Reconstructing Deformation History by using Microstructural and Petrographic analysis of Sorobo, Konso area, Southern Ethiopia

MSc Thesis

By

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RECONSTRUCTING DEFORMATION HISTORY BY USING MICROSTRUCTURAL AND PETROGRAPHIC ANALYSIS OF SOROBO, KONSO AREA, SOUTHERN ETHIOPIA

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Abstract

The deformation history of Sorobo, Konso area (southern Ethiopia) within the Mozambique Belt, is described using microstructural and petrographic analysis. The area is characterized by folds and metamorphic fabrics that trend between NNE and NNW and consist of high-grade, amphibolite- to granulite-facies rocks. It is affected by five deformational phases (D1 to D5) and two metamorphic events (M1 &M2). During shortening deformation events (D1 to D3) the development of gneissosity (D1), the formation of tight to isoclinal and recumbent folds(D2) and the superposition of secondary (upright) fold (D3) on earlier recumbent fold resulting in type-3 fold interference pattern are formed respectively. During fourth deformation phase (D4) most of the rock units of the area are affected by shearing or shows east and west vergence. From field observation and thin section analysis, the area is affected by both sinistral and a dextral sense of shearing but dextral shear-sense appears dominant. Brittle type of deformation phase (D5) was developed and resulting in different types of faults varies in orientation. Peak progressive metamorphism of the granulite facies (M1) and retrogression (M2) are also associated with the deformational phase. The breakdown of biotite to chlorite mineral and transformation of plagioclase to clay mineral by alteration, and the metamorphic mineral assemblage Hbl + Pl + Qtz +/- Cpx +/- Bt manifested a retrograde metamorphism (M2) and have attained upper amphibolite facies.

Keywords: Microstructure, Deformation, Metamorphism, Progression, Retrogression

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Acronyms

ANS=Arabian-Nubian Shield

AP=Axial plane

B=Biotite

Chl=Chlorite

Cpx=Clinopyroxene

D1=First deformation phase

D2=Second deformation phase

D3=Third deformation phase

D4=Fourth deformation phase

D5=Fifth deformation phase

E=East

EAO=East Africa Orogeny

EIGS=Ethiopian institute of geological survey

F1=1st fold phase

F2=2nd fold phase

Fig=Figure

Hbl=Hornblende

K-Ar=Potasium-Argon age dating

Km=Kilometer

Km^2=Square kilometer

M1=First metamorphic phase

M2=Second metamorphic phase

Ma=Million years ago

MB=Mozambique Belt

N=North

N=Number of data

Pl=Plagioclase

PPL=Plane polarized light

Qtz=Quartz

RHR=Right Hand Rule

S=South

S1=Foliation

So=Bedding

UTM=Universal Transverse Mercarot

W=West

XPL=Cross polarized light

°=Degree

%=Persent

σ =Sigma

CHAPTER ONE

1. Introduction

1.1. Background

Microstructural analysis describes the textural features of the rock, and can provide information on the conditions of formation, petrogenesis, and subsequent deformation, folding or alteration events. The study of metamorphic rock microstructures aims to determine the timing, sequence and conditions of deformations, mineral growth and overprinting of subsequent deformation events. A microstructural and metamorphic study of a naturally deformed rock provides evidence of behavior of earth during progressive deformation. Therefore this study concerns the reconstruction of deformation history of Konso area, southern Ethiopia within East Africa orogeny (EAO).

Pan-African Orogeny is a tectonic, magmatic and metamorphic activity that took place in Neoproterozoic to early Paleozoic age (Kroner and Stern, 2004). Pan – African cannot be a single orogeny but must be a protracted orogenic cycle reflecting the opening and closing of large oceanic realms as well as accretion and collision of buoyant crustal blocks (Kroner and Stern, 2004).

Pan-African tectono-thermal activity in the Mozambique Belt was broadly contemporaneous with magmatism, metamorphism and deformation in the Arabian–Nubian Shield. The difference in lithology and metamorphic grade between the two belts has been attributed to the difference in the level of exposure, with the Mozambican rocks interpreted as lower crustal equivalents of the juvenile rocks in the Arabian–Nubian Shield (Kusky et al., 2003).

The concentrations of granulitic rocks in the Mozambique Belt and their absence from the Arabian–Nubian Shield support the interpretation that crustal thickening, erosion, and intensity of deformation increase to the south. On the other hand, occurrences of granulite as far north as central Sudan suggests at least two episodes of granulite-facies metamorphism, Archean and Neoproterozoic (Stern and Dawoud, 1991 as cited in Tsige et al ., 2005).

EAO has been proposed for the combined upper crustal Arabian – Nubian shield in the north and lower Mozambique Belt in the south comprising mostly pre – Neoproterozoic crust with a Neoproterozoic – early Cambrian tectono-thermal overprint. The ANS makes up the northern half of the EAO and stretches from southern Israel and Jordan south as far as Ethiopia and Yemen. ANS is distinguished from the Mozambique belt by its dominantly juvenile nature, relatively low grade of metamorphism and abundance of island – arc rocks and ophiolites. The Mozambique belt defines the southern part of the EAO and essentially consists of medium to high – grade gneisses and voluminous granitoids. It extends south from the ANS into southern Ethiopia, Kenya and Somalia via Tanzania to Malawi and Mozambique and also includes Madagascar (Kroner and Stern, 2004).

The Mozambique Belt is a Neoproterozoic, polycyclic, collisional belt that extends along and underlies the eastern margin of much of the African continent (Shackleton, 1979 as cited in Asrat and Barbey, 2003). It is characterized by folds and metamorphic fabrics that trend between NNE and NNW and consists of high-grade, amphibolite- to granulite-facies rocks (Gichile, 1992) forming a gneissic-migmatitic complex. In Ethiopia, the MB is exposed in the south and south-west and forms a front with the ANS, a lower grade (greenschist facies) calc-alkaline volcano-sedimentary terrain to the north (Fig. 1.1).

In Northern Mozambique the highest – grade gneisses, granulites and migmatites of the MB were interpreted two distinct events, namely the Mozambique cycle at 1100 – 850 Ma, also known as Lurian orogeny, and the Pan – African cycle at 800 – 550 Ma (Kroner and Stern, 2004).

Southern Ethiopia is underlain by Neoproterozoic – early Paleozoic rocks, which were formed and/or deformed during the EAO associated with collision between East and West Gondwana (Stern, 1994) after the closure of the Mozambique ocean (Santosh et al., 2006; Vaughan and Pankhurst, 2008). Older rocks, late Archean to paleoproterozoic granitoid gneisses, strongly reworked during the Pan – African orogenic cycle and locally migmatized and/or mylonitized during Pan – African events or are separate crustal entities (exotic blocks) of unknown origin (Kroner and Stern, 2004).

In southern Ethiopia the rocks are subdivided into lower complex, middle complex and upper complex (Kazmin, 1972). The lower complex consists of Burji gneiss, Yavello gneiss, Awata gneiss, Alghe gneiss and Konso gneiss. The middle complex comprises the terrigenous rocks of the Wadera group. The upper complex is represented by Adola group.

Amenti (1996) argued the Precambrian rocks of the southern Ethiopia form the northern part of the Mozambique Belt. He described the lithologic units of the southern Ethiopia into high grade gneiss, pelitic to psammitic as well as mafic to felsic that are partially migmatized.

According to Gilboy (1970) the lower group consists of monotonous banded gneiss (biotite and biotite - hornblende gneiss), non – banded biotite gneiss and biotite – muscovite gneiss (frequently banded). The middle group consists of non - banded gneiss and schist/semi – pelitic/ psammite assemblage, semi – pelitic/carbonate/pelitic assemblage and pelitic/amphibolite assemblage. The upper group is presented by rocks that commonly retain primary depositional features (phyllite, melanocratic amphibolite, and metamorphosed arkosic sandstone). These rocks are intruded by early and late intrusives based on the structural relation and metamorphic events.

Samuel (1991) suggested that the Archean rock with E – W foliation trend that are considered as craton by the earlier workers are not craton, but the rocks represent a Proterozoic supracrustal sequence. He classified the geology of the area of biotite – quartzofeldsphathic gneiss and few intercalations of basic metavolcanics and at places intruded by plutons. He also suggested the protolith of the amphibolite and tonalite formed by Pan- African island arc magmatism over a west dipping late Proterozoic subduction zone. D1 to D3 episode of deformation responsible for the development of isoclinal to open upright folds are identified by him.

Woldegebriel et al. (1994) classified the geology of the area in to Precambrian basement rocks, Cenozoic volcanics and quaternary cover in the north of Ageremariam sheet. They classified the volcanic rocks in to pre – rift and post – rift volcanics.

According to Kazmin (1971) the region is underlain mainly by Precambrian metamorphic rocks of konso gneiss, Arero and Burji gneiss, Yavello gneiss, granitic gneiss of Yavello type, Adola group and associated intrusives. The Neogene – Quaternary volcanic are represented by mostly basaltic with subordinate acid varies and he classified them in to lower, middle and upper units.

According to Ethiopian institute of geological survey (EIGS) (2010), the Precambrian metamorphic rocks show variation in composition, structural style, degree of metamorphism and texture. Based on the above parameters the rocks are classified in to high grade and low grade metamorphic rocks. Interlayered gneiss and granitic gneiss represent the high grade rocks. The interlayered gneiss is represented by biotite – quartz – feldspar gneiss, hornblende gneiss, biotite gneiss, marble and biotite – muscovite gneiss rock types. The low grade rock consists of only metabasalt.

Granites are shown to be excellent geochronological (Harris, 1996), structural (Bouchez et al., 1997) and geodynamical (White and Chappell, 1983; Pearce et al., 1984; Whalen et al., 1987; Barbarin, 1999) markers. Therefore, a systematic and comparative petrological, geochemical, geochronological and structural study of granites from both the ANS and the MB in Ethiopia appears to be crucial to understand the geodynamic evolution of these terrains and their relationships. This contribution dealing with the MB is part of an integrated study of the late- to post tectonic granitic magmatism in both the ANS (Asrat et al., 2003) and the MB. A pluton in the MB of southern Ethiopia which is the Konso pluton (Fig1.1) was regarded as a Pan-African post-tectonic body (Davidson, 1983).

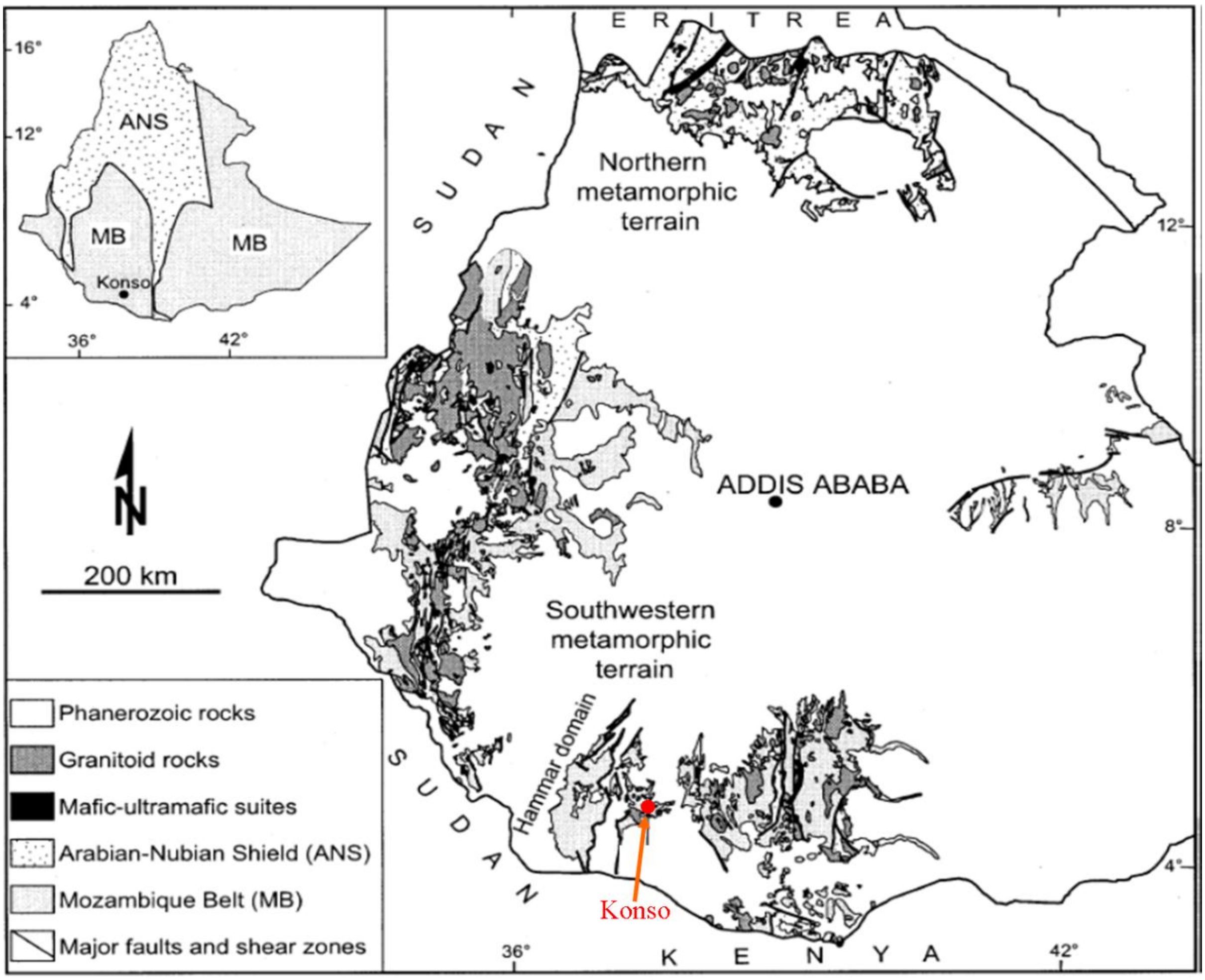


Fig 1.1 A simplified geological map of the metamorphic terrains of Ethiopia that shows the distribution of the ANS and the MB rocks (Asrat, 2003)

1.2. Goal and scope of the research

This research is a study of microstructures and the reconstruction of deformational history of Sorobo area in Konso district. The area is dissected /cut/ by streams showing good-outcrops (exposure). To determine the relative age relationship identification or careful examination of cross-cutting relationship is focused. The main purpose of this research project is to reconstruct deformation history and metamorphic events which characterize the area. This is done with careful microstructural studies, petrological studies and field observations. The correlation between small scale and large scale data are also used to reconstruct the history; and the detailed mapping in the area is done.

1.3. Location

Konso area is located at about 595 km south of Addis Ababa, 362 km SW from Hawasa, 150 km E from Jinka and 110 km NW from Yavello in the South Nation Nationality and people regional state, Ethiopia. The specific study area is about 17km far from the town of Konso, Karat in the NW direction. It is bounded between 594000-599000N and 0320000-0324000E UTM reading covering 20km^2. The Konso area covers between minimum elevations 501m to maximum elevation up to 2000m above mean sea level at Baticara Mountain. It is accessed through the main asphalt road from the town Karat through Jinka and/or through Arbaminch main road.

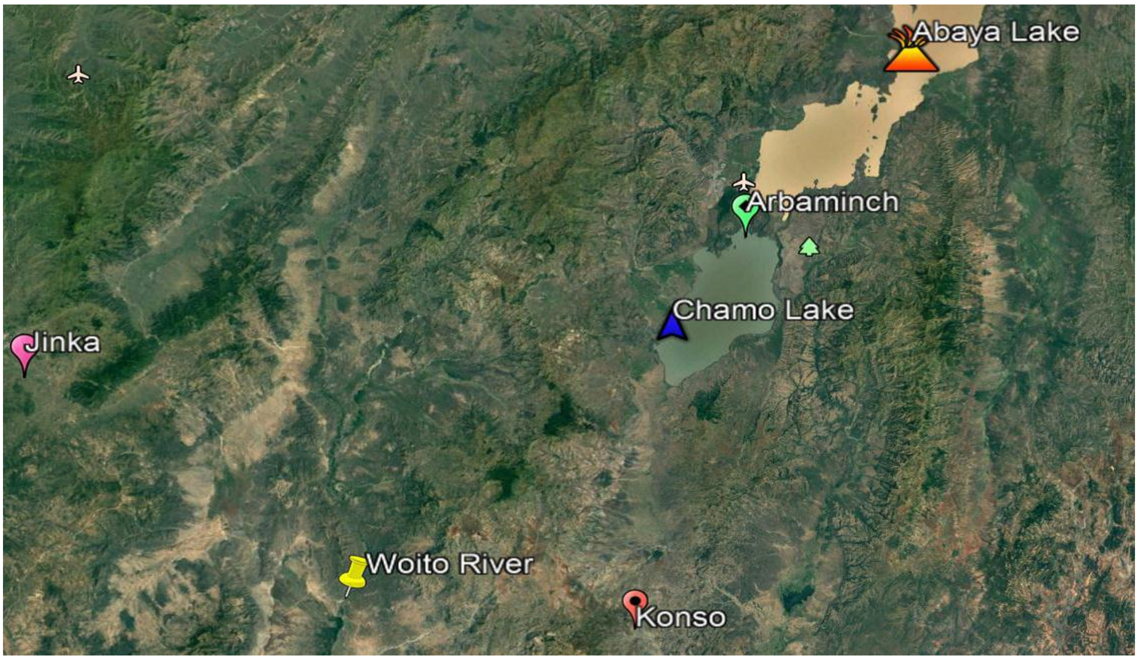


Fig 1.2 Physiography and location of the study area

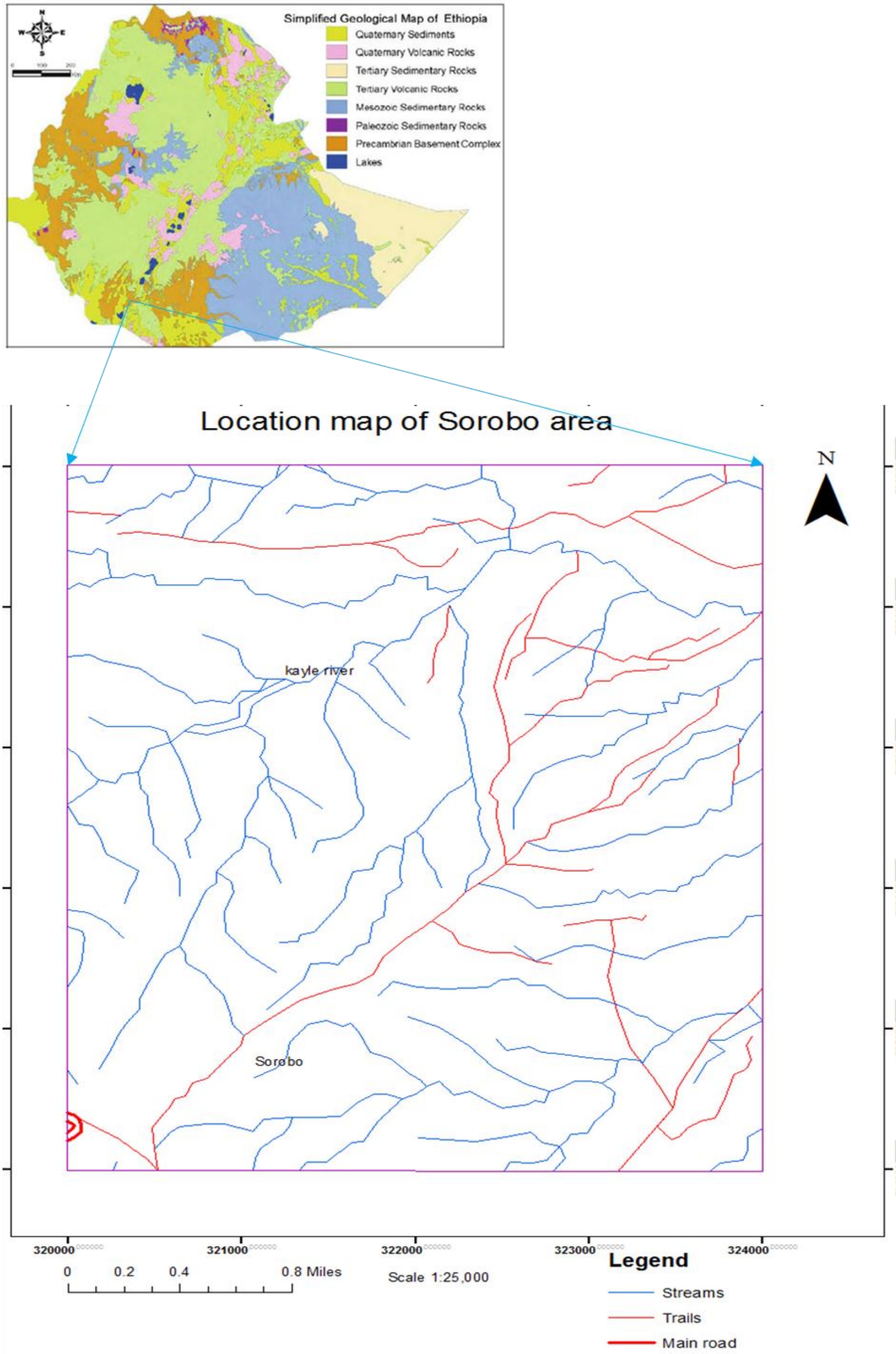


Fig 1.3 Location map of the study Sorobo area

1.4. Accessibility

The study area is located at a distance of about 612 km from Addis Ababa and accessed from Addis Ababa either via Yavello or Sodo. The road from Addis Ababa – Arbaminch is asphalt and from Arbaminch – Konso is both asphalt and gravel. On the way from Konso town, Karat to the study area, there is a gravel road connecting different villages. However, from the study area to surrounding locality there are several foot trails rather than gravel to take good exposure over the entire area from the main road to the target location.

