pyrite formed at early stage of crystallization, secondly pyrite, gold, pyrrhotite and sphalerite galena formed lastly pyrite is crystalized.

The maximum concentration observed in chlorite-sericite-carbonate schist at carbonate-quartz veins which is altered by sulfide mafic schist while the lowest concentration observed in silicified rock or chert.

The mineralization is not only associated with quartz vein and calcite vein but it also precipitated alone along deformational minor fractures.

What lithological unit provides the hydrothermal orogenic ore components (metals and fluids) is still debating in metamorphic hydrothermal model. But, based on mass balance calculation (Phillips et al., 1987), demonstrates basaltic to andesitic volcanic rocks liberate 1-2 ppb gold during metamorphism to form giant deposits eg Kalgoorile.

Some scholars argued to gold rich protholiths is a requirement and others suggest that gold rich source rocks are not a requirement. E.g. Black carbonaceous metasedimentary rocks with abundant syngenetic/digenetic pyrite with 10ppb Au whole rock concentrations are required to form giant Au deposit (Large et al., 2011, Tomkins; 2010). Others metamorphic model without any favorable protholith rocks, rather with any pyrite bearing lithology (eg. Turbidites) may devolatilized to yield S and Au (Phillips, 1993). Since pyrite grains in metasedimentary rock sequences provide their Ag, As, Au, Sb, Hg) at higher temperature conditions (Pitcairn et al., 2010). But in the case of Ashashire the gold possibly sourced from volcano-sedimentary rocks that metamorphosed to chlorite-sericite-carbonate schist (TS12 and CH16).

The geochemistry results both fire assay and ICP-MS shows the Ashashire gold and base metals doesn't show a clear relationship infers that the deposit is gold only.

## **8.2. Recommendations**

Most previous works have done in gold finding without well defining the geology, structures so further detail works needs in geological/lithological description and mapping. This is very important to easily describe the genesis of gold and sulfide minerals in mineral formation process and the area is affected by micro to macro level discontinuities. As a result, detailed scale geological mapping is very critical to expand the exploration surrounding Ashashire.

## APPENDIXES

Table 1 Whole rock geochemical data

S. ID	Recvd wt Kg	SiO2	Al2O3	Fe2O3	CaO	MgO	Na2O	K2O	Cr2O3	TiO2	MnO	P2O5	SrO	BaO	Total	LOI
CH01	0.02	42	11.6	14.45	8.95	4.8	3.14	0.04	0.013	1.94	0.21	0.16	0.02	<0.01	96.23	8.91
CH02	0.05	55.9	15.75	5.97	5.72	2.71	3.85	1.83	0.006	0.67	0.1	0.18	0.04	0.04	101.77	9
CH03	0.05	40.3	13.3	15.45	8.5	5.64	2.2	0.2	0.019	1.59	0.19	0.11	0.02	<0.01	100.87	13.35
CH04	0.05	65.9	6.65	7.06	5.59	2.82	1.01	0.32	0.01	0.83	0.11	0.05	0.02	<0.01	98.38	8.01
CH05	0.08	45	13.25	16.45	12.25	5.23	0.94	0.02	0.018	1.68	0.21	0.13	0.01	<0.01	101.48	6.29
CH06	0.07	49.7	11.25	9.04	8.87	3.86	1.76	0.74	0.011	0.77	0.17	0.05	0.02	0.01	96.15	9.9
CH07	0.07	66.3	15	2.37	2.4	1.24	4.63	1.56	0.006	0.19	0.03	0.07	0.05	0.05	98.03	4.13
CH08	0.06	44.3	9.55	6.75	11.35	7.56	0.16	2.61	0.113	0.19	0.13	0.01	0.05	0.04	101	18.19
CH09	0.06	61.7	15.5	3.13	4.1	2.46	5.5	1.35	0.014	0.29	0.05	0.16	0.06	0.06	101.03	6.66
CH10	0.07	53.5	15.05	12.3	3.88	4.32	5.85	0.13	0.003	0.7	0.17	0.14	0.01	<0.01	99.51	3.46

APPENDEXES 1. showing whole rock geochemical major and minor elements concentration data. Major and minor element concentration data using ME-MS06 with wt%, FUS-LI01 at a temperature 1025°C with 0.01 detection limit

Table 2. Multi element whole rock geochemical data from Ashashire, Western Ethiopia.

