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ADDIS ABABA UNIVERSITY  
COLLEGE OF NATURAL SCIENCES  
SCHOOL OF EARTH SCIENCES

DIFFERENTIATING STRUCTURES AND LITHO-UNITS OF THE TSALIET  
GROUP AROUND NEGASH AREA, TIGRAY, NORTHERN ETHIOPIA

BY:

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## ABSTRACT

The present study investigates the geology across an area of about 28 km<sup>2</sup> in the vicinity of Negash village, Tigray, Northern Ethiopia. The investigation has been carried out petrographical and geochemical properties of volcanic rocks in the area. Field and laboratory works have revealed that the study area comprises dominantly low-grade schistosed metavolcanics and pyroclastics belonging to Tsaliet Group exposed in the western limb of Negash syncline. This contribution aimed to study and differentiate the Negash Tsaliet Group and map, and to present the salient micro-structural analysis of this Group. The mapped units are characterized by volcanic origin protoliths. Based on petrographic description, this Tsaliet Group of the area was affected by three prominent metamorphic episodes referred to as M<sub>1</sub>, M<sub>2</sub>, and M<sub>3</sub>. Further, field observation and petrographic description provided detailed information on the relative timing of deformation, which is as follows: (1) an early deformation stage (D<sub>1</sub>) followed by (2) D<sub>2</sub> stage and 3) brittle phase (D<sub>3</sub>). D<sub>1</sub> and D<sub>2</sub> are associated with low-grade greenschist facies metamorphism. The timing relationship between metamorphic and deformational events is also deciphered as follows: the regional metamorphism (M<sub>1</sub>) accompanied an early Pan-African stage (D<sub>1</sub>) and M<sub>3</sub> metamorphism associated with D<sub>2</sub> deformation stage. However, M<sub>2</sub> is contact metamorphism associated with local pluton. The ductile deformation phases D<sub>1</sub> and D<sub>2</sub> are associated with low-grade greenschist facies metamorphism. A brittle stage (D<sub>3</sub>) is responsible for the emplacement of granitic veins, faults and joints. D<sub>1</sub> tectonic seem to be the main deformation style in the area, which developed the dominant schistosity (S<sub>1</sub>), regionally persistent in the terrain.

The geochemical interpretation presented in this study has been used to decipher the tectonic evolution of metamorphic rocks of Negash study area. Rocks of intermediate to rhyolitic composition in Negash Tsaliet Group show calc-alkaline trends of evolution as confirmed by the chemical classification on various plots of geochemical data. On tectonic discrimination diagrams, the overall geochemical characteristics of Negash metavolcanic rocks provided evidence indicating that the area is most likely represents a part of volcanic island-arc tectonic setting. The field characteristics, petrography and geochemistry of Negash Tsaliet are similar to those of volcanic arcs described elsewhere in Northern Ethiopia.

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## CHAPTER- ONE

### 1. INTRODUCTION

#### 1.1. PREAMBLE

The East African Orogen (EAO) (Stern, 1994) consists of deformed and metamorphosed rocks of the low grade Arabian-Nubian Shield in the north and higher grade and more strongly deformed rocks of Mozambique Belt in the southern half (e.g. Stern, 1994; Kroner and Stern, 2004). These fragments of Neoproterozoic rocks now exposed in the Arabian, African, Madagascar, and Indian Plates once they were intact until the dispersal of Gondwana in the Early to Middle Jurassic (Johnson et al., 2011).

The Precambrian rocks of northeast Africa and western Arabia is called the Arabian-Nubian Shield (ANS). It is predominantly composed of juvenile continental crust materials that were formed when smaller arc terranes were generated within and around the margins of a large oceanic tract known as Mozambique Ocean, associated with closure of the ocean basin due to subduction (Stern, 1994). These juvenile numerous intra-oceanic arc/back-arc crusts collided and coalesced to form larger composite terranes through accretion during the Neoproterozoic Pan-African orogeny (Stern, 1994; Asrat et al., 2001; Johnson and Woldehaimanot, 2003; Kroner and Stern, 2004) prior to the collision between east and west Gondwana to form Greater Gondwanaland (Stern, 1994; Miller et al., 2009), and is the largest tract of juvenile continental crust on Earth (Patchett and Chase, 2002 as cited in Stern et al., 2004 and Johnson et al., 2011). Due to collision between east and west Gondwana the arc terranes were then tectonically thickened. The timing of the collision between east and west Gondwana thought to have occurred after ~ 630 Ma when deformed dykes were emplaced in southern Israel but before the ~ 610 Ma post-tectonic Mereb granites were emplaced in northern Ethiopia, but precise timing is still being resolved (Kroner and Stern, 2004). Older crusts occur at the flanks of ANS (e.g. see Teklay et al., 1998).

The ANS can be subdivided into northern and southern halves. In the northern ANS, it is relatively easy to identify structures such as pillowed basalt and such excellent preservation of earlier structures largely reflects the fact that these northern ANS are relatively less obscured during terminal collision between east and west Gondwana (Stern et al., 2004; Johnson et al., 2011). In contrast to northern ANS, deformation

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associated with terminal collision is more intense in the southern ANS and the intensity of this deformation has made a greater challenge to identify ophiolites to the southern ANS of Eritrea, Ethiopia, and southern Arabia. This area was closer to and thus more intensely affected by the end- Neoproterozoic terminal collision because the ANS is narrower in the southern part and wider in northern part, such that structures related to ophiolite obduction are transposed or obliterated (Abdelsalam and Stern, 1996; Kroner and Stern, 2004; see Fig. 1.1), and the whole succession is metamorphosed to greenschist or amphibolite facies (Stern et al., 2004). This argument supports the view of Stern (1994) who postulated the formation and subduction of large areas of oceanic crust in the north part but little in the south.

An understanding of the geodynamic evolution of the Precambrian basement of Ethiopia will help to better understand the evolution of the East African Orogen as exposures of the greenschist-facies juvenile volcano-sedimentary sequences of the Arabian-Nubian Shield and the high-grade Mozambique Belt join in the country (Kazmin, 1973; Kazmin et al., 1978; Miller et al., 2003; Yibas et al., 2003; Avigad et al., 2007).

The Precambrian rocks of Ethiopia outcrop in four major regions around the plateau margins (Fig.1.2): in the north (Tigray), in the west/southwest (Gojjam, Wollega, Illubabor and Kefa), in the south (Sidamo & Bale) and in the east (Hararghe) (Kazmin, 1973; Mengesha et al., 1996). The general tectonostratigraphic classification-- Lower, Middle and Upper Complexes (Kazmin, 1973; Kazmin et al., 1978)-- for the Precambrian of Ethiopia has long been in use, even if it was based mainly on metamorphic grade and structural complexities. Following geochronological studies of Ethiopia (e.g. Teklay et al., 1998; Yibas et al., 2002 and review in Asrat et al., 2001) however, the validity of this classification which suggested an occurrence of Archean gneisses in the Precambrian of Ethiopia has been challenged recently.

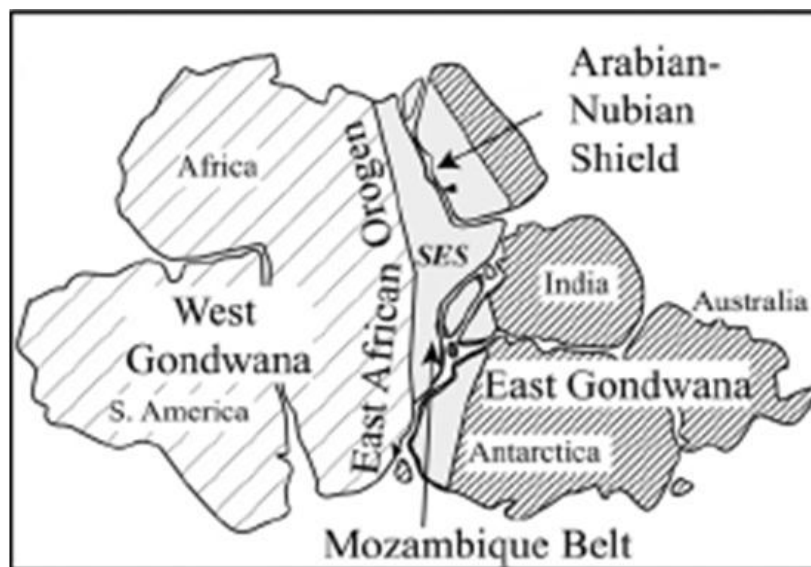


Fig.1.1. Location of the East African Orogen at the juncture between East and West Gondwana, reconstructed prior to the Jurassic and younger rifting. **SES**- Southern Ethiopian Shield (Stern et al., 2012).

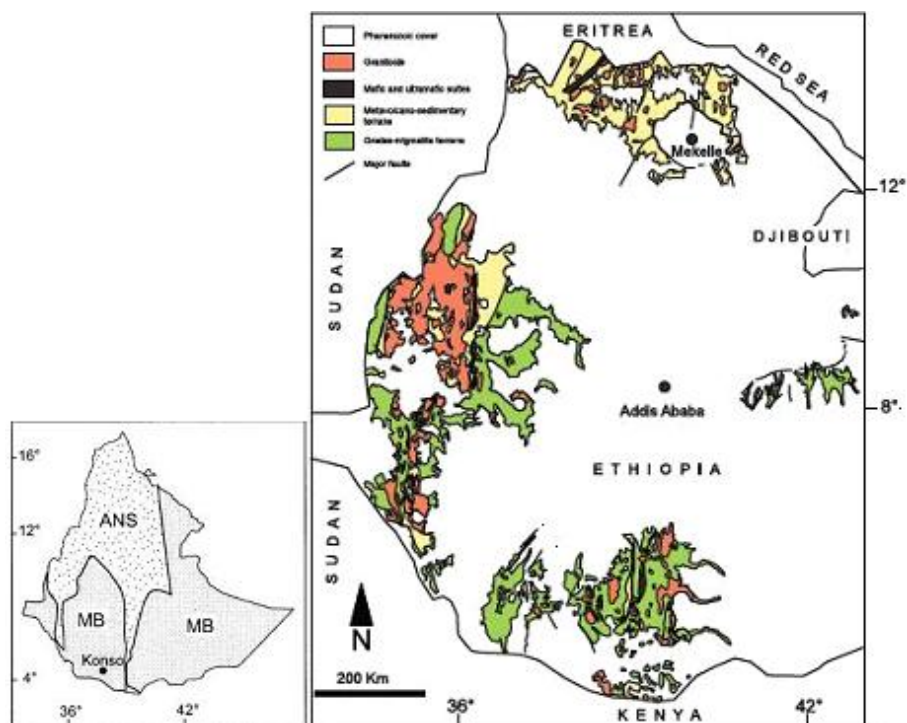


Fig.1.2. (Right) generalized geological map showing the spatial distribution of Ethiopian Precambrian rocks (modified from Asrat et al. 2001 as cited in Gebresilassie, 2009), and (left) map showing the proposed boundaries between the ANS to the north and the MB to the south in Ethiopia and Eritrea (Asrat and Barbey, 2003).

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## **1.2. LOCATION OF THE STUDY AREA**

The area of study around Negash is located about 55 km north of Mekelle on the way to Adigrat in Tigray region, northern Ethiopia. It is situated between 560000E to 565300E and 1530400N to 1538000N and it covers an area of about 28km<sup>2</sup>.

## **1.3. ACCESSIBILITY AND PHYSIOGRAPHY OF THE STUDY AREA**

The area is accessible through a main asphalt road from Mekelle to Axum. There are also all-weather motorable road crossing the area. Throughout the study area there is a good network of foot trails connecting the various settlement and villages; these serve as a traversing routes in the area.

The Negash study area is part of the Tigray plateaus. Large part of the area is characterized by moderately rugged topography and is bounded by E-W Wukro fault in the south (Beyth, 1972; Bheemaligeswara and Tadesse, 2009). On the western part it is bounded by a granodioritic body and is marked with a clear intrusive relationship with the surrounding rocks.

The interest area is one of the sparsely vegetated areas in the region. The principal vegetation covers of the area are sparse shrubs, thorn bushes, and deciduous trees such as acacia.

The study area is characterized by semi-arid climatic condition. The area has a mean annual rainfall of 600mm, and the monthly mean temperature values are usually within 20<sup>0</sup>C to 25<sup>0</sup>C (Garland, 1980).

The main stream in the area of study is May Demba, flowing almost along the strike of the regional foliation. Native habitants of the area are Tigrigna speaking people, and most of them are farmers. Peoples' lives depend on small scale agriculture and domestic animals breeding- cattle, goat, sheep, and donkey. They grow corn, teff, barley, dagussa, sorghum, and wheat.

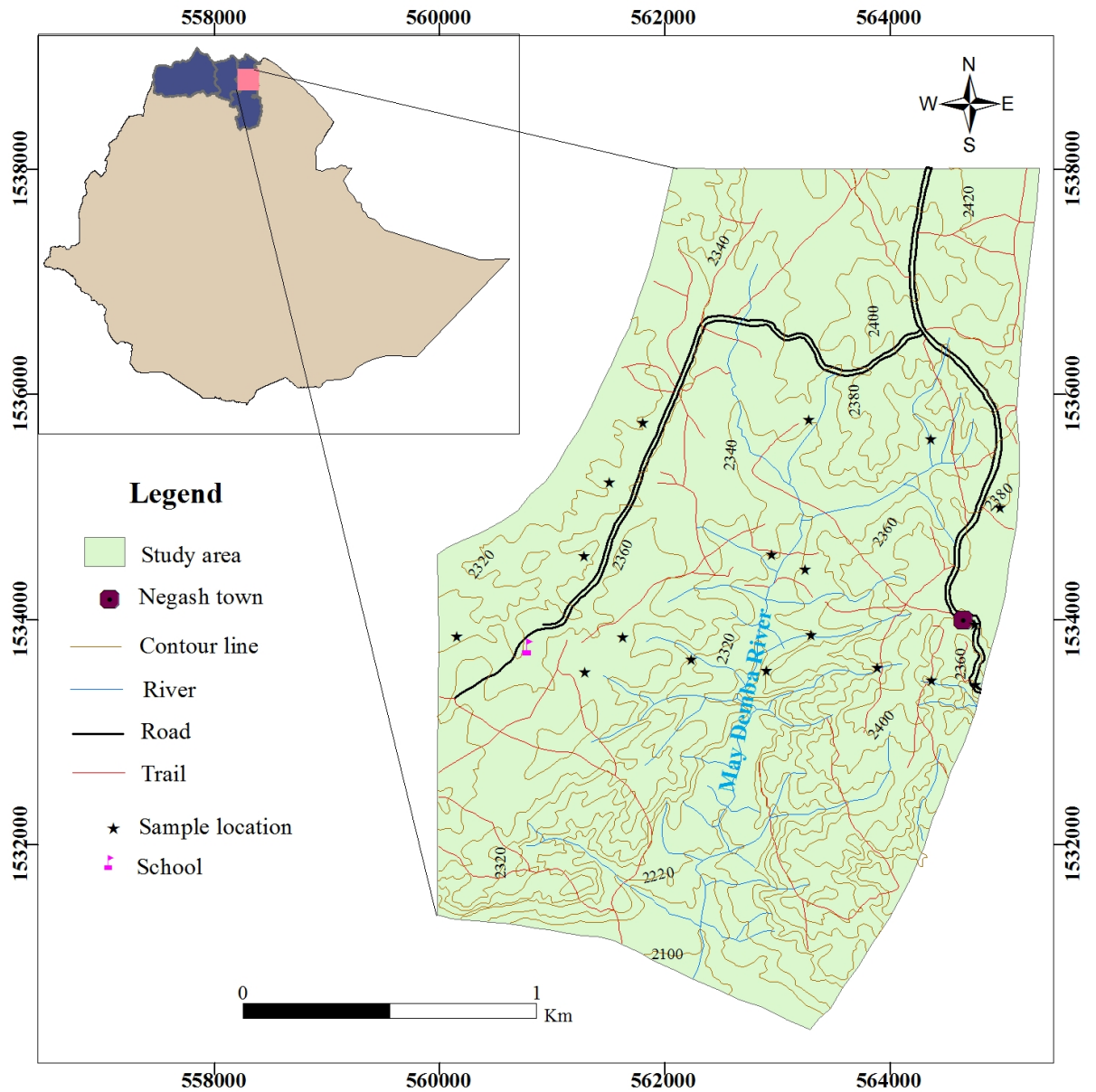


Fig.1.3. Location map of the study area

#### 1.4. SIGNIFICANCE OF THE PRESENT STUDY

Even though the metamorphic terrane of northern Ethiopia has been studied before, often at smaller scale, the existing data seems to justify further work at a larger scale. In this study, a new large-scale (1:25,000) map showing and differentiating the Tsaliet Group rocks of the western limb of Negash synclinorium is presented together with petrographical and geochemical data for selected rock samples. This new result of geological mapping may

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complement the existing structural and stratigraphical data of the area making a significant contribution to decipher the tectonic history of the Precambrian of northern Ethiopia in general, Negash synclinorium in particular.

## **1.5. OBJECTIVE OF THE STUDY**

### **1.5.1. GENERAL OBJECTIVE**

A principal goal of this study is to differentiate Tsaliet Group in the Negash study area to better understand the regional geologic history of the Neoproterozoic metavolcanics. Although different authors at different times confirmed the occurrence of low-grade Tsaliet metavolcanics in northern Ethiopia, yet the Tsaliet Group in Negash synclinorium of the study area has not been differentiated, hence the present study account to differentiate Tsaliet metavolcanics based merely on field observations, petrographic and limited geochemical studies.

### **1.5.2. SPECIFIC OBJECTIVES**

- ❖ To map a large scale geological and structural map of the Tsaliet Group of the Negash area (at 1: 25,000 scale)
- ❖ To describe the lithology and petrography of the various rock units
- ❖ To differentiate the deformation and metamorphic phases of the area
- ❖ To study the metamorphic texture and microstructures and infer the relative timing between deformation and metamorphism
- ❖ To reconstruct the stratigraphy of the Tsaliet Group rocks
- ❖ To analyze the geochemistry of the metavolcanic rock units and discriminate their probable tectonic setting in light with the evolution of the Arabian-Nubian Shield

## **1.6. METHODS OF STUDY**

The study has been conducted using data obtained from the literatures, as well as several field data and laboratory analyses.

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### **1.6.1. PRE-FIELD WORK**

Literature review and aerial photo interpretation were the core methods that have been employed during pre-field work. The literature review included published papers and unpublished reports.

### **1.6.2. FIELD WORK**

Field work has been carried out for a period of 15 days. Several selected traverses were made throughout the area and forty seven (47) rock samples were collected from different lithological units. The contact relations among the rock types are not obliterated by metamorphism and deformation, hence, integration of obvious lithological difference, metamorphic extents, field appearance (color, textures) and structural styles (by taking different structural measurements) have been used to identify and classify the rock succession into different units. The geologic information gathered from the ground is then mapped using topo maps.

### **1.6.3. POST- FIELD WORK**

Laboratory studies include: (1) the detailed petrographic and fabric/microstructural examination of 22 thin sections of metamorphic rocks under polarizer microscope in order to understand the metamorphic conditions of each deformation, and to support and/or control the results of structural analysis carried out during field studies; (2) geochemical analysis.

#### **1.6.3.1. THIN-SECTION PREPARATION**

Twenty two (22) rock samples were chosen and sliced to prepare rock thin sections at the School of Earth Sciences, Addis Ababa University, for petrographic studies using Leica petrographic microscope. The sections are all cut perpendicular to the main foliation in the rock sample.

#### **1.6.3.2. GEOCHEMISTRY ANALYTICAL PROCEDURES**

Fifteen (15) selected rock samples were pulverized using a rotary Automatic Swing mill (MG 183) in the School of Earth Sciences, Addis Ababa University. Geochemical analysis that includes major, trace and rare earth elements has been carried out on representative samples from different lithological units by inductively coupled plasma mass spectrometry (ICP-MS) technique at Activation Laboratories Ltd., Ancaster, Ontario, and the results have been used

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to constrain the tectonic setting of the metavolcanic rocks. Precision is generally on the order of 1% of the amount present.

### **1.6.3.3. SOFTWARE ANALYSIS**

Stereographic projection software (GEOrient, version 9.5 software) has been used to quantitatively represent three-dimensional orientation data (such as the attitudes of lines and planes) on a two-dimensional plot to analyze the structural data and visualize the connection between the orientations of structures in the field or on the map and the complex patterns of lines/planes plotted on the stereonet.

Field information was compiled using ArcGIS software to generate the detail geological map at scale of 1:25,000, which shows lithological units, major geological structures, stratigraphic sequences and foliation orientation.

## **1.7. REVIEW OF PREVIOUS GEOLOGICAL WORKS**

Different authors described the Precambrian geology of Ethiopia, the stratigraphy, the protolith rocks (whether they are originated from sedimentary or volcanic rocks) and they also classified the basement rocks. Significant progress in understanding the northern Ethiopia, for which no geological maps at scales greater than 1:250, 000 (e.g. Beyth, 1972) exist, has been made in the past half century. The study of different authors introduced the various rock units and documented valuable information about the geology of the study area. The general stratigraphy of northern Ethiopia first compiled in the Mekelle map sheet, which includes the present study area, by Arkin et al. (1971) and three main rock complexes were identified in the region: low-grade metavolcanic and metasediments rocks overlain by Paleozoic and Mesozoic sediments and Tertiary Trap basalts. Kazmin (1973) compiled his observation and the results of other workers in the 1:2,000,000 geological map of Ethiopia. The stratigraphy of the Neoproterozoic low-grade basement rocks of north Ethiopia was described by Levitte (1970), Beyth (1972), Garland (1980) and also other geologists from the Ethiopian Institute of Geological Survey (e.g. Tadesse, 1997). The basement rocks in northern Ethiopia were grouped under an Upper complex division of the three fold classification of Ethiopian basement rocks, based on metamorphic and structural complexities (Kazmin 1973; Kazmin et al. 1978). The geologic framework of Neoproterozoic time in Tigray is known in greater detail from four geologic maps of 1:250,000 scale produced by the

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Geological Survey of Ethiopia: namely the Mekelle (Arkin et al., 1971), the Adi Arkay (Hailu, 1975), the Adigrat (Garland, 1980), and the Axum (Tadesse, 1999) sheets. With the exception of the Axum sheet, the maps and the general tectonostratigraphic successions were established long before having the understanding of the tectonic processes responsible for the formation of the ANS. Several research has been conducted on the Precambrian rocks of the Mai Kenetal, Hawzien and Negash areas by Beyth (1972), Beyth et al. (2003), Asrat (1997), Asrat et al. (2001, 2003), Alene (1998), Alene and Sacchi (2000) and Alene et al. (2000, 2006). Most of these studies focus on understanding the mode of formation, age and evolution of the rocks in the areas. The previous workers identified and mapped extensive low grade Precambrian basement comprising metavolcanics, metavolcaniclasts, metasediments and intrusives of varied composition in northern Ethiopia. Beyth (1972) and Garland (1980) broadly subdivided the basement rocks of the ANS in the Tigray region into two major stratigraphic groups (Fig.1.4): (i) the lower Tsaliyet Group, and (ii) the upper Tambien Group. It was Beyth (1972) who originally named the today's Tsaliyet Group. The Tsaliyet Group in northern Ethiopia has been studied by various geoscientists. The rock units in this Group is dominated by metavolcanics and metavolcaniclastics units and the overlying Tambien Group consists of shallow marine metasedimentary succession of slates, phyllites, greywacke and carbonates (Beyth, 1972; Kazmin, 1973; Tadesse, 1996; Alene, 1998; Beyth et al, 2003). According to petrographic study and results of previous investigators (e.g. Beyth, 1972; Tadesse, 1997; Tadesse et al., 1999), it is concluded that the parent rocks of the Tsaliyet metavolcanics of northern Ethiopia were volcanic rocks with minor sedimentary intercalations.