1.5. Physiography

The study area is situated within lowland in southern Ethiopia. Therefore, the area is characterized by flat to gently lying topography. There are also highly and moderately rugged topographic terrains represented by different lithological units. The area is covered by soil and some places have been covered by quartz rocks. The highest and lowest elevation in the area is 1463m SW and 1289m NE of the study area above mean sea level respectively.

The prominent drainage pattern of the area is dendritic with associated parallel and radial patterns in some area. Even though the area is extremely exposed to erosion, a comprehensive terracing was carried out against hill terrain which helps to retain moisture and prevent fragile soil from being washed away by surface runoff. Generally, the elevation is gradually increasing from the NE to SW part of the study area shown in figure 1.2.

Fig 1.4 photographs of Vegetation cover of the study area

1.6. Objectives

1.6.1. General objective

The main objective of this research is reconstructing deformation history by using microstructural and petrographic analysis of Sorobo, Konso area, southern Ethiopia.

1.6.2. Specific objectives

The specific objectives of this research are:

- To determine the number of deformation phases and metamorphic events affecting the area.
- To determine the relative ages of different structures.
- To identify the relationship between deformation and metamorphism on the basis of field and microstructural data.
- To understand the deformation and metamorphic history of the study area.

1.7. Methodology

To achieve the above objectives the following methods and approaches were used:

Different available information about the area and previous works are gathered, this includes reading and organizing published and unpublished reports on geology, analyzing topographic, geological and structural maps of the area at a scale of 1:50,000 and 1:25,000 and also interpreting satellite images of an area.

Preliminary field work /road geology/ was conducted around Konso area of southern Ethiopia.

During the main field season, different traverse lines were selected across the geology following river routes. In each traverse, many stations are taken along the traverse line at different places.

To construct the geological and structural map, a systematic record of structural features and lithology has been done, with a special emphasis on the earlier nature of the rocks.

Field data is well organized and compiled and a geological and structural map at a scale of 1:25,000 is produced (see Fig 3.9) using ArcGIS (version 10.3) software. The timing of transformation of various minerals with respect to specific deformation and metamorphic events is established based on microstructural and petrographic analysis.

1.8. Significance of the study

In the study area a few regional studies were conducted based on a small scale geologic mapping. Therefore, systematic field, structural and petrographic studies based on large scale (1:25,000) mapping are needed in order to provide a better understanding of the nature of tectonic and geological evolution of the area and its deformation mechanisms. In this study, the local microstructural and petrographic details of the Precambrian rocks integrated with their field observations are provided in an attempt to determine a tectonic significance of the relationship between micro and mesoscale structures of the area within the Mozambique belt of southern Ethiopia.

The area is not only important for academic interest, but also is related to the occurrence of mineral deposits of economic interest. The result will help as a reference for students and different researchers and provide data on the deformation history with respect to the growth of various minerals and mineral deposits. In addition, it will serve as an important data source for mining companies to better understand which types of minerals are associated /related/ to which types of structures and rocks. It is also important for partial fulfillment of the requirements for master’s degree of science in structural geology.

CHAPTER TWO

2. Regional Geology

2.1. Regional Tectonics

In southern Ethiopia the Neoproterozoic–Early Paleozoic rocks have a fundamentally important tectonic position in that they occupy the interface between the Mozambique Belt and Arabian- Nubian Shield to the south and north respectively. These rocks are bounded to the east by Mesozoic sedimentary rocks whereas in the west Normal faults of the Main Ethiopian Rift affects Tertiary volcanic rocks (Tsige and Abdelsalam, 2005).

East African Orogen includes both Mozambique Belt (MB) and the Arabian-Nubian Shield (ANS) (Stern, 1994) (Fig. 2.1). Furthermore, Burke and Sengor (1986), Bonavia and Chorowicz (1992) and Stern (1994) invoked escape tectonics and proposed that the N-trending structures in southern Ethiopia are the roots of northward expulsion of the Arabian-Nubian Shield from the Mozambique Belt, following a Tibetan-type continent–continent collision between east and west Gondwana along the Mozambique Belt after the consumption of the Mozambique Ocean.

To explain the relationship between the Mozambique Belt and the Arabian-Nubian Shield various models have been proposed. According to Vail (1976), Kazmin et al. (1978) and Pinna et al. (1993), the high grade rocks of the Mozambique Belt extend beneath the low-grade rocks of the Arabian-Nubian Shield forming a basement–cover relationship. Others such as De Wit and Chewaka, 1981; Key et al., 1989; Berhe, 1990; Stern and Dawoud (1991) and Stern (1994) have suggested that the Mozambique Belt and the Arabian- Nubian Shield were developed in metamorphic and structural continuity during the Neoproterozoic Pan- African event.

According to Holmes (1951) who first recognized from structural evidence, supported by K–Ar ages in Kenya, Tanzania and Mozambique, the older E-W trending structures of the Archean cratons are overprinted by N-S trending structures of the Mozambique Belt. The model for explaining this N-S change involves Tibetan-style collision between east and west Gondwana at the latitude of the Mozambique Belt, and at the same time oblique collision in the Arabian-Nubian Shield to the north (Stern, 1994). This model accounts for the differences in intensity of deformation, lithospheric thickness and grade of metamorphism that is generally higher in the Mozambique Belt relative to the Arabian-Nubian Shield (Stern, 1994).

From the gravitational tectonic collapse model information has been inferred as signaling the last tectonic event in the eastern part of the Saharan Metacraton (Abdelsalam et al., 2002) where close to the western margin of the Arabian- Nubian Shield N-trending low-angle normal faults have been observed (Denkler et al., 1994; Harms et al., 1994; Abdelsalam et al., 2003). In northern Madagascar low angle Normal-slip detachments have been interpreted as an indication for Neoproterozoic tectonic collapse of this part of the East African Orogen (Collins et al., 2000). Also there is a possibility of gravitational tectonic collapse in other parts of the Arabian-Nubian Shield especially in places like southern Ethiopia where the Pan-African Orogeny may have resulted in a significant lithospheric thickening due to its proximity to the roots of the continent-continent collision of east and west Gondwana, along the Mozambique Belt (MB).

In the Neoproterozoic–Early Paleozoic rocks of southern Ethiopia the structural style is characterized by the presence of major north-trending fold and thrust belts such as the Megado and Kenticha. These fold and thrust belts deform dominantly ophiolites and island arc assemblages sandwiched between medium- to high-grade gneissic and migmatitic terranes in a fashion that may be related to lithospheric thickening. The difference in grade of metamorphism between MB and ANS as well as the abundance of Neoproterozoic juvenile material in the ANS compared to the MB has been a puzzling observation. One popular model is that due to continent–continent collision between east and west Gondwana along the Mozambique Belt, the Arabian-Nubian Shield was tectonically expelled in a northward direction after the consumption of the Mozambique Ocean (Burke and Sengor, 1986; Bonavia and Chorowicz, 1992; Stern, 1994) similar to the eastward expulsion of the south China Sea due to the northward indentation of India into Europe–Asia plate (Tapponnier et al., 1982). Remnants of the Mozambique Ocean are now preserved as the island arc–back arc–ophiolite assemblages of the Arabian-Nubian Shield. This is a model recommended for an escape tectonic relationship between the two belts. In the western part of the Neoproterozoic terranes in southern Ethiopia (Megado and Kenticha) the N-trending belts have been mapped as refolded fold and thrust belts that indicate dominant NW-SE shortening due to collision between various terranes (Beraki et al., 1989; Woldehaimanot, 1995; Worku, 1996; Worku and Schandelmeier, 1996).

In southern Ethiopia rock age data indicate that magmatism, metamorphism and deformation occurs between about 900 and 500 Ma. However, detrital zircon ages of 1657 Ma from a meta-rhyolite (Teklay et al., 1993) and ages between 1300 and 2050 Ma from a diorite gneiss (Yibas, 2000) are also evidence for the existence of Archean to Mesoproterozoic continental lithospheric component in southern Ethiopia. Worku (1996) based on structural, petrological, geochemical, isotopic and geochronological studies of the Adola Belt proposed that, the Precambrian rocks of Ethiopia constitute a reworked Pre-Neoproterozoic and a Neoproterozoic juvenile lithosphere.

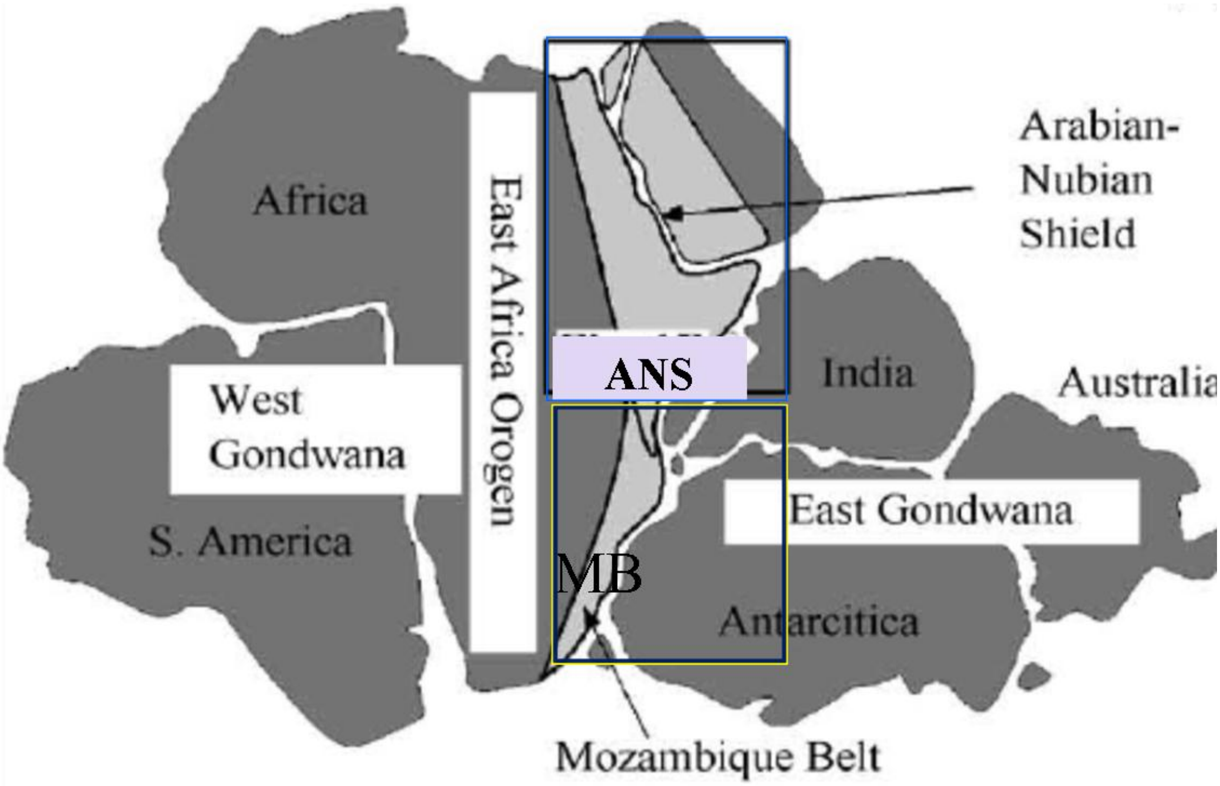


Fig. 2.1 The East African Orogen between east and west Gondwana (Tsige and Abdelsalam, 2005).

A major Proterozoic structural and metamorphic unit of East Africa which is the northeastern branch of the Mozambique Belt extends from Kenya through Ethiopia and the Horn of Africa into southern Arabia (Warden & Horke, 1984). There are three major divisions (Lower, Middle and Upper Complexes) in the Mozambique Belt of southern Ethiopia that have been differentiated by characteristic contrasts in structural style, lithology and metamorphism (Kazmin et al., 1978).

Metasedimentary rocks (graphitic phyllites, biotite schists and metacalcareous rocks) in the Adola area form the uppermost unit of the Upper Complex of southern Ethiopia. On the basis of this scheme, the rocks of the Moyale region are correlated with the lower part of the Upper Complex, and are probably Neoproterozoic in age (Alene & Barker, 1993). According to Hussien (1999) the rock association in the Moyale area consisting of metamorphosed mafic-ultramafic rocks, fore-arc and accretional wedge-derived metasediments and associated rocks. He also suggested that the lithological association in the Moyale domain indicates the existence of oceanic crust prior to subduction. The major orogenic belts of the Horn of Africa, Mozambique Belt (MB) and Arabian-Nubian Shield (ANS) intersect in the Moyale region (Vail et al., 1986). The local geology consists of granodiorites, polydeformed and metamorphosed mafic and ultramafic rocks and subordinate amounts of meta-sedimentary rocks. The dominant rock units of the Moyale area are quartz-feldspar-mica schist, amphibole schist, graphite schist, granodiorite and quartzite (Fentaw et al., 2000).

There is a transition between Mozambique Belt (MB) and Arabian-Nubian Shield (ANS) which is marked by a change from less deformed and less metamorphosed, juvenile crust in the north to more deformed and metamorphosed, remobilized older crust in the south, with the structural transition occurring farther north than the lithological transition. Significant differences in structural style, rock type, age and metamorphic evolution suggest that the belt as a whole constitutes a Pan-African Collage of terranes accreted to the eastern margin of the Congo and Tanzania cratons and that significant volume of older crust of these cratons were reconstituted during this event (Fig 2.2) (Kroner and Stern, 2004).

According to de Wit and Chewaka (1981), Davidson (1983) and Gichile (1992), the evolution of southwestern metamorphic terrain forms part of the whole evolution of the Precambrian of Ethiopia, which involved early rifting that gave way to an ocean basin at ~1,100– 1,000 Ma. Compression occurred in a west-dipping subduction zone and associated volcanic arcs at ~900– 750 Ma and the island arc crust was extended later at ~750–650 Ma. The gneissic-granulitic complex is formed from periodic closure of the inter-arc basins through uplift, subduction and Himalayan- type continental collision and associated metamorphism followed by retrogression at ~650–450 Ma. Emplacement of plutonic suites started prior or subsequent to the first metamorphic event (syntectonic plutons), and possibly continued even some tens of millions of years after the closing stages of collision (post-tectonic plutons) (Asrat and Barbey, 2003).

The Hammar domain (Davidson, 1983), which corresponds to the eastern sector of the south-western metamorphic terrain of Ethiopia (Fig 1.1), contains two major rock groups: an older gneissic complex and several generations of plutonic suites of which the Konso pluton is one. The gneissic complex consists of mafic, intermediate, felsic as well as metasedimentary gneisses and granulites, which were metamorphosed to middle-upper amphibolite and locally to granulite facies conditions (Davidson, 1983). The gneissic rocks are strongly and steeply folded, and show regional NNW–SSE-trending foliations with steep NE dips. The plutonic rocks occur as discrete bodies of gabbros, diorites, syn, late and post-tectonic granites accompanied with leucogranite, aplite and pegmatite dikes. The emplacement of intraplate alkali-granite ring complexes and associated volcanic rocks started at 450 Ma and continued till 20 Ma in the surrounding Pan- African terranes in Sudan and Somalia (de Wit and Chewaka, 1981; Vail, 1985 ; 1989).