Samp.ID.	CH01	CH02	CH03	CH04	CH05	CH06	CH07	CH08	CH09	CH10
Cs	0.02	0.35	0.07	0.04	0.03	0.12	0.21	0.38	0.23	0.05
Rb	0.6	29.4	2.1	5.4	0.2	13.4	24.1	37.9	26.1	1.5
Ba	4.9	326	17.8	37	4.9	106	457	343	506	27
Th	0.55	1.96	0.28	0.17	0.26	0.23	1.07	0.25	4.22	0.63
U	0.13	0.68	0.07	0.14	0.06	0.12	0.61	0.2	1.48	0.28
La	5.5	12	3.9	1.9	4.1	2.5	7.7	1.9	25.2	5.2
Ce	15.3	24.3	11	5.5	12	6.3	13.6	4.5	45.4	11.5
Dy	6.89	2.52	5.7	2.52	6.29	3.32	0.45	1.22	1.13	2.36
Er	4.21	1.48	3.89	1.6	3.68	1.92	0.26	0.82	0.55	1.65
Eu	1.7	0.85	1.32	0.56	1.4	0.66	0.33	0.35	0.78	0.64
Ga	18.4	18.7	19.5	9.1	21	13.2	18.3	10.4	18.6	17.5
Gd	6.33	2.59	4.56	2.29	5.26	2.5	0.71	0.97	1.99	2.31
Hf	3.8	2.1	2.6	1.3	2.7	1.3	1.6	0.5	2.8	1.3
Ho	1.41	0.49	1.16	0.53	1.24	0.64	0.09	0.22	0.19	0.52
Lu	0.59	0.21	0.44	0.22	0.49	0.28	0.03	0.1	0.07	0.22
Nb	3.8	2.6	2.4	1.2	2.6	1.5	2.4	0.7	5.9	1.3
Nd	14.3	12.6	10	5	10.9	5.4	5.9	3	18.1	7.6
Sm	4.52	2.83	3.4	1.69	3.86	1.84	1.13	0.92	2.73	2
Sn	1	1	1	bdl	1	1	bdl	bdl	bdl	Bdl
Sr	157.5	311	137	185	137	255	376	460	528	63.4
Ta	0.3	0.2	0.2	0.1	0.2	0.1	0.1	bdl	0.3	0.1
Tb	1.01	0.38	0.82	0.37	0.83	0.45	0.08	0.15	0.21	0.37
Tm	0.58	0.24	0.51	0.2	0.5	0.32	0.03	0.12	0.07	0.23
W	2	12	2	7	2	32	5	9	2	Bdl
Y	38.4	14	31.1	13.4	34.2	17.8	2.1	6.8	5.4	14.3
Yb	3.84	1.47	3.02	1.48	3.48	1.97	0.17	0.72	0.44	1.73
Zr	131	77	91	45	98	47	67	20	104	42

*APPENDEXES 2. Trace element concentration of host rocks from Ashashire, Western Ethiopia.*

Table 3. Trace element concentration

Trace element concentration of mineralized carbonate-quartz veins using ICP-MS (ME-MS41) method																							
S.No.	Elts.	CH11	CH12	CH13	CH14	CH15	CH16	CH17	CH18	CH19	CH20	S.No.	Elts.	CH11	CH12	CH13	CH14	CH15	CH16	CH17	CH18	CH19	CH20
1	Au	4.36	2.04	2.4	1.87	1.59	8.38	0.06	0.02	0.98	<0.02	22	La	5.1	3.2	0.6	6.9	2.7	3.2	9.7	2.1	4.3	9.9
2	Ag	1.83	0.55	0.25	0.98	0.46	1	0.04	0.01	1.57	0.04	23	Mn	1740	1790	1000	1560	1320	995	304	1460	1130	683
4	Pb	2.8	2.3	3.8	3.5	1.7	2.4	0.7	0.9	1.7	0.9	24	Nb	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.07	<0.05
5	Zn	141	72	55	157	98	56	18	123	133	53	25	Ni	73.9	59.8	161.5	88.6	52.8	30.6	9.4	64.7	71.9	32.4
6	Cu	323	92.6	21.5	274	245	56.6	24.7	199	232	56.5	26	Rb	1.5	1	1.3	1.5	1	1	1.5	1	1.2	1.9
7	W	0.59	0.36	0.16	0.61	1.1	0.11	0.08	0.06	118.5	0.8	27	Re	0.001	0.002	0.001	0.001	0.001	0.001	<0.001	<0.001	0.001	<0.001
8	Co	57.8	50.4	35.6	73.2	42.3	25.7	6	55.5	48.9	16.5	28	Sb	3.91	2.51	0.22	2.15	0.2	0.78	0.45	0.29	1.52	0.35
9	Mo	0.08	0.28	0.84	0.25	0.65	0.28	0.12	0.14	0.82	0.23	29	Sc	27.3	17.1	3.9	33	19.2	6.8	0.5	23.1	19.8	5.4
10	Ni	73.9	59.8	161.5	88.6	52.8	30.6	9.4	64.7	71.9	32.4	30	Se	0.7	0.7	0.5	1.3	1.1	0.8	<0.2	<0.2	0.3	<0.2
11	As	12	31.6	3.6	7.9	1.2	1	0.2	1.8	6.2	1	31	Sn	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	0.2	0.2	<0.2
12	Ba	10	10	10	10	10	10	20	<10	40	10	32	Ta	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
13	Be	0.24	0.1	0.07	0.43	0.12	0.1	0.07	0.27	0.18	0.14	33	Te	5	2.58	70	2.53	1.43	11.35	0.06	0.02	1.05	0.01
14	Bi	0.34	0.18	0.24	0.29	0.28	0.48	0.02	0.02	0.13	0.02	34	Th	0.6	0.4	<0.2	0.5	0.2	0.4	1	0.2	0.7	1.1
15	Cd	0.28	0.2	0.21	0.18	0.16	0.15	0.03	0.09	0.37	0.1	35	Ga	11.1	3.16	0.48	15.9	9.23	2.19	1.06	16.65	7.57	6.26
16	Ce	14.55	9.41	1.35	20.6	9.01	8.57	17.4	6.37	11.65	19.6	36	Ge	0.07	<0.05	<0.05	0.1	0.06	<0.05	<0.05	0.08	0.06	<0.05
17	Cr	50	17	41	59	41	7	3	94	57	26	37	Hf	0.04	0.02	0.02	0.02	<0.02	<0.02	0.02	0.02	0.05	0.03
18	Cs	<0.05	<0.05	<0.05	0.05	<0.05	0.05	<0.05	<0.05	0.07	0.54	38	V	145	69	7	180	160	29	3	247	164	52
19	Hg	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	39	Y	9.43	3.76	1.21	7.1	6.87	2.67	1.03	15.75	5.7	8.29
20	Tl	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	40	Zr	1.3	0.5	<0.5	0.6	<0.5	<0.5	0.6	<0.5	1.3	1.2
21	U	0.1	0.07	0.05	0.12	<0.05	<0.05	0.05	0.05	0.11	0.09												

