ADDIS ABABA UNIVERSITY
SCHOOL OF GRADUATE STUDIES
SCHOOL OF EARTH SCIENCES

PETROGRAPHIC DESCRIPTION AND STRUCTURAL HISTORY OF THE MEGAB - HAWZIEN AREA,TIGRAY, NORTHERN ETHIOPIA

BY

MEHARI KINFE

A Thesis Submitted to School of Graduate Studies of Addis Ababa University, in Partial Fulfillment of the Requirements for the Degree of Master of Earth Sciences (Petrology)

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June, 2015

Abstract

The Megab - Hawzien area is a part of the Neoproterozoic basement rocks of Northern Ethiopia. The Northern Ethiopia is one of the regions where the basement units consisting of older, low-grade meta-volcanic rocks known as the Tsaliet Group and younger, low grade meta-sedimentary rocks referred to the Tambien Group. These low-grade meta-volcanic and meta-sedimentary rocks have long been considered to be part of the Arabian-Nubian Shield. The study area contains metavolcanic (i.e., meta-acidic) and metavolcanoclastic(i.e., felsic meta-volcanic breccia) rocks which belong to the Tsaliet Group; Phanerozoic formations such as Enticho sandstone, Adigrat sandstone and Edaga Arbi Glacials which are part of the Tambien Group; felsic sub intrusive; granite, and phyllite(i.e., spotty micaceous and quartzo-feldspathic) rock units. The largest part of the study area is covered by the MV and MVC rock units followed by the granite rock unit. The phyllite unit of the study area is not part of either the meta-volcanic or the meta-sedimentary units. It is rather an intervening zone between these two main units.

Depending on the field structural data analysis, the rock out crops of the study area has three phases of deformation. These are:- (i) the first or earlier phase of deformation(D1), (ii) the Second phase of deformation(D2), and (iii) the third phase of deformation(D3). D1 is associated with folding of primary bedding and appearance of tight to isoclinal minor folds, persistent foliation (S_1), and linear fabrics defined by platy minerals. D2 is related to N-S trending upright, open folds and crenulation lineations with sub horizontal fold axes without producing a pervasive foliation. D3 is recognized by brittle structures like reverse faults, quartz veins and joints.

Based on the petrographic study, the out crop units of the study area are dominated by index minerals such as chlorite, albite, epidote, muscovite, biotite, calcite and hornblende. These minerals indicate low grade metamorphism and this particularly belongs to the lower greenschist facies. The time relationship between metamorphism and deformation of the rock units of the study area are formed between the two tectonic events D1and D2 and hence they are called late or inter-tectonic.

Key words: Pan-African orogeny, Neoproterozoic, Arabian Nubian Shield, Megab-Hawzien area, metavolcanic rocks, metavolcanoclastic rocks, Phyllite, petrography, metamorphism, deformation, structures, porphyroblasts

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I would also like to extend my gratitude to the administrator of Megab-Hawzien town and the kind community living in and around the town. Especially Gidey Kiros who is working on the Hawzien Woreda Water Super vision deserves big thanks for making his many valuable activities during my unstable conditions raised by the local people of the study area.

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Lists of Acronyms/Abbreviations		
Technical Terms	**Minerals with their Symbols**	**Name of Area**
ANS = Arabian Nubian Shield	Ab = albite	M = Megab
EAO = East African Orogeny	Act =Actinolite	H = Hawzien
MB = Mozambique Belt	Bt=Biotite	HM = Hawzien-Megab
MV = Meta volcanic	Cal = calcite	asl = above sea level
MVC =Metavolcanoclastic	Chl = Chlorite	
F = fold	Ep = Epidote	
L = lineation	Grt = Garnet	
S = foliation	Hbl = Hornblende	
P = Pressure	K-fs = Potassium feldspar	
T = Temperature	Mcl = Microcline	
PPL = Plane Polarized light	Ms =Muscovite	
XPL = Cross Polarized light	Or =orthoclase	
Fig. = Figure	Op = Opaque	
	Pl = Plagioclase	
	Py = Pyrite	
	Qtz = Quartz	
	Ser = Sericite	

CHAPTER - ONE

INTRODUCTION

1.1.Back ground information of the study

The Pan-African Orogeny in north-east Africa consists of two major terrains. These are the Arabian-Nubian Shield (ANS) and the Mozambique Belt (MB). A review of existing data (Asrat et al., 2001) indicates that the ANS is an accretionary terrane of juvenile material (volcanic and volcano-sedimentary rocks) with dominantly subduction-related magmatism, where as the MB involved more recycling of older crustal material (gneisses and migmatites) and dominantly post collisional magmatism Asrat (2003).

The Ethiopian basement rocks are exposed in eastern, western, northern, and southern parts of the country (Asrat et al., 2001). The Northern Ethiopia is one of the regions where the basement units consisting of low-grade meta-volcanic and meta-sedimentary rocks are extensively exposed. These low-grade meta-volcanic and meta-sedimentary rocks have long been considered to be part of the Arabian-Nubian Shield (Alene M., 2006). The Arabian-Nubian Shield is the largest terrane, which is well exposed over much of north-east Africa and western Arabia, which consists of dominantly Juvenile Neoproterozoic rock. It extends from Jordan and southern Israel in the north to Eritrea and Ethiopia in the south and from Egypt in the west to Saudi Arabia and Oman in the east(Fig.1.1A) (Miller et al., 2009). The basement rocks of the Tigray and Eritrea plateau are part of the younger complex of the Precambrian rocks of Ethiopia, which represents a folded geosynclinal belt in the Mozambique Belt (Kazmin,1970 as cited in Beyth M., 1971). The basement complex are mainly shales, limestones and meta-volcanics . The shales and metavolcanics may be represented by quartzite's as metamorphic products. Quartz veins are very common in all rock types . the Basement complex is peneplaned and preserved in its original form by the overlain sediments (Levitte D., 1970).

Furthermore, the geology of northern Ethiopia is composed of Precambrian (Neoproterozoic) crystalline basement rocks that are overlain by Paleozoic and Mesozoic sediments , and at the top by Cenozoic volcanics.

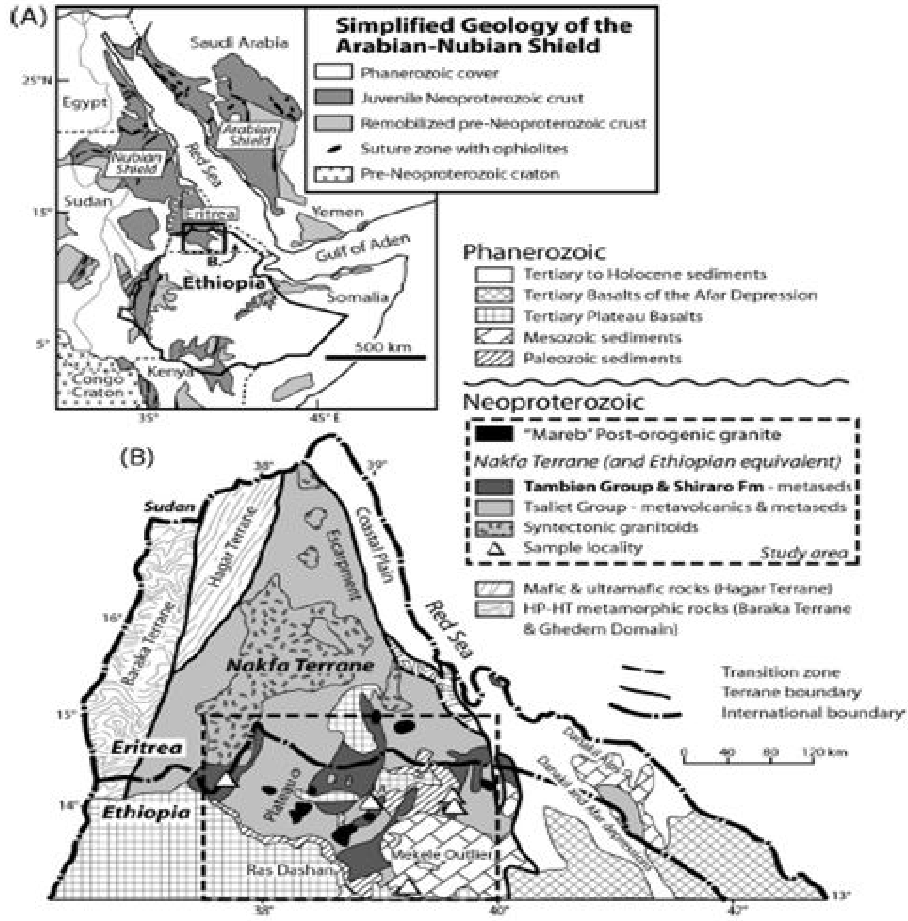


Fig.1.1 (A) The extent area in Northern Ethiopia with in juvenile Neoproterozoic crust of the Southern Arabian- Nubian Shield.(B) Enlargement of area(Fig. 1.1 A inset map) showing the general geology and distribution of Tambien group in relation to the extension of southern part of ANS (Miller et al., 2009a).

The crystalline basement consists of low-grade metamorphic rocks that were intruded by Syn- and post-tectonic granites and granodiorites. The metamorphic rocks are composed of an older island arc meta-volcanic sequence, the Tsaliet group, and a young meta-sediment sequence which is termed as the Tambien group. The Tambien group consists of inter-bedded carbonates and siliciclastic sediments, locally covered by glaciogenic diamictites (Fig.1.2). All studied paleo-landforms of glacial erosion, except of the intra-formational grooves in the Megab area, occur on Precambrian basement or on lower Enticho sandstone directly beneath or on lapped by the Edaga Arbi Glacials (Bussert R., 2010a).

In general, the late Precambrian 'basement ' stratigraphy of Northern Ethiopia (Tigray region) can be classified and ordered as follows: (i) Late-to post-tectonic granitoids(the youngest); (ii) Shiraro Formation; (iii) Didikama Formation; (iv)

Tambien Group(younger); and (v)Tsaliet Group(the oldest) Alene(1998); Beyth(1972); Kazmin(1972) and Mengesha et al.(1996). A considerable part of Northern Ethiopia is underlain by low-grade belt (Tsaliet Group) which is presumably younger than the low-grade belts in southern and western Ethiopia (Fig.1.2). The youngest Precambrian units that underlie Northern Ethiopia are dominantly clastics with subordinate carbonates (Tambien Group). The Tambien Group has been divided into the Arequa Formation (lower unit) and Mai- Kenetal limestone (upper unit). The Arequa Formation is mainly dominated by slates. This formation is subdivided into Werei Slate, Assem Limestone and Tsedia slate, from bottom to top and all have conformable relationships (Garland, 1980). Didikama Formation conformably overlies the Tambien Group in central and eastern Tigray region. However, in the West where the Tambien Group is not fully developed or the upper formations of the Tambien Group are missing, it rests unconformably on older formations. In the Shiraro area, at Negash Syncline, it is unconformably overlapped by the youngest Precambrian formation in Ethiopia, Matheos Formation (Garland: 1980). According to Beyth et al.(2003), the Tambien group contains slates, phyllites, greywakes, limestone, quartizic dolomites that are deposited on the geosynclinal basins of the region as opposed to the Tsaliet metavolcanics which are found on the anticlines. Moreover, the Tambien group are exposed on four isolated synclinoria, from west to east. These are the Shiraro, Mai-Kenetal, Chemit and Negash forming probably unconformable contact with the underlying older Tsaliet metavolcanics (Beyth, 1971, 1972; Miller et al., 2009).

Asrat et al.(2003) proposed that, the Tigray basement complex is generally characterized by steeply dipping and extensively folded, low-grade metamorphic rocks intruded by various granitic and mafic intrusions. Intrusive igneous rocks of granitic origin collectively known as ‘Mereb’ Granites (Beyth, 1972) that post dated the tectonic activities in the area penetrates the older units of metamorphic rocks of both volcanic and sedimentary origin with almost circular massif consisting of monzogranites, granodiorites, diorites-gabrodiorites, and hybrid diorites (Asrat et al., 2003). The metamorphic rocks found near the granitoids commonly exhibit a poiklitic texture due to the heat released from the intrusive granitic bodies. Potential economic mineral deposits are usually associated with these granitoids found in the northern Ethiopia. Because the post tectonic granitic intrusives facilitates the hydrothermal activities while the highly foliated Precambrian host rocks are controlling the nature of mineralization (Tadesse et al., 2003 as cited in Desta, 2014).

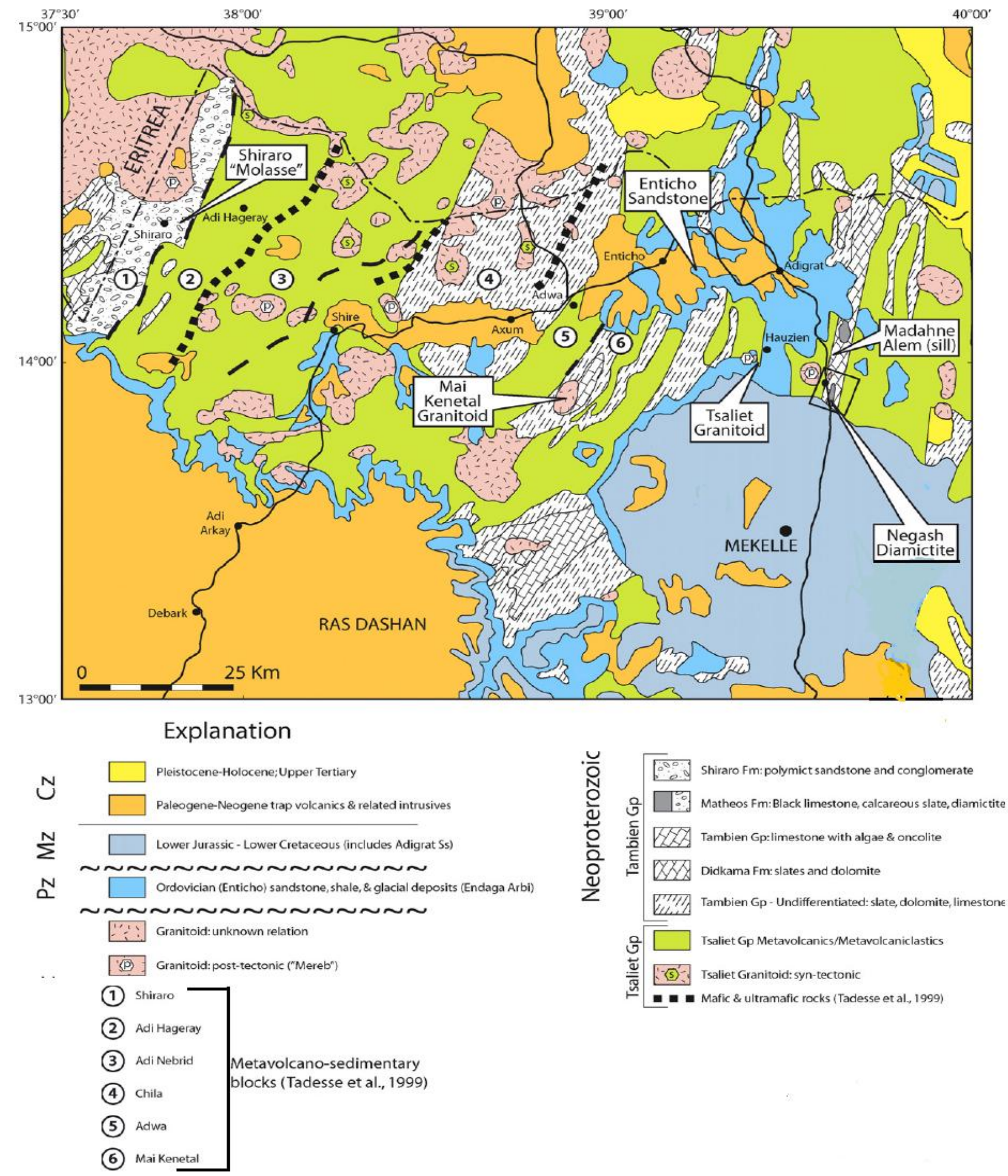


Fig. 1.2. Distribution of rock types in Northern Ethiopia, Tigray (Modified from Avigad et al., 2007as cited in Desta Dawit., 2014).

1.2 Description of the study area

1.2.1 Location and accessibility

The Megab metamorphic terrain is located in the Hawzien woreda, in the NE of Tigray regional state, Northern Ethiopia. It is located at about 120km, northeastern of Mekelle city, which is the capital city of Tigray region, that is located 780km from the capital city of the country, Addis Ababa. However, the study area is 7km far away from the Hawzien woreda town in the direction of Southwestern (Fig.1.3). The Asphalt road is running from Addis Ababa through Debre Brhan -Alamata - Mekele to Wukiro - Fireweyni -Adigrat-Adwa town, and gravel road from Friweyni to Hawzien. But the gravel road is now being up-graded to Asphalt. There are also all- weather motorable gravel roads crossing the area. Throughout the study area there is a good network of foot trails connecting the various settlement and villages; these serve as a traversing routes in the area. Geographically, the study area is bounded by/located between/ Easting: 0540000 to 0547000 and Northing: 1535000 to 1541000 in UTM. It has a total area of 42km^2.

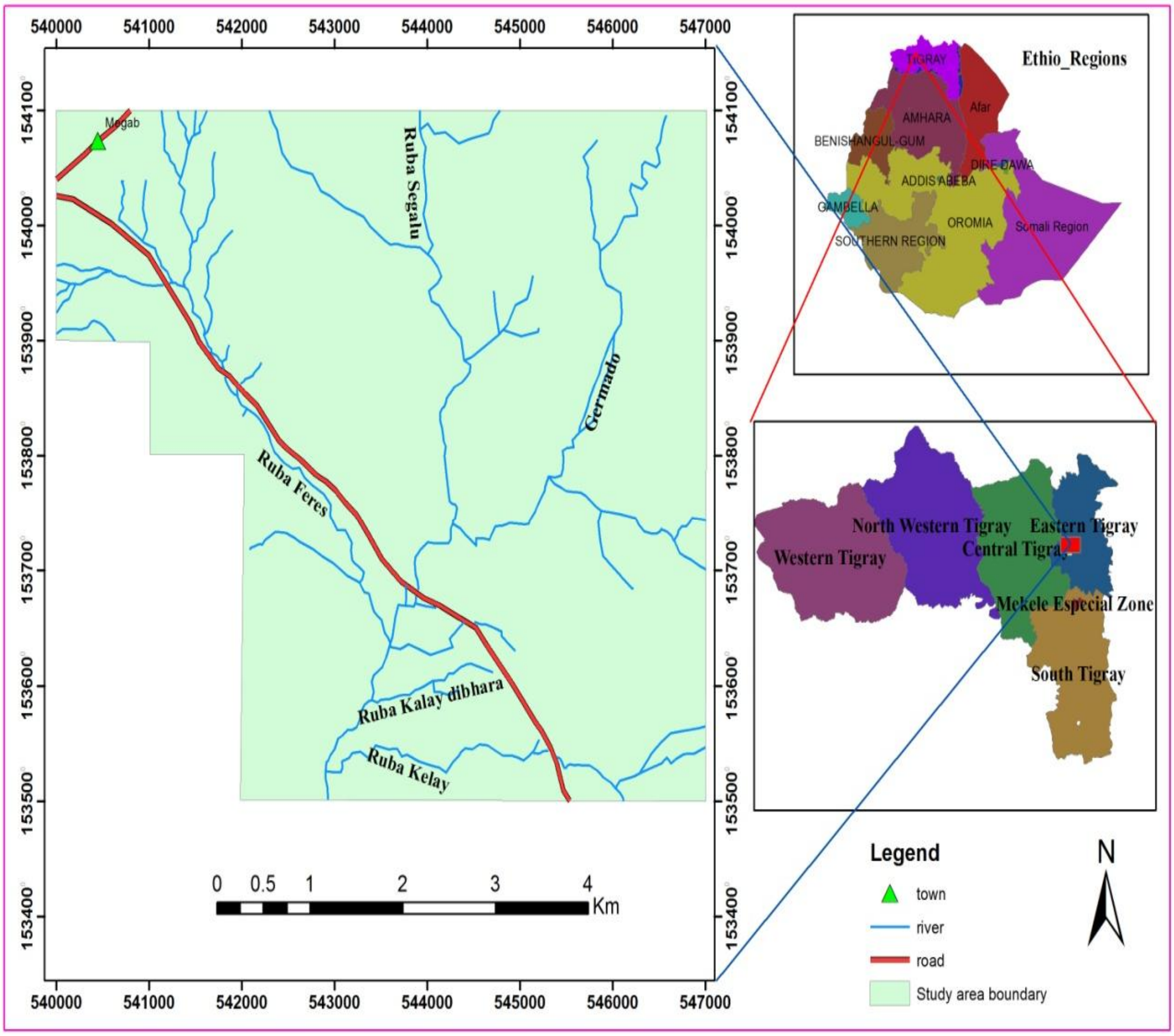


Fig. 1.3 Location map of the study area.

1.2.2 Physiography

The study area lies within the highland and lowlands of the basement complex of Northern Ethiopia, and is characterized by variable flat and rugged topographies. The elevation value of the study area varies from 1960m a.s.l in the south-western part to about 2160m a.s.l in the north-eastern part(Fig.1.4). In south-western part of the study area; the topography is dominantly highland that is covered by phanerozoic formations (including the Adigrat sandstone cliffs) where as in the central and north-eastern part of the study area; the topography is relatively dominated by flat(low) land that is mostly covered by granite (pluton); phyllite; and meta-volcanic and meta-volcanoclastic units. The drainage pattern of the study area is mainly controlled by the intermittent Ruba Segalu, Ruba Feres, Geremado and Ruba kelay, which are a tributary for the perennial Ruba kalaydibhara in the south-western of the study area.

The study area, in general Tigray is one of the northern province / part of Ethiopia and which is one of the historical regions of the country where ancient city like Axum and Yeha are found. The region is also known for its various monuments like Axum Obelisks; old historical churches such as Axum Tsion, Abune Aregawi Damo , Abreha we Atsbeha (hewn rock church) ; monasteries such as Waldiba Gedam , Debre Abay ; mosques such as Negash (Wukiro) and sculptures.

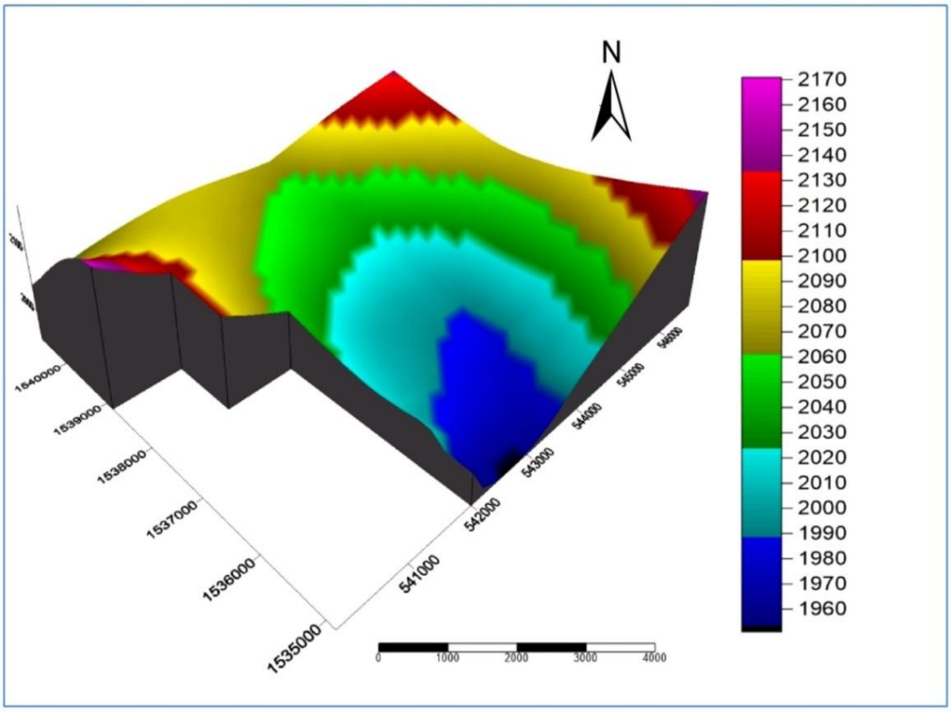


Fig.1.4 Physiographic map digital elevation model of the study area

1.2.3 Climate and vegetation

The study area is mainly characterized by arid and semi-arid climatic conditions with the major rainy season (locally called kiremti) lasts for 3 to 4 months, between June and mid-September.

