ADDIS ABABA UNIVERSITY

SCHOOL OF GRADUATE STUDIES

SCHOOL OF EARTH SCIENCE

STRUCTURE, LITHOLOGY AND METAMORPHISM OF PHYLLITE ZONE AROUND HAWZIEN, TIGRAY, NORTHERN ETHIOPIA.

BY TESFAYE REGASA

12/08/2013

ADVISOR: MULUGETA ALENE (PhD)

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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 (Structural Geology).

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APPROVED BY EXAMINING BOARD	**SIGNATURE**
Examiners	
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Advisor	
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Last but not least I want to say thank you to the almighty God for everything!

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.

Tesfaye Regasa

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ABSTRACT

The Phyllite unit, which is found around Hawzien town, Tigray Northern Ethiopia, is known as the intervening zone between the two main groups of the Neoproterozoic basement rocks of Northern Ethiopia. The two groups, Tsaliet Group and Tambien Group, generally consist of metavolcanics and metasediments respectively. These low-grade metamorphic rocks, which constitute the southern Arabian-Nubian Shield, are the least studied zone among Precambrian rocks of the country. As a result the Phyllite unit has been variously interpreted; as metasedimentary (Arkin et al., 1971), metavolcanic (Garland, 1972, 1980) and transitional lithology (Miller et al., 2003).Moreover, the unit has been depicted as a single lithology in various geological maps.

However the detailed mapping, field investigation, petrographic study and data analysis revealed that the zone is not a single monotonous unit.

It consists of various units and subunits; including different type of phyllites such as spotty qurtzo feldspathic phyllite, undifferentiated slate and phyllite, chloritic slate and phyllite, spotty micaceous phyllite, metagreywake, metasubintrusives, granitoids, graphite and quartz vein.

The key mineral assemblages such as sericite muscovite, chlorite and albite, indicate the rocks in area experienced low-grade metamorphism that belongs to lower green schist facies. The occurrence of relict and preserved primary structure like bedding also imply the prevalence of the low-grade metamorphism.

Structural data analysis, both mesoscopic and microscopic, discloses the study area has experienced at least three phases of deformation. D1 resulted in the development of the pervasive N-S trending and west dipping secondary foliation (S1). Whereas the later phase of deformation (D2) has caused the formation of incipient S2 cleavage and mesoscopic and regional scale overturned folds.

The E-W trending and vertically dipping joints that cross cut bedding and foliations are related to D3.

CHAPTER ONE

1 INTRODUCTION

1.1 Back ground

The Neoproterozoic basement of Ethiopia lies at the transition between the northern and southern sectors of the East African Orogen namely the Arabian-Nubian Shield and the Mozambique Belt respectively (Miller et al.,2003*)* (Fig.1.1A).

Northern Ethiopia is one of the regions where the basement units consisting of Low-grade metavolcanic and metasedimentary rocks are extensively exposed (Kazmin, 1971; Beyth, 1972; Garland, 1980).These low-grade metavolcanic and metasedimentary rocks have long been considered to be part of the Arabian–Nubian Shield (ANS)by several authors (Kazmin et al.,1978; Beyth, 1972, Garland, 1980, Chewaka and de Wit, 1981, Kroner et al., 1991, Miller et al.,2009, Alene 1998, Asrat et al. 2001).

The ANS is the largest terrane, which is well exposed over much of NE Africa and western Arabia, consists of dominantly juvenile Neoproterozoic rock (Patchett and Chase, 2002, Kroner and Stern, 2005). It extends from Jordan and Israel in the north, through to Ethiopia and Sudan in the south (Berhe, 1990; Kroner et al., 1991; Stern, 1994; Teklay et al., 1998, 2001) (Fig. 1.1A and B).

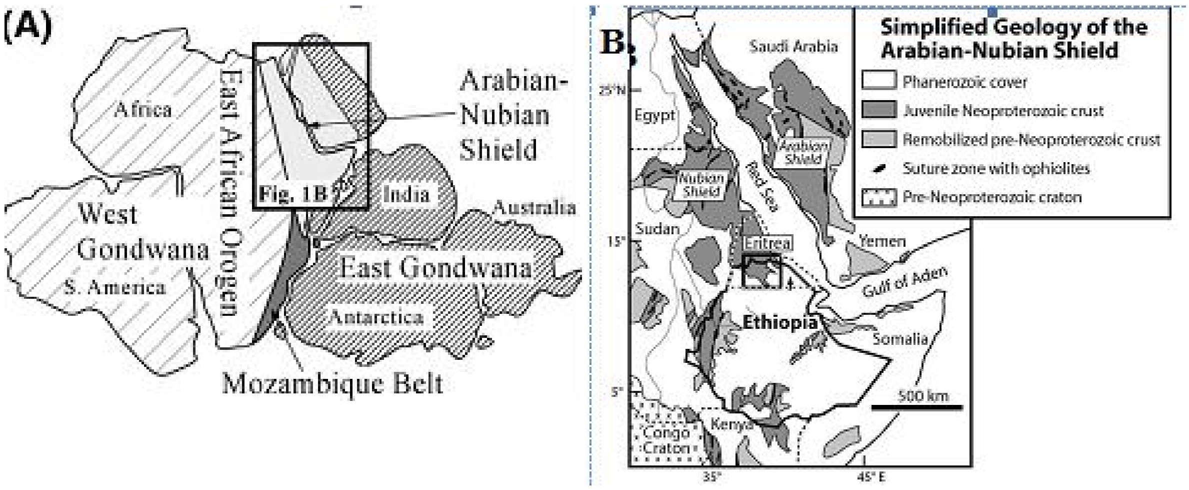


Figure 1.1 (A) The East African Orogen between East and West Gondwana.

(B) Extent of the Arabian-Nubian Shield, its Ssuthern part and relationship with Mozambique belts in Ethiopia (after Miller et.al, 2009)**.**

The formation and evolution of the Shield is related to Neoproterozoic supercontinent cycle notably: the breakup of the supercontinent Rodinia in the first half of the era, formation and closure of major ocean basin, and there by the formation of the new supercontinent, Gondwana, near the era end (Stern, 1994).

The processes are not a single event rather it consists of the collision and coalescence of numerous juvenile island arcs terranes in between 870-630 Ma. The island arcs were created in association with subduction to close the major ocean basin i.e. Mozambique Ocean (Stern, 1994; Kroner and Stern, 2005).

Continual accretion of island arcs and microcontinents and terminal “Pan African” collision between parts of E and W Gondwana at about 600Ma formed the East African Orogen (Kroner,2001;Meert, 2002) (Fig5).

As a result the Shield is largely composed of sutured low-grade assemblages of Neoproterozoic volcanic, volcano-sedimentary and sedimentary units, intrusive, and contains many remnants of oceanic crust in the form of ophiolite (Abdelsalam and Stern, 1996; Tadesse, 1996; Tadesse-Alemu, 1998). A number of gneissic domes consisting of deformed high-grade rocks also occur (Beyth et al., 1997).

The basement rocks of Northern Ethiopia (Tigray province), which constitutes the southern ANS, generally categorized into two groups based on stratigraphic relationships Beyth (1972), (Fig.1.2).

(i) The Tsaliet Group,the older and covers wider area ,consisting majorly metavolcanics , and

(ii) The Tambien Group (which is largely comprising of metasediment)

An intervening phyllite unit around Hawzien displays a transitional lithology (Miller et al., 2003). It has been also variously interpreted by different authors; as metasedimentary (Arkin et al., 1971) and metavolcanic (Garland, 1972, 1980) unit.

The peak regional metamorphism exhibited by mineral assemblages of the metavolcanic, which is estimated using chlorite thermometry, is at ~245-375°C (pumpellite-actinolite to lower greenschist facies, Alene 1998)

Neoproterozoic metasediments and associated metavolcanoclastics of northern Ethiopia are useful to study geological evolution and paleoenvironment; because it has recorded and/ or preserved the history of plate tectonic, climatic, and biotic events that is characteristics of Mozambique Ocean realm during this time (Miller et al., 2009).

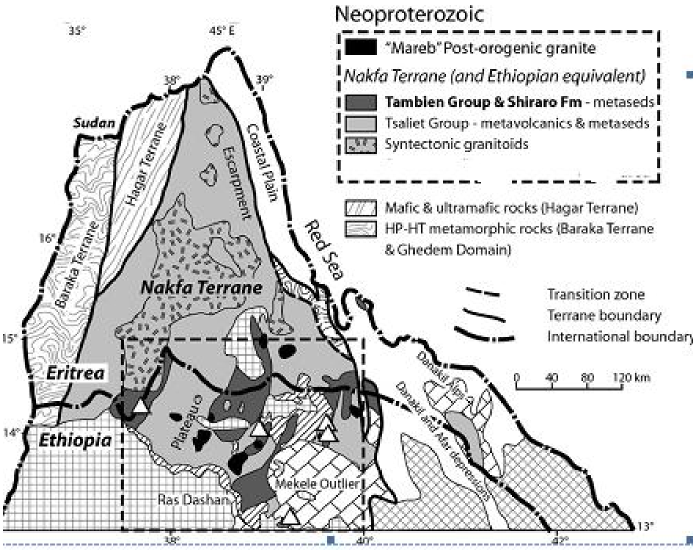


Figure 1.2 The general distribution of Neoproterozoic rock in northern Ethiopia (after Miller et.al,2009).

1.2 Problem Statement

The phyllite unit of the Hawzien area, as shown in the above geologic map, in northern Ethiopia has been mapped as different unit by different authors; as metasedimentary (Arkin et al., 1971) and as metavolcanic (Garland, 1972, 1980). On the other hand, Miller et al., (2003) described this unit as a transitional lithology.

Furthermore, during the preliminary site visit, it is observed that the rock has been subjected to multiple phases of deformation and metamorphosed to certain extent. The events are manifested by the development of superimposed secondary structures and mineral growth.

For instance, the occurrence of lineation on cleavage plane, presence of various generations (concordant and discordant) quartz vein strangers, and alteration of existing minerals and growth of new minerals indicate the lithology has experienced polyphase deformation and associated metamorphism.

However this unit has not been studied at large scale yet; consequently, the zone is not well defined in terms of structures, the type of lithologies it consists and the degree of metamorphism.

In addition the quartz veins contain yellowish oxidized voids/ leached out mineral that are probably sulfides that can be a good indication for metallic mineral occurrence, such as gold.

Therefore, investigating the phyllite unit in the area to certain detailed level (at scale1:25,000) will have a great benefit to understand the structures, to differentiate the type of lithologies it consists, along with the degree of metamorphism, and associated possible mineralization exist in the area.

1.3 Geography of the study area and Tigray

The study area is located around Hawzien town lying between UTM coordinates of minimum easting of (535000, 538000) and nothing (1549000, 1553000) respectively (Fig.1.3).

Hawzien is found about 80km north of Mekelle city, which is the capital city of Tigray National regional state, located 780 km from the capital city of the country, Addis Ababa.

It can be reached using daily flight from Addis Ababa or via the main highway through towns such as, Debrebirhan, Desse, and Maichew in the northeast direction. However the study area is located about 17 km from, the nearest town, Hawzien. It is reached through Asphalt road from Mekele to Fireweyne town, and gravel road from Friweynie to Hawzien. The gravel road is being up-graded to Asphalt.

Tigray is the northern province of Ethiopia and one of the historical regions of the country where ancient city like Axum is found.

The region is also known for its various monuments like Axum Obelisks, old historical churches, monasteries, mosques and sculptures.

Climate conditions of Tigray region vary from arid to semi-arid with average annual rainfall of 600-800 mm and annual average temperature of 25°C (Garland, 1980).

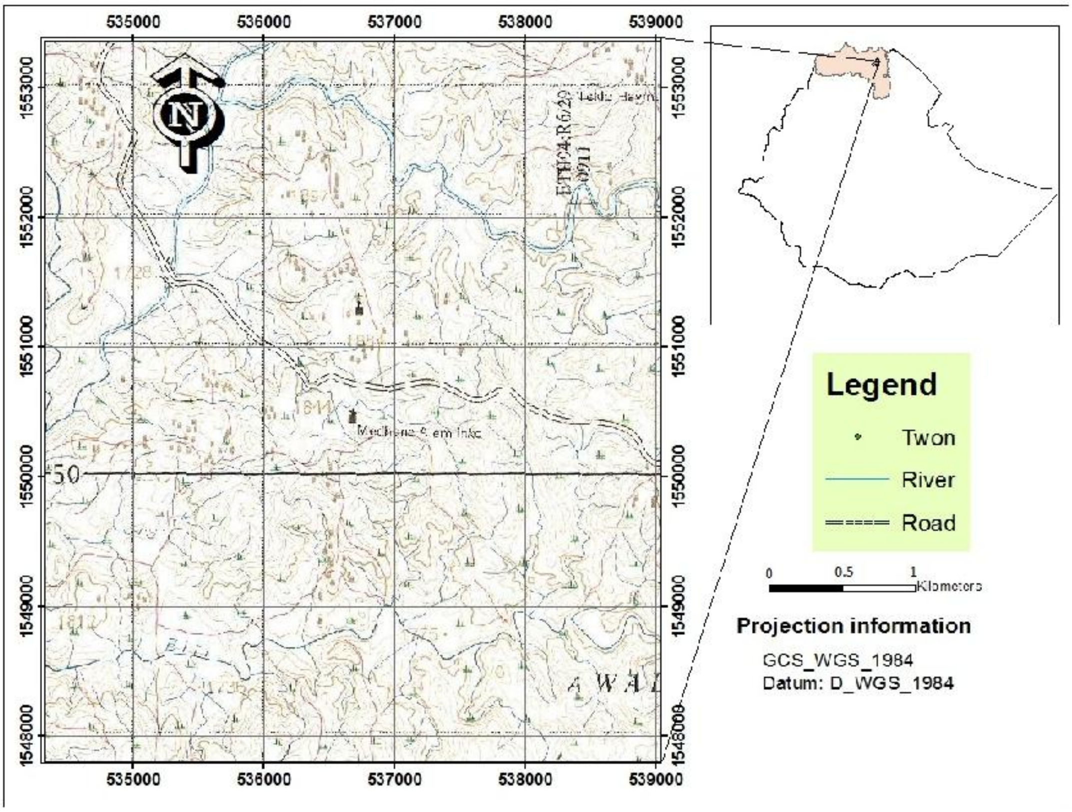


Figure 1.3 Location map of the study area

1.4 Objectives

1.4.1 General Objective

- ❖ To identify, describe and understand the geological structures, various lithologic units and metamorphism in the Precambrian phyllite unit of the Hawzien area, Tigray, northern Ethiopia.

1.4.2 Specific Objectives

- ➢ To characterize the orientation and style of various generations of structures in outcrops in order to get clue to the orientations and styles of related regional structures.
- ➢ To identify and describe rock units which probably have potential for economic mineral occurrence
- ➢ To recognize and differentiate phases of deformation and metamorphism

- To deduce the metamorphic facies and grade.
- To examine the time relationship between deformation and metamorphism/ mineral growth and deformation,
- To understand the geologic history of the area using rock fabric and mineral growth relationship**;** because of the fact that coupling of metamorphism and deformation can produce distinctive rock fabrics that are powerful tools for unraveling complex geologic histories.
- To produce detailed geological map at a scale of 1:25,000.

1.5 Methodology

1.5.1 Field work

Various tasks have been accomplished before the commencement of the field work. The main office work includes reviewing and compiling literatures and related books, reviewing, extracting and compiling of relevant information from geological and/ or topographic maps and areal image. The base map, with the scale of 1:25,000, has also been obtained by enlarging from Nebelet topographic map of sheet number 1439 C4.

Field mapping, sample collection and data recording have been accomplished, during the second visit to the area, from March 21, 2013 to March 28, 2013. Five east-west traverse lines have been systematically selected 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.

Accordingly, while going along the chosen route geological mapping, outcrop/lithological description, rock sampling and structural measurement and recording, both planar and linear, 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), gross characteristics (fracture, weathering, ridge-former); and the contacts relation present in outcrop.

For further structural analysis the strike and dip (amount and directions) of planar geologic structures and the plunge amount and direction of lineation are recorded and plotted.

Besides taking measurements attempt have been made to determine, by as much as possible the relative ages, orientations, and styles of different generations of structures.

The earliest generation observed labeled with letter subscripts (SA, FA, etc.). Because when mapping is begun the relative ages of structural elements is not known. Once the relative ages have been established, these subscripts can be changed to numbers (S1.F1.etc.)

In addition, several photos have been taken, using a Sony digital camera with 7mega pixels, in order to complement and enhance the clarity of descriptions.

About a total of fifty (50) representative samples have been selected for hand specimen, thin section, and geochemical analysis; 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.

1.5.2 Laboratory and data analysis

1.5.2.1 Petrographic analysis

In order to identify minerals, particularly transparent minerals such as silicates and carbonates, and rock fabric/texture/microstructures under petrographic microscope, relatively fresh and representative samples have been collected. Then the rocks are cut perpendicular to foliation/ lineations to prepare thin sections. About fourteen (14) thin sections have been prepared at the School of Earth Sciences, Addis Ababa University.

Thin sections have been examined, under Leica petrographic microscope, for mineral assemblage, fabric identification as well as for microstructural and micro-texture 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**.** One of the premises, a particularly useful guide in studying any deformed region is that the orientation and style of small, outcrop-scale structures (minor structures) mimic the orientation and style of regional-scale structures.

It means structural fabric elements are generally consistent in style and orientation at all scales.

1.5.2.2 Geological Data and Structural data Analysis

Different software such as Arc GIS 10, Stereo Pro. and Georient ver 9.5.0 are used to produce maps, to visualize and analyze data.

Equal-area or equal-angle plots (informally known as stereo plots) are also used to illustrate structural and geometric relationships, to check hypotheses, and to find and compare relationships locally that normally known to occur regionally.

1.6 Application of the results

Mapping of one area at larger scale than what has previously been done provide a number of advantage. For instance minor (local) structures, which have not been identified at smaller scale in previous work, will be mapped and described in detail. Hence they can be used for comparing to the regional structures, to reconstruct the tectonic history of the area and in studying the role of structures for mineralization.

Similarly different lithologies with various significance and character, which have been mapped and known as a single unit due small scale of mapping will be identified and described. In addition the extent and actual coverage of the rock units will be indicated on the map relatively at a better accuracy.

On the other hand, the outcome of the research will benefit companies and organizations, particularly those undertaking exploration activities such as mineral prospecting, ground water investigation in and around the study.

It can also be used by construction companies (road and other construction) to locate stable and unstable sites. That is because the degree of weathering and the nature of geologic structures like fault planes, joints/fractures, contacts and foliation which will have adverse effect on the stability of infrastructures will be identified.

Furthermore, the result of the thesis can be used for scientific society and/ or researchers who may work on any geological investigation in the area.

CHAPTER TWO

2 REGIONAL GEOLOGY

2.1 Evolution of the East African Orogen

The term East African Orogen has been proposed for the combined upper crustal Arabian-Nubian Shield and lower crustal Mozambique Belt (Kroner and Stern, 2005). It comprises two major segments: the Arabian–Nubian Shield (ANS) in the north, and the Mozambique Belt in the south (Stern 1994; Stern 2002) (Fig.2.2).

The orogen represents one of Earth's greatest collision zones which extends about 6000 Km long that stretches from southern Israel in the north to Madagascar to the south.

It was formed during Neoproterozoic time by closure of the Mozambique Ocean during the collision of East and West Gondwana that has finally resulted in the formation of Gondwana Supercontinent (de Wit and Chewaka 1981; Stern 1994, 2002; Kroner and Stern, 2005) (Fig.2.2).

The evolution of the EAO demonstrated a Wilson Cycle orogeny, that had taken place over a time period of about 350 Ma between 850 -557Ma (Stern, 1994, 2002);
(Figs 2.1,2.2 and 2.3).

The following major geological stages /event have been proposed during the mentioned time (Beyth et al., 1994, 1997; Teklay, 1997; Ghebreab, 1999a, b; Tadesse et al., 1997; cited in Beyth et al., 2003).

1) Rifting of Rodinia, development of the Mozambique Ocean, and formation of juvenile crust by sea-floor spreading (~850–750 Ma);
2) Extensive sub-aerial chemical weathering and deposition of pelitic clays on the eastern margins of this ocean (~800 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 and escape tectonics (~625–610 Ma,Beyth et al., 1994); and
6) Extensional tectonics and magmatism (~600–545Ma), and end of escape tectonics 577Ma according to Kusky and Matsah, (2000).

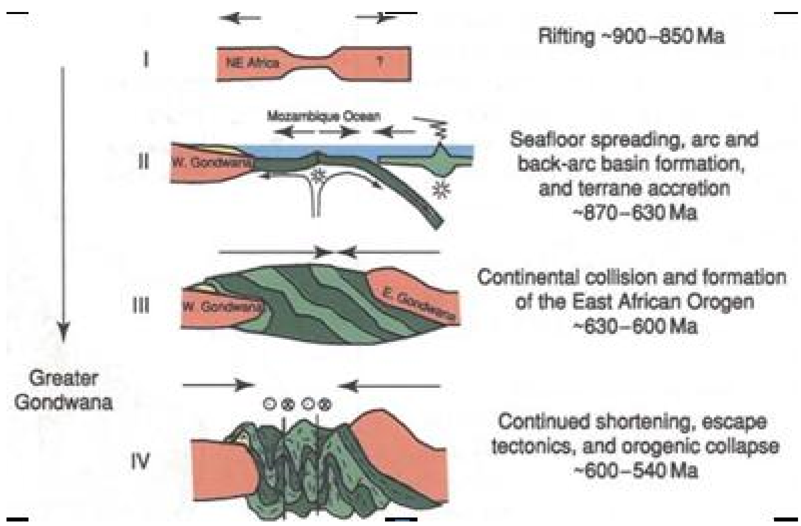


Figure 2.1 A diagram of the suggested evolution of the Arabian-Nubian Shield (after Kroner and Stern, 2005).