Tsaliyet Group had already been sub-divided into: the lower metavolcanic flow and the upper metavolcaniclastics/pyroclastics (Beyth, 1972) which together form the largest unit in northern Ethiopia (Beyth, 1972; Tadesse, 1996). The Tsaliyet metavolcanics occur in the Tsae anticlinorium, east of Mai kenetal synclinorium, Bereh anticlinorium, west of Negash synclinorium, Atsbi Horst and in most of the escarpment area around Berahle (Beyth, 1972). In addition, as Beyth (1972) noted the Tsaliyet metavolcanics of the northern Ethiopia occupy anticlines and the Tambien Group occupies synclines. The geochemical characteristics of metavolcanic rocks in the northern Ethiopia-Adi Hageray block, Adi Nebrid block, Zager

mafic–ultramafic belt, and Adwa block metavolcanics by Tadesse et al. (1999); Mai Kenetal-Negash area by Alene et al. (2000); Werri area by Sifeta et al. (2005)- have been investigated. A geochronological work for the metavolcanics of northern Ethiopia was already available by different authors (Miller et al., 2003; Asrat et al., 2004; Avigad et al., 2007). Maximum age of the Tambien Group is estimated to be 740–850 Ma based on the age of syn-tectonic Tsaliet granites which were related to Tsaliet arc related igneous activity (Avigad et al., 2007). Tsaliet Group metavolcanic rocks of Ethiopia and similar rocks in Eritrea are constrained to ~800–854 Ma (Teklay, 1997 in Miller et al., 2003). Tadesse et al. (2000) argued that the consistency in ages from Ethiopia and Eritrea indicated a similar arc setting between 750 and 850 Ma. Isotopic data suggest that all of similar sequences in Eritrea, Ethiopia and Sudan are Neoproterozoic additions of juvenile continental crust (Avigad et al., 2007). De Souza Filho and Drury (1998) also noted that the dominant rocks in the largest Nakfa Terrane of eastern Eritrea are greenschist-facies metavolcanic rocks and volcanoclastic sediments. On the whole, the Precambrian crust of northern Ethiopia is part of the southernmost sector of the Arabian-Nubian Shield (Alene, 1998; Tadesse et al., 1999; Asrat et al., 2001; Avigad et al., 2007; Miller et al., 2003, 2009).

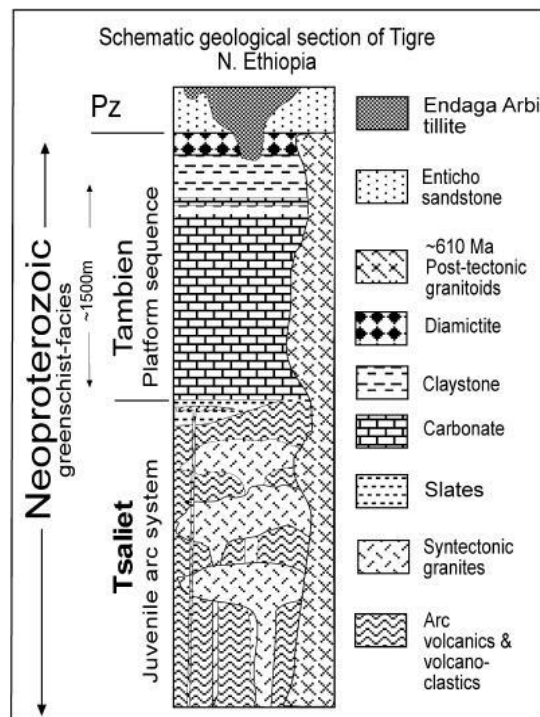


Fig.1.4. Generalized schematic geologic columnar section of northern Ethiopia, Tigray region showing main rock units and the relation of Neoproterozoic section with syn- and post-tectonic granitoids (Avigad et al., 2007).

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## CHAPTER TWO

### 2. REGIONAL GEOLOGY

#### 2.1. REGIONAL GEOLOGIC SETTING

The Arabian–Nubian Shield is northern part of the East African Orogen formed in late Proterozoic (900–550 Ma) by accretion and amalgamation of oceanic and continental magmatic arcs during subduction and obduction of oceanic crust, and the closure of Mozambique Ocean, suturing East and West Gondwana (Stern, 1994; Rogers et al., 1995 in Stern, 2002). The deformation sequence-arc accretion--terminal collision--tectonic escape- indicates that the Mozambique Ocean closed to form Greater Gondwanaland around 640-700 Ma (Stern, 1994).

ANS contains many remnants of oceanic crust in the form of ophiolites in addition to low-grade assemblages of volcanic, volcano-sedimentary and sedimentary units, intrusives (Stern, 1994; Abdelsalam and Stern, 1996; Tadesse, 1996). The ANS cover over a distance of ~3000 km from the farthest north almost to the equator, and >1000km from the west to the east, encompassing an area of about two million square kilometers (Stern et al., 2004). The ANS is interpreted in terms of Wilson Cycle plate tectonics-progressing from rifting to sea-floor spreading and subduction-with the following stages of evolution (Stern, 1994; Abdelsalam and Stern, 1996; Kroner and Stern, 2004; Stern and Johnson, 2010 cited in Johnson et al., 2011) (see also Fig.2.1):

- 1) Rifting of super-continent Rodinia at ~900-850Ma lead to formation of Mozambique oceanic basin
- 2) Between ~870-630Ma sea-floor spreading begins and the created intra-oceanic arc/back-arc basin were accreted together to form juvenile crust in ANS resulting in arc-arc suture formation that are aligned east to NE in the northern ANS and north to NE in the south.
- 3) The closure of Mozambique ocean led to shortening in ANS due to its collision with the two fragments of the Gondwanaland between ~630-600Ma.
- 4) The continuation of oblique collision of east and west Gondwana resulted in crustal shortening and escape tectonics of ANS along the northern EAO between ~600-550Ma.

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Gondwanaland was assembled by oblique subduction of oceanic lithosphere between crustal blocks, including the Mozambique Ocean between West and East Gondwanaland (Kazmin et al., 1978; Shackleton, 1986; De Wit and Chewaka, 1981 in Worku and Schaldelmeier, 1996; Tadesse, 1997; Veevers, 2003; Alemu and Abebe, 2007). During closure of Mozambique Ocean basin, in Arabian-Nubian Shield there were variable subduction zones dipping in different directions which are now preserved as variably dipping suture zones in terrane complexes. Such zones include East or SE- dipping subduction zone in Saudi Arabia; SE or W dipped subduction zone in Sudan (Vail, 1983; Shackleton, 1986); eastward subduction zone in eastern Ethiopia and Somalia (Kazmin et al., 1978; Shackleton, 1986); east-directed subduction of oceanic lithosphere in west Ethiopia (Kazmin et al., 1979 cited in Alemu and Abebe, 2007); westward subduction in southern Ethiopia (Worku and Schaldelmeier, 1996); SE dipping subduction zone of the Tullu-Dimtu Belt (Alemu and Abebe, 2007); westward (Shackleton, 1986) and southeast (Tadesse, 1996) dipping subduction zones in northern Ethiopia and an east-dipping subduction zone along the Barka suture in Eritrea noted by Drury and Berhe (1993) as cited in Alemu and Abebe (2007). Moreover, there are terranes which exhibit subduction zones dipping in the same direction across the Red sea i.e. in western Nubian Shield and the Arabian Shield part of the ANS. E.g. Haya terrane of Nubian Shield has similar lithology and correlable to Jiddah terrane of Arabian Shield, and both have SE dipped subduction zone (Johnson and Woldehaimanot, 2003). In general, one can understand from these that ANS was formed by a collage of numerous island-arc/back-arc terranes during EAO as a result of intra-oceanic subduction-related arc-arc and ultimately arc-continent collisions (Johnson and Woldehaimanot, 2003; Avigad et al. 2007; Johnson et al., 2011).

Within the Neoproterozoic time there were two major phases of igneous activities that thought to have been responsible for the crustal growth of ANS of northern Ethiopia: the older phase was at ~820-760 Ma and related to juvenile crustal growth due to closure of ocean basins by subduction, and the younger phase occurred at 620-580 Ma and was related to crustal thickening and collision of East and West Gondwana (Avigad et al., 2007 and see Fig.2.1). During or after inactive phase of island- arc magmatism, shallow marine siliciclastic and carbonate sedimentation of Tambien Group occurred after the syn-tectonic intrusives (Tsaliet granitoids) and the Tsaliet Group metavolcanics were produced during the first island

arc volcanic phase (Beyth, 1972; Kazmin, 1973; Tadesse et al., 1999; Alene et al., 2006; Avigad et al., 2007). However, a swarm of late-tectonic intrusives termed ‘Mareb’ granitoids dated to 600–620 Ma (Miller et al., 2003, 2009; Asrat et al., 2004) were generated by the second phase of post-Tambien Group magmatism associated with thickening and orogeny related to Gondwana assembly, and they pierced the whole deformed Tsaliet-Tambien complexes (Beyth, 1972; Kazmin, 1973; Alene, 1998; Avigad, 2007 and see Fig.1.4). These timing of magmatism well augment the recent works in the Axum area of northern Ethiopia by Tadesse et al. (1999) and (2000) cited in Avigad et al. (2007) yielded ages for arc-related magmatism between 740 and 820 Ma and post-orogenic magmatism at ~550 Ma. The absence of interleaved metavolcanics/volcaniclastics from the Tambien carbonate indicates that during the formation of Tambien Group, island arc volcanism was culminated or inactive (Avigad et al., 2007). In addition, chemical weathering indices in thick slate of the lower Tambien Group also indicate the Tsaliet Group arc accretion complex underwent intensive weathering prior to carbonate deposition (Miller et al., 2009), so presumably Tambien Group unconformably overlying the Tsaliet Group. In general, the Neoproterozoic Tsaliet Group metavolcanics and the metasediments of Tambien Group of northern Ethiopia accumulated in marine environments of Mozambique Ocean which was closed by subduction process generating numerous island arc systems (Tadesse, 1997; Avigad et al., 2007; Miller et al., 2009).

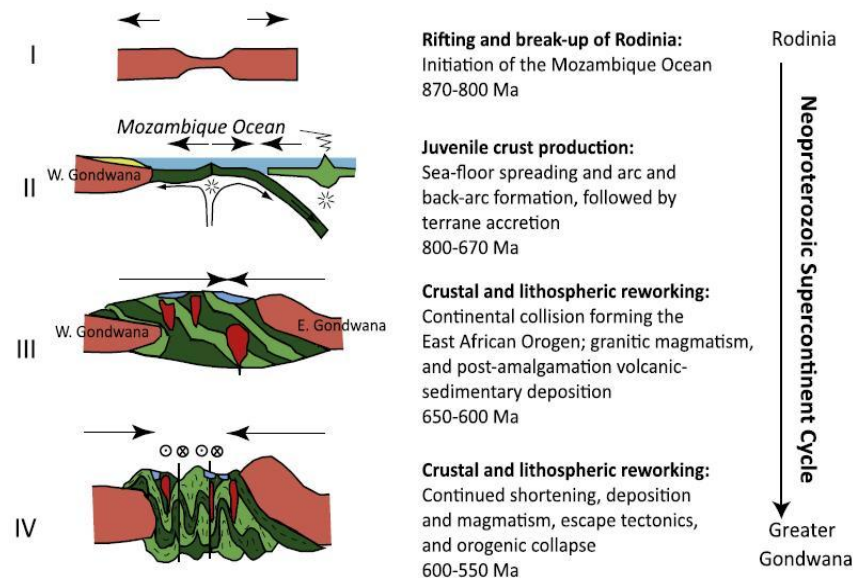


Fig. 2.1. A schematic diagram of the suggested stages of tectonic evolution of the Arabian-Nubian Shield (after Stern and Johnson, 2010 cited in Johnson et al., 2011).

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The litho-geochemical diversity of the Neoproterozoic metavolcanics of northern Ethiopia has been associated with their formation in a wide variety of paleo-tectonic settings (Tadesse et al., 1999). Tadesse et al. (1999) suggested a development of metavolcanics of the region by lateral accretion of oceanic island arcs that might have formed far apart from each other with contrasting chemistry from west to east. Accordingly, a supra-subduction zone setting of Adi Hageray block, Zager belt and Adi Nebrid block in the west might have formed island arc tholeiitic basalts during the early stages of subduction, whereas the distinct occurrence of the eastern Adwa calc-alkaline metavolcanics in island arc setting suggests its development in a more advanced stage of arc evolution. The chemical similarity between the Adwa metavolcanics and the volcanic units in the Maikenetal-Negash area and elsewhere in Sudan, Egypt and Saudi Arabia imply a widespread generation of calc-alkaline magma in a volcanic arc setting in the ANS (Alene et al., 2000). In addition, geochemical study conducted by Sifeta et al. (2005) in the Werri metavolcanics of northern Ethiopia depicts the calc-alkaline island arc volcanic similar to the neighboring Adwa metavolcanics and also comparable with that of Nakfa terrane in eastern Eritrea (Drury and De Souza Filho, 1998). Therefore, the Tsaliet Group of Negash area in northern Ethiopia forms the southern extension of the Nakfa terrane of Eritrea formed of metavolcanics and metavolcanoclastic sediments (Tadesse et al., 1999; Alene et al., 2006; Miller et al., 2009).

## **2.2. NORTHERN ETHIOPIA REGIONAL TECTONIC STRUCTURE**

The subsequent closure of oceanic basin and final collision of the two Gondwana fragments formed collisional zone (Stern, 1994; Abdelsalam and Stern, 1996) and this gave rise to later phase of deformation which is recorded both in Tsaliet and Tambien Groups of northern Ethiopia (Alene, 1998). The Proterozoic rock units in northern Ethiopia experienced at least two major structural episodes (Alene, 1998; Alene and Sacchi, 2000; Sifeta et al., 2005; Alene et al., 2006; Avigad et al., 2007). Earlier N–S compression ( $D_1$ ) accompanied with E–W trending minor recumbent folds (cm to dm scale wave length) ( $F_1$ ), stretching lineation and pervasive regional foliation. Later E–W directed shortening ( $D_2$ ) in association with end-phase collision between East and West Gondwana manifested by upright folding, thrusting and lateral displacements, in which Negash synclinorium is one of the structures. The later E–W directed phase of ductile deformation refolded and reoriented earlier tectonic structures ( $D_1$ ) along SW trending sub-horizontal fold axis to produce large upright open to tight folds.

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According to those authors, the present attitude of Negash fold, which show sub-horizontal plunges, is the result of D<sub>2</sub> deformation. Negash syncline is an overturned fold, with the fold axis aligned parallel to the foliation direction, which is roughly NE-SW. The fold is plunging southwestward by about 15° and terminates at the major Wukro fault (Beyth, 1972). Miller et al. (2009) also described this structure as an elongate (5 km wide×30km long) SW-plunging, west dipping, slightly overturned synclinorium.

The predominant foliation structures trend NE-SW that developed during D<sub>1</sub> deformation (Alene, 1996 in Asrat et al., 2003) and this is well consistent with the structural patterns of the metavolcanic-metasedimentary sequences in other parts of Ethiopia and neighboring countries like Eritrea, Sudan (e.g. Denkler et al., 1994; Worku and Schaldelmeier, 1996; Yihunie and Tesfaye, 1998; Ghebreab, 1999; Yihunie, 2002; Beyth et al., 2003; Alemu and Abebe, 2007). However, Sifeta et al. (2005) considered NE–SW striking and NW dipping pervasive regional foliations within the Werri area, northwestern of Negash syncline presumably to be formed during E-W compression. The tectonic evolution in the northern Ethiopia commenced with ductile deformation and terminated with brittle deformation (Tadesse, 1997). The metamorphic mineral associations in the Tsaliyet metavolcanics of East African Orogen in northern Ethiopia indicate that the rock units have experienced from pumpellyite-actinolite-facies up to the lower greenschist- facies at temperature of 245–375 C° (Alene, 1998).

### **2.3. REGIONAL GEOTECTONIC CORRELATION**

The northern Ethiopian low grade Neoproterozoic volcanic and sedimentary rocks were deformed almost N-S and presumably correlate with similar rocks of other parts of the country and the neighboring countries. According to the results of previous investigators (e.g. Kazmin, 1973 & 1975; Kazmin et al., 1978; Garland, 1980; Tadesse et al, 1999; review of Asrat et al., 2001), it is concluded that the Precambrian metavolcanic rocks of northern Ethiopia are correlated with similar low-grade rock units of eastern, western and southern parts of the country based on gross lithological similarities in the field, degree of metamorphism, and geochronological and isotope studies. Hence, Adola Group of southern Ethiopia, Birbir Group of western Ethiopia, and Soka Group of eastern Ethiopia are correlated with juvenile Tsaliyet Group of northern Ethiopia (Asrat et al., 2001).

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Structural styles associated with some of the ophiolites in the ANS (of Ethiopia) are interpreted as part of fold and thrust belts which manifest the subduction/collision tectonics between arc terranes (Drury and Berhe, 1993 in Tadesse, 1996). Similarly, Worku and Schandelmeier (1996) argued that a sequence of continuous deformation events developed by oblique plate convergence in southern Ethiopia: (i) subduction related folding and thrusting ( $D_1$ ), (ii) collision of crustal blocks ( $D_2$ ), leading to re-folding of  $D_1$  structures and development of folds. In a regional context, structures that formed during  $D_1$  and  $D_2$  are correlative with those structures formed in relation to the major collision event in the ANS (Woldehaimanot, 2000).

Detail studies conducted in southern Ethiopia by Worku and Schandelmeier (1996) postulated that  $D_1$  recumbent folds related with subduction-obduction event in which the subduction was west-directed and obduction in southeast direction. In addition,  $D_1$  recumbent, tight to isoclinal fold structures in Tulu-Dimtu Belt of western Ethiopia might be related to collision as a result of oceanic back-arc basin closure which resulting in the northwestward obduction of Tulu-Dimtu ophiolites (Alemu and Abebe, 2007). Similar rocks from northern Ethiopia also recorded the recumbent  $F_1$  and the upright  $F_2$  folds (Alene, 1998; Sifeta et al., 2005). Mafic-ultramafic rocks which are marked by arc-like ophiolitic sequences were identified by Tadesse (1996) in northern Ethiopia in which its structural style is characterized by fold and thrust belt type of tectonics. As he interpreted structural fabrics of the area in his work, the Zager mafic-ultramafic belt in northwestern part of northern Ethiopia were developed by subduction-obduction related tectonic process over an oblique southeast dipping subduction and northwest directed obduction. Overall, regional lithological and structural correlations of Zager fold and thrust belt in northern Ethiopia depict that the area has presumably similarities to deformation phase responsible for the development of earlier  $D_1$  structures identified in relatively well studied western Tulu-Dimtu Belt and southern parts of the country. Noting the presence of the recumbent  $D_1$  structures formed by subduction-related collision processes in these regions of the country, one could accept that there was subduction related collision in northern Ethiopia to develop  $D_1$  deformational structures. In addition, even though the  $D_1$  recumbent folds in all regions were formed by subduction/collision process (as it is noted from previous works); it seems that their directions of subduction were different. Lastly, whether northern Ethiopian  $D_1$  structures evolved over westward subduction zone

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(Shackleton, 1986) or southeast dipping subduction (Tadesse, 1996), or evolved over both subduction zones must await further reliable geochemical and geochronological data.

The pervasive D<sub>1</sub> event in southern Ethiopia is interpreted to have occurred at 620–610 Ma dated from a syn-tectonic granitoid that was deformed by the D<sub>1</sub> event, and the D<sub>2</sub> event ended prior to 554 Ma as suggested from dated post-tectonic (post-D<sub>2</sub>) granitoids (Yihunie, 2002). This is comparable with the interpretation of Miller et al. (2003) who suggested that D<sub>1</sub> deformation is older than 613Ma, the age of post-D<sub>1</sub> granitoids from the Negash area. According to Beyth et al. (2003), the Tsaliet metavolcanics and the overlying Tambien metasedimentary successions of northern Ethiopia are equivalent with the metavolcanic-metasedimentary successions of Bizen Domain in eastern Eritrea. Moreover, Tsaliet Group metavolcanic rocks of the Nakfa terrane in southeastern Sudan and Ethiopia and similar rocks in Eritrea are constrained to 800–854Ma by zircon evaporation ages and intrusive relationships (Miller et al., 2003). This correlation suggests that Tsaliet metavolcanics are parts of upper Basement Complex which are Neoproterozoic in age.

The correlation of the geochemical characteristics of Neoproterozoic ophiolitic fold and thrust belts of southern Ethiopia (Yibas et al., 2003) with the northern Ethiopian metavolcanics and the calc-alkaline island-arc related rocks from Nakfa terrane of east Eritrea (Woldehaimanot, 2000) suggests likely southward extension of the ANS. Most of the metavolcanic-sedimentary rocks of the west Ethiopia are also thought to be island arc derived (Warden et al., 1982). Generally, ANS in Ethiopia which is dominantly exposed in northern part of the country (Kazmin, 1973; Asrat et al, 2001) (see also Fig.1.2), is mantle-derived juvenile continental crust formed by subduction-related arc accretion (e.g. Tadesse et al., 1999; Avigad et al., 2007).

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## CHAPTER THREE

### 3. LOCAL GEOLOGY OF THE STUDY AREA

#### 3.1. LITHOLOGY

At the eastern boundary of the study area, the gradational contact between the Tsaliet and the Tambien Groups is noticed and tectonic contacts are also observed in north and northeastern part of boundary between the two Groups (Fig.3.1). The geology of the study area is shown in the geologic and structural map (Fig.3.12). The greater part of the western limb of Negash syncline of northern Ethiopia is underlain by Precambrian basement rocks, exposed in all parts of the study area and it comprises a broadly northwest dipping but locally southeast dipping intermediate to acidic metavolcanics and metapyroclastics. The Tsaliet Group of the study area is mainly represented by metavolcanics (MV) – metabasaltic andesite and meta-andesite, and heterogeneous metavolcaniclastics (MVC) – metabreccia of coarse pyroclastics, associated metagreywacke (reworked coarse metavolcaniclastics), phyllite, slate and interleaved minor metatuff unit and carbonate unit within the metabreccia. The rocks of Tsaliet Group of the area show varying degrees of deformation, ranging from massive, undeformed bodies to strongly foliated rocks.

The MV and the MVC commonly occur in separate outcrops, but in some places both units are interbedded. The intermediate metavolcanic rocks are generally non-foliated and are restricted to the central part of the study area. At places these rocks are characterized by primary volcanic textures (porphyritic and sometimes vesicular, or amygdaloidal). The metavolcaniclastic unit covers most of the study area, and is composed of repetitive beds of volcanic metabreccia, metatuff, often associated with interbedded phyllite unit. This unit extends over eastern and most of the central part of the study area. The pyroclastic rocks are typically well foliated, and contain stretched, mainly intermediate to felsic, rock clasts. The contacts of these mapped units are variable. At some places, they are sharp/distinct and stratigraphic; in the other cases, the boundaries are gradational from one unit to the other. Generally, chlorite, epidote, and actinolite-tremolite green mineral assemblages in the study area show a variably distributed low-grade, greenschist facies of interbedded lithologies of metavolcanics and pyroclastics.