The climate is generally sub-tropical with an extended dry period of nine to ten months and a maximum effective rainy season of two to three months. The rainfall pattern is predominantly uni-modal (June to early September). In short, the study area has semi-arid climate characterized by long dry and short rainy season. The mean annual rainfall is 535 mm and most of the rainfall exists between June to September. The maximum and minimum rainfall record is 707 mm in 1983 and 360 mm in 1982 respectively. The mean maximum and mean minimum temperature of the study area is 27.9 °C in May and 7.8 °C in December respectively. According to local agro-climate zone classification based on altitude and rainfall, the study area is categorized under Weyinadega agro-climatic zone (18 years statistical analysis data of Hawzen district (1979-1989 and 2000-2006) as cited in Fasil E., 2007). But when we see the climate condition regionally, the Tigray region climatic condition vary from arid to semi-arid with average annual rainfall of 600-800mm and annual average temperature of 25°C (Garland, 1980). The vegetation cover of the study area is relatively sparse and poor. However, there is lots of terracing is done on most of the hills of the area by the local people to increase the vegetation cover of the area and encouraging results have been obtained so far which are clearly seen on the area. The relatively vegetated areas are covered by thorny bushes, shrubs, grasses, and deciduous trees such as acacia, which are characteristics of the semi-arid climate condition.

1.2.4 Settlement

The area is inhabited by Tigrigna speaking people and the official language of the Tigriyan people /Tigray region/ is Tigrigna . The density of the population varies from place to place and most of them are farmers. Generally, the society is sparsely populated and their main living and economic potential is dependent on small scale agricultural activities and domestic animals like breeding- cattle, goat ,sheep and donkey. The agricultural crops that grow in the study area includes corn, teff, barley, dagussa, sorghum, maize and wheat. In addition to this, some of the local people perform panning activities from streams to drive gold as an additional economic source. Within the Megab, which is small town found within the study area; the population is denser due to the easily accessible of infrastructures, facilities and roads. Whereas the rest of the study area is sparsely populated due to limited availability of infrastructures, facilities and roads. Their religion is mostly Orthodox Christians with very few Muslim, Tehadiso and protestant.

1.3.Problem statement

The phyllite unit of the study area (Megab-Hawzien area, Tigray, Northern Ethiopia) which has previously been mapped as different unit by different authors; as meta-sedimentary or Tambien Group (Arkin et al., 1971) , as meta-volcanic or Tsaliet Group (Garland, 1972; 1980). On the other hand, Miller et al.(2003) described this unit as a transitional lithology.

Furthermore, this unit has not been studied at large scale. Hence, the study area is not well defined in terms of the type of lithologic units, structural features and the degree of metamorphism as well as phase of deformation. Therefore, investigating the petrologic (phyllite unit), mineralogic and structural features in the area to certain detailed mapping (1:25,000) will have a great advantage to understand and differentiate the type of lithologic units, mineralogy and structures along with the degree of metamorphism and phases of deformation that exist in the study area (Tesfaye Ragasa., 2013).

Finally, detailed mapping of the lithologic (petrologic), mineralogic and geologic structures at large scale has never done in the study area before and this research intends to fill this gap.

1.4.Objective of the Study

1.4.1 General Objectives

The general objectives of this Study includes:-

- ❖ To elucidate/ clarify the characteristic features of the phyllitic unit of the study area.
- ❖ Understanding the Metamorphic and Deformational history of the area.

1.4.2 Specific Objectives

The specific objectives of the study includes:-

- ✓ Petro-graphic analysis of representative samples from each units to determine the litho-logic units and mineralogical composition of the study area.

- ✓ Structural data analysis and interpretation of the study area. These can be folds, foliations, faults and joints.
- ✓ To determine the characteristic features of the observed meta-volcanic rocks and meta-sediments of the study area.
- ✓ To produce a geological map of the study area at a scale of 1:25,000.

1.5 Significance of the study

After successful compilation of this research the following intended peoples and organizations are benefited directly or indirectly. These includes:-

- Governmental organizations (mines and energy bureau of the region as well as the country).
- Different non-governmental organizations such as exploration and mining companies.
- Research institutions
- To fill the existing gap of detail information about metamorphic terrain in the Hawzien woreda, Tigray, Northern Ethiopia.
- This is also important for partial fulfillment of the requirements for the Degree Master of Science in Petrology.

1.6 Materials and Methodology

1.6.1 Materials

The required field and laboratory instruments for this study during the geological investigations are:-

- Topographic map(s), Aerial photos and satellite images.
- GPS (Geographic Positioning System)
- Geological Hammer
- Hand Lenses
- Sample Bag
- Brunton Compass
- Digital Camera
- Meter Tapes (30m)
- Hcl (10% solution)
- Petrographic Microscope(Leica)
- Softwares such as Stereographic projection(Stereo net 8), Arc CIS 10, Global Mapper 11, Surfer 10 and Strater.

1.6.2.Methodology

To achieve the general and specific objectives of the study successfully; the following methods and approaches will be followed/conducted:-

1.6.2.1. Pre-Field Work

The main activities that were conducted during the pre-field work includes reviewing and compiling literatures(published papers and unpublished reports) and related books; reviewing, extracting (delineating) and compiling of relevant information from geological and/ or topographic maps, aerial photos and Satellite images. The base map, with the scale of 1:25,000, has also been obtained by enlarging from Hawzien topographic map (1 : 50,000) of sheet number1339 A2.

1.6.2.2. Field Work

Field work has been carried out from February 18- 28, 2015 during the second visit to the study area. Seven(7) east-west and one (1) south-west traverse lines have been systematically selected based on the assumption that the different rock units are encountered through this line; targeting to cross the general N-S trending regional structures/foliation that helps to find maximum lithological and structural variations; and also enable to cover the study area. Geologic map of Adigrat and Mekele sheets at scale of 1:250,000 , geological map of Ethiopia 2nd Ed-1 at a scale of 1: 2,000,000 , topographic map of Hawzien at scale 1:50,000 and Google earth maps at scale of 1:25,000 are used during mapping the study area. Accordingly, while going along the chosen route geological mapping, outcrop/lithological description, rock sampling and structural measurement and recording, both planar and linear structures have been conducted. Lithologic units are described in terms of color, mineralogy, texture/fabric and structures (both primary and secondary structures i.e. foliation, lineation, fold, joints, veins, fractures); and the contacts present in the outcrop. For further structural analysis the strike and dip (amounts and directions) of planar geologic structures and the plunge amount and direction of lineation are taken, recorded and plotted for understanding the structural history of the area.

In addition, several photos have been taken, using a Canon digital camera with 16mega pixels, 8x optical zooming and HD, in order to complement and enhance the clarity of descriptions. About a total of twenty five (25) representative samples were collected for petrographic and hand specimen study, and for micro-structural analysis during the 10days of field work from which 16 samples are selected for final thin section lab preparation. The samples are carefully labeled (sample number and location) and inserted in to new separate plastic bag. Following the completion of the field map, the geological map was scanned, geo-referenced and digitized using Arc GIS 10.

1.6.2.3 Post-Field Work

There are two major tasks that were conducted during the post-field work. These includes:- petrographic /laboratory/ analysis and structural data analysis. Let we describe them individually.

1.6.2.3.1 Petrographic /Laboratory /analysis

In order to identify any variations in mineralogy and rock fabrics and /or microstructures under petrographic microscope, relatively fresh and representative samples have been collected from the study area.

After that, the rock samples are cut perpendicular to foliations/ lineations to prepare thin sections. 16 (sixteen) thin sections have been prepared at the School of Earth Sciences, Addis Ababa University. Thin sections have been examined, under Leica petrographic microscope for the purpose of identification of mineral assemblages, rock fabrics, understanding the metamorphic conditions as well as for micro-structural and micro-textural analysis. Such studies are very useful in the interpretation of the relative ages of different structures; because magnification allows identifying crosscutting and other detailed relations more clearly.

1.6.2.3.2 Structural data analysis

Analysis of all structural data collected from the field contains different structural elements such as foliations, joints, lineations, fractures /cracks, fault planes and folds are plotted using Equal-area or equal-angle plots (informally known as stereo plots) or stereo projection software(*Stereo net 8* software).

Stereographic projection software (stereo-pro) has been used to quantitatively represent three-dimensional orientation data (such as the attitudes of lines and planes) on a two-dimensional plot to analyze the structural data and visualize the connection between the orientations of structures in the field or on the map and the complex patterns of lines/planes plotted on the stereo-net.

Field information was compiled using Arc GIS software to generate the detail geological map at scale of 1:25,000, which shows lithological units, major geological structures, Stratigraphic sequences and foliation orientation/attitude. Furthermore, differentiation of deformational phases, classification of structural elements and domains have been made regarding to this work .

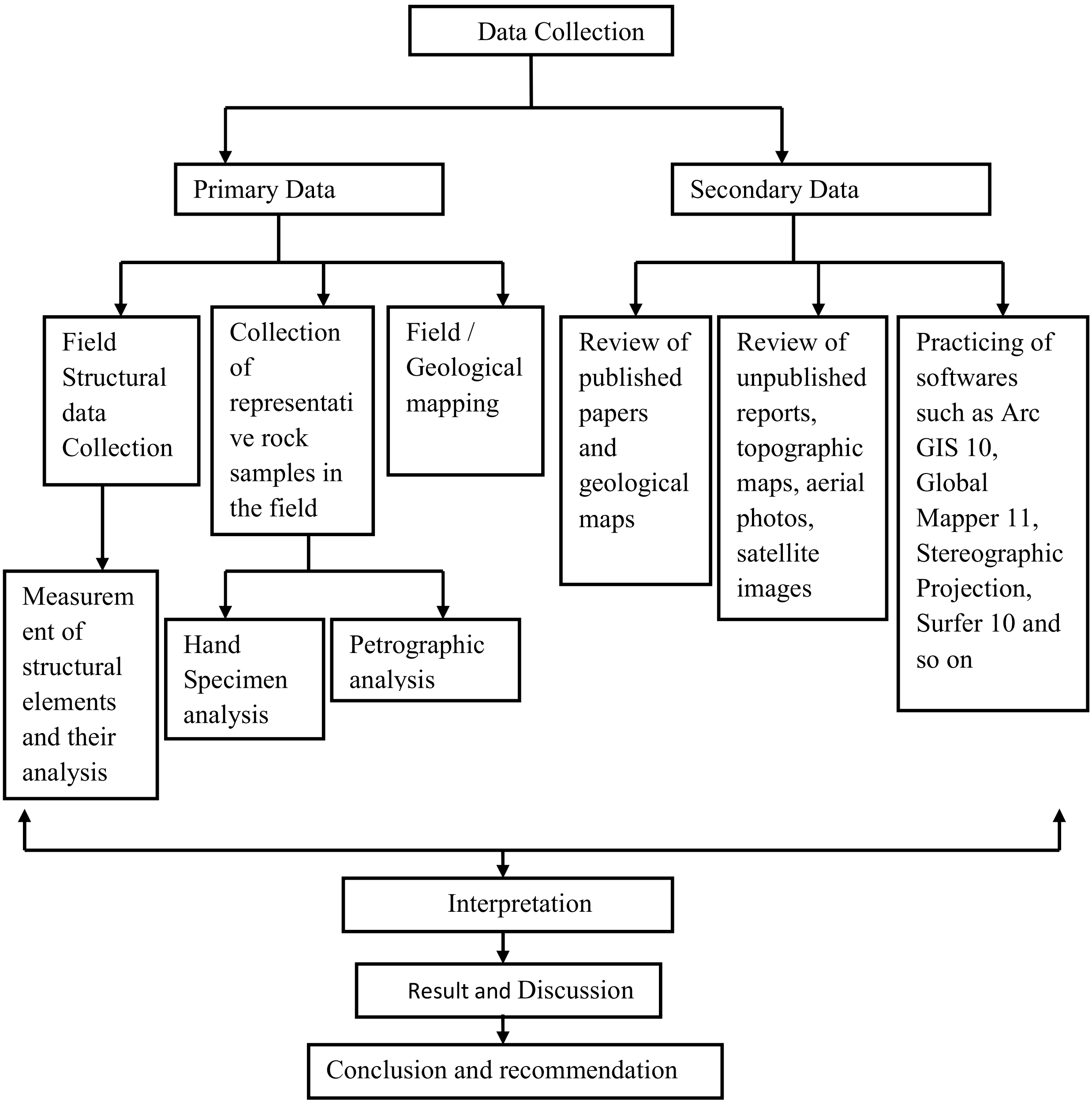


Fig. 1.5 Schematic flow diagram of data collection that summarize the Methodology.

CHAPTER - TWO

REGIONAL GEOLOGY OF THE STUDY AREA

2.1 Pan- African / East African Orogeny

The Gondwanaland was assembled during the Neoproterozoic from two fragments--East and West Gondwanaland--along the Pan-African Mozambique Belt of East Africa and its extension to the north, the Arabian Nubian Shield(McWilliams(1981)as cited in stern(1994)).
According to Tsige and Abdelsalam (2005), the Neoproterozoic (1000-550Ma) tectonics in the Arabian-Nubian Shield and the Mozambique Belt is often referred to as the Pan African Orogeny or East African Orogeny (Fig.2.1).

The East African Orogeny is developed due to the collision of East and West Gondwana (Fig. 2.1) during the late Proterozoic and finally formed the Gondwana Supercontinent. It represents one of Earth's greatest collision zones with about 6000 Km long and evolved over a time period of about 350 Ma (Stern 1994; Stern 2002; Stern et al., 2005 as cited in GebreMariam S. (2009)).

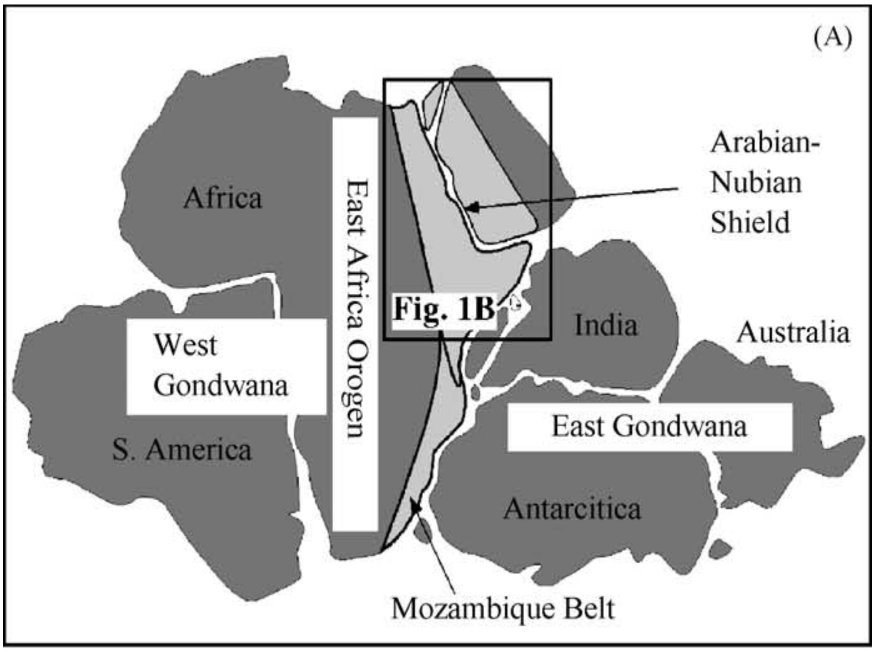


Fig. 2.1 The East African Orogen /Pan African Orogen/ between east and west Gondwana (Tsige and Abdelsalam, 2005).

According to Beyth et al.(2003) and Stern et al.(2006), the evolution of the East African Orogeny manifested a Wilson cycle with the following major geological stages and timing(Fig.2.2):

(1) rifting of Rodinia followed by development of Mozambique Ocean, and formation of juvenile crust by sea-floor spreading (~850–750 Ma);

(2) seafloor spreading, arc and back-arc basin formation, and terrain accretion (870 - 690 Ma);

(3) subduction and continental collision of East and West Gondwana (750–634 Ma);

(4) intrusion of late orogenic granitoids (~650 Ma);

(5) transitional period in which escape tectonics occurred (~625–610 Ma); and

(6) extensional tectonics and magmatic activities (~600–545Ma). According to Berhe (1990) and Asrat et al.(2001), the southern part of the East African Orogen is represented by the Mozambique Belt, which is formed by Himalayan-type collision. This comprises high-grade gneisses, migmatites and schists that can be traced in southern, western, and eastern Ethiopia.

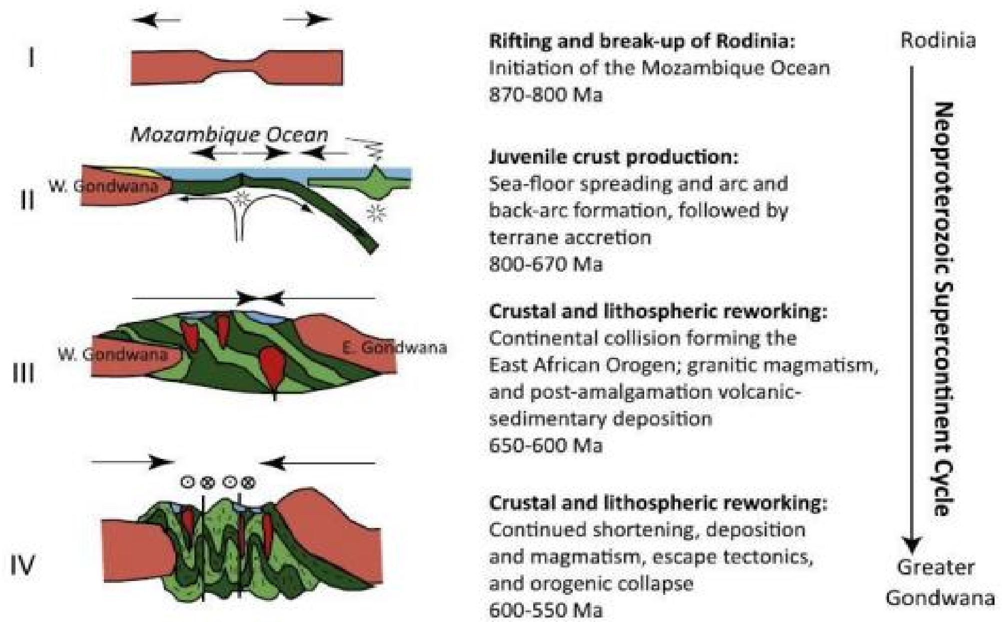


Fig. 2.2 A schematic diagram of the suggested stages of tectonic evolution of the East African Orogeny (modified after Stern and Johnson, 2010 as cited in Eyob Abebe., 2013).

2.2 Geology of the Arabian -Nubian Shield

The Pan-African orogeny contains two broad types of mobile belts. The first one consists predominantly of Neoproterozoic supracrustal and magmatic assemblages, many of juvenile (mantle derived) origin, with structural and metamorphic histories that are similar to those in Phanerozoic collision and accretion belts. These belts expose upper to middle crustal levels and contain diagnostic features such as ophiolites, subduction- or collision-related granitoids, island-arc or passive continental margin assemblages as well as exotic terrains that permit reconstruction of their evolution in Phanerozoic-style plate tectonic scenarios. The Arabian-Nubian shield of Arabia and north-east Africa are included in such belts. The second type of mobile belt generally contains polydeformed high-grade metamorphic assemblages, exposing middle to lower crustal levels, whose origin, environment of formation and structural evolution are more difficult to reconstruct. The protolith of these assemblages consist predominantly of much older Mesoproterozoic to Archaean continental crust that was strongly reworked during the Neoproterozoic. The Mozambique Belt of East Africa, including Madagascar are examples of such belts. This type of belt represents deeply eroded Part of a collisional orogen and that the two types of Pan-African belts are not fundamentally different but constitute different crustal levels of collisional and/or accretional Systems. That is why, the term East African Orogen has been proposed for the combined upper crustal Arabian-Nubian Shield and lower crustal Mozambique Belt (Figure 2.3). The ANS is characterized by its dominant juvenile nature, relatively low grade of metamorphism, and abundance of island-arc rocks and ophiolites comparing to the Mozambique Belt (Kroner and Stern, 2005).

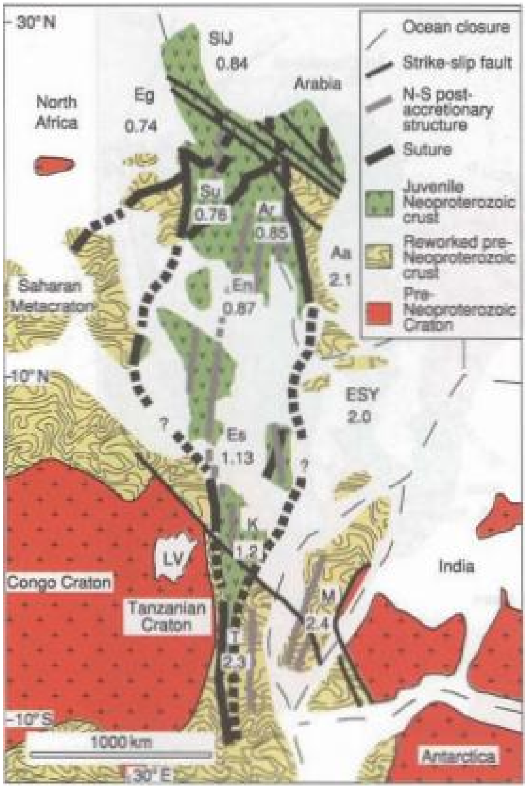


Fig.2.3 PreJurassic configurations of elements of the East African Orogen in Africa and surrounding regions. Regions include Egypt (Eg), Sudan (Su), Sinai-Israel-Jordan (SIJ), Afif terrane, Arabia (Aa), rest of Arabian Shield (Ar), Eritrea and northern Ethiopia (En), southern Ethiopia (Es), eastern Ethiopia, Somalia, and Yemen (ESY), Kenya (K), Tanzania (T), and Madagascar (M). Numbers in italics beneath each region label are mean Nd-model ages in Gy (After Kroner and Stern, 2005).

The ANS contains many accretion of terrenes. For this reason, it is known as a collage of terranes (Johnson and Woldehaimanot, 2003).This took place from ≈780 Ma to ≈550 Ma. The ANS consists of three principal units (Fig. 2.3). These are:-

The first one(1) is gneissic terrenes dominated by quartzo feldspathic gneisses, migmatites, and meta-sediments of amphibolite to granulite facies, which are found in the western part of the Nubian shield (e.g. Halfa and Bayuda terranes, Sudan), eastern Arabian shield (Afif and Al Rayn terranes, Saudi Arabia), and in some regions of the central part of the shield such as the Barka and Ghedem Terranes of Eritrea, Red Sea Hills of Sudan, and Aswan region of Egypt (Vail 1985; Johnson and Woldehaimanot, 2003). These high grade rocks were derived from continental crust recycled during the East African Orogen(EAO).

The second one (2) is green schist to lower amphibolite metamorphosed volcano-sedimentary terranes including calc-alkaline basaltic and andestic lavas, tuffs, pyroclastics, and rhyolites, which are intruded by various pre-, syn-, and post-tectonic granitoids and occurring between the western and eastern gneissic terrain (Vail, 1985). Geochemical and Nd, Sr, and Pb isotope characteristics of the rocks of this terrain shows that they resulted from accretion of intra-oceanic island arcs composed of juvenile Neoproterozoic crust, which is mainly derived from a depleted mantle source (Kröner et al., 1991; Stern, 1994; Stern, 2002; Beyth et al. 1997; Stern and Abdelsalam, 1998, Tadesse et al., 1999; 2000; Teklay et al., 2002, Anderson et al., 2006 as cited in GebreMariam S., 2009).

The third one(3) is mafic-ultramafic suites comprising ophiolite assemblages, narrow discontinuous belts of dismembered serpentinites, gabbros, sheeted dikes, pillow lavas, and ultramafic rocks. These mafic-ultramafic suites are interpreted to represent suture zones between intra-oceanic plates or continent-island arc margins (Kröner ,1985; Vail 1985; Berhe 1990). According to Abdelsalam and Stern (1996), the ANS has to two deformational belts. These are: (1) Related to arc-arc and arc-continent collision, which are both associated with sutures. The arc-arc deformation belts are manifested by the occurrence of E-W and N-S verging ophiolities in the northern and southern parts of the ANS respectively. The E-W verging ophiolities are steepened by upright folds, whereas those of N-S vergence are deformed by up-right folds and strike slip faults related to oblique collision of the terranes at about 800-700 Ma. The arc continent deformation belts are related to the collision of East and West Gondwana. (2) Post accretionary structures (~650-550 Ma) resulted from continuous shortening of the ANS and developed NW trending strike slip faults and shear zones during the waning stages of ANS formation (GebreMariam S., 2009).