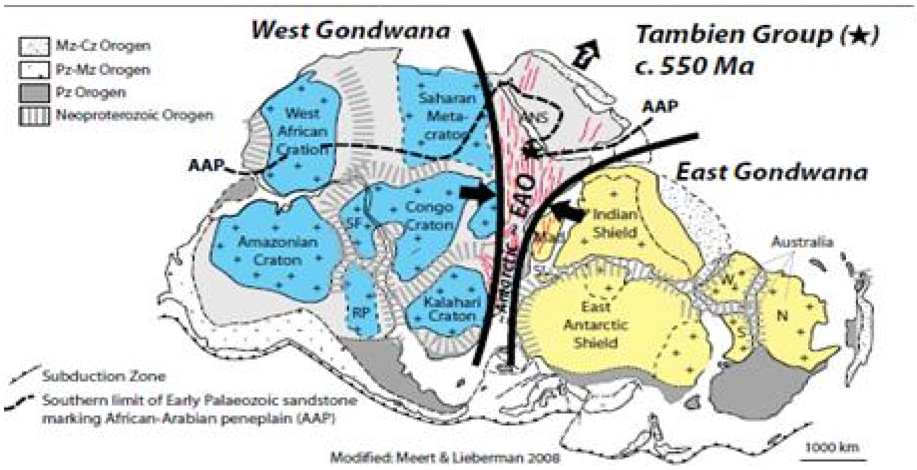


Figure 2.2 Gondwana amalgamation and emergence of the Antarctic-EAO. (After; Meert & Lieberman 2008; Gray et al.,2008). The fig. Also shows global palaeogeographic reconstructions for 550 Ma,

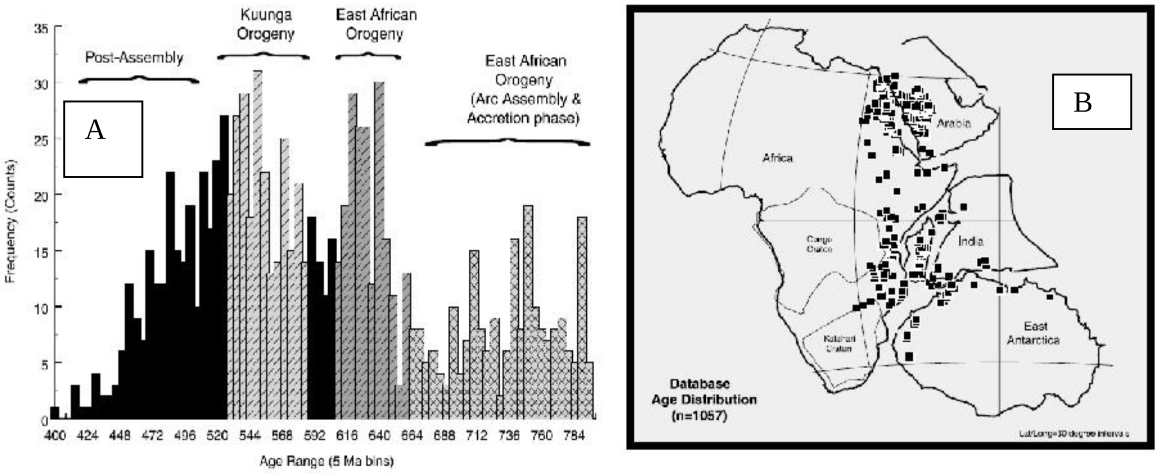


Figure 2.3 (A) A histogram showing the frequency of published ages from the entire database (in 5 Ma bins). Orogenic events are given at the top of the diagram.
(B) Location of geochronologic studies within eastern Gondwana used in the database. Due to the scale of the map, multiple-age determinations may be represented by a single point (After Meert (2002)).

2.2 The Geology of Arabian-Nubian Shield

The tectonic setting and geochronology of the Arabian–Nubian shield (ANS) and its environs were discussed by a number of authors.

Among these to mention some, Kazmin, 1971 and 1975; Kazmin et al., 1978; Gass, 1981; Stoeser and Van Camp,1985; Vail (1983,1985), Shackleton, 1986; Kroner et al., 1990; Berhe, 1990; Stern, 1994; Windley et al., 1996; Al-Saleh et al., 1998; Cosca et al., 1999; Blasband et al., 2000; Johnson and Kattan, 2001; and Whitehouse et al., 2001.

Its creation is a result of a multistage process; within the Neoproterozoic supercontinent cycle, notably the breakup of the supercontinent Rodinia in the first half of the era followed by formation of the major Mozambique ocean basin and the new supercontinent, Gondwana, associated with the closer of the ocean near the era’s end (Stern, 1994). Subduction to close the Mozambique Ocean generated numerous island arcs (juvenile crust) above intra-oceanic convergent plate boundaries (juvenile arcs) and perhaps oceanic plateaux (870-630 Ma). These juvenile terrains collided and coalesced to form larger composite terrains (Stern, 1994; Kroner and Stern (2005).

As ANS evolution was correspondingly associated with submarine volcanism and marine sedimentation, it is largely consists of sutured low-grade assemblages (mostly green schist facies) of Neoproterozoic volcanic, volcano-sedimentary and sedimentary units and intrusives (granites, gabbros, and dikes) that are deformed at different intensity. In addition significant amount of ophiolite, remnants of oceanic crust, are found (Abdelsalam and Stern, 1996; Tadesse, 1996; Tadesse-Alemu, 1998; Avigad et al., 2007). Deformed high-grade rocks also exist forming gneissic domes (Beyth et al., 1997).

Based on Kroner and Stern (2005) deformation associated with terminal collision is more intense in the southern ANS, with tight, upright folds, steep thrusts, and strike-slip shear zones controlling basement fabrics in Eritrea, Ethiopia, and southern Arabia**.** The most intense collision that is manifested by greatest shortening, highest relief, and greatest erosion occurred south of the ANS, in the Mozambique belt.

Hence, the north-south trending structures related to intense collision obscure the earlier structures in the southern ANS that are related to arc accretion, and the intensity of this deformation has also made it difficult to identify ophiolitic assemblages in southern Arabia, Ethiopia, and Eritrea

Compared to the strong deformation and metamorphism experienced during collision in the Mozambique belt, the ANS was considerably less affected by the collision.

North-west trending left lateral faults of the Najd fault System of Arabia and Egypt (Figs. 2.4 and 2.5) formed as a result of escape tectonics associated with the collision and were active between about 630 and 560 Ma.Deformation in the ANS ended by the beginning of Cambrian time, although it has locally continued into Cambrian and Ordovician time farther south in Africa.

Kroner and Stern (2005) also suggest that the final stages in the evolution of the ANS witnessed the emplacement of post-tectonic 'A-type'_granites, bimodal volcanics, and molassic sediments. These testify to strong extension caused by orogenic collapse at the end of the Neoproterozoic. Extension related metamorphic and magmatic core complexes are recognized in the northern ANS but are even more likely to be found in the more deformed regions of the southern ANS and the Mozambique Belt.

The shield merges with the Mozambique Belt in Ethiopia which is the southern half of the EAO and formed during intense Himalayan-type collision between East and West Gondwana fragments (e.g. Stern, 1994) (Fig.1.1A).

The Belt comprises medium to high-grade gneisses, migmatites and schists and voluminous granitoids and can be traced in southern, western, and eastern Ethiopia (Berhe, 1990; Asrat et al., 2001).

ANS is distinguished from the Mozambique Belt by its dominantly juvenile nature, relatively low grade of metamorphism, and abundance of island-arc rocks and ophiolites.

Thus, the transition between the ANS and the Mozambique Belt is marked by a change from less deformed and less metamorphosed, juvenile crust in the north to more deformed and more metamorphosed, remobilized older crust in the south, with the structural transition occurring farther north than the lithological transition.(Asrat et al.,2001;Kroner and Stern, 2005).

ANS terrane boundaries (Fig.1.1b and 2.4) are frequently defined by suture zones that are marked by ophiolites, and the terranes are stitched together by abundant tonalitic to granodioritic plutons (Kroner and Stern, 2005).

Most ANS ophiolites have trace element chemical compositions suggesting formation above a convergent plate margin, either as part of a back-arc basin or in a fore-arc setting. Many sutures have appreciable strike–slip offsets, and these may broadly relate to c. 600 Ma escape tectonics (Burke & Sengo¨r, 1986), during which ANS terranes were progressively sandwiched by, and offset between, obliquely converging Gondwana cratonic blocks (de Souza Filho & Drury 1998,cited in Miller et.al., 2011).

According to Miller et al (2009) sediments, that constitute sedimentary units of the ANS, are mostly immature sandstones and wackes derived from nearby arc volcanoes. Deposits that are diagnostic of Neoproterozoic 'snowball Earth' episodes have been recognized in parts of the ANS, and banded iron formations in the northern ANS may be deep-water expressions of snowball Earth events.

In general, the region is viewed as accretionary collage of juvenile arc terrains, microcontinent and associated ophiolitic remnants formed in the Mozambique Ocean beginning around 900 Ma (Stern, 1994; Abdelsalam and Stern, 1996; Shandelmeier et al., 1994; Greiling et al., 1994).

Geochemical and isotopic signatures indicate that these rocks are dominantly mantle-derived juvenile crust (Stern, 2002; Stoeser and Frost, 2006). In other word it is Neoproterozoic crust that had been exposed due to uplifting during Cenozoic rifting to form the red sea according to Kroner and Stern, (2005) and Stern et al., (2004). The greater ANS now bisected by the Oligocene and younger Red Sea rift. It is superbly exposed over much of NE Africa and western Arabia (Fig. 1.1B).

The ANS has been the source of gold since Pharaonic Egypt. Nowadays the Sheld has become the main target for mining and mineral exploration activity, particularly in Sudan, Arabia, Eritrea, and Ethiopia (Kroner and Stern, 2005).

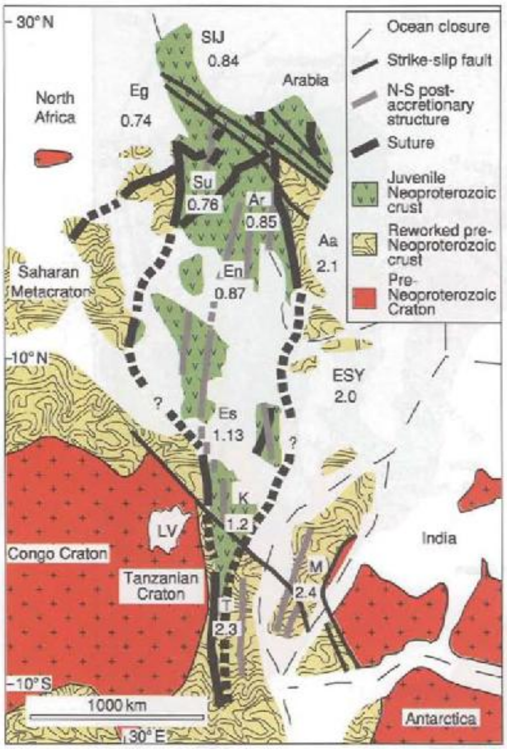


Figure 2.4 PreJurassic configurations of elements of the East African Orogen in Africa and surrounding regions.

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-rnodel ages in Gy. (After Kroner and Stern, 2005).

2.3 Geology of the Ethiopian Basement Terrain rocks

The Ethiopian basement rocks are exposed in eastern, western, northern, and southern parts of the country (Alene et al., 2000, 2006), and Asrat et al. (2001) (Fig. 2.5).

They have been studied for the last four decades by several authors to mention some Kazmin (1971), Kazmin et al. (1978), Beyth (1972), de Wit and Chewaka (1981),Ayalew et al. (1990), Alemu (1998), Tadesse (1996),Teklay et al.,(1998), Tadesse et al. (1997, 1999, 2000), Alene (1998), Alene et al.(2000, 2006), Kroner (2001), Asrat et al. (2001,2004), Yibas et al.(2002), Miller et al.(2003,2009, 2011) and Avigad et al.(2007).

The Precambrian rock of the country has been classified into three complexes, by Kazmin (1971 and 1975) and Kazmin et al., 1978, based on compositional, deformational and metamorphic grade variations. In other words his three fold division of stratigraphic model was based on solely on lithological and structural mapping with little or no geochronologic data.

According to his model, the Lower complex (older than 2.5 Ga) formed of high grade gneisses and represent cratonic basement; the Middle complex (lower Proterozoic to middle Proterozoic) is composed of metasediment. The Upper complex (upper Proterozoic to lower Paleozoic) consists low grade rocks including ophioliitic rocks, andesitic metavolcanics and associated metasediment and to less extent metacarbonates.

The high-grade rocks were considered as Archean basement underlying the Neoproterozoic volcano-sedimentary sequence (Kazmin et al., 1978) but later geochronology showed that the high-grade sequence is similarly composed of Neoproteroic protholiths (e.g. Ayalew et al., 1990; Teklay et al., 1998;Yibas et al., 2002; and review in Asrat et al., 2001).

The age of the basement rocks of Ethiopia is between early to late Proterozoic (Rogers et al., 1965, Garlad, 1980; Alemu, 1998; Tadesse et al., 2000, Ayalew et al., 1990; Teklay et al., 1998). Maximum age is 1997Ma yr from Harar tonolitic zenolith Teklay et al., 1998.

According to Asrat et al. (2001) and Yibas et al. (2002) the Ethiopian basement rocks are composed of two major blocks.

(i) A gneissic and migmatitc terrain, which essentially consisting of high-grade para and orthogneisses , deformed and metamorphosed granitoids, previously known as the Lower and Middle Complex (Kazmin 1971, 1975), and correlated with the Mozambique Belt;

(ii) A low-grade volcano-sedimentary terrain, the ophiolitic fold and thrust belts, which comprises all the rocks of the Upper Complex and is correlated with the ANS (Fig. 2.5).

Pre-,syn-, and post-tectonic granitoids intruded the Ethiopian basement rocks (Asrat et al. 2001).These two distinct lithotectonic terranes show contrasting lithological association, internal structures and grade of metamorphism (Yibas, 2000; Yibas et al., 2000a).

The bulk of the granite-gneiss terrain is underlain by para- and ortho-quartzo-feldspathic gneisses, intercalated with amphibolites, sillimanite–kyanite-bearing schist and marbles, and granitoids, and extends into northern Kenya (Fig. 2.5. Lithologically, the paragneisses resemble the gneisses of northern Kenya (Yibas, 2000; Yibas et al., 2000a).

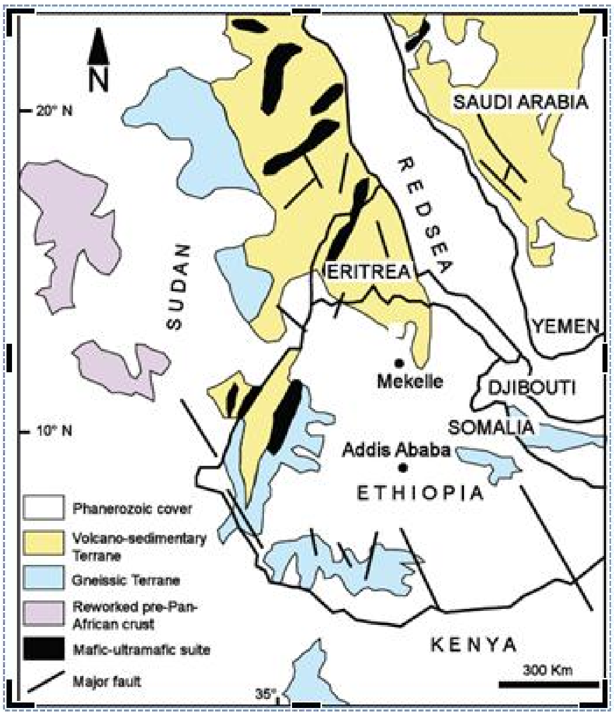


Figure 2.5 Distribution of rocks of the Arabian-Nubian Shield and Mozambique belt, which form the basement rocks Arabian Peninsula,northeast Africa (Egypt and Sudan), and Ethiopia (After Ayalew et al. 1990; Berhe 1990; Asrat et al.2001).

2.4 Geology of Tigray basement rocks

2.4.1 Introduction

The metamorphic terrain of northern Ethiopia is one of the least studied areas in eastern and

Northeastern Africa relative to the well investigated Arabian, Egyptian and Sudanese sectors (Tadesse, 1999).

The basic Neoproterozoic stratigraphic framework for northern Ethiopia was established by Beyth (1971, 1972). Levitte (1970) and Garland (1980) had conducted regional mapping of parts of the geology of northern Ethiopia; that is the geology of Mekele Sheet (geology of central part of Tigray) and the geology of Adigrat area respectively. Arkin et al. (1971) had compiled the main aspect of Tigre's Neoproterozoic basement and its stratigrphy for the first time in the Mekele (1:250,000) sheet map.

However,the Neoproterozoic geologic framework of Tigre is known in greater detail from four 1:250,000 maps, produced by the Geological Survey of Ethiopia/Ministry of Mines, namely the Mekele(Arkinet al.,1971), Adi Arkay (Hailu, 1972 unpublished),

Adigrat (Garland, 1980), and Axum (Tadesse, 1999). The studies have a great role in identifying major lithologic units, their general thicknesses and contact relations; and also to understand the relationships of the metavolcanics and metasedimentary units to syn- and post-tectonic intrusive. Furthermore the work has revealed that the deformed Neoproterozoic basement was unconformably overlain by Paleozoic and Mesozoic rocks (Enticho and Adigrat Sandstones, respectively).

Beyth (1972) broadly divided the basement rocks of the region, part of the Upper Complex, into two (Fig.2.8).

i. The Tsaliet Group, an older predominantly metavolcano-sedimentary rocks, and
ii. The Tambien Group, a younger metasedimentary succession.

They represent an accretion of compositionally different (immature to evolved) intra-oceanic island arcs Tadesse et al. (1999).

Recently Avigad et al., (2007) proposed that these basement rocks, the two main group and the intrusions, that constitutes the southern Arabian–Nubian Shield (ANS), formed in two major episodes. His proposal is based on detrital zircon geochronology of Neoproterozoic diamictites and Ordovician siliciclastics in the region.

The earlier episode (0.9–0.74 Ga) represents island arc volcanism, whereas the later phase culminated at 0.62 Ga and comprised late to post orogenic granitoids related to crustal differentiation associated with thickening and orogeny accompanying Gondwana fusion. These magmatic episodes were separated by about ∼100 ma of reduced igneous activity (a magmatic lull is detected at about 0.69 Ga), during which subsidence and deposition of marine carbonates and mudrocks displaying Snowball-type C-isotope excursions (Tambien Group) occurred.

Furthermore, Tadesse (1996) and Tadesse et al (1999) have divided the northern Tigray basement rock terrane into six tectonic blocks(from west to east: they are the Shiraro, Adi Hageray, Adi Nebried, Chila ,Adwa and Mai Kenetal Blocks). They are characterised by distinct cycles of magmatic activities separated by ophiolite belts analogous to the situation in Arabia (Fig.2.6).

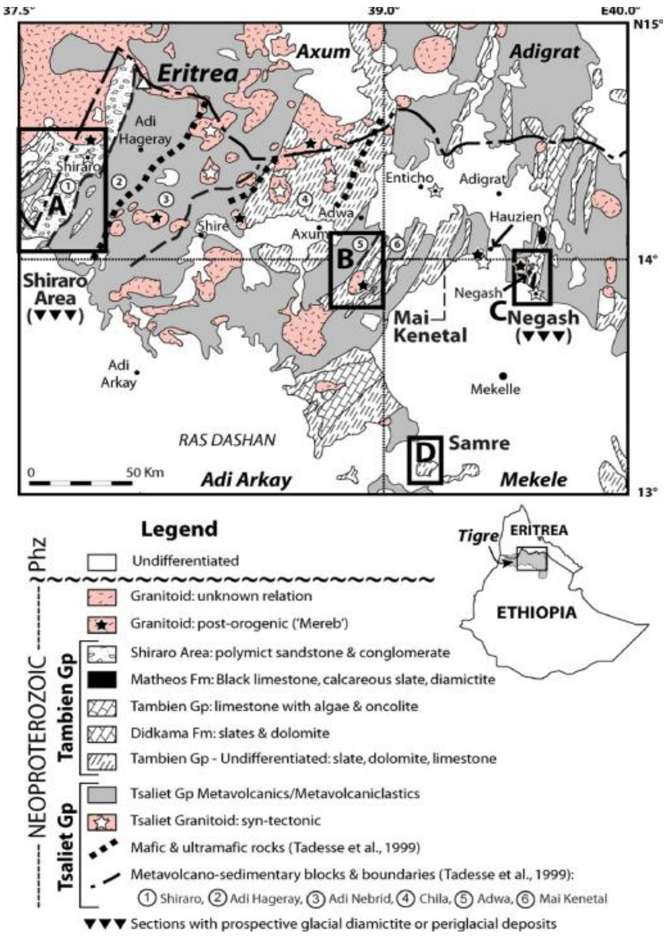


Figure 2.6 General geological map of northern Ethiopia (Tigre province).
The prominent NE-SW structural grain developed after Tambien Group deposition in response to pan-African collisional deformation associated with development of the East African orogen. White and black stars respectively show locations of dated arc-related (syn-tectonic) and post-orogenic intrusives (Tadesse et al., 2000; Miller et al., 2003; Asrat et al., 2004), and U–Pb zircon geochronology localities sampled (Avigad et al., 2007). The Tambien Group lithologies shown are generalized from Kazmin (1972). Dashed box to the right of the Mai Kenetal study area (B), shows the Werri area studied by Sifeta et al. (2005) for chemical weathering indices (after Miller et al., 2009**.**

2.4.2 Stratigraphy

The Tsaliet Group

The Tsaliet Group covers large part of the northern Ethiopia basement terrain (Fig. 10a).It is is several kilometers thick and represents an arc volcano-sedimentary sequence (Teklay, 1997; Alene et al.,1998; Tadesse-Alemu,1998; Tadesse et al.,1999, cited in Avigad et al. 2007) or an arc–back–arc system (Teklay,2006).It mainly consists of arc-related metavolcano-sedimentary rocks including metavolcanic/volcanoclastic rocks, sericite-chlorite schist, slate, and greywacke, and metacarbonates, calcareous siltstone, intermediate to acidic welded tuffs, lappili tuff, and agglomerates (Beyth,1972; Tadesse et al.,1999; Alene, M., 1998; Alene et al., 2000,2006;Beyth et al.,2003).

The Tsaliet Metavolcanics of north Ethiopia is equivalent to the metavolcanics of the Bizen Domain in east Eritrea (Beyth et al. 2003).

The thickness is unknown however, according to Beyth (1972) it is estimated more than 1500 m. Based on chlorite thermometry conducted on mineral assemblages of the metavolcanic rocks show peak regional metamorphism at ~245-375°C (pumpellite-actinolite to lower greenschist facies) (Alene 1998).