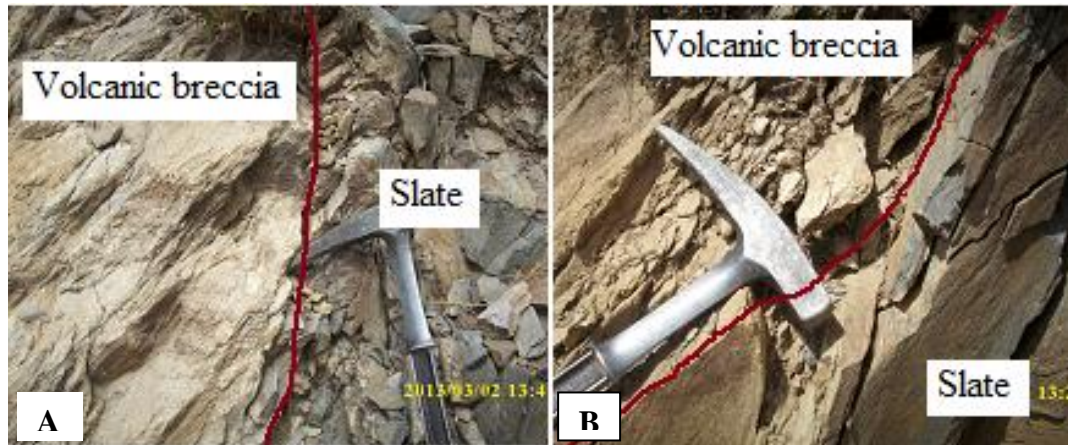


Fig.3.1.The tectonic contacts between the metavolcanics and the slate of Tambien Group at northeastern part of the Negash town. Location: A (0565100E, 1535295N) and B (0565004E, 1535105N)

According to field relations and petrographic works, two suite units of volcanic rocks have been recognized: (a) lower volcanic suite of intermediate composition (metavolcanics: basaltic meta-andesite and meta-andesite); and (b) upper volcanic suite of more silicic pyroclastic rock units (ash/tuffs: slate or phyllite, and metavolcaniclastics: metabreccia/metagreywacke).

Where the relict primary features of a metamorphic rock dominate over those created during metamorphism, the common practice employed by geologists is to apply a name reflecting the parent rock, preceded by the prefix “meta.” If, however, the grade of metamorphism is the range where schist would form, intermediate or mafic igneous parent rocks do start to develop a sort of schistosity by alignment of certain minerals. This is the case for nearly all rocks in the Negash study area. Aplitic dykes and quartz veinlets are found in rocks of the area. The aplitic dykes are intermediate to coarse grained, composed of quartz and feldspars. The width of the dyke reaches up to 1.5m. The dykes are displaced by normal fault exposed along the road of Wukro-Negash towns.

Based on the spatial distribution, and contact relationships the sequence of main rock units exposed in the area is arranged from oldest to youngest below and discussed in that order here.

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Local stratigraphic sequence of Tsali Group in the Negash study area:

Slate / Phyllite

Metavolcaniclastics (metabreccia)

Metavolcanics (metabasaltic andesite and meta-andesite)

The field observation might indicate the volcanism in the area was characterized by episodic lava flow of intermediate composition and pyroclastic deposits of mainly acidic composition. This argument suggests that the intermediate lava flow is the oldest which are followed by pyroclastics, reworked pyroclastic rocks, respectively. The metabreccia rocks in the Negash area overlie the metabasaltic andesite on topographically low-lying surfaces, well exposed along the river cut at SW of town of Negash. Due to the lack of convincing field data, in this study the tentative stratigraphic order is given above.

### **3.1.1. METAVOLCANIC ROCK**

This rock unit is encountered mainly in the central part of the mapped area and occurs as ridge-forming outcrop in a NE-SW direction along the strike. It varies in width along the strike, it is wider in the south and narrower in the north; the belt pinches out and cannot be traced northward. It is also exposed at the eastern boundary of the study area around the Negash town, but it is small and unmappable. The metavolcanic rock is hard, compact, massive, often fractured, and it is green or greenish grey, generally fine grained and sometimes porphyritic with phenocrysts of feldspar mineral. At places, the intercalated and foliated tuffaceous slate wrapping around the rock suggests that it is well deformed. In this rock unit some elongated, pale green amphibole (actinolite) is present locally. At some places the rocks are highly fractured. The metavolcanic rock unit is presumably the oldest unit in the area, since it is exposed rock in the river bed and overlain by metabreccia.

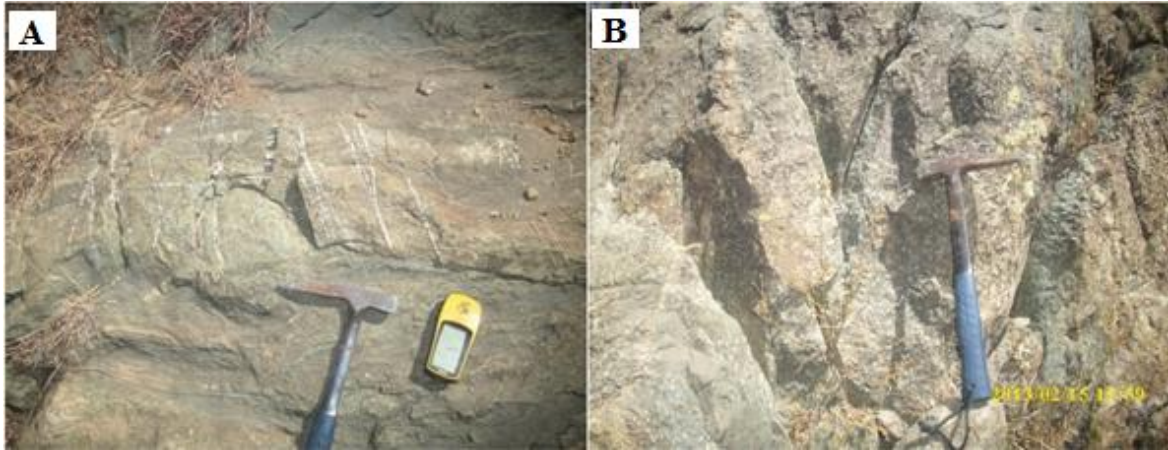


Fig.3.2. Field photographs showing small quartz veins cross-cutting the metavolcanic rock (A) and the porphyritic texture of the rock (B). Note the massive texture of the metavolcanic rock.

### 3.1.1.1. PETROGRAPHY

The metavolcanic rocks have an average composition of 35% epidote, 20% plagioclase, 16% actinolite-tremolite, 10% chlorite, 7% muscovite/biotite, 6% quartz, 4% calcite, trace amount of relict olivine and pyroxene. The epidote minerals and colorless needle shaped tremolite showing random distribution indicates decussate texture. The metamorphism, related to the regional deformations, in MV rocks of present area is characterized by extensive epidotization. Metamorphic mafic rocks (e.g. greenschist) are derived from mafic igneous rocks, mainly basalts and andesites. The history of a metamorphic rock is recorded in its mineralogy and textures (to some extent, geochemistry). For this reason, based on the mineral composition and salient schistosity under microscope, the rock has been named as olivine-pyroxene bearing mica-chlorite-actinolite-tremolite-plagioclase-epidote schist. Volcanic rocks (e.g. basaltic andesite) have plagioclase with increasingly higher calcium (Ca) content in which intensive alterations may occur in the MV rock of the study area (Fig.3.3). Epidote, actinolite-tremolite, chlorite, and sericite are alteration products; as a result it was originally a Ca, Mg-rich rock. Metamorphic epidotes occur as large clots that may also be pseudomorphs after fine grain amphibole or pyroxene mafic minerals. In another case, albitic plagioclase is noted in this rock which is not common in basaltic andesite. This may indicate that Ca-rich plagioclase (basaltic andesite or andesite) was recrystallized into Na-rich (meta-basaltic andesite or meta-andesite) during metamorphism. Hence, on the basis of field observation,

the associated mineralogy and geochemical study, the parent rocks of Tsaliet MV of Negash area were basaltic andesite and andesite (intermediate composition).

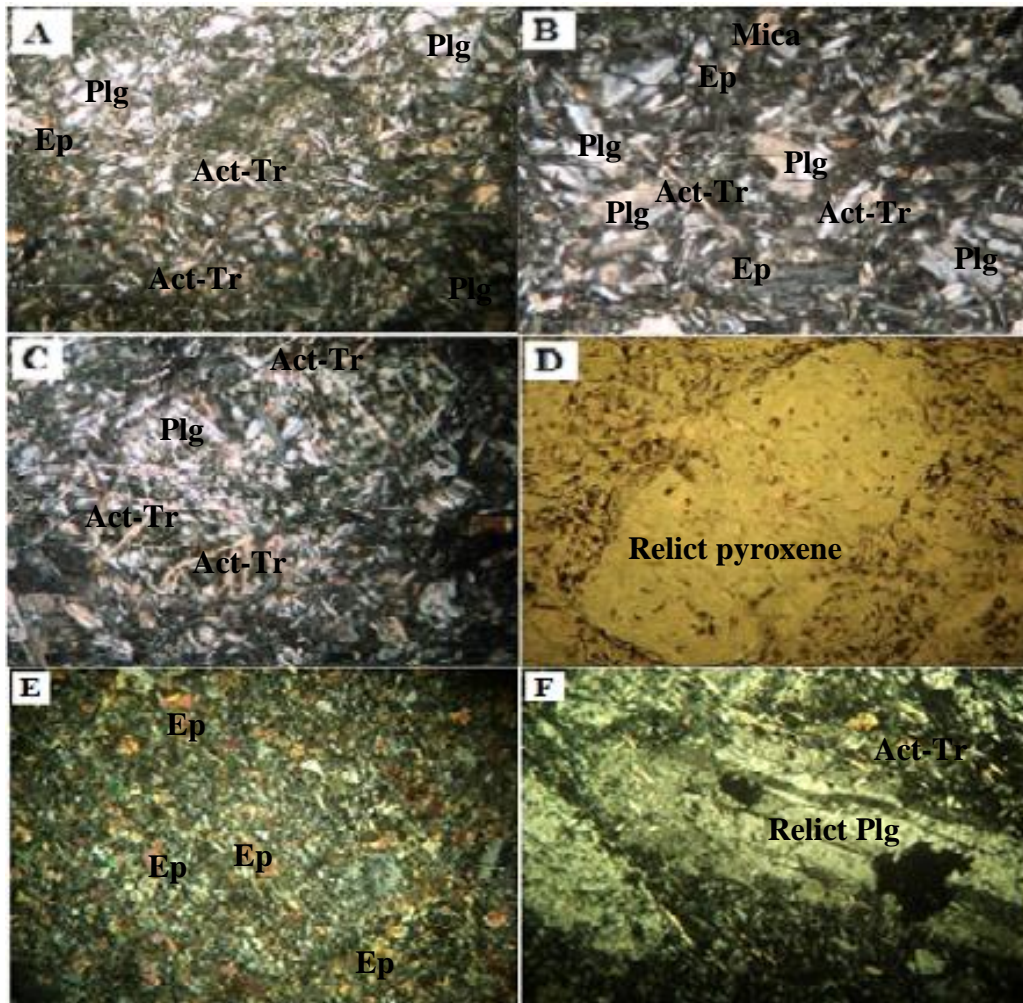


Fig.3.3. Microphotographs of meta-basaltic andesite and meta-andesite exhibiting alteration of Ca-plagioclase and mafic minerals into secondary minerals including Na-plagioclase, epidote and partially actinolite-tremolite minerals. (A) partial altered plagioclase minerals into actinolite (XPL view); (B) randomly oriented plagioclase laths (XPL view); (C) highly altered pyroxene minerals into actinolite-tremolite (XPL view); (D) thin section (C) under PPL view; (E) epidote mineral showing intense epidotization in meta-basaltic andesite (XPL view); and (F) slightly altered relict plagioclase (XPL view). Thin-section No. (A, B, C, D and (E) total magnification 40x while section No. (F) total magnification 100x. [MV rock NT4-1 and NT4-2].

### 3.1.2. METABRECCIA

This is the most extensively exposed rock unit in the area and it stretches for the whole NE-SW length of the study area. This unit is foliated, coarse, agglomerates. The unit is characterized by the occurrence of angular, sub-rounded to rounded, and also elliptical volcanic clasts of variable shape, engulfed in fine to medium grained greenish matrix. These are mostly consisting of mafic and rhyolitic fragments mostly about 1 to 20 cm in size. At some places, basaltic fragments are engulfed in an acidic matrix or vice versa. These units show variable hardness, some are very hard and others are weaker. Another feature of the metabreccia in the area is its variation in color from greenish-gray to dark/dirty gray. They are interbedded with whitish/yellowish, friable, soft rock unit probably of unmappable tuff. The interleaved resistant metabreccia and softer rocks produced undulating topographic features. On the basis of the field observation, including the abundance of basaltic to rhyolitic clasts and random orientation, the rock is considered to be volcanic-derived. This rock unit is also sporadically exposed in southwestern boundary of the area. The clasts grade in size from very coarse volcanic bombs/blocks in the east to fine in the west and the rock becomes tuffaceous phyllite near the contact with the Negash granite body and the volcanic vent location may be at eastern part. There is also well laminated bed of slate in contact with the metabreccia rock unit. In addition, thin lense of gray, finely crystalline carbonate rock is found at the central part of study area, and is parallel to the strike of the foliation. It is karstified and crossed by quartz veins.

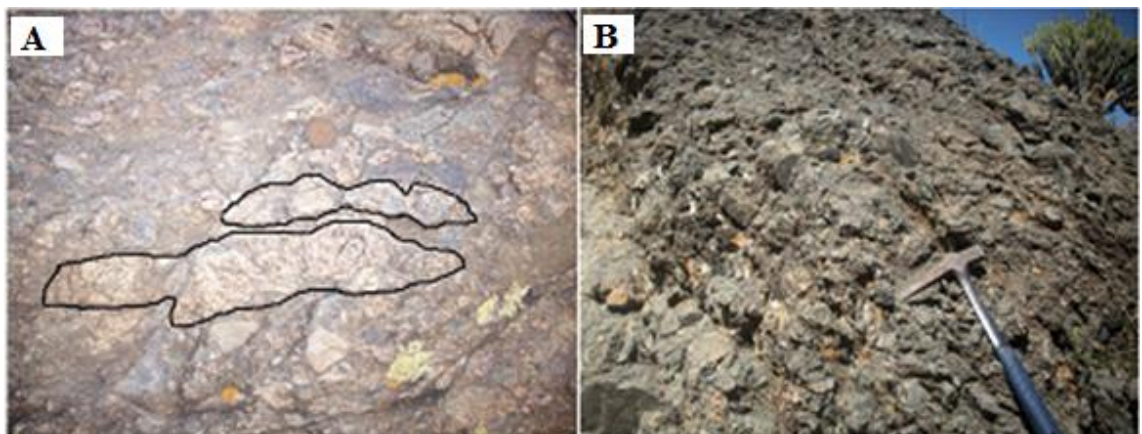


Fig.3.4. Field photographs showing rounded to elongated big granitic clasts in acidic metabreccia rock units (A) and same rock displaying gray color (B).

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Within metabreccia, there is also minor intercalation of water reworked volcanoclastic rock units, metagreywacke. Metagreywacke and metabreccia contain similar rock fragments except that the sizes of the fragments are finer in the former. It is light gray and contains some amount of rounded lithic fragments indicating little transportation. In general the thin blanket of the rock unit is not shown on the map.

The less common, fine-grained pyroclastic rock is considered as metatuff, with average grain size of the pyroclasts less than 2 mm. The metatuff has markedly more felsic composition being principally of rhyolite to andesite. The unit forms subdued topographic features relative to the interbedded stronger rock units. The metatuff is yellowish, fine-grained and shows lamination. Only thin layers (5 to 10 m thick) of the metatuff are frequently intercalated with the other rock units and as a result it is not mapped separately.

#### **3.1.2.1. PETROGRAPHY**

The metapyroclastic rocks are composed mainly of crystal fragments of quartz and plagioclase together with few rock fragments, with well developed schistosity; the fragments are being wrapped by the mica minerals. The rock fragments are irregularly distributed and vary in composition from mafic (pyroxenes) to felsic (quartz and feldspars). The deformed quartz in the foliated rocks is usually elongated parallel to the foliation direction with pronounced undulatory extinction. Petrographic study of thin sections show that the average modal composition of acidic metabreccia rocks is 40% quartz, 20% relict plagioclase, 15% lithic fragments, 13% muscovite, 10% chlorite, 2 to 7% opaque. Occasionally calcite also partly replaced the plagioclase minerals. In some thin sections, minute sericite grains, after plagioclase, and minor randomly oriented biotite porphyroblasts are also present. The metamorphic textures observed in thin-sections mainly granoblastic aggregate. These mineral assemblages give the metamorphic name as chlorite-muscovite-plagioclase-quartz schist. On the basis of field and petrographic data, the majority of the observed metapyroclastics are identified as volcanic metabreccia (Fig.3.5). There are also indications of the presence of a matrix comprises of glassy material in some section providing evidence of a volcanic origin. Compositionally, majority of petrographically studied volcanic metabreccia contains significant modal percentage of acidic minerals, hence, show acidic composition (see Fig.3.5). In the field it is also mainly characterized by acidic character (Fig.3.4 and 5.1A).

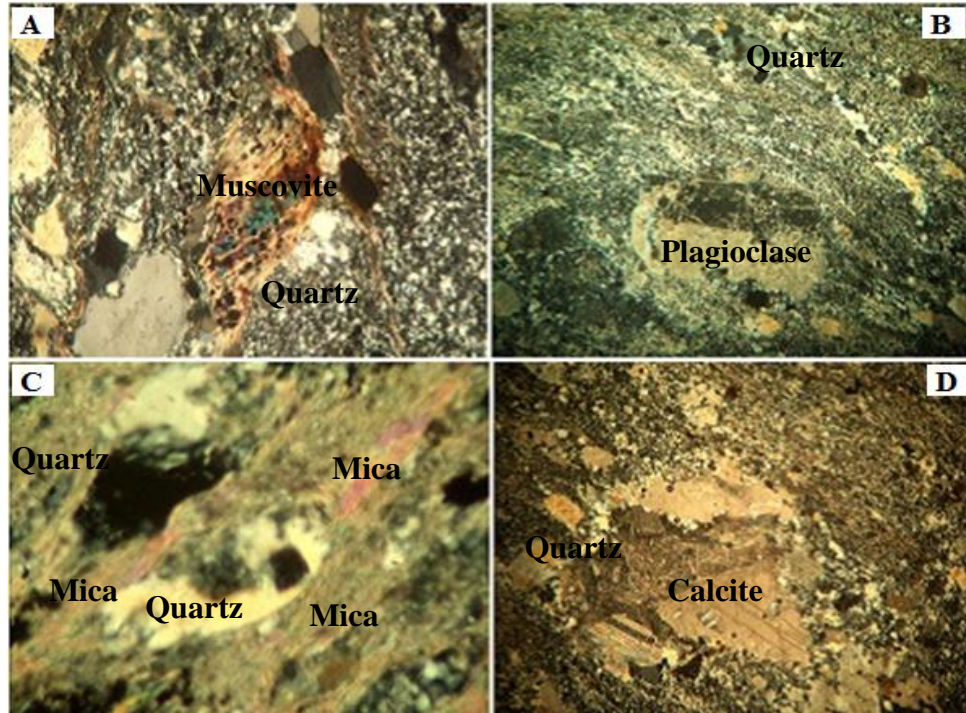


Fig.3.5. Microphotographs of volcanic metabreccia showing different clasts. (A) Muscovite porphyroblast exhibiting shearing effect (XPL view), (B) plagioclase porphyroblast (XPL view), (C) elongated quartz grain along the main foliation (XPL view), (D) calcite grains (XPL view). Total magnification 40x.

Petrographic study of the rock thin sections from metagreywacke show that the average modal composition is 35% quartz, 19% relict plagioclase, 14% lithic fragment, 12% sericitic muscovite, 9% calcite, 4% epidote, 3 to 8% chlorite and opaque. More or less similar modal mineral composition of metagreywacke and metabreccia and close association of the two rock units in the field observation indicate that the possible origin of both rock units was volcanoclastics.

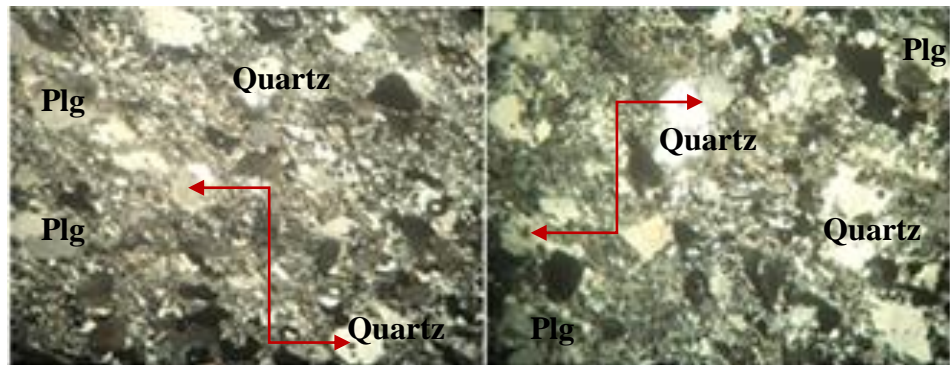


Fig.3.6. Microphotographs of volcanic metagreywacke showing rounded to sub-rounded quartz minerals (arrowed). Under XPL view, total magnification 40x.

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### 3.1.4. SLATE

It is very fine grained, and well laminated; with steeply inclined foliations, and has variegated colors including dark grey, grey-green, reddish, whitish, pale yellowish and purplish. At places, the rock is affected by closely spaced joints. From the field observations, it is noted that compositional banding and cleavage are parallel to each other defining composite fabric. In this study, the rocks have been metamorphosed. If the metamorphic changes in the rock obscure the properties of the parent rock, then the rock should be given a metamorphic rock name, such as slate or phyllite.



Fig.3.7. Field photographs showing (A) composite fabric on the slate, and (B) slabs of slate

#### 3.1.4.1. PETROGRAPHY

Five thin-sections from slate have been studied petrographically. Petrographic examination of the slate shows that its average modal composition is 36% mica, 24% quartz, 21% chlorite, 3% epidote, and up to 6% opaque minerals with trace amount of plagioclase feldspar. The grain size of the minerals are generally fine with occasional large (sand sized), sub-rounded grains of quartz and feldspar. The alignments of sericite along with the dimensional orientation of quartz and feldspar minerals define the slaty fabric.

The slate is challenging to identify its origin or protolith (igneous or sedimentary) but here it is attempted to identify its origin at the present scale of observation. The name slate carries no connotation as to protolith, although to most readers slates are derived from shale. One could

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get a foliated rock if metamorphosed shale or a volcanic rock like volcanic ash/tuff. During some volcanic eruptions, the showers of ashes often follow one another to form thick masses of tuff that have mostly a stratified character although this can also be due to sedimentary origin shale. In present area, the petrographic study of the slate is not sufficient to determine the protoliths of the rock as it is very fine grained to identify the relict volcanic (such as volcanic glasses) or sedimentary features. However, the nature of the original protolith nearly made out from the shapes and properties of the little crystals which occur in the chloritized matrix. As it is known, clay minerals are hydrous sheet silicates (phyllosilicates) composed of sheets of  $\text{SiO}_4^{4-}$  and of Al, Fe and/or Mg. There are no mafic minerals (like olivine, anorthitic plagioclase) found in sedimentary shale because the minerals are not resistant to chemical weathering and decomposed to clay minerals and so are uncommon in sedimentary origin rocks. The more the mafic minerals (e.g. anorthitic plagioclase) were present in volcanic rocks, the more epidote mineral is formed during metamorphism which is the case in the slate of the study area (see Fig.3.8). Based on the absence or trace amount of feldspars in the sections (which may indicate the plagioclase was undergone high saussuritization) one amply may conclude that the parentage is sedimentary not igneous. But, there are metamorphic minerals like epidote in the present slate, in which it would have been possible to find mafic minerals in the protoliths for their formation. Hence, the presence of mafic metamorphic minerals (epidote and chlorite) may lead to the conclusion that the slate has a volcanic or volcanoclastic origin at present scale of observation. The close association of the slate to other clearly volcanic origin rocks (MV and MVC) in the field also shows the slate is not sedimentary origin.