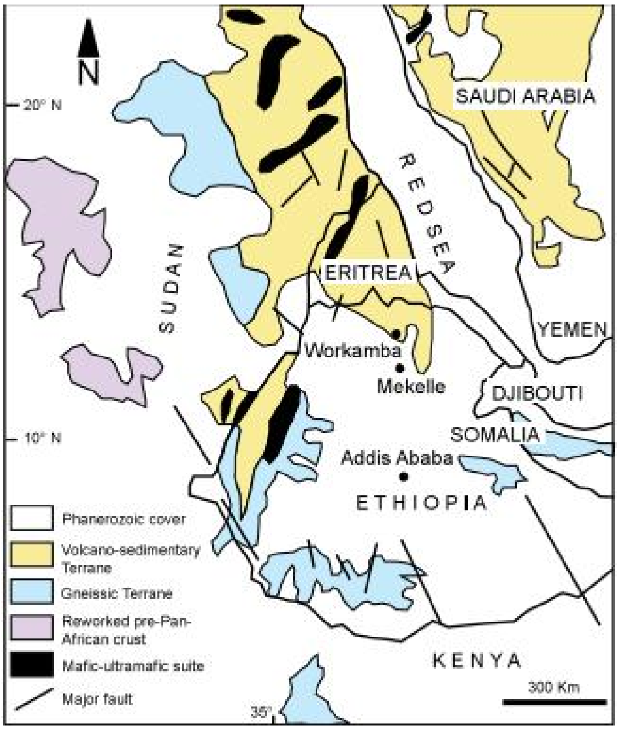


Fig. 2.4 Distribution of rocks of the Arabian-Nubian Shield, which form the basement rocks Arabian Peninsula, northeast Africa (Egypt and Sudan), and Ethiopia (modified from Ayalew et al., 1990; Berhe,1990; Asrat et.al., 2001 as cited in GebreMariam S., 2009).

2.3 Geology of the Ethiopian Basement Complex

Based on the compositional, deformational and metamorphic grade variations; the Ethiopian basement rocks are classified into three complexes. These are the Lower, Middle and Upper Complexes (Kazmin, 1975; Kazmin et al., 1978).

The Lower Complex formed of high grade gneisses represent older (older than 2500 Ma) cratonic basement and it is believed to be a direct northward continuation of Mozambique Belt.

The gneisses of the Archaean complex have been grouped into the following five major Units:

1. Konso Group which consists of relatively mafic rich hornblende gneiss, amphibolite and a mafic rich granulite.

2. Alghe Group consisting of dominantly gray biotite-hornblende gneiss and granulite of variable color, in part containing ill-defined masses of relatively uniform orthogneiss of granodioritic, tonalitic and dioritic compositions.

3. Awata Group which comprises well layered gneiss and granulite containing clearly recognizable meta-sedimentary components.

4. Yabello Group made of pale pink to light gray quartzo-feldspathic gneiss and granulite, generally leucocratic and having a granitic composition.
5. Baro Group consisting of ortho and paragneisses and migmatite, metamorphosed to upper amphibolite facies in the Western part of the country.

The Middle Complex (clastic meta-sediments) is presumably the Lower to Middle Proterozoic platform cover. Wadera Group and Boye Group have been identified in Sidamo and Hararghe regions and possibly occur in the western part of the country. The lower parts of the Complex are well developed in Sidamo and Wollega regions (Kazmin, 1972; Kazmin.et al., 1978). The Late Proterozoic Birbir and Tulu Dimtu Groups crop out in Wollega and extend through Gojam into northern Ethiopia. They form the youngest Precambrian basement units in northern Ethiopia (Kazmin, 1975, Garland, 1980).

The Upper Complex consists of low-grade rocks such as ophiolitic rocks, andesitic metavolcanics and associated meta-sediments, clastic and to less extent carbonate sediments. Furthermore, the Upper Complex rocks occur in the South, Adola zone (Adola Group and Kadjimiti beds), in the West (Birbir Group), in the East (Soka Group) and in the North (Tsaliet Group, Tambien Group, and other Younger meta-sediments).

The Ethiopian basement rocks also called the Precambrian rocks of Ethiopia are exposed in four major regions around the plateau margins. These are: (1) the Precambrian rocks of Northern Ethiopia (Tigray); (2) the Precambrian rocks of Southern and Southwestern Ethiopia (Sidamo and Konso); (3) the Precambrian rocks of western Ethiopia(Gojjam, Wollega, Illubabor and Birbir) and (4) the Precambrian rocks of Eastern Ethiopia (Hararghe).

2.3.1.The Precambrian rocks of Northern Ethiopia

The Northern Ethiopian Precambrian rocks are characterized by the occurrence of low-grade volcanic, volcano-sedimentary, mafic and ultramafic rocks of ophiolitic character, and plutonic rocks of typical Arabian-Nubian Shield assemblages. The Precambrian rocks of northern Ethiopia are classified into: - (i) Tsaliet Group, (ii) Tambien Group, (iii) Didikama Formation, and (iv) Shiraro Formation (Beyth, 1972; Kazmin, 1972 and Mengesha et al., 1996). A considerable part of northern Ethiopia is underlain by low-grade belt (Tsaliet Group) which is presumably younger than the low-grade belts in southern and western Ethiopia. The youngest Precambrian units that underlie northern Ethiopia are dominantly meta-sediments (Tambien Group).

2.3.2. The Precambrian rocks of Southern and Southwestern Ethiopia

Stern (1994) proposed that the Precambrian rocks of Southern and south western Ethiopia occupies an important position within the Pan-African Mozambique Belt and the Arabian–Nubian Shield. These rocks were traditionally divided into Lower, Middle and Upper Complex based on the variation in grade of metamorphism (Kazmin, 1972; Kazmin et al., 1978). In addition to this, the Precambrian rocks of south and southwestern Ethiopia comprises both high-grade gneissic terrain of the Mozambique Belt and low-grade metavolcano-sedimentary sequences of the Arabian-Nubian Shield. Furthermore, Stern (1994) proposed that the N-trending structures in southern Ethiopia are the roots of northward expulsion of the Arabian-Nubian Shield from the Mozambique Belt, following a Tibetan-type continent-continent collision between east and west Gondwana along the Mozambique Belt after the consumption of the Mozambique Ocean. Moreover, in Precambrian rocks of Southern and south western Ethiopia, lithotectonic terranes that comprise high-grade gneisses of the Mozambique Belt and low-grade metavolcano-sedimentary sequences of the Arabian-Nubian Shield are juxtaposed along north-south sheared thrust contacts, which are marked by arc-like ophiolite sequences, which are overprinted by post accretionary structures including north-trending shortening zones and major northwest-trending sinistral and minor northeast-trending dextral strike-slip faults. These lithotectonic terranes are mainly represented by Moyale, Adola and Bulbul belts.

(1)The Moyale Belt

The Moyale Belt is formed part of the Mozambique Orogenic Belt, which is characterized by generally north-trending upright, doubly plunging tight to isoclinal folds. Three main lithological units are recognized within Moyale region of southern most Ethiopia (Alene and Barker, 1993). These are ortho-amphibolites intercalated with minor quartzo-feldspathic rocks and quartz schists; dismembered bodies of mafic and ultramafic intrusives interpreted as ophiolite; and syn- to late tectonic granitoids metamorphosed in the upper greenschist- to middle amphibolite facies. The Moyale ophiolite may have evolved in a back-arc setting (Berhe, 1990).

(2)The Adola Belt

The Adola Belt is a late-Precambrian, north-south trending fold and thrust belt of volcanic-sedimentary and ophiolite-like units overlying ‘basement rocks’ (gneisses and granitic gneisses). Structural analysis reveals that the Adola Belt has undergone three major deformational events. The earliest deformational event produced low-angle thrusts, recumbent folds and associated flat-lying foliation. The second deformational event gave rise to upright folds, north-south trending and generally west dipping regional schistosity and oblique to reverse sense shear zones. The third deformation reactivated the earlier structures and produced subvertical, discrete strike-slip shear zones along previous discontinuities (Worku and Schandelmeier, 1996).

(3) The Bulbul Belt

The Bulbul Belt is ~ 100 km long, which is characterized by north-south fold and thrust tectonics, overprinted by a north-northeast-south-southwest shear zones. A three stage tectonic model is proposed to explain the evolution of the Bulbul Belt. The early stage in the evolution of the belt is manifested in the form of east-west trending gneissic and migmatitic layering and folds, and probably high temperature metamorphism. The second deformational event seems to be the result of a regional compressive tectonic event, which was associated with collision between the high-grade gneiss and migmatites and the low-grade metavolcano-sedimentary rocks along a suture that has been subsequently overprinted by the north-northeast trending shear zones (Bulbul and Wadera shear zones). The final stage in the evolution of the Bulbul Belt is dominated by an oblique normal-slip shearing with considerable strike-slip component. It can be interpreted that the oblique normal-slip shearing to be related to regional gravitational tectonic collapse (Tsige and Abdelsalam, 2005).

2.3.3. The Precambrian rocks of western Ethiopia

Major litho-tectonic blocks that comprise high-grade gneissic–migmatitic associations and low-grade metavolcano-sedimentary sequences intruded by syn- to late-tectonic granodioritic and granitic plutons are exposed throughout western Ethiopia. The gneissic rocks of the MB are exposed to the east and west of a relatively narrow, but northward-widening zone of low-grade volcano- sedimentary- plutonic sequences of the ANS (Kazmin, 1972; Tefera et al., 1996). In summary , the Precambrian rocks of western Ethiopia contains: - (i) high grade gneiss and migmatites, (ii) low-grade metavolcano-sedimentary rocks and associated intrusive rocks and, (iii) metavolcano-sediments and associated mafic-ultramafic rocks of probable ophiolitic origin.

2.3.4. The Precambrian rocks of Eastern Ethiopia

The Precambrian rocks of eastern Ethiopia is little known compared to the other Precambrian exposures of the country. According to Kazmin et al.(1978) the Precambrian rocks of eastern Ethiopia has three-fold divisions. These are: - (i) Lower Complex, comprised of high-grade gneiss and migmatites, (ii) the Boye Group (Middle Complex of Kazmin, 1972), comprising meta-arkose, metapelite, quartzite and marble, and (iii) the Soka Group (Upper Complex of Kazmin, 1972), consisting phyllite, chlorite schist, metavolcanics and lenses of ultramafic rocks.

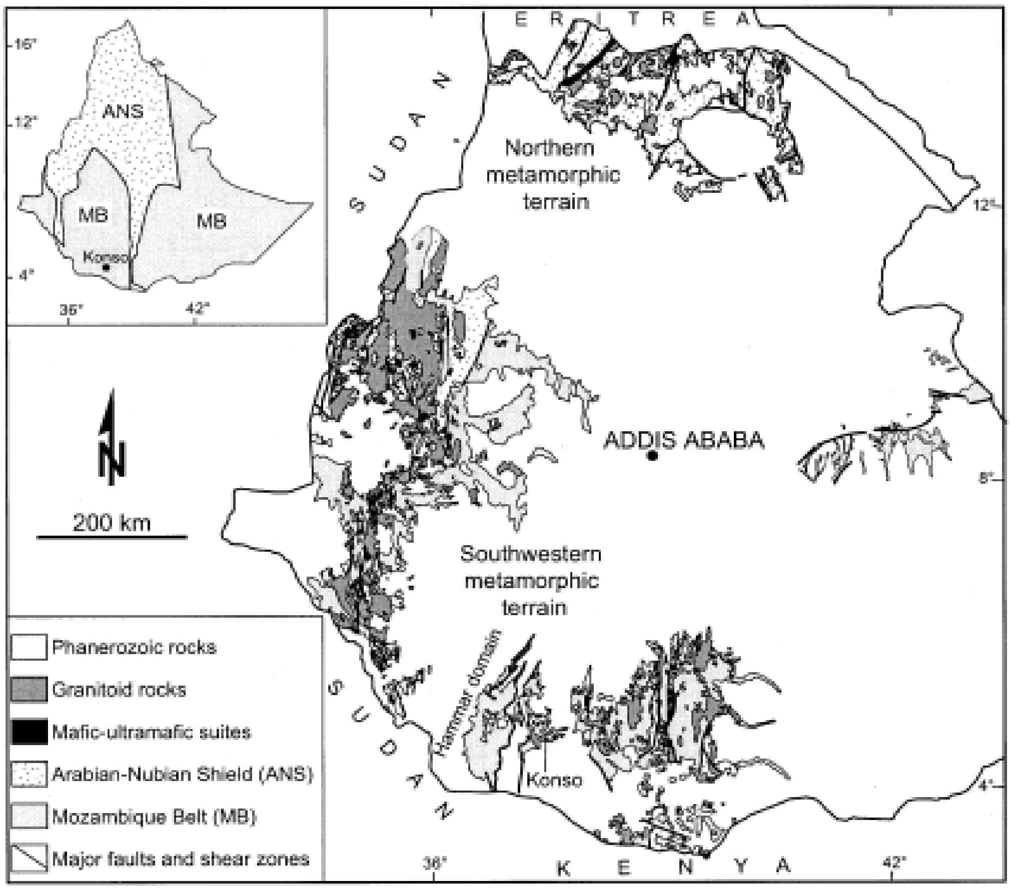


Fig. 2.5 A simplified geological map of the metamorphic terrains of Ethiopia that shows the distribution of the ANS and the MB rocks. Inset shows the boundaries between the ANS to the north and the MB to the south (Asrat et al., 2003).

2.4 Basement Geology of Northern Ethiopia

2.4.1 Introduction

The Precambrian basement rocks of northern Ethiopia are predominantly composed of metavolcano-sedimentary assemblages (Kazmin, 1973 ; Tadesse, 1996; Drury and De Souza, 1998 as cited in Bheemlingeswara and Nata Tadese, 2009). They form in the southern part of the Arabian-Nubian Shield (ANS) (Kazmin et al., 1978; Vail, 1983; 1988), which in turn constitute a large segment of juvenile Neoproterozoic crust formed by accretion of oceanic arc terrains (Stern, 1994; Johnson and Woldehaimanot ,2003). The ANS is flanked by the older basement, which was remobilized during the Pan-African orogenic cycles (850–550 Ma) and eventually led to the formation of Gondwana(Fig.2.2). But recent studies on the basis of the geochronological and isotopic data (Teklay et al., 1998 and others) have suggested that the Precambrian basement rocks are dominantly Neoproterozoic in age and have experienced different grades of metamorphism. Depending on the geochronological data, the basement rocks of Ethiopia are regrouped into two major blocks. These are: - (1)the Volcanic-sedimentary terrain (including the younger meta-sediments) and (2)the Gneissic – migmatitic terrain, separated by numerous Ophiolitic sutures (Asrat et al., 2001).

According to Beyth (1972) and Garland (1980), the low grade metamorphic rocks of the Northern Ethiopia, are broadly classified as the Tsaliet and the Tambien group depending on the origin, age, and types of rocks(Fig.2.6A). Among the two groups, the Tsaliet group is composed of rocks with volcanic origin that formed during arc-accretion (~775 Ma-740 Ma) (Miller et al., 2009) that latter metamorphosed in to a low grade metavolcanic rocks of various kinds including agglomerates, tuffs, mafic to felsic volcanic flows, and volcano-clastic sedimentary rocks (Beyth, 1971; Tefera et al., 1996; Sifeta et al., 2005) which are lithostratigraphically beneath the Tambien group of sedimentary origin. Furthermore, Beyth (1971, 1972) and Miller et al.(2009) identified that, the Tambien group are exposed on four isolated synclinoria directing from west to east. These include:- Shiraro, (i) Mai Kenetal, (ii) Tsedia, (iii) Chemit and (iv) Negash forming probably unconformable contact with the underlying older Tsaliet metavolcanics(Fig.2.6B).

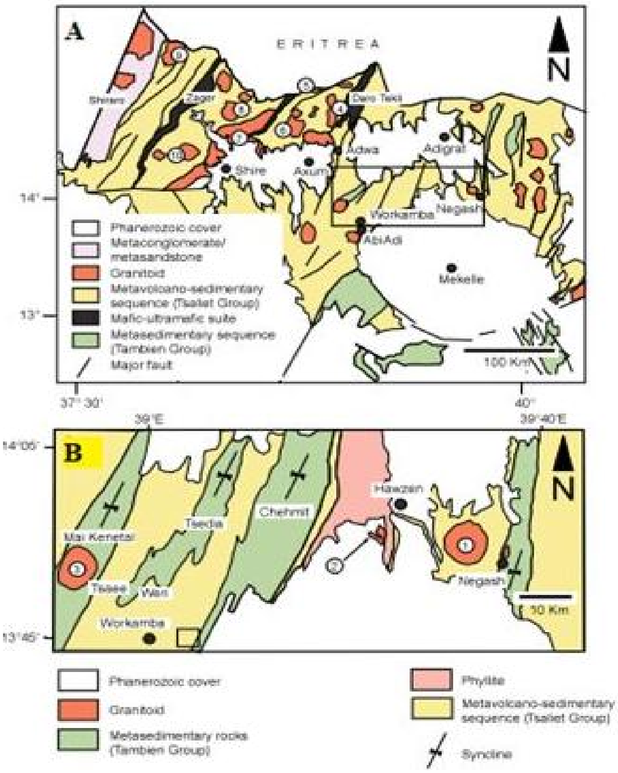


Fig. 2.6 (A) Distribution of the Tsaliet and Tambien groups in the Tigray region, northern Ethiopia. The inset rectangle shows the region near the study area where the Tambien Group is exposed; (B) Close-up of the area between Workamba and Negash. The Tambien Group occurs in four synclinoria inliers (modified from Tadesse et al. 2000; Asrat et al., 2001; Alene et al., 2006 as cited in GebreSilassie S., 2009). The location of the study area is indicated. The circles with number represent the location of dated granitoids in the region, which are both syn- and post-tectonic in origin (1= Negash, 2 = Hawzien, 3 = Mai Kenetal, 4 = Rama, 5 = Mereb, 6 = Chila, 7 = Shire, 8 = Deset, 9 = Azeho, and 10 = Sibta granitoids).

2.4.2 Stratigraphy

Depending on the stratigraphical relationship, the basement rocks of the ANS in the Tigray region is broadly classified into two groups (Beyth, 1972). These are:- (i) the Tsaliet Group, and (ii) the Tambien Group . The Tsaliet Group covers most of the area of the region occupied by basement rocks (Fig. 2.6A). It consists of arc-related metavolcano-sedimentary rocks including metavolcanic/volcanoclastic rocks, sericite-chlorite schist, slate, greywacke, impure marble, calcareous siltstone, well bedded, intermediate to acidic welded tuffs, lappili tuff, and agglomerates (Beyth 1972; Beyth et al. 2003, Tadesse et al., 1999; Alene et al., 2000). Primary sedimentary structures such as graded bedding exists in this area which indicate that the sedimentary sequence was laid down in a submarine environment with intense deformation making it difficult to recognize the younging direction (Tefera et al., 1996; Tadesse et al., 1999; Miller et al., 2009). There are few way-up indicators showing fining upward sequences and phototropic organo-sedimentary structures showing the up-direction of sedimentation (Miller et al., 2009). The Tambien meta-sediments are younger in age than the Tsaliet meta-volcanics although there is an ongoing debate that they are deposited at the same time during the formation of arc-accretion arguing that volcanism and the deposition of the sediments from the continental area occurred simultaneously referring to the 'gradational contact' (Alene, 1998 as cited in Alene et al., 2006) between them and the age constraints though Beyth (1971) identified unconformable basal contact between them. Seemingly conformable and gradational to fault bounded contact is described by Sifeta et al., 2005. However, they are generally believed to have occurred over an island arc accretion complex during or after the waning phases of arc magmatism and ended prior to the formation of East African Orogen (Avigad et al., 2007; Miller et al., 2009).

According to Beyth (1971); Alene et al.(2006) and Miller et al.(2009), four major formations were identified with in the Tambien group based on the Mai Kenetal type section. These are:- (1) the Werii Slate, (2) the Assem Limestone (3) the Tsedia Slate, and (4) the Mai Kenetal Limestone from bottom to top respectively. Garland(1980) subdivided the Negash Tambien group succession into the lower Didikama formation and overlying Matheos formation. These are also regrouped or subdivided in to four units. These includes:- Negash Slate, Dolomite and Slate, Negash Limestone, and Pebbly Slate (Alene et al., 2006).

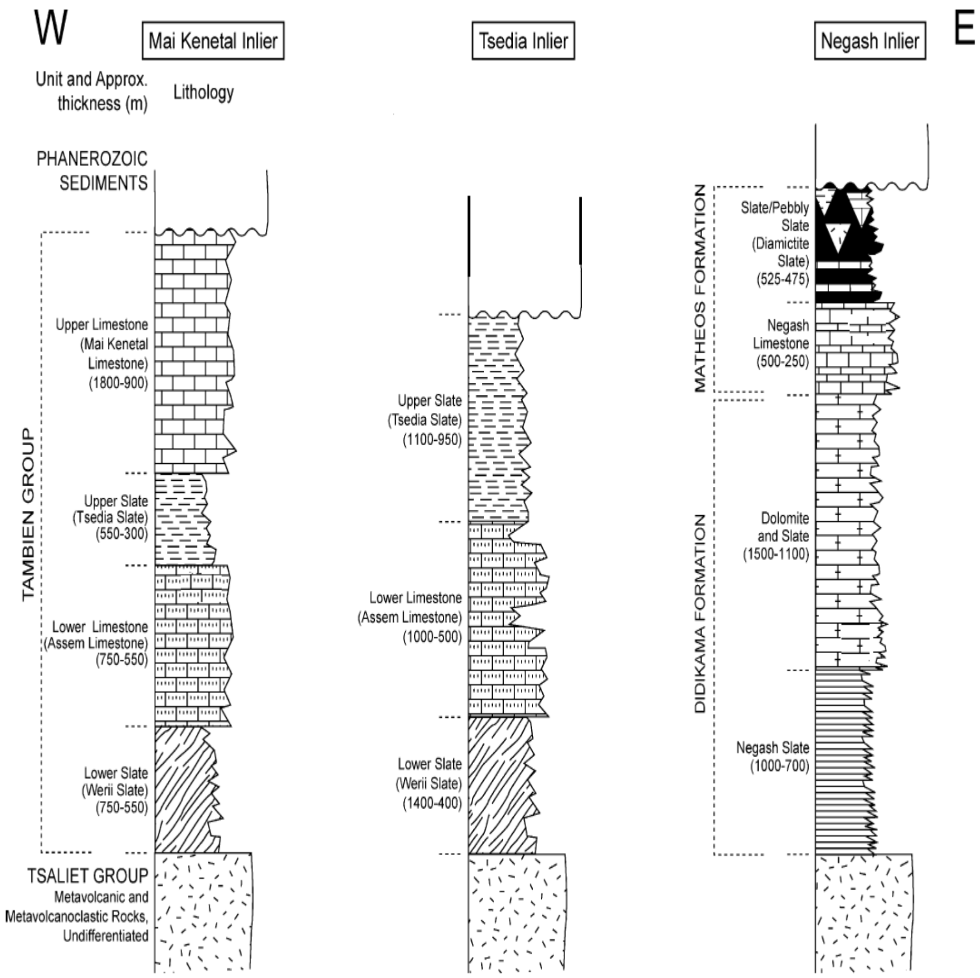


Figure 2.7 Stratigraphic sequence of the Tambien Group meta-sediments in the Mai Kenetal, Tsedia and Negash sections, northern Ethiopia. Unit names given in parentheses are those used by Beyth, 1971; modified from Alene et al., 2006 as cited in Desta Dawit., 2014.

2.4.3. Structural frame work

Both the Tsaliet and the Tambien groups are strongly affected by various types of geological structures that are formed by several deformation phases. The amalgamation of island arcs in the ANS had generated stress, that is responsible for the formation of tectonic structures during Neoproterozoic age(Johnson et al., 2003). According to Alene (1998); and Alene et al.(2000); two phases of deformation (D1 and D2) are recognized in the region, which are the result of N–S and E– W regional compression, respectively. D1 is associated with folding of primary bedding and appearance of tight to isoclinal minor folds, elongation lineation and a pervasive regional foliation including a transposed fabric. On the other hand, D2 caused large, predominantly upright, open folds with sub-horizontal axes without producing a pervasive cleavage. Structural evidence within their contact zones shows that many of the Mereb granitoids probably intruded the Tambien Group prior to D2. D2-structures are most simply explained as reflecting terminal collision between E and W Gondwana.

Alene (1998) identified that there are three metamorphic phases depending on the mineral assemblages and textural features. These are:-(1) an early, regional pumpellyite–actinolite to lower-greenschist facies coeval with D1; (2) a local contact metamorphism (growth of andalusite and staurolite) caused by granitoid intrusion; and (3) a late phase probably related to D2 folding and uplift. The distribution of major structures in Northern Ethiopia or Tigray region is shown in Fig. 2.9. According to Tadesse (1996) and Tadesse et al. (1999), NE to SW trending thrust faults and shear zones within the low-grade metavolcano-sedimentary sequences are recognized in the western part of Tigray. In Central Tigray, major NE-SW oriented synclinoria such as the Mai Kenetal, Tsedia, Chehmit and Negash, which folded the Tambien Group rocks are commonly found (Beyth, 1972; Alene et al., 2006). NNE striking faults are also common in the Tsaliet and Tambien Group rocks(GebreMariam S., 2009).