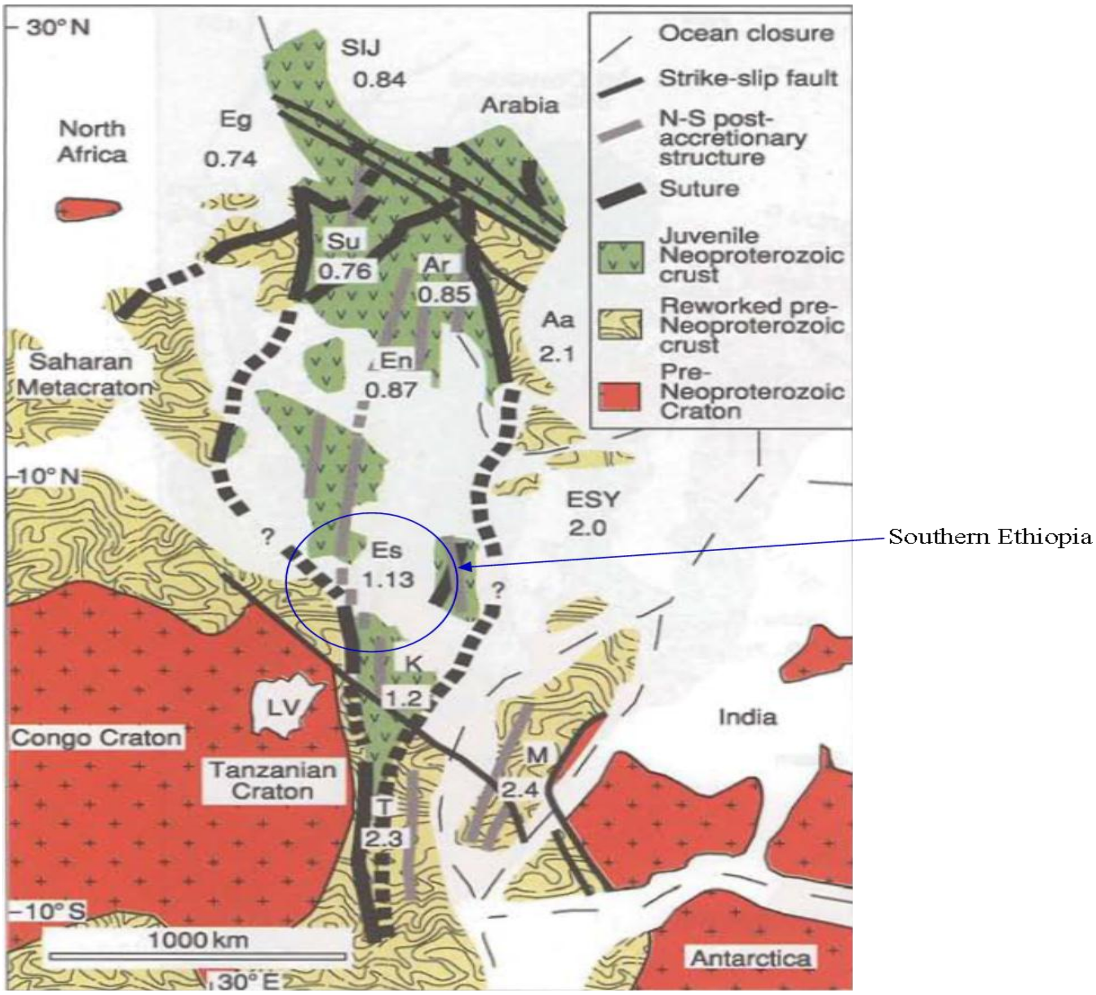


Fig 2.2 Pre-Jurassic configuration of elements of the East African Orogen in Africa and surrounding regions; Egypt (Eg), Sudan (Su), Sinai-Israel-Jordan (SIJ), Afif terrane, Arabia (Aa), rest of Arabian Shield (Ar), Eritrea and northern Ethiopia (En), southern Ethiopia (Es), eastern Ethiopia, Somalia, and Yernen (ESY), Kenya (K), Tanzania (T), and Madagascar (M). Nurnbers in italics beneath each region label are mean Nd-model ages in Gy. (Kroner and Stern, 2004).

2.2. Regional Stratigraphy

There are four major geologic unit distributions in the Omo river project map area. These are post-rift sediment (volcanics), pre-rift volcanics, Permian sediments and crystalline basement (Davidson, 1983). There is a contrast in the basement geology in the southeast and northwest parts of the project area in terms of rock assemblages, grade of metamorphism and structural style. The southeastern basement rocks are predominantly gneisses of several kinds, formed from rocks of both supracrustal and plutonic origin. They are intruded locally by syn-tectonic and post tectonic plutons, chiefly granitoid in composition, although minor gabbroic and ultramafic intrusions are also present. Metamorphic grade is mainly middle to upper amphibolite facies, but has reached granulite facies in two broad areas. Structural trend is northwesterly; in the western part of the southeast block, structures are relatively shallowly inclined toward the northeast, steepening eastward and reversing to southwest inclinations near the east side of the map area (Davidson, 1983). The northwestern basement block is characteristically similar to those of the southeastern block prevail along the east margin. Metasedimentary and metavolcanic schist and gneiss are common in this area and shows middle greenschist to middle amphibolite facies. Structural are north-trending, and have variable easterly inclination for the most part, and include west-directed thrust faults (Davidson, 1983).

The crystalline basement in the Omo river project area is divided in to three domains (Hamar, Akobo and Surma) based on lithological, metamorphic and structural contrast (Fig 2.3). The main difference between them is: Akobo domain generally shows lower metamorphic grade and Hamar domain generally shows high metamorphic grade. There is a sharp eastward rise in metamorphic grade in the project area. The boundary between the Akobo and Surma domains appear to be a tectonic one, involving transposition of Akobo domain rocks in to straightened gneisses with a northwesterly trend, accompanied by increase in metamorphic grade southwestward across the boundary zone. The Hamar domain underlies all of the project area east of the Omo River. It contains two major rock groups: a complex of older gneiss and granulite, highly deformed, recrystallized and in part migmatized, and a suite of younger plutonic rocks. Within the older gneiss complex, gneisses of both supracrustal and plutonic origin are found in many places (Davidson, 1983).

The main difference among the gneisses of the older complex is expressed in different ways: there are five major lithologies. a) Relatively mafic hornblende gneiss and amphibolite. b) Well layered biotite gneiss, containing clearly recognizable metasedimentary components. c) Dominantly grey biotite-hornblende gneiss of variable color index, in part containing ill-defined masses of relatively uniform orthogneiss of granodioritic, tonalitic and dioritic composition. d) Pale pink to light grey quartzofeldspathic gneiss, generally leucocratic and having a granitic composition. e) Biotitic granitoid gneiss, commonly containing a little muscovite. Relatively mafic hornblende gneiss and amphibolite, well layered biotite gneiss, dominantly grey biotite-hornblende gneiss of variable color index and pale pink to light grey quartzofeldspathic gneiss occur in granulite facies in east of the Omo River. A considerable proportion of undifferentiated relatively mafic hornblende gneiss and amphibolite, well layered biotite gneiss and pale pink to light grey quartzofeldspathic gneiss are found in west and northwest of the Omo River (Davidson, 1983).

Metamorphic and tectonic history recorded in the crystalline basement rocks of southwest Ethiopia is more complicated. The older supracrustal rocks of the Hamar domain have been metamorphosed twice, and were intruded by plutonic rocks both prior and subsequent to the first metamorphic event. The older metamorphism was associated with development deep in the crust of a large, upward-opening fold fan whose west side forms most of the exposed Hamar domain in the parts of Illubabor, Kefa, Gemu Gofa and Sidamo, Ethiopia. Subsequent or continuing deformation, with partial retrogression of earlier formed granulites, was accompanied and outlasted by plutonism. Sedimentary and volcanic rocks were laid down on the west side of this complex, possibly prior to its second metamorphism. They were deformed before west-directed overthrusting of Hamar domain rocks, structurally modified and metamorphosed of relatively low grade during this earlier event, folded again following imbrication and introduction of thrust sheets from the east, and lastly intruded by late-to post-tectonic granites, perhaps related in time to the youngest intrusions in the eastern Hamar domain. The latest event apparent in the whole region involved the juxtaposition of gneissic rocks of the Surma domain against both gneisses of the Hamar domain and younger supracrustal rocks of the Akobo domain along a steep, northwest-oriented, sinistral shear belt (Davidson, 1983).

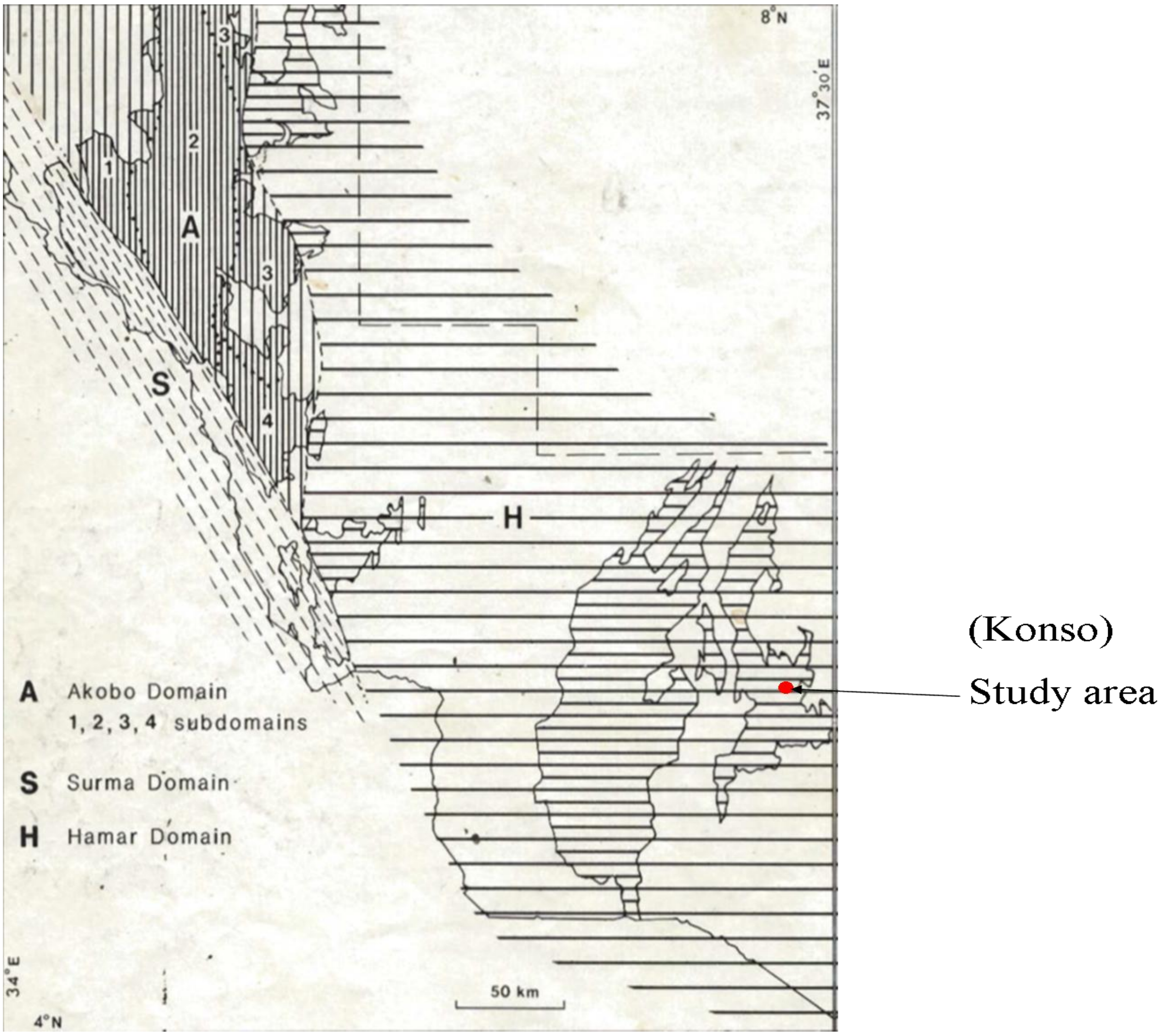


Fig 2.3 Geological domains within the crystalline basement (Davidson, 1983)

CHAPTER THREE

3. Local Geology

3.1. Introduction

The Sorobo area is largely covered by metamorphic rocks which have undergone medium to high grade of metamorphism and are exposed mostly along the stream cut. The rocks include amphibole gneiss, granulite, granitic gneiss and amphibolite. There are also different geological structures in the study area like: dikes, different type of veins, fault, joints, foliation and lineation. Based on fieldwork a geological and structural map of Sorobo area is prepared in 1:25,000 scale (see Fig. 3.9).

3.2. Lithological description

3.2.1. Granulite

This lithologic unit is mainly exposed at the W and NE part of the study area along the beds of the large Kayle River. The granulite is a medium- to coarse–grained, non-foliated metamorphic rock with a granoblastic texture (approximately equi-granular) and gneissose to massive structure. It is composed of mainly clinopyroxene, plagioclase, hornblende, quartz and accessory garnet minerals. In outcrop level the granulite is visually quite distinct with abundant small pink or red garnets in a granular matrix as shown in Fig 3.1. The minerals, as seen in a thin-section, occur as small rounded grains forming a closely fitted mosaic (Fig 3.2). They are somewhat sub-rounded found in -between the larger grains of quartz and feldspar. In the field photographs the garnets are easily visible with the eye as pink spots on the surfaces of the rock. Based on crosscutting relationship in Sorobo area the older granulite rock is included (trapped) within younger amphibole gneiss and granitic gneiss. The presence of clinopyroxene (early crystallized) mineral in a rock unit indicates a high temperature of crystallization with lack of water. The harder and older granulite rock is exposed to the surface along the beds of Kayle River when the overlying gneisses rock eroded. The temperature and pressure fall due to uplift when the overlying rock eroded and the formation of hornblende from clinopyroxene are an indication for retrogression in the area. The mineral assemblage of this rock unit with granular textural features indicates the granulite facies metamorphism.

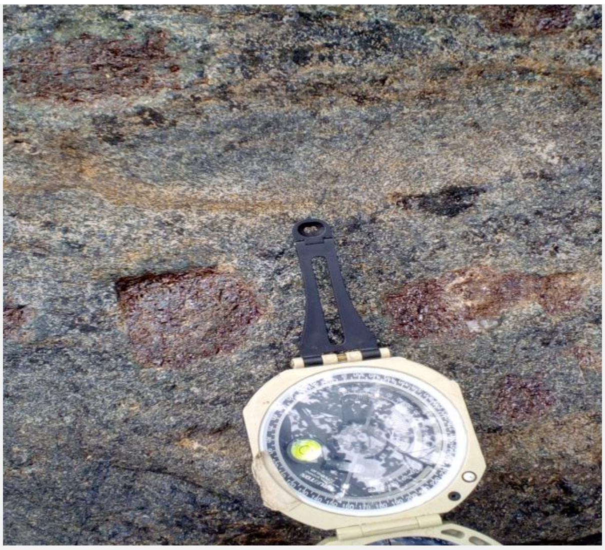


Fig 3.1 Garnet-bearing granulite from Sorobo area; serpentine mineral surrounds around garnet at the top left

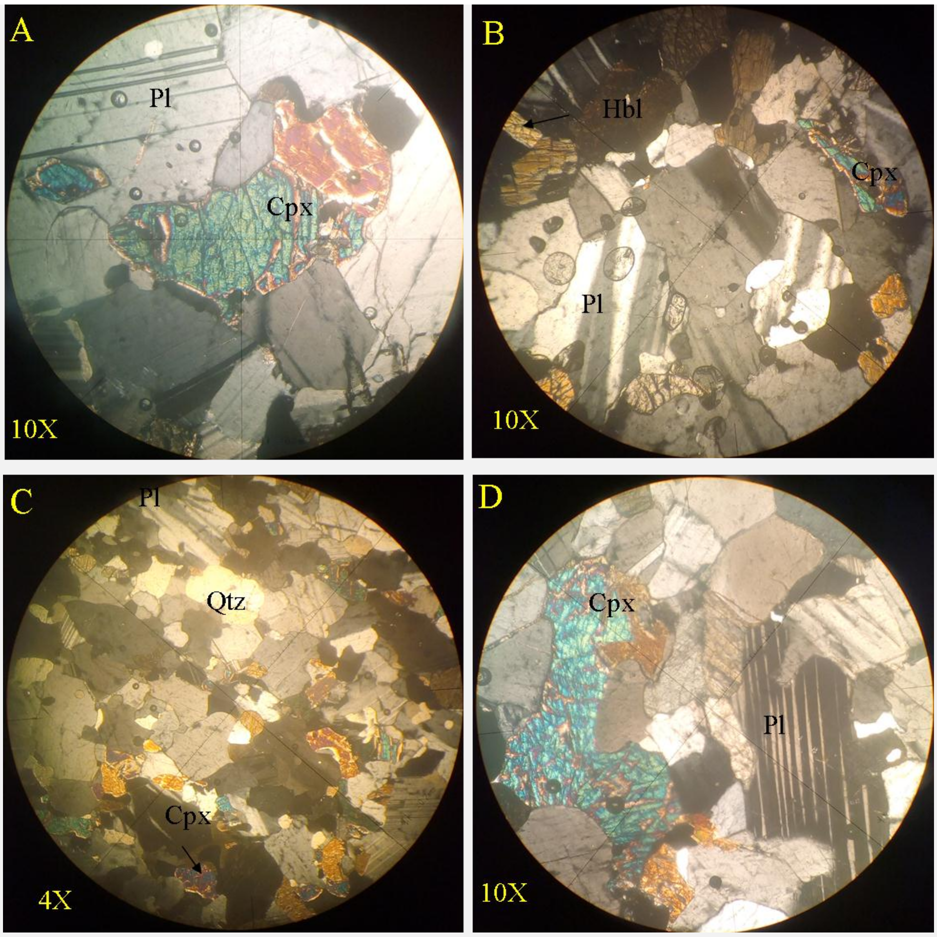


Fig 3.2 Microphotograph of granulite rock in thin section; A) xenoblastic plagioclase and clinopyroxene minerals B and C) formation of hornblende from clinopyroxene due temperature drop and plagioclase with fluid inclusion D) plagioclase crystal shows a distinct banding effect of polysynthetic twinning in the rock unit, all are under XPL.

3.2.2. Amphibolite

The amphibolite is dark and non-foliated metamorphic rock and characterized by medium- to coarse- grained texture (Fig 3.3). It is exposed at the stream cut and covers a small portion of the study area. Hornblende, plagioclase, quartz, +/- clinopyroxene, +/- biotite and +/- chlorite are the main constituents of this rock unit (Fig 3.4). The mineral assemblage of this rock unit indicates the upper amphibolite facies metamorphism. This rock shows spheroidal weathering (pills like skin of an onion) as the result of chemical weathering of systematically jointed, massive rocks (Fig 3.3 C). The differences in weathering rates between the corners, edges, and faces of a bedrock block will result in the formation of spheroidal layers of altered rock that surround a rounded boulder-size core of relatively unaltered rock.

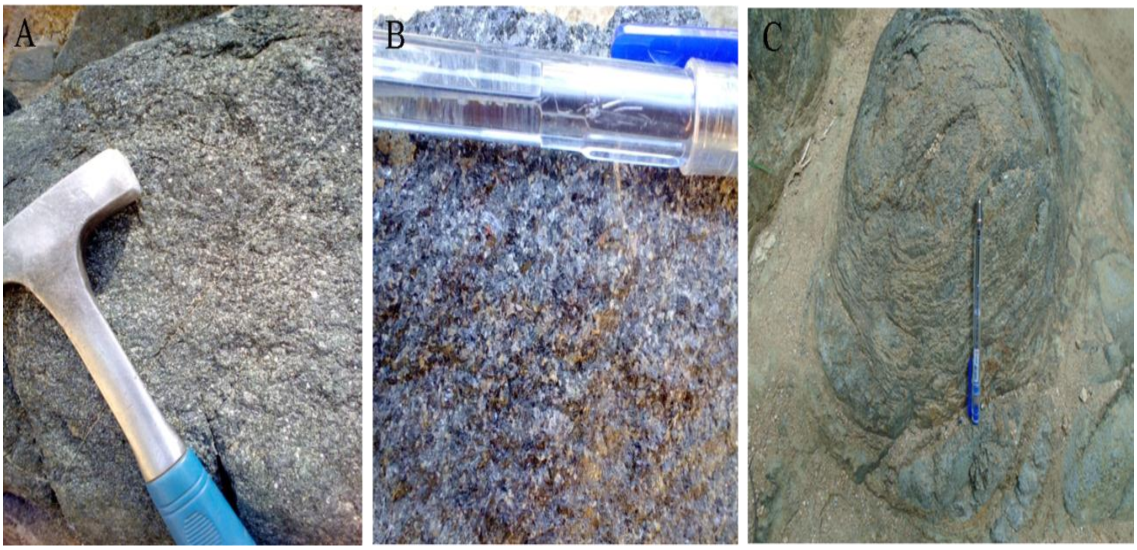


Fig 3.3 Photographs taken from the study area shows A & B) Amphibolite rock in outcrop level exposed at the SW and SE of the study area. C) Spheroidal type of weathering in amphibolite rock.