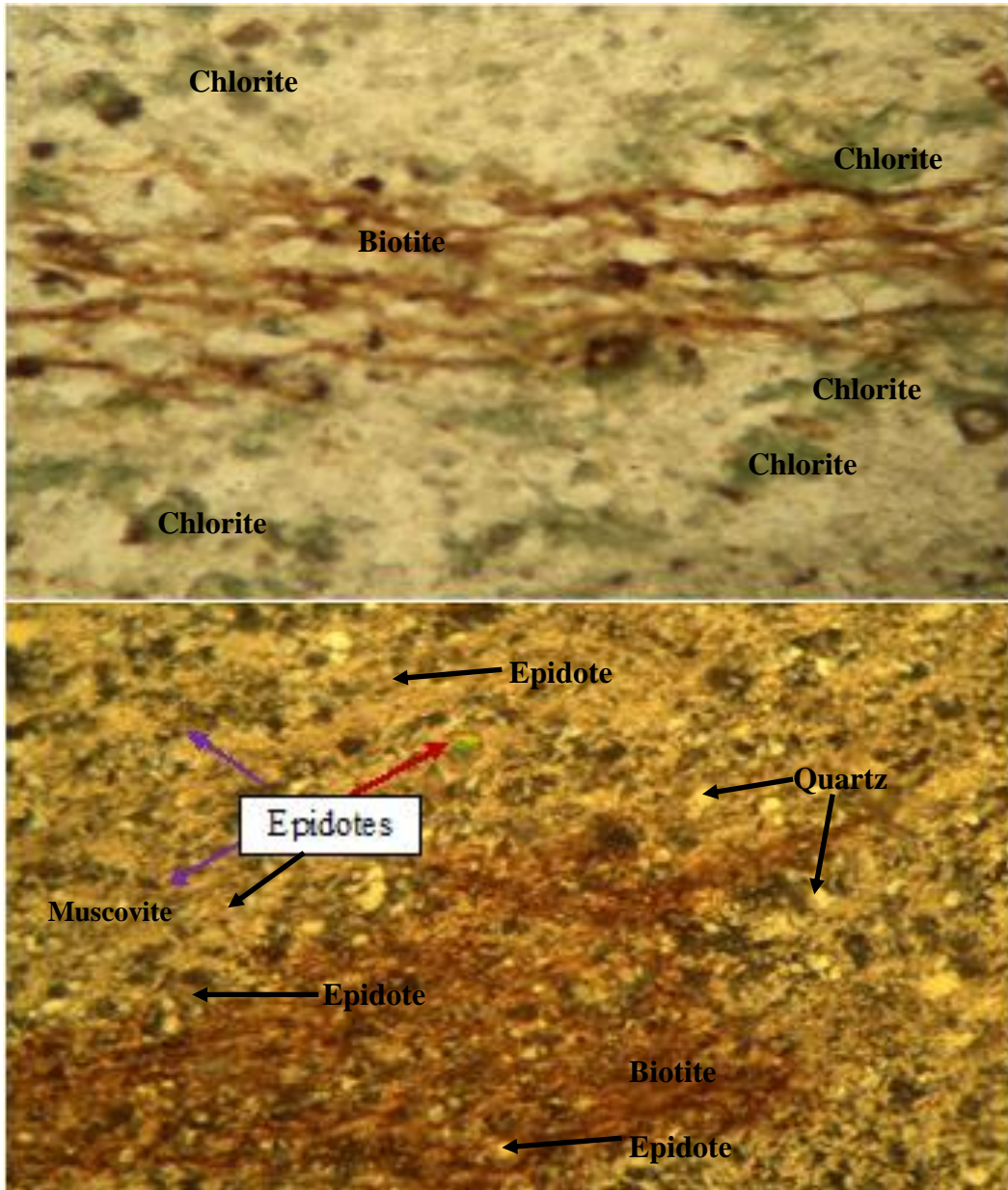


Fig.3.8. Microphotographs of slates showing the grains of deep green color chlorite mineral (top) under PPL view, and granules of epidote mineral (bottom) under XPL view. Note the porphyroblasts of biotite minerals along the slaty cleavage. Total magnification 100x for both thin-sections.

### 3.1.5. PHYLLITE

The phyllite is fine grained and recognized by its phyllitic foliation when the fabric-forming mica minerals show continuous and visible shiny surfaces. In this rock, grain size coarsening and growth of flaky biotite crystals are well developed along the intrusive contacts giving the rock spotty texture. Near the granite intrusion, the phyllitic rocks are laminated and striped or

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banded with black biotite minerals. It is presumably minor folds that repeat part of the unit within short distances as evidenced by the limb of the same unit dip in different directions.

The slate is probably changed into phyllite due to the intrusion of Negash granite body as observed by the contact metamorphism including the growth of andalusite porphyroblasts. Phyllites are transitional between slates and schists and share associations and properties of both. Many geologists actually recognize coarser grained version of the slaty cleavage as schistosity; however, the boundaries between the schistosity and phyllitic foliation have never been formally defined. So, in this study both fabric features are used interchangeably. At places phyllite, graded into mica-schists.

#### **3.1.5.1. PETROGRAPHY**

The phyllite has almost the same composition as in the slate, but coarser minerals are aligned to produce the schistosity in phyllite. The rocks have an average composition of 45% muscovite, 20% quartz, 13% plagioclase, 10% chlorite, 6% biotite, 6% opaque. So it is named as biotite-chlorite-plagioclase-quartz-muscovite schist. The flattened elliptical shapes of the clasts together with the wrapping of the matrix around the clasts strongly suggest that the rock is well deformed. All parts of the phyllite are well foliated and the foliation is generally concordant with compositional layering defining composite fabric. The phyllite in the area is highly crenulated, indicating that the rock has undergone at least two phases of ductile deformation.

Since this phyllite is derived from the slate due to thermal metamorphism the similar metamorphic minerals (e.g. epidote) are present in phyllite, hence it is considered as a volcanic origin. In the field phyllite is closely associated with metabreccia in which phyllite is sporadically exposed as a thin lenses within metabreccia. So, these field relations may also suggest that the rock is metavolcaniclastic in origin. The quartz-mica phyllite indicates the presence of low-grade andalusite mineral which is, as noted in Barker, (1998), a very good indicator of low pressure and a temperature up to 400C<sup>0</sup> conditions. The andalusite is present as idiomorphic to sub-idiomorphic porphyroblasts with inclusions of quartz, and muscovite. In general, the green mineral assemblages and the shown textures are indicative features of greenschist facies metamorphism of originally volcanic rocks. Thus, petrographic study of the Tsaliel Group from the study area has revealed that the regional metamorphism progressed up to lower greenschist facies.



Fig.3.9. Phyllite rock in the field showing shiny cleavage surface with spotty texture

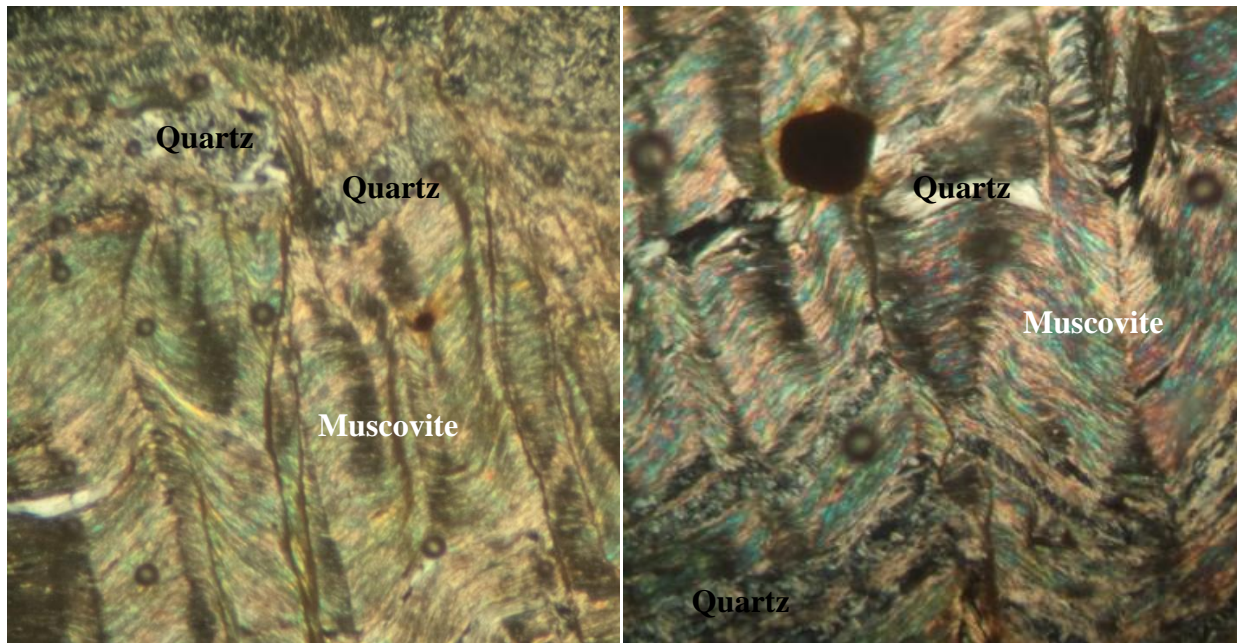


Fig.3.10. Microphotographs of phyllite showing crenulation cleavage of muscovite mineral under XPL view (total magnification 40x).

### 3. 1.6. QUARTZ VEIN

The rocks in the area are intruded by numerous quartz veins. A float of quartz grains are common in almost all metavolcanic rock units which may indicates the presence of quartz veinlets, and less occurrence northward in the study area. Small quartz veinlets are very common in all rock types. The veins are range in width from 1.5-3cm. It is noted that the quartz veins of different generations in Negash area show NW to NE trend with moderately dipping toward SW and NW respectively.

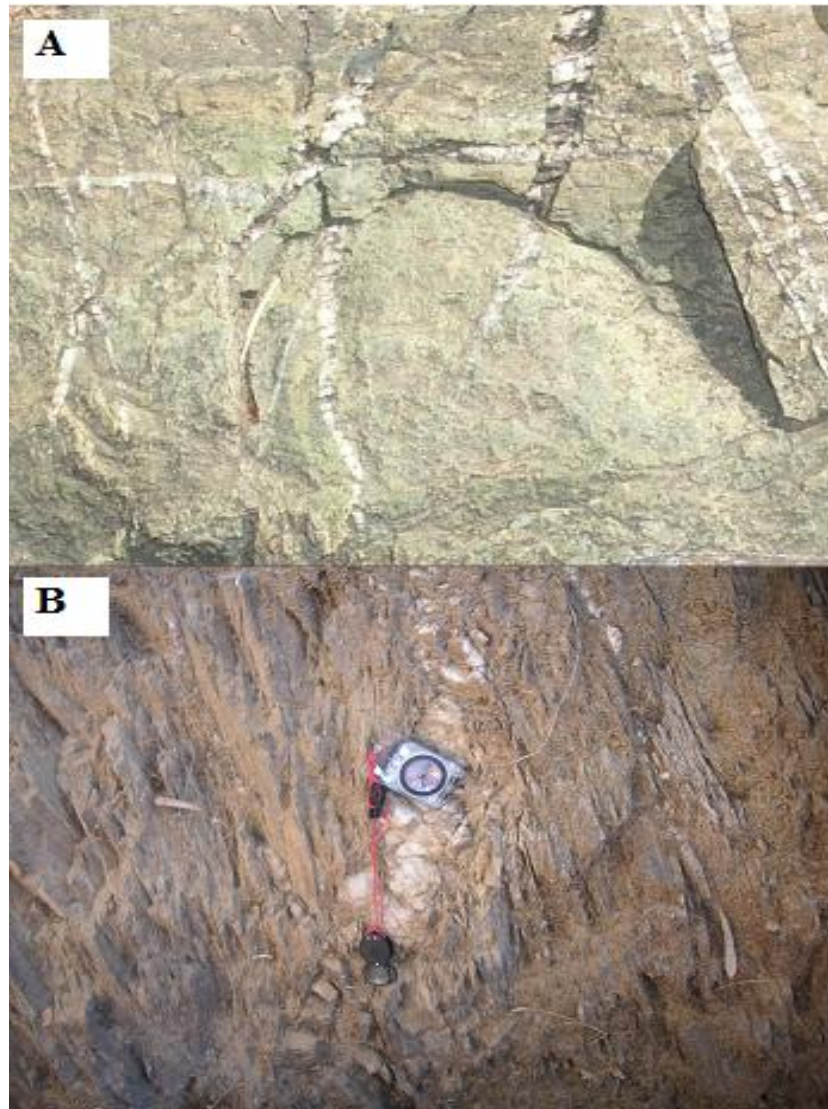


Fig.3.11. Field photographs showing quartz veins (A) occurring in greenish metabasaltic andesite rock, and trending across the regional foliation (B). Photo B taken within small open pit.

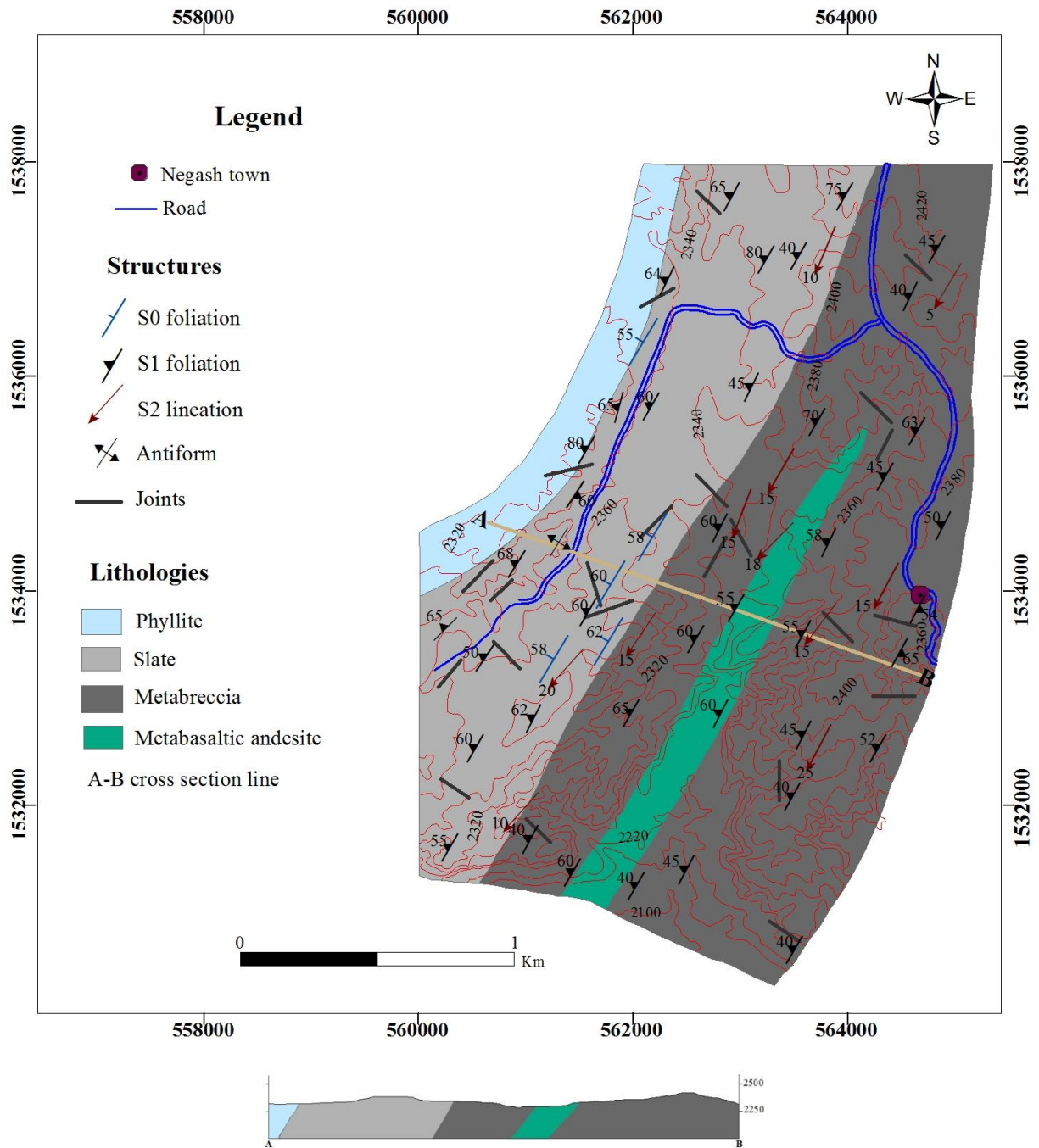


Fig.3.12. Lithological and structural map of the study area with geological cross-section having no vertical scale exaggeration

In the figure, except local variations, it is clear that the regional structural trend is NE-SW and also dips at variable angle to NW. Synformal and/or antiformal structures near the granite body (see Fig.3.12) are mapped from the change in the directions of the S<sub>1</sub> foliation and duplication of lithologic units.

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## CHAPTER FOUR

### 4. MINERAL ASSEMBLAGES AND METAMORPHISM

#### 4.1. INTRODUCTION

Petrographic examination has been carried out on 22 thin sections representing all major rock units of the study area including the metavolcanic, metavolcaniclastic, slate, and phyllite rocks. The mineral assemblage and visually estimated mineral modes of the selected samples for different rock types are shown in Appendix-1 and summarized below.

Most of the metavolcanic (MV) and metavolcanoclastic (MVC) rocks contain relic minerals such as plagioclase, and K-feldspar phenocrysts and metamorphic minerals such as chlorite, muscovite, sericite, biotite, epidote, calcite, tremolite-actinolite, opaque, and quartz. Each of the metavolcanic and metavolcanoclastic rocks is texturally and mineralogically distinctive. Relict volcanic features include porphyritic texture, glass shards, and pyroclastic materials. Metamorphic features include phyllosilicate cleavage in certain thin-sections. Epidotization seems to be common to all rock units in study area.

#### 4.2. METAMORPHISM OF THE TSALIET GROUP

The green color of the Tsaliet Group rocks results from the modal dominance of green minerals notably Chl, Act, Ep and these minerals together with  $Ab \pm Qtz$  are the most characteristic assemblage of greenschist facies. In most of the studied rocks, chlorite is found as green color stained crystals that are probably derived from mafic minerals in the matrix.

In some cases, where epidotization is intense, epidote aggregates make up to 60% of the meta-basaltic andesite rock composition in the study area, and it may be this composition which gives the rock anomalously deep green color. The presence of these green color minerals and some relict igneous minerals (like olivine and pyroxene) indicate the rock has undergone low grade metamorphism (greenschist facies). The epidote occurs as irregular patches and also as veins (Fig.5.13). They are commonly found in the matrix and near the contact of plagioclases. In some samples, metamorphic minerals show nematoblastic texture with actinolite-tremolite defining the fabric. However, quartz and plagioclase also define granoblastic texture in certain thin-section. Chloritization, sericitization, actinolitization and to some extent carbonitization are also major metamorphic alterations of plagioclase feldspar producing chlorite, sericite, actinolite and calcite respectively.

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The metamorphic textures observed in the thin sections of volcanic metabreccia range from aggregate to nematoblastic. Moreover, biotite and muscovite occur as porphyroblasts and fine aggregates or small needles in the matrix along with quartz, plagioclase and opaque minerals along the main foliation. Metagreywacke characterized by rounded to sub-rounded prominent quartz grains reflecting that the rocks were reworked, and mafic minerals were destroyed to left behind quartz grains. Hence, the rock is felsic in composition (Fig.3.6). The development of green secondary minerals and presence of basaltic to rhyolitic clasts indicate that metabreccia and metagreywacke were affected by low grade metamorphism.

The alignment of secondary minerals in slate defines a strong slaty cleavage. The trace amounts of plagioclase possibly indicate that the plagioclase grains are highly saussuritized. Petrographic examination of phyllite shows that it has more or less similar mineralogical and textural characteristics to the slate. The mineral assemblages together with the preservation of primary bedding in slate and phyllite indicate that the area has been subjected to a low grade of metamorphism (greenschist facies).

The secondary minerals are formed from metamorphic reaction at the expense of mineral originally found in the protoliths. Because the growth of metamorphic minerals is a function of overall composition of the rock, the absence of a particular mineral does not necessarily imply a different facies or conditions. For example, actinolite is typical of metamorphosed basaltic andesite in the greenschist facies of study area, but is not found in slate. In general, all of the studied rocks have been metamorphosed to lower greenschist facies as indicated by incoming of lower greenschist minerals. Since the grade of the metamorphism is low, one would not notice many changes in the rock. This is consistent with the general conclusion of Alene (1998) that the rocks in the area metamorphosed at greenschist facies conditions.

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## CHAPTER FIVE

### 5. DEFORMATION AND STRUCTURES

#### 5.1. INTRODUCTION

The Negash area basement is characterized by a poly-phase deformation. The occurrence of different types of structural elements such as folds, crenulation lineation, different types of foliation and faults marks the existence of poly-phase deformation. Three major phases of deformation are recognized in the field as well as from thin-section study and they are designated as  $D_1$ ,  $D_2$  and  $D_3$  in the local structural chronology. The earlier deformation ( $D_1$ ) is represented by composite fabric in which the schistosity and the original layering ( $S_0$ ) are parallel to each other (Figs.5.1D and 5.8). The  $D_1$  event is recorded in the metamorphic rocks and it is associated with the development of an  $S_1$  foliation.  $S_1$  foliation was crenulated by  $D_2$  deformation phase, and it is recognizable in the field from small scale crenulation cleavage observed at mesoscopic level (Fig.5.2) and as relic at the microscopic scale (e.g. see Figs.3.10, 5.9, 5.10 and 5.11). In the metamorphic rocks of the study area, the  $S_2$  planes are unequally distributed. They are mostly visible in phyllitic rocks as axial plane schistosity for the  $F_2$  micro-folds at a microscopic scale. The crenulation lineations are defined by hinge lines of the microfolds in a foliation surface.  $D_3$  deformation phase is considered as last deformational imprints, and is marked by brittle structures which are normal, and reverse minor faults, and set of joints.

#### 5.2. STRUCTURES

In this section, data on both meso- and micro-scale geological structures obtained and investigated during the field and laboratory studies is presented. The major structures in the study area include foliation, lineation, folds, joints and faults.

##### 5.2.1. FOLIATION

The penetrative foliation is visible in the outcrop, hand specimen, and in thin sections under the microscope. Many cleavages are axial planar and thus represent an important link between tectonic foliation and folds in deformed rocks. In deformed slate and phyllite, the original layering ( $S_0$ ) is locally preserved and it is parallel or subparallel to the  $S_1$  fabric defining composite fabric (see Figs. 3.7A, 5.1D, 5.8 and 5.9).