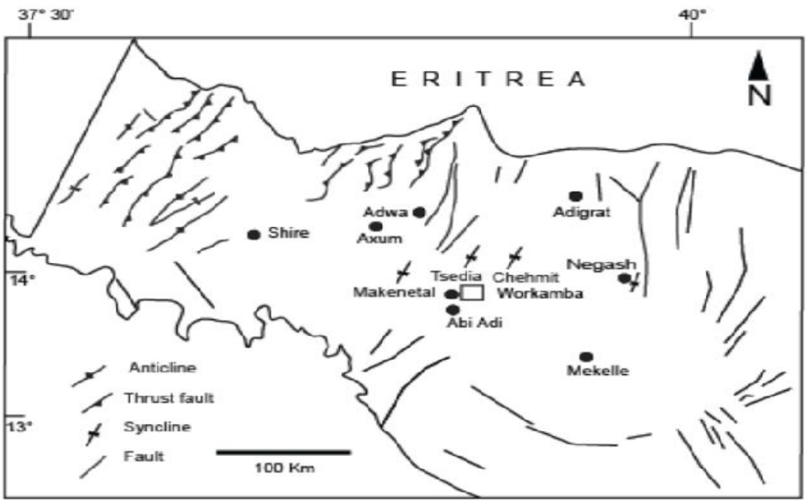


Fig. 2.8 Distribution of major geological structures in Northern Ethiopia(Tigray) GebreMariam (2009).

CHAPTER - THREE

LOCAL GEOLOGY OF THE STUDY AREA

3.1 Introduction

The Megab-Hawzien area is part of the low grade metamorphic terrain of northern Ethiopia that is dominated by both Tsaliet and Tambien Groups including the phyllite and granite rock units. The Tsaliet Group is represented by metavolcanics and metavolcanoclastics that are exposed in the northern and eastern part of the study area. The Tambien Group is also represented by Phanerozoic formations such as Adigrat sandstone, Enticho sandstone, Alluvial deposit and Edaga Arbi shale intercalated with Edaga Arbi Tillite rocks that are exposed in the western, northern, south western and central part of the study area (Fig.3.1). The Tsaliet Group rocks are overlain by the Tambien Group rocks. The phyllite unit / rock is relatively highly foliated, crenulated and sheared. Most of the rocks of the study area display several sets of joints as well as quartz veins.

Based on the textural description and mineralogical composition of the rocks observed during field investigation and thin section lab/ petrographic analysis, the out crops of the study area are divided and described as follows:

1) Metavolcanoclastic and metavolcanic units

2) Phyllite unit (Spotty micaceous and Spotty Quartzo-Feldspathic)

3) Felsic subintrusive unit

4) Granite unit, and

5) Phanerozoic formations

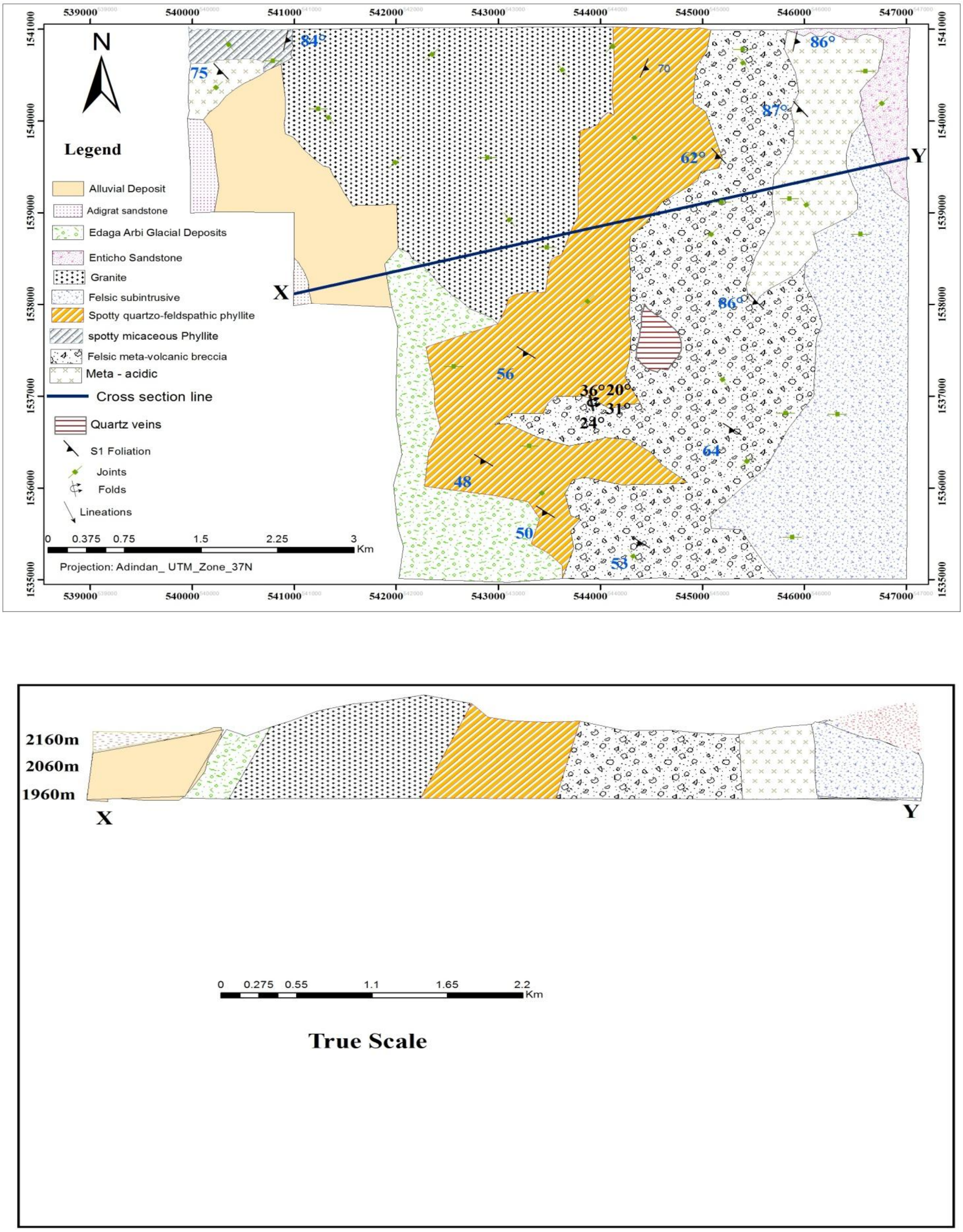


Fig. 3.1 Geological map and cross section of the Megab-Hawzien area

3.1.1 Metavolcanoclastic (MVC) and Metavolcanic (MV) Rock Unit

This unit covers the largest portion of the study area. It consists of meta-acidic and felsic meta-volcanic breccia. These different lithologies show considerable lateral variations and contacts. They are marked by the relative dominance of one with respect to the other and are not easily differentiated. However, these rocks are mapped individually. The MV and MVC unit is also characterized by forming ridge topography. The felsic meta-volcanic breccia is occurred largely when compare to the other remaining units mentioned above. In the northeastern part, the contact relation of this unit with the overlying meta-sedimentary rocks (Tambien Group) is gradational but in the western part and southeastern part the contact is sharp (tectonic) (Fig 3.1). Fabric development and related features within the unit varies with the type of lithology. The mappable units/ lithologies of MVC and MV are listed and described below as follows:

- Meta-acidic rock
- Felsic meta-volcanic breccia

3.1.1.1 Meta- acidic rock unit(s)

3.1.1.1.1 Field description

The meta-acidic rock unit is particularly part of the metavolcanic unit. This rock unit is mainly exposed in the northeastern part of the study area and it is also intercalated with the meta-volcanoclastic rock(s). It also found as lenses in phyllite unit. The color of this rock unit varies from light gray to light yellow. These rocks are characterized by their weak foliation striking S05°W with steeper dips (70°-85^0) to northeast. It has two direction systematic joint sets which are perpendicular to each other.

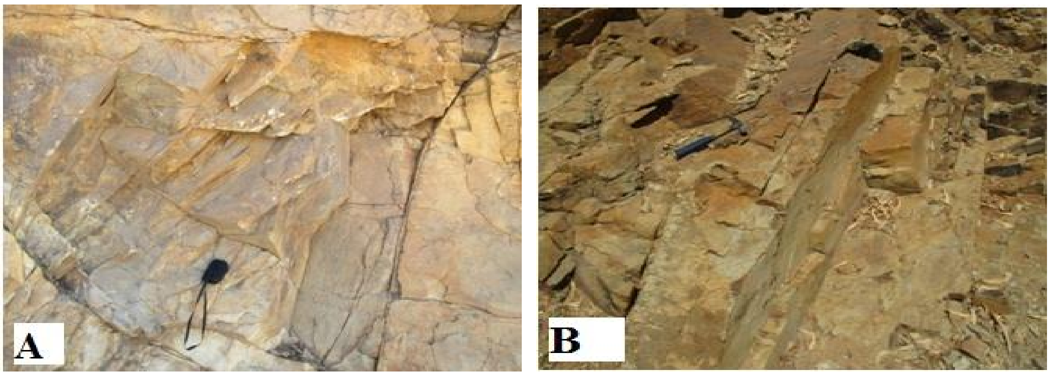


Fig. 3.2 Field photo pictures of meta-acidic rock units. (A)The photo is taken looking west (Location:- 0540101E, 1540662N). (B) The photo is taken looking NE (Location: 0546630E, 1541034N).

3.1.1.1.2 Petrographic description

Under petrographic microscope this unit shows weak to medium foliation, fine grain and hence low grade.

The modal abundances of minerals in thin section include sericite/mica = 60%, quartz = 25%, plagioclase feldspar = 10% and opaque minerals = 5%. "This rock is relatively undeformed and still retains a superficial appearance primarily because large plagioclase grains retain their original texture (Yardley et al., 1990)". The xeno-blastic quartz and idioblastic plagioclase feldspars are elongated and parallel to the foliation plane (HM-2). The quartz inclusion is grown before deformation process is taking place. In general, the overall texture of this unit shows decussate texture.

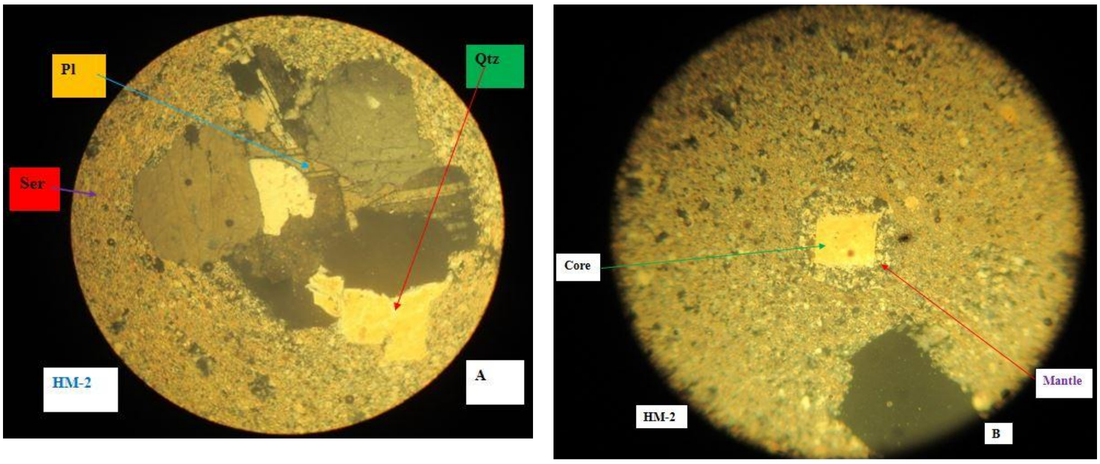


Fig. 3.3 Microscopic photo-pictures showing the meta- acidic rock unit of the study area(total magnification = 10x * 10x = 100x under XPL for both of them). (A) this plate photo shows weak to medium foliation that is caused due to deformation and metamorphic process. The quartz and plagioclase inclusions at the center of the photo plate shows development of these inclusions are before the deformation process. The plagioclase is also altered and fractured due to this process (Location: 0540101E, 1540662N). (B)There is mineral zoning/core and mantle texture/ in quartz located at the center. This probably indicates the role of dynamic recrystallization in the rock (Location: 05046630E, N1541034 N).

3.1.1.1. 2. Felsic meta- volcanic breccia rock unit(s)

3.1.1.1.2.1. Field description

The felsic meta-volcanic breccia rock unit is particularly part of the meta-volcanoclastic unit. This rock unit is mainly exposed in the northeastern , southeastern and southwestern part of the study area bounded by the Enticho sandstone unit in the north and the remaining part is bounded by phyllite, MV and MVC unit(i.e., meta-acidic) and felsic subintrusive units of the study area. It has light grayish and black greenish color because of the presence of the commonly greenish minerals such as epidote, chlorite and altered mica/sericite. This rock unit is highly weathered compared to other rock units of the study area. The contact between the phyllite and the other variety of MV and MVC, and the felsic-subintrusive rock units are more or less a type of sharp contact. This unit mainly forms a relatively rugged topography and is cut by seasonal river streams across its strike than the surrounding other lithologies. It has a variable thickness from place to place. In general, it has an average thickness of about 500m.

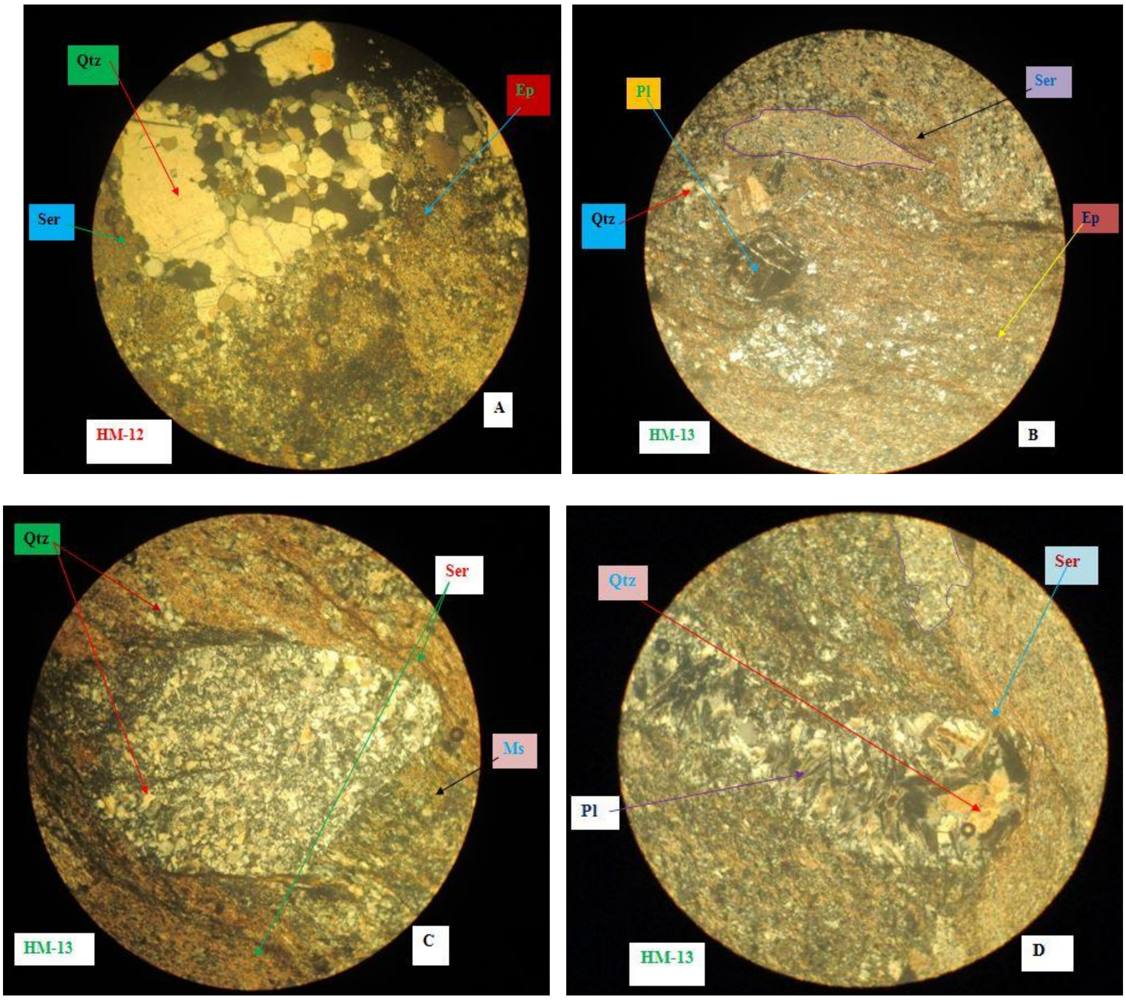
The exposures in the southwestern part of the study area are relatively less weathered and foliated. The southeastern breccias are relatively stiffer and form higher topography showing a N-S trending ridge. Furthermore, the felsic meta-volcanic breccia rock unit contains some clasts/rock fragments. The size of the clasts or pebbles varies from few mm scale to 5cm and have angular to sub angular and sub rounded shapes (Fig 3.4 HM-12).

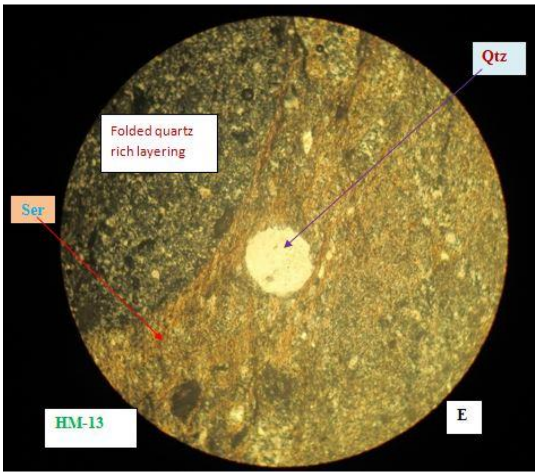
Fig. 3.4 Field photo pictures of the felsic meta-volcanic breccia rock units of the study area. (HM-12) light grayish rock unit with pebbles or clasts (with a size range of mm to 5 cm) are deformed having ellipsoidal shape. The photo is taken looking north (Location: 0545135E, 1539768N). (HM-13) Black greenish rock unit with weak to moderate foliation containing some clasts. The photo is taken looking southeast(Location: 0545002E, 15438015N).

3.1.1.1.2.2. Petrographic description

This rock unit is highly brecciated with most of the primary sericite and quartz having finer inclusions of minor opaque minerals are mechanically bended (Fig. 3.5A).The sample number HM-12 of the meta-breccia rock unit shows that the rock is composed of epidote=60%, recrystallized anhedral to subhedral quartz = 35% and opaque materials =5% (Fig.3.5A). Little Preferred orientations of these minerals define weak foliation. The petrographic analysis of sample number HM-13 shows the modal abundances of this rock unit include altered mica/sericite = 40%, plagioclase/ albite = 20%, quartz = 15%, rock fragments/clasts =10%, epidote = 7.5%, muscovite =5%, and opaque minerals(may be ilmenite)=2.5% (Fig.3.5B-F).

This rock unit shows strong foliation and it is highly deformed. We can say this type of deformation is Late tectonic, because it shows pressure shadow and the inclusions have preferred alignment inside the quartz /plagioclase feldspar(Fig.3.5 B, C,D, E and F).





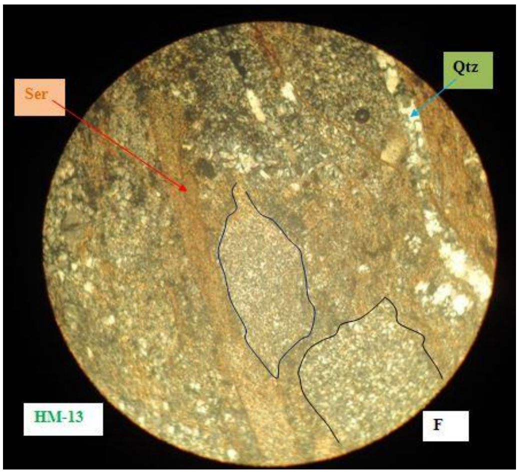


Fig. 3.5 Microscopic photo-pictures showing the felsic meta- volcanic breccia rock units of the study area (total magnification = 10x *10x = 100x under XPL). A) The Core and mantle structures in which the coarser quartz crystals are rimmed by the finer quartz grains (HM-12A). Location : 0545135E, 1539768N. It is an indication of low grade metamorphism.

B) The microscopic photo pictures of B-F (HM-13) are from one out crop unit of the same location that have important structures used for interpretation purposes. Location : 0545002E, 15438015N. Generally, this rock unit has a markedly poikiloblastic/ porphyroblastic texture with very large (> 1cm) euhedral or subhedral (may be plagioclase feldspar or quartz) grains in a fine matrix. Chlorite and muscovite occur with quartz in the matrix and define a complex fabric formed over at least two stages of deformation which apparently pre-dated the peak metamorphic temperatures. The discordance between internal and external schitosities, schistosity around the porphyroblasts provide firm evidence that plagioclase grew before the deformation that produced the main schistosity of the rock, but after the early deformation that gave rise to the N-S fabric (Yardley et al., 1990).

3.1.2 The phyllite Unit

The phyllite rock unit of the study area is characterized by fine grained, low grade metamorphic rock and recognized by its phyllitic foliation when the fabric-forming mica minerals show continuous and visible shiny surfaces. In this rock unit , grain size coarsening and growth of flaky biotite crystals are well developed along the intrusive contacts giving the rock spotty texture. Near the granite exposure, the phyllitic rock units are laminated and banded with mica (biotite) minerals.

This due to the intrusion of Negash granitic body caused by the effect of hydrothermal/ contact metamorphism result in the growth of quartz vein or plagioclase porphyroblasts (Eyob Abebe., 2013).

In thin section, the foliation is defined by the preferred alignment of platy minerals. Felsic minerals are also elongated in preferred direction and hence show planar fabrics. There are also a lot of systematic joints in this rock unit oriented N-S and E-W direction respectively.

Depending on the structural, lithological and/ or mineralogical variations including color; the phyllite rock unit of the study area is classified into two:-

- Spotty micaceous (*Light black yellowish color*) phyllite
- Spotty quartzo-feldspathic (Light black greenish color) phyllite

The petrographic analysis revealed that the spotty micaceous(*Light black yellowish color*) phyllite is dominated by mica minerals where as the spotty quartzo-feldspathic (Light black greenish color) phyllite unit is dominated by quartz and feldspar minerals. Two thin sections are analyzed from this unit (HM-1 and HM-22).

3.1.2.1 Spotty micaceous (*with light black yellowish color)phyllite unit*

3.1.2.1.1 Field description

This out crop unit is located in the northern part of the study area. It covers an approximately 300 square meter of the study area and it is also intercalated with the metavolcanic unit mainly meta-acidic in the western direction and granite in the northeast direction along the road cut from Megab to Hawzen town. It is a light black yellowish to vitreous shinny with perfect and strong foliation. In addition to this, this unit is also characterized by having strong Crenulation cleavage, reverse fault plane and set of systematic joints that generally striking NE direction. There are also So and S1 foliation /cleavage surfaces.

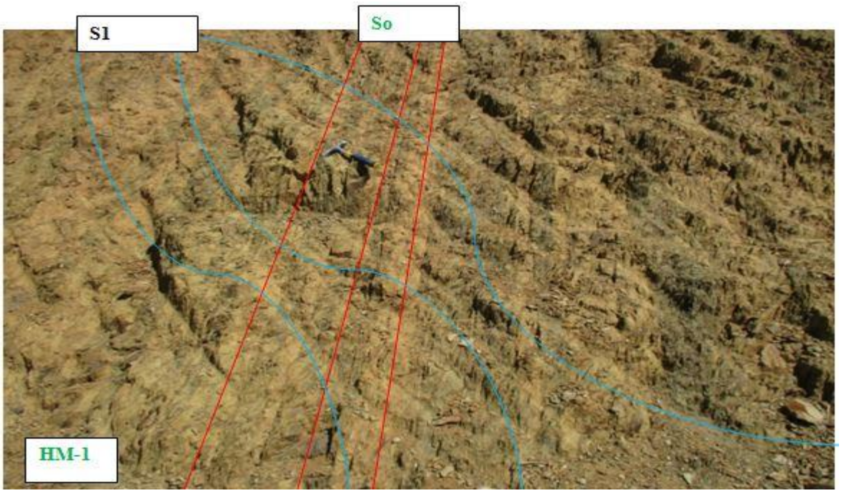


Fig. 3.6 Field photo picture of the spotty micaceous (*Light black yellowish color) phyllite* of the study area. The photo is taken looking south (Location:- 0540245E, 1540724N).