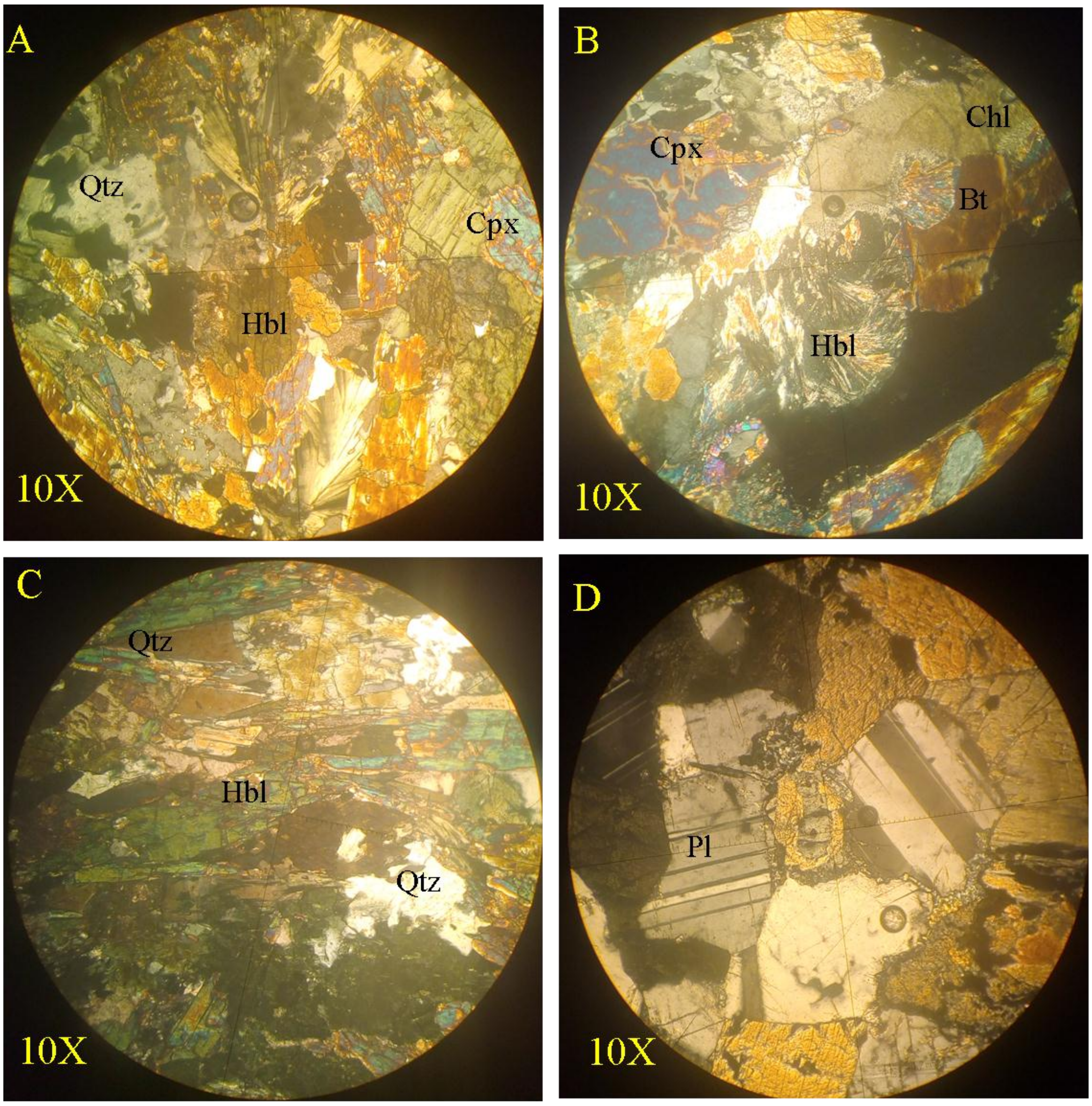


Fig 3.4 Microphotograph of mineral grain in amphibolite rock unit in thin sections; A) Hornblende mineral at extinction position, B) chlorite mineral is retrogradically formed from biotite, C) laths of hornblende contains quartz inclusion and D) plagioclase crystal shows a distinct banding effect of polysynthetic twinning in the rock unit; all are under XPL.

3.2.3. Interlayered Gneiss

This unit is well foliated, representing alternating layers composed of mafic and felsic minerals (Fig 3.5 and 3.7). In the study area there are two varieties of interlayered gneiss, amphibole gneiss and granitic gneiss.

3.2.3.1. Amphibole Gneiss

This rock unit covers the largest area in the study Sorobo area. In hand specimen, the rock is medium- to -coarse grained (high grade) and shows gneissose fabric and in some places dissected with quartzo-feldspathic veins. Dark bands typically dominated by hornblende (and some biotite) and pyroxene and light bands typically dominated by mosaic textures of quartz and feldspar were observed in hand specimens. In addition to the gneissose fabric; mafic and felsic dikes, quartz veins and pegmatites are common structures in this rock unit. Generally, this rock unit is composed of hornblende, plagioclase feldspar, and quartz and trace amount of biotite and opaque minerals. Besides, tourmaline mineral is found as accessory minerals.

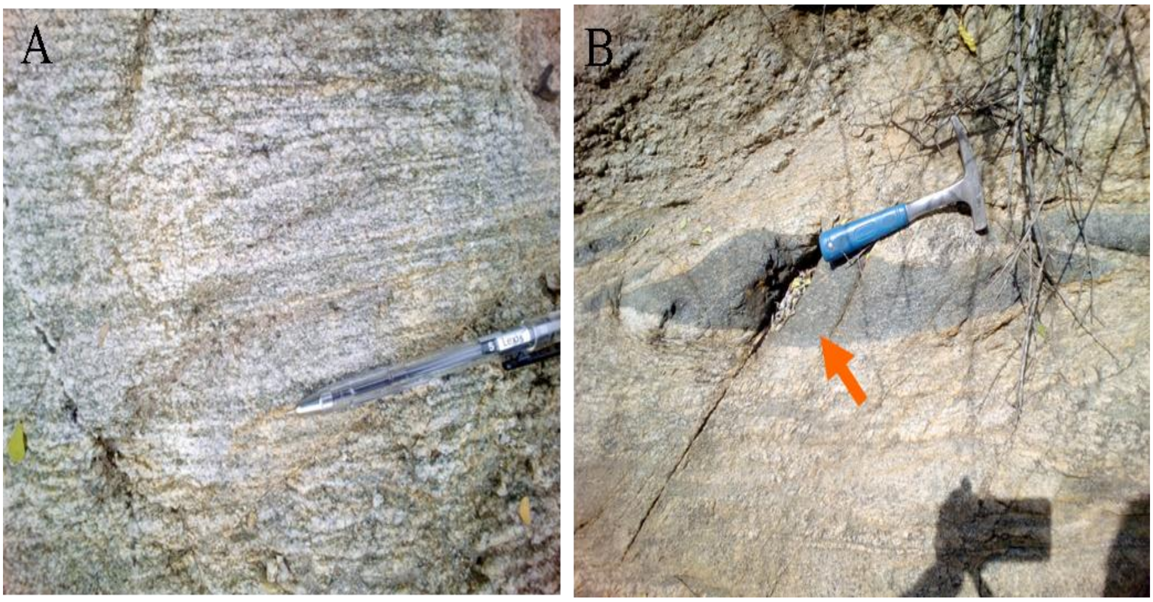


Fig 3.5 A) Field Photograph of amphibole gneiss rock clearly showing foliation. B) Weakly deformed xenoliths of amphibole within amphibole gneiss rock.

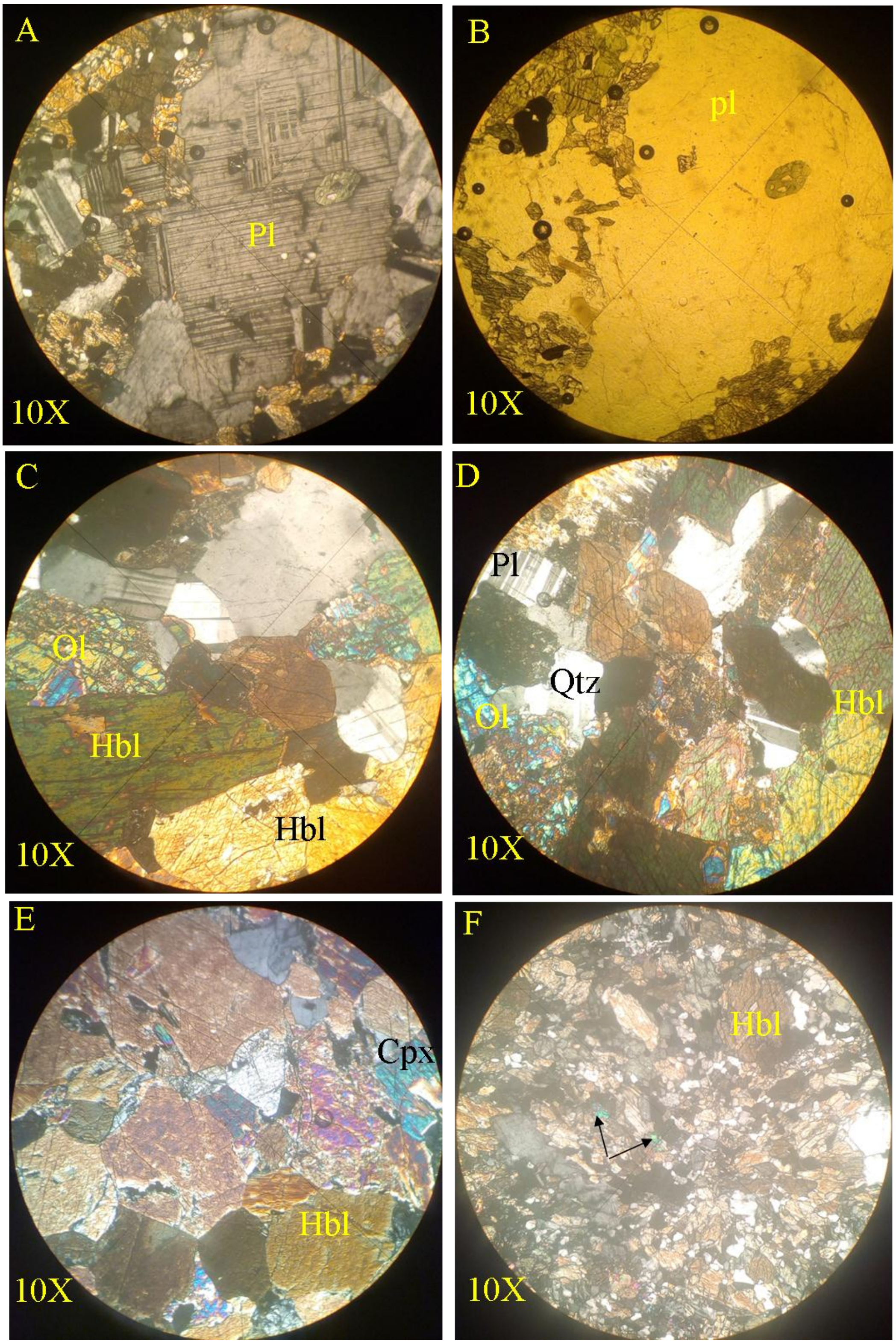


Fig 3.6 Microphotograph of mineral grains in amphibole gneiss rock in thin section: all are under XPL except B, B in PPL.

3.2.3.2. Granitic Gneiss

Granitic gneiss is medium- to -coarse grained rock and covers a small area with respect to the other units of the mapped area. It is exposed in the southwest of the study area (Fig 3.7) and intimately intercalated with amphibole gneiss. It is well foliated and locally banded. Plagioclase, quartz, hornblende, biotite and +/- clinopyroxene are the main constituents of this rock unit. Banding is defined by segregation of felsic (quartz and feldspar) and mafic (biotite and hornblende) minerals. Plagioclase feldspar is characterized by elongated and foliated fabric and is a major component of the rock.

Fig 3.7 Field photograph of granitic gneiss rock in outcrop level exposed at the SW of the study Sorobo area

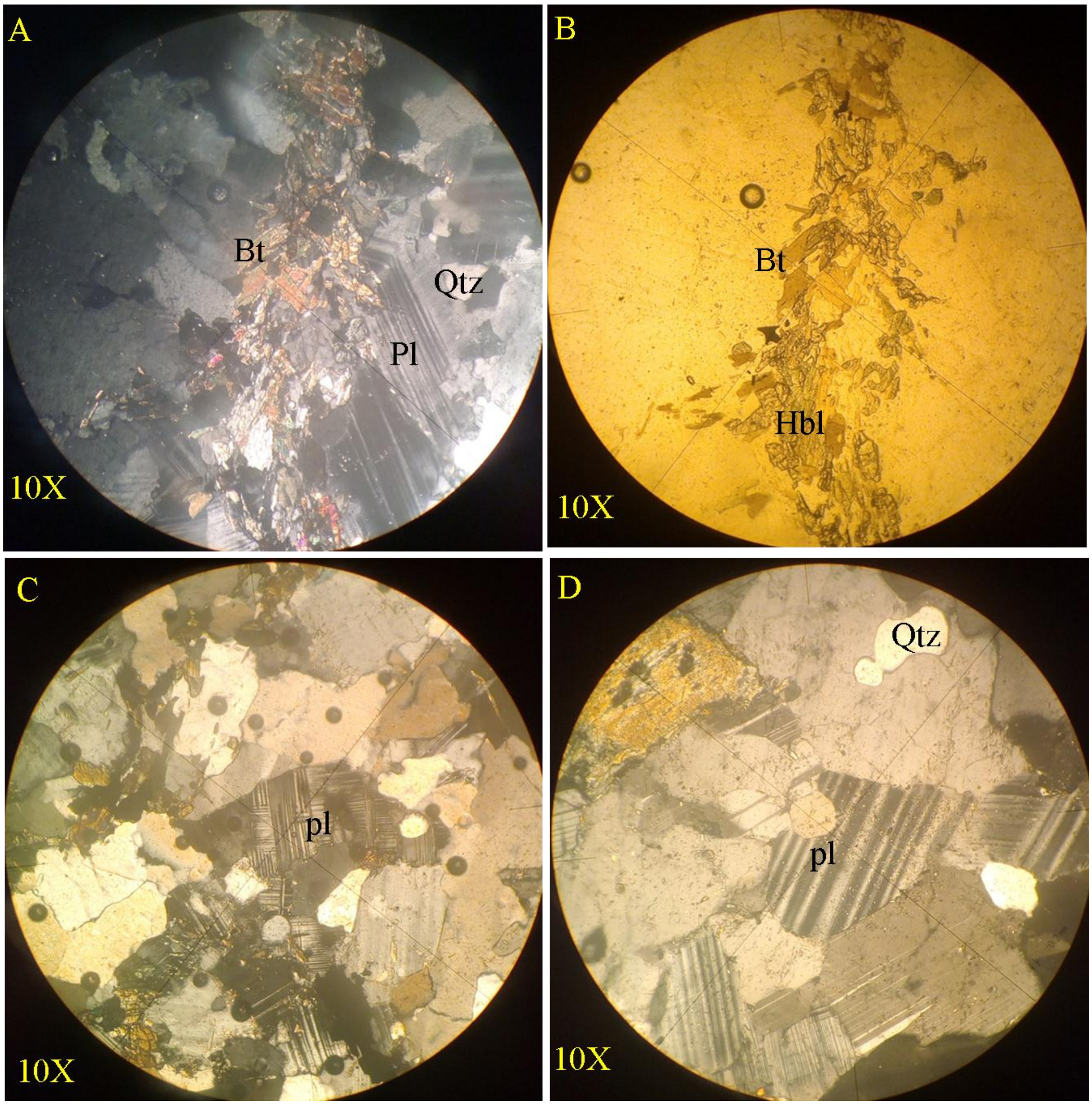


Fig 3.8 Microphotograph of mineral grains in granitic gneiss rock in thin section; A and B) shows polysynthetic twinning in plagioclase, C) shows crosshatched twinning in plagioclase, D) shows deformation and growth twinning in plagioclase; all are under XPL except B, B under PPL.

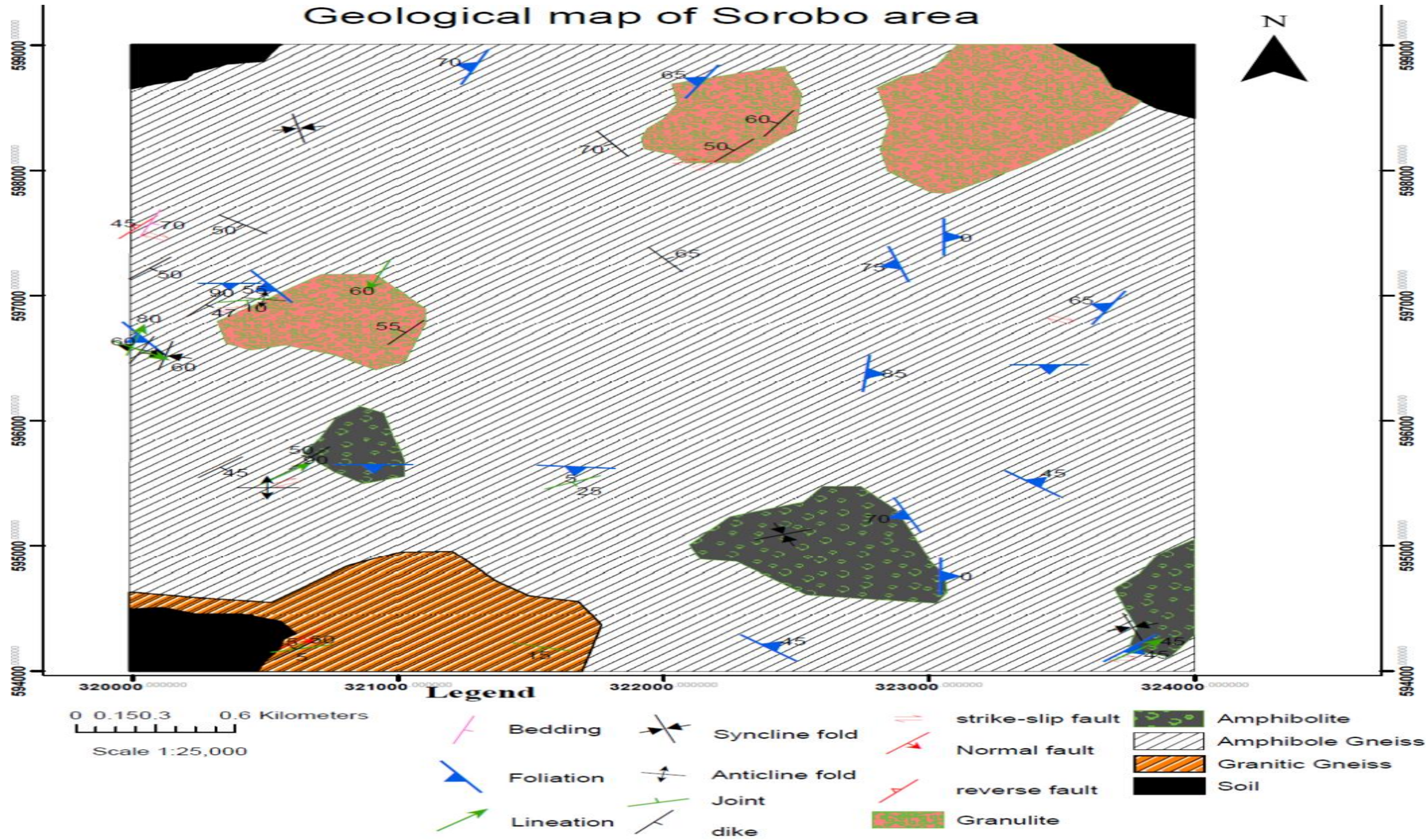


Fig 3.9 Geological and structural map of the study Sorobo area

CHAPTER FOUR

4. Geological Structures

4.1. Introduction

There are both brittle and ductile geological structures observed in the study area. Tectonic processes are responsible for the many discontinuity planes and they resulted in different geologic micro- to macrostructures. Foliation, lineation, fold, fault, joint, dike, veins and veinlet's and other microstructures are the major deformational structures observed in Sorobo area. The study Sorobo area is subjected to at least four phases of deformation (Aspiron, 2015) and there are six deformation events identified from Agere Maryam area (Melesse and Demerew, 2003). This study has been made on the basis of different structures and classified the deformation into five phases. An equal-area plot and rose diagram shows the orientation of all fabric, which indicates multiphase deformation. The presence of fold interference pattern resulted from the superposition of later fabric, folding of gneissosity of an earlier fabric, shearing and faulting of an earlier fabric are indications of polyphase deformation in the study Sorobo area.