NE-SW trending shear zones with a sinistral-strike slip sense of movement affect the rocks of this group (Tadesse et al. 1999).

The age of the Tsaliet Group is not well constrained. However, metavolcanic sequence in Eritrea,which is lithologically similar to the Tsaliet (Alene et al. 2006), and yielded a zircon age of 854 ± 3Ma (Teklay, 1997,). Tsaliet Group in the western Tigray are also intruded by syntectonic granodiorites, which yielded Sm–Nd and Rb–Sr isochron ages of 720–800 Ma (Tadesse et al., 2000).

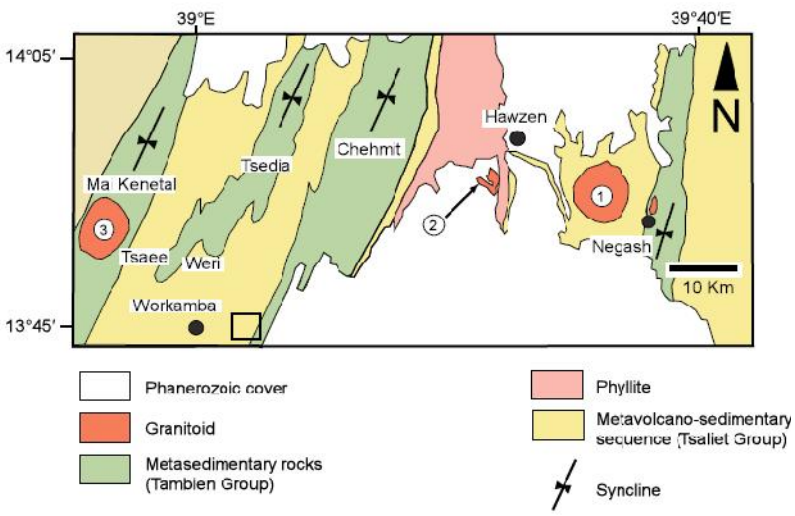


Figure 2.7 Distribution of the Tsaliet and Tambien groups,Phyllite unit and granitoids around Hauzien,area, Tigray region, northern Ethiopia.

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 = Hawzen, 3 = Mai Kenetal, 4 = Ram a, 5 = Mereb, 6 = Chila, 7 = Shire, 8 = Deset, 9 = Azeho, and 10 = Sibta granitoids). Their ages are given in Table 2.1. ;(modified from Tadesse et al. 2000; Asrat et al. 2001; Alene et al. 1998, Cited in Gebresilassie, 2009)

The Tambien Group

The Tambien Group, which overlies the Tsaliet group, (Beyth, 1972; Miller et al., 2003; Alene et al., 2006), is mainly a shallow marine sedimentary cover of carbonates and mudstones locally topped by a diamictite. Its thickness is estimated to be about 2-3 km (Alene et al 2006).

In centeral Tigray it is exposed in a series of four synclinal inliers surrounded by the Tsaliet Group rocks. These four synclinoria are from west to east: Mai Kenetal, Tsedia, Chehmit, and Negash inliers (Beyth 1972; Alene et al. 2006, Fig.2.7).

Typical sections are defined in the Mai Kenetal and Negash Synclinoria (Beyth, 1972); Fig.2.8 & 2.9.

The sections generally consist, from oldest to youngest, of the following lithologies:

a) The Lower Slate (Weri Slate), which mainly consists of black to blue-greenish, well laminated and foliated slate, greenish calcareous slate, and black silty greywacke. Locally, this unit contains phyllite or graphite schist (Beyth 1972).
b) The Lower Limestone (Assem Limestone) comprising mainly black to brown-greenish limestone (~90 wt. % calcite) with stromatolitic lamination and dark stylolites (Alene et al. 2006);
c) The Upper Slate (Tsedia Slate) consisting of purple silty non-calcareous slate, greenish grey feldspathic slate, greenish grey vitreous slate, and greenish grey slaty marl (Beyth 1972);
d) The Upper Limestone (Mai Kenetal Limestone), which is exposed at the core of the Mai Kenetal synclinorium.The Upper is black Limestone and composed of up to 95 wt. % calcite with minor amounts of detrital quartz and albite (Alene et al. 2006).

Stratigraphic and age relations show that the deposition of these sequences occurred between ∼800 Ma (the age of the underlying volcanics, Teklay, 1997) and ∼545 Ma (the age of the late Mareb granitic intrusions at the Axum area, Tadesse et al., 1997) or ∼650 Ma (the age of the Mai Kenetal granite intrusion Beyth, 1972)(see also Fig.2.5).

According to Beyth et al. (2003), the association of the Tambien Group sedimentary rocks particularly (stromatolitic limestone, laminated dolomite, polymict conglomerate and pebbly slate), their stratigraphic order, and the age of deposition match the description of cap-carbonates which is a characteristic element of “Snowball Earth” sediments (Hoffman and Schrag, 2000).

The geologic setting where the Tambien Group sediment is thought to have initially deposited is in an intra-oceanic platform (above a substratum of consolidated arc terranes) following the main phase of Tsaliet arc magmatism in the region (c. 780+30 Ma; Avigad et al., 2007).

The extent to which Tsaliet arc subterranes were fully accreted prior to Tambien Group deposition is uncertain, and some syndepositional relief differentiation related to ongoing shortening and/or extension is possible (Miller et al. 2009).

The entire metamorphic sequence at Tigrai was intruded by postorogenic 600–620 Ma Mereb granites (Miller et al., 2003; Asrat et al., 2004; Fig.2.8 and 2.9).

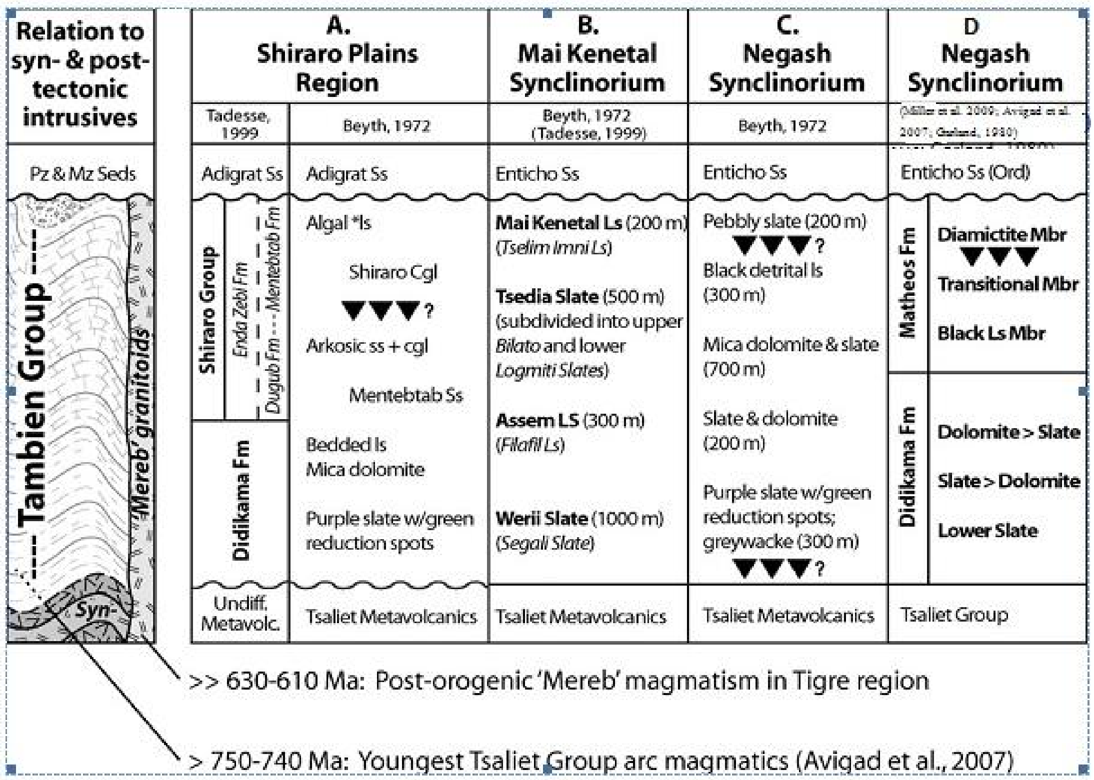


Figure 2.8 (a) Lithostratigraphic subdivision of the Tambien Group in previous work (Modified from Miller et al. 2009).

The general stratigraphic section of the basement of the region is compiled here below.

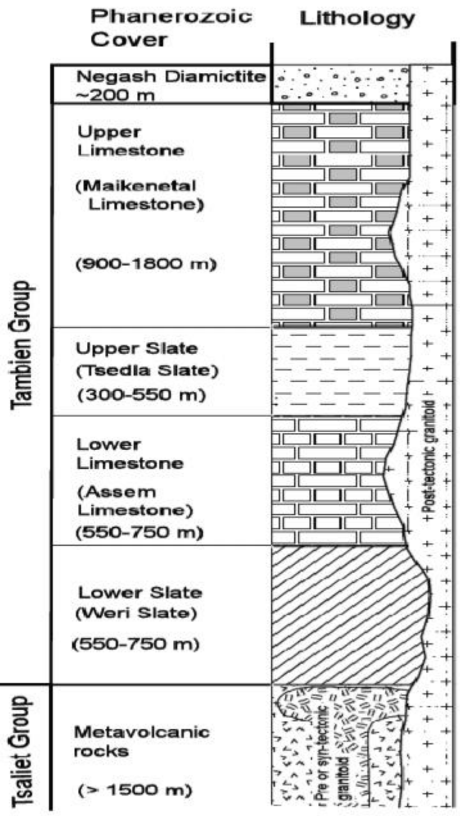


Figure 2.9 Stratigraphic section of Tigray basement rocks showing relationship between the Tsaliet and Tambien group rocks.

The pre- or syn-tectonic granitoids intruded the Tsaliet Group at about ~800 to 735 Ma, whereas the post-tectonic granitoids intruded both the Tambien and Tsaliet groups as well as the diamictites between ~620 and ~520 Ma (modified from Beyth 1972; Alene et al. 2006, Avigad et al. 2007,cited in Gebresilassie, 2009).

2.4.3 Tectonic structures

The two groups of basement rocks in the region, the Tsaliet and Tambien, are strongly affected by various types of geological structures that are formed by several deformation phases.

Johnson et al. (2003) proposed that amalgamation of island arcs to form ANS during Neoproterozoic had generated stress that is responsible for the formation of tectonic structures. Generally in the region two phases of deformation (D1 and D2) are recognized (Alene, 1998; Alene et al., 2000; Alene et al., 2006), 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 lineations 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, and this is consistent with the new zircon ages reported below.

Mineral assemblages and textural features point to three metamorphic phases (Alene, 1998)

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. Chlorite IVAl geothermometry (Alene, 1998) suggests metamorphic temperatures in the range of 245–375 ◦C.

The distribution of major structures in Tigray is shown in Fig. 2.10. In western Tigray, NE to SW trending thrust faults and shear zones are identified within the low-grade metavolcano-sedimentary sequences (Tadesse 1996; Tadesse et al. 1999).

Major NE-SW oriented synclinoria such as the Mai Kenetal, Tsedia, Chehmit and Negash, which folded the Tambien Group rocks are present in central Tigray (Beyth 1972; Alene et al. 2006). NNE striking faults are also common in the Tsaliet and Tambien Group rocks.

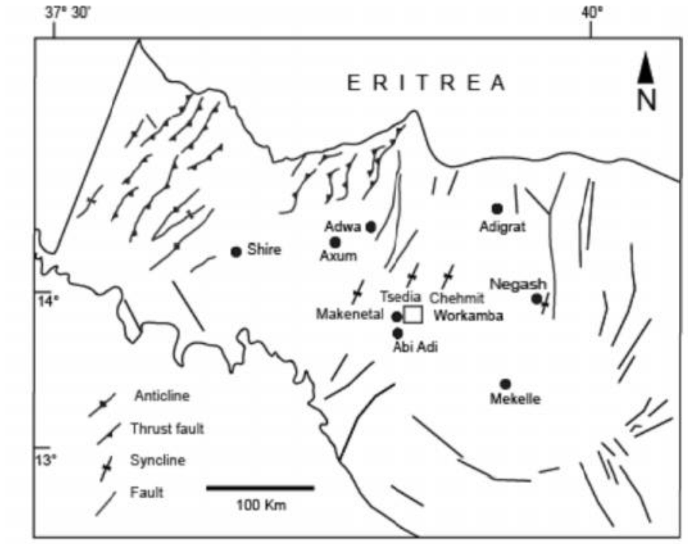


Figure 2.10 Distribution of major tectonic structures in Tigray (Tadesse et al 1996, 1999 and Asrat et al.2001).

CHAPTER THREE

3 LOCAL GEOLOGY

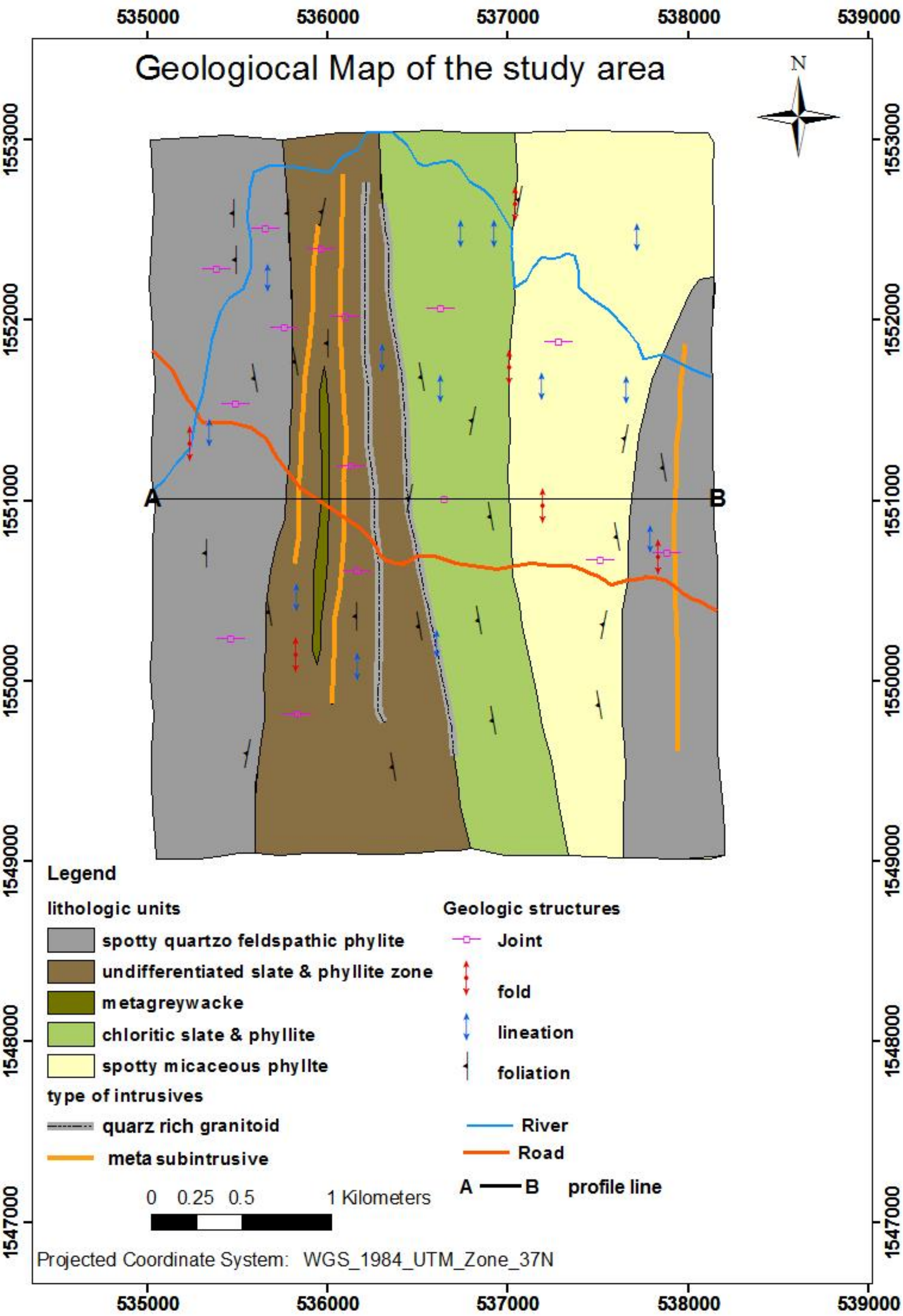
The physical nature of each lithologic unit is investigated and described. During geological mapping, structural elements, gross characteristics (fracture, weathering, ridge-former), mineralogical and textural conditions, color, mineralisation, metamorphism or alteration, and intercalation intensity between each rock type have been described.

The name for the lithological unit is given based on the textural and mineralogical constituent of the rocks observed during field investigation and thin section/petrographic analysis. Although the study area is dominantly coved by phyllitic rock, the rocks show variations in mineralogy, micro textural, color and types of intercalated lithologies. In the study area five mappable units and two minor unmappable lithologic units are encountered (Fig.3.1).The mappable units are: spotty quartzo feldspathic phyllite, chloritic slate and phyllite, undifferentiated slate and phyllite zone, spotty micaceous phyllite and metagreywacke.

The undifferentiated slate and phyllite zone or intercalated zone consists of various lithologies that have different extent, thickness and frequency.

Although the zone is largely consisting of phyllite and slate, there are other minor unit such as metagreywacke, metasubintrusive and quartz-rich granitoids. Quartz veins and graphite are minor unmappable units occurred in the area.

The detailed descriptions of these different units are given as follows from west to east.


Geologiocal Map of the study area
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A
B
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undifferentiated slate & phyllite zone
metagreywacke
chloritic slate & phyllite
spotty micaceous phyllte
type of intrusives
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Geologic structures
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Projected Coordinate System: WGS_1984_UTM_Zone_37N

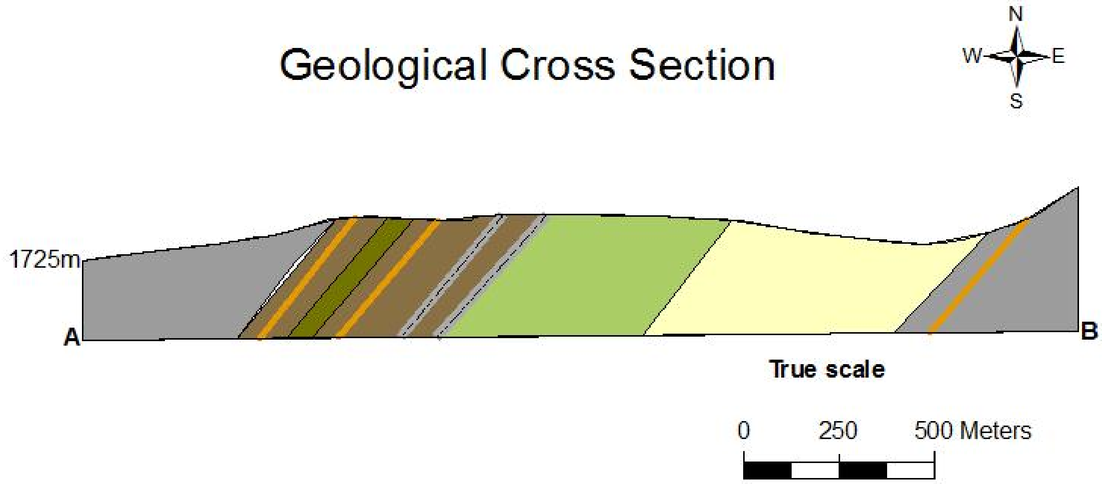


Figure 3.1 Geological map and cross section of the study area.

3.1 Spotty quartzo-feldspathic-phyllite

This unit is the dominant lithologic type occurring in the eastern and western part of the mapped area (Fig. 3.1). It is characteristically grey in color, with sheen lustrous (shiny) fresh surface and well-foliated rock. Another distinctive feature of the rock is, it consists of abundant reddish brown strongly oxidized porphyroblast of rhombic minerals (ankarite?) and yellowish oxidized spots pyrite (Py)? (See Figs.3.2A-D & 4.2C.).

The porphyroblasts are not found uniformly throughout the rock; they show some variation in abundance along and across the strike. They also found in different size that ranges from less than mm to 1.5cm.The prefix spotty is used to indicate the presence of such well grown randomly disseminated, weakly to non-deformed minerals.

The rock is often found strongly weathered (oxidized) as a result it is hardly possible to find fresh outcrop on surface.

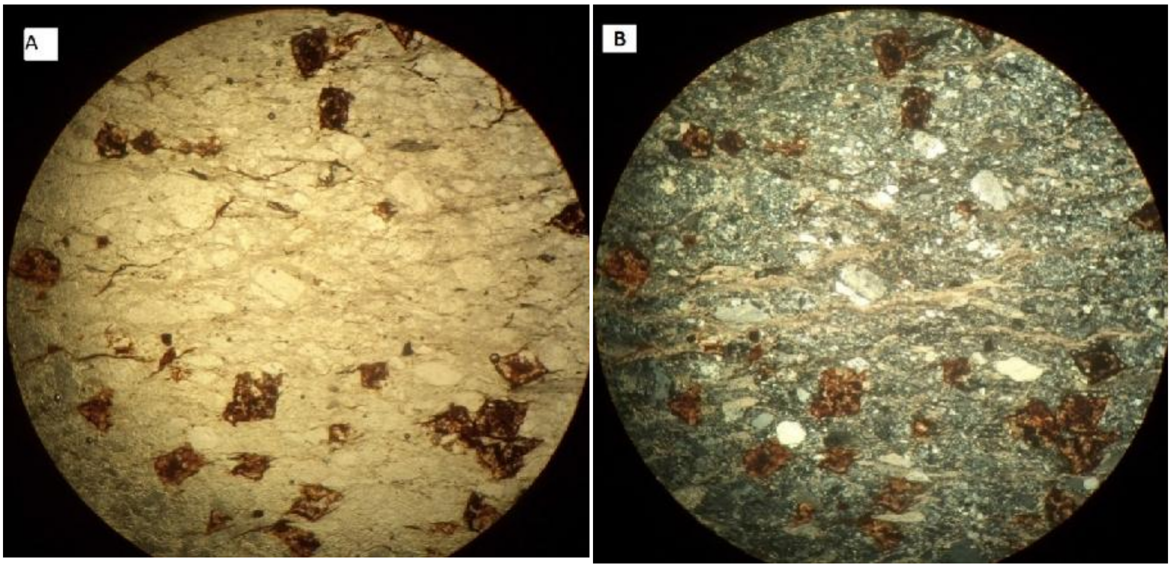
The rock is commonly light grey, grey and dark grey. Sometimes, it appear as brownish yellow and grayish brown when it the highly weathered and/ or oxidized.