3.1.2.1.2 Petrographic description

Thin section study of this rock unit (sample number HM-1) shows that it contains muscovite = 60%, quartz = 30% and opaque minerals =10%. (Fig.3.7). Minerals mainly muscovite, sericite, and deformed quartz are aligned parallel to S_0 foliation which is in turn crenulated perpendicular to the prominent regional foliation and formed S_1 foliation. Sericites in this rock unit are being altered into muscovite when it grades in to a higher temperature. Muscovite micas are the dominant phase in this rock unit.

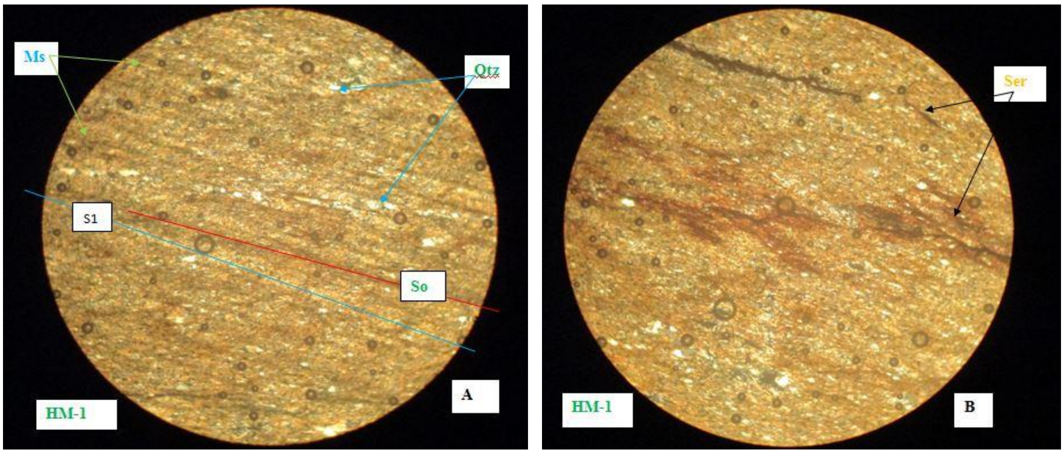


Fig. 3.7 Microscopic photo-pictures showing the spotty micaceous phyllite rock unit of the study area (total magnification = 10x * 10x = 100x under XPL). Location:- 0540245E, 1540724N.
A) strong foliation / cleavage that include S0 and S1, and compositional layering defined by alternating quartz rich and muscovite layers. B) Highly altered sericite that is being changed to muscovite minerals. There are also quartz veins that have the same orientation with the foliation surfaces .

3.1.2.2 Spotty quartzo-feldspathic(with light black greenish color) phyllite unit

3.1.2.2.1Field description

The spotty quartzo-feldspathic phyllite unit is located along the northern, central and southern part of the study area. It has a thickness of an approximately 1(one) km of the study area and it is intercalated with the metavolcanic unit mainly felsic meta - breccia in the southeastern direction and granite in the northern direction along the road cut from Megab to Digum town/Abreha We Atsbeha historical rock hewn church/. It is a light black greenish to vitreous shinny with perfect and strong foliation. This rock unit is fresh/less weathered comparing to the micaceous one (Fig. 3.8). Furthermore, this out crop unit is characterized by having many phases of deformational mechanisms/ structures such as D1and D2; foliation/ cleavage/ surfaces such as S_0, S_1 and S_2; strong Crenulation lineation; and systematic joints with very shiny and phyllitic cleavage surfaces.

Figure 3.8 Field photo picture of the spotty quartzo-feldspathic phyllite (Light black greenish color) phyllite of the study area. The photo is taken looking southeast (Location:- 0543943E, 1536885N).

3.1.2.2.2 Petrographic description

When we see this rock unit under petrographic microscope, its mineralogy is dominated by white quartz and plagioclase minerals (HM-22) with considerable amount of opaque minerals. Its modal abundances include quartz =30%, plagioclase/albite = 25%, mica/muscovite =20%, chlorite = 15% and opaque materials =10%. As in the case of spotty micaceous phyllite, this rock unit is also characterized by strong persistent foliation that is defined by phyllitic cleavage.

The metamorphic grade is relatively higher in phyllite rock unit than the rest of the other rock units exposed within the study area. The petrographic examination of this rock unit indicates that its mineral assemblage is dominated by quartz and feldspar minerals containing mica minerals (HM-22). The dominance of these minerals indicates that the protolith of these rocks are clay rich pelitic rocks (sedimentary origin). So the increase in metamorphic grade in phyllite might be related to the local heat (granitoids intrusion) influence (Tadele Tesema., 2012).

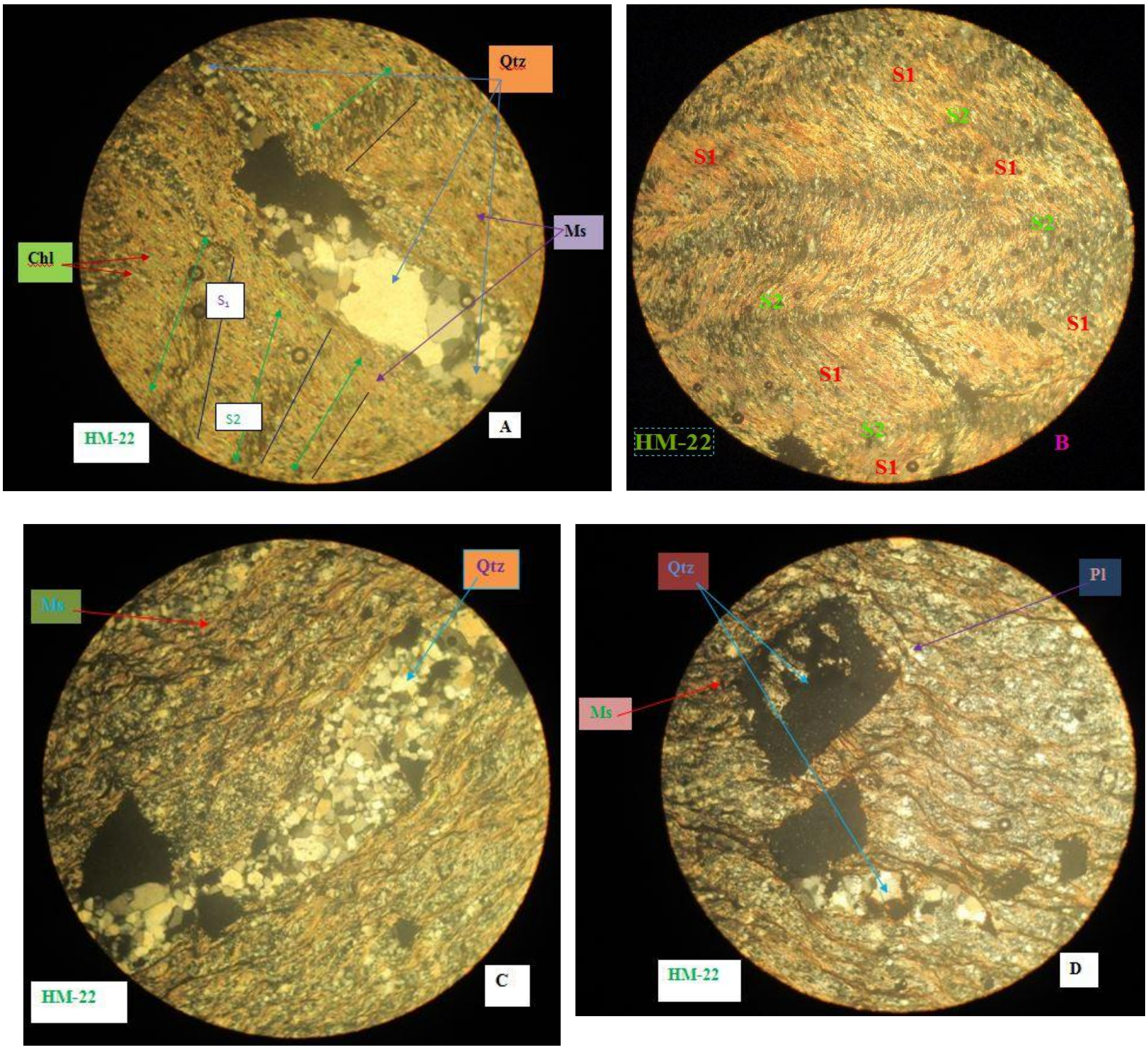


Fig. 3.9 Microscopic photo-pictures showing the spotty quartzo-feldspathic phyllite rock unit of the study area (total magnification = 10x * 10x = 100x under XPL for A, B, C and D; with the same Location:- 0543943E, 1536885N).

A) Strong Crenulation cleavage that contains S1 and S2 and compositional layering defined by alternating muscovite rich layers. The quartz vein has discordant/ cross cutting relationship to the compositional layering of an alteration muscovite layers.

B) This phyllite unit contains S1 and S2 foliation and strong Crenulation cleavage. Bedding is represented by mica-rich zone at the center and more felsic with lesser mica at the corner part of the plate. S1 foliation is parallel to bedding defined by the left to right alignment of the minerals and Crenulation cleavage has developed at high angle to the foliation.

C and D) These rock units show highly deformed sericitization process parallel with quartz veins resulting Kinking type of structure due to post foliation deformation.

Note that all the above microscopic photo pictures indicate strained quartz veins with sutured boundaries in spotty quartzo-feldspathic phyllite.

3.1.3 Felsic-subintrusive rock unit(s)

3.1.3.1 Field description

The felsic-subintrusive rock unit is located in the south eastern part of the study area. It covers an average of one(1) square km. Based on grain size and color, this out crop unit contains two subgroups. The first one is a felsic-subintrusive out crop with medium to coarse grain, grayish/pinkish black color(HM-20). The second one (B) is a felsic-subintrusive out crop with fine grain to medium grain, black greenish color (HM-21). It is also strongly affected by alteration and/or weathering that makes the rock to appear yellow when it is broken (Fig.3.10). At hand specimen, the felsic-subintrusive rock with fine to medium grain is difficult to identify by our necked eye. It looks simply grayish black color and massive with some quartz and volcanic glass. But the one with medium to coarse grain shows pinkish black color, massive and consisting of fine to medium grain minerals such as quartz, chlorite, mica (mainly muscovite), yellowish and brownish oxidized minerals probably sulphides and /or altered iron rich minerals (pyrite?) are the dominant minerals that we observe. Hence, from the nature of the outcrop pattern and the composition of the rock it is interpreted that the unit could be weathered/altered felsic sub intrusive body.

Fig. 3.10 Field photo pictures of the felsic-subintrusive rock units of the study area. The felsic-subintrusive out crop with medium to coarse grain, grayish/pinkish/ black color massive to very weak foliation structure (HM-20). The photo is taken looking east(Location:- 0545091E, 1535599N). The felsic-subintrusive outcrop unit with fine grain to medium grain with black greenish color and massive structure (HM-21). The photo is taken looking southeast (Location:- 0545163E, 1535576N).

3.1.3.2 Petrographic description

When we see the felsic-subintrusive rock unit under petrographic microscope, two types of samples are existed. The first one is sample number HM-20 and the second one is HM-21.Thin section study of sample number HM-20 shows that this rock unit contains quartz =35%, alkali feldspar (i.e., orthoclase) = 30%, chlorite = 15%, Hornblende (altered) = 7.5% and opaque materials = 2.5% (Fig.3.11A). Thin section study of sample number HM-21 shows that this rock unit contains quartz = 30%, calcite =25%, chlorite = 20%, sericite/mica = 12.5%, ground mass = 7.5% and opaque/ferromagnesian minerals(may be pyrite) =5% (Fig.3.11 C-D).

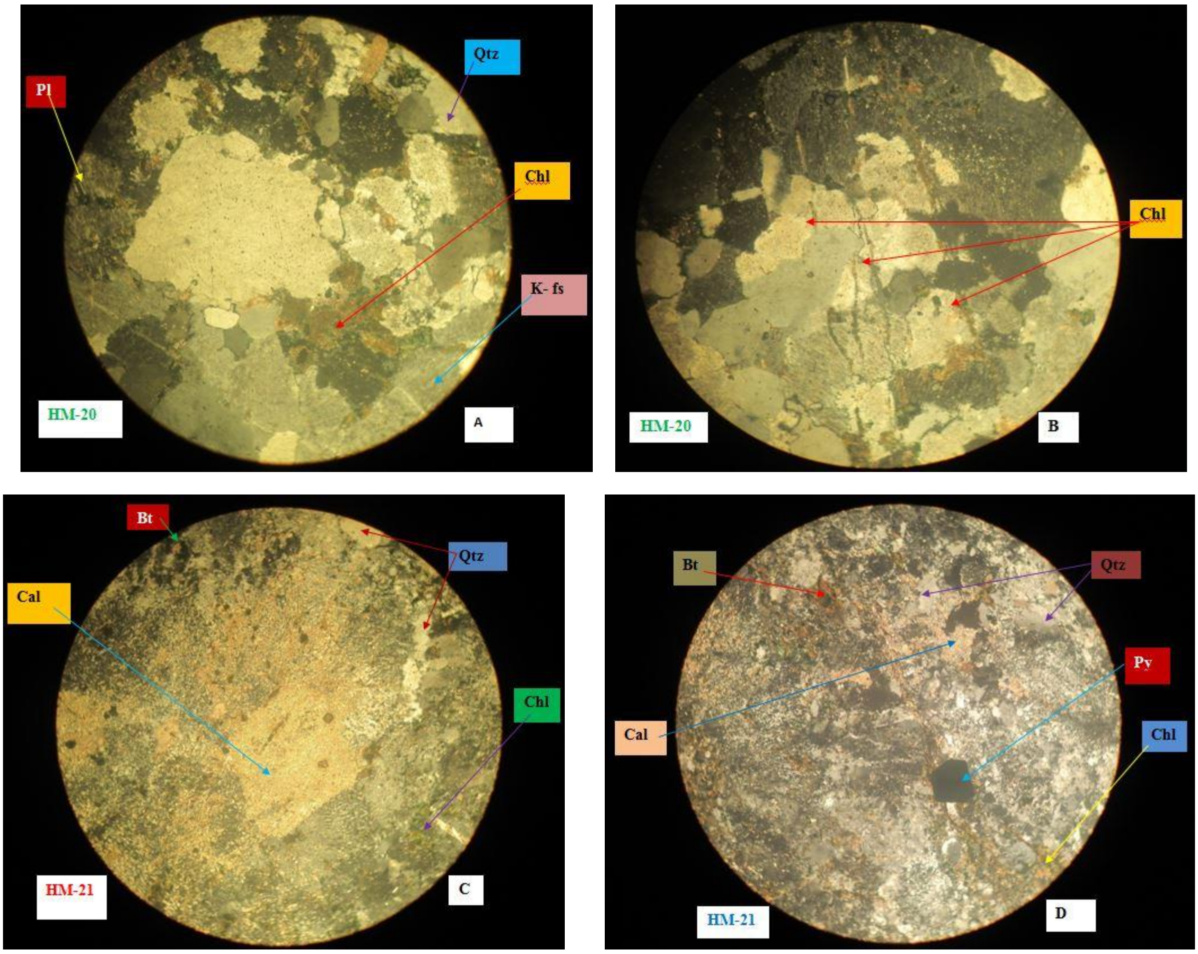


Fig. 3.11 Microscopic photo-pictures showing the felsic-subintrusive rock units of the study area. (A) Felsic-subintrusive rock unit (HM-20) with medium to coarse grain, grayish/pinkish/ black color that is dominated by quartz, K-fs, and chlorite minerals. It shows massive to very weak foliation. Total magnification = 10x * 10x = 100x under XPL. (B) Felsic-subintrusive rock unit (HM-20) with medium to coarse grain, grayish/pinkish/ black color that is dominated by quartz, K-fs, and chlorite minerals. It shows very weak to medium foliation structures. There is also preferred alignment of chlorite minerals caused due to the effect of deformation. Total magnification = 10x * 10x =100x under XPL. (C and D) Felsic-subintrusive rock unit (HM-21) that are dominated by quartz, calcite and chlorite with some mica/sericite. There are also accessory/opaque minerals (such as zircon, pyrite) that clearly show euhedral shapes. Total magnification = 10x* 10x = 100x under XPL.

3.1.4. Granite rock unit

3.1.4.1 Field description

The granite rock unit is mostly found on the northern part of the study area. It covers approximately 3 (three) square Km area of the upper northern part of the study area. This out crop / rock unit contains generally dark grayish and weathered to light yellow colors; but sometimes when it is broken the fresh rock appear as light gray and/or whitish gray color. It is weakly foliated to massive structure, consisting dominantly medium to coarse grained quartz, biotite mica/sericite and plagioclase, alkali feldspar and trace mica/sericite. In addition to this, this out crop unit contains many joints and cracks with general orientation of N-S direction. It has also concordant relationship with the phyllite, Alluvial deposit and Edag Arbi Tillite contacts**.**

Fig. 3.12 Varieties of Granite out crop from the northern part of the study area.

(A) Granite rock unit with medium to coarse grain, dark whitish color (Location : 0541509E, 1540463N). The photo is taken looking NE (Location : 0541509E, 1540463N).

(B) Granite rock unit with fine to medium grain, white pinkish color(Location: 0541918E, 1539936N). The photo is taken looking south (Location: 0541918E, 1539936N).

(C) Granite rock unit with coarse grain, weathered to light yellow color. The photo is taken looking NW(Location: 0543802E, 1541001N).

3.1.4.2 Petrographic description

Under the petrographic microscope, this rock out crop shows weak foliation defined by the muscovite as indicated in Fig.3.13B. The granite rock unit varies in color, mineral composition and grain size. Accordingly, sample number HM-5 contains modal abundances of quartz = 40%, microcline(K-feldspar) = 25%, plagioclase = 15%, biotite = 12.5%, orthoclase = 5%, and muscovite = 2.5%. From the thin section analysis we observed that this granite unit has massive to very weak foliation and it has also medium to coarse grains. Based on the thin section petrographic microscope, sample number HM-6 contains modal abundances of quartz = 50%, muscovite = 30%, plagioclase = 15% and microcline = 5%.

From the thin section analysis we observed that this granite unit has massive to very weak foliation and it has also fine to medium grains. The another last thin section sample number HM-10 contains modal abundances of quartz = 60%, biotite = 20%, microcline = 15%, and plagioclase = 5%. In general, the overall texture of this rock unit is characterized by decussate texture i.e., crystals are hpidioblastic, prismatic, and randomly oriented.

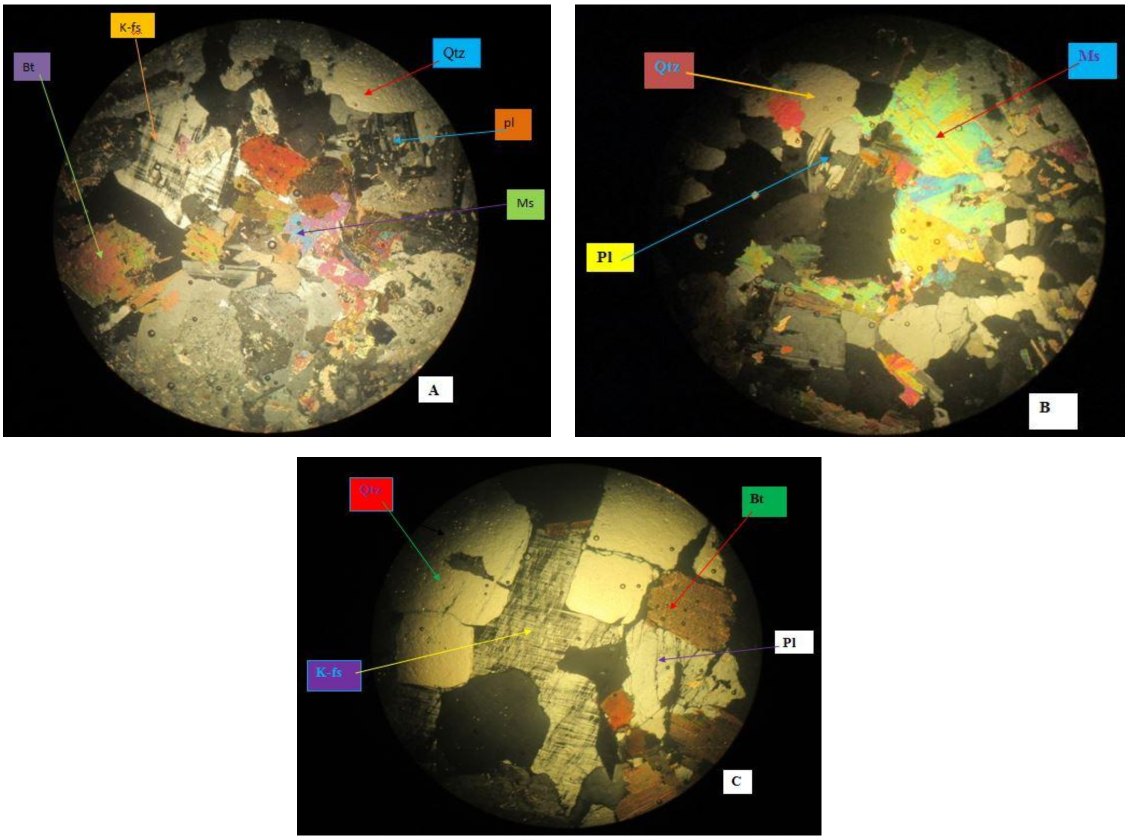


Fig. 3.13. Microscopic photo-pictures showing the different varieties of the granite rock units of the study area (total magnification = 4x*10x = 40x under XPL).

A) sample number HM-5 of the thin section represent the photo picture A of the field in the above with the same location. In this case, the quartz followed by microcline are the dominant minerals. The mica group(Bt and Ms) show certain mineral alignments.

B) sample number HM-6 of the thin section represent the photo picture B of the field in the above with the same location. In this case, quartz followed by muscovite are the dominant minerals. Some of the plagioclase minerals shows twinning with tapered end (needle like) due to deformation.

C) sample number HM-10 of the thin section represent the photo picture C of the field in the above location with same location. In this case , the quartz followed by biotite are the dominant minerals. Some of the biotite minerals also show certain alignments which is an indication of weak foliation due to deformation.

Therefore, the granite out crop is named as quartz rich granite/granitoid**.**

3.1.5.Phanerozoic Formations

The Phanerozoic formation of the study area include Paleozoic and Mesozoic sediments. These rocks show angular unconformity with the lower Precambrian basement. Now let we see them one by one.

A) Paleozoic sediments

The Paleozoic sediments of the study area are classified into Enticho sandstone and Edaga Arbi Glacial deposits such as Edaga Arbi shale intercalated with Edag Arbi Tillite, containing granite boulders up to 6meters in diameter (Arkin et al., 1971).

- The Enticho sandstone which has light gray and brownish color, shiny medium grained with some sandstone commonly calcareous, with lenses of conglomeratic grains. This unit is exposed in the northern part of the study area with a location of 0546162E, 1540929N.In addition to this, this unit contains many cracks and it shows angular unconformity with underlying metamorphic rocks.
- The Edaga Arbi shale intercalated with Edaga Arbi Tillite is characterized by light greenish color, fine grained and bedding. This rock unit is exposed in western part of the study area that has a vertical thickness of about 50m and conformably overlain the light reddish/pinkish/ Adigrat sandstone. It is regionally correlated with Edaga Arbi glacial deposit (Beyth, 1972).

B) Mesozoic sediments

The Adigrat Sandstone is categorized under the Mesozoic sediments. This rock unit is exposed in the western part of the study area. It has reddish/pinkish/color; and many cracks, joints, and other sedimentary structures such as bedding. In addition to this, this rock unit has fine to medium grain size that forms at the uppermost of the Phanerozoic formation. It forms a beautiful land escapes and/ or mountains that contain many historical rock hewn churches and /or monasteries.

CHAPTER -4

DEFORMATION AND METAMORPHISM

4.1 DEFORMATIONAL STRUCTURES

The metamorphic (generally low grade) rocks of the Megab-Hawzien area have been subjected to both type brittle and ductile deformations(Fig.4.1). The brittle deformation structures include joints, faults and quartz veins. The ductile deformation structures are folds, foliations, and lineations. For this reason, Poly-phase deformation exists due to these various types of structural elements mentioned above. The rocks of the study area show three phases of deformation: D1 (First or earlier phase of deformation), D2 (Second phase of deformation) and D3 (Third phase of deformation). D1 is related with folding of primary bedding and appearance of tight to isoclinal minor folds, pervasive foliation (S_1) and linear fabrics(i.e., intersection lineation) defined by platy minerals. Some rock units show N-S trending foliation but in most parts the foliation trends either NE or NW. D2 is represented by N-S trending upright, open folds and crenulation lineations with sub horizontal axes without producing a pervasive foliation. D3 is represented by brittle structures. These are NE trending reverse faults, and N-S, E-W, NE-SW and NW-SE trending set of joints and sheared structures such as quartz veins. The various structures are described in some detail in the following sections.