Fig.5.1. Field photos showing fabric structures in different litho-units (A) highly cleaved light grey acidic volcanic metabreccia, (B) slightly foliated light greenish/dark grey volcanic metabreccia (intermediate composition), (C)  $S_1$  foliation in slate and (D)  $S_1$  foliation structure developed in slate parallel to compositional layering defining composite fabric

Prominent structures observed in the basement complexes of the study area are  $S_1$  foliations. The alignment of the foliation is uniform throughout the area of study, except in some areas which are locally disturbed along the contact between the basement rocks and the granitic intrusion. Foliations are common in most rock units of the area. The regional strike is NE-SW and the whole sequence is dips in two preferred directions- NW and SE in the study area. The  $S_1$  foliation is shallow to vertical ( $35^\circ$ -  $90^\circ$ ) dipping mainly to NW and partly to SE. The variation in the attitude of foliations in the area reflects the effect of fold overprinting. The foliations locally dips NW and SE in the western part as well as south of near Negash town and presumably defines an antiform since the foliation dips away from each other and axial traces can be traced NE-SW as foliation is often developed parallel, or roughly parallel, to the axial surfaces of folds. Hence, this foliation surface probably strikes parallel to the major folds. This relationship is common because both structures originate from the same deformation event. Poles to  $S_1$  foliations in Fig.5.5 show the occurrence of dominantly NE-

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trending regional cleavages in the study area. Crenulation cleavage from mesoscopic outcrop of the study area is typically an  $S_2$  foliation that has been superimposed on an earlier ( $S_1$ ) foliation. The  $S_2$  foliation is interpreted as axial planar to  $F_2$  Folds.

### **5.2.2. LINEATION**

Linear structures go hand in hand with planar structures in deformed rocks, where they are mesoscopic structures pointing in a specific direction. The elongated pebbles/clasts have been observed mainly in the rocks displaying elongation lineation in the field (see Figs.3.4 and 3.5C). The orientations of the stretching lineations are sub-parallel to the  $S_1$  regional foliation suggesting that these lineations are formed by  $D_1$  deformation.

The crenulation linear fabrics ( $L_2$ ) which plunge subhorizontally towards NE and SW are commonly observed on most foliation surfaces (Fig.5.2). Crenulation lineation in the area inferred from mesoscopic folds with sub-horizontal axes, and is defined by the parallel alignment of axes of the SW plunging mesoscopic  $F_2$  folds. The  $L_2$  lineations are generally roughly parallel to the fold axes of the encountered minor sub-horizontal  $F_2$  folds and plunge SW implying they are possibly of the same generation. Due to being affected by later  $F_2$  folding, the lineation fabric gently plunging mainly towards the SW, and secondary towards NE. The lineations prepared from 15 measurements shows a mean trend of approximately NE–SW and shallow plunge of about  $12^\circ$  towards SW (204) (Fig.5.7). The mean geometric orientation of crenulation lineations of this study is parallel to that of the major fold axes described by previous investigators. The lineation is defined mainly by crenulation lineation in mica rich lithologies as observed in outcrop (Fig. 5.2). Note the consistent NE–SW shallow plunge of lineation as seen from stereonet plot with that of field measurements as observed in Fig.5.2. In most cases crenulation lineations are related to folding, with the lineation running parallel to the axial trace and the hinge line. The parallelism of the lineation with the long axis of more locally developed hinge lines suggests that the lineation is crenulation lineation.

### **5.2.3. FOLD**

The Tsali Group of the study area, as mentioned earlier, is exposed on the western limb of a macroscopic, Negash syncline structure and preserves a domainal cleavage, which locally grades into a schistosity. During field work, no apparent large fold structure has been recognized. However,  $S_1$  fabric generally dips to the NW; with local variations which dip to

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the SE that shows duplication of similar litho-units in a short distance in the area. This could be interpreted as due to the presence of possible antiformal and/or synformal fold structures. In general, this field observation could lead one to the conclusion that at megascopic scale in the study area folding displays antiformal and synformal structures with axes oriented NE-SW. All the fold axes trends are parallel and vary between N15°E and N70°E with low plunge (5 - 25° SW) as recognized from the small scale exposures of folded rock (see Fig.5.2). A crenulation folding has also been observed with a series of microfolds at the centimeter scale or less with parallel axial surfaces. Hence, the rocks were deformed by two phases of ductile deformation as noted in the field and from micro-structural study.

As it is observed in thin-section, the metamorphic rocks of the Negash area show strong pervasive  $S_1$  cleavage so it could be considered as the  $D_1$  deformation represent the main deformation phase of the area. The relatively stiff quartz-rich layers formed broad, gentle folds, while weaker mica-rich layers folded into crinkles with a much shorter wavelength (see Fig.5.9).



Fig.5.2. Field occurrence of rock showing mesoscopic  $F_2$  folds forming  $L_2$  crenulation lineation; direction of view is northeastward (coin is 2cm wide).

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#### **5.2.4. FAULT**

In northeast of Negash town, there is minor reverse fault, which brings the lowest formation of Tsaliyet Group above uppermost Tambien Group (Fig 5.3A) and the fault plane orient about N60E, 80SE. A normal fault displacing the N-S or NE-SW trending aplitic dikes along the Wukro-Negash towns is also observed. They are trending in NW-SE and NE-SW directions. NE-SW striking minor fault is younger than the NW-SE striking one as it is indicated by many joints which are parallel to the younger fault which terminate against the older one because an extension fractures cannot propagate across a free surface such as another extension fractures (cross-cutting relationship).

#### **5.2.5. JOINTS**

Joints are common in all the rock units of the study area. There are two major sets of joint trends in NW-SE and NE-SW directions in the rocks with non-systematic sets. These are followed by NNW-SSE (or approximately N-S) and ENE-WSW (approximately E-W) trending minor joints. In all rock units the joints are mostly near vertical to vertical. Fracture events are traditionally characterized as difficult to date. Clearly, they form sometime after the host rock developed. For example, if a fracture runs through a dike, then the dike came first.

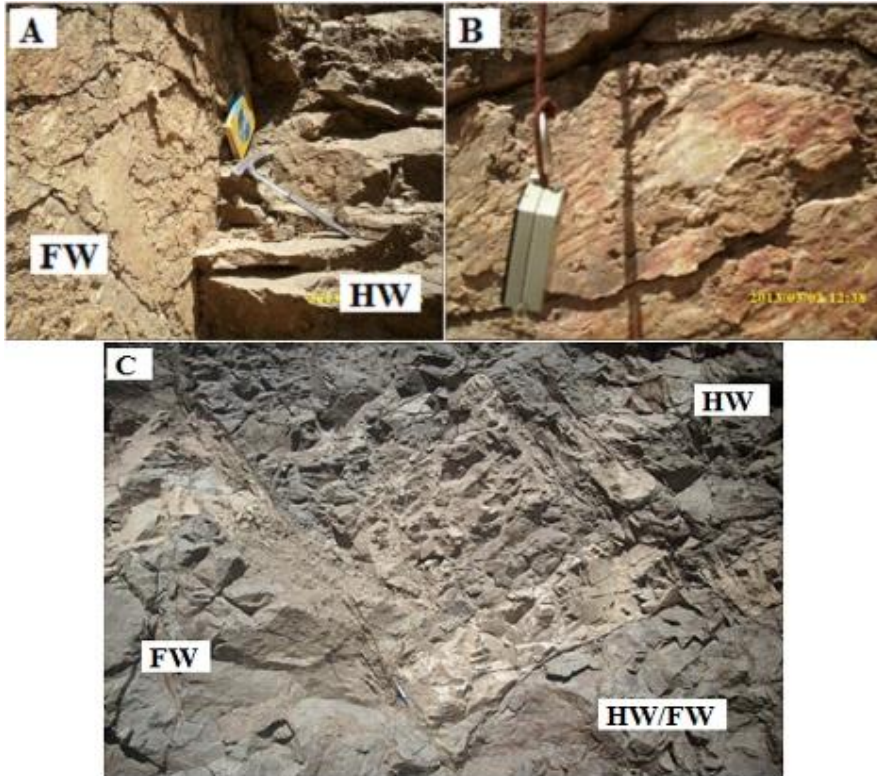


Fig.5.3. Field photographs showing, A) reverse fault and B) smooth surface with slickenlines, and C) minor normal faults exposed along Wukro-Negash road section and set of joints. The notebook in figure A is along fault plane. FW= foot wall and HW= hanging wall

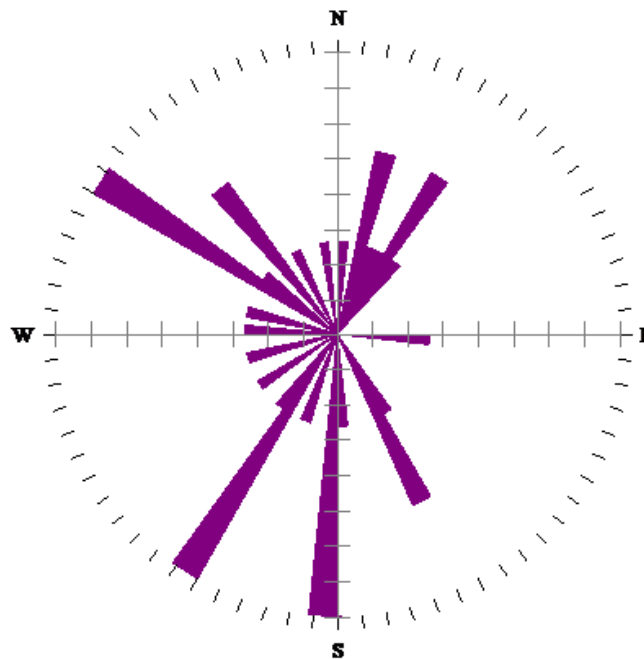


Fig.5.4. Rose diagram of the joints in study area

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### 5.3. STEREOGRAPHIC PROJECTION AND FOLD AXIS ORIENTATION

One of the most widespread uses of spherical projections in structural geology is determining the mean orientation of fold axes in a region. Large-scale folds that are poorly exposed may be impossible to analyze in the field and in such cases, data from isolated outcrops may be combined and analyzed stereographically to characterize the orientation patterns of structural data. A common method of determining the fold axis from a number of foliation or bedding measurements is to represent the orientations as poles to foliation or bedding. Ideally, in a cylindrical fold all poles would plot along a single great circle with the fold axis being the pole to the great circle. However, in nature folds are not exactly cylindrical and there may be considerable scatter in the distribution of poles (like the present study orientation of data), and the best estimate of the fold axis (beta axis) is chosen to be the pole to the calculated best-fitting great circle. It is common to present orientation data on spherical projections in a contoured form for ease in locating the concentration of data and also as convenient graphical display. The contours signify the number of times the data are more concentrated than a random orientation of the data. To get a dominant orientation of the foliations, and find and compare structural relationships locally that expected to occur regionally, the poles of the plane orientations of study area have been plotted and contoured in lower hemisphere Schmidt diagrams using conventional GEORient software (Fig.5.5). As shown on Fig.5.5, the beta axis obtained from the mean girdle of poles to the  $S_1$  foliation indicates that the regional Negash syncline plunges at  $10^0$  to  $210^0$  (shallowly SW-plunging). This calculated beta axis in a plot of poles to planes approximates the axis of regional sub-horizontal ( $15^0$ ) SW plunging Negash syncline determined by previous researchers (e.g. Beyth, 1972 and Miller et al., 2009).

Moreover, the structural data have been plotted and manipulated in the traditional way—by hand to visualize the connection between the orientations of structures. The data plotted and contoured manually using Kamb method (Fig 5.6) and using powerful GEORient software show no great difference in orientations of  $S_1$  structures. Regardless of how contoured stereograms are generated, they have been interpreted and depict that pervasive  $S_1$  foliation dip broadly toward NW-direction.

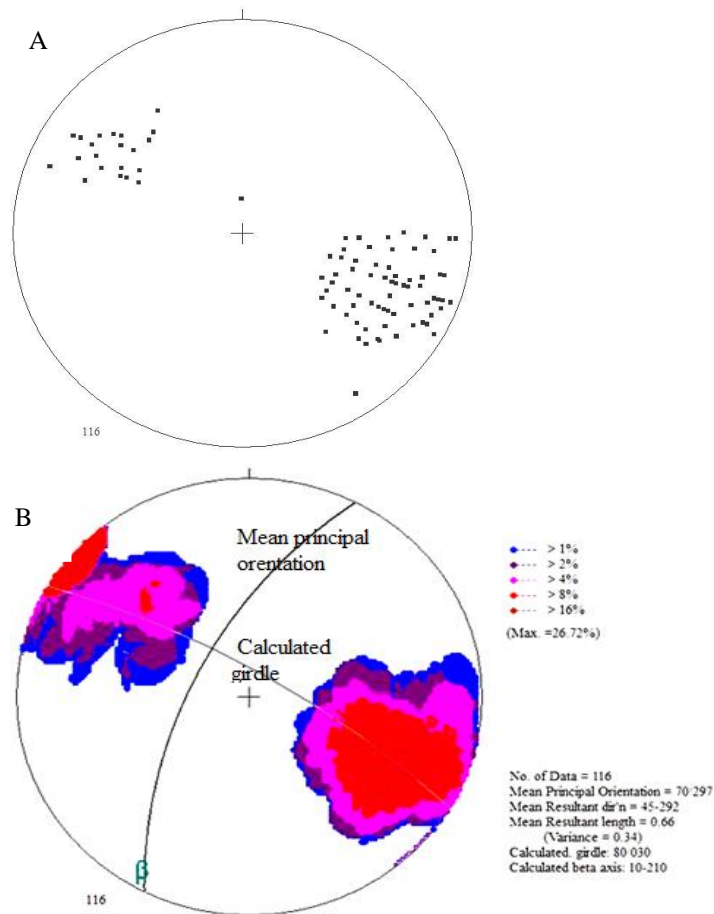


Fig.5.5. Lower hemisphere equal area stereonet plot of S<sub>1</sub> foliation data. (A) plot of poles to the foliation, and (B) contoured polar plot. The plot indicates that the metavolcanics is folded about a shallowly SW-plunging axis.

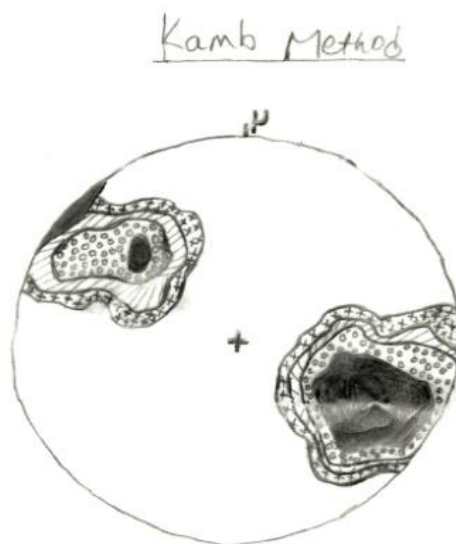


Fig.5.6. Manual lower hemisphere equal area stereonet plot of S<sub>1</sub> foliation data

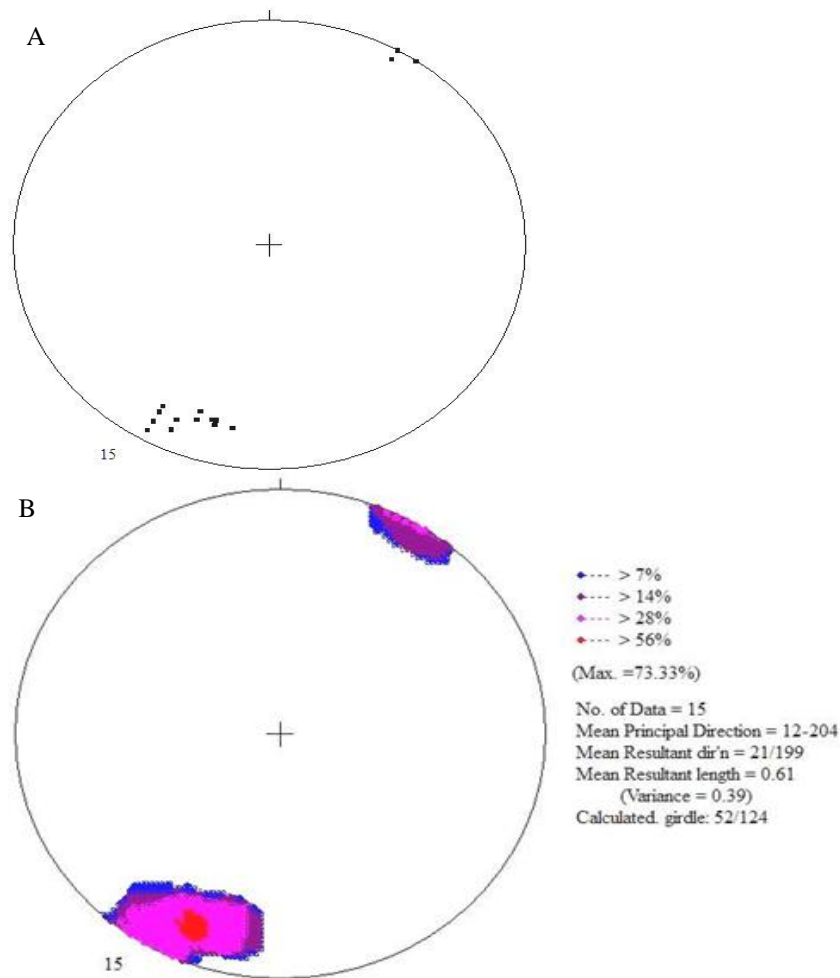


Fig.5.7. Linear (A) and contoured linear (B) lower hemisphere equal area stereonet plot of crenulation lineation

The geometrical relation among planar and linear geological structures in present study can be understood from the data plotted as poles in stereographic projection (Fig.5.5 and 5.7). As it is clearly seen from the Fig.5.5 the poles of the plotted planar structures are not concentrated around one area in the stereonet which possibly indicates the area has experienced different phase of deformations. They show certain pattern; that is the majority of the poles are generally clustered in southeastern part of the net. The stereographic projection of the plunge of linear structures is concentrated dominantly in SW and secondarily NE part of the stereonet. However, the average value of the plunge of the lineations is  $12^{\circ}$  toward  $204^{\circ}$  (SW) with a few exception of NE-plunging lineations (Fig.5.7), and this orientation is almost parallel to the statistically calculated regional fold axis in Fig.5.5 and to the average orientation of the mesoscopic fold axis.

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## 5.4. MICROSTRUCTURES

### 5.4.1. INTRODUCTION

Porphyroblasts with inclusion patterns contain information on the nature of early deformation and metamorphic events, and on the relative age of mineral growth and deformation (Passchier and Trouw, 2005). It is therefore usually advantageous to decipher the porphyroblast–matrix relationship in metamorphic rocks in any area for large-scale tectonic studies. If the matrix around the growing porphyroblasts had a compositional layering or a shape preferred orientation of grains, this fabric may be partly preserved when grains are included in the porphyroblasts leading to an inclusion pattern, which mimics the pre-existing fabric. Understanding the timing of porphyroblast growth relative to the development of surrounding metamorphic foliations is a fundamental requirement for useful applications of porphyroblast microstructures in regional deformation-metamorphic studies (Passchier and Trouw, 2005). Porphyroblasts which are formed prior to a specific deformation episode (pre-tectonic porphyroblasts) generally show strong deflection of matrix foliation around the porphyroblast that indicates the pre-existence of the rigid grain prior to the deformation causing the development of the matrix foliation (Barker, 1998). The inclusion pattern within post-tectonic porphyroblasts is identical to and continuous with the external fabric (Passchier and Trouw, 2005).

The microstructures used to describe and identify phases of deformation and metamorphic processes are these internal and external foliations. The study of foliation in thin section is an important tool to unravel the tectonic and metamorphic evolution of an area, and foliation is also used as reference structures to establish the relative growth periods of metamorphic minerals, especially porphyroblasts (Passchier and Trouw, 2005). Overprinting relations between foliations are probably the most useful tools to study the tectonic evolution of a body of rock. According to Pumpelly's rule small structures are a key to and mimic the orientation of larger structures of the same generation within particular areas. The principle for establishing a sequence of foliation planes is quite simple: if microfolds are visible the folded surfaces are always older than the fabric elements developed along the axial surface, or cutting the folds. A second phase of deformation ( $D_2$ ) commonly produces a crenulation cleavage, folding  $S_1$  (Passchier and Trouw, 2005).

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In the present contribution it was attempted to decipher the history of deformation and metamorphic mineral growth in the Tsaliet Group in Negash study area through the study of different micro-textures. Thus, in the present study various microstructures observed in the Tsaliet rock units especially in slate, phyllite, and to some extent in quartz-mica schists or metabreccia has been described. This micro-textural analysis has been used to understand micro-scale deformation stages, and an attempt is made to relate these microstructures to the regional deformational events. Moreover, a correlation is established between metamorphic and deformation events on the basis of porphyroblast-matrix relationships preserved in porphyroblasts found in the studied rocks of the area. In general, microstructural features suggest that there are different generations of matrix fabrics growth from syn-D<sub>1</sub> to at least early-D<sub>2</sub> events. As the small scale structures are a key to understand the regional structures of the area focus on microstructures should be considered.

#### **5.4.2. S<sub>0</sub>/S<sub>1</sub> FABRIC**

Out of 22 studied thin-sections, eight (8) samples were selected for micro-structural description because they show prominent metamorphic fabrics and also porphyroblast growth. The common case observed in the study area is to find compositional layering (bedding, S<sub>0</sub>) in slate and phyllite parallel to a tectonic fabrics. The primary/relict lithological layering is characterized by alternating concentrations of phyllosilicate-rich (mica) and quartz-rich domains where the domain boundary trends parallel to the foliation showing variable thickness from cm to mm scale (see Fig.5.8). As it is noted in Passchier and Trouw (2005), the presence of layering in the slate has been considered as primary compositional foliation in that considerable variation in thickness, variable composition and grain size of layers and usual planar layering was recognized which is not the case in secondary bedding formed due to metamorphic differentiation. Hence, it is reasonable to interpret the microcompositional layering as relict pyroclastic beds.

Slates possess a slaty cleavage defined by aligned fine grained platy phyllosilicates (micas and chlorite). The strongly developed S<sub>1</sub> cleavage is parallel to the bedding resulting in a composite fabric (see Figs.5.8 and 5.9). Samples of phyllite from the area have prominent penetrative S<sub>1</sub> foliation fabrics. Biotite and muscovite occur as sub-idioblastic laths and show remarkable parallelism, defining the main S<sub>1</sub> foliation. Microscopically, the dominant

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structural fabric in rocks of interest area is a regional cleavage defined by the preferred orientation of muscovite laths, elongate quartz and plagioclase grains.