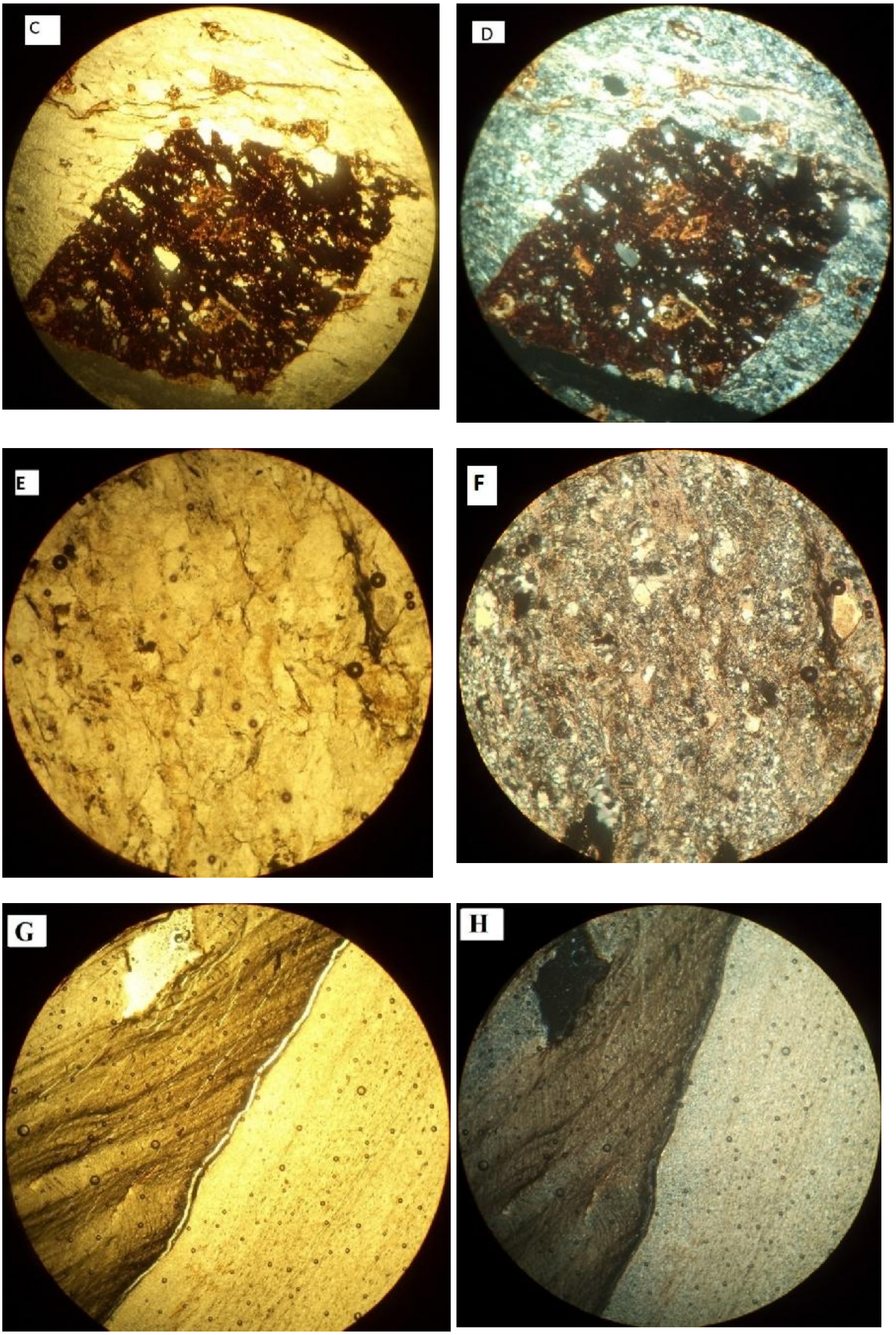
The unit depicts some variation in color and composition of bedding across strike; for instance it becomes light color when it consist less graphitic layers but dark gray when it becomes graphitic rich.

Thin section study of the representative samples (Fig.3.2A-H) revealed that unit is largely composed of, quartz, feldspar (k-feldspar and plagioclase/albite), muscovite/sericite and opaque minerals. There are also significant amount of calcite, graphite and trace amount of chlorite that vary from specimen to specimen. Plates A-F in Fig.3.2 represents the dominant type of the lithology that has been mapped as spotty quartzo feldspathic phyllite. At places the unit becomes rich in sericite and graphite (Fig.3.2G & H); hence it is named as spotty quartz graphite micaceous phyllite.

Locally, this unit is cut by zones of continuous and discontinuous quartz vein lets/stringers with different orientations (Fig.3.8). The vein density is quite variable, in some places particularly in the southern part of this unit, abundant, mineralized concordant quartz vein with a range of thickness from 10 to 60cm observed (Fig.3.8C).

The contact it makes with the adjacent units is not clear. It is more of gradational type as some different units, like slate, slate-phyllite intercalation and meta-sub-intrusive occur around the end of the zone.

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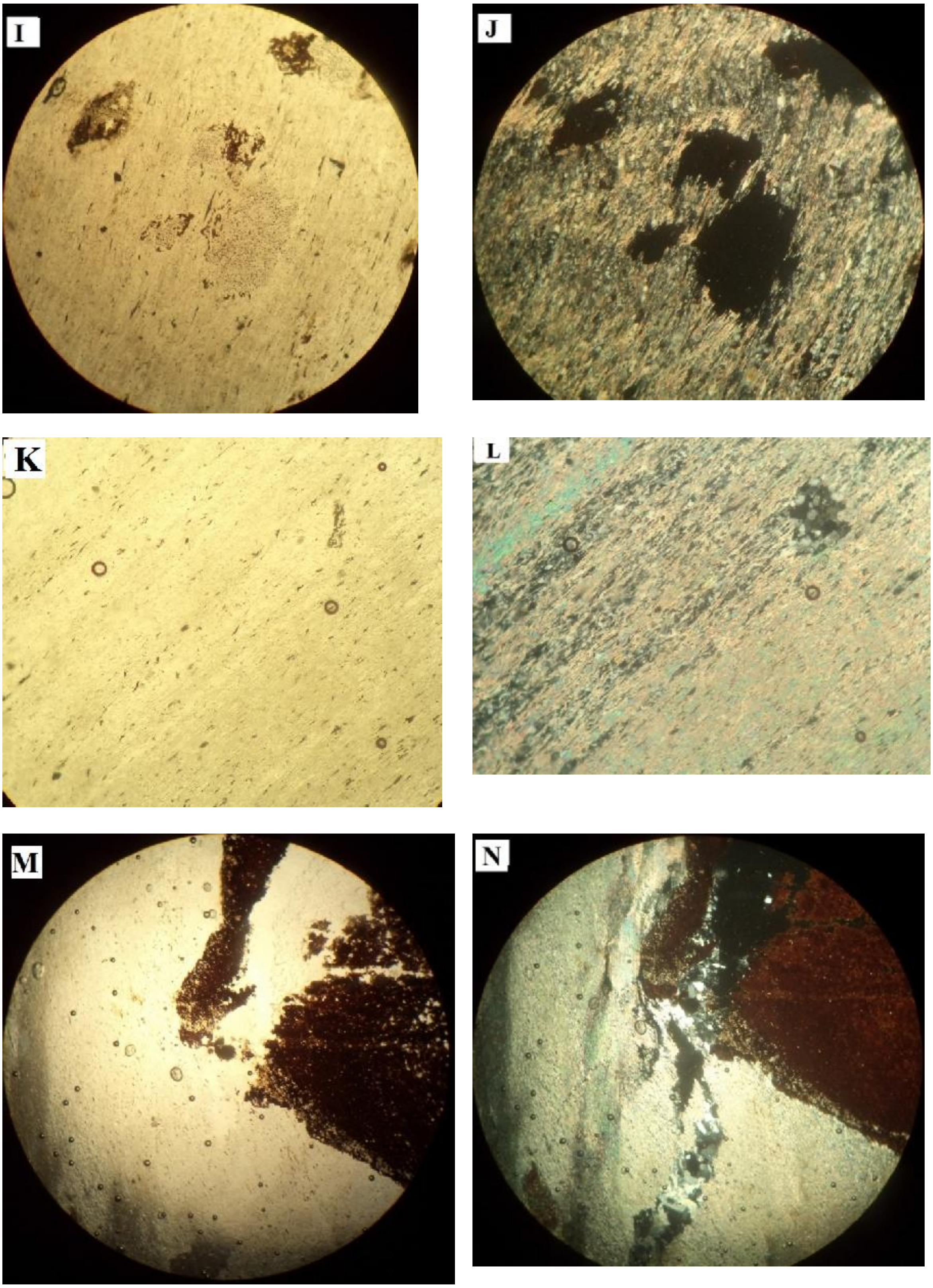


Figure 3.2 Photomicrographs of the various types of Phyllites that represent spotty quartzo feldspathic phyllite and spotty micaceous phyllite from different locations.

Plate A, B, C and D are the same sample (sample#100); where A and C are in PPL but B and D in XPL.

Magnification 4x. Sample location (0535397E,1551669N)

Note: plate C and D are inserted to analyze the time relationship b/n mineral growth (metamorphism) and deformation.

Mineral content: quartz 40%,plagioclase/albite 20%,mica/sericite 15%,opaque 20%,chlorite 3 % and minor constituents 2% calcite; The quartz grains are recrystallized and deformed. They have rounded to angular shape exhibiting undulose extinction. The feldspar /plagioclase show alteration to calcite and sericite.

Texture and/ or microstructure: The spaced foliation (S1) is defined by the platy minerals mica/sericite and chlorite. The foliation wrap around angular to sub rounded quartz and feldspar grains/phenocrysts that constitute microlithons. The microlithons are not crenulated hence the foliation can be called disjunctive foliation.

The presence of angular to sub rounded quartz and feldspar grains/phenocrysts of different size set in fine grained ground mass sericite/mica,minor chlorite? Hence the rock could be sheared and metamorphosed felsic greywacke.

The brownish opaque porphyryoblasts are dominantly random / have no preferred alignment. In other words, they appear to be randomly overprinting the pre-existing foliation and are probably post-tectonics to D1.

Certain minerals like quartz and opaque are enclosed in the bigger porphyryoblast (**plate C & D**) giving the host crystal a spongy appearance poikiloblastic structure, or sometimes termed sieve structure.

Rock name: spotty quartzo feldspathic phyllite.

E and F, sample#8, are PPL and XPL pictures respectively, 10 X magnification.Location (0535220E, 1551310N).

Mineral content: quartz 40%, mica/sericite 30%, plagioclase / albite20 %, opaque 5% and minor constituents calcite3%, chlorite 2 % .It also shows disjunctive foliation similar to sample A and B.

Rock name: spotty quartzo feldspathic phyllite.

Plate G and H, sample# 4, are in PPL and XPL. Magnification 10x. Location (0535655E, 1551424N).

Mineral content; Mica/sericite 35%, Graphite 30% (dark brown both under ppl and XPL), felsic minerals (quartz & feldspar) 30 %, opaque 4% and trace biotite and chlorite.

Texture and/ or micro structure: trace of bedding (S0) clearly defined by compositional variation, the quartz micaceous layer (right half) and graphite micaceous layer (left half).in these two layers there is well developed continuous cleavage (S1) that runs parallel to the bedding; hence, S1 is a composite fabric formed as result of D1.In addition the S1 in graphite micaceous layer has been folded/ crenulated by D2 resulting in crenulation cleavage (S2). The S2 is more pronounced in this zone due to the compositional variation.

Rock name: spotty quartz graphite micaceous phyllite.

Plate I and J, Sample # 7, in PPL and XPL respectively. It is representative sample of spotty micaceous phyllite unit. Location (0537452E, 1552485N). Magnification 4x.

Mineral content: Mica/Sericite ~55%, quartz 30%, opaque10%, feldspar 4% and trace calcite and chlorite.

Rock name: spotty micaceous phyllite.

Texture and/ or micro structure: the minerals (mica, quartz and feldspars) are somewhat coarse and define continuous foliation i.e schistosity (S1) that runs from top to bottom. Weak differentiated crenulation cleavage S2, define by grayish (quartz and feldspar) zone, is seen running from top right to bottom left. It has been caused by D2 deformation. The opaque minerals are also deformed during the formation of S2 but they simply over print the S1. Hence they are intertectonic.

Rock name: spotty micaceous phyllite.

K, L, M and N represent a single sample (sample#103) but in different views. **K and M** are in PPL, **H and J** are in XPL.The unit, where the sample is taken, has been mapped as spotty micaceous phyllite. Magnification 4x.Sample location (0537188E, 1550940N).

Note that plate **M and N** is inserted for microstructural analysis discussed below.

Mineral content: Mica/Sericite ~65%, felsic minerals (quartz & feldspar) 25%; and Minor chlorite ~3% and opaque 7%.

Texture and/ or microstructure: the very fine grained minerals constituting the rock are well aligned with no microlithons between cleavage domains. Hence it defines continuous foliation/cleavage.

Moreover, plate **L** shows two clear layering that defined by mica rich zone (bluish & yelowish layer) and quartz feldspar rich zone (dark grey layer). These layers have different thickness, and they are planar (not wavy as that of tectonic bands or layers) hence they could be beddings (S0). The beds are parallel to the continuous foliation (S1).In other words S1 is composite cleavage i.e. fabric developed parallel to the bedding.

Plate M and N on the other hand indicates the formation of incipient S2 which resulted from the micro folding/crenulation of S1. As it is clearly seen the opaque porphyryoblast is also deformed/ bent and cut by the quartz vein. Therefore, the opaque which makes the phyllite spotty are interpreted as inter tectonic.

Rock name: Spotty micaceous phyllite

3.2 Undifferentiated slate and phyllite zone

This zone is represented by intercalation of various type lithologies such as phyllite, slate, metagraywacke/metabreccia, metasubintrusive and quartz rich granitoids. In the zone, the thicknesses and frequency of intercalation of various rocks are commonly different from place to place. Phyllite and slate are the dominant lithologies among the constituent sub units in the zone.

Generally, the zone forms higher topography/ridge relative to the other units that could be most probably due to the existence of weathering resistant lithologies and intrusives.

3.2.1 Phyllite

The unit is lithologically similar to the spotty quartzo feldspathic phyllite described above, but with less and/or at places absent porphyroblasts. The grey to light grey phyllite-schist is the dominate rock, and it shows relatively fairly developed phyllitic cleavage. Whereas, the pale yellow, grey to dark grey and stripped phyllite-schist are very minor in occurrence unlike the spotty phyllite zone.

3.2.2 Slate

The unit has yellowish and tan color, with slaty cleavage (Figs. 3.6C&D**,** 4.2B). It forms gentler topography and found randomly in various thicknesses (2-45m) in the zone. As it is less resistant to erosion/weathering, at places the outcrop is encountered highly weathered and dissected by streams. In these places beds having variegated colors, i.e various beds decorated with yellowish, purplish, reddish, whitish and brownish color, are well exposed (Fig.4.1E).

3.3.3 Metagreywacke

In the zone, the unit is mapped as minor lensoid as it has small areal coverage. At places, it also occurs as thin lens/layer that is too small to map. The unit is greenish gray weakly to moderately foliated fine grained rock. At hand spacemen the rock looks brecciaed because coarser angular rock fragments, consisting quartz and feldspar, are observed set in finer grayish green (chlorite) ground mass. Thin section study reveals that the rock consists of mica, quartz, plagioclase, chlorite and graphite; see Fig. 3.3.

The rock is relatively a harder than slate and phyllite unit; and found intercalated in slate unit near the mid of the ridge (Fig. 3.1)

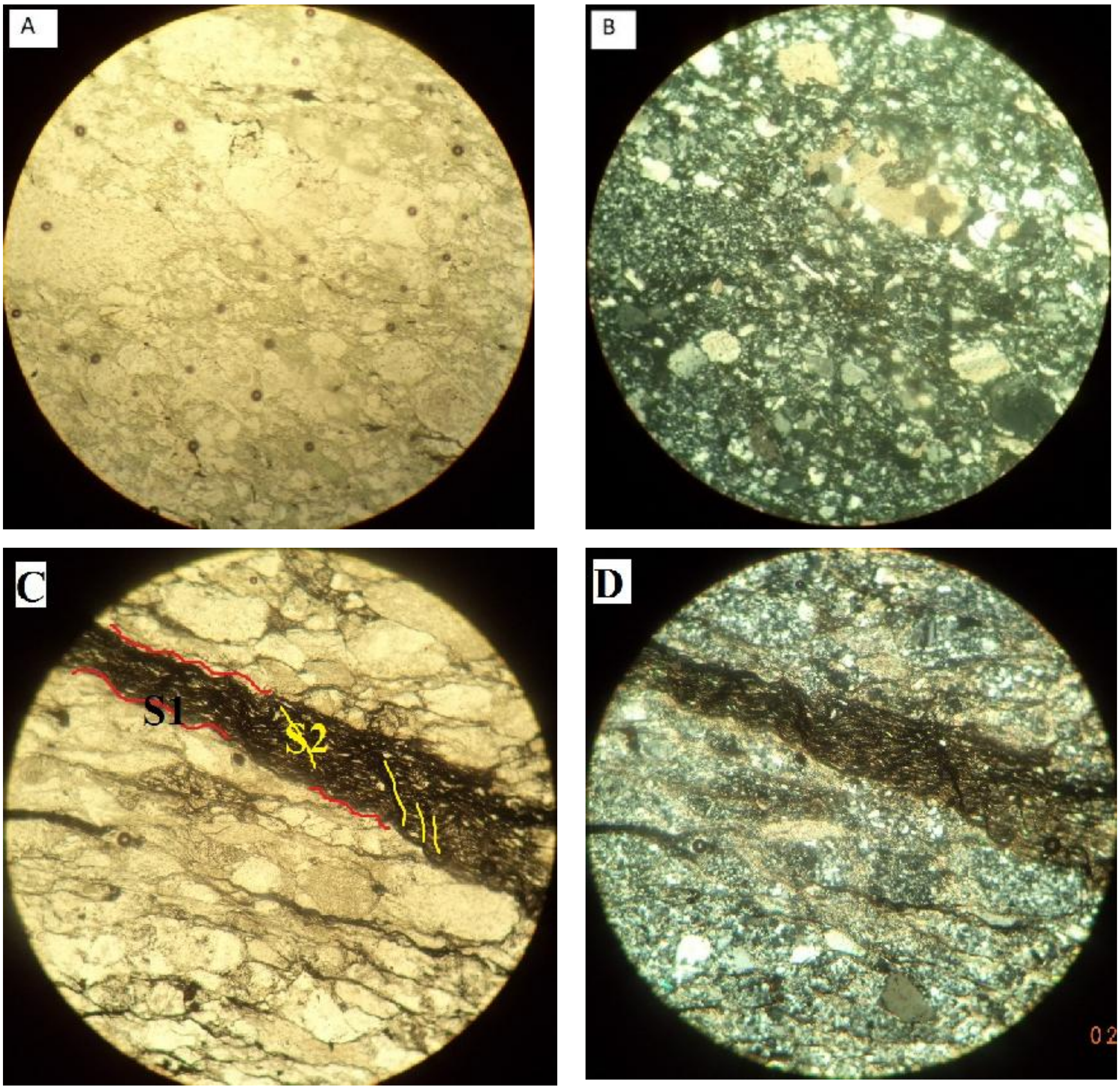


Figure 3.3 Photomicrographs of metagreywacke sample # 2(A and B) and sample #10 (C and D).

Location of samples: (0535968E, 1551638N) & (536223E, 1550248N) respectively and 4x magnification.

Plate A and B are in PPL and XPL respectively.
Mineral content: quartz 40%, chlorite 20%, feldspar 20%, sericite 10%,lithic fragments 5%, albite 4% and calcite 1%, .
Texture and/ or microstructure: angular to sub rounded quartz grains,phenocrysts and lithic fragmenets of different size set in fine grained ground mass chlorite. It is moderately foliated, spaced foliation, depicted by chlorite alignment.

C and D are in PPL and XPL respectively.
Mineral content: quartz 35%, plagoclase 20%, graphite 15%, sericite 13%, lithic fragments 7%, albite 5%, chlorite 3% & calcite 2%.
Texture and/ or micro structure: S1 defined by spaced foliation with non crenulated microlithones in quartz and feldspar rich layer. Whereas in graphitic rich layers,the foliation is continuous (no/ microlithones) and crenulated resulting in the formation of S2 cleavage. Hence, the crenulation cleavage is caused by D2 deformation.

3.2.4 Metasubintrusive

This unit is among the minor unmappale minor lithologies that commonly occur in undifferentiated slate and phyllite, and rarely in spotty quartzo feldspathic phyllite.

Most often, it is found concordant to the regional foliation at random frequency and various thicknesses (3m-10m) and extent forming a ridge. It is also strongly affected by alteration and/or weathering that makes the rock to appear yellow when it is broken (Fig.34A). At hand specimen, the rock is yellow, massive, consisted of fine to medium grained minerals. Quartz, mica/sericite, yellowish and brownish oxidized minerals probably sulphides and /or altered iron rich minerals (goethite (FeO.OH)?) are the dominant minerals noted.

Thin section study shows that rock is dominantly consists of sericite/mica 30 %, quartz 25%, opaque 25%, and feldspar/plagioclase 15% (Fig.3.4).

Hence, from the nature of the outcrop pattern and the composition of the rock it is interpreted that the unit could be weathered/altered intermediate or felsic intrusive body.