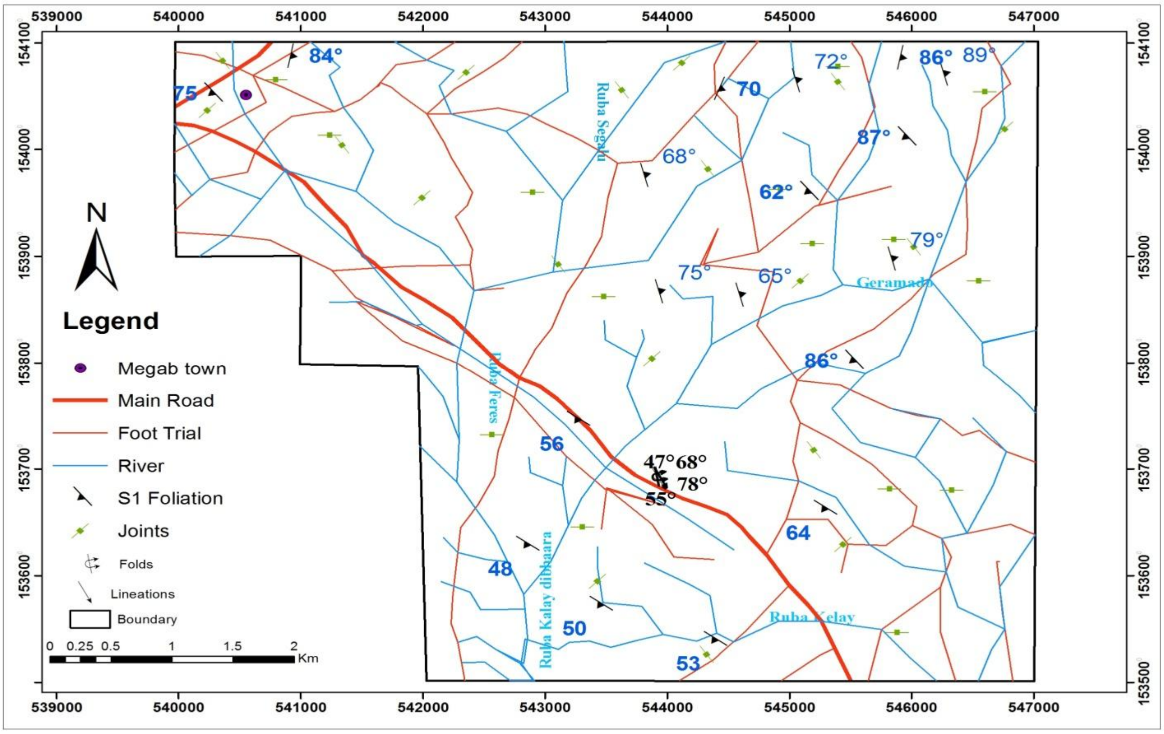


Fig. 4.1 Structural Map of the Megab-Hawzien area

4.1.1. First phase of deformation(D1) and related structures

4.1.1.1 S1 foliations

The rock unit outcrops of the study area is dominated by S1 foliation structures. Furthermore, S1 foliations are the major structures observed in the basement rocks of the study area. These foliations are most often defined by the alignments of platy minerals in the phyllite out crop and generally speaking the alignment of these foliations are uniform throughout the study area, except in some areas which are locally distributed along the contact between the basement rocks and the granitic intrusion. The regional foliation(S1) has a general trend of NNE, WNW and SE with the whole sequence sub horizontal to vertical(30°-89°) dipping in to two preferred directions-NW and SW in the study area. The variation in the attitude of foliations in the area reflects the effect of fold overprinting. Moreover, this foliation surface probably strikes parallel to the major folds. Hence, this relationship is common because both structures originate from the same deformation event.

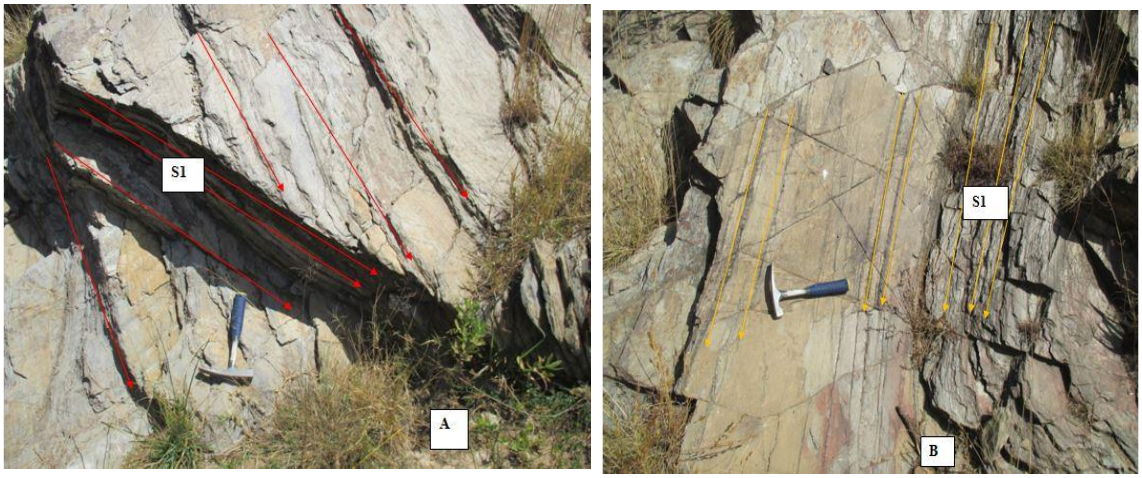


Fig. 4.2. Field photo pictures showing S1 foliations. (A) spotty quartzo-feldspathic phyllite that shows sub horizontal to sub vertical alignment of S1 foliations dipping in the same direction (west). The photo is taken facing SE-direction. Location: 0543943E, 1536880N. (B) spotty quartzo-feldspathic phyllite that contains stretching lineations. The photo is taken facing SE-direction. Location: 0543936E, 1536879N.

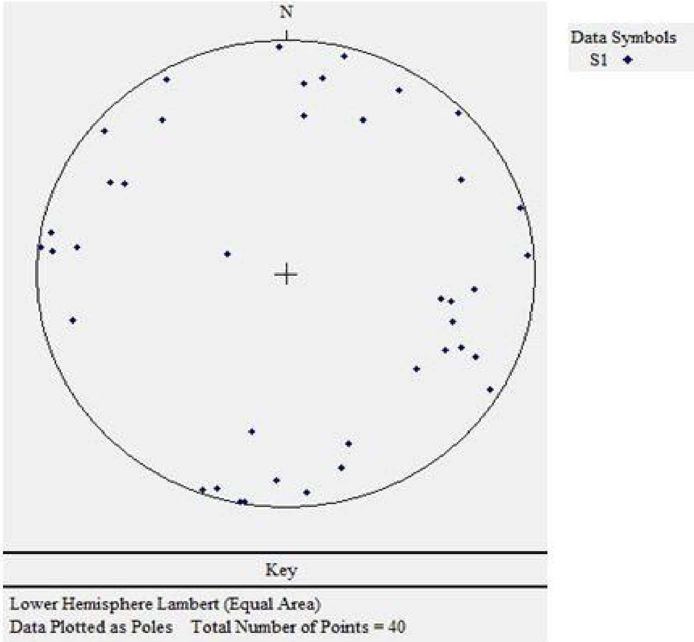


Fig. 4.3 Stereographic plots of S1 foliations as poles.

The S1 foliation has a general trend of NNE, WNW and SE directions.

4.1.2 Second phase(D2) deformation and its related structures

4.1.2.1 F2 Folds

The F2 folds are not abundant all over the out crop units of the study area. They are found in the spotty quartzo-feldspathic phyllite out crop unit within one small area located in the SE- direction of the study area. Generally speaking, no apparent large fold structures has been recognized during field work in the area. However, S1 fabric generally dips to the NW- direction with minor orientation which dips to the NE- direction that shows duplication of similar litho-units in a short distance in the area. This could be interpreted as due to the presence of possible antiformal and/or synformal fold structures. When we describe the F2 folds located in the study area; they are characterized as predominantly upright, open folds with sub-horizontal fold axes. Furthermore, the F2 folds of the study area also identified by their small to moderate wave length of their folds which ranges from less than 10cm up to ≈ 30cm (Fig. 4.4 A&B). All folds plunging N-S direction are correlated to D2 that resulted from E-W shortening (Alene et al. 2006 as cited in Tadele Tesema., 2012).

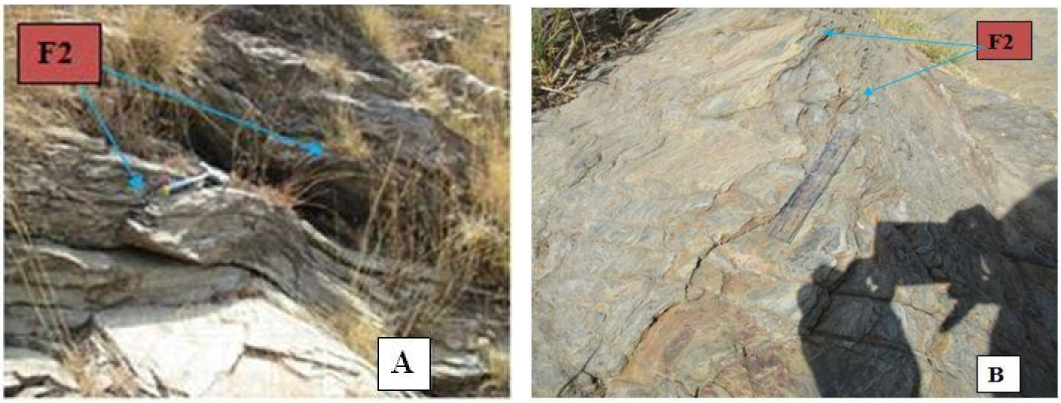


Fig. 4.4 Field photo pictures showing F2 folds of the study area. (A) Horizontal (gentle) minor folds with a convex side upward on the spotty quartzo-feldspathic phyllite unit . The photo is taken facing east direction. Location: 0543938E, 1536881N. (B) Horizontal minor folds on the quartzo-feldspathic phyllite unit. The photo is taken facing SE-direction. Location: 0543946E, 1536886N.

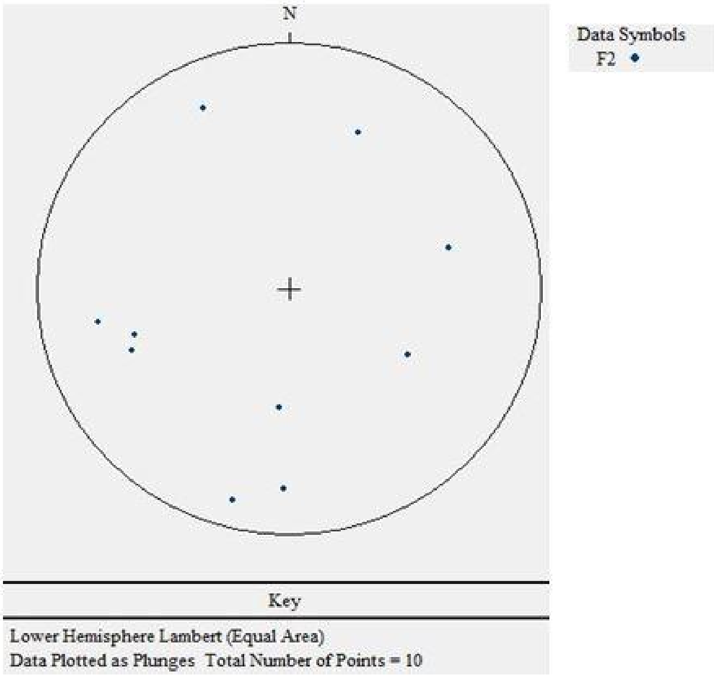


Fig. 4.5Stereographic plots of F2 folds.

Note that the F2 folds are sub-horizontal plunging toward south direction.

4.1.2.1 S2 foliations

S2 foliations are mainly found in the spotty quartzo-feldspathic phyllite rock unit exposed in the southeastern part of the study area. We cannot clearly identify the S2 foliation in the field area; but we can clearly understand/identify microscopically. As a result, the microscopic study shows that S2 foliation is traced along the crenulation surfaces of Phyllite outcrop unit and is nearly perpendicular to S1 foliations when its surface is crenulated(Fig. 3.9; HM-22(A&B)).

4.1.2.3 L2 Lineations / Crenulation Lineations/

The linear features or lineations (L2) are the most important ductile structures that are found almost throughout the majority of lithologic units on the study area. The crenulation lineations are the common type of lineations observed in the spotty quartzo-feldspathic phyllite rock unit(Figs 4.6 A & B). In addition to this, the lineations in general have similar orientation with the fold axes of minor reclined folds that has occurred in the study area. In most cases crenulation lineations are related to folding, with the lineation running parallel to the axial trace and the hinge line. The parallelism of the lineation with the long axis of more locally developed hinge lines suggests that the lineation is crenulation lineation. This indicates that they are probably of the same generations. Most of them indicate that sub horizontal to shallowly plunging south. Microscopic examination of thin sections prepared from phyllite rock unit shows that a development of micro-folding and reorientation of mineral grains due to (D2) second phase of deformation. Earlier deformation (D1) has foliated and aligns the minerals in certain direction. But due to the later deformation (D2) the foliation has already crenulated and reoriented (HM-1 A&B, HM-22 A-D).

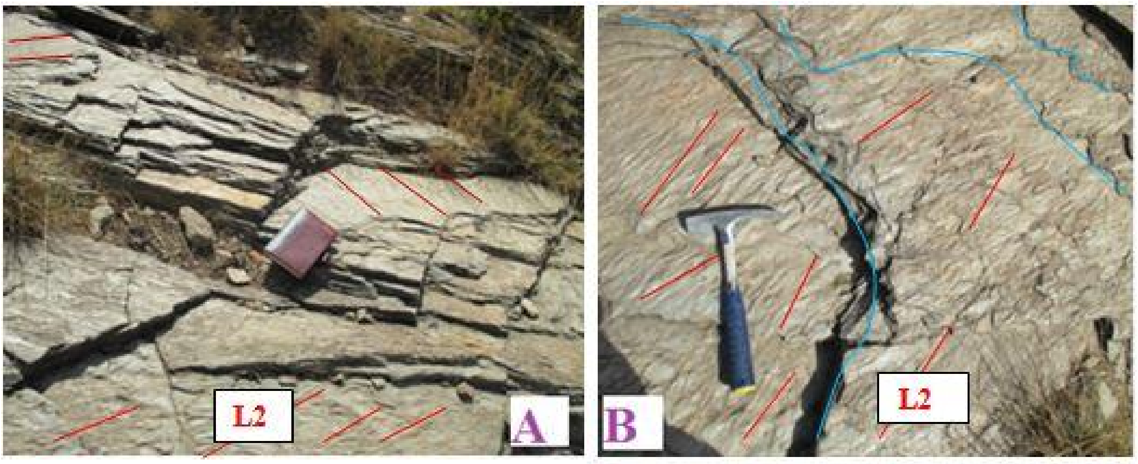


Figure 4.6 Field photo pictures showing L2/crenulated lineations/ on the phyllite(spotty quartzo-feldspathic) rock unit. (A) Crenulation lineation/L2/ having a plunge of ($49^0 \rightarrow 292^0$) that contain another structures such as anticlinal folds with crenulated cleavage on the upper right side. The photo is taken facing to south direction. Location: 0543941E, 151536874N. (B) Highly Crenulated lineation with reclined folds on the phyllite outcrop unit. The photo is taken facing SW- direction. Location: 0543954E, 1536892N.

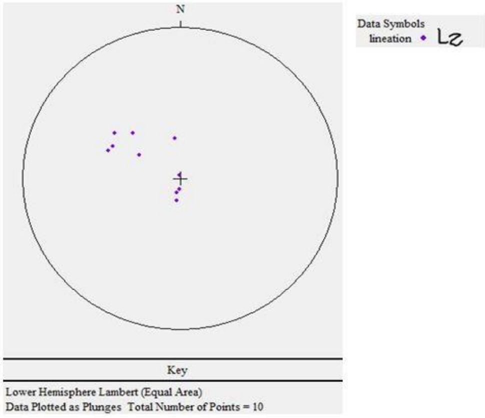


Figure 4.7 Stereographic plots of L2 crenulation lineations.

The L2 crenulation lineations are mostly sub horizontal to shallowly plunging south.

4.1.3.Brittle Deformation /Third phase of (D3) deformation/

The brittle deformation part of the study area has different types of structural elements. These include reverse faults, quartz veins and joints.

4.1.3.1. Reverse fault(s)

The reverse faults of the study area are found in the northwestern part in the micaceous phyllite out crop. In this out crop, there are two reverse faults depending on the location, strike and dip values. The first one has a strike and dip of N61°E, 86°SE respectively. The second one has a strike and dip of N82°E, 88°SW respectively. Generally, the two reverse faults have an exposure thickness of ≈15-20m. In addition to this, the hanging wall is uplifting ≈1m related to the foot wall in these faults. The phyllite(micaceous) outcrop unit is highly foliated and crenulated. The fault plane in both faults is oriented E-W direction. There is also a vein or crack with black color perpendicular to the fault plane.

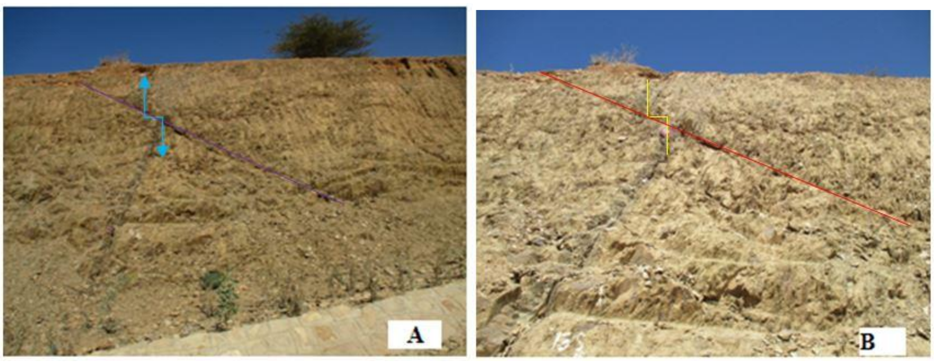
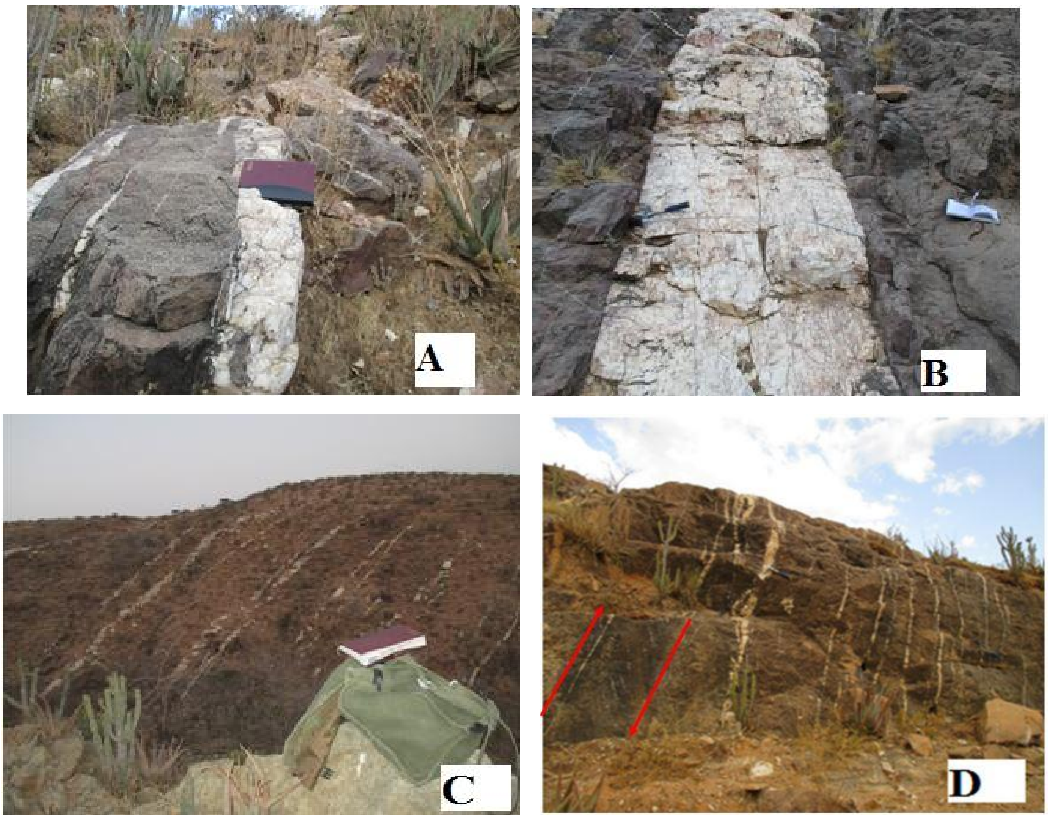


Fig. 4.8 Reverse faults on the phyllite out crop of the study area. The photo is taken facing north direction for both these faults. (A) Location: 0540211E, 1540716N. (B) Location: 0540165E, 1540715N.

4.1.3.2 Quartz vein(s)

The quartz veins are located mainly at the central part of the study area with a coverage of ≈350square meter. The quartz Veins are found both at microscopic and macroscopic scale. The quartz veins have a thickness range from < 1m-3m. It is noted that the quartz veins in the study area show NE to SE trend with moderately dipping toward SW and NW respectively. Quartz veins are dominated by quartz with some dark materials (may be micas, alkali feldspar and volcanic glass). Intense quartz and associated gold mineralization is observed on the quartz veins specially around at the central part in the south eastern direction of the study area and the thickest quartz veins are also measured on this area. They are mainly found on the felsic meta-volcanic breccia rock unit and is about a maximum thickness of 3m having a strike of N85°W and dip of 81°NE with a discordant relationship to regional foliation cutting the host rock unit across the strike (Fig.4.9B). N-S trending quartz vein is found on the contact between phyllite and granite rock units which shows concordant relationship with the main foliation of these (phyllite) units. (Fig.4.9E). The quartz veins in general have coarse grain, glassy texture and milky white to white color. They contain yellowish oxidized spots or sulfides. The abundance of the oxidation spots is quite more in the older and concordant veins. There are also semi brittle shear zone structures such as en echelon quartz veins that indicate sinistral sense of movement (Fig.4.9D).



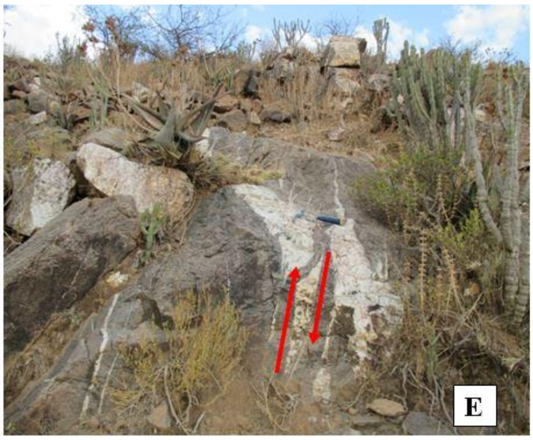


Fig. 4.9 Field photo pictures of the quartz veins of the study area. All the above photos except photo plate (F) are taken facing south east where as the photo plate (F) is taken facing north direction.

A) Quartz veins which are oriented E-W direction that show cross cutting relationship to the host body. They have a thickness of ≈ 25 cm. Location:- 0544802E, 1537709N.

B) Quartz vein with a thickness of 140m which is oriented SE-NW direction. This thick quartz vein has discordant relationship to that of felsic meta-volcanic breccia rock unit. Location:- 0544410E, 1537724N.

C) Quartz veins that have almost NW dipping direction. They show unidirectional parallel alignment that have cross cutting relationship with the host rock unit. Location:- 0544328E, 1537565N.

D) Felsic meta-volcanic breccia rock unit that contain single set of an en echelon quartz veins which indicate sinistral/ left lateral/ sense of shearing. Location :-0544416E, 1537904N.

(E)Felsic meta-volcanic breccia rock unit that contain sheared quartz vein which indicate sinistral/ left lateral/ sense of shearing(Fig.4.13E). Location : 0544410E, 1537732N.

F) A quartz vein that is intercalated at the contact between phyllite and granite unit in which they are related by concordant relationship. Location:- 0543218E, 1537579N.

4.1.3.3. Joints

The rock unit out crops/exposures of the study area is commonly dominated and highly affected specially the phyllite and meta-breccia rock units by joints. The joints are common in all the rock out crop units of the study area. For instance, the cracks found on granite out crop has a strike range of N15°W-N80°W and has nearly vertical(87°NE-89°NE) dip. The cracks/joints found on Adigrat sandstone out crop unit has also a strike range between N03°W- N88°W and is nearly vertical dipping (72°- 83° NE). The cracks event are mostly formed after the host rocks are developed. In addition to this, the space openings of these structures have an average of 5cm-25cm (Fig.4.10 B,C, E and F).