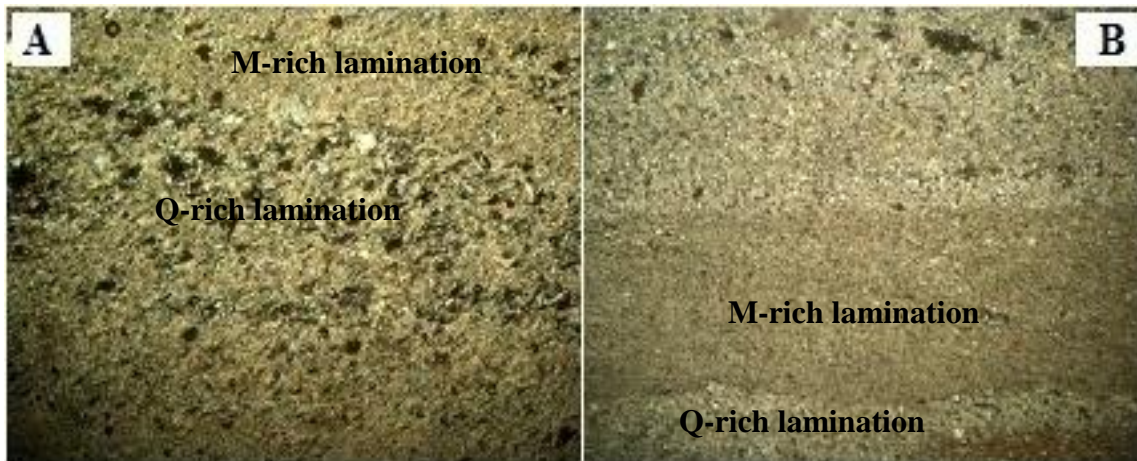


Fig.5.8. Photomicrographs showing foliation defined by compositional layering in slate. Note alternate bands of quartz- and mica-rich domains showing variable thickness (under XPL view, total magnification 40x)

#### 5.4.3. S<sub>2</sub> FABRIC

In phyllite and slate weak to strong crenulation cleavage developed due to the later deformation (D<sub>2</sub>). During D<sub>2</sub> deformation phase, new minerals have grown oblique to the pre-existing S<sub>1</sub> foliation and developed crenulation cleavage (see top of Fig. 5.9), and it is defined by mica, recrystallized quartz, calcite, chlorite, and epidote. The second schistosity is the crenulation cleavage which was formed on account of crenulation of S<sub>1</sub> foliation during D<sub>2</sub> (see Figs.3.10 and 5.10A). The S<sub>2</sub> has developed almost perpendicular to the S<sub>1</sub> and is observed to have formed only in the phyllosilicate rich layers (Fig.5.9). In quartz-mica phyllite, micro-folding of bedding is recognized (see Fig 5.9 below). Thus, if the earlier fabric was approximately bedding-parallel, the crenulations form with their axial planes at a high angle to bedding.

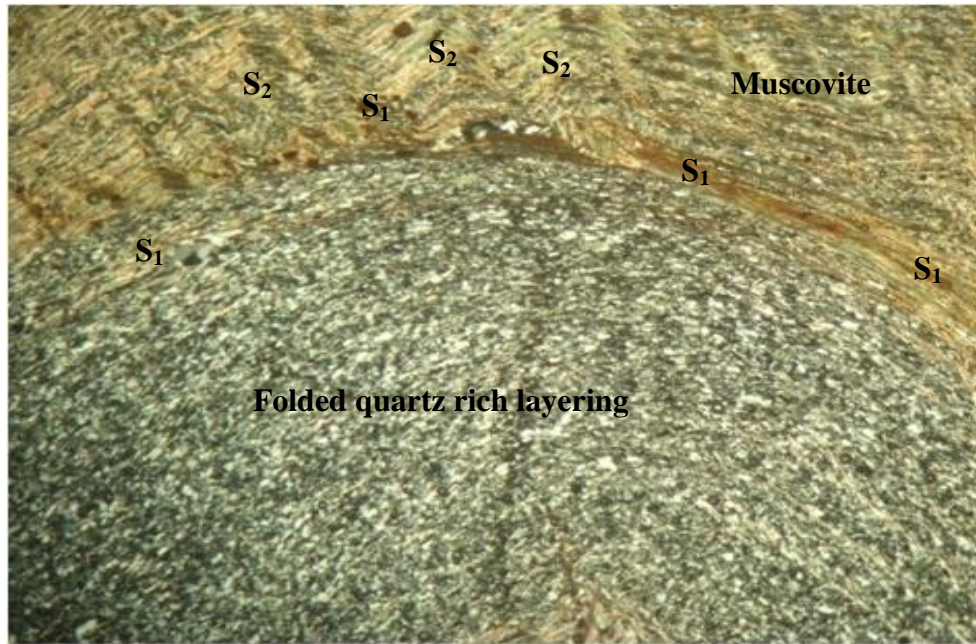


Fig.5.9. Photomicrograph showing folded bedding  $S_0$  with strong  $S_1$  cleavage, and weak and spaced  $S_2$  crenulation cleavage. An older slaty cleavage ( $S_1$ ) is present subparallel to  $S_0$  (under XPL view, total magnification 40x).

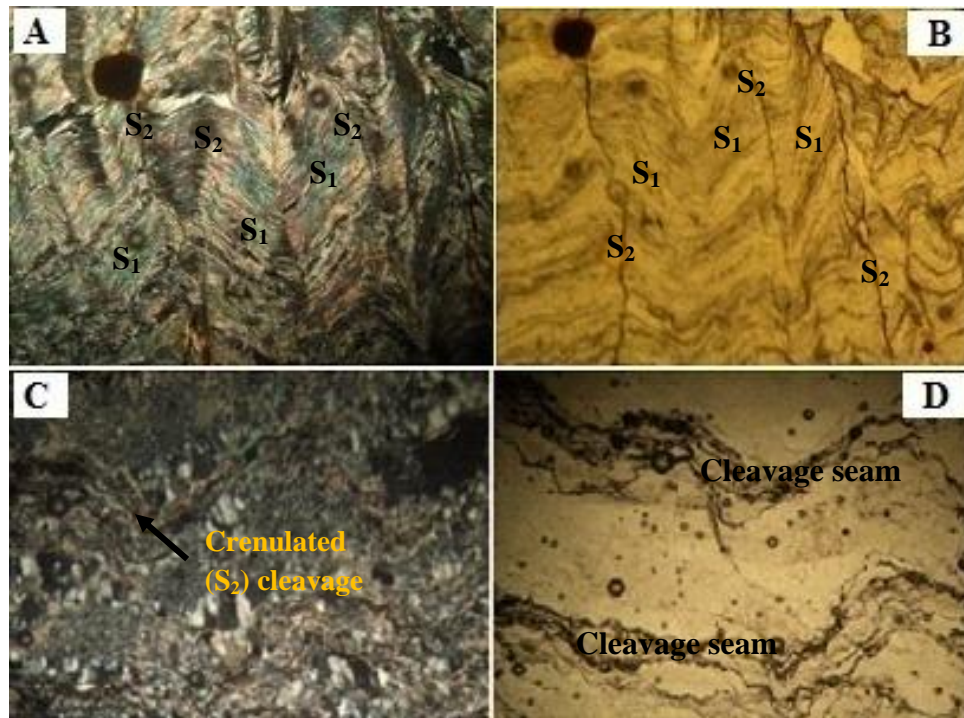


Fig.5.10. Photomicrographs exhibiting A) crenulated  $S_1$  fabric forming crenulation cleavage viewing under XPL; B) similar thin-section under PPL; C) slightly folded  $S_1$  and quartz vein observed under XPL and D) note that the folded cleavage seams are clearly visible under PPL. (40x total magnification).

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Pressure solution and solution transfer of material is dominant at low grade metamorphic conditions where the seams of opaque minerals showing cleavage zones are abundant and suggesting fluids are abundant (Passchier and Trouw, 1998), which is the case in the Negash region. According to Passchier and Trouw (1998), the alignment of dark cleavage seams (opaque minerals) indicates the transfer of more soluble materials (e.g. silica) out of the local system by dissolution solution along cleavage surfaces. In such cases, thin dark cleavage seams of the insoluble opaque minerals form. The cleavage zones as dark seams are completely devoid of quartz which otherwise occurs in microlithon (Fig.5.10D). This may indicate that pressure solution was one of mechanisms for crenulation cleavage development of Tsaliet Group rocks in study area.

#### **5.4.4. MICRO-VEINS**

Veins are sub-planar concentrations of minerals that have precipitated from solution in fractures. If a large number of deformed veins of different orientation are present in a rock, they can be used to obtain information on the deformation process. Microscopic study of the rocks of study area shows a variety of relations between veins and schistosity. Monomineralic veins such as quartz veins are common in most of rock units along the schistosity and also cutting across the main fabric. Microscopically, deformed quartz veins in slate-phyllite rock units can be used to determine the deformation phases of present study area. A close examination of the veins reveal the presence of multiple generations in the area: (1) the first one comprises early and widespread veins that are mainly concordant, deformed and folded with enclosing rocks by  $D_2$  deformation, and deflecting the crenulation cleavage formed by  $D_2$  (see Fig.5.11A). The veins of this type seem to be introduced along major bedding structures; (2) the second generation represents a younger phase of less abundant veins, and intrudes the  $S_0$  and  $S_1$  fabric but slightly folded by  $D_2$  deformation (Fig.5.12). In addition, monomineralic veins of epidote also occur in a few samples (Fig.5.13). These metamorphic epidote veins either replaced plagioclase as veins or precipitate out of a fluid (hydrothermal process) that accompanied the greenschist facies metamorphism as the vein cross the incipient foliation. These veinlets of metamorphic minerals may indicate some brittle deformation during or before metamorphism in which veins were precipitated in the joints and later deformed. The axis of folded quartz veinlets is parallel to the  $S_2$  schistosity plane which indicates they are co-axially folded. Moreover, the quartz grains in the veins are

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unstrained and shows triple junction (e.g. see Figs.5.11) which possibly indicating that the veins are developed pre-deformation and later recrystallized due to metamorphism associated with the regional deformation.

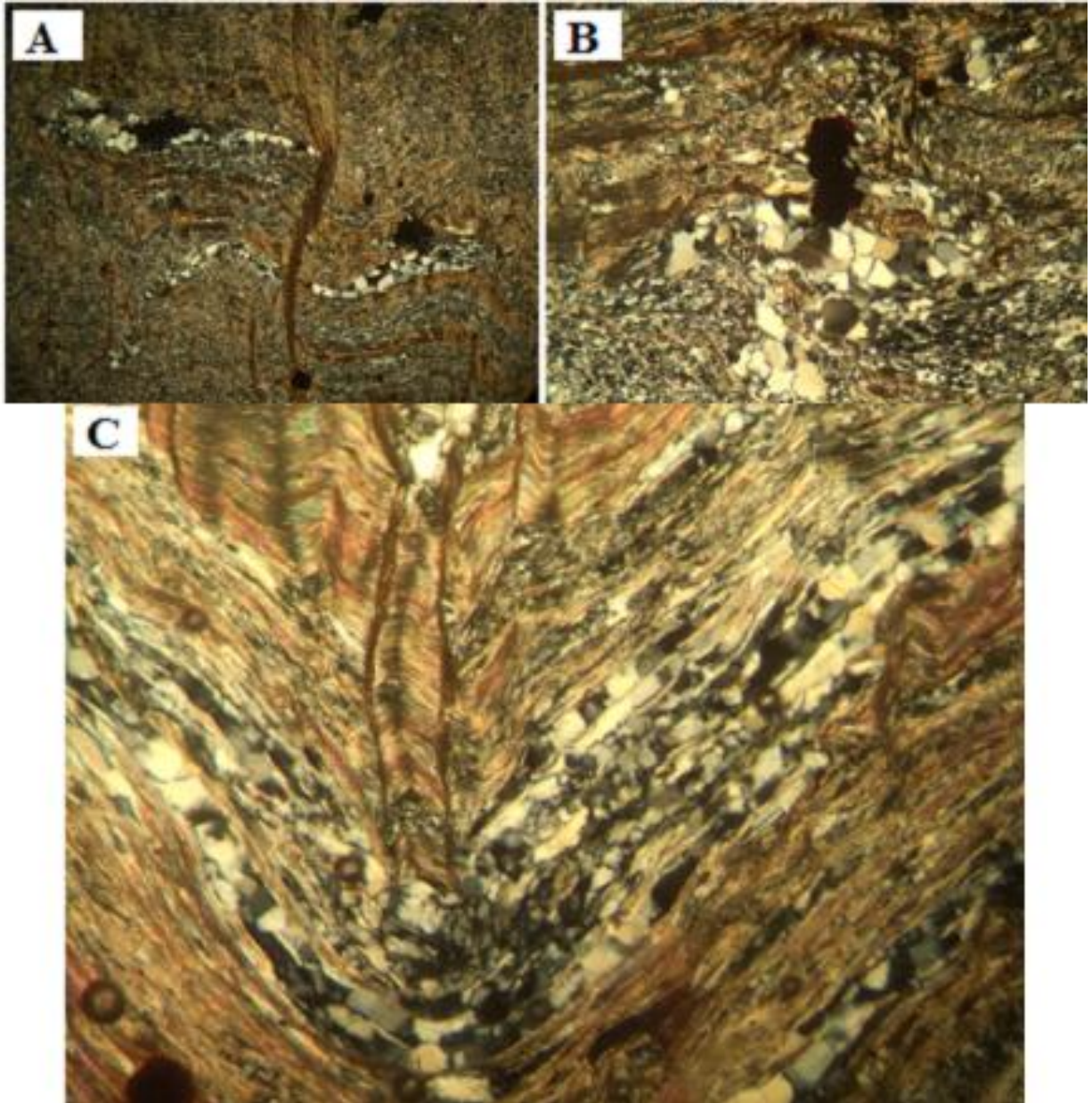


Fig.5.11. Photomicrographs showing folded quartz lenticles/veins in phyllitic rock unit (A) the development of strong crenulation cleavage deflecting around the quartz lenticles. Notice the detachment of the vein due to pressure solution effects at the limbs of the fold; B) openly folded quartz vein; C) tightly folded quartz veins along  $S_1$  fabric refolded by microfolds ( $F_2$ ). Note that in (Fig. 5.11C) a phyllitic cleavage dies out towards a folded competent lamina (under XPL, 40x total magnification)

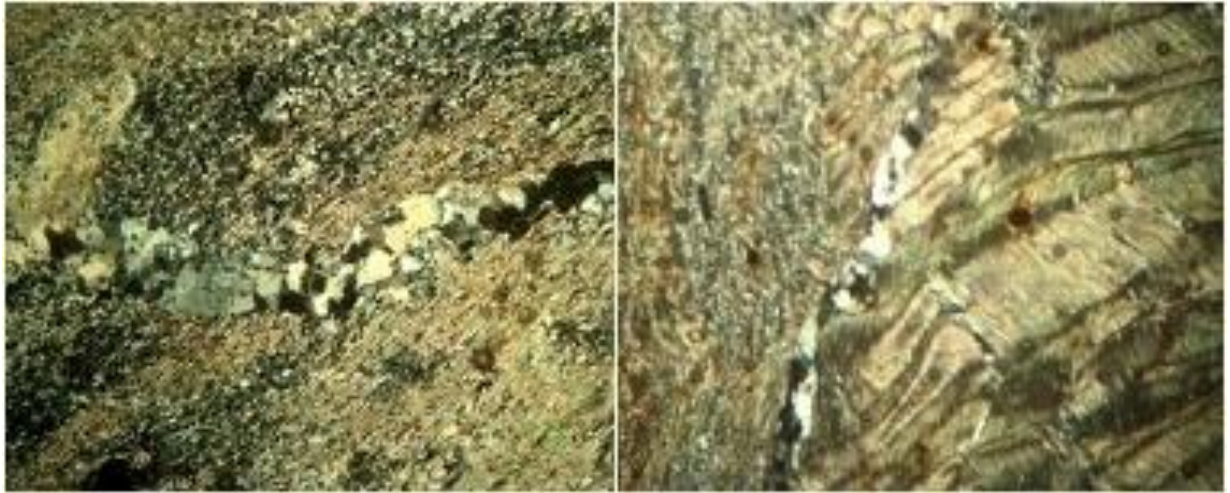


Fig.5.12. Microphotographs showing slightly folded discordant quartz veins in volcanic metabreccia (left) and in highly crenulated phyllite (right) (under XPL view, 40x total magnification)

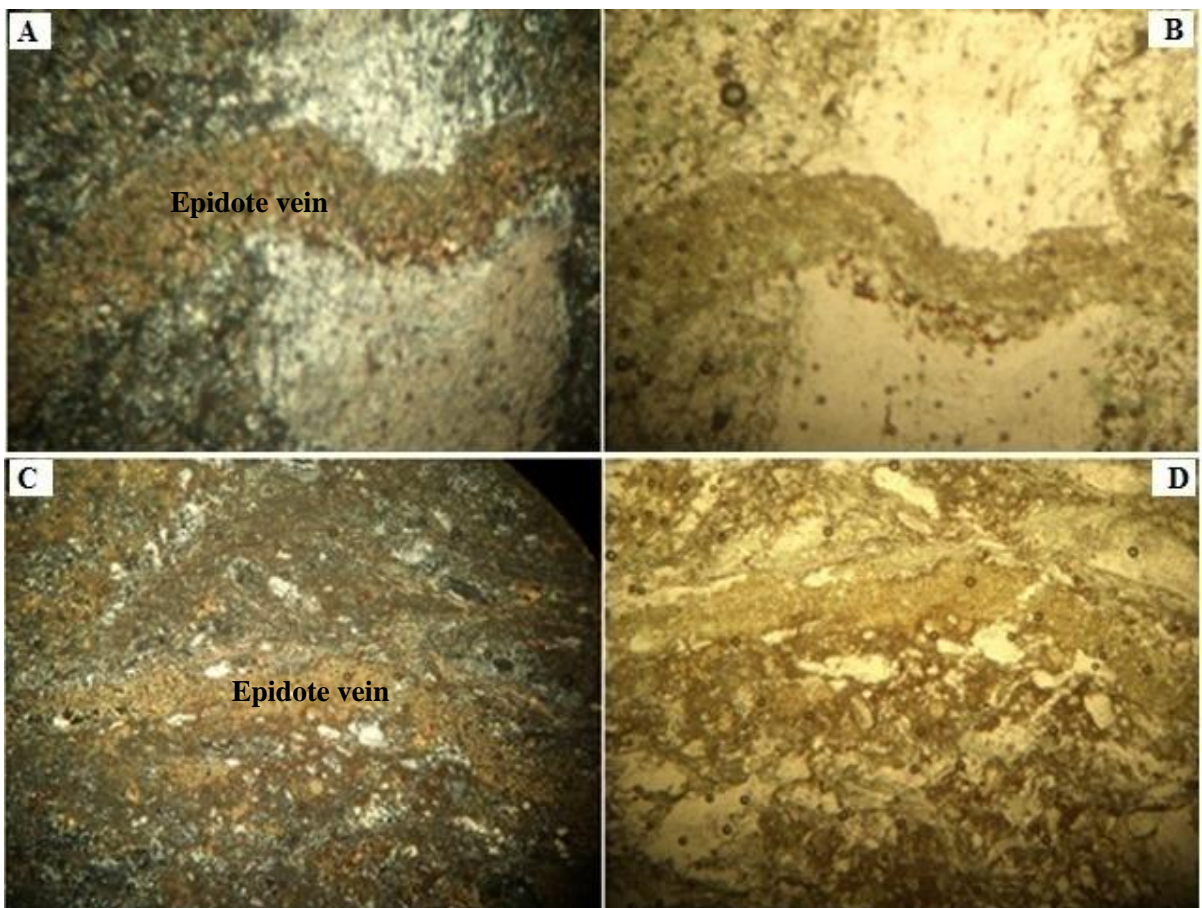


Fig.5.13. Photomicrographs of epidote veins in metabasaltic andesite (sample no. NT4-1 and NT4-4), (A and C) - under XPL view; (B and D)-under PPL, 40x total magnification.

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## 5.5. TIME RELATION OF DEFORMATION AND METAMORPHISM

The relationship between  $S_i$  within the porphyroblasts and the matrix foliation ( $S_e$ ) outside the porphyroblast was used to determine the relative timing of growth of minerals with reference to foliation of a particular generation. As observed from mineral assemblages and microstructural features, the Tsaliet Group of study area record three metamorphic events: (1) an early, regional lower greenschist facies synchronous with  $D_1$ ; (2) a local thermal metamorphism (growth of low pressure and temperature andalusite mineral) caused by granitoid intrusion; (3) a late phase presumably related to  $D_2$  folding. Chlorite, muscovite and biotite crystals occur along foliations of different generations and are accordingly classified. Chlorite<sub>1</sub>, muscovite<sub>1</sub> and biotite<sub>1</sub> occur (Fig. 3.8) along the  $S_1$  schistosity and are syn- $D_1$ , hence belong to  $M_1$  stage of metamorphic event. Information on the  $M_1$  metamorphism of the area also comes from internal schistosity inside porphyroblast of andalusite in more schistosed rock units. The reference for  $S_i$  inclusions made here is that they are early in the sense that they were enclosed within the growing porphyroblasts. Internal fabric  $S_i$  in the andalusite porphyroblast is marked by muscovite<sub>1</sub>, quartz (quartz<sub>1</sub>) grain of relatively small, inequant to slightly equant grain size whereas quartz (quartz<sub>2</sub>) grains of the external foliation are elongated, coarse and occasionally shows polygonal texture (see Fig.5.14). The planar  $S_i$  fabric marked by such small, tiny quartz and muscovite grains in the porphyroblasts may be considered as relict of initial schistosity and their growth history may be correlatable with syn-tectonic stage of metamorphism ( $M_1$ ) i.e.  $M_1$  stage of  $D_1$  deformation. Typically, deflection of  $S_e$  matrix at the margins of the porphyroblasts (Fig.5.14) indicate that growth history of the larger mineral was prior to the formation of external schistosity during  $D_2$  deformation and hence treated as post-tectonic to  $D_1$  or pre-tectonic to  $D_2$  (inter-tectonic between  $D_1$  and  $D_2$ ) and marked as  $M_2$  metamorphic indicator (andalusite<sub>2</sub>). Hence, it is apparent that the  $S_i$  fabric of the andalusite<sub>2</sub> porphyroblast shows the evidence of earlier foliation as relict (pre- $S_2$ ). In addition, the regional primary foliation ( $S_1$ ) is folded by  $F_2$  fold forming crenulation cleavage ( $S_2$ ) that is considered as syn-genetic to  $M_3$  metamorphic stage synchronous to  $D_2$  deformation (e.g. Fig.5.9). Strain shadow zone (low strain zone) can be inferred in the porphyroblasts. Such coarse quartz-rich pressure shadow zone confirms that the andalusite acts as rigid body during the formation of matrix foliation ( $S_2$ ), and may be

referred to as quartz<sub>3</sub> indicative of phase of syn-genetic to D<sub>2</sub> deformation, showing relatively strain-free grains with straight grain boundaries (see Fig.5.14).