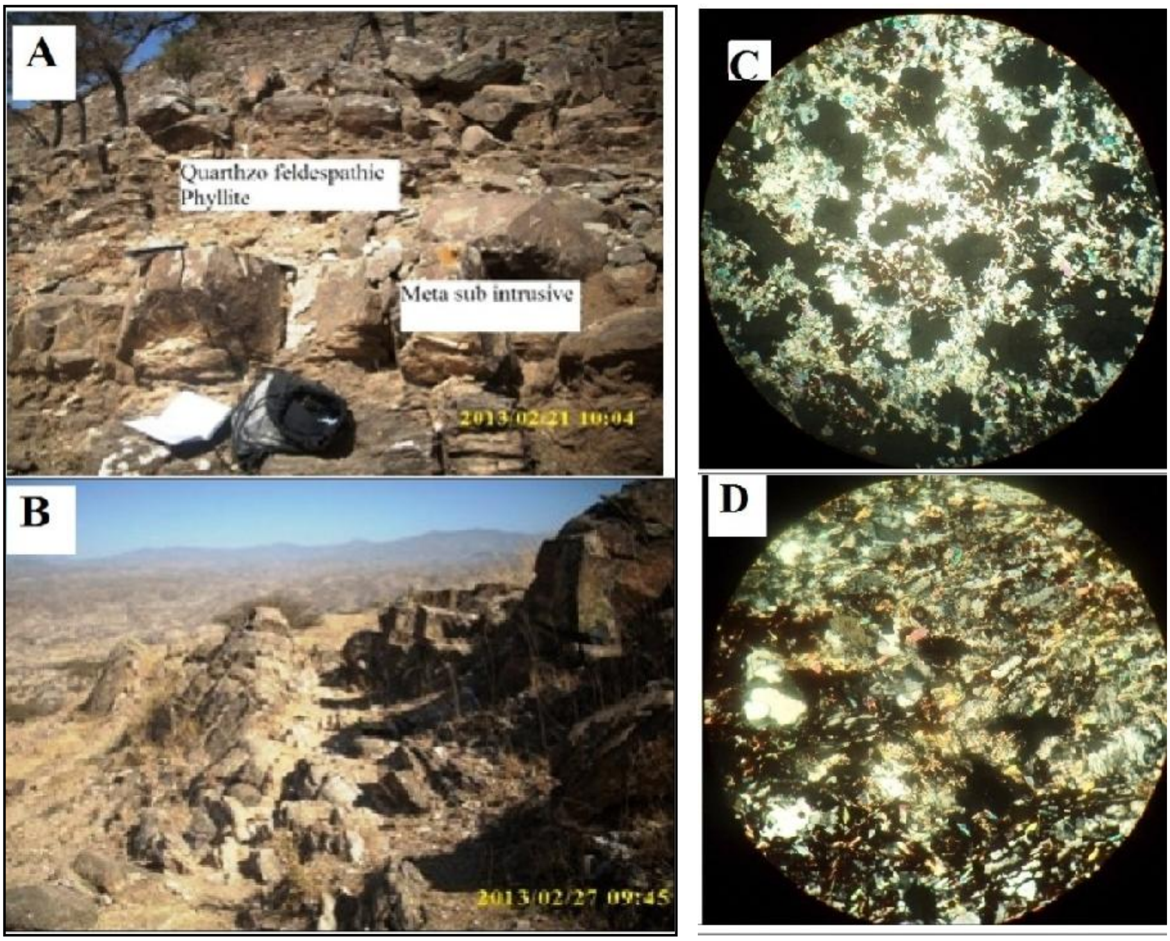


Figure 3.4 Outcrop of sub intrusive (A & B) and thin section pictures of the representative samples (C & D).

Note the concordant intercalation of the intrusive in phyllite.
C and D, XPL, Photomicrograph of sample #107 and 109 of the sub intrusive rocks consisting randomly oriented, different size minerals. Magnification 4X for C, but D 10x;
Major constituents: sericite/mica 30 %, quartz 25% , opaque 25%, feldspar/plagioclase 15% the rest are voids. The voids, lost out minerals, and the strongly oxidized opaque that give the rock yellowish appearance could be sulphide, pyrite?.
Note: Both the rocks are massive i.e. Constituting minerals do not have preferred alignment/orientations implying the unit is later than the major deformation events. Location of C is 535854E, 1551638N and D is sampled from 537934E, 1551307N.

3.2.5 Quartz rich granitoids

The outcrop is often found weathered with light yellow color; but sometimes when it is broken the fresh rock appear as light gray and/or whitish grey color. It is weakly foliated to massive, consisting dominantly medium grained quartz, mica/sericite and plagioclase, alkali feldspar and trace biotite. It occurs concordantly in the zone in various thickness (5-10m), frequency and strike length. In few places, it is also crop out intruding the greenish slate zone. Under microscope, the rock shows faint foliation defined by the muscovite as depicted in Fig.3.5 A.

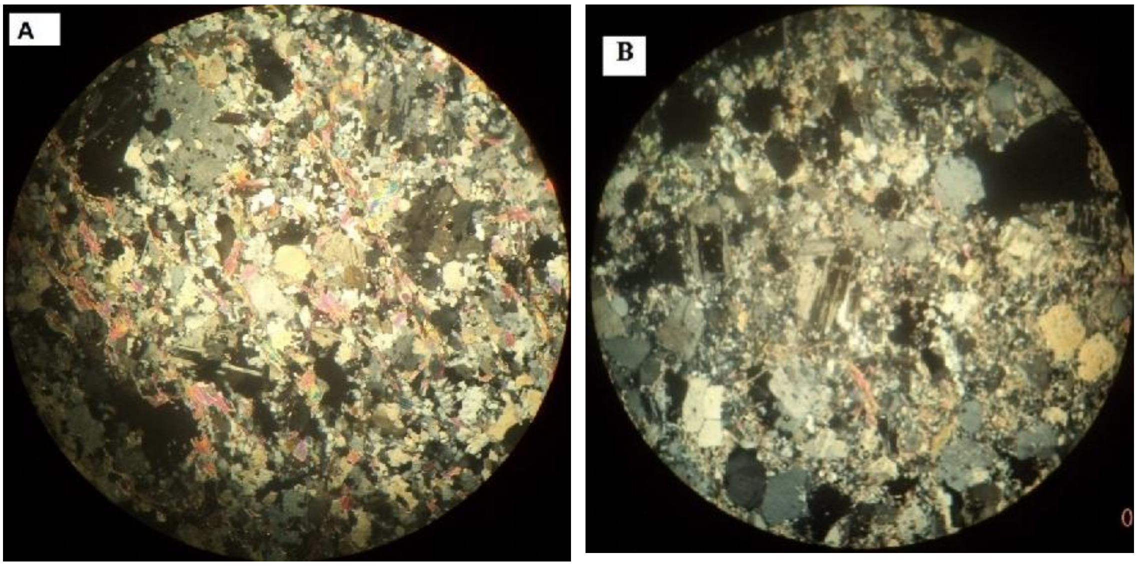


Figure 3.5 Microscopic photos of representative quartz rich granitoids under XPL (4x magnification).

Sample locations of A and B are (0536245E, 1551481N) & (536630E, 1550419N) respectively. **Constituting minerals of A and B** (sample #3 and 6 respectively): quartz 50%, Mica/sericite 25 %, and plagioclase 20 %, alkali feldspar 5-% .Note that the micas in plate A show certain mineral alignment unlike plate B. Some of the plagioclase in plate B shows twinning with tapered end (needle like) due to deformation.It is named as **quartz rich granitoid.**

3.3 Chloritic slate and phyllite

The unit is easily recognized by its light green to grayish green color. The rock is fine to very fine grained with well-developed cleavage (Fig.4.1E**)**. Thin section investigation of representative sample shows it consists of dominantly sericite and felsic minerals (quartz and feldspar) with significant amount of chlorite (Fig.3.6A & B).

The unit is characterized by the occurrence of abundant deformed quartz veinlets particularly at its eastern and western parts (Fig. 4.6C).

Unlike the spotty phyllite, this unit lacks the dark brown and rhombic opaque minerals.

Relatively this zone has more vegetation cover and enabled most of the local people to dwell and farm the land.

Foliation, crenulations (micro folds) and lineation are the common secondary structures present in this zone.

It is separated from the adjacent units, by the existence of natural break (slope break) and variation in vegetation cover i.e. denser in this zone. In addition, the occurrence of the quartz rich granitoid in its western boundary marks its transition to the undifferentiated unit (Fig.3.7A-D). On the other hand the presence of variegate slate, intercalation of phyllite and quartz graphitic layers marks its eastern boundary (Fig.3.7 E-G).

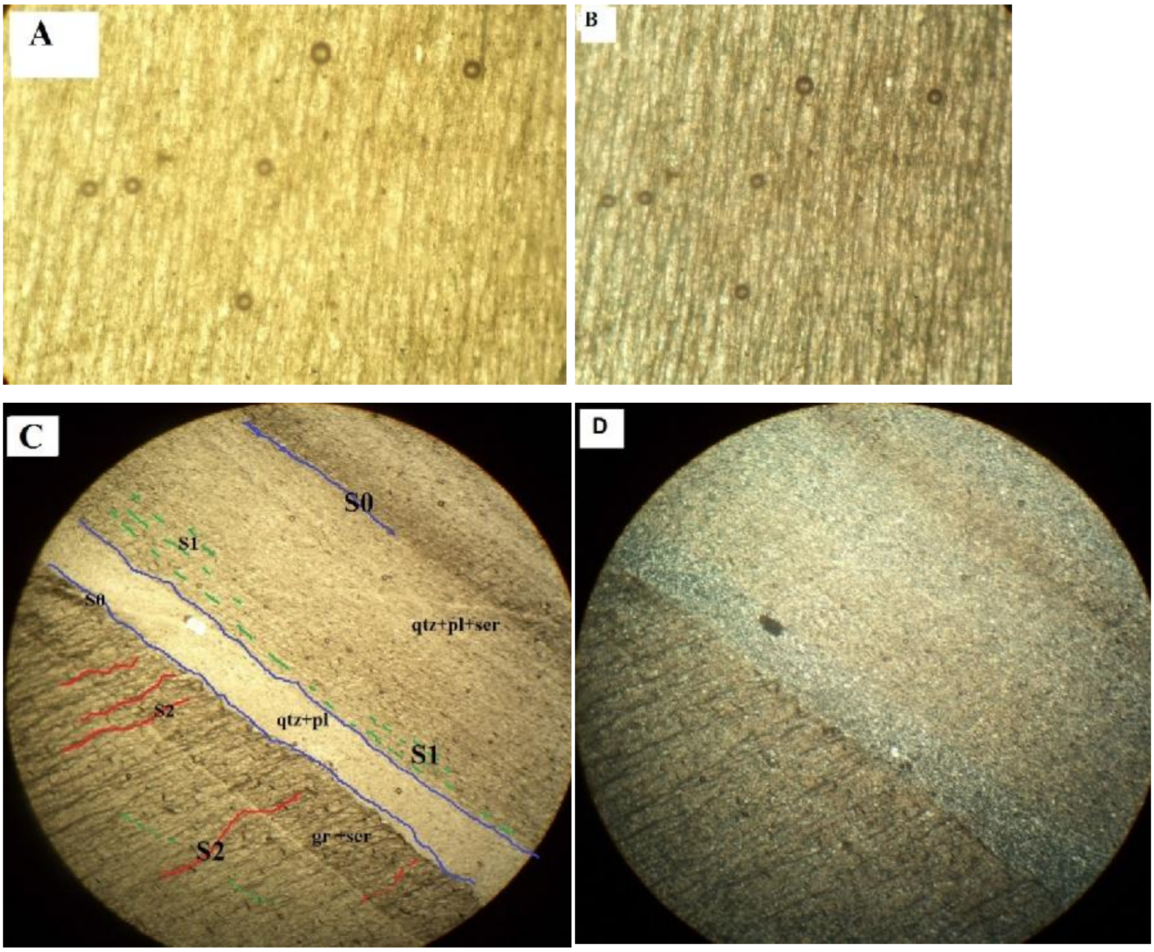


Figure 3.6 Photomicrograph of chloritic phylite and slate. A and C are in PPL, B and D in XPL (10X magnification).

Plate A and B, Sample # 105, chloritic phyllite, that show closely spaced crenulations see (Fig.25C), **Mineral content**: Mica/sericite 50 %, felsic minerals (quartz and feldspar) 30 %, chlorite 20%.

Texture and/ or micro structure: very fine grained, showing well developed two foliations S1 is defined by continuous cleavage that runs from top left to bottom right. On the other hand, micro folding/crenulation of S1 resulted in very closely S2 crenulation cleavage formation. The lineation, faint green lines (from top to bottom), associated with crenulation is defined by chlorite and mica. Location of the sample is 536720E,1552467N.

Plate C and D (Sample # 9 slate). Sampled from undifferentiated slate and phyllite zone. Location (0535818E, 1552500N).

Mineral content: Mica/sericite 40 %, felsic minerals (quartz and feldspar) 40% , graphite 15 %, chlorite 5%

Texture and/ or micro structure: very fine grained, exhibiting primary (bedding S0) and secondary foliations i.e. well developed continuous cleavage S1 and crenulation cleavage S2. The bedding (So) is formed by alternating layers, which depicts different colors and thickness zones. The S0 is also affected by continuous cleavage (S1) that is parallel to the bedding; hence, S1 is composite foliations or fabric. S2 is formed due to D2 that crenulated S1 in brownish layer (graphitic rich layer).

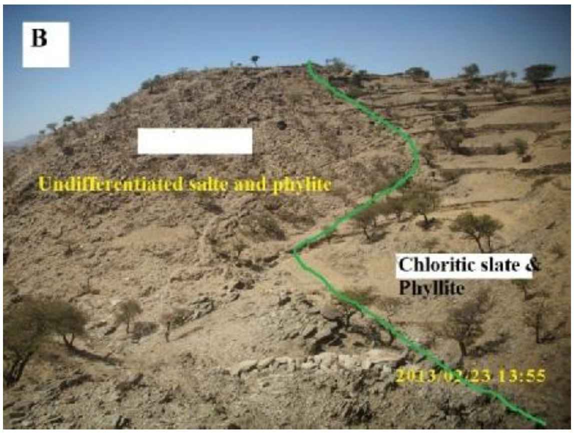
3.4 Spotty micaceous phyllite

The zone containing this unit is easily identified as it form narrow distinct grayish-to-grayish white zone with sparse vegetation cover and rarely used by local people for farming activities see Fig.3.7 E-H.

The unit is exposed in the eastern part of the study area and forms relatively lower topography compared to the rest of the units (Fig. 3.7E&F).

The micaceous phyllite is strongly altered, oxidized and seriticized with abundant quartz veinlets. It consists of abundant reddish brown strongly oxidized porphyroblast of rhombic minerals (ankarite?) and yellowish oxidized spots pyrite (Py). Abundant floats of grayish and white phyllite mixed with quartz are also found widespread in the zone.

Thin section study of this unit indicates that the rock is dominantly composed of sericite/ mica, quartz and minor feldspar (Fig.3.2 G, H, J and I).



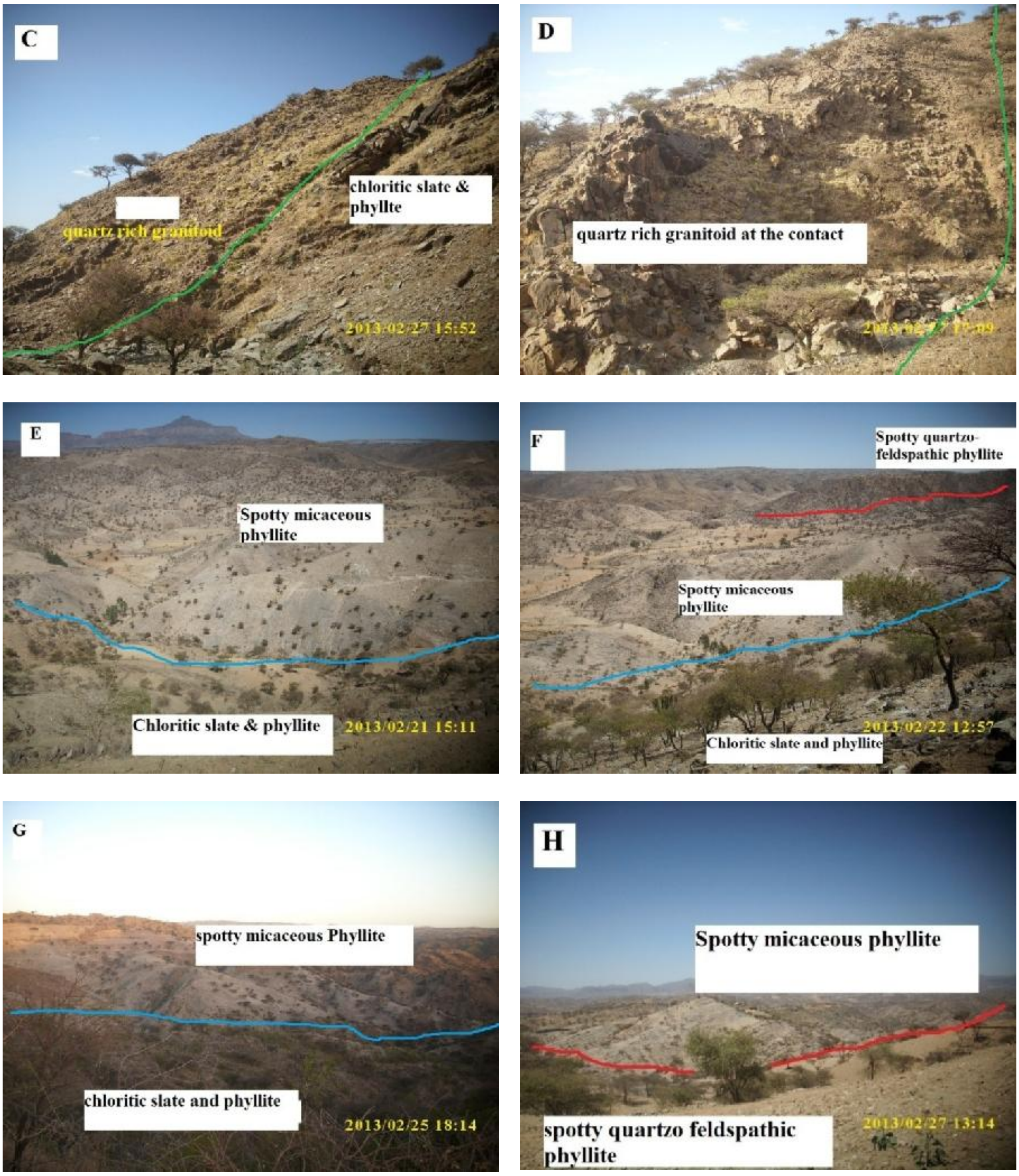


Figure 3.7 Field photographs to show contacts between the different phyllitic units.

A, B, C and D contact between undifferentiated slate and phyllite zone and chloritic slate and phyllite at different locations. All pictures shot facing North. C & D taken from the location of (0536499E,1552210N)

E, F and G contact zone b/n chloritic slate and phyllite and spotty micaceous phyllite at different location. Note clear variation of plant distribution. Photographs taken facing east.
E and F taken from the location of 536720E, 1552467N.
G is taken standing at location of 0536652E, 1550176N.
H Gradational contact between eastern spotty quartzo felspatic phyllite and spotty micaceous phyllite. Picture has been taken looking west.

3.5 Quartz veins

Majorly concordant and discordant quartz veins/veinlets are observed in all the mapped units in various concentrations. The dominant quartz veinlets, which are concordant to the foliation, trend in NNW-SSE to N-S and moderately dipping to west. Whereas, the less commonly occurring discordant quartz veins have an E-W to NE-SW and NW-SE strike (Fig. 5.1D).Hence based on the orientation, the quartz veins/vein lets can be categorized into three generations.

The concordant quartz veins show a pinch and swell form, folding and boudinage (Figs 3.8, 4.2A&D & 4.5B-D).Thickness of the quartz veins/veinlets ranges from less than a centimeter to a maximum of 40 cm. At certain places there are also quartz stringers that have random orientation and found as networked structures (Fig. 3.8 A&B).

Mostly the quartz veins/veinlets moderately dips (25-60°) W, NW and NE and in some cases the veins are very steep to vertical.

The quartz veins in general have glassy texture and milky white to white color. They contain yellowish oxidized spots/vugs after sulfides.

The abundance of the vugs/oxidation spots is quite more in the older and concordant veins.

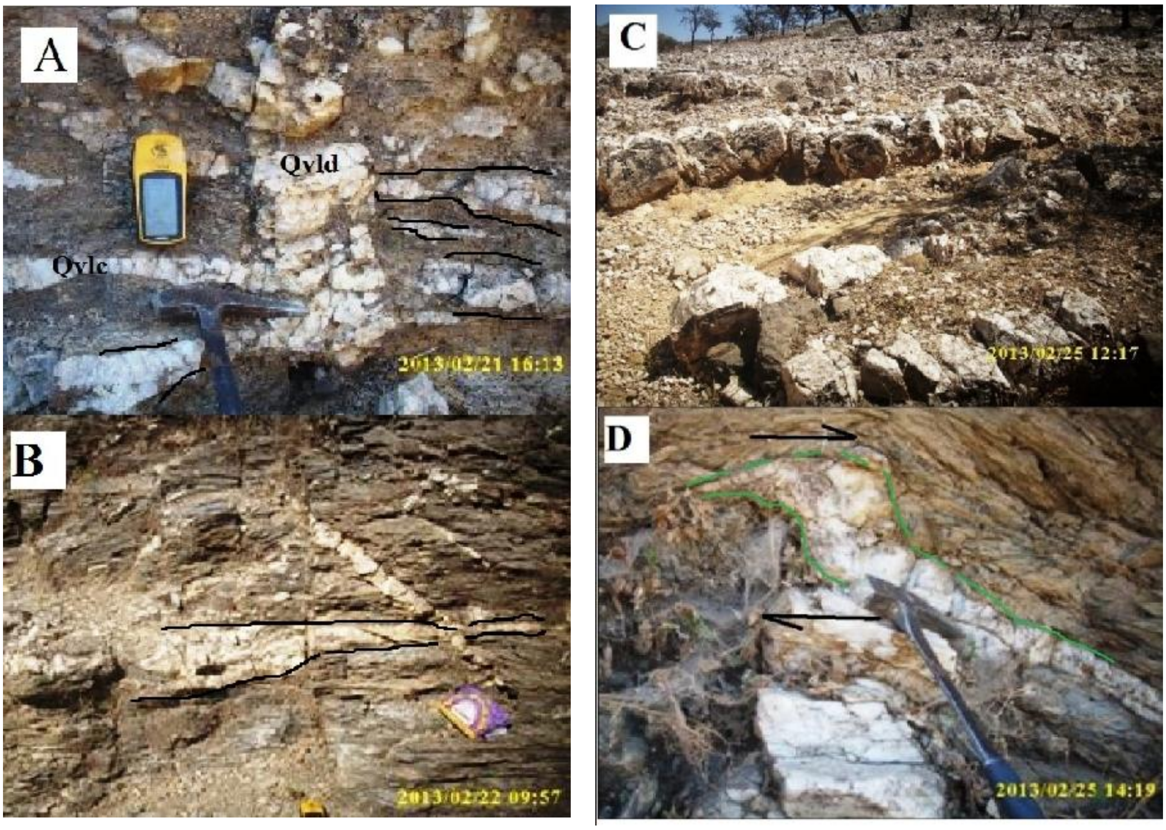


Figure 3.8 Quartz vein lets of various generations.
Note that the concordants are those parallel to the major foliation (N-S) and the discordants are those cross cut both the foliation and the concordant quartz veinlets. In all cases the veins consists yellowish oxidized spots and vugges that are probably after sulfide though quite more abundant in the concordant veins.