4.2. Mesoscopic geological structures

4.2.1. Foliation

Foliation is a planar structure in a metamorphic rock resulting from the ductile flattening of grain aggregates (plagioclase and quartz) and mica in Sorobo area (Fig 4.1). Since the rock units in the study area is high grade metamorphic rock, the amount of mica mineral is less; this requires much time and energy to reorganize hornblende, plagioclase and feldspar minerals to form foliation. Alteration of feldspar minerals to micas may generate gneissose fabric in the study area. Fig 4.1A shows gneissic banding formed from tectonic segregation of mafic and felsic minerals, which are formed prior to folding. The first phase of deformation (D1) was formed due to northwest – southeast compressional stress and resulting west – east trending foliations in the study area (Fig 4.1A). Folding of gneissose fabric resulted during the second deformation phase (D2) (Fig 4.1B). The refolding of foliation by later deformation event (D3) resulted in the formation of type-3 fold interference pattern. There are ductile shear sense indicators in the study are which are characterized by showing different vergence directions. These veregence directions are indications for D4 deformation phases which show east and west vergence direction in the area (Fig 4.4). This is resulted from sinistral (left-lateral) and dextral (right lateral) shearing. From this, determination of the relative age of foliation in a given outcrop or area is done in order to construct the deformational history of an area. Lineation in the study area is sub-parallel to parallel linear fabric elements resulted due to stretching of grain aggregates and re-orientation of elongate mineral grains (hornblende) in a rock body (Fig 4.7C). It is commonly penetrative at the outcrop and/or the hand specimen scales of observation and commonly at the microscopic scale as well. The general trend and plunge of lineation are 045°/40°SE. Equal-area and rose diagram shows the orientation of foliation (fig 4.2) and lineation (fig 4.6). Foliation appears to be axial planar to a minor folds with very much longer westerly dipping than easterly dipping limbs but, shows the general SW, SE, NW and NE dipping attitudes.

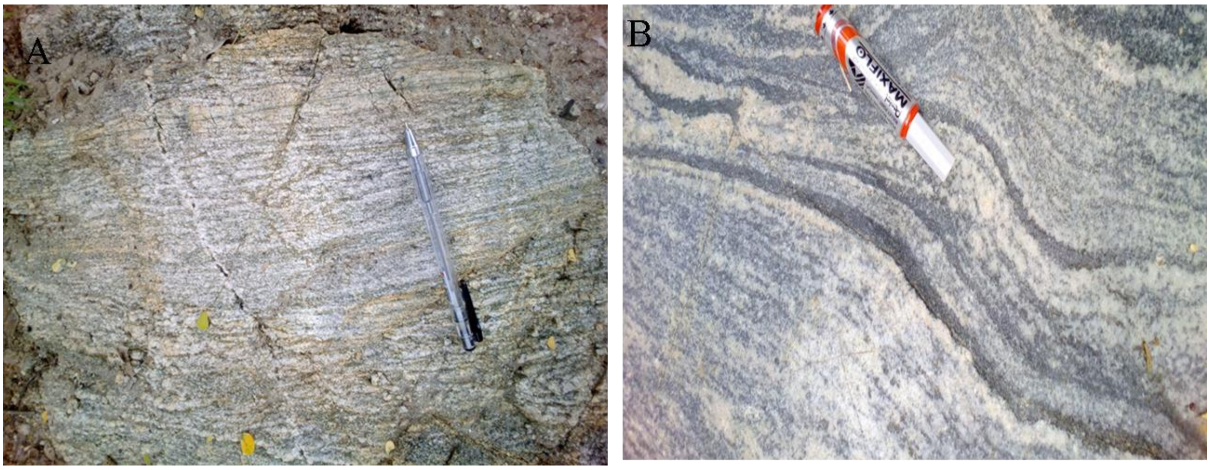


Fig 4.1 Field photograph show A) Gneissosity formed from segregation of mafic and felsic minerals resulted during D1 and B) Folding of gneissose fabric develops gentle fold resulted during the second deformation phase (D2).

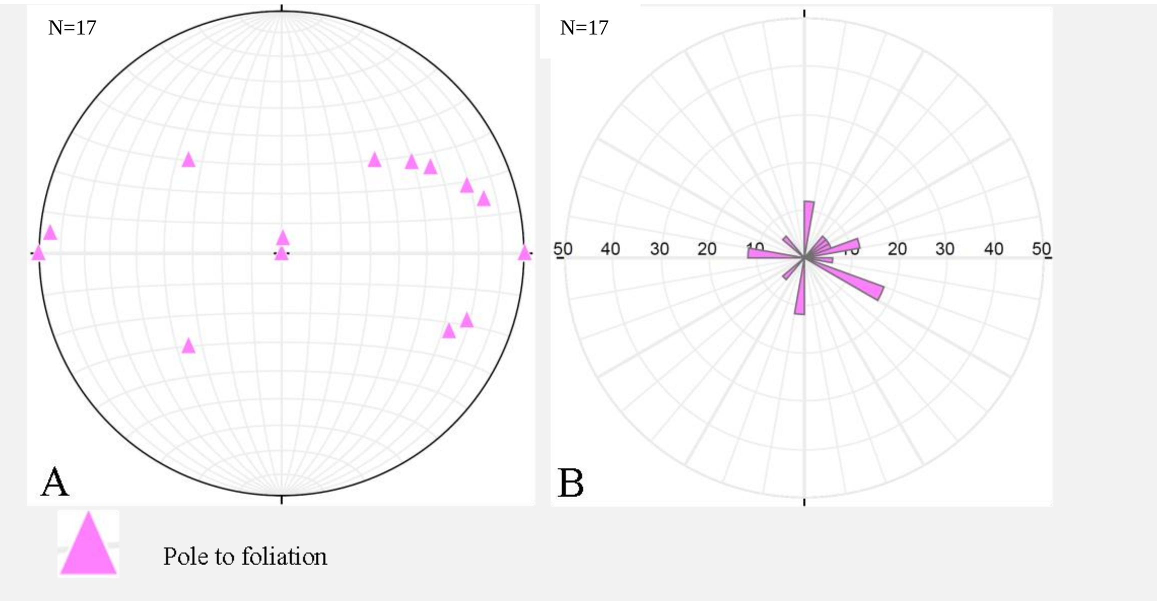


Fig 4.2 Stereoplots of A) poles to foliation shows the prevalence of moderate westerly dipping and shows the general NW-NE trending orientation and B) Rose diagrams of pole to foliation shows the stress direction of gneissosity formation. This randomly distributed pole to foliation indicates polyphase deformation.

4.2.2. Fold

There are many fold structures observed in the study area. Symmetrical, asymmetric (east and west verging folds (Fig 4.4 and Fig 5.2)), Anticline, Syncline and recumbent folds are a major minor fold structures present in the study area (Fig 4.3).

During field investigation, there are parasitic folds in which hinge zones and limbs of large folds often display folds of smaller wavelength and amplitude where the F1 (earlier fold) hinge lines are deformed to bend over F2 (later fold), the sense of asymmetry of earlier (F1) parasitic folds develop on adjoining limbs of F2 (Fig 4.5). They are indicative of the axial traces of the major folds, which has parallel fold axes to the major fold axes. The orientation of parasitic (second-order fold) structures is representative of the orientation of the large or regional (first-order) structures. The sense of asymmetry is consistently towards the hinges of second-order antiforms. It varies systematically across the axial surfaces of the first-order folds. The presence of parasitic folds in the study Sorobo area is a manifestation of two generations of folding in the area. However, the sense of rotation of the parasitic folds reveals the presence of an overturned Syncline fold in the study area with axial trace trending and plunge 130/40SW respectively (Fig 4.5). The sense of asymmetry of different folds in Sorobo area depends up on the sense of shear strain parallel to the verging surface. During fold interpretation careful visualization of vergence direction has been done in order to understand the sense of movement of the upper limb relative to the lower one. West verging folds developed by a layer-parallel shortening combined with a sinistral shear strain along the verging surface when this surface rotates anticlockwise in progressive deformation. East verging folds formed under a dextral shear strain in layers which shorten, but rotate clockwise. Ptygmatitic folds are also found in the study area, which involves an irregularly folded, isolated layer, typically a quartzo-feldspathic vein in a ductile amphibolite rock unit. Rounded and near-parallel, commonly concentric folds in which the amplitude is large and the wavelength small with respect to the almost constant layer (vein) thickness (Fig 4.3D). An equal-area plot and rose diagram shows the orientation of fold axes (Fig 4.6)

Some folds have a continuous axial plane (harmonic fold) across successive folded layers that show approximately the same wavelength and amplitude. Others show discontinuous axial plane along folded layers (disharmonic) in which the amplitude, wavelength and style change along discontinuous axial surfaces from one layer to another. These disharmonic folds develop because of different rheology in the different layers. The incompetent beds are squeezed and adopt to the form imposed by the competent beds.

By using a contoured equal-area point diagram the orientation of the axial trace of fold is determined from a large number of data points of pole to foliation and pole to fold axes. The high density region is a π-maxima and the great circle that passes through π-maxima is π-circle and the line perpendicular (pole) to it is π-axis or axial planar, which show the orientation of fold axes. This contoured π-diagram indicates the style of folds. The shape of the girdle /the bands of contours across the diagram/ reflects the shape of the fold (Annex I fig 1). Annex I figure 1 of pole to foliation shows asymmetric fold whose westward-dipping limbs are longer than the eastward-dipping limbs and have NNW trending axial trace. Pole to fold axes in annex I figure 1 also show asymmetric overturned Anticline fold, which fold axes trending NE.

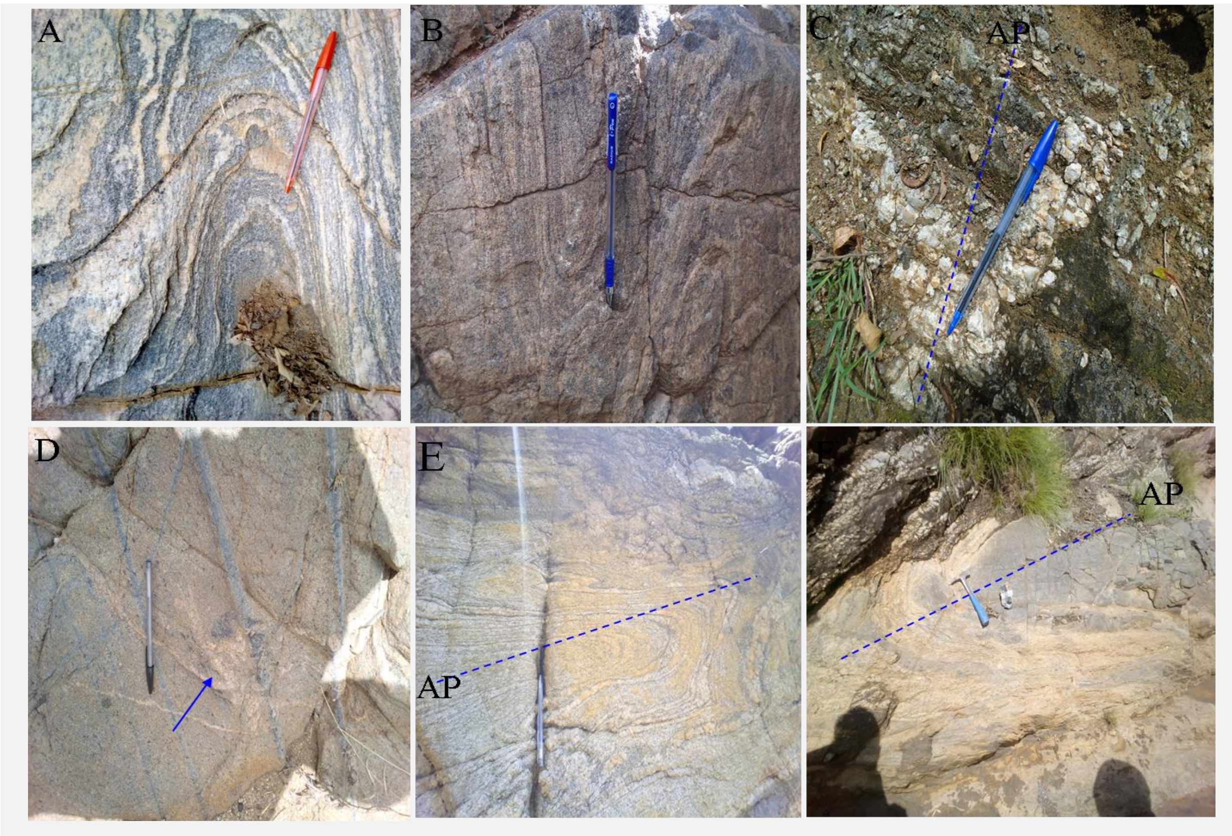


Fig 4.3 Fold photographs taken from the field; A) Anticline fold, B) Syncline fold which have a vertical axial plane, C) Symmetric folds with straight limbs, sharp angular hinges and have acute inter-limb angles of angular fold, D) the arrow shows irregularly folded ptygmatic fold, which is disharmonic and typically quartzo-feldspathic vein and E & F) recumbent fold, which have sub-horizontal axial surface/hinge line resulted during D2, AP in figure is axial plane of folds; Photo taken looking for all NW except angular fold which is looking towards NE.

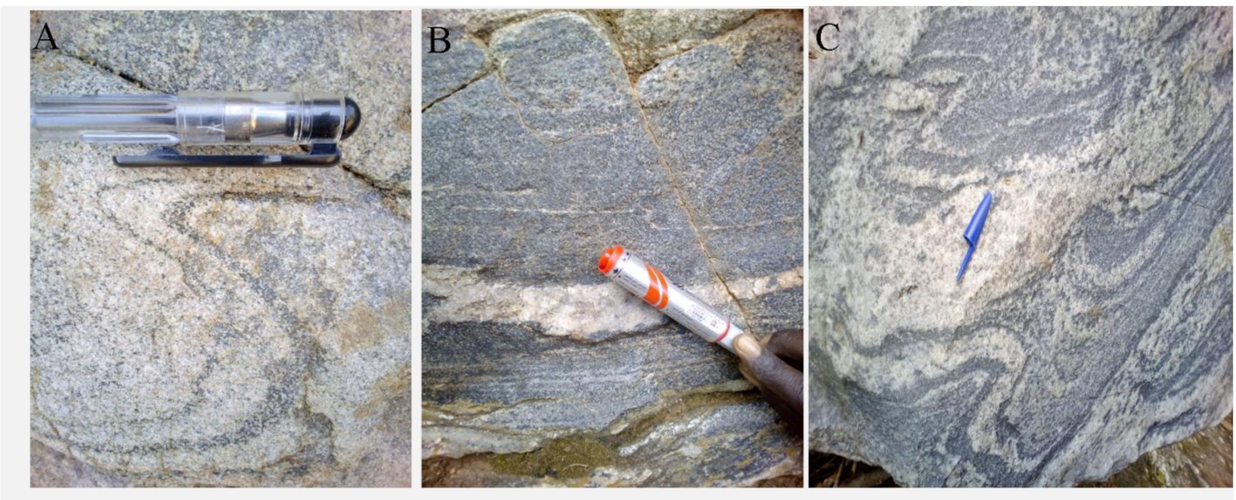


Fig 4.4 Field photograph taken from the field shows vergence direction A) west-vergence shows left-lateral (sinistral) shearing; B and C) East-vergence shows right-lateral (dextral) shearing which shows clockwise rotation; resulted during D4.