Table-5.1: Stages of deformational events and their correlation with growth of various minerals indicative of grade of metamorphism

M <sub>1</sub>	M <sub>2</sub>	M <sub>3</sub>
Syn-tectonic to D <sub>1</sub>	Inter-tectonic between D <sub>1</sub> and D <sub>2</sub>	Syn-tectonic to D <sub>2</sub>
-----	Andalusite <sub>1</sub>	-----
Biotite <sub>1</sub>	Biotite <sub>2</sub>	Biotite <sub>3</sub>
Muscovite <sub>1</sub>	Muscovite <sub>2</sub>	Muscovite <sub>3</sub>
Quartz <sub>1</sub>	Quartz <sub>2</sub>	Quartz <sub>3</sub>
Chlorite <sub>1</sub>	Chlorite <sub>2</sub>	Chlorite <sub>3</sub>

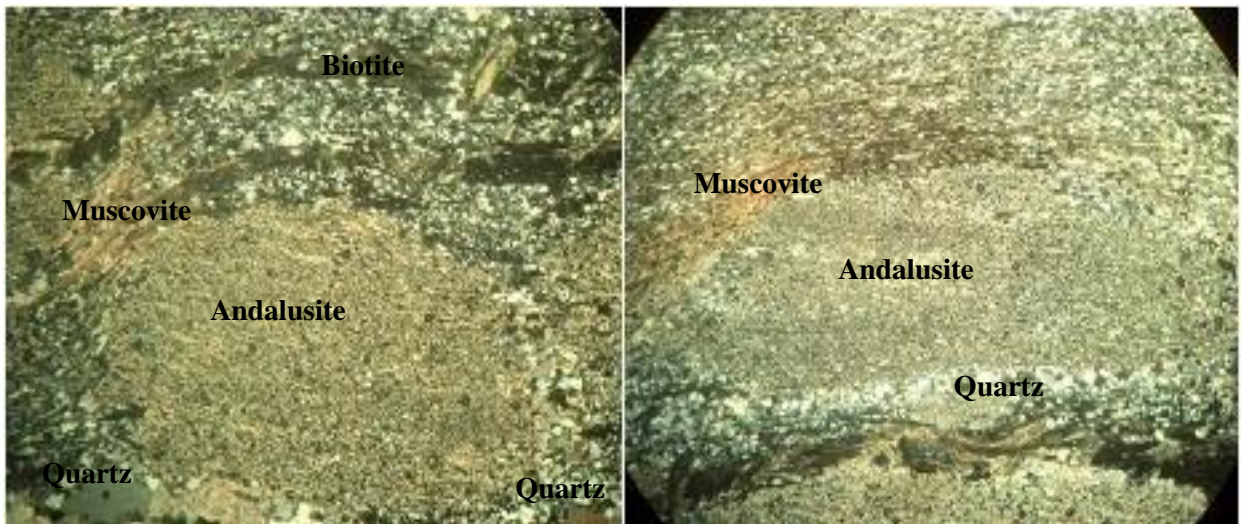


Fig.5.14. Deflection of S<sub>e</sub> around the porphyroblast (altered andalusite), and the pressure shadow in phyllite (under XPL view, 40x total magnification)

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## CHAPTER-SIX

### 6. GEOCHEMICAL ANALYSIS AND INTERPRETATION

#### 6.1. ROCK GEOCHEMICAL CHARACTERISTICS

Tsaliet Group rock units of the study area are characterized by a wide compositional range of some major oxides and trace elements concentrations (45.05– 65.48 wt. %  $\text{SiO}_2$ ), (1.18–14.11 wt. %  $\text{MgO}$ ), (0.095- 0.189 wt. %  $\text{MnO}$ ), and (0.02-1.9 wt. %  $\text{KO}_2$ ), high Cr (90- 460ppm), Ni (<20–130 ppm), and Nb (0.2-9.3 ppm). Both analyzed rock units show very low  $\text{KO}_2$  contents (<1.9ppm).  $\text{Fe}_2\text{O}_3$  (T) content seems to be relatively high ranging between 4.15 and 9.48 wt %. The high iron contents appear to reflect an abundant secondary opaque phase (magnetite?). The metavolcanic rock samples have higher Cr (220-460ppm) content than the metavolcanicclastics (90-110ppm). The three samples of MV show low Zr, Rb and Ba content and the remaining samples of MVC show high content. In addition, both rocks are characterized by very low content of Ti.

Chemical data of the analyzed samples are presented in Table-6.1, and plotted in a number of variation and tectonic discrimination diagrams (Figs. 6.1–6.5). In order to explain the possible alteration effects of metamorphism and deformation, element mobility is noticed through plotting major and selected trace elements against silica ( $\text{SiO}_2$  wt %). Fig. 6.1 shows major oxides Harker-type variation diagrams of the studied samples, from which it is evident that  $\text{Al}_2\text{O}_3$ ,  $\text{Fe}_2\text{O}_3$  (T),  $\text{MgO}$  and  $\text{MnO}$  are correlate negatively with increasing  $\text{SiO}_2$  (magmatic differentiation). It is likely that the trends indicate the fractionation of olivine, pyroxene, and magnetite during evolution of the magma. Conversely,  $\text{Na}_2\text{O}$  and  $\text{K}_2\text{O}$  correlate positively with increasing  $\text{SiO}_2$  concentration, which are incompatible with the presence of mafic minerals. Similarly, after initial enrichment,  $\text{TiO}_2$  concentrations simultaneously decrease, indicating the crystallization of Ti-bearing pyroxene and Fe-Ti oxides (hematite/ilmenite). Major element Harker variation diagrams reveal an expected linear variation for a group of co-genetic lavas.

The total alkalis vs  $\text{SiO}_2$  classification (Cox et al., 1979) shows that three samples of studied rocks fall in basaltic andesite, and andesite field suggesting intermediate

composition, and the remaining two samples fall in rhyolite field reflecting rhyolitic composition (see Fig. 6.5C).

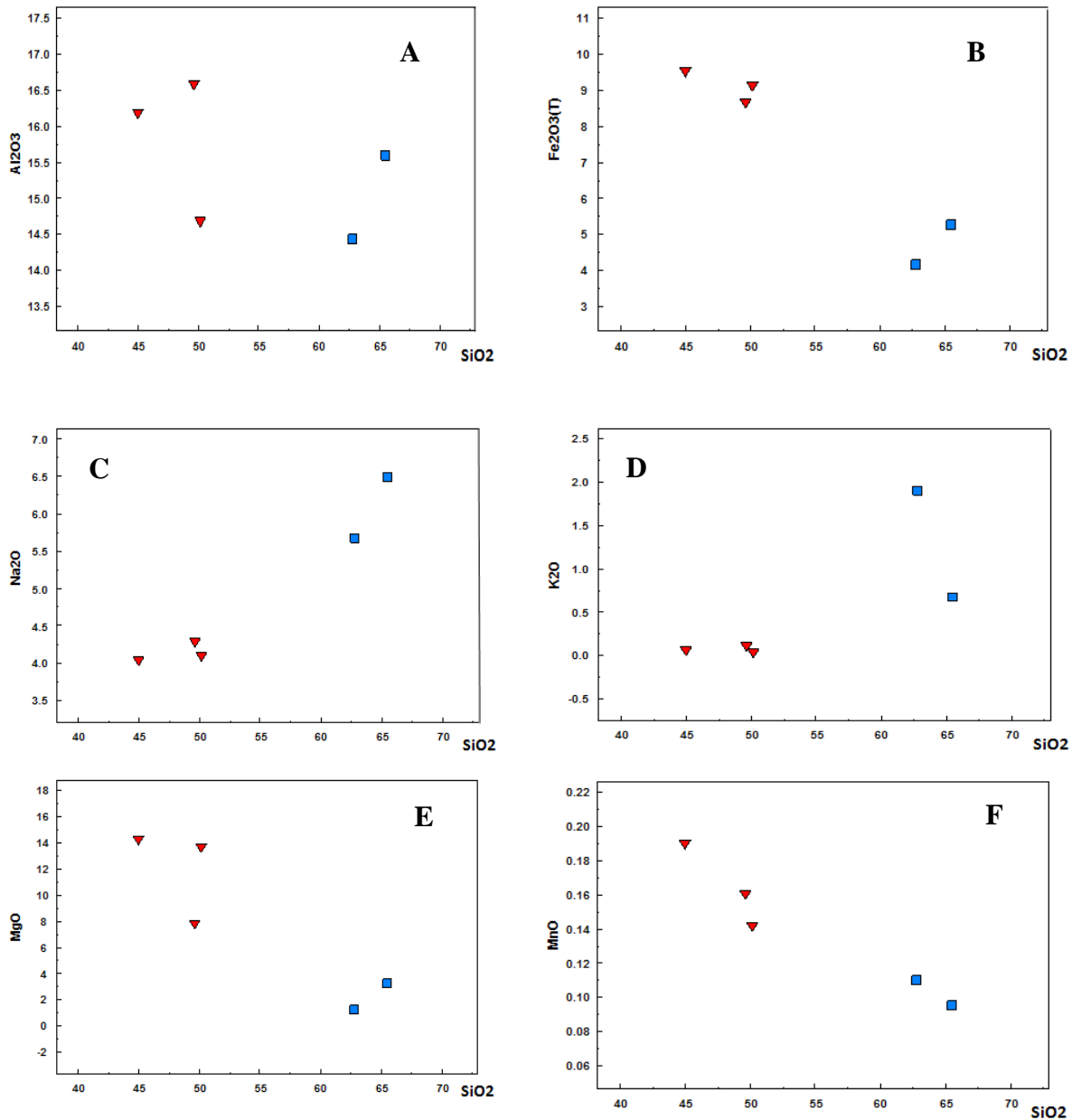


Fig.6.1. Harker-type variation diagrams showing the variation in A) Al<sub>2</sub>O<sub>3</sub>, B) Fe<sub>2</sub>O<sub>3</sub> (T), C) Na<sub>2</sub>O, D) K<sub>2</sub>O, E) MgO, and F) MnO with respect to SiO<sub>2</sub> for the rocks of study area (Symbols: Closed triangle = MV (metabasaltic andesite and meta-andesite), and closed cubic box =MVC (metabreccia))

Table-6.1. Major, trace and REE elements data of the Tsaliyet Group rocks from Negash area

Analyte	Unit	Detection Limit	(NT4-1)	(NT3-5)	(NT4-2)	(NT3-7)	(NT4-5)
<b>SiO<sub>2</sub></b>	%	0.01	49.66	65.48	45.05	62.76	50.15
<b>Al<sub>2</sub>O<sub>3</sub></b>	%	0.01	16.55	15.59	16.16	14.43	14.65
<b>Fe<sub>2</sub>O<sub>3(T)</sub></b>	%	0.01	8.63	5.26	9.48	4.15	9.07
<b>MnO</b>	%	0.001	0.16	0.095	0.189	0.11	0.141
<b>MgO</b>	%	0.01	7.67	3.17	14.11	1.18	13.54
<b>CaO</b>	%	0.01	8.79	1.19	2.9	4.97	1.27
<b>Na<sub>2</sub>O</b>	%	0.01	4.26	6.48	4.02	5.66	4.08
<b>K<sub>2</sub>O</b>	%	0.01	0.09	0.67	0.04	1.9	0.02
<b>TiO<sub>2</sub></b>	%	0.001	0.551	0.594	0.958	0.51	0.512
<b>P<sub>2</sub>O<sub>5</sub></b>	%	0.01	0.1	0.18	0.27	0.15	0.09
<b>LOI</b>	%		3.22	1.91	5.55	3.85	5.87
<b>Total</b>	<b>%</b>		<b>99.7</b>	<b>101</b>	<b>98.7</b>	<b>99.7</b>	<b>99.4</b>
<b>Sc</b>	ppm	1	38	15	32	11	41
<b>Be</b>	ppm	1	< 1	1	< 1	< 1	< 1
<b>V</b>	ppm	5	247	128	244	84	255
<b>Cr</b>	ppm	20	220	90	390	110	460
<b>Co</b>	ppm	1	40	15	49	6	44
<b>Ni</b>	ppm	20	60	< 20	130	< 20	80
<b>Cu</b>	ppm	10	< 10	10	540	< 10	< 10
<b>Zn</b>	ppm	30	70	90	110	30	80
<b>Ga</b>	ppm	1	17	18	19	13	15
<b>Ge</b>	ppm	0.5	2.3	1.7	1.2	2.3	1.6
<b>As</b>	ppm	5	< 5	< 5	< 5	5	< 5
<b>Rb</b>	ppm	1	1	10	< 1	27	< 1
<b>Sr</b>	ppm	2	290	153	123	325	27
<b>Y</b>	ppm	0.5	10.6	19.2	15.3	17	10.2
<b>Zr</b>	ppm	1	26	113	53	115	21
<b>Nb</b>	ppm	0.2	0.7	3	1.3	9.3	0.2
<b>Mo</b>	ppm	2	< 2	< 2	< 2	< 2	< 2
<b>Ag</b>	ppm	0.5	< 0.5	1.1	< 0.5	1.1	< 0.5
<b>In</b>	ppm	0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
<b>Sn</b>	ppm	1	< 1	< 1	< 1	1	< 1
<b>Sb</b>	ppm	0.2	1.2	0.8	1.2	0.5	0.9
<b>Cs</b>	ppm	0.1	< 0.1	0.3	< 0.1	0.6	< 0.1
<b>Ba</b>	ppm	3	56	112	21	618	13

<b>La</b>	ppm	0.05	2.6	12.9	6.78	12.2	2.3
<b>Ce</b>	ppm	0.05	6.32	34.9	17.3	26.9	5.07
<b>Pr</b>	ppm	0.01	0.87	3.54	2.46	3.44	0.96
<b>Nd</b>	ppm	0.05	4.29	15.4	12.2	13.9	5.12
<b>Sm</b>	ppm	0.01	1.34	3.66	3.17	3.51	1.66
<b>Eu</b>	ppm	0.005	0.495	1.02	1.06	0.891	0.586
<b>Gd</b>	ppm	0.01	1.72	3.29	3.1	2.94	1.72
<b>Tb</b>	ppm	0.01	0.33	0.61	0.53	0.53	0.32
<b>Dy</b>	ppm	0.01	2.06	3.72	3.23	3.31	2.01
<b>Ho</b>	ppm	0.01	0.42	0.75	0.64	0.67	0.41
<b>Er</b>	ppm	0.01	1.23	2.17	1.8	1.96	1.21
<b>Tm</b>	ppm	0.005	0.186	0.326	0.261	0.294	0.175
<b>Yb</b>	ppm	0.01	1.26	2.23	1.66	1.95	1.12
<b>Lu</b>	ppm	0.002	0.203	0.377	0.262	0.325	0.173
<b>Hf</b>	ppm	0.1	0.7	2.6	1.4	2.7	0.6
<b>Ta</b>	ppm	0.01	< 0.01	< 0.01	< 0.01	0.31	< 0.01
<b>W</b>	ppm	0.5	0.7	< 0.5	< 0.5	< 0.5	1
<b>Tl</b>	ppm	0.05	< 0.05	< 0.05	< 0.05	0.18	< 0.05
<b>Pb</b>	ppm	5	< 5	< 5	< 5	11	< 5
<b>Bi</b>	ppm	0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
<b>Th</b>	ppm	0.05	0.28	2.22	0.38	2.12	0.21
<b>U</b>	ppm	0.01	0.14	0.78	0.13	0.78	0.09
<b>La/Sc ratio</b>	ppm		0.07	0.86	0.21	1.11	0.06
<b>La/Y ratio</b>	ppm		0.25	0.67	0.44	0.72	0.23

Plots of SiO<sub>2</sub> versus some selected compatible and incompatible trace elements concentrations are illustrated in Fig. 6.2. In general, incompatible LILE (Ba and Rb) and the high field strength element (Nb) show a fairly positive correlation with increasing SiO<sub>2</sub>. A broad negative correlation is observed between Ni, Co and Cr (Figs. 6.2B, C and E) and other compatible trace elements with increase in SiO<sub>2</sub>, suggesting fractionation of olivine, spinel and pyroxene.

Spider diagrams have been normalized with primary mantle and chondrite, and interpreted the process of magma formation. In the chondrite-normalized REE pattern (Fig. 6.3A), values of Sun and McDonough, 1989), all the analyzed rocks samples display an overall similar behaviour of the samples and define enrichment in

fractionated incompatible light rare earth element (LREE: La, Ce, Pr, Nd and Sm) contents relative to heavy rare earth elements (HREE: Tb, Dy, Ho, Er, Tm, Yb and Lu) contents with lack of Eu anomaly. The degree of REE fractionation is moderate with fairly steep slope pattern for MVC rock units while the REE are very weakly fractionated with almost flat pattern in MV rocks. There is almost parallel relationship between the REE of the studied rock samples, suggesting that they may be genetically related rocks. The absence of a Eu anomaly is an indication that plagioclase has not been an important fractionating phase since Eu is compatible in plagioclase (Rollinson, 1993).

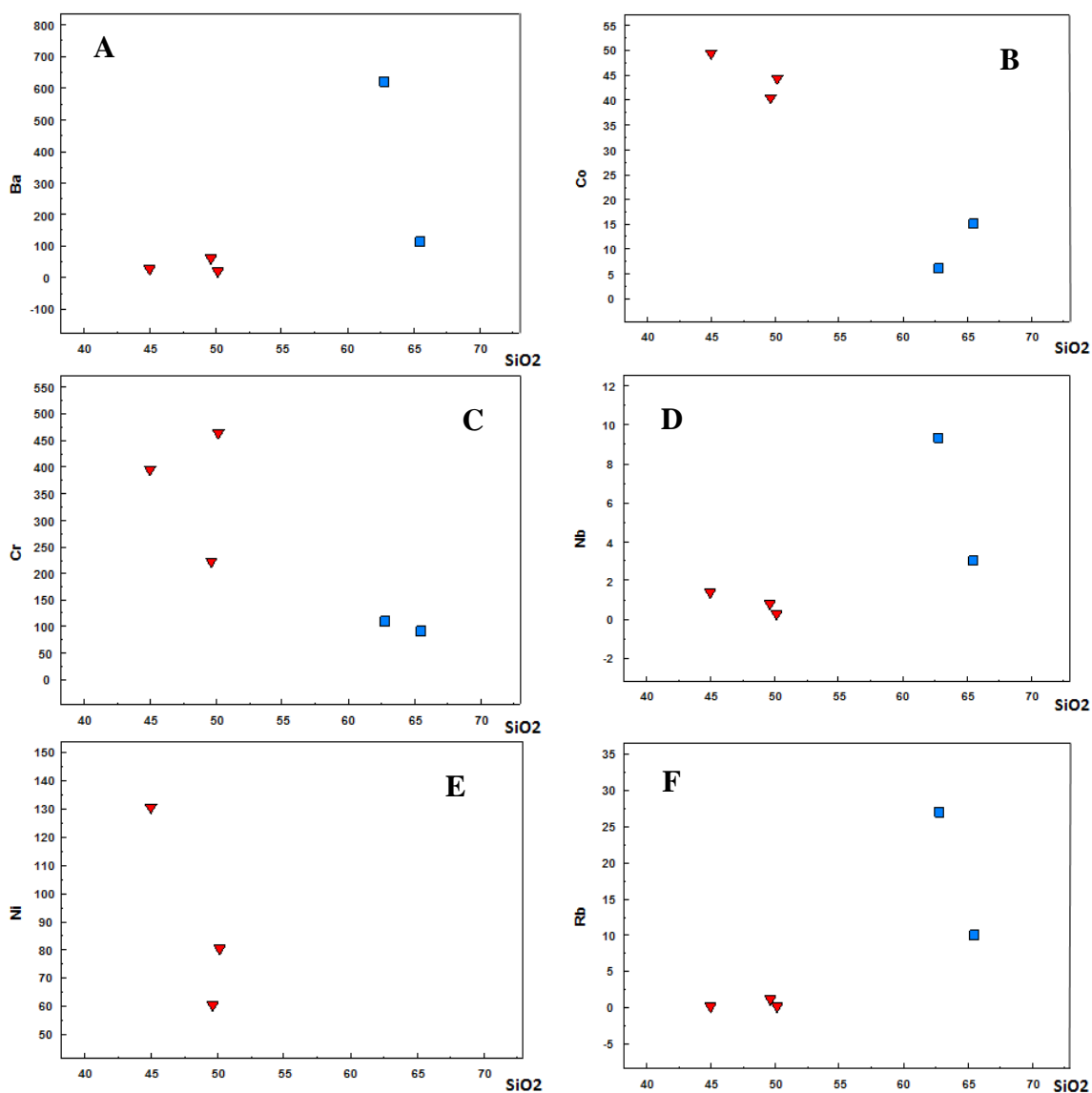


Fig.6.2. Harker-type variation diagrams showing the variation of some selected compatible and incompatible elements A) Ba, B) Co, C) Cr, D) Nb, E) Ni, and F) Rb, with respect to SiO<sub>2</sub> for the Tsaliet rock units (Symbols: as in Fig. 6.1)

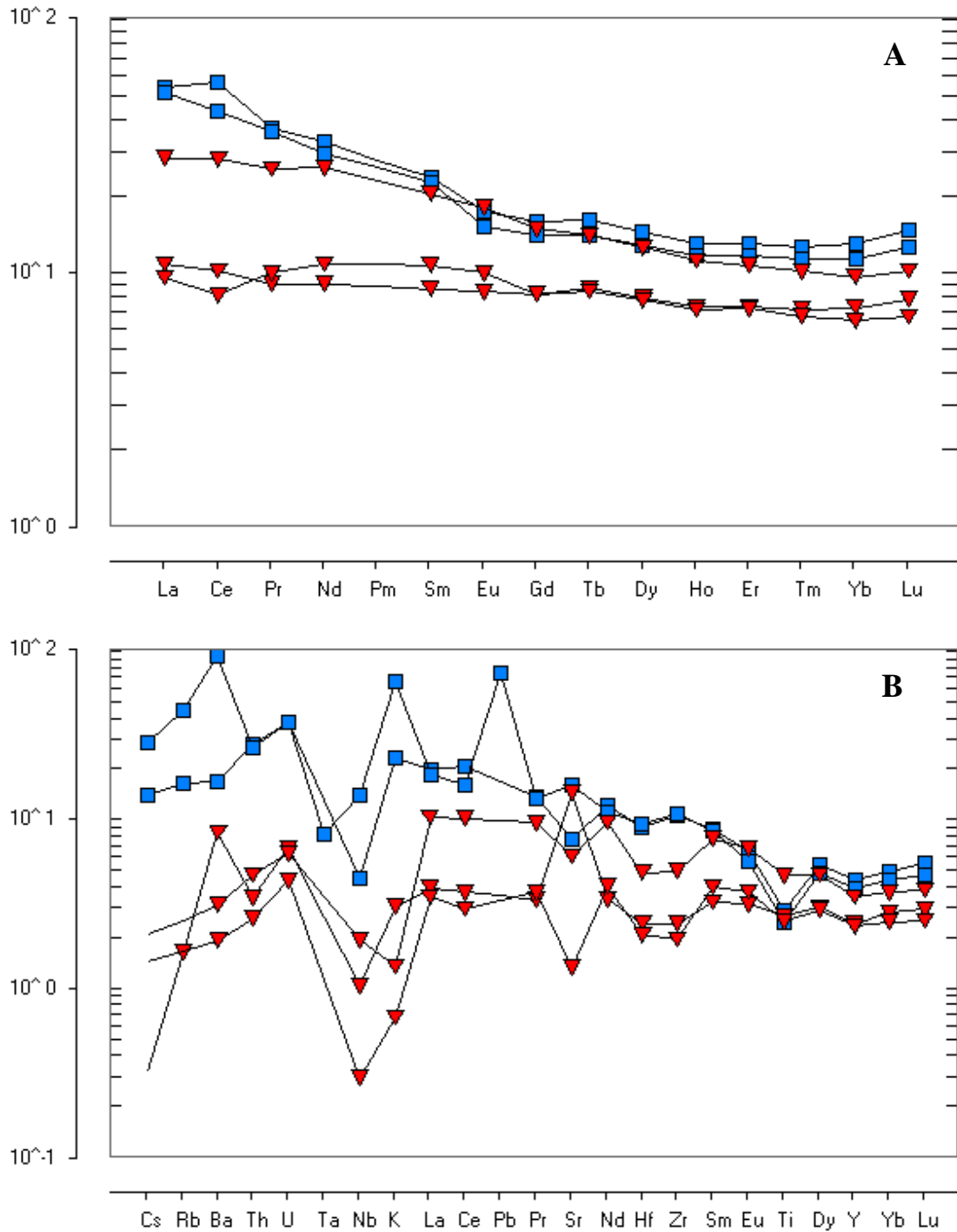


Fig.6.3. (A) Chondrite-normalized REE diagram for the Tsali Group. Chondrite normalization values are from Sun and McDonough (1989); (B) mantle-normalized multi-element diagram of the rock samples from the study area, (McDonough and Sun, 1995) (Symbols: as in Fig. 6.1)

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The marked negative Nb and slight Ti anomalies on primitive mantle normalized diagram (Fig. 6.3B), values of McDonough and Sun (1995), is considered as a diagnostic feature of subduction-related volcanic rocks as noted in White (2001). According to this author, it is probably due to the low solubility of those elements and the aqueous fluids generated by dehydration of the subducting oceanic crust could not transport these elements into the magma genesis zone of island arc volcanoes. The incompatible element enrichment of island arc magmas results from a continental component in them, originating either through sediment subduction or assimilation of crust (White, 2001). On discrimination diagram the rocks of study area possess a typical calc-alkaline island arc geochemical affinity. Hence, magmas were apparently derived from subduction zone magmatism.