There are two major sets of systematic joints that are occurred in the study area. The first(major) systematic joints are oriented approximately NNE-SSW (≈N-S) and the second(minor) systematic joints are oriented approximately ENE-WSW (≈ E-W) direction (Fig.4.15B). Mostly these joints have dip value range from near vertical to vertical in all rock unit exposures. Furthermore, these joints have a cross cutting relationship with the regional foliation and their openings are empty meaning that they are not filled by any secondary material(s). The distribution of these joints are also not uniform in terms of occurrence and frequency and /or spacing meaning that the density of the these joints is variable in different units and various places . All of the rock units of the study area have joints emphasizing that the latter brittle deformation is wide spread covering the entire portion of the study area and they are considered as third (D3) deformation phase.

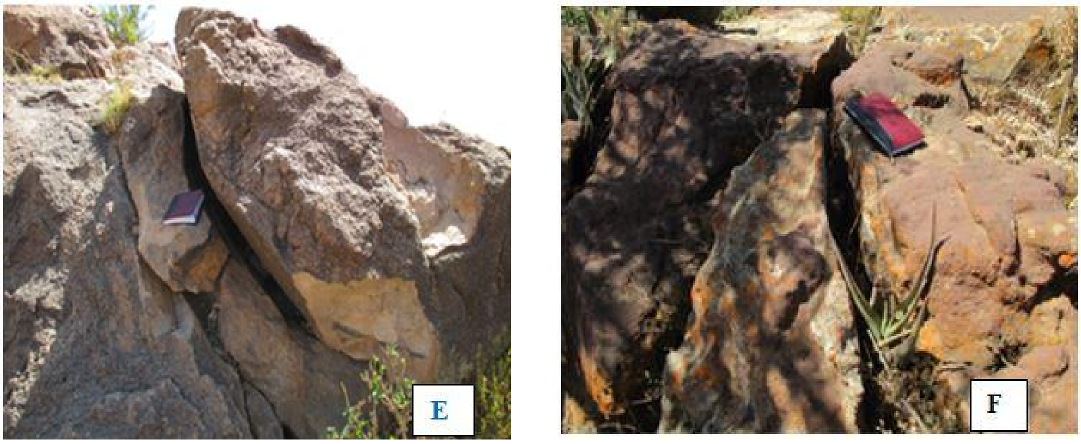


Fig. 4.10 Field photo pictures showing the distribution of two sets of systematic joints all over the study area. (A) Joints formed on the spotty quartzo-feldspathic phyllite out crop. Location: 0543933E, 1536872N. The photo is taken facing SE-direction. (B) Cracks /joints formed on the Adigrat sandstone unit. Location: 0542231E, 1537051N. Photo is taken facing east direction. (C) Cracks/joints that formed on the spotty quartzo-feldspathic phyllite unit. Location: 0543941E, 1536873N. The Photo is taken is facing SE-direction. (D) Joints formed on the spotty quartz-feldspathic phyllite unit. Location: 0543314E, 1537099N. The photo is taken facing north direction. (E) Cracks /joints formed on the granite unit. Location:- 0541510E, 1540445N. Photo is taken facing south direction. (F) Cracks/ joints formed on the Enticho sandstone unit. Location: 0545991E, 1541108N. Photo is taken facing north direction.

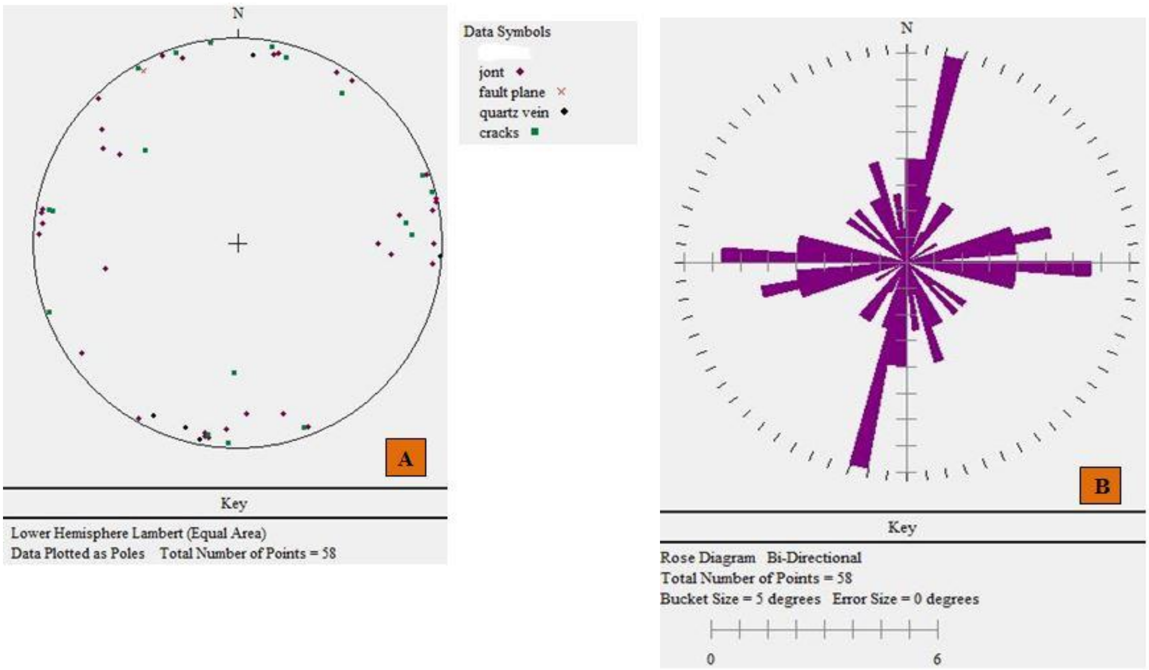


Fig. 4.11 Stereographic plots of joints, quartz veins and fault planes showing the distribution of two sets of systematic joints all over the study area. (A) the plate A shows the relationship and distribution of poles of joints, quartz veins and reverse fault planes. The poles of these plotted structures are neither clustered at a single place nor randomly spread throughout the stereo net. Rather they show certain pattern; that is the majority of the poles are generally clustered around specific areas in four different regions (NEN, WNW, ESE and SWS) of the stereo net. The poles are represented by different symbols and colors as we see in plate A at the top right part. (B) Plate B shows the Rose diagrams of joints, quartz veins and reverse fault planes with general trend of NEN, WNW, ESE and SWS orientation.

4.2 METAMORPHISM

4.2.1 Introduction

Petrographic examination has been carried out on sixteen(16) thin sections representing all major rock units of the study area including the spotty micaceous and spotty quartzo-feldspathic Phyllites; metavolcanic and metavolcanoclastic; and granite rock units. Most of the metavolcanic (MV) and metavolcanoclastic (MVC) rocks contain relict minerals such as plagioclase(i.e., albite), and K-feldspar (i.e., microcline and orthoclase) phenocrysts and metamorphic minerals such as chlorite, muscovite, sericite, biotite, epidote, calcite, opaque, and quartz. Each of the metavolcanic and metavolcanoclastic rocks is texturally and mineralogically distinctive.

In addition to this, the rock units of the study area have been subjected to different degree of deformation and metamorphism in which the original sedimentary and volcanic features are changed to varying extent. Some of these rocks have preserved their original relict minerals and primary textures and other show little mineralogical and textural changes. In some of these rocks larger laths of plagioclase are being altered in to calcites with remnant albitic twinning left to identify the plagioclase. Chlorite and epidote are formed as an alteration product of the mafic minerals during metamorphism.

4.2.2 Metamorphism

Metamorphism can be determined by careful analysis of the characteristics of the minerals constituting the rocks. Identifying how each and every mineral are affected by tectonic and related activities occurred throughout its formation is useful to evaluate the degree of metamorphism that the rock has undergone. Analyzing to what extent the original structures and textures of the parent rocks are preserved in the rocks also helps us to understand the history of metamorphism. In addition to this, the characteristic mineral associations and their degree of alteration in response to the pressure-temperature conditions give us an important clue in dealing with metamorphism of the study area. Consequently, the dominant lithologic units in the study area are described primarily in terms of their texture and /or fabric and mineralogy.

The phyllitic rocks are well foliated often with phyllitic cleavage, crenulated and shiny surfaces compared to the other rock out crops of the study area such as the meta-volcanic and granite units due to the variation in intensity or degree of metamorphism and deformation. Furthermore, the phyllitic rocks are metamorphosed at higher grade than these out crop units and this could be due to the variation in depth of burial or the effect of local heat source. The presence of the recrystallized quartz, altered feldspar, and secondary minerals such as muscovite, chlorite, epidote, calcite and porphyroblasts of opaque minerals indicate significant mineralogical change during metamorphism. Based on the dominance of constituting minerals and textures observed in the low grade metamorphic rocks it is possible to understand the protolith (the parent rock). Accordingly, the initial materials for the spotty micaceous (light yellow) phyllite and spotty quartzo-feldspathic (light black green) phyllite could be pelitic/clay rich/ sediments, and for the remaining rock units like the MV and MVC, and granites could be Pyroclastic and clastic sediments(quartzo-feldspathic meta-sediments) origin respectively. Because the majority of these rocks are composed of dominantly mica/sericite, quartz and feldspar (plagioclase) and also they have angular to sub rounded quartz and feldspar grains/ phenocrysts set in fine grained ground mass (Fig.3.6; HM-12(A), Fig. 3.10; HM-22(C&D)). Moreover, these rock units could have resulted from clay rich sediments. Clay minerals such as illite, kaolinite and montimorinolites were probably recrystallized to give chlorite and muscovite during the early low-grade metamorphism of shale and mudstone. Similarly silicate minerals with abundant magnesium can be changed into chlorite. Grade of metamorphic rocks can be estimated by using index mineral assemblages, which form in a specific range of temperature and pressure or distinctive conditions. Hence, identifying the key mineral assemblages are useful to determine the grade and metamorphic facies.

The most dominant mineral assemblages of the different rock units of the study area are given below. The bold and underlined are the index minerals that are useful to evaluate the grade of metamorphism.

1. Metavolcanic and metavolcanoclastic rock units

1.1meta-acidic rock unit

<u>Ms</u> + Qtz + **<u>Ab</u>** + Op

1.2 Felsic meta- breccia rock unit

a. **EP** + Qtz + OP

b. **Ms** + **Ep** + **Ab** +Qtz + **Hbl** + Bt + Op + rock fragments

2. Phyllite rock units

2.1 spotty micaceous phyllite

Ms + Qtz + Op

2.2 spotty quartzo-feldspathic phyllite

Ms + **Ab** + **Chl** + Qtz + Op

3. Felsic- subintrusive rock units

a. Qtz + K-fs/Or + **Chl** + **Ab** + **Hbl** + Op

b. Qtz + **Cal** + **Chl** + **Ms** + ground mass + Op

In general, all of the studied rocks have been metamorphosed to lower greenschist facies as indicated by incoming of lower greenschist minerals such as Ms+ Chl +Ep + Ab ± Qtz ± Hbl. As a result, the grade of the metamorphism is low, one would not notice many changes in the rock. This is consistent with the general conclusion that the rock units in the study area are metamorphosed at lower greenschist facies conditions (Alene M., 1998).

4.3. TIME RELATION BETWEEN METAMORPHISM AND DEFORMATION

The interpretation of time relationship between metamorphism and deformation is conducted due to the petrographic study of the rock units of the study area. Even if the metamorphic history of the rock out crops exposed in the study area is a bit challenging to reconstruct confidently, attempt is made to unravel/work loose the relationship between the two events. This is largely caused due to the low grade and fine-grained nature of the rock units. As discussed earlier in this chapter the rock units show three prominent planar structures (S0, S1 and S2). S1 and S2 developed during D1 and D2 respectively. The So foliation(s) represent the primary bedding or original foliation and it is occurred in some rock units like the spotty micaceous phyllite unit of the study area. The S1 or regional foliations are the major planar structures formed in the majority of the rock units like the MV and MVC, and phyllite(spotty micaceous and quartzo-feldspathic) rock units of the study area. These foliations are most often defined by the alignments of platy minerals in the phyllite out crops and generally speaking the alignment of these foliations are uniform throughout the study area, except in some areas which are locally distributed along the contact between the basement rocks and the granitic intrusions. Minerals such as sericite/muscovite, chlorite, calcite and some recrystallized quartz are formed during D1. Hence, they are aligned and defined S1foliations (i.e., phyllitic cleavage). Therefore, metamorphic event is considered to be contemporaneous with D1 (Mamtani et al., 2001). On the other hand, some minerals like mica and chlorite undergo alteration and perhaps recrystallization during D2 and form S2 cleavage. No evidence of growth of new minerals cutting across D2 is observed in the chlorite schists, this implying that D3 was generally devoid of any metamorphism. The paragenesis observed is chlorite, muscovite and quartz which is typical of a chlorite zone within the greenschist facies (Yardley, 1989; Spear, 1993 as cited in Mamtani et al., 2001). As a result, S2 and associated lineations (i.e., crenulation lineations) are associated with D2 micro folds. Furthermore, weak S2 crenulation cleavage defined by alternating bands of felsic (quartz and feldspar) and micaceous minerals are observed in some rock samples (Fig.3.9; HM-22(A,C &D)). Dissolution of quartz and feldspar as a result of pressure solution and reprecipitation at the hinges of the micro folds where the pressure is lower which is not uncommon feature during crenulation folding. According to Mamtani et al.(2001) pressure solution is an important deformational mechanism during the early stages of crenulation cleavage and this imparts the domainal fabric to the rock.

In addition to this, another means of investigating the time relationship between deformation and metamorphism is to study porphyroblastic and foliation relationship (Passchier and Trouw, 2005). The felsic meta-volcanic breccia rock unit in the study area is characterized by the presence of porphyroblastic minerals. Most of the grains or inclusions inside the porphyroblasts show more or less preferred orientation (Fig.3.5; HM-13(B-D) and Fig.3.9; HM-20(D)) and they have overprint relationship with S1 foliation(s). This shows that they are formed later than S1 (i.e., post-tectonic to D1). However, they are pre-D2 as some of them appear to be affected by the D2 deformation. Generally, the porphyroblasts are formed between the two tectonic events D1and D2 and hence they are called inter-tectonic. Recrystallization during regional metamorphism, or hydrothermal fluid alteration or a contact metamorphic aureole can be the cause for the formation of the porphroroblasts.

CHAPTER - FIVE

RESULT AND DISCUSSION

The Pan-African Orogeny also known as the East African Orogeny is developed due to the collision of East and West Gondwana. This Orogeny in north-east Africa consists of two major terrains. These are the Arabian-Nubian Shield (ANS) and the Mozambique Belt (MB). The ANS is characterized by its dominant juvenile nature, relatively low grade of metamorphism, and abundance of island-arc rocks and ophiolites comparing to the Mozambique Belt. The Mozambique Belt generally contains polydeformed high-grade metamorphic assemblages, exposing middle to lower crustal levels, whose origin, environment of formation and structural evolution are more difficult to reconstruct.

The metamorphic rocks of Northern Ethiopia are composed of an older island arc meta-volcanic sequence which is referred to the Tsaliet Group, and a younger meta-sediment sequence which is termed as the Tambien Group. Both groups are part of the ANS and in this regard, the Megab - Hawzien metamorphic terrain belongs to the Arabian Nubian Shield.

The phyllite unit of the study area has previously been mapped differently by different authors: as meta-sedimentary or Tambien Group (Arkin et al., 1971) , as meta-volcanic or Tsaliet Group (Garland, 1972, 1980). On the other hand, Miller et al. (2003) described this unit as a transitional lithology.

The result of this study indicates that the phyllite unit contains two sub units: the micaceous and quartzo-feldspathic phyllites , and they are mapped separately from the nearby MV &MVC, and meta- sedimentary units (Fig.3.1). Previously the phyllite unit has been mapped and described separately(e.g. Alene, 1998) for the following reasons. These are :- (1) the rock fabric is different from that of metavolcanoclastics, it is characterized by alternating quartzo-feldspathic and micaceous bands occurring in mesoscopic as well as in microscopic levels; the rock is relatively more altered, foliated and often crenulated; but the metavolcanoclastic unit is composed of dominantly massive, greenish grey metagreywackes associated with meta-breccias; (2) the meta-sedimentary unit shows very fine-grained, slaty fabric; and intercalation of calcareous beds, but the phyllite unit does not contain these properties; (3) the large parts of the phyllite unit is uniquely decorated with brownish spots (mainly oxidized porphyroclastic grains and euhedral calcite) which is not common in the other units; (4) micro-granitic and aplitic dykes as well as quartz veins are typically abundant in this unit; and (5) unlike the meta-sedimentary slates which occur along valleys and major synforms, the phyllite unit forms smaller alternating antiforms and synforms. Consistent with the previous study, the phyllite unit in the study area also contains various types of lithologies mainly the spotty quartzo-feldspathic phyllite and the spotty micaceous phyllite at large scale mapping (i.e.,1:25,000). Furthermore, other rock units are now recognized and described in the study area including the MV and MVC units, phyllite units, granite units and Phanerozoic formations.

Based on the field work description, petrographic examination and structural data analysis, the following results are also recognized. These include:-

(1) Deformational phases. The rock units of the study area are subjected to three phases of deformation. These include:- D1,D2 and D3. These deformational phases are related to the structures produced by the pan-African /East African orogeny. According to Alene (1998); and Alene et al.(2000), two phases of deformation (D1 and D2) are recognized in the region, which are the result of N–S and E– W regional compression, respectively. D1 is associated with folding of primary bedding and appearance of tight to isoclinal minor folds; intersection and /or stretching lineations and a pervasive regional foliation(S1). On the other hand, D2 caused large upright, open folds with sub-horizontal axes without producing a pervasive foliation.

D2-structures are most simply explained as reflecting terminal collision between E and W Gondwana. The brittle deformational structures like the reverse faults, quartz veins, and joints which cut across the D1 and D2 structures are related to the younger deformational phase (D3).

Consequently, this field study area and other field studies conducted in the low grade metamorphic terrain of the Northern Ethiopia indicate that this terrain is more or less characterized by these types of deformational phases.

(2)Petrography and Grade of metamorphism. The rock units of the study area are characterized by fine to medium grain size, xenoblastic to hypidioblastic crystal form, decussate texture and mineral zoning. The growth rate plays an important role for grain size and crystal form. For instance, the fine grained and largely xenoblastic texture of most of these rocks is considered to show relatively faster growth rate. Zoning in metamorphic minerals relates to changing composition of the matrix and fluid, which in a closed system is directly related to availability of reactants and degree of completion of reaction. Decussate texture is special type of granoblastic structure where crystals are subhedral, prismatic and randomly oriented.

The petrographic study shows the presence of several mineral assemblages. These include quartz, feldspars/plagioclase and K-fs/, chlorite, albite, epidote, muscovite, biotite, and calcite. Such mineral assemblages are the main characteristic feature of the lower greenschist facies. Therefore, the study area indicates lower greenschist facies. This facies is considered to cover a relatively small range of temperature and low to intermediate Pressure. These results are again consistent with previous studies conducted on different areas in Northern Ethiopia(e.g., Alene, 1998; Tadele Tesema., 2012; and Tesfaye Ragasa., 2013).

(3) Time relationship between deformation and metamorphism.

The time relationship between deformation and metamorphism is studied by two methods/ approaches. These include:-(i) petrographic study, and (ii) porphyroblastic and foliation relationship. Based on these two approaches mentioned above, the time relationship between deformation and metamorphism of the rock units of study area (particularly the spotty quartzo-feldspathic phyllite and the felsic meta-volcanic breccia) are related to the inter-tectonic event.

On the basis of the present petrographic study, the time relationship between deformation and metamorphism can be established. As mentioned earlier, these rocks show three prominent planar surfaces (S0, S1 and S2). S1 and S2 developed during D1 and D2 respectively. Chlorite and muscovite crystals are formed during D1(Fig.3.9; HM-22(A) and Fig.3.11; HM-20(A, B & D)). These underwent rotation along S2 and some recrystallization during D2. No evidence of growth of new minerals cutting across D2 is observed in the chlorite schists, thus implying that D3 was generally devoid of any metamorphism. The paragenesis observed is chlorite + muscovite + quartz which is typical of a chlorite zone within the greenschist facies (Yardley, 1989; Spear, 1993 as cited in Mamtani et al.(2001).

In addition to this, another means of investigating the time relationship between deformation and metamorphism is to study porphyroblastic and foliation relationship (Passchier and Trouw, 2005). The felsic meta-volcanic breccia rock unit in the study area are characterized by the presence of porphyroblastic minerals. Most of the grains or inclusions inside the porphyroblasts show more or less preferred orientation (Fig.3.5; HM-13(B-D) and Fig.3.9; HM-20(D)). Moreover, they are formed later than S1 (i.e., post-tectonic to D1). However, they are pre-D2 as some of them appear to be affected by the D2 deformation. Generally, the porphyroblasts are formed between the two tectonic events D1 and D2 and hence they are called inter-tectonic. Recrystallization during regional metamorphism, or hydrothermal fluid alteration or a contact metamorphic aureole can be the cause for the formation of the porphroroblasts.

CHAPTER - SIX

CONCLUSION AND RECOMMENDATION

6.1 Conclusion

Depending on the office work (secondary data), field work and laboratory analysis the study area/Megab-Hawzien area) contains the following rock units. These are:- the metavolcanic and metavolcanoclastic rock units or Tsaliet group, the meta-sedimentary rock units (Phanerozoic formations) or Tambien group, the felsic subintrusive rock unit, the granite unit, and the phyllite units. The largest part of the study area is covered by the MV and MVC rock units followed by the granite rock unit . The MV and MVC units contain meta-acidic and felsic meta-volcanic breccia rock units respectively. These units include minerals such as sericite/mica, epidote, quartz, and plagioclase feldspar and some opaque minerals. Moreover, these rock units are mainly exposed in the northeastern part of the study area. The phyllite unit in the study area is mapped independently. This means that this unit is not included in both major units. To some extent, it is bounded by the MV and MVC units in the SE-direction and meta-sedimentary units in the NW-direction. In addition to this, the phyllite rock unit is divided into spotty micaceous and quartzo-feldspathic rock units. The spotty micaceous phyllite unit contains muscovite, quartz and sericite minerals and it is exposed in the NW part of the study area. On the other hand, the spotty quartzo-feldspathic phyllite rock unit includes quartz, plagioclase/albite, muscovite, chlorite and some opaque minerals and it is exposed in the SE part of the study area. Generally, the phyllite unit is characterized by fine grain, low grade metamorphic rock, shiny and phyllitic cleavage. Based on grain size and color, the felsic subintrusive rock unit is divided in to two subgroups. The first one is a felsic-subintrusive out crop with medium to coarse grain, grayish/pinkish black color(HM-20) that contains minerals like quartz, alkali feldspar/orthoclase, chlorite, hornblende and opaque materials. The second one is a felsic-subintrusive out crop with fine grain to medium grain, black greenish color (HM-21) that contains quartz, calcite, chlorite, sericite/mica, ground mass and opaque minerals. This shows a little parallel alignments of minerals comparing to the first one.

The granite rock unit is mostly found on the northern part of the study area. It covers approximately 3 (three) square Km area of the upper northern part of the study area. This rock unit is identified by its massive structure, medium to coarse grains, light gray or whitish gray colors that contains minerals such as quartz, K-feldspar/microcline and orthoclase/, plagioclase, biotite and muscovite. The Phanerozoic formations of the study area include Paleozoic and Mesozoic sediments. The Paleozoic sediments are classified into Enticho sandstone and Edaga Arbi Glacial deposits such as Edaga Arbi shale intercalated with Edag Arbi Tillite, containing granite boulders up to 6(six) meters in diameter. These sediments/ rock units are exposed in the western part of the study area. The Mesozoic sediments include the Adigrat Sandstone. This rock unit is exposed in the western part of the study area. Generally, the phanerozoic formations cover smaller area comparing to the other rock units of the study area.

Moreover, the study area have been subjected to both type of deformation namely; brittle and ductile deformations. The brittle structures of the study area include joints, reverse faults and quartz veins. The ductile structures are folds, foliations and lineations. On the other hand, the results of petrographic and structural evidence shows that the rock out crops of the study area are poly- deformed and has three phases of deformation. These are: D1, D2 and D3. D1 is characterized by pervasive/regional foliation(S_1) and linear fabrics(i.e., intersection lineations) defined by platy minerals. Furthermore, D1 is associated with folding of primary bedding and appearance of tight to isoclinal minor folds. D2 is characterized by N-S trending upright, open folds and crenulation lineations with sub horizontal fold axes without producing a pervasive foliation. D3 is characterized by brittle structures such as NE trending reverse faults, and N-S, E-W, NE-SW and NW-SE trending set of joints and quartz veins. The brittle deformation in the area cut the structural elements of the preceding deformation and hence, is the latest deformation event. The rock units of the study area also shows three prominent planar surfaces (S0, S1 and S2). In addition to this, the petrographic examination of collected rock samples from litho-units of the study area indicates that the protolith of igneous minerals and textures were mainly destroyed by alteration accompanied with deformation and metamorphism. Hence, recrystallization of the quartz and plagioclase minerals, and growth of chlorite and epidote minerals produce generally decussate textures.