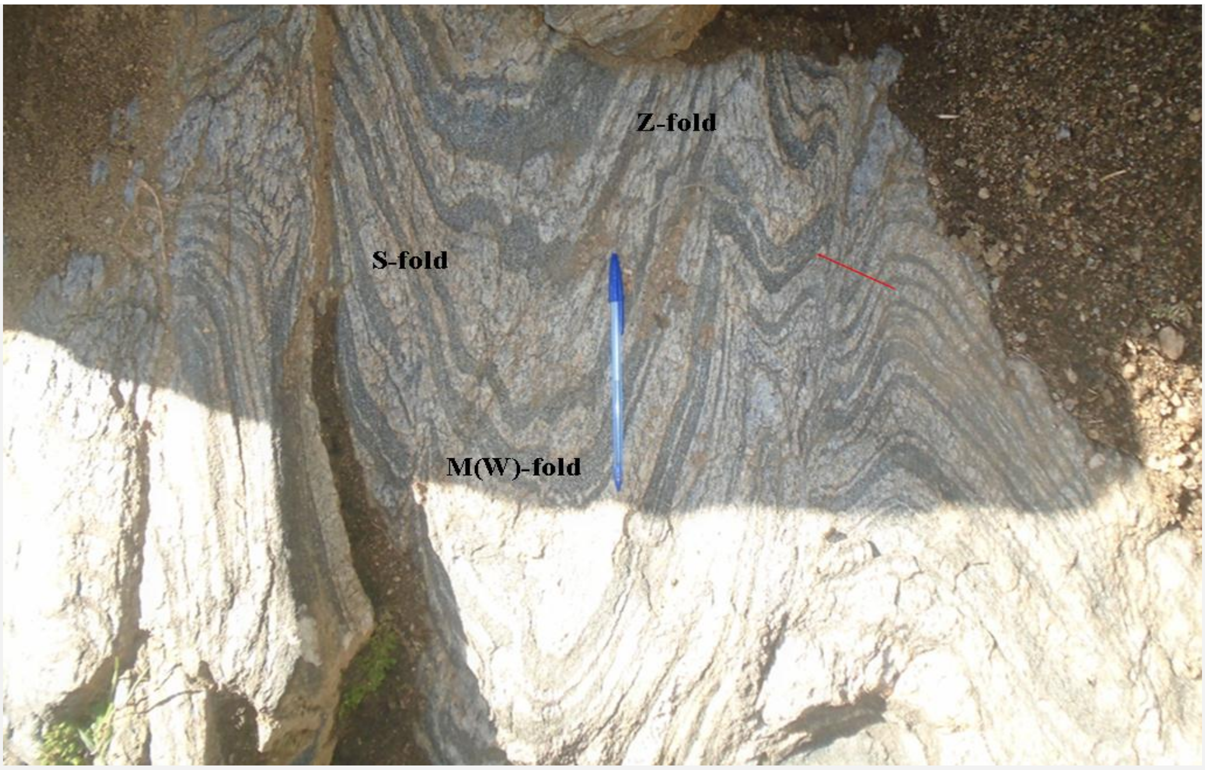


Fig 4.5 Field photographs of parasitic folds. The sense of rotation is pointing towards synclinal axial trace. The red arrow shows detachment fold which indicates fold transposition, photo taken looking east.

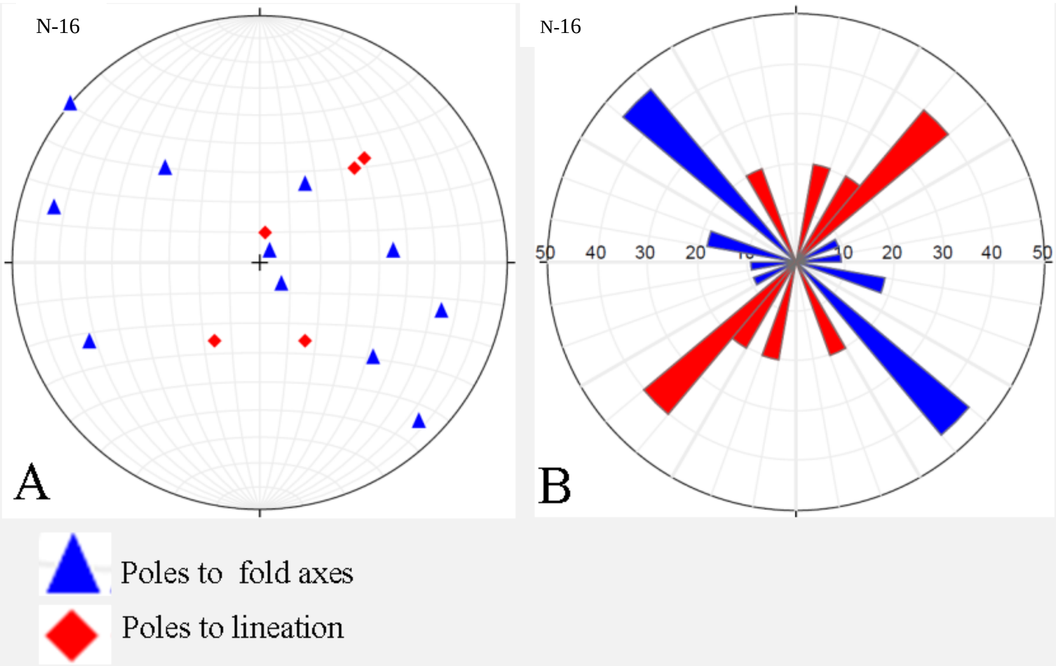


Fig 4.6 Stereoplots of structural elements from different rock units shows A) northwest and southeast plunging poles to fold axis and southwest and northeast plunging lineation. B) Rose diagram indicating the stress direction of fold axes and lineation.

4.2.3. Joints

Joints are fractures formed without any significant displacement and observed in amphibolite, dike (basaltic dike) and amphibole gneisses units of the study area and resulted during brittle D5 deformation phase. There are different generations of joints in different parts of the study area which are parallel or oblique to foliation. The major striking directions of joints measured in the field are SE, NE, SW and NW and the dip amount range from 5° to 90° (Fig 4.7A). An equal-area plot and rose diagram shows E-W, NE and NW trending orientation of joints (Fig 4.8).

4.2.4. Dikes

These structures found in the study area are tabular in shape and discordant in orientation with the surrounding rock. Some are mafic in composition (Fig 4.7 A) and some are felsic (felsite) (Fig 4.7 B and D) formed when magma intrudes to the country rock. Their average thickness range from 20 cm to 2 m and have variable length. An equal-area plot and rose diagram shows the orientation of dikes (Fig 4.8).

4.2.5. Veins

Vein/veinlet is sub-planar concentrations of minerals that have precipitated from solution. In the study area there are both pegmatite and quartz veins. Pegmatite vein mainly contains medium to coarse grained minerals of quartz, plagioclase, muscovite, and small amount of biotite and accessary garnet. In quartz vein the solubility of silica in aqueous (H_2O-rich) solutions decreases dramatically with decreasing temperature, such that quartz dissolves into fluid at high temperature, but then precipitates as the solution cools and becomes supersaturated. They range from 3 centimeter to 2 meter width with various lengths are observed in the study area. Both pegmatite and quartz veins are parallel, oblique or perpendicular to the plane. In general, there are at least two generations of veins: one is parallel to the gneissosity and the other cross cut gneissosity (Fig 4.7 D and E). The study area shows 5 episodes of events: granitic magma intrusion, metamorphism (gneissosity development), fracture (joint) development, fracture filling (vein formation) and displacement of veins (Fig 4.7F). An equal-area plot and rose diagram shows the orientation of veins (Fig 4.8)

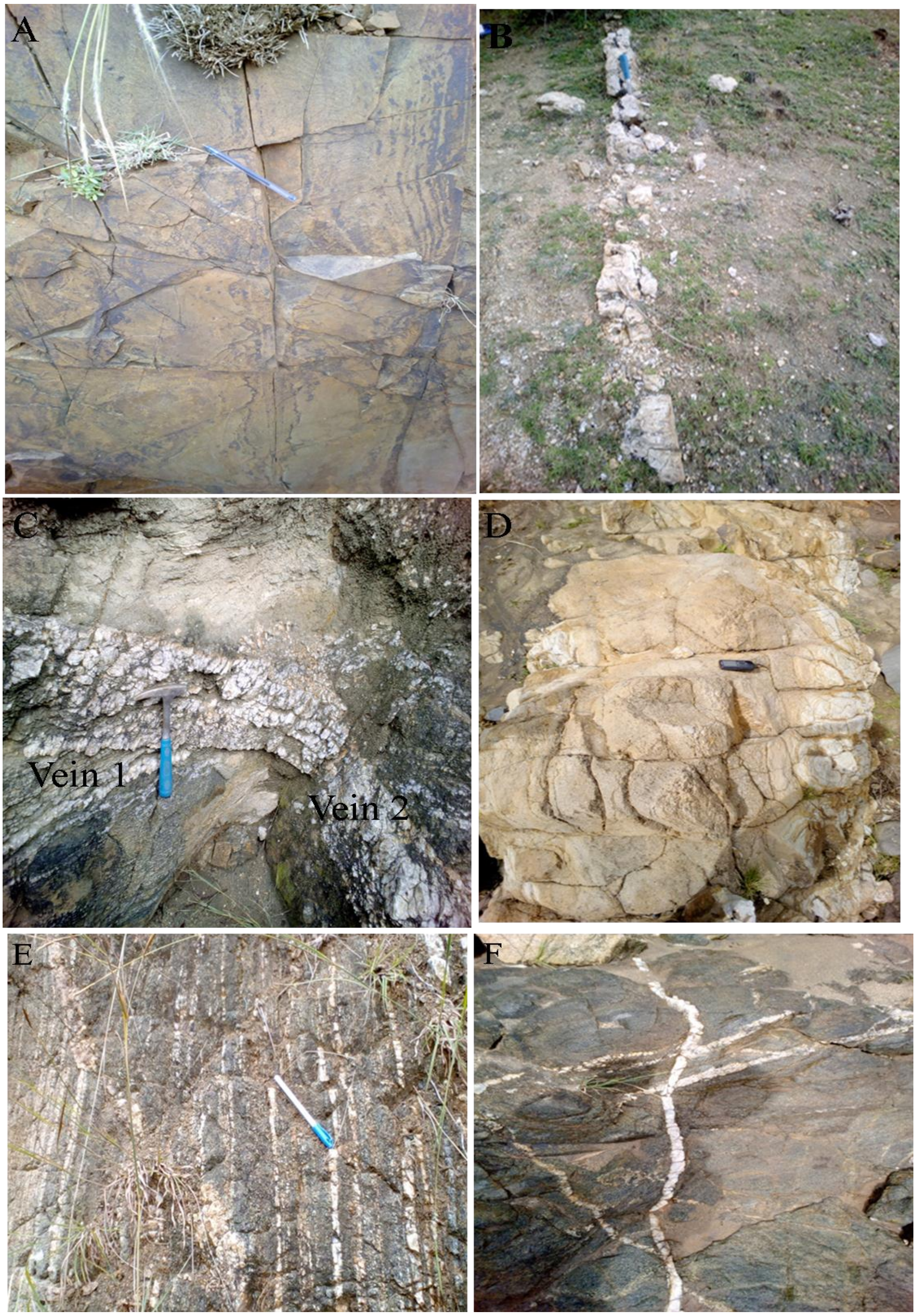


Fig 4.7 Field photograph taken from Sorobo area shows A) Non-systematic joints on basaltic dike, B) Pegmatite Veins cut amphibole gneiss country rock, C) Pegmatite Veins are cross-cut to each other, vein 1 is parallel to lineation, vein 2 cuts lineation obliquely and folded, sub-parallel to parallel elongate linear fabric elements in the rock . D) felsite dike, E) quartz veins parallel and oblique to gneissosity and F) showing the relative age of veins based on the cross-cut relationship in the study area. Photo taken looking A towards SE; B towards NE; C towards N; D, E and F towards NW

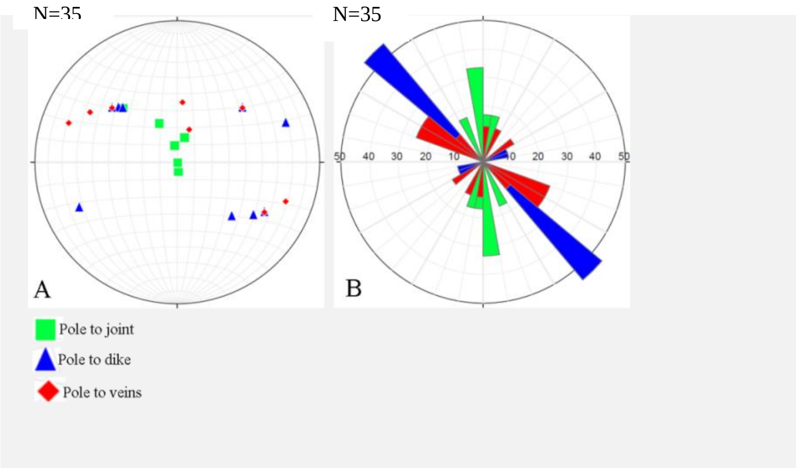


Fig 4.8 Stereoplots shows A) the distribution of data points of poles to joint, poles to dike and poles to veins and B) rose diagram indicating the direction of stress for joints, dikes and veins.

4.2.6. Boudinage

Boudins in the study Sorobo area form when lengthening affects a layered rock formation involving competent felsic layers (granite/pegmatite intrusion) boudinaged within a less competent, easily deformable, host rock (amphibolite rocks). Upon extension, the stronger layers which are competent layer lengthen via heterogeneous thinning leading to the development of pinch and swell structures (i.e. thinning of the strong layer is periodic). Amplification of thinning in the pinched regions eventually led to the segmentation of the stronger layers into boudins separated by the necks. Thinning and necking in the stronger layers often initiates via the development of extensional fractures. Extension proceeds without rotation and evolves with symmetric boudins (Fig 4.9).

Fig 4.9 Field photograph show Pinch-and-Swell structures, competent felsic layers boudinaged within a less competent amphibolite rocks.

4.2.7. Faults

The faults in the study area are minor and micro-faults. There are several minor faults observed in the study area and contain both dip-slip and strike-slip faults (Fig 4.10). This brittle type geological structure resulted following ductile-brittle shear deformation phase (D4) during D5 and has dip amount ranges from 25° to 90°. An equal-area plot and rose diagram shows the orientation of fault plane (Fig 4.11) which mostly trends NW-NE and dipping southward.

Fig 4.10 Fault photographs taken from the study Sorobo area; A, B, and C shows reverse fault in the study area; D) show right lateral (dextral) strike-slip fault. Photo taken looking A towards East, B, C and D towards North.

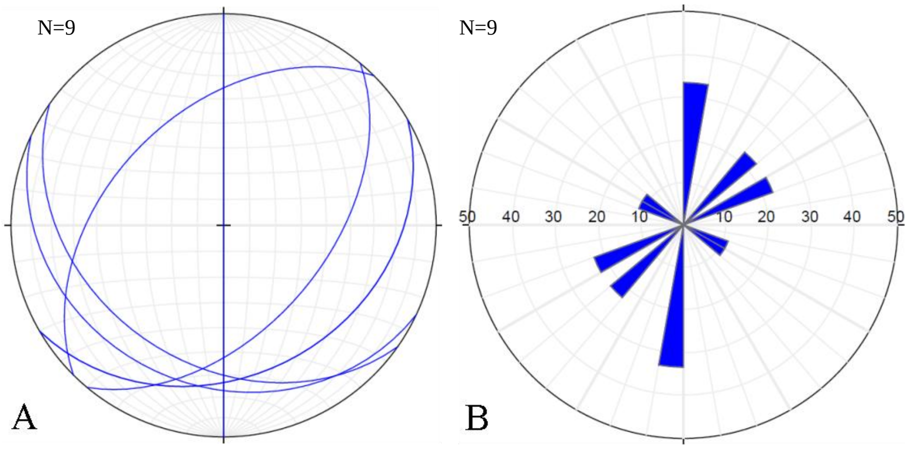


Fig 4.11 Stereoplots using an equal-area projection for the fault data from different rock units observed in the entire area indicating A) NE–NW trending fault plane and B) rose diagram shows the trend of fault planes.

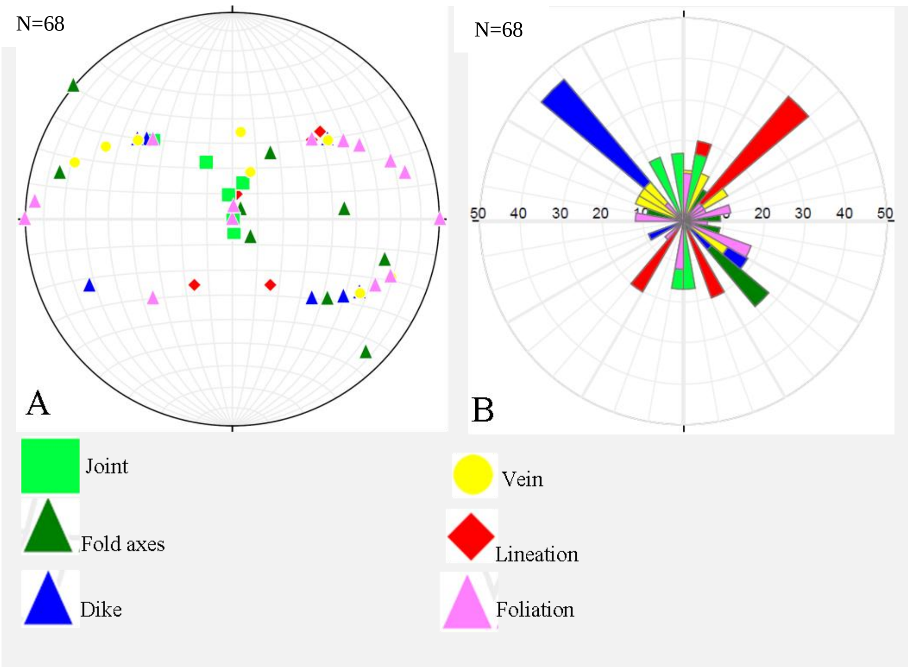


Fig 4.12 Equal-area projections for the whole data from Sorobo area; A) Stereoplots using an equal-area projection to show the generalized distribution of data points from different rock units observed in the study area. B) The radial histogram in the rose diagram shows the direction of strike; the direction of the strike indicates the direction of the main force of plate tectonics in the area.

4.3. Microstructures

4.3.1. Micro-fault

Micro-faults in the study area are shear micro-fractures formed by cataclasis that contain rigid grain fragments. It is a good indicator of brittle shear zones; Fig 4.13 A and B show dextral and sinstral sense of shear respectively. Displacement parallel to a micro-fault surface can be identified from displaced grain boundaries or fragments. In the study area there is the inconsistent sense of offset of a number of grain boundaries at a variety of angles to the micro-crack, this is a useful indication of true shear displacement.

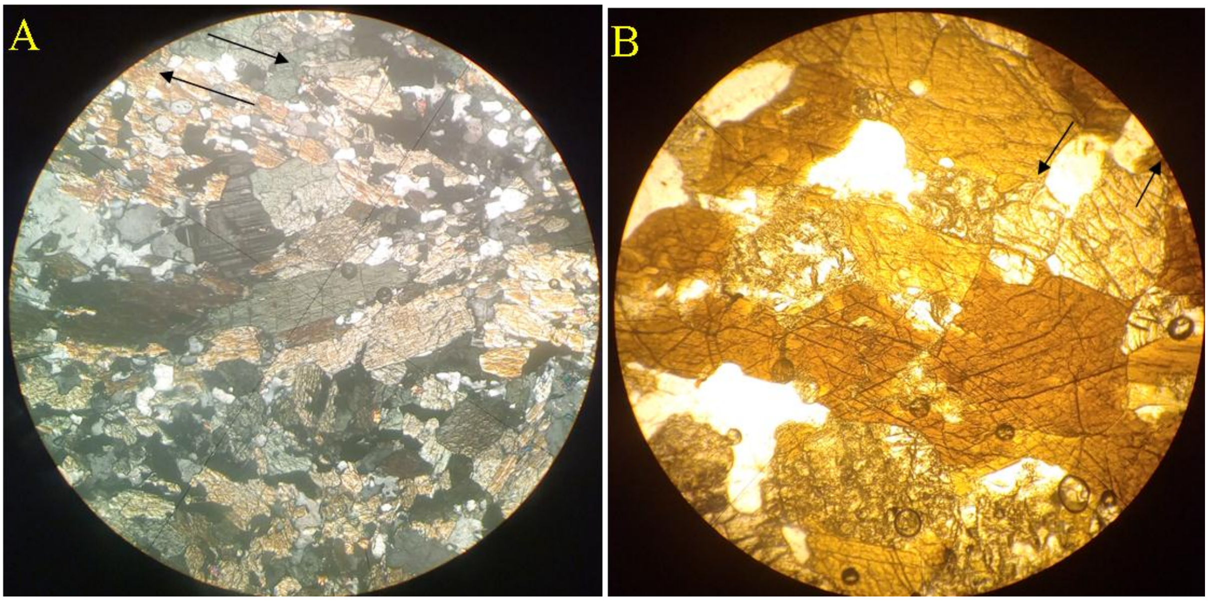


Fig 4.13 Microphotograph of mineral grain shows micro faults transecting quartz porphroclasts A) show a dextral sense of shear B) show sinistral sense of shear. 10X, A under XPL, B under PPL

4.3.2. Fibrous veins

The repeated crack-seal growth is resulted to the formation of fibrous vein; syntaxial fibre veins developed in the study area (Fig 4.14). These veins involve progressive fibre growth from each wall of the fracture towards the center. The crystals forming the fibres show a close compositional link with the rock through which the vein cuts.