A. Exposure of spotty micaceous phyllite, bearing quartz veins (Qvl. & Qvld. represents concordant and discordant quartz veinlets in their order) at location of 0537096E, 1552348N.
B. Concordant vein pinches out along strike implying non uniform thickness along strike, indicated by black line at. Location 0535420E, 1552260N. A and B taken facing west.
C. The most abundant and thickest quartz veins found in the study area about 200m north east of the ferroginized phyllite at the location of 0535312E, 1551516N.The veins are concordant to the host i.e spotty quartzo feldspathic phyllite.
D. Locally sheared concordant quartz vein let, dextral sense of shear. Shot taken facing south. Location (0535459E, 1550467N).

3.6 Graphite

The graphite occurs only as a thin layer about 10 m thick and 20 m long at the location 0537044E, 1552560N. It exposed at the contact zone between greenish phyllite and micaceos phyllite. The rock is strongly foliated defined by well-developed continuous cleavages that are parallel to the regional foliations. The outcrop contains thin, abundant concordant quartz vein lets and quartz strangers (Fig. 3.9C). Graphite, sericite, quartz and feldspar are the dominant minerals that constitute the rock see Fig. 3.9.

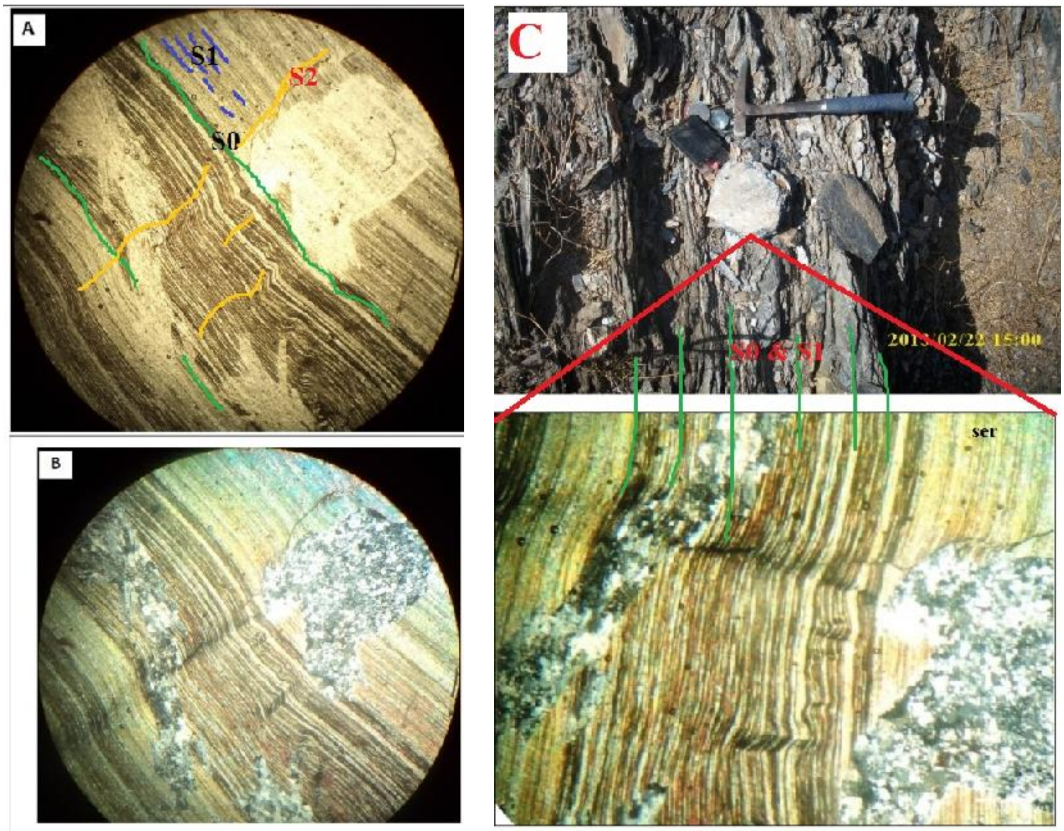


Figure 3.9 Plates **A and B** are photo micrographs of graphite schist, in PPL and XPL respectively (4x magnification).

Constituent Minerals: graphite % 40, Mica/sericite 35%, quartz 25%.

Texture and/ or micro structure: very fine grained, showing both primary and secondary foliations; shown by different colors in plate A.

The bedding (So) is defined by the alternating layering of graphitic rich and quartz micaceous layers/laminations i.e. black and white alternating planer bands with various thicknesses. The bedding (S0) is again cleaved by D1 and resulted in continuous slaty cleavage (S1). S1 is also affected by later deformation phase (D2) that folded S1 and created weak creanulation cleavage (S2). S2 is particularly enhanced in graphitic rich zone. The big quartz vein lets that cross cut the S1 is clearly later than S1 but it is folded by D2 implying it is pre to S2 but later than S1 indicating it is intertectonic.

Plate C is graphite schist out crop, hand specimen and its thin section picture, shot taken facing north. Location 0537044E, 1552560N.

CHAPTER FOUR

4 GEOLOGICAL STRUCTURES AND METAMORPHISM

4.1 Primary structures

4.1.1 Bedding and lamination

Bedding and laminations are the common primary structures that are preserved and observed in all mapped units.

However, it is more commonly encountered in spotty quartzo-feldspathic phyllite and undifferentiated slate and phyllite units (Fig.4.1). The beds have various color, composition and thickness that range from 1cm to 60 cm. The bedding/laminations majorly consists of greenish (chlorite), light gray (plagioclase and/or quartz sericite), grayish (plagioclase and/or quartz) and dark gray to dark (graphitic) layer (Fig.4.1F), separated by composite cleavage. Usually the beds are dipping 45-70^0 degree with arrange of strike from 350-010.In some places, particularly in valleys and stream, the beds are highly weathered and exhibits variegated color (Fig.4.1E).

Thin section investigation of samples from different lithologies and locations also support the presence of bedding and laminations; see Figs.3.2G&H, J, K&L, 3.6C&D and 3.9A.

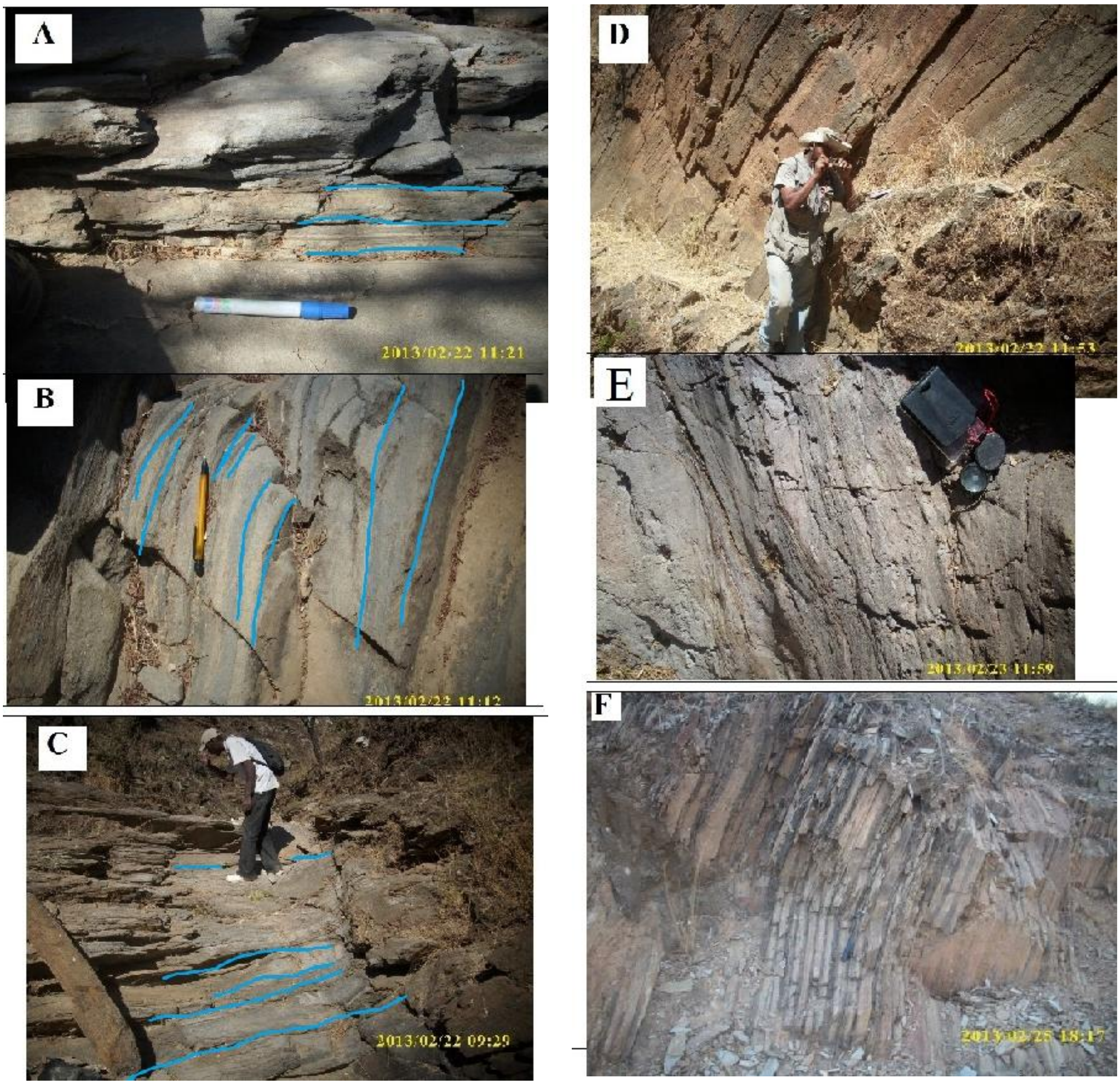


Figure 4.1 Field photographs of bedding in various units from different locations.

Plate A, B displays bedding and lamination in outcrop of graphitic phyllite and slate intercalation in undifferentiated zone. The bedding and/or laminations, in A and B, have variable thickness of beds striking N-S dipping 55º to west; the head of pencil and the tip of marker (blue) points to north. Both shot taken from top facing north at Location (0535818E,1552500N),

C shows Bedding in spotty quartzo-feldspathic phyllite at location of 0535393E, 1552198N) picture taken looking west.

D outcrop of **Quartzo feldspatic phyllite/ Quartz feldspar sercite schist** showing bedding and composite fabric/cleavage. shot to ward west. Location **(0536094E, 1552543N) in** undifferentiated slate and phyllite.

E shows thin bedding and/or lamination manifested by the variegated colors (green, brown, red, purple and yellowish) in slate of undifferentiated slate and phyllite. Location 0535967E, 1551461N.

Picture taken facing south.

F outcrop of chloritic slate with lamination of black (graphitic) layer and greenish grey beds.

It also shows slaty cleavage. The outcrop is a part of chloritic slate and phyillite.

Picture is taken toward north, location (0536652E, 1550176N).

4.2 Deformation Structures

Different phase of deformations are manifested by the formation of superimposed secondary ductile and brittle structures of various generations. These secondary structures include folds, foliations, intersection lineation, crenulation lineation and joints.

4.2.1 First phase deformation (D1) and associated structures

4.2.1.1 S1 Foliations

This structure is the predominant and characteristic feature of the majority of units in the area (Fig.4.2).The foliations are most often defined by the alignments of platy minerals in the slate and phyllite. Spaced and continuous cleavages are the common type of S1 foliation in the area. At certain places the foliation is defined by coarser mica, chlorite and/or graphite and results in the development of schistosity. The chloritic phyllite also shows, at places, certain coarsening in texture and appears as chlorite schist.

Microstructural analyses of thin sections also reveal that the foliations are of different types including continuous, spaced and crenulated foliations (Figs. 3.2, 3.3, 3.6, 3.9 and 4.3D).In addition in certain thin sections the foliations are parallel to relict of bedding (S0), and described as composite fabric.

The foliation shows slight variation in strike from NNW to NNE (350-010), and dips 40-65° west, northwest and southwest.
This variation in orientation (Fig. 5.1A & B) is considered to be related to later folding.

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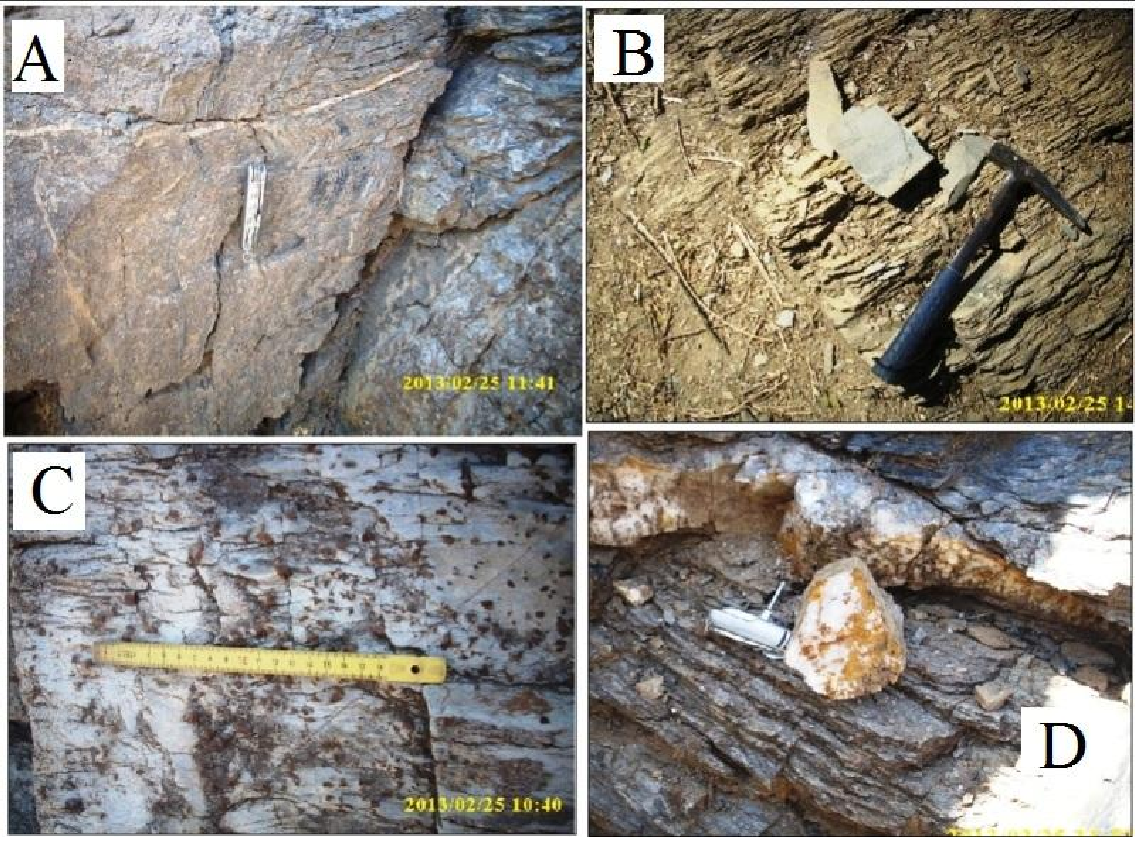


Figure 4.2 Field photos to show S1 foliations.

- **A.** Quartz and graphitic lamination/ layers in western spotty quartz-feldspathic phyllite. Layers are folded and broken. The scratcher inserted in the directin of fold axis.Shot facing south at location of 0535220E, 1551310N.
- **B.** Slaty cleavage in yellowish graphitic slate of undifferentiated slate and phyllite zone. The well-developed slaty cleavage is truncated by a younger, generally east-west trending and vertical cleavage. Shot from top facing to east at location (0535818E, 1552500N).
- **C.** Cleavage surface with lineation in outcrop of western spotty quartz-feldspar-micaceous phyllite, shot from top facing east.
- **D.** well developed phyllitic cleavage in western spotty quartz-feldspar-micaceous phyllite with quartz vein let

4.2.2 D2 structures

4.2.2.1 Lineations

These features are the most prominent ductile structures that are found almost throughout the majority of lithologic units on the cleavage plane. Crenulation and intersection lineation are the common type of lineations observed (Figs 4.3 & 4.4 A &D).

In addition, the lineations in general have similar orientation with the fold axes of minor recumbent/overturned folds encountered. That could imply they are probably of the same generations.

Most are horizontal to sub horizontal (0-10°) and gently plunging either N or S.

The stereo plots of all measured lineation including fold axes show a cluster of points in two regions i.e at northern and southern poles either very close to the primitive circle or on the primitive circle of the net that indicates shallow plunging (Fig.5.2).

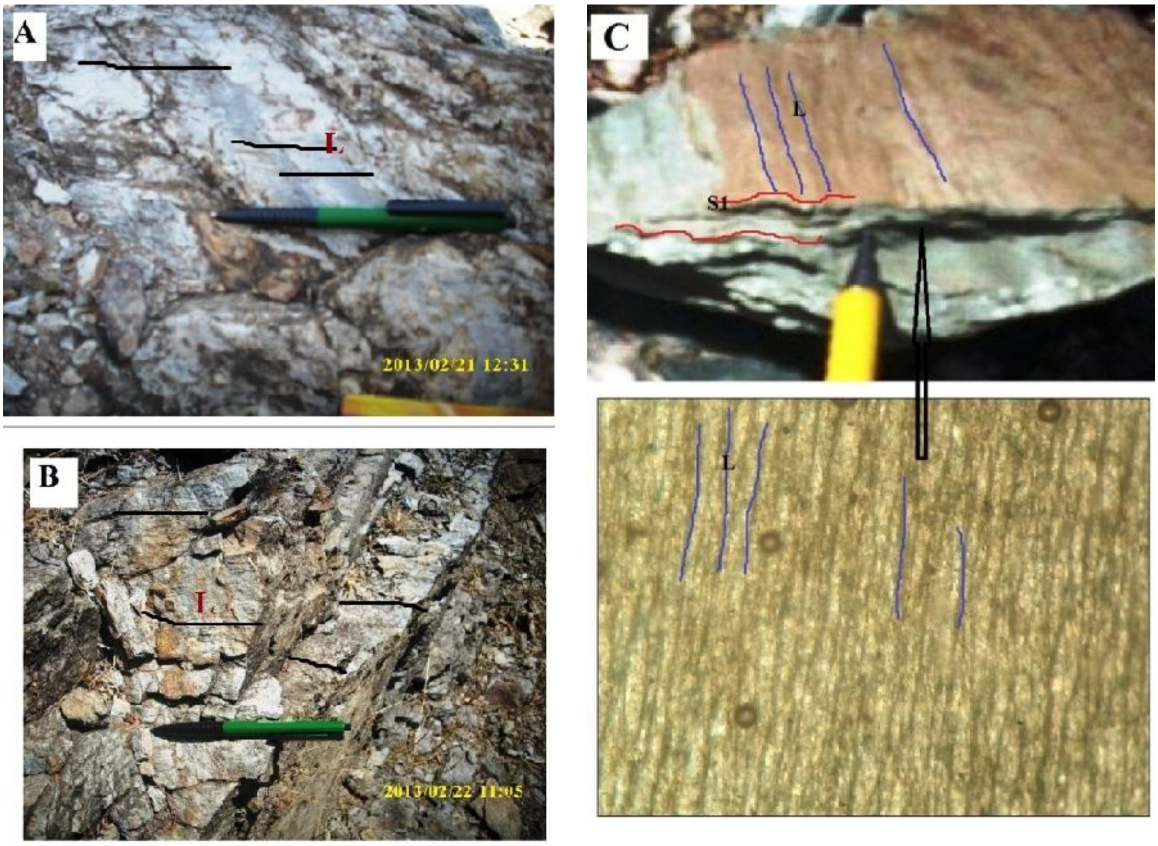


Figure 4.3 **A** and **B** well developed lineations on the cleavage surface of spotty qurtzo feldspatic phyllite; tip of the pen toward the plunging direction i.e. ($7^0 \rightarrow 344$ in A and $6^0 \rightarrow 332$ in B).
In addition, in **A** lamination of dark layers (graphite) and some porphyroblasts of yellowish minerals observed. Note the typical sheen/ lustrous surface of the phyllite and the joints that cross cut the foliation in B.Location of A and B are (0535826E, 1551980N) & (0535749E, 1552495N) respectively; both photos taken facing east.
Plate C is hand specimen and its thin section picture showing strong crenulation lineation (L) formed by the folding of S1. Sampled from chloritic phyllite zone at the Location 536720E, 1552467N.

4.2.2.2 S2 Foliation and related intersection lineation

S2 is incipient and /or weakly developed foliations that clearly cross cut the regional foliation locally (Fig.4.4). It is commonly observed in the micaceous phyllite unit and in the graphite bearing layers elsewhere. It generally strikes in NNW-SSE and NNE-SSW; and dips steeply to NE and SE respectively.

Micro structural analysis revealed that the foliation is defined by continuous realignments of fine-grained platy minerals and very thin graphitic layers (Figs.3.2G-J & N, 3.3C&D, 3.6, 3.9 & 4.4A).