APPENDEXES 3. Trace element geochemical data in ppm at Ashashire, Western Ethiopia.

Table 4. Multi element concentrations

Fire Assay (Au-AA25) and IC-PMS (ME-MS41) Method for Precious and base metal assay result in ppm and major element in wt%																									
Hole ID	S.ID	Au1	Au2	Ag	Au2/Ag	Cu	Pb	As	Co	Cr	Mo	Ni	Sn	Zn	Al	Ca	K	Mg	Na	P	S	Ti	S	Sr ppm	Fe
ASDD002	CH11	5.04	4.36	1.83	2.3825	232	2.8	12	57.8	50	0.08	73.9	<0.2	141	3.37	6.91	0.08	3.27	0.02	930	2.96	0.009	2.96	230	11.2
ASDD002	CH12	2.49	2.04	0.55	3.7091	92.6	2.3	31.6	50.4	17	0.28	59.8	<0.2	72	0.84	7.65	0.05	2.99	0.06	560	4.92	<0.005	4.92	154.5	10.1
ASDD002	CH13	6.76	2.4	0.25	9.6	21.5	3.8	3.6	35.6	41	0.84	161.5	<0.2	55	0.19	6.51	0.08	3.22	0.04	10	1.9	<0.005	1.9	285	3.99
ASDD010	CH14	2.72	1.87	0.98	1.9082	274	3.5	7.9	73.2	59	0.25	88.6	<0.2	157	3.33	0.26	0.08	1.44	0.06	1020	0.02	0.01	0.02	38	15.7
ASRCD009	CH15	2.99	1.59	0.46	3.4565	245	1.7	1.2	42.3	41	0.65	52.8	<0.2	98	1.95	5.23	0.05	2.41	0.05	1070	2.25	0.02	2.25	80.8	8.84
ASRCD009	CH16	10.3	8.38	1	8.38	56.6	2.4	1	25.7	7	0.28	30.6	<0.2	56	0.66	4.55	0.05	2.31	0.04	130	3.62	<0.005	3.62	161.5	5.82
ASRCD009	CH17	8.81	0.06	0.04	1.5	24.7	0.7	0.2	6	3	0.12	9.4	<0.2	18	0.29	1.67	0.08	0.68	0.05	320	0.34	<0.005	0.34	51.6	1.32
ASDD010	CH18	0.1	0.02	0.01	2	199	0.9	1.8	55.5	94	0.14	64.7	0.2	123	3.49	0.55	0.06	2.58	0.1	870	<0.01	0.102	<0.01	24.4	9
ASDD001	CH19	2.38	0.98	1.57	0.6242	232	1.7	6.2	48.9	57	0.82	71.9	0.2	133	1.71	0.36	0.05	0.53	0.04	650	0.01	0.022	0.01	23.6	9.65
ASDD001	CH20	0.07	<0.02	0.04	Nd	56.5	0.9	1	16.5		0.23	32.4	<0.2	53	2.12	2.97	0.09	1.98	0.02	540	<0.01	0.026	<0.01	62.4	3.11

APPENDEXES 4. Fire assay(Au-AAS) the precious metal gold (Au1), and base metal and major element concentrations results using ME-MS41-ICP-MS. Table of trace element contents of mineralized calcite-quartz veins, geochemical data

Where Au1 is gold concentration using fire assay and Au2 represents gold concentration from ME-MS41-ICP-MS. Where 'nd' not defined.

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