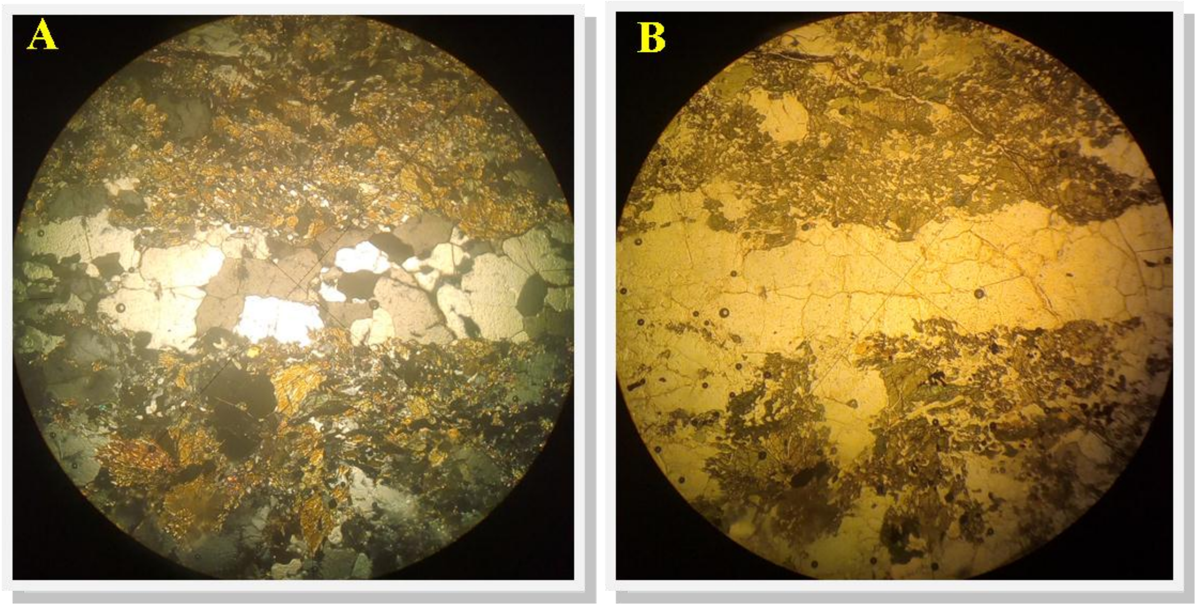


Fig 4.14 Microphotograph of crack-seal structure; 10X, A under XPL and B under PPL.

4.3.3. Deformation lamellae

Quartz minerals in the study area show intracrystalline deformation or deformed internally without brittle fracturing by movement (Fig 4.15).

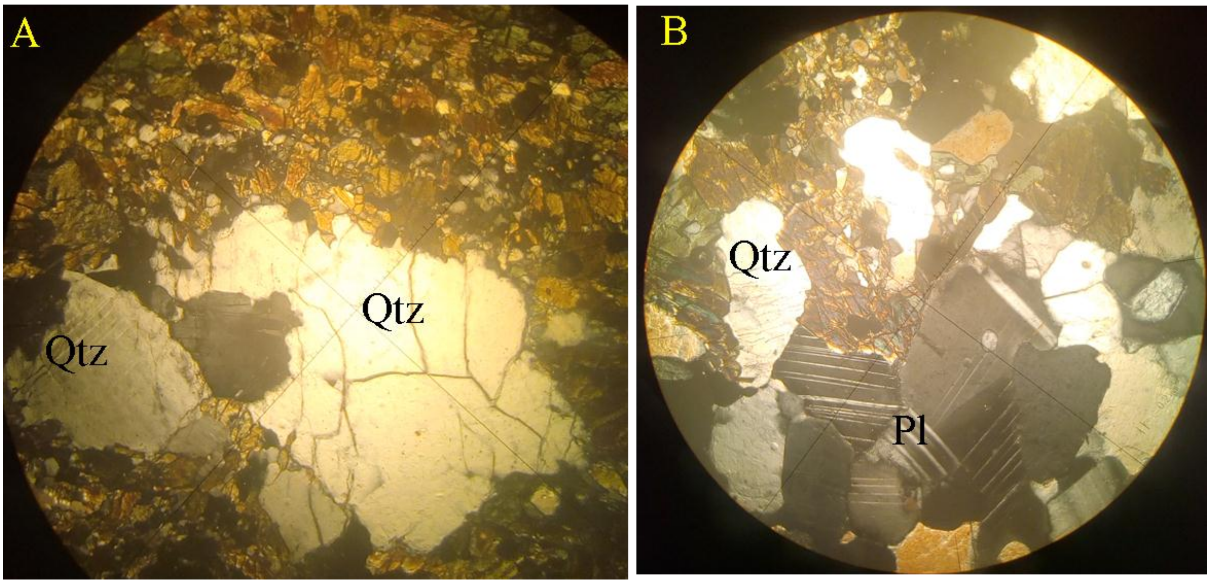


Fig 4.15 Microphotograph shows deformation lamellae and micro-cracks in quartz; 10X, XPL.

4.3.4. Twinning

Thin section shows plagioclase mineral is indicative of both deformation twinning (mechanical) and growth twinning. Both of them have their own characteristic features. Deformation twin is distinguished from growth twins by its shape; which is tapered towards the crystal center (Fig 3.4D and 3.8) and is concentrated at high strain sites where two crystals touch each other or at the rim of the crystal. It does not involve breaking of the crystal lattice, and therefore considered as plastic deformation mechanism.

4.4. Ductile shear sense indicators

There are several meso-scales (Fig 4.16D) and micro-scale (Fig 4.16 A, B & C) ductile shear zone indicator features in the study area which is used to determine the sense of shear. These shear sense indicators are asymmetric folds and mica fish. Asymmetric fold shows a fold axis at a high angle to foliation, may indicate the sense of shear. Fig 4.16D shows the rotation of the fold axial plane from vertical towards right, indicates dextral shear sense.

Large single mineral grains with an elongate sigma shape, consisting of internally undeformed and isolated mineral grain in a relatively fine-grained matrix have been observed from thin section analysis (Fig 4.16 A, B & C). This type of microstructure form by slip on the flat surfaces of the structure and are thought to remain stable in orientation during ductile deformation. Their orientation is commonly tilted against the general sense of shear and can form a small tail of recrystallized material that can be interpreted the same as sigma-type tails. The geometry of mica fish structure is the result of dissolution, growth and internal deformation. Commonly, trails of small mica fragments extend into the matrix from the tips of isolated mica fish.

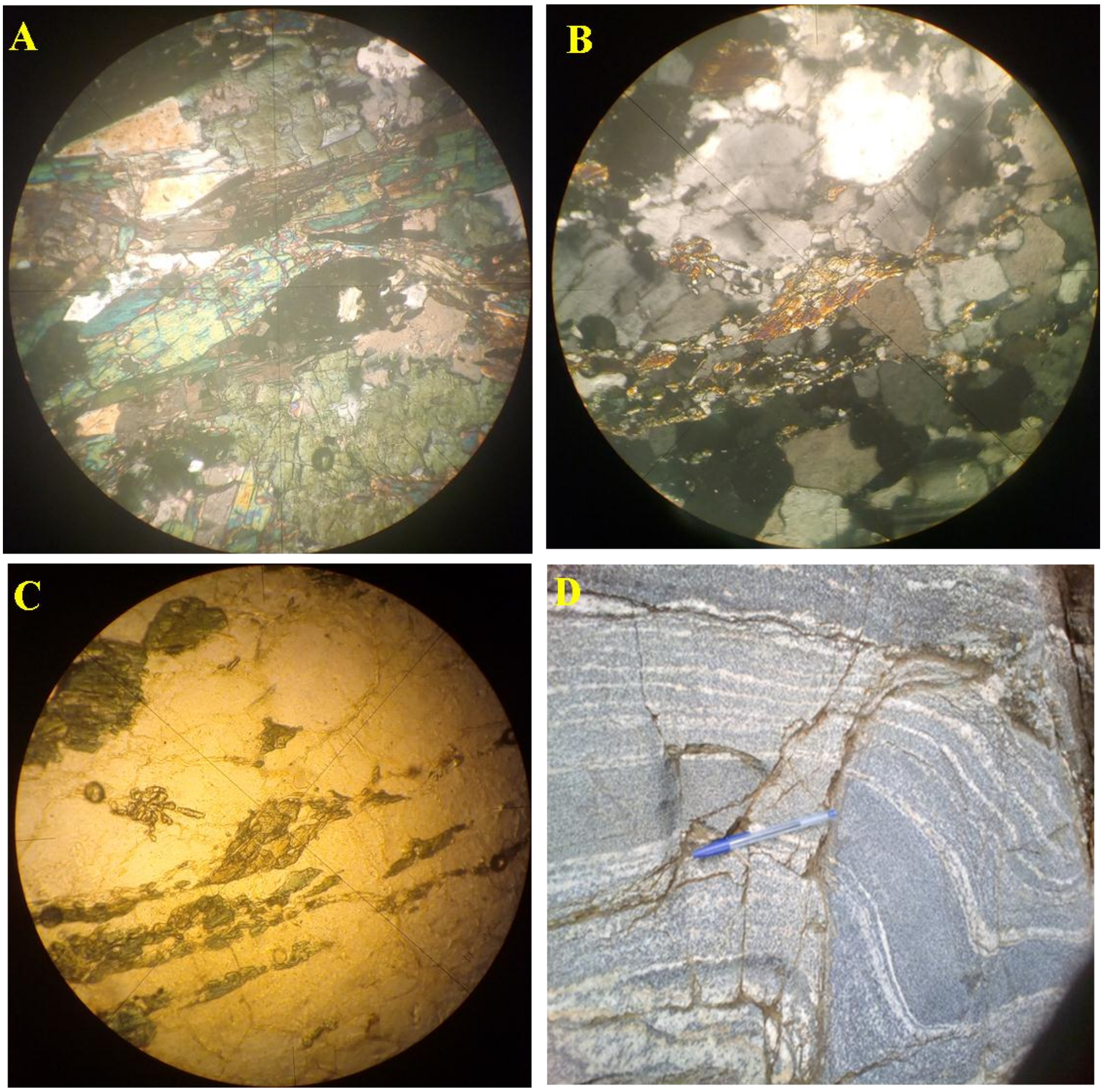


Fig 4.16 Microphotograph of A, B, and C are Mica fish contains a stair-stepping of the wings of mica fragments and D is asymmetric fold from the field, indicates a dextral shear sense. The matrix contains quartz mineral which is dynamically recrystallized and developed an oblique foliation; A and B under XPL, C under PPL, 10X.

CHAPTER FIVE

5. Deformation and Metamorphic History

5.1. Introduction

Deformation and metamorphic history can be distinguished by analysis of minerals and microstructures in metamorphic rocks. By analyzing the sequence in which the minerals and structures were formed, more than one phase can be found in the area. By using this analysis different deformation phases and metamorphic events was determined, showing when the rock was under a certain pressure-temperature conditions. The obtained phases show when the deformation phase ended and crystallization of new minerals occurred.

Thin section study of rock has been an important source of information in that the deformed rocks are one of the few direct sources of information available for the reconstruction of deformation and metamorphic events. Observations on the geometry of structures in deformed rocks have been used with care; they are the end product of an often complex evolution (Passchier, 1998). The reconstruction of this study has been made by careful interpretation and analysis of both thin section and field data of the end stage of deformed rock.

The study area consists of three gneissic rock units (interlayered gneiss, granulite and amphibolite), where interlayered gneiss unit contains amphibole gneiss and granitic gneiss. From the field observation and thin section analysis at least two phases of metamorphism and five deformation phases are encountered/identified/. They are designated as M1, M2, D1, D2, D3, D4 and D5 (where M and D refer to metamorphic event and deformation phase respectively).

5.2. Deformation history

The superposed folds in the study area are formed as a result of 3 sets of Deformation. S0 plane was not discernible as it was almost parallel to S1. Throughout this outcrop there is a well-developed gneissosity (marked by the alternation of light and dark color) on the S1 surface. This fabric is associated with the first generation of deformation (D1). Since S1 & S0 both are parallel in all area except at hinge, F1 is a tight isoclinal Fold formed during D2.

D1, D2 and D3

This is a shortening deformation event. Gneissosity (S1) is formed during D1 and the D2 deformation event is characterized by tight to isoclinal folding (F1) of metamorphic segregation layering in the rock unit; F1 folds are recumbent and associated with a prominent axial planar fabric, S1 (Fig 5.1). S1 is defined by aligning hornblende, feldspar, quartz and +/- mica minerals in the rock unit. Subsequently, the entire ensemble was folded during the D2 deformation along near-vertical axial planes, F2 fold axis are parallel to F1. This upright F2 fold is round hinged, close to open fold. S1-S2 intersection forms a prominent intersection lineation parallel to F2 fold axes. A secondary set of fold which is upright fold may superimpose on an earlier fold which is recumbent fold, resulting in type 3 fold interference patterns which have a parallel fold axis and shows convergent-divergent pattern (Fig 5.1); this refolding is due to D3.

Upright folding (F2) of the S1 foliation during the D2 deformation is seen in the study area, at times with the development of an axial planar foliation, S2.

Fig 5.1 Field photograph from the study Sorobo area documenting 3 sets of deformation phases: Gneissosity (S1) during D1, folding of S1 during D2 and refolding of S1 during D3.

D4-D5

A fourth deformation phase is a shear/strike-slip/ deformation event. D4 deformation phase is formed following the D1-D3 deformation phases, which is characterized by dextral and sinistral strike-slip shearing, affects most lithology of the study area with differing intensity. In the study area the evidence of D4 deformation is in the form of occasional narrow, NNW-SSE trending sub-vertical shear planes with dextral sense (Fig 5.3). It is also characterized by showing different vergence directions (Fig 5.2 and Fig 4.4). This is resulted from sinistral (left-lateral) and dextral (right lateral) shearing. It is inferred to be the result of rotation of pre-existing planar features through the shortening field during progressive dextral and sinistral shearing. In general both dextral and sinistral shear – sense is recorded in the study area but dextral movement appears dominant. D5 deformation phase is a brittle type of deformation phase, which is formed following D4 shear/strike-slip/ deformation phases and was resulting in different types of faults of varying intensity and orientations (Fig 4.10).

Fig 5.2 Field photograph shows NW-vergence, asymmetric or sinistral (left-lateral) shearing from different area which shows counter-clockwise rotation and resulted during D4.

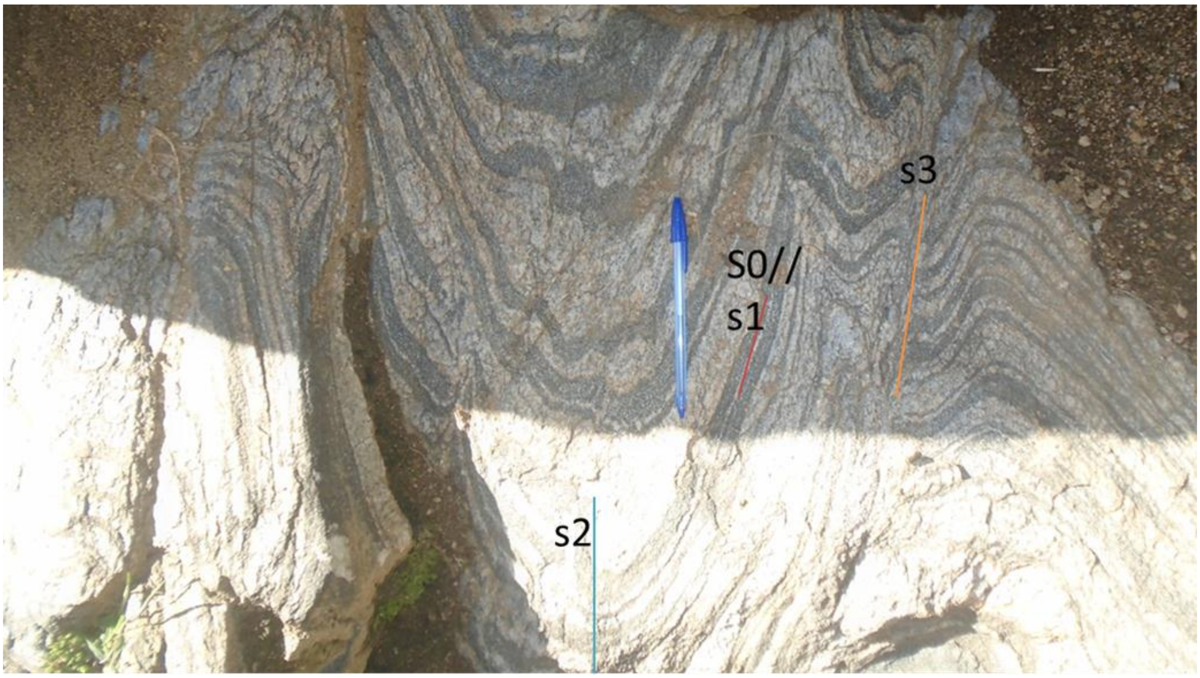


Fig 5.3 Field photograph indicating foliation series and different sets of deformation phases from D1-D4 in one outcrop

5.3. Metamorphic history

There are two stages of metamorphic events documented in the study area which are designated as M1 and M2. This is done from thin section/petrographic/ analysis of rock samples. M1 lies synchronous with the first phases of deformation (D1) during regional prograde metamorphism and M2 lie in retrograde regional metamorphism mineral assemblages during the late deformation phase (D4) event or shear/strike-slip/ deformation event.

Figure 5.4A show when plagioclase feldspar alters and produces clay minerals. The feldspar mineral is completely replaced by a new mineral phase, but the area occupied by the clay still has the configuration of the original feldspar crystal. Thus, feldspar is pseudomorphed by clay. Characteristic textures are also generated by pseudomorphic replacement of amphibole mineral to clinopyroxene mineral phases (Fig 5.4C) caused by reactions involving a hydrous fluid, regular intergrowth from unmixing or exsolution lamellae in pyroxene (Fig 5.4 D).