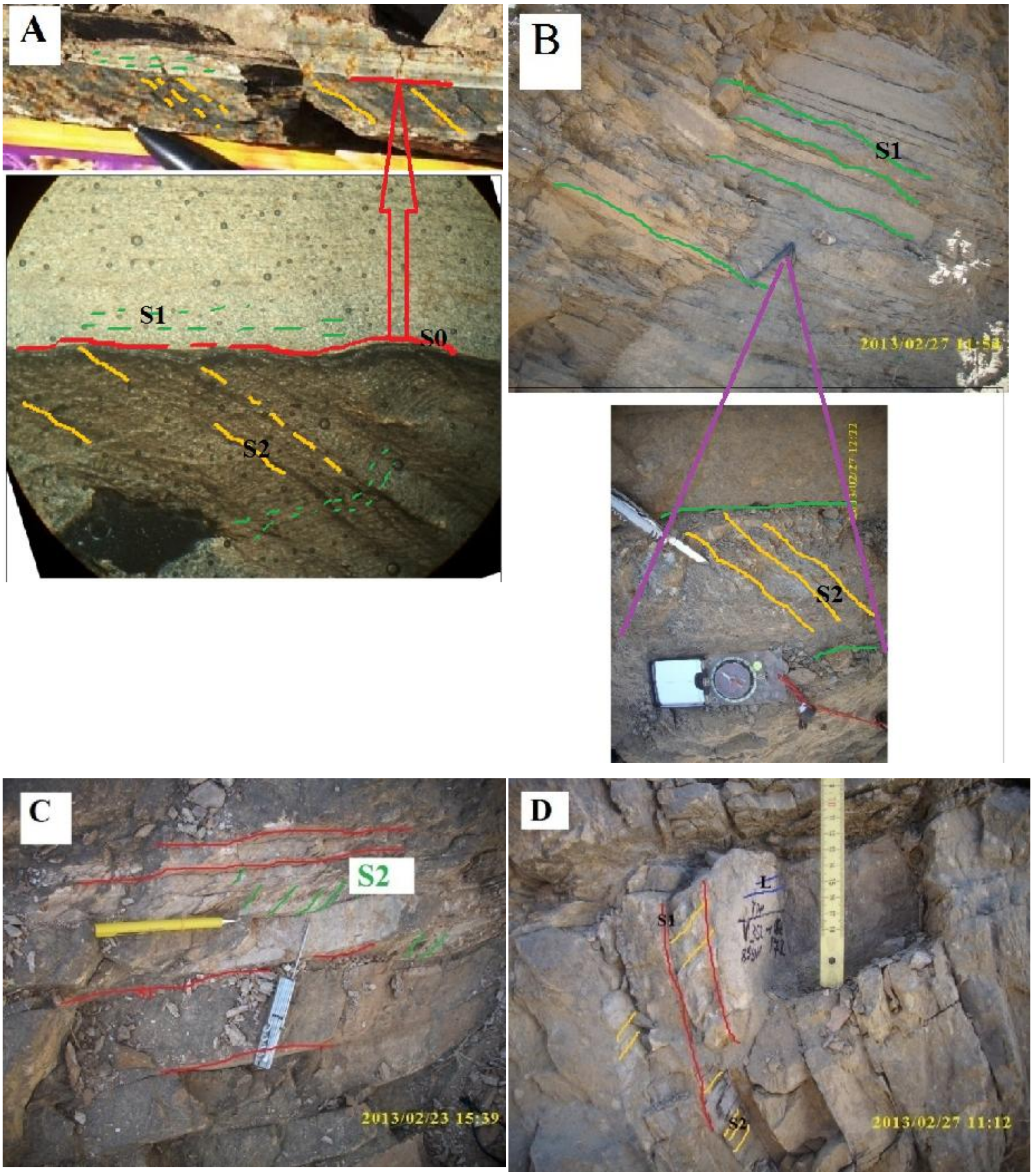


Figure 4.4 Field photographs of the S2 foliation in phyllite and slate exposures at various locations.

- **A.** The hand specimen and its microscopic pictures of spotty quartz graphite micaceous phyllite with S0, S1 and S2.Location (0535522E, 1551526N).
- **B.** Out crop of spotty phyllite showing S0, S1 and S2.Green line shows S0 and S1, yellow for S2. Picture taken from top facing west. Location 0537703E,1550538N
- **C.** Displays S1 and S2 by red and green line respectively in spotty micaceous phyllite. Shot from top facing west, Location (0536933E, 1551538N).
- **D.** Exhibits S1 (red line), S2 (yellow) and L intersection lineation (blue) formed by the intersection of the two foliations. Shot taken facing south. Location (537944E, 1550834N).

Note that in all cases S1 is prominent foliation where as S2 is not as such clearly observed from distance even if well developed cleavage in the finer materials like graphitic and micaceous layers.

4.2.2.3 F2 Folds

Many of the rock units display mesoscopic open (70^0 to120°), sub-horizontal folds that affect S1 foliations and concordant quartz veins (Fig.4.5).

The folds have fold axes plunging 0-10° N or S and are parallel to the other L2 lineations described above Fig.5.2.

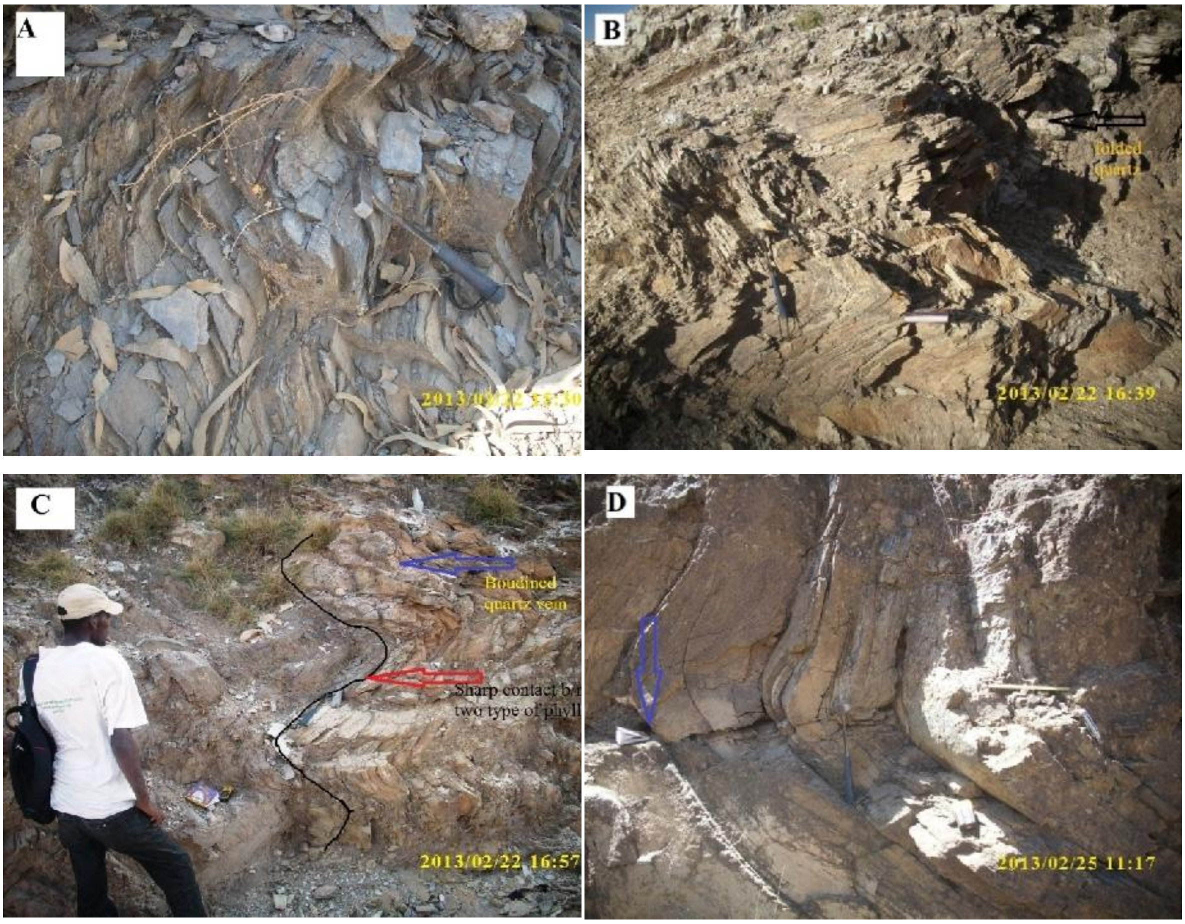


Figure 4.5 .Mesoscopic (out crop scale) field photos of folds with horizontal to sub horizontal axial planes and fold axes. The folds are observed at different location in the study area.

- **A.** Graphitic phyllite near contact zone (between chloritic slate and phyllite unit and spotty micaceous phylite) tip of pencil toward plunge of the fold axis (10-352) parallel to the prominent lineations and sub horizontal axial surface 345/15NE. location (0537036E,1552650N)
- **B.** Recumbent fold in phyllite, axial surface (015/10SE) indicated by the exercise book and fold axis by pencil tip plunging 6-018 (left) location (0537065E,1551773N).
- **C.** Folded sharp contact b/n micaceous and quartz feldspathic phyllite exposed by road cut. Location (0537066E, 1551773N).
- **D.** Open sub horizontal fold in spotty quartzo feldspathic phyllite with thin graphitic layers, axial surface (120 toward 090) indicted by note book and fold axis (plunge $9^0 \rightarrow 180$). Location (0535312E, 1551516N).

Note the concordant quartz vein and the phyllite folded together. Shot A,B and C facing towards north; but D towards south.

4.2.3 D3 structures

4.2.3.1 Joints

Almost all of the litho units in the study area have been affected by these brittle structures that generally striking in E-W direction and dipping vertical to sub vertical. The distributions of these predominant joints are not uniform in terms of occurrence and frequency/spacing i.e. the density of the joints is variable in different units and various places. They are observed more abundantly and more closely to each other in the slate and phyllite units of undifferentiated zone Fig.4.6.

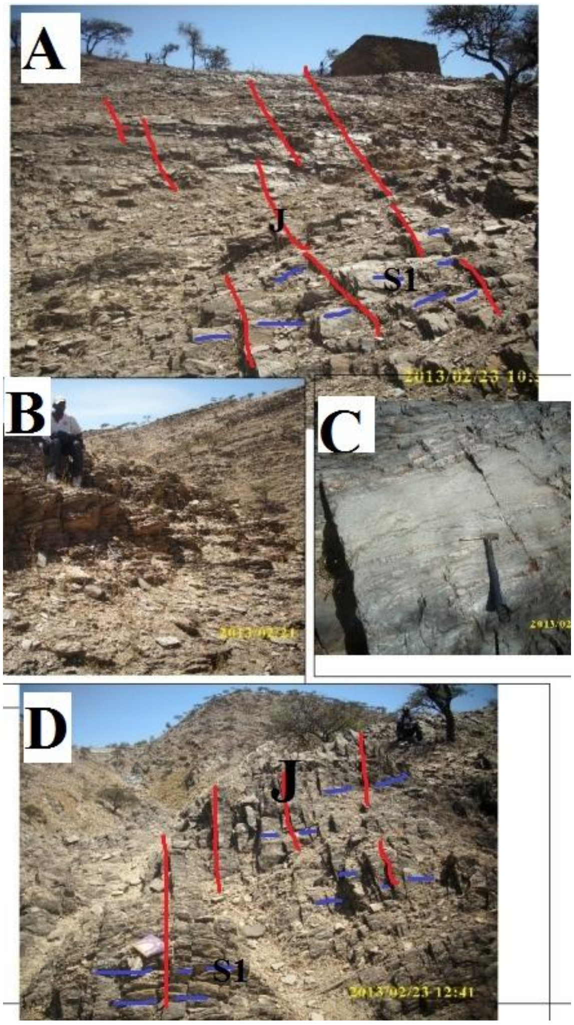


Figure 4.6 Recent joints cross cutting all units in the area.

A. Generally E-W striking vertical joints in the spotty phyllite rock. Location (0535557E, 1551501N).
B. E-W striking and almost vertically dipping joints in variegated color (yellowish, reddish, pinkish and brownish) intercalated slate and phyllite. Location (0535898E, 1552060N).
C. Shows joint 080/vertical in cross cutting the greenish slate and concordant quartz vein let. Location449 (0536568E, 1550820N).
D. Closely spaced joints (range of stike 080-100 and vertical dip) cutting across slaty cleavage (358/45SW). Location (0536072E, 1551510N).

Note A, C and D taken facing east, but B towards west.

4.3 Metamorphism

The majority of lithologic units in the study area have experienced textural and mineralogical changes that indicate the rocks have been subject to different environment from which they originally formed. In other words the rocks were subjected to different temperature, pressure and/or active hydrothermal fluid that changed the existing equilibrium and their by forced the constituting minerals to alter or facilitate the formation/growth of new minerals from the pre exiting rock constituents As discussed in chapter three the dominant lithologic units in the mapped area are described primarily in terms of their texture/fabric and the minerals they contain. The phyllitic rocks are well foliated often with shiny/sheen cleavage surface compared to the slates due to variation in intensity or degree of metamorphism and deformation. Obviously the phyllites are metamorphosed at higher grade than the slates 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 sericite, chlorite, epidote, calcite, graphite and porphyroblasts of opaque minerals indicate significant mineralogical change during metamorphism.

Based on the dominance of constituting minerals and texture observed in the low grade metamorphic rocks it is possible to infer the protolith (the parent rock). Accordingly the initial materials for the mapped units, spotty quartzo-feldspathic phyllite, spotty micaceous phyllite and greenish slate and phyllite, could be felsic greywacke and pelitic sediments. Because the majority of the phyllitic rocks are composed of dominantly mica/sericite, quartz and feldspar (plagioclase) and have angular to sub rounded quartz and feldspar grains/phenocrysts set in fine grained ground mass (Fig.3.2A-L).

The slate, graphite and quartz graphite micaceous phyllite (Fig3.2M & N) 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 critical (index) mineral assemblage, which forms in a specific range of temperature and pressure or distinctive conditions. Hence identifying the key mineral assemblage is useful to determine the grade and metamorphic facies.

The most dominant mineral assemblages of the various rock units are shown below. The critical minerals that can indicate the grade of metamorphism are in bold and underlined.

1. spotty quartzo feldspathic Phyllite

a. **ser** + **ab** + **chl** + cal + qtz +Pl + op± kfs

b.**ser**+ **ab** **+chl** + cal + qtz + Pl + op

2. Slate

a. **ser** + plg+ gr + qtz ± kfs ± bt ± **c**al

b. **ser** +**chl** + gr+ qtz ± kfs + py + cal.

3. Metagreywacke

a. **chl** + **ser** + **ab** + cal +qtz + pl ± kfs

4. Chloritic slate & phyllite

a. **ser** + **chl** + qtz +pl ± ab± cal

6. Graphite schist

a. **ser** + **ms**+ qtz + gr +cal± ab ±kfs

6. Micaceous Phyllite

a. **ser** + **chl+** cal +qtz + Pl + op ± cal ± bt± kfs

Keys for abbreviations of minerals' name

ser =sericite

ab=albite

chl=chlorite

ms=muscovite

cal=calcite

qtz=quartz

Pl=plagioclase

op=opaque

kfs=potassium feldspar

bt=biotite

py=pyrite

gr=graphite

These assemblages demonstrate that the rocks underwent regional metamorphism in the lower green schist facies in chlorite muscovite sub-facies.

4.4 Mineralisation and alteration

The main alteration types encountered in the studied areas associated with the different units are oxidation/limonitization, formation of goethite (FeO.OH), sericitization and carbonate alteration. Limonite (FeO.OH.nH2O) is amorphous a hydrated iron oxide. Whereas goethite is an iron hydroxide (FeO.OH) that is widespread in sediments as yellow-brown mineral and could be a weathering product of other iron-rich minerals, representing less oxidizing conditions than haematite (Fe_2O_3).The oxidation of goethite yields haematite which give the rock red color.

Carbonate alteration or carbonation is a metasomatism that involves the addition of carbondioxide (CO2), water (H2O) and potassium (K).

The alteration process and products are controlled by Rock composition, temperature and XCO2 (Poulsen, 2012).

For example,

A. epidote + actinolite + CO2 = calcite + chlorite

B. chorite + calcite + CO2 = sericite + dolomite/ankerite

On the other hand chloritization, which is commonly observed in chloritic phyllite, can be resulted from the addition MgO (+FeO).

At places the chloritic phyllite, particularly at the eastern and western part, are hard and may be silicified. Oxidation/limonitization is usually seen everywhere within all units, but it is well pronounced in subintrusive.

Regarding mineralization there exist quite good evidences that indicate the rocks in the area are mineralized. The indicators are: the occurrence of disseminated yellowish cubic oxidized minerals in the host rocks (ankarite? and /or sulphides), and the existence of abundant quartz veinlets with leached out spots/ vuges or box work structures most probably after sulphides (pyrite?). Moreover the local people (artesian miners) have been mining gold from the rivers in the area.

CHAPTER FIVE

5 ANALYSIS OF THE RELATIONSHIP BETWEEN DEFORMATION AND METAMORPHISM, AND GEOLOGICAL STRUCTURES

5.1 Time relationship between deformation and metamorphism

On the basis of the present petrographic study, the time relationship between deformation and metamorphism can be established.

Even if the metamorphic history of the lithologies exposed in the study area is a bit challenging to reconstruct confidently, attempt is made to unravel the relationship between the two events. The difficulty is largely due to the fine-grained nature of the rocks.

As discussed earlier in chapters three and four the rocks show three prominent planar structures (S0, S1 and S2). S1 and S2 developed during D1 and D2 respectively. Minerals such as sericite/muscovite, chlorite, calcite, graphite and some recrystallized quartz are formed during D1 hence they are aligned and defined S1foliations; i.e. slaty cleavage and phyllitic cleavage. Therefore, metamorphic event is considered to be contemporaneous with D1.

On the other hand some minerals like mica, graphite, and chlorite underwent rotation and perhaps recrystallization during D2 and form S2 cleavage. Hence S2 and associated lineation (intersection and crenulations lineations) are associated with D2 crenulations/ micro folds (Figs.3.2G-J & N, 3.3C&D, 3.6, 3.9, 4.3C & 4.4).

In addition, weak S2 crenulation cleavage (probably related to weak (M2) metamorphic differentiation) defined by alternating bands of felsic (quartz and feldspar) and micaceous minerals is observed in some samples (e.g. Fig.3.2J). 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 is not uncommon feature during crenulation folding.

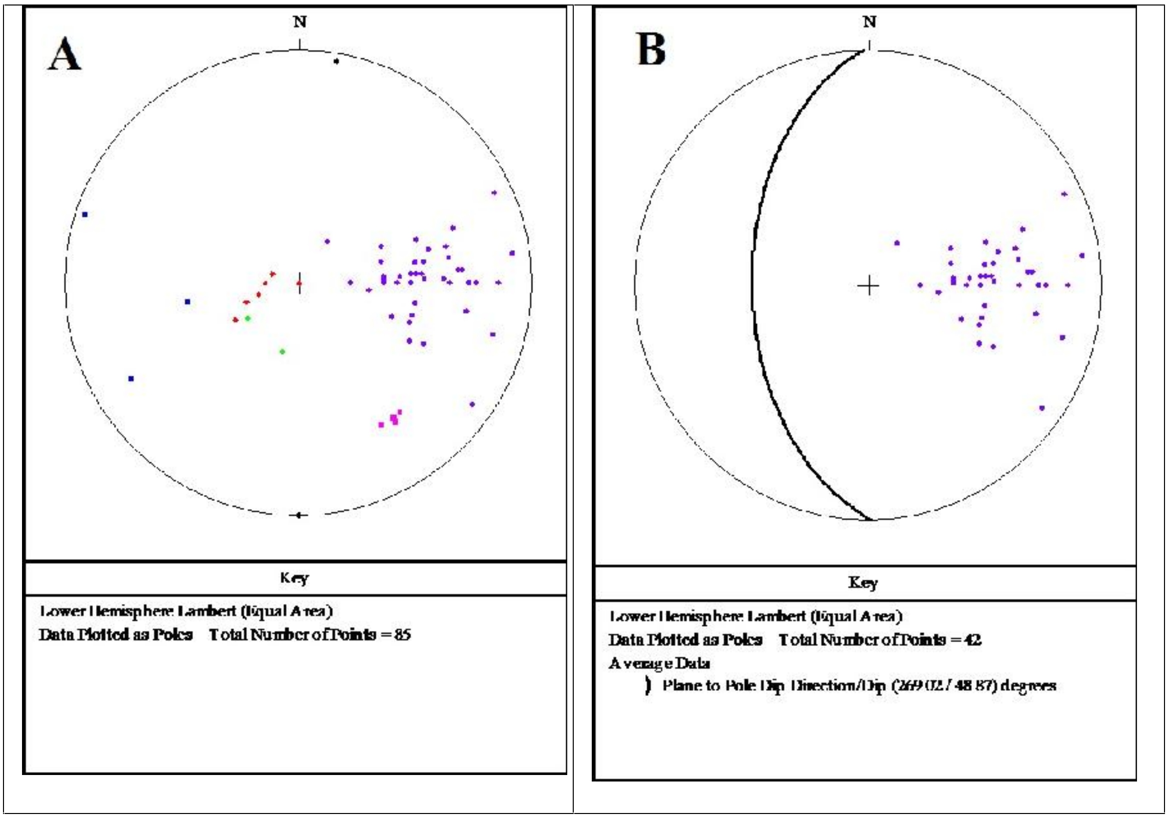
Another means to investigate the relationship between deformation and metamorphism is to study porphyroblast and foliation relationship (Passchier and Trouw, 2005).

The various phyllites in the study area are characterized by remarkable spotty appearance due to the presence of opaque porphyroblastic minerals. Most of these porphyroblasts do not show preferred orientation and simply overprint S1 (Fig.3.2A-D, G-H and M). That imply they are 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.

5.2 Stereographic projection and structural analysis

The geometrical relation among planar structural components such as foliation (S0, S1 and S2), axial plane, and quartz veinlets and joints can be evaluated and understood from the data plotted in stereographic projections (Fig.5.1).