Generally, geochemical variation on figures above indicate that the Negash Tsaliet Group volcanic rocks resemble the Tsaliet volcanics elsewhere in Northern Ethiopia, particularly in their low K<sub>2</sub>O and total alkali contents, hence the rocks are belong to low-K sub-alkaline magma series (Fig. 6.4).

## **6.2. PALEOTECTONIC SETTING OF THE METAVOLCANICS**

Tectonic setting is well established only for rocks in relatively youthful settings, because as rocks become more tectonized with increasing age, their original tectonic setting becomes less certain. Major, trace and rare earth element (REE) compositions of rock units from the Tsaliet Group in the Negash district of northern Ethiopia were determined to examine their tectonic setting for the genesis of their magmas. Since HFSE such as Ti, Zr, Y, Nb and P are insensitive to secondary processes (insoluble and immobile in aqueous fluids) they will be stable up to medium metamorphic grades, so these elements are good to construct tectonic discrimination diagrams (White, 2001). Hence, they can provide information on the pre-metamorphic history of the rocks of the interest area.

The discrimination diagram after Pearce, 1982 (Fig. 6.5A) indicates that the Negash Tsaliet volcanic rocks fall in volcanic arc basalt (VAB) field. In addition, many of the analyzed samples have low La/Sc (<1.1) and La/Y (<0.80) ratios. This could reflect a typical volcanic island arc setting (Bhatia and Crook, 1986 as cited in Alene et al., 2000). For the magma type, AFM discrimination diagram of Irvine and Baragar, 1971

(Fig. 6.5B) indicates that petrochemical composition of Negash Tsaliet fall within the calc-alkaline series field. Moreover,  $\text{TiO}_2$  values of the studied rocks are generally  $< 1\%$ , the range accepted in calc-alkaline magma (Pearce and Cann, 1973 as cited in Lissan and Bakheit, 2010). There is no sufficient geochemical evidence for precise determination of tectonic setting of the Negash Tsaliet group in this study, as the number of analyzed geochemical samples is small. However, the suites elsewhere studied in the region compared together with the limited present geochemical data and the results are almost consistent with the previous investigations. Based on the geochemical characteristics, Tadesse et al. (1999), Alene et al. (2000), and Sifeta et al. (2005) show that the Tsaliet volcanics fall within volcanic arc basalt field and calc-alkaline in nature.

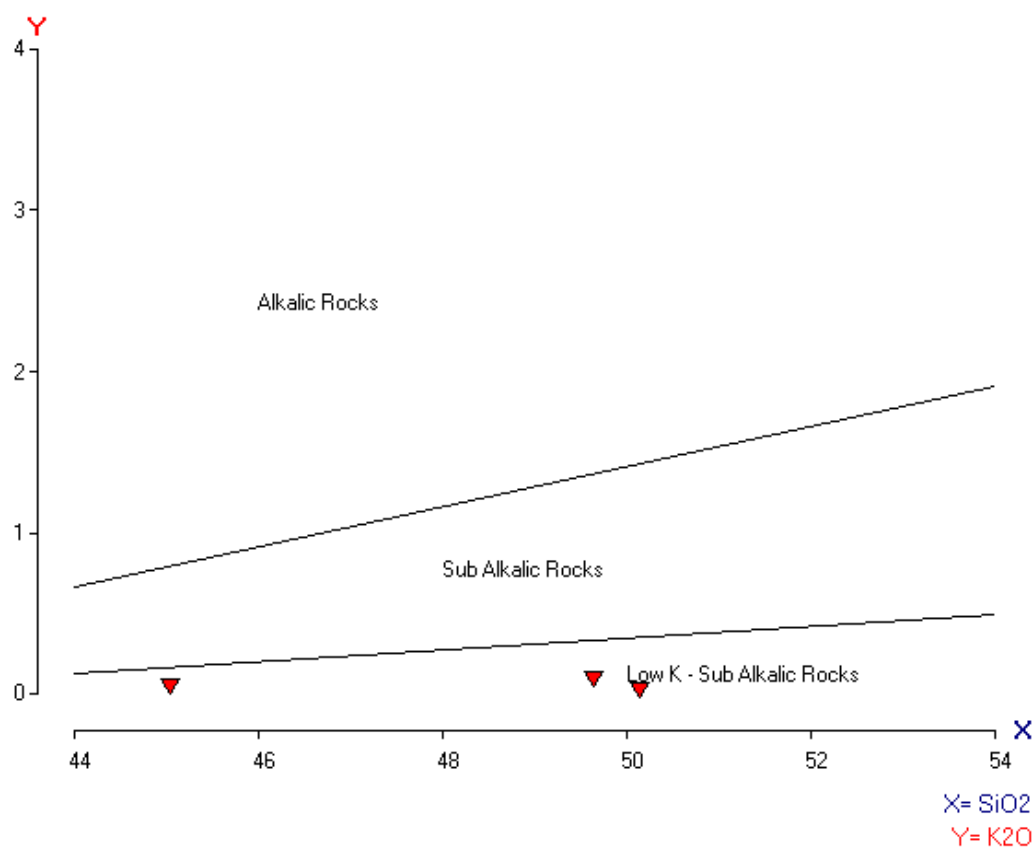


Fig.6.4.  $\text{K}_2\text{O}$  vs  $\text{SiO}_2$  plot (Middlemost, 1975) illustrating low K- sub-alkaline trends in the studied rocks Negash area (Symbols: as in Fig. 6.1)

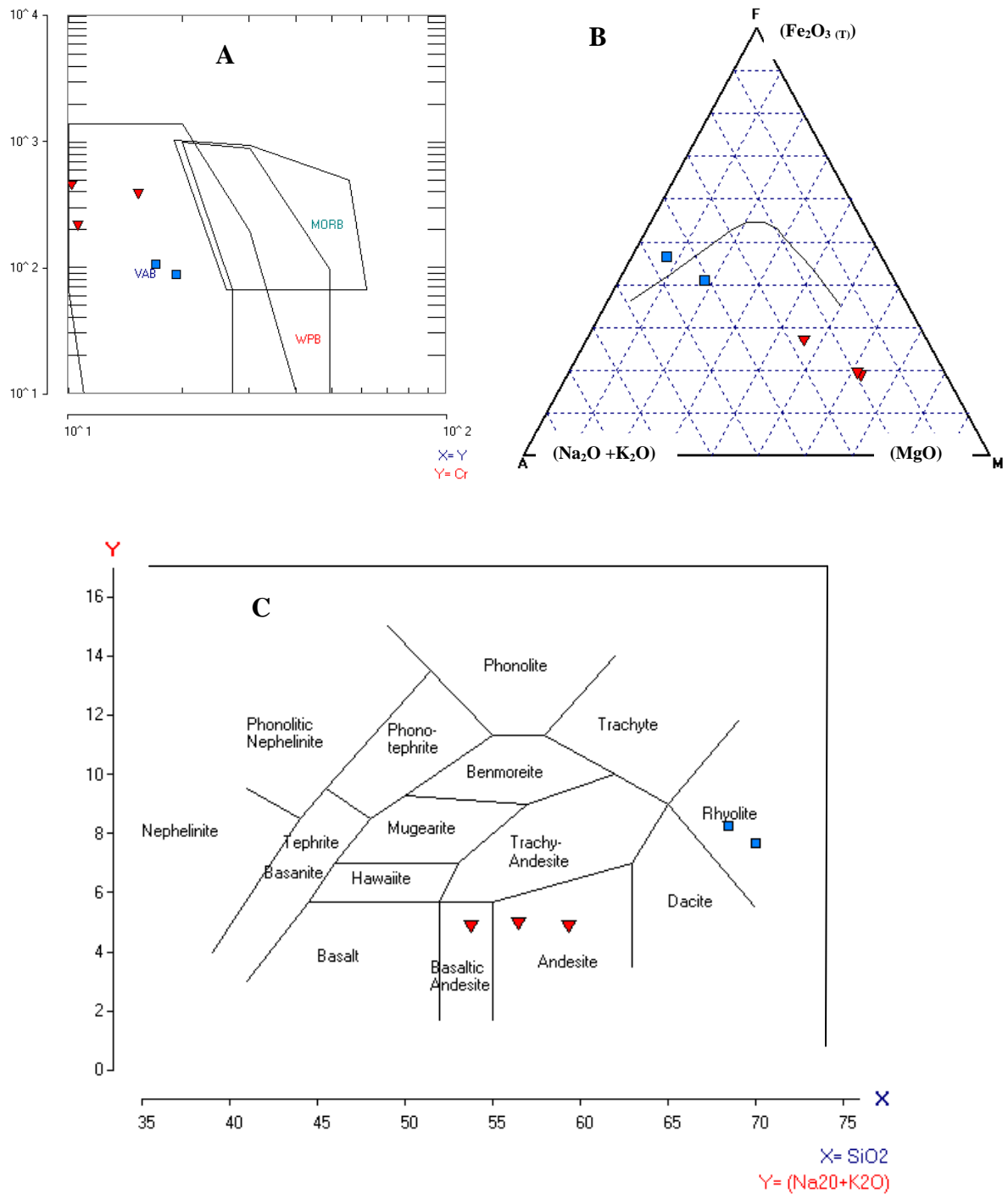


Fig.6.5. **A**) Discrimination diagrams for establishing the tectonic setting of metamorphic rocks of rocks of the studied area, Cr vs Y (Pearce, 1982); **B**) an AFM triangular discrimination diagram for the rock samples (Irvine and Baragar, 1971); **C**) chemical classification diagram based on TAS (wt %) ( $Na_2O + K_2O$  vs.  $SiO_2$ ) of Cox et al. (1979) (Symbols: as in Fig. 6.1)

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## CHAPTER- SEVEN

### 7. CONCLUSION AND RECOMMENDATIONS

#### 7.1. CONCLUSION

On the basis of field and petrographic observations, the rocks of the study area have been classified into metabasic (metabasalt), volcanic metabreccia, slate and phyllite. The dominant metamorphic rocks are from volcanic protoliths. The large part of the area is covered by the metabreccia. Stratigraphically, metabasic is found below metabreccia which is overlain by slate and phyllite. The tectonic evolution in the Negash area commenced with ductile deformation and terminated with brittle deformation. Petrographic examination of collected rock samples from litho-units of Tsaliyet Group show that the original igneous minerals and textures were mainly destroyed by alteration accompanied with deformation and metamorphism. Hence, recrystallization of the quartz and plagioclase, and growth of chlorite, epidote, and actinolite produced granoblastic to nematoblastic microtextures. In this study, the results of petrographic and structural evidence show that the Tsaliyet Group rocks of Negash area are poly-deformed and show two stages of ductile deformation: (i) The first  $D_1$  stage, characterized by  $S_1$  schistosity; (ii) the second  $D_2$ . In the studied rocks,  $D_2$  folded the  $S_1$  schistosity and quartz veins. The third phase of a brittle deformation is recognized in the field as minor normal and reverse faults, and joints. The brittle deformation in the area cut the structural elements of the preceding deformation and hence, is the latest deformation events. It is concluded that the region experienced a ductile to brittle transition deformation. These rocks show three prominent planar surfaces ( $S_0$ ,  $S_1$  and  $S_2$ ). On the basis of the present study, the time relationship between deformation and metamorphism can be established. Regional metamorphism  $M_1$  accompanied  $D_1$  and  $M_2$  related to local thermal event.  $M_3$  was accompanied the stages of  $D_2$  following the thermal metamorphism. In the rocks of Negash area, the low grade metamorphism (greenschist facies metamorphism) is inferred from the green metamorphic mineral assemblages like chlorite, epidote and actinolite and also from the presence of relict primary bedding. Minor folds which accord with the major fold structures obey Pumpelly's rule so that the axes and axial planes of the minor folds found in the area could be parallel to those of

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the major folds. These might indicate that they were formed by same deformation phase. From the microstructural evidences, it is clear that the peak metamorphic condition saw the growth of andalusite in the phyllite near to the granite intrusion. Andalusite porphyroblasts formed either pre-D<sub>2</sub> or early syn-D<sub>2</sub> trapping S<sub>1</sub> as S<sub>i</sub>. During D<sub>2</sub> deformation, S<sub>2</sub> fabric was developed wrapping around the porphyroblast. The S<sub>1</sub> fabric, concordant quartz veins and quartz lenticles are co-folded by micro F<sub>2</sub> folds. Microfolds F<sub>2</sub> are associated with crenulation cleavage which indicates two generation of ductile deformation.

In this study, the local geochemical data of the metavolcanic rocks is provided in an attempt to determine the geochemical affinities and depict tectonic setting of the area within the Arabian-Nubian Shield realm. Petrographically, the Tsaliet Group of Negash study area is discriminated into metabasic, slate, phyllite, and the majority of pyroclastics which are represented by volcanic metabreccia. Similarly, according to limited geochemical study the metavolcanic rocks are classified generally as basaltic-andesite and andesite fields of conventional alkali–silica diagram. The geochemical data plotted on tectonic discrimination diagrams show that the Tsaliet rock units represent a sub-alkaline affinity in which calc-alkaline chemistry is dominant, but very few of them display a tholeiitic calc-alkaline trend. During petrographic study, the sporadic occurrence of relict grains of olivine and pyroxene suggests that they are derived from basic to intermediate volcanic rocks. Consistent with petrographic observations, the geochemical data of Tsaliet Group rocks indicate variation in their composition from intermediate to acidic. The overall geochemical characteristics of the Negash metavolcanic rocks provided essential evidence indicating that the area is a part of the volcanic island-arc setting. Chemical classification confirm what was suspected from field and petrographic work, the existence of a volcanic protoliths consisting of intermediate and acidic rock types. The trace and REE patterns observed to Negash rocks are almost identical, suggesting a fractionation from a common melt.

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## **7.2. RECOMMENDATIONS**

1-Microstructural study of co-folded veins in the Tsaliet Group of the study area lends strong support for pressure solution as one of the dominant mechanism responsible for their development. So, the support to this mechanism is further strengthened by detail study of microstructures of folded veins to differentiate the folding mechanisms in near future that may contribute to the better understanding of this Tsaliet Group part of the Negash Syncline in relation to the deformation and metamorphism.

2- The future study in the area will provide a better foundation on which to build the porphyroblast micro-structural analysis which is rapidly growing sub-discipline of structural and metamorphic geology. Since brittlely segmented porphyroblasts such as andalusite are found in the rocks of study area, using this brittle porphyroblast future work could concentrate on the determination of finite longitudinal strain (extensions).

3- Further studies on (1) geochemical data using large number of rock samples, (2) various section of the 'Tsaliet Group' rocks to make stratigraphic correlations as well as reconstruction of the tectonic settings, (3) radiometric data for age determination could be recommended.

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## APPENDIX

Appendix-1: Petrographic description of selected metamorphic rocks, Negash study area.

Sample No	Mineral present (%)	Description	Rock type
NT1-3	Muscovite (43) Quartz (27) Chlorite (16) Opaque (8) Epidote (4)	The rock is a mica-rich and is fine-grained. It shows primary bedding ( $S_0$ ), and turns a bit greenish in color. The rock is characterized by significant amount of chlorite. The aligned platy grains in the slate define a lepidoblastic texture. No clear plagioclase crystals found in the rock not due to the absence of plagioclase in the original rock, presumably the rock shows saussuritization due to the replacement of original plagioclase by quartz, calcite, and sericite as evidenced from relict shape and extinction of the replaced crystals. The presence of epidote show volcanic origin of the rock.	Slate
NT1-4	Mica (30) Chlorite (26) Quartz (23) Calcite (10) Opaque (5) Biotite (4) Epidote (2) Trace amount of plagioclase	The brown patches of biotite porphyroclasts show preferred orientation parallel to $S_1$ fabric and together with other phyllosilicate define the slaty cleavage. The quartz grains show undulose extinction. No clear plagioclase crystals found in the rock not due to the absence of plagioclase in the original rock. The green color is due to the large development of chlorite.	Slate
NT2-1	Muscovite (48) Quartz (20) Plagioclase(14) Chlorite (9) Biotite (5) Opaque (4)	The studied rocks are generally composed of muscovite, quartz, chlorite, and opaque minerals in the decreasing order of abundance. The minerals are fine grained and show a well developed foliation. Two sets of foliation trends are observed as indicated by the alignment of fine grained muscovite, chlorite and quartz. In the rock there are concordant veins and later folded together with the $S_1$ as it is evidenced from the parallelism of axial plane of the vein and the hinge of crenulated muscovite, and also slightly folded discordant quartz veins are noted. The bedding is parallel to the primary foliation defining composite fabric	Quartz-mica phyllite

		<p>developed during first phase of deformation, and later folded. The foliation wrapped around the vein. Minor amounts of opaque minerals are seen associated with later quartz veins. Due to crenulation preferential dissolution of quartz takes place at higher angle to the shortening direction; relict quartz grains become increasingly inequidimensional. Precipitation of quartz is seen taking place predominantly in the fractures cutting across the crenulations. Opaque minerals do follow the trend of foliation. The aligned platy grains, such as micas and chlorite in the low-grade phyllites, define a lepidoblastic texture.</p>	
<p><b>NT2-3</b></p>	<p>Muscovite/ sericite (43) Quartz (20) Chlorite (12) Plagioclase(1 2) Biotite (8) Opaque (3) Andalusite (2%)</p>	<p>This rock is characterized by the ghost structure of andalusite hosted within a fine grained matrix, and acidic in composition. The original regional foliation (<math>S_1</math>) is overprinted by the disconnected skeleton (ghost structure) of andalusite. The <math>S_2</math> matrix schistosity strongly wraps the andalusite porphyroblasts, although some <math>S_2</math> fabric truncations along the porphyroblast margins have also been observed. An ellipsoidal texture of andalusite porphyroblasts developed during a thermal overprinting of previous regional metamorphism. This is interpreted as inter-tectonic orogeny porphyroblasts. The foliation and the bedding is parallel defining strong composite fabric. The andalusite is partially or totally altered to fine grained muscovite, preserving any internal structure. Low-temperature recrystallization of slate in contact aureoles creates poikiloblasts of andalusite, or mica, forming spotted phyllite. The matrix schistosity defined by oriented chlorite and biotite, ascribed to syn-tectonic crystals.</p>	<p>Phyllite</p>
<p><b>NT5-2</b></p>	<p>Quartz (30) Calcite (20) Plagioclase (albite) (15) Lithic fragments (12) K-feldspar (8) Sericite (7)</p>	<p>Plagioclase is highly disturbed and shows alteration to epidote, calcite and quartz. Occasionally the rock show weak schistosity of mica which wrap around relict plagioclase, but no distinct foliation or rock cleavage develops. The sample shows felsic composition. The rocks have rounded to sub-rounded grains and matrix rich.</p>	<p>MVC (metagreywack e)</p>

<b>NT3-2</b>	Epidote (5) Opaque (3)		
	Quartz (40) Plagioclase (18) Lithic fragments (12) Muscovite (10) Chlorite (15) Opaque (5)	The rock is dominated by the presence of medium to coarse grained clasts of quartz and feldspar minerals which are partly recrystallized. Quartz is irregular to sub-rounded in shape and plagioclase feldspars occur as laths. The clasts show elongation due to deformation, parallel to the schistosity. Because they are competent, produce cracks which are later filled by the incompetent sheet silicates, secondary quartz, feldspar and opaque minerals. The lithic fragments are mostly mafic and hence are highly altered and produced iron oxides. Mica minerals/muscovite wrapped around the fragments, and the mica minerals are folded. Opaque minerals fine to coarse in size (probably pyrite) and are mainly in association with quartz veins. The matrix is fine grained and consists of volcanic derived tuff glass. On the basis of the nature of the clasts and associated mineralogy and field association the rock is metavolcaniclast. The volcanic rocks tend to be richer in minerals with a higher amount of silica such as phyllo and tectosilicates including the feldspars, quartz and muscovite, thus felsic in composition.	MVC(metabrecia)
<b>NT3-2</b>	Quartz (26) Plagioclase (22) Lithic fragments (16) Muscovite (13) Chlorite (8) Calcite (10) Opaque (5)	The rock shows evidence of pronounced mineral alignment and deformation. It also show recrystallization microstructure, showing relatively strain-free grains with straight grain boundaries that meet at angles of about 120°. It has quartz rich and poor domains. The primary foliation is slightly crenulated, and also calcite/quartz veins are highly folded. The aligned platy grains, in the thin-section define a lepidoblastic texture.	Metabreccia
<b>NT4-1</b>	Epidote (60) Plagioclase (18) Tremolite-actinolite (10)	This thin section is of a fine-grained and massive. It is mainly composed of epidote and randomly oriented, elongate to needle-like plagioclase laths reflecting nematoblastic texture. The relict plagioclase is altered to epidote. The groundmass is very fine-grained and massive in appearance and	MV(meta-basaltic andesite)

<b>NT4-2</b>	Chlorite (7) Quartz (5) ± Carbonate	chloritized. Elongate to needle-like tremolite crystals are also present within the groundmass as well as on the surface of relict pyroxenes. Quartz and plagioclase together show granoblastic texture.	
	Plagioclase (25) Epidote (20) Tremolite-actinolite(15) Chlorite (11) Biotite (7) Calcite (6) Muscovite (5) Quartz (5) Opaque (4) Sphene (2)	The section is of highly altered meta-andesite and fine-grained testified by the high abundance of green minerals. It shows an aggregate of interpenetrating elongated or columnar grains (decussate texture) such as colorless tremolite/pale green actinolite needles, and highly altered plagioclase relicts with undulose extinction within chloritized/epidotized matrix. Plagioclase is highly disturbed and shows extensive alteration to epidote, and also to chlorite. The calcite usually occurs between quartz grains, and along fractures in plagioclase. Trace amount of unaltered olivine and pyroxene mafic minerals are found in this thin-section. The pyroxene (mostly relicts) minerals show alteration to epidote and tremolite-actinolite. Opaques related to alteration of mafic minerals are also present but in minor amounts.	MV (meta-andesite)
<b>NT4-4</b>	Epidote (30) Tremolite-actinolite (23) Plagioclase (17) Quartz (15) Chlorite/ biotite (7) Calcite ( 5	The rock is dark green, fine-grained and massive. The section is of highly altered metabasaltic andesite with epidotized/chloritized matrix. Plagioclase altered to epidote, chlorite and to some extent to calcite. Epidote forms as more calcium released. Colorless tremolite/pale green actinolite needles are prominent reflecting nematoblastic (aligned acicular or columnar grains) textures. The relict plagioclase is recrystallized, producing an interlocking albitic plagioclase and it has been totally and partially altered to epidote granules. The epidote also occurs as a vein.	MV(meta-basaltic andesite)

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**DECLARATION**

I hereby declare that this thesis entitled " Differentiating Structures and Litho-units of the Tsaliet Group around Negash area, Tigray, Northern Ethiopia" is my original work and has not been presented for a degree in any other University, and that all source of material used for the thesis have been duly acknowledged.

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Eyob Abebe (Candidate)

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Date

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

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Dr. Mulugeta Alene (Advisor)

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Date