Finally, based on the presence of certain mineral assemblages such as chlorite, albite, sericite and muscovite, it is interpreted that the rock units in the study area are experienced at a relatively small range of T and at low to intermediate P(i.e., low grade metamorphism) that belongs to lower greenschist facies. The occurrence of relict and preserved primary structures like bedding also imply the prevalence of the low degree of metamorphism and this coevals with the earliest phase of deformation. The petrographic examinations; and the porphyroblasts and foliation relationship show that the time relationship between deformation and metamorphism of the study area is related to the inter-tectonic /late tectonic type.

6.2 RECOMMENDATION

- Some of the study area show intense and sheared quartz veins. So, it is strongly recommended to explore the area for metallic minerals, particularly for gold, as the rocks in the study area are altered and show very good indication of mineralization.
- Detailed and/or Larger scale mapping than the present work (1: 25,000), like 1:10, 000 , 1 : 5,000 etc,.. could enables to differentiate the intercalated units or zones (like the MVC and MV units intercalated with the phyllite units) in detail.
- Geochemical analysis using large number of rock samples is also highly recommended to identify the porphyroblastic minerals and to know exactly the protolith of the different type of metamorphosed rocks in the area.

REFERENCE

Abdelsalam, M.G., and Stern, R.J.(1996). Sutures and shear zones in the Arabian-Nubian Shield. Journal of African Earth Sciences 23, 289-300.

Alene, M., and Barker, A.J.(1993).Tectonometamorphic evolution of the Moyale region, Southern Ethiopia. Precambrian research 62,271-283.

Alene, M.(1998). Tectono-magmatic evolution of the Neoproterozoic rocks of the Mai Kenetal–Negash area, Tigray, northern Ethiopia. Unpublished Ph.D. Thesis, University of Turin.

Alene, M., Ruffini, R., Sacchi, R.(2000). Geochemistry and geotectonic setting of Neoproterozoic rocks from northern Ethiopia (Arabian–Nubian Shield). Gondwana Res. 3, 333–347.

Alene ,M., Jenkin G., Leng M. and Darbyshir F. (2006). The Tambien Group, Ethiopia: an early Cryogenian (Ca. 800-735 Ma) Neoproterozoic sequence in the Arabian-Nubian Shield, Precambrian Research. 147: 79-99.

Arkin, Y., Beyth, M., Dow, D.B., Levitte, B., Temesgen, H., Tsegaye H.(1971). The Geological map of Mekele area (1:250,000). Ministry of Mines, Addis Ababa.

Asrat, A., Barbey, P., and Gleizes, G. (2001). The Precambrian Geology of Ethiopia: a review, Africa Geoscience Review. 8: 271-288.

Asrat, A., Gleizes, G., Barbey, P., and Ayalew, D. (2003). Magma emplacement and mafic–felsic magma hybridization: structural evidence from the Pan-African Negash pluton, Northern Ethiopia. Journal of Structural Geology. 25: 1451-1469.

Avigad, D., Stern, R.J., Beyth, M., Miller, N., McWilliams, M.O.(2007). Detrital zircon U-Pb geochronology of Cryogenian diamictites and Lower Paleozoic sandstone in Ethiopia (Tigray): Age constraints on Neoproterozoic glaciation and crustal evolution of the southern Arabian-Nubian Shield. Precambrian Research 154, 88-106.

Berhe, S. M.(1990). Ophiolites in Northeast and East Africa: implications for Proterozoic crustal growth. Journal of Geological Society of London 147, 647-657.

Beyth, M.(1971). The geology of central and western Tigre. Unpublished report, Ministry of Mines, Addis Ababa.

Beyth, M.(1972). The geology of central and western Tigre. PhD Thesis, University of Bonn, Germany, 155pp.

Beyth, M., Avigad, D., Wetzel, H.U., Matthews, A., Berhe, S.M.(2003). Crustal exhumation and indications for Snowball Earth in the East African Orogen: North Ethiopia and East Eritrea. Precambrian Research 123: 187–201.

Bheemlingeswara, K. and Tadesse, N.(2009). Petrographic and Geochemical study of low grade metamorphic rocks around Negash with reference to base metal mineralization and groundwater quality, Tigray, Northern Ethiopia, Mekelle University, Mekelle. 1(2): 106-132.

Bussert, R.(2010). Exhumed erosional land forms of the late Paleozoic glaciation in northern Ethiopia: Indicators of ice-flow direction, paleolandscape and regional ice dynamics, Gondwana Res.(2010), doi:10.1016/j.gr. 2009.10.009.

Desta Dawit.(2014). Geological structures and tectonic evolution of the Neoproterozoic terrain of the Guwila area, Tigray, Northern Ethiopia. Unpublished MSc Thesis, Addis Ababa University, Addis Ababa , Ethiopia, 87pages.

Eyob Abebe.(2013). Differentiating structures and litho-units of the Tsaliet group around Negash area, Tigray, Northern Ethiopia. Unpublished MSc Thesis, Addis Ababa University, Addis Ababa , Ethiopia, 85pages.

Fasil E.(2007). Geographical and Hydrogeological settings in defining threshold spacing of shallow Hand-Dug Wells. A case study in Debrekidan watershed, north Ethiopia: Norwegian University of life sciences; Master thesis,page10-14.

Garland, C.R.(1972). Geological Map of Adigrat Area. 1:250,000 (ND 37-7). GSE, Addis Ababa, Ethiopia.

Garland, C.R. (1980). Geology of the Adigrat Area. Ministry of Mines, Addis Ababa. Memoir No.1: 51.

GebreMariam, S.(2009). Nature and characteristics of metasedimentary rock hosted gold and base metal mineralization in the Workamba area, central Tigray, Northern Ethiopia. Ph.D. Thesis. http://edoc.ub.uni-muenchen.de/10882/1/Gebremariam_Solomon.pdf, viewed 28 Oct 2012.

Johnson, P.R., Woldehaimanot, B.(2003). Development of the Arabian–Nubian Shield: perspectives on accretion and deformation in the northern East African Orogen and the assembly of Gondwana. Geological Society, London. p289-325.

Kazmin, V.(1972). The geology of Ethiopia. Ethiopian Institute of Geological Surveys. Note No. 821-051-12: 208.

Kazmin, V.(1973). The geological map of Ethiopia, 1:2,000,000. Ethiopian Institute of Geological Surveys, Addis Ababa, Ethiopia.

Kazmin, V.(1975). The Precambrian of Ethiopia and some aspects of the Geology of the Mozambique Belt. Bulletin Geophysics. Obs., Addis Ababa University 15, 27-43.

Kazmin, V., Shiferaw, A., Balcha, T.(1978). The Ethiopian basement: stratigraphy and possible manner of evolution. Geologische Rundschau 67, 531–548.

Kröner, A.(1985). Ophiolites and the evolution of tectonic boundaries in the late Proterozoic Arabian-Nubian Shield of northeast Africa and Arabia. Precambrian Research 27, 277- 300.

Kroner, A., and Stern, R.J.(2005). Africa/Pan- African Orogeny. Encyclopedia of Geology, v. 1. Elsevier, Amsterdam.

Levitte, D.(1970). The geology of central part of Mekelle sheet (ND37-11). Ethiopian Institute of Geological Survey. Note No. 821-201-12: 66.

Mamtani, A., Merh, S.S., Karanth, R.V., Greiling, R.O. (2001). Time relationship between metamorphism and deformation in Proterozoic rocks of the Lunavada region, Southern Aravalli Mountain Belt (India) - a microstructural study, Journal of Asian Earth Science19: 195-205.

Miller, N. R., Alene, M., Sacchi, R., Stern, R., Conti, A., Kroner, A. and Zuppi, G.(2003). Significance of the Tambien Group (Tigre, Northern Ethiopia) for snowball Earth events in the Arabian–Nubian Shield. Precambrian Research, 121, 263–283.

Miller, N.R., Avigad, D., Stern, R.J., Beyth, M. & Schilman, B.(2009). Cryogenian slate carbonate sequences of the Tambien Group, Northern Ethiopia (I): Pre-“Sturtian” chemostratigraphy and regional correlations, Precambrian Research 170: 129–156.

Passchier.C. and Trouw.R.J.(2005). Microtectonics. Springer-Verlag Berlin Heidelberg, Germany.

Ramsay, J.G.(1967). Folding and Fracturing, The Black Burn Press. pp. 9.

Sacchi, R., Mulugeta, A., Barberi M., and Conti, A.(2007). On the Paleozoic Tillite of the Adigrat Group(Tigray, Ethiopia). Per. Mineral 76, 2-3, 241- 251.

Sifeta, K., Roser, P., Kimura, J. (2005). Geochemistry, provenance, and tectonic setting of Neoproterozoic metavolcanic and meta-sedimentary units, Werri area, Northern Ethiopia, Journal of African Earth Science 41: 212-234

Stern, R.J. (1994). Arc assembly and continental collision in the Neoproterozoic East African Orogen: implications for consolidation of Gondwana land, Annual Reviews Earth Planetary Sciences. 22: 319-351.

Stern, R.J.(2002). Crustal evolution in the East African Orogen: a neodymium isotopic perspective. Journal of African Earth Sciences 34, 109–117.

Stern, R.J., Avigad, D., Miller, N.R., and Beyth, M.(2006). Evidence for the Snowball Earth hypothesis in the Arabian-Nubian Shield and the east African Orogen. Journal of African Earth Sciences 44, 1-20.

Tadele Tesema.(2012). Petrography, structure and chemostratigraphic correlation of the Chehmit area, Tigray, Northern Ethiopia. Unpublished MSc Thesis, Addis Ababa University, Addis Ababa , Ethiopia, 111pages.

Tadesse, G., and Allien, A.(2005). Geology and geochemistry of the Neoproterozoic Tuludimtu Ophiolite suite, western Ethiopia, Journal of African Earth Sciences 41: 192–211.

Tadesse, T.(1996). Structure across a possible intra-oceanic suture zone in low-grade Pan-African rocks of northern Ethiopia. Journal of African Earth Sciences 23, 575-381.

Tadesse, T., Hoshino, M., Sawada, Y.(1999). Geochemistry of low grade metavolcanic rocks from the Pan-African of the Axum area, northern Ethiopia, Precambrian Research. 99: 101–124.

Tefera, M., Chernet, T. and Haro, W.(1996). Explanation of the geological map of Ethiopia (scale 1:2,000,000), 2nd ed., Ethiopian institute of geological surveys. Addis Ababa, bulletin no. 3.

Teklay, M., Kröner, A., Mezger, K., and Oberhansli, R.(1998). Geochemistry, Pb-Pb single Zircon ages and Nd-Sr isotope composition of Precambrian rocks from southern and Eastern Ethiopia: implications for crustal evolution in East Africa. Journal of African Earth Sciences, 26, 207-227.

Tesfaye Ragasa.(2013). Structure, Lithology and Metamorphism of Phyllite zone around Hawzien, Tigray, Northern Ethiopia. Unpublished MSc Thesis, Addis Ababa University, Addis Ababa , Ethiopia, 80pages.

Tsige, L., Abdelsalam, M.G.(2005). Neoproterozoic - Early Paleozoic gravitational tectonic collapse in the southern part of the Arabian- Nubian Shield: The Bulbul Belt of Southern Ethiopia. Precambrian Research 138, 297-318.

Twiss, R.J., and Moores, E.M.(1973). Structural Geology. W.H. Freeman and Company, New York. 532 pages.

Vail, R.V.(1983). Pan-African crustal accretion in north-east Africa. Journal of African Earth Sciences 1, 285-294.

Vail, J.R.(1985). Pan-African (late Precambrian) tectonic terrains and the reconstruction of the Arabian-Nubian Shield. Geology 13, 839-842.

Worku, H., and Schandelmeier, H. (1996). Tectonic evolution of the Neoproterozoic Adola Belt of southern Ethiopia: evidence for a Wilson cycle process and implications for oblique plate collision, Precambrian Research. 77: 179–210.

Yardley, B.W.D., MacKenzie, W.S. and Guilford, C.(1990): Atlas of Metamorphic Rocks and their textures. Longman, London. 126p.

APPENDIX

Appendix-1: Structural measurements of different structural elements

No	Measured Structural Elements	Dip	Dip Direction	Location	Unit
1	Axial Plane	51°	272°	0543943E, 1536885N	Spotty quartzo-feldspathic phyllite
2		48°	276°	0543944E ,1536884N	Spotty quartzo-feldspathic phyllite
3		54°	281°	0543945E ,1536883N	Spotty quartzo-feldspathic phyllite
4		36°	294°	0543943E ,1536881N	Spotty quartzo-feldspathic phyllite
5		66°	215°	0543939E ,1536882N	Spotty quartzo-feldspathic phyllite
6		87°	205°	0543943E ,1536880N	Spotty quartzo-feldspathic phyllite
7		37°	295°	0543939E ,1536883N	Spotty quartzo-feldspathic phyllite
8		86°	200°	0543941E ,1536873N	Spotty quartzo-feldspathic phyllite
9		70°	350°	0543937E ,1536878N	Spotty quartzo-feldspathic phyllite
10		79°	277°	0543936E ,1536879N	Spotty quartzo-feldspathic phyllite
11		88°	250°	0543932E ,1536878N	Spotty quartzo-feldspathic phyllite
12		60°	273°	0543925E ,1536870N	Spotty quartzo-feldspathic phyllite
13		72°	279°	0543933E ,1536872N	Spotty quartzo-feldspathic phyllite
14	Bedding (So)	81°	255°	0542338E ,1537147N	Edaga Arbi glacial deposits / Shale and Tillite/
15		68°	357°	0542332E ,1537139N	Edaga Arbi glacial deposits / Shale and Tillite/
16		76°	245°	0542331E ,1537135N	Edaga Arbi glacial deposits / Shale and Tillite/
17		74°	187°	0542344E ,1537140N	Edaga Arbi glacial deposits / Shale and Tillite/
18		66°	355°	0542340E ,1537135N	Edaga Arbi glacial deposits / Shale and Tillite/
19		73°	195°	0542346E ,1537148N	Edaga Arbi glacial deposits / Shale and Tillite/
20		72°	346°	0542336E ,1537149N	Edaga Arbi glacial deposits / Shale and Tillite/
21		30°	200°	0542334E ,1537148N	Edaga Arbi glacial deposits / Shale and Tillite/
22		70°	120°	0542327E ,1537157N	Edaga Arbi glacial deposits

					/ Shale and Tillite/
23		81°	250°	0542320E ,1537153N	Edaga Arbi glacial deposits / Shale and Tillite/
24		83°	153°	0542317E ,1537153N	Edaga Arbi glacial deposits / Shale and Tillite/
25		77°	062°	0540611E ,1539381N	Alluvial Deposit
26		89°	181°	0539755E ,1539974N	Edaga Arbi glacial deposits / Shale and Tillite/
27		83°	300°	0539747E ,1539968N	Edaga Arbi glacial deposits / Shale and Tillite/
28		56°	323°	0539723E ,1539953N	Edaga Arbi glacial deposits / Shale and Tillite/
29		80°	085°	0539716E ,1539949N	Edaga Arbi glacial deposits / Shale and Tillite/
30	S1 (Foliation)	83°	355°	0540098E ,1540672N	Meta-acidic
31	S1	87°	265°	0540236E ,1540725N	Spotty quartzo-feldspathic phyllite
32	S1	65°	121°	0540233E ,1540732N	Spotty quartzo-feldspathic phyllite
33	S1	89°	097°	0540243E ,1540723N	Spotty quartzo-feldspathic phyllite
34	S1	72°	143°	0540226E ,1540721N	Spotty quartzo-feldspathic phyllite
35	S1	85°	130°	0540217E ,1540712N	Spotty quartzo-feldspathic phyllite
36	S1	58°	012°	0543218E ,1537579N	Spotty quartzo-feldspathic phyllite
37	S1	77°	003°	0543314E ,1537099N	Spotty quartzo-feldspathic phyllite
38	S1	66°	294°	0543934E ,1536863N	Spotty quartzo-feldspathic phyllite
39	S1	57°	280°	0543940E ,1536875N	Spotty quartzo-feldspathic phyllite
40	S1	71°	185°	0540094E ,1540670N	Meta-acidic
41	S1	73°	295°	0543184E ,1537554N	Phyllite contact with Edaga Arbi glacial deposits
42	S1	56°	308°	0543186E ,1537549N	Phyllite contact with Edaga Arbi glacial deposits
43	S1	86°	150°	0545130E ,1539596N	Felsic meta-Volcanic breccia
44	S1	21°	110°	0545136E ,1539597N	Felsic meta-Volcanic breccia
45	S1	70°	119°	0545139E ,1539592N	Felsic meta-Volcanic breccia
46	S1	62°	205°	0545144E ,1539598N	Felsic meta-Volcanic breccia
47	S1	88°	020°	0545141E ,1539602N	Felsic meta-Volcanic breccia
50	S1	84°	096°	0540943E ,1540974N	Felsic meta-Volcanic breccia

51	S1	89°	011°	0545943E ,1540978N	Felsic meta-Volcanic breccia
52	S1	74°	098°	0545951E ,1540977N	Felsic meta-Volcanic breccia
53	S1	85°	017°	0545952E ,1540981N	Felsic meta-Volcanic breccia
54	S1	89°	010°	0545951E ,1540973N	Felsic meta-Volcanic breccia
55	S1	87°	225°	0545944E ,1540960N	Felsic meta-Volcanic breccia
56	S1	86°	101°	0545938E ,1540960N	Felsic meta-Volcanic breccia
57	S1	75°	345°	0545506E ,1538015N	Felsic meta-Volcanic breccia
58	S1	86°	194°	0545513E ,1538013N	Felsic meta-Volcanic breccia
59	S1	85°	301°	0545509E ,1538016N	Felsic meta-Volcanic breccia
60	S1	58°	186°	0545512E ,1538014N	Felsic meta-Volcanic breccia
61	S1	77°	077°	0540755E ,1541398N	Spotty micaceous phyllite
62	S1	87°	178°	0540757E ,1541395N	Spotty micaceous phyllite
63	S1	61°	297°	0540745E ,1541399N	Spotty micaceous phyllite
64	S1	59°	287°	0540753E ,1541376N	Spotty micaceous phyllite
65	S1	65°	275°	0540764E ,1541366N	Spotty micaceous phyllite
66	S1	80°	210°	0540758E ,1541376N	Spotty micaceous phyllite
67	S1	66°	341°	0540757E ,1541380N	Spotty micaceous phyllite
68	S1	53°	280°	0540763E ,1541378N	Spotty micaceous phyllite
69	S1	70°	240°	0540761E ,1541386N	Spotty micaceous phyllite
70	S1	88°	253°	0540756E ,1541375N	Spotty micaceous phyllite
71	S1	74°	190°	0540776E ,1541382N	Spotty micaceous phyllite
72	Joints	84°	163°	0540381E, 1540792N	Spotty micaceous phyllite
73		85°	009°	0540741E, 1540656N	Spotty micaceous phyllite
		89°	158°	0541186E, 1540135N	Granite
74		87°	093°	0542846E, 1539603N	Granite
75		86°	096°	0543428E, 1538624N	Granite
76		87°	100°	0541360E, 1540718N	Granite
77		64°	274°	0542314E, 1540693N	Granite
78		85°	010°	0543651E, 1540519N	Granite
79		58°	270°	0541954E, 1539516N	Granite
80		85°	339°	0543131E, 1538884N	Granite
81		89°	258°	0544081E, 1540780N	Granite
82		88°	136°	0540196E, 1540718N	Meta-acidic
83		56°	079°	0546215E, 1540457N	Meta-acidic
84		87°	099°	0546550E, 1540544N	Meta-acidic

85		85°	276°	0545422E, 1540594N	Felsic meta-Volcanic breccia
86		80°	004°	0545052E,1538736N	Felsic meta-Volcanic breccia
87		86°	210°	0545224E,1537138N	Felsic meta-Volcanic breccia
88		88°	030°	0545400E,1536259N	Felsic meta-Volcanic breccia
89		87°	215°	0544345E,1535218N	Felsic meta-Volcanic breccia
100		84°	192°	0545348E,1540780N	Felsic meta-Volcanic breccia
101		69°	260°	0540138E, 1539120N	Felsic meta-Volcanic breccia
102		83°	191°	0545769E,1536816N	Felsic meta-Volcanic breccia
103		85°	270°	0546500E,1538769N	Felsic-Sub intrusive
104		76°	130°	0547627E,1536804N	Felsic-Sub intrusive
105		70°	125°	0545831E,1536466N	Felsic-Sub intrusive
106		62°	127°	0544357E,1539776N	Spotty quartzo-feldspathic phyllite
107		72°	357°	0542710E,1536900N	Spotty quartzo-feldspathic phyllite
108		75°	345°	0543391E,1535912N	Spotty quartzo-feldspathic phyllite
109		83°	055°	0543837E,1538005N	Spotty quartzo-feldspathic phyllite
110		83°	010°	0542512E,1537324N	Spotty quartzo-feldspathic phyllite
111		86°	250°	0543255E,1536457N	Spotty quartzo-feldspathic phyllite
112		54°	135°	0544877E,1539628N	Spotty quartzo-feldspathic phyllite
113		88°	250°	0544149E,1540516N	Granite contact with spotty quartzo-feldspathic phyllite
114		89°	257°	0544149E,1540130N	Granite contact with spotty quartzo-feldspathic phyllite
115		86°	260°	0544150E,1540519N	Granite contact with spotty quartzo-feldspathic phyllite
116	Fault Plane	86°	151°	0540211E ,1540716N	Spotty micaceous phyllite
117		88°	172°	0540165E ,1540716N	Spotty micaceous phyllite
118	Quartz Vein	87°	011°	0544405E ,1537912N	Felsic meta-Volcanic breccia
119		83°	016°	0544416E ,1537904N	Felsic meta-Volcanic breccia
120		83°	026°	0544375E ,1537818N	Felsic meta-Volcanic breccia
121		89°	274°	0544410E ,1537732N	Felsic meta-Volcanic breccia
122		81°	185°	0544410E ,1537724N	Felsic meta-Volcanic breccia
123		80°	088°	0544393E ,1537688N	Felsic meta-Volcanic breccia

No	Measured Structural Elements	Plunge	Plunge Direction	Location	Unit
1	Crenulation Lineation (L2)	49°	292°	0543941E ,1536874N	Phyllite(quartzo-feldspathic)
2		88°	345°	0543947E ,1536887N	Phyllite(quartzo-feldspathic)
3		82°	194°	0543951E ,1536881N	Phyllite(quartzo-feldspathic)
4		65°	301°	0543953E ,1536883N	Phyllite(quartzo-feldspathic)
5		84°	186°	0543953E ,1536885N	Phyllite(quartzo-feldspathic)
6		50°	297°	0543954E ,1536892N	Phyllite(quartzo-feldspathic)
7		55°	315°	0543956E ,1536892N	Phyllite(quartzo-feldspathic)
8		78°	190°	0543962E ,1536891N	Phyllite(quartzo-feldspathic)
9		47°	306°	0543955E ,1536887N	Phyllite(quartzo-feldspathic)
10		68°	352°	0543953E ,1536884N	Phyllite(quartzo-feldspathic)
11	F2	28°	120°	0543938E ,1536881N	Phyllite(quartzo-feldspathic)
12	F2	25°	075°	0543937E ,1536884N	Phyllite(quartzo-feldspathic)
13	F2	17°	185°	0543946E ,1536886N	Phyllite(quartzo-feldspathic)
14	F2	20°	182°	0543939E ,1536883N	Phyllite(quartzo-feldspathic)
15	F2	12°	195°	0543940E ,1536884N	Phyllite(quartzo-feldspathic)
16	F2	23°	248°	0543946E ,1536880N	Phyllite(quartzo-feldspathic)
17	F2	24°	260°	0543947E ,1536881N	Phyllite(quartzo-feldspathic)
18	F2	21°	230°	0543950E ,1536882N	Phyllite(quartzo-feldspathic)
19	F2	30°	253°	0543950E ,1536884N	Phyllite(quartzo-feldspathic)
20	F2	29°	335°	0543954E ,1536891N	Phyllite(quartzo-feldspathic)

DECLARATION OF ORIGINALITY

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

.... …………………………

Mehari Kinfe (Candidate) Date

This is to certify that the above declaration made by the candidate is correct to the best of my knowledge.

.... ………………………

Dr. Mulugeta Alene (Advisor) Date