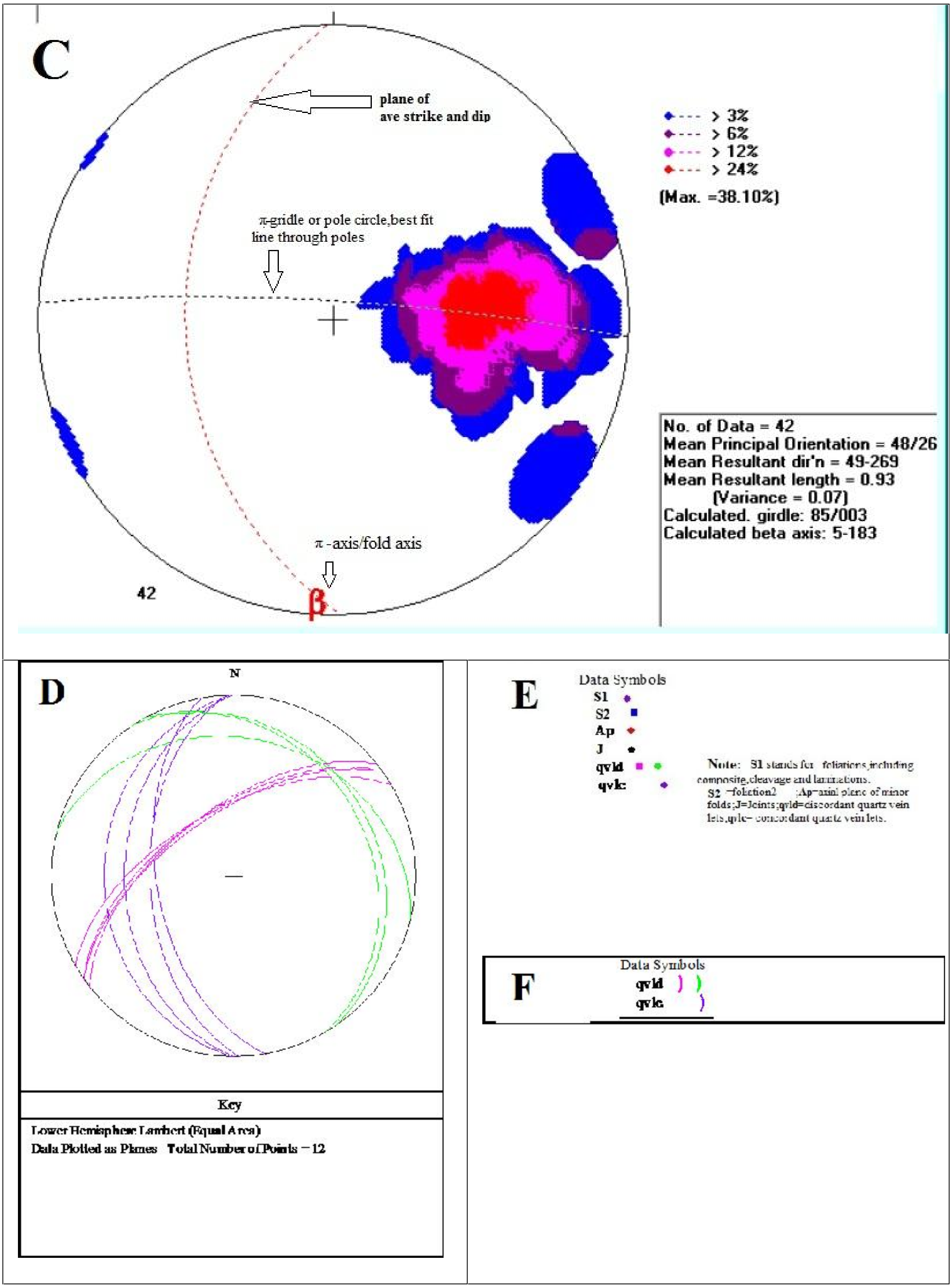

C
plane of
ave strike and dip
> 3%
> 6%
> 12%
> 24%
(Max. =38.10%)
π-gridle or pole circle,best fit
line through poles
No. of Data = 42
Mean Principal Orientation = 48/26
Mean Resultant dir'n = 49-269
Mean Resultant length = 0.93
(Variance = 0.07)
Calculated. girdle: 85/003
Calculated beta axis: 5-183
π -axis/fold axis
42
β
D
N
Key
Lower Hemisphere Lambert (Equal Area)
Data Plotted as Planes Total Number of Points = 12
E
Data Symbols
S1
S2
Ap
J
qvld
qvlc
Note: S1 stands for foliations,including composite,cleavage and laminations.
S2 =foliation2 ;Ap=axial plane of minor folds;J=Joints;qvld=discordant quartz vein lets,qvlc= concordant quartz vein lets.
F
Data Symbols
qvld
qvlc

Figure 5.1.1Plots of planar structures as poles on lower hemisphere Lambert (equal area) net.

Plate A shows the relationship and distribution of poles of various planar structures, such as S1, S2, axial planes of minor folds, quartz vein lets and joint. The poles are represented by different symbols and color see plate E for legend.
Plate B displays the plots of S1 foliation as the poles and as a plane (black line). The plane is the average value of all measured strikes and dips of foliation i.e strike N-S, dipping 49W.
C shows gridded density, mean strike, dip and dip direction of the prominent foliations (S0 & S1).It also exhibits the calculated great circle gridle or π-circle (best fit great circle/line through poles of foliations) and calculated β-axis (pole of π-circle) which represents the fold axis.
D is the plots of different quartz vein generations (three) as planes.
E and F are the keys for the symbols and shapes. E is a legend for Plates A and B; but F is key for D.

As it is shown in Fig 5.1A the poles of the 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 three different regions of the net. The poles of the dominant structural elements which include S0,S1 and the concordant quartz vein lets are generally concentrated in the eastern part of the net nearly around the half way from the centre to the primitive circle (symbolized by purplish sold diamond).

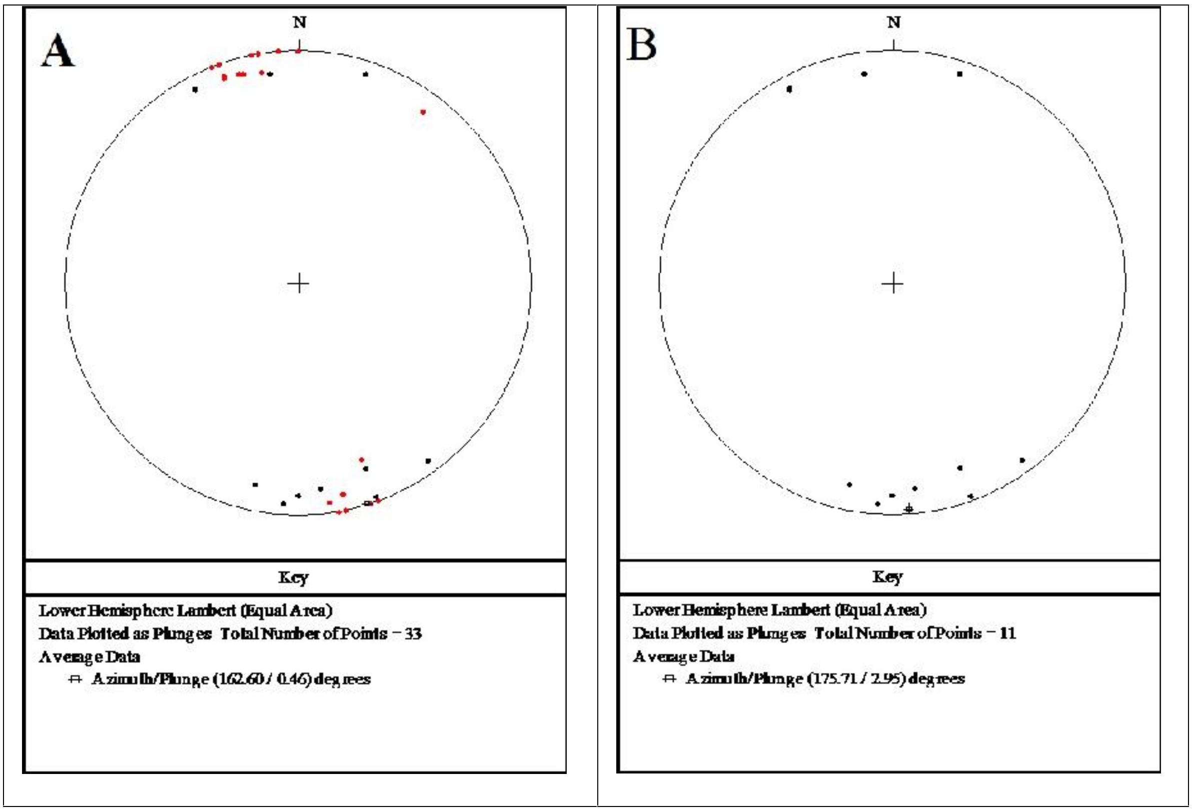
Whereas the poles of the other structures such as the axial plane of minor folds and the S2 foliation are roughly clustered in the west of the plot. Therefore these structures can be associated with the different phase of deformation (D2).

In addition the D2 fold axes and L2 intersection lineation have similar trend and plunge, as can be expected (Fig. 5.2).

The third region where the poles clustered at a single point is on the primitive circle at the southern end; this projection represents the poles of E-W striking and vertically dipping predominant joints. These joints are observed in the field that they cross cut all the exiting previous structures. Hence, they are considered as the youngest structure resulted from deformation occurred during the third phase of deformation D3.

The stereographic projection of the linear structure displays systematic clustering of points in two opposite area of the stereo net. The dominant structures are concentrated at the northern and southern region dominantly either on the primitive circle or close to it (Fig.5.2A). This implies the lineations and minor fold axes are either horizontal or shallow plunging to the north or south. However the average values of the plunges of the lineations and fold axes are almost horizontal trending generally in N-S direction (Fig.5.2A). On the other hand the projection of the minor fold axes (Fig.5.2B) indicates the majority of the fold axes plunges shallowly to south with average plunge amount of 3^0

towards 176^0.This value is nearly the same as the calculated beta axis (β-axis) with value of 5^0-183^0 (Fig.5.1C).The β-axis is the pole of the π-circle or π-gridle that represents the fold axis. π-circle or diagram is the best fit great circle through the poles of the folded surface/ foliations (Marshk and Mitra. (1988)).Therefore, it is interpreted that the β-axis represents the fold axis of the obscured major folds and the visible minor folds (Figs.4.2A & 4.5).



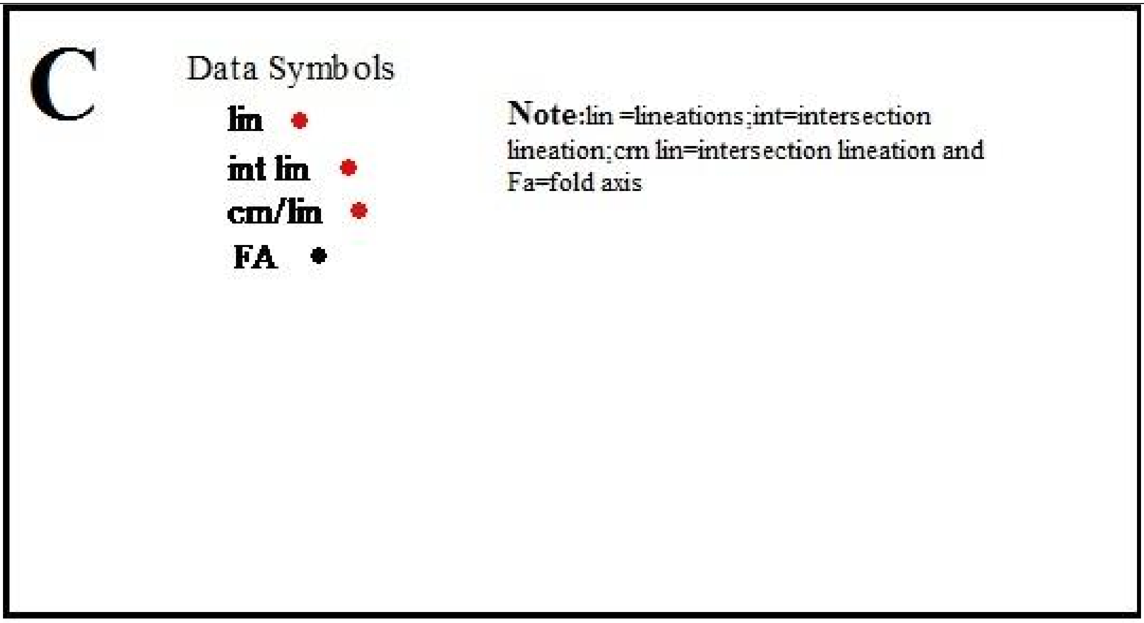


Figure 5.2 plots of all measured lineations as plunges.

A. The lineations include intersection, crenulations and fold axes.It also shows the average values of all the measured plunge i.e 0.46 toward 162 implying horizontal lineation trending SSE-NNW.

B. Depicts the plots of minor fold axes as plunges and their average. The average value indicates the minor folds plunges shallowly (~3degree) towards S.

C. Represents the key for the symbols.

CHAPTER SIX

6 CONCLUSION AND RECOMMENDATION

6.1 Conclusion

The following conclusions are made based on observation and various type of analysis made in the field, office and laboratory.

The phyllite unit in the area is not monotonous that consists a single lithology. Rather it is composed of various types of lithologies that can be detected at large scale mapping.

Spotty quartzo-feldspathic-phyllite, undifferentiated slate and phyllite, metagreywacke chloritic slate and phyllite and spotty micaceous phyllite are the mappable units; whereas, metasubintrusive, quartz rich granitods and graphite are the minor unmapple unit.

Based on the presence of certain mineral assemblages such as chlorite, albite, sericite and muscovite it is interpreted that the rocks in the area experienced low grade metamorphism that belongs to lower green schist facies. The occurrence of relict and preserved a primary structure like bedding also imply the prevalence of the low degree of metamorphism.

Regarding deformation and structures, the rock units in the study area have experienced at least three phase of deformations. These deformations caused the formation of various secondary structures.

D1 resulted in the creation of the pervasive N-S trending and west dipping secondary foliation (S1).

D2 is manifested by, folding of the foliations i.e. formation of regional scale overturned folds which are mimicked by the mesoscopic/minor folds observed in the field. In addition, D2 has also resulted locally in the formation of S2 cleavage and associated intersection and crenulation lineations.

The E-W trending and vertically dipping joints that cross cut the foliation and all lithologies are related to D3.

6.2 Recommendations

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. Larger scale mapping than the present work, like 1:10, 000, could enables to differentiate the intercalated zone.

Geochemical analysis is also recommended to identify the porphyroblastic minerals and to know exactly the protolith of the different type of metamorphosed rocks in the area.

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List of Appendix

Appendix 1 structural measurement of different structural element

No	Measured structural element	Dip	Dip direction	Location	Unit
1	S1	36	266	0535584E,1551997N	spotty qurtzo feldspathic phyllite
2	S0	42	290	0536373E,1552431N	spotty qurtzo feldspathic phyllite
3	S0	30	255	0535393E,1552198N	spotty qurtzo feldspathic phyllite
4	S0	42	286	0535393E,1552198N	spotty qurtzo feldspathic phyllite
5	S1	65	270	0535448E,1552385N	undifferentiated slate and phyllite
6	S1(cleavage)	62	270	0535818E,1552500N	slate
7	S0&S1 (composite)	55	270	0536094E,1552543N	slate
8	S1(schistosit y)	48	255	0536720E,1552467N	sericite chlt schist(slt)
9	S0&S1	25	276	0536967E,1552506N	spoty phyllite/slate
10	S1(schistosit y)	62	270	0537044E,1552607N	graph schist
11	S1	40	270	0537452E,1552485N	phy+qvl
12	S1	45	260	0535397E,1551669N	spotty qurtzo feldspathic phyllite
13	S0&S1 (composite)	42	260	0535522E,1551526N	spotty qurtz feldspathic phyllite
14	S0&S1 (composite	30	268	0535557E,1551501N	spotty qurtzo feldspathic phyllite
15	S0&S1 (composite)	60	250	0535557E,1551501N	spotty qurtz feldspathic phyllite
16	S1	42	265	0535655E,1551424N	spotty qurtz feldspathic phyllite
17	S1	35	290	0535967E,1551461N	on slate
18	S1	35	270	0536072E,1551510N	Metagrey wacke
19	S1(schistosit y)	45	268	0536146E,1551510N	Metagreywacke
20	S1(cleavage)	55	256	0536542E,1551505N	Slate
21	S1(cleavage)	40	265	0536834E,1551628N	chloritic phyllite
22	S0&S1 (composite)	75	270	0536911E,1551536N	phy+grph
23	S2 (cleavage)	86	108	0536933E,1551538N	spotty micaceous phyllite /contact zone
24	S1 (cleavage)	80	305	0536933E,1551538N	spotty micaceous phyllite/contact zone
25	S1 (cleavage)	80	305	0536933E,1551538N	spotty micaceous phyllite
26	S0&S1 (composite)	62	280	0537773E,1551509N	spotty micaceous phyllite
27	S0&S1 (composite	45	298	0535257E,1551328N	spotty qurtzo feldspathic phyllite
28	S0	75	285	0535309E,1550696N	spotty qurtz feldspathic phyllite
29	S0	32	246	0535309E,1550696N	spotty qurtz feldspathic phyllite
30	S1	30	265	0535152E,1550693N	Concordant contact b/n subintrusive and phyllite
31	S1	45	250	0535492E,1550226N	Slate
32	S1 (cleavage)	44	265	0535567E,1550196N	Slate
33	S1 (cleavage)	58	265	0536131E,1550042N	chloritic phyllite

34	S0/S1	50	296	0536160E,1550040N	Concordant contact b/n chloritic phyllite & granitoid.
35	S1 (schistosity)	18	215	0536500E,1550206N	Quartz feldspar sericite schist
36	S1 (cleavage)	55	260	0536652E,1550176N	Chloritic slate and phyllite
37	S0	55	260	0536652E,1550176N	Chloritic slate and phyllite
38	S1	82	245	0537528E,1550226N	Phyllite
39	S1	82	245	0537929E,1550724N	Concordant contact b/n subintrusive and phyllite
40	S1 (cleavage)	42	280	0537605E,1550578N	Phyllite
41	S2 (cleavage)	40	080	0537703E,1550538N	Phyllite
42	S0	18	270	0537552E,1550660N	Quartz feldspar phyllite
43	S1	82	262	0537475E,1550754N	Phyllite
44	S0	60	265	0536945E,1550798N	Slate
45	S2	72	060	537944E,15508343N	Phyllite and slate
46					
47	S3	90		0535859E,1551999N	Joint
48	S3	90		0535898E,1552060N	Joint
49	S3	90		0535420E,1552260N	Joint
50	S3	42	80	0535749E,1552495N	Joint
51	S3	90		0535749E,1552495N	Joint
52	S3	86	190	0537452E,1552485N	Joint
53	S3	90		0533522E,1551526N	Joint
54	S3	90		0535762E,1551476N	Joint
55	S3	90		0535826E,1551487N	Joint
56	S3	90		0535826E,1551487N	Joint
57	S3	90		0536072E,1551510N	Joint
58	S3	90		0536146E,1551531N	Joint
59	S3	86	190	0537452E,1552485N	Joint
60	S3	90		0536146E,1551531N	Joint
61	S3	90		0535220E,1551310N	Joint
62	S3	90		0535154E,1550416N	Joint
63	S3	90		0535492E,1550226N	Joint
64	S3	90		0535492E,1550226N	Joint
66	S3	90		0535492E,1550226N	Joint

67	S3	90		0537939E,1550720N	Joint
68	Ap	0		0536251E,1550948N	Axil plane of minor fold in slate
69	Ap	15	75	0537036E,1552607N	Axil plane of minor fold in phyllite
70	Ap	10	110	0537065E,1551773N	Axil plane of minor fold in spotty phyllite/slate
71	Ap	0		0537188E,1530948N	Axil plane of minor fold in spotty phyllite
75	Ap	12	90	0535220E,1551310N	Axil plane of minor fold in spotty phyllite
76	Ap	0		0535815E,1550122N	Axil plane of minor fold in greenish phyllite
77	Ap	20	70	0535815E,1550122N	Axil plane of minor fold in phyllite with graphite.
78	Ap	26	60	0537852E,1550637N	Axil plane of minor fold in Slate & phyllite intercalation
No	Type of structure	plunge amt	plunge direction	location	description of type
1	L_1	8	345	0535584E,1551997N	Crenulation lineation phyllite
2	L_a	7	340	0535653E,1551985N	Striation lineation in subintrusive
3	L_a	7	344	0535826E,1551980N	crenulation lineation phyllite with graphite
4	la	6	332	0535749E,1552495N	lineation in phyllite
5	La	9	350	0535818E,1552500N	Intersection lineation in slate
6	La	0	352-172	0536720E,1552467N	crenulation lineation chloritic phyllite
7	La	10	350	0536967E,1552506N	crenulation lineation in intercalation of ,slate,and phy
8	La	6	340	0536967E,1552506N	crenulation lineation in graph schist
9	La	0	348-168	0537044E,1552007N	lineation
10	La	0	338-158	0535397E,1551669N	lineation on slate and graph
11	La	0	338-158	0535512E,1551535N	intersection lineation on graphitic phyllite
12	La	10	36	0535967E,1551461N	lineation on slate
13	La	0	340-16	0536072E,1551510N	Lineation
14	La	0	350-170	0536542E,1551505N	intersection lineation
15	La	6	176	0536626E,15514788N	crenulation lineation in chloritic slate
16	La	0	355-175	0536834E,1551628N	intersection lineation grn slt/chlt sch
17	La	0	360-180	0536933E,1551538N	intersection lineation
18	La	0	354-170	0535257E,1551328N	intersection lineation
19	La	0	348-168	0536160E,1550040N	crenulation lineation in chloritic slate
20	La	20	160	0537852E,1550637N	intersection Lineation
21	La	0	350-160	0537703E,1550538N	intersection lineation phyllite
22	La	5	172	0537475E,1550754N	intersection lineation in phyllite
23	La	8	168	0537269E,1550754N	Striation lineation in applite
No	Fold axis	Plunge amut	Plunge dire	location	
1	F2	16	160	0537852E,1550637N	

2	F2	2	160	0535815E,1550122N	
3	F2	12	192	0535815E,1550122N	
4	F2	5	184	0535366E,1550261N	
5	F2	9	180	0535220E,1551310N	
6	F2	6	144	0537188E,1530948N	
7	F2	6	18	0537065E,1551773N	
8	F2	10	352	0537036E,1552607N	
9	F2	7	332	0536251E,1550948N	
10	F2	6	332	0535749E,1552495N	
11	F2	12	174	0537118E,1552426N	