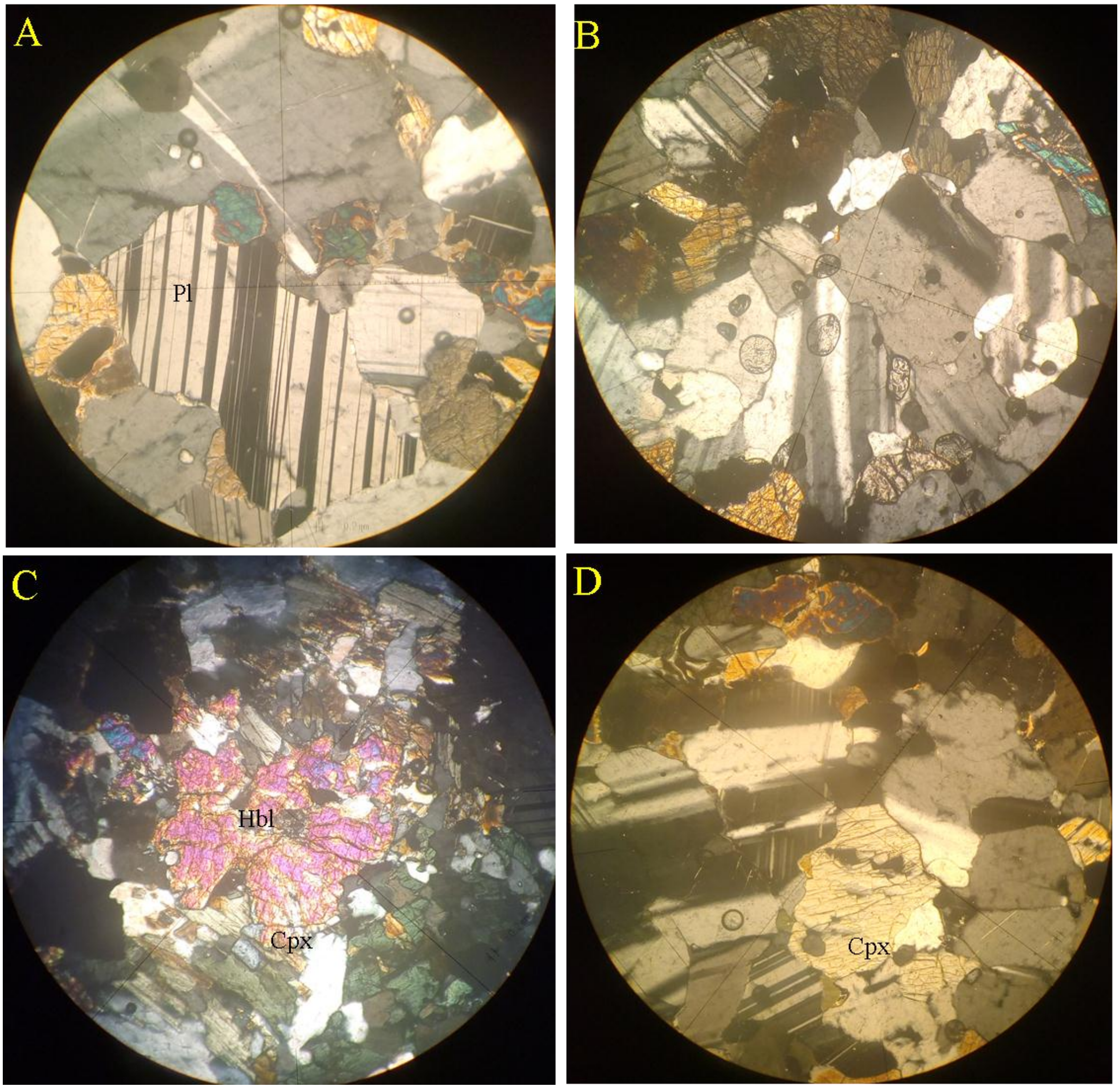


Fig 5.4 Microphotograph of A) alteration of plagioclase and plagioclase crystal with distinct banding effect of polysynthetic twinning B) fluid inclusion in plagioclase C) prograde replacement of the amphibole mineral by clinopyroxene and D) exsolution lamellae in clinopyroxene; 10X, XPL

5.3.1. Prograde metamorphism (M1)

Petrographic determination of metamorphic mineral assemblage from the representative thin sections of each rock unit has been done; this is important to the identification of different stages of metamorphism event. In the study area the metamorphic mineral assemblage in the granulite rock sample is composed of Cpx + Pl + Qtz + Hbl +/- Bt +/- opaque minerals (Fig 3.2); this is a characteristic mineral assemblage of granulite facies. Other rock units are also composed in the same manner in the study area, but differ in the percentage of major minerals and +/- other accessary minerals. This mineral assemblage also indicates the metamorphic rock contains of igneous protolith. The presence of index mineral garnet in the field (Fig 3.1) also shows the metamorphic peak (M1) of the rock in the study area. The replacement of amphibole mineral by pyroxene in amphibole gneiss rock unit (Fig 5.4C) is manifested a prograde metamorphism. The metamorphic mineral assemblages of the rock unit are characterized by a mineral that are found in a wide range of temperature and pressure condition. Therefore, the metamorphic rocks of the area have attained graulite facies.

5.3.2. Retrograde metamorphism (M2)

This is characterized by a transformation of metamorphic minerals that were stable in the M1 phase of metamorphism to a new metamorphic alteration product /secondary minerals/ under lower P-T condition. From the thin section analysis the breakdown of biotite to chlorite mineral (Fig 5.5), and transformation of plagioclase to clay mineral (cloud in thin section) by alteration (fig 5.4A) manifested a retrograde metamorphism (M2). The metamorphic mineral assemblage in the amphibolite rock sample is composed of Hbl + Pl + Qtz +/- Cpx +/- Bt +/- opaque minerals (Fig 3.4). The metamorphic mineral assemblages of the rock unit are characterized by a mineral that are found in a medium range of temperature and pressure condition. Therefore, the metamorphic rocks of the area have attained upper amphibolite facies.

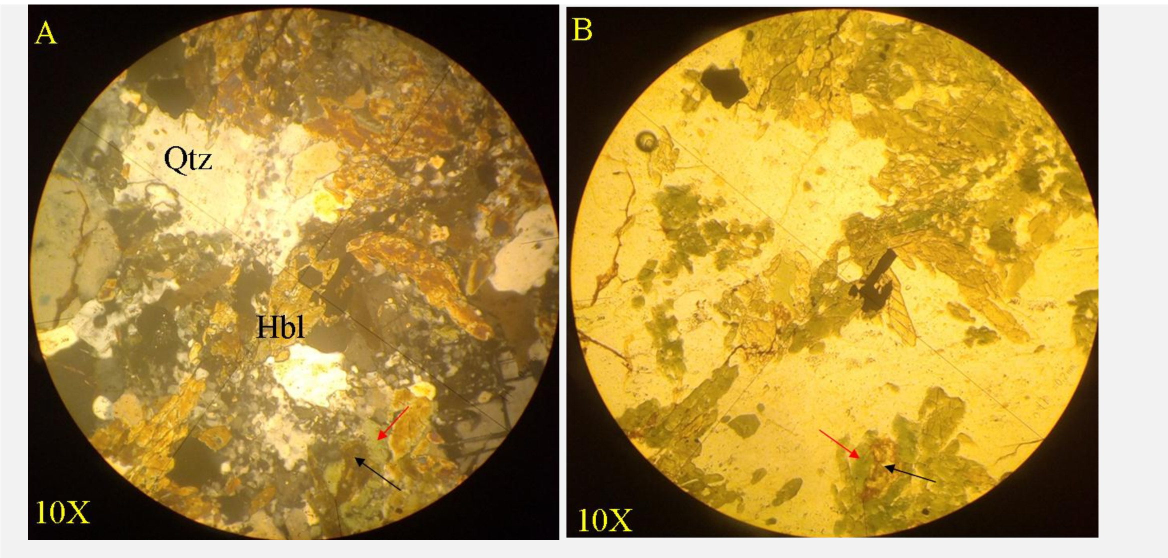


Fig 5.5 Microphotograph of mineral grain shows Transformation of Bt to Chl by alteration; the breakdown of biotite to chlorite; A and B) shows biotite is going to die out in XPL and PPL respectively. Small residual brownish patches of biotite still occur in PPL (chlorite after biotite); 10X, manifestation of retrogression.

CHAPTER SIX

6. Discussion

In the study Sorobo area, the deformation and metamorphic history was investigated by field, microstructural and petrographic analysis. The aim of this study was to understand the deformational and metamorphic history of the Sorobo area, by documenting the characteristics and timing of different generations of geological structures.

Thin sections of rocks have been an important source of information for this study. Deformed rocks are one of the few direct sources of information available for the reconstruction of tectonic evolution (Passchier, 1998). From field investigation, observations on the geometry of structures should be used to reconstruct the tectonic evolution by correctly interpreting the end stage. From a volume of rock which contains a distribution and orientation of fabric, tectonic evolution of an area was determined.

In most deformed rocks in the study area, structures with different style and orientation and minerals which represent different metamorphic grades overprint each other. This means that equilibrium is generally not attained at each stage: mineral assemblages representative of different metamorphic conditions may be 'frozen in' at different stages during burial and uplift. Compared with similar data on a larger scale by carrying out the literature, by carrying out further field and thin section analysis from the study area; deformation phases and metamorphic events were established.

To construct the structural evolution of rock units with complex deformation patterns in geological literature the concept of deformation phases has been used (Ramsay, 1967; Hobbs et al., 1976; Ramsay and Huber, 1987; Marshak and Mitra, 1988). Due to differential stress in a volume of rock a permanent deformation occurs. During permanent deformation the older fabric elements are not always smoothly erased or modified to a new fabric. Since deformation in a rock is commonly concentrated in certain domains and less concentrated or absent in others; relics of older fabric elements are locally preserved. At high strain the older fabric will be completely erased or by rerystallization and grain growth under favourable metamorphic condition (Passchier, 1998).

In the study area different rock units and geological structures mesoscopically and microscopically identified and described. Microstructures and meso-structures are analyzed and interpreted in order to understand the tectonic evolution of an area. Also geological and structural map of the area was carefully plotted. Pegmatites and quartz veins are emplaced within amphibole gneisses, amphibolites, granitic gneisses and granulite host rocks. Their host rocks were petrographically analyzed. Field and mineralogical properties of the major rock types that underlie the study area are also presented.

Relevant data are gathered through detailed mesoscopic field observations and thin Section analysis provides a contribution to the analysis of the required scientific questions. From each outcrop the rock has been carefully studied and photographed. A photo-stitch of the whole rock has been generated to facilitate detailed interpretation. The study also contains stereoplots (equal-area projection and rose diagram) of the orientation of the main fabric and linear elements, which are important to ease understanding of the orientation of several geological structures on two-dimensional. Ductile shear sense indicators are also analyzed and interpreted in order to understand the sense of shear/movements/ of blocks. Each of these ductile shear sense indicators has their own characteristic features. Within Sorobo area there are both sinistral/left-lateral/ and dextral/right-lateral/ sense of shearing are identified. This is from both field observation and thin section analysis.

According to Gichile (1992) the Mozambique belt is characterized by NNE and NNW trending folds and metamorphic fabrics and consists of high grade, amphibolite to granulite facies rocks, which shows similarity in metamorphic facies and orientation of metamorphic fabrics of the study area. Davidson (1983) also states the gneisses rocks of Hamar domain in the eastern sector of the southwestern metamorphic terrain of Ethiopia are strongly and steeply folded, and shows regional NNW-SSE-trending foliation with steep NE dips. From this Sorobo area is also correlated with Hamar domains within omo river project area due to its lithological, metamorphic and structural similarities.

In order to attain objectives the relationship between deformation and metamorphism was identified from this regional metamorphic environment. Each of them has an influence to one another. From this, interrelationship between deformation and metamorphism microstructural evolution of a given rock was identified. Deformation processes accompanying metamorphism vary as a function of the prevailing confining pressure, temperature, the strain rate and lithological factors (mineralogy, porosity, grain size and permeability). The above listed variables affect the rheological behavior of a given rock and accompanying metamorphism. Within regional metamorphic environments of the study area, deformation accompanies metamorphism, and more particularly in fault and shear zones. Around faults and shear zones due to high concentration of strains and strain rates in narrow zones, there is a significant influence of active deformation and mechanical energy on metamorphic processes.

The role of deformation during metamorphic transformation can be significant in different ways. There is a reduction of grain-size to increase the surface area and more surface free energy to facilitate/promote/ reaction. This enhances permeability and fluid movement through areas such as shear zones. Therefore, grain size reduction is a result of deformation and important for metamorphic reactions. Deformation also enhances the production of strained grains with high dislocation densities. This also enhances solubility relative to unstrained grains of the same phase. This is because of strained grains are easily dissolved in fluid rather than unstrained one, as a result solubility of strained grain promotes metamorphic reaction. Shear zones are an area known by increased fluid flow. This enhances permeability, grain-boundary sliding, which generates cataclasite deformation and is important for metamorphic reaction to take place. The concentration of loose bonds and dislocation provides ideal sites for fluid-mineral interaction around grain boundaries. This leads to reaction and nucleation of new phases. There is also the production of heat produced by the release of strain energy. This is when due to shearing there is an increase in temperature, and as a result enhances metamorphic reaction. Therefore, deformation has a great role/influence/ on metamorphic processes and are interrelated.

Metamorphism also has an effect on deformation processes. The elevated pore-fluid pressure in response to melting or in dehydration reaction facilitates cataclasis. This is occurring in response to metamorphic processes as a result of pore-fluid pressure. Under rapid production of fluid during metamorphism, hydraulic fracturing occurs and fractures propagate until such a time as pore-fluid pressure subsides. Therefore, the increasing pore-fluid pressure due to devolatilisation reactions may causes cataclastic flow and leads to increase deformability (plastic deformation). The rheological behavior of the rock is also significantly modified as a result of grain-size reduction. Diffusion-accommodated grain-boundary sliding has occurred as a result of grain-boundary diffusion. This grain boundary diffusion is due to the releasing of fluid during dehydration reaction and this facilitates deformation from the effects of metamorphic reaction. During metamorphic phase transformation, there is a significant volume change, which in turn influences rock deformation. Due to the transformation-induced volume change during metamorphism also enhances plasticity (plastic deformation). This occurs in actively deforming rocks where metamorphic reactions are simultaneously in progress. Metamorphic reaction increases ductility (plastic deformation) by producing 1) small grains and allow grain size sensitive flow processes such as grain- boundary sliding to operate and 2) soft, strain free grains. Grain size sensitive flow processes are also facilitated from the development of fine-grained reaction products during metamorphic reaction.

Generally, from the above identification of the relationship between deformation and metamorphism, the number of deformational and metamorphic events affecting an area was determined and metamorphic and deformational history of an area was understood.

One major brittle /fault/ and four ductile deformational phases and two metamorphic events are now recognized in Sorobo area based on field observation and thin section analysis. M1 and M2 are designed as 1st and 2nd metamorphic events respectively. D1, D2, D3, D4 and D5 are designed as 1st, 2nd, 3rd, 4th and 5th deformation phases respectively. Retrogression and progression are also associated with deformational phases. Layer-parallel high strained fabrics which are formed prior to folding, as shown by evidence preserved in the macro-features of the fold structures (Fig 4.1B).

During shortening deformation event (D1-D2-D3) gneissosity, tight to isoclinal relatively recumbent folds and refolding of F1 area formed respectively. The superposition of secondary (upright) fold on earlier recumbent fold, resulting on type-3 fold interference pattern, which shows parallel fold axis and convergent-divergent patterns, this happens during D3. The dominant folds and their associated fabrics in the Sorobo area have a style and the orientation similar to D2 structures identified by Aspiron (2015), suggesting they developed during the same deformation event. Transposition of the layers is occasionally observed.

The study area is known by shear zone, this is happened during fourth deformation phase which is shear deformation event. During fourth deformation phase (D4) most of the rock units of the area are affected by dextral shearing. East and west verging different folds was formed during this phase. Following D4, brittle type of deformation phase (D5) was developed and resulting in different types of faults of varying orientation. The presence of mica fish and micro-faults are good microstructural evidences for D4 and D5 respectively. The characteristics of the deformation events are summarized in (Table 6.1).

The relative age of different geological structures is determined by using crosscutting relationships, in that any feature that cuts across a rock or layer is younger than the rock or layer it cuts. Figure 4.10 shows faults which cuts and displaces the veins. Hence, faults are younger than a vein. Figure 4.7 A & D shows dikes which cut the host rock and are younger than the host rock they cut. There are several dikes and veins present in the study area. Those all are younger than their host rock they cut according to crosscut relationship. Poles to the fabric of the whole data points do not plot on a great circle on a stereonet rather it shows a random distribution of poles to fabric (Fig 4.12), this is a manifestation of polyphase deformation (represents a combining effect of two or more phases).

Granitic magmas are moved through fractures and lineaments and hold important minerals in the study area. Different economic concentrations of minerals were transported and precipitated from hot aqueous solutions through interconnected channel ways (fractures). Therefore, geological structures in the study areas like faults, joints & fissures, shear zones and folds are important depositional sites for different hydrothermal economic mineral deposits.

Deformation events	Style
D1	Development of gneissosity (alternating bands of mafic and felsic layers)
D2	Tight to isoclinal, inclined folds, wavelength varies from several centimeter to meter depends on competency of host rocks
D3	Refolding of earlier fold, shows convergent-divergent pattern and have parallel fold axis
D4	Shows different vergence directions resulted from dextral and sinistral shearing
D5	Brittle type (faults) which is displacements of earlier fabric

Table 6.1 Summarized characteristics of main deformation events recognized in Sorobo area

CHAPTER SEVEN

7. Conclusion and Recommendation

7.1. Conclusion

The study area is found in Konso area, southern Ethiopia within East African Orogeny (EAO) and covered by high grade metamorphic rocks which are exposed mostly along the stream cut. Based on field and thin section study granulite, amphibolite, amphibole gneiss and granitic gneiss rocks are identified. The larger parts of the area are covered by the amphibole gneiss rock unit. There are also different mesoscale geological structures and metamorphic rock fabrics are found.

The study area is affected by different episodes of events like: granitic magma intrusion, metamorphism, folding, fracture (joint) development, fracture filling (veins and veinlet's formation) and displacements of veins by faults and shearing.

Five deformation phases and two metamorphic events are recognized from the study area. Development of gneissosity (D1), folding of gneissosity (D2), refolding (D3), east and west shearing (D4)) and faulting (D5) are a major deformation phases of the study Sorobo area. There is no isotropic garnet mineral in thin section, but have in the field suggested the metamorphic peak (M1). The peak metamorphic (M1) mineral assemblages are Cpx + Pl + Hbl + Grt and show the characteristic assemblage of granulite facies. The metamorphic mineral assemblage Hbl + Pl + Qtz +/- Cpx +/- Bt manifested a retrograde metamorphism (M2) and have attained upper amphibolite facies.

Equal-area projection and rose diagrams were plotted in order to emphasize the distribution of orientation of data's. The orientations of different structures from the field and stereonet plots are consistent with the Precambrian metamorphic rock (Mozambique Belt) fabric of southwestern Ethiopia. The randomly distributed data points on great circles on stereoplot of pole to different fabric element are a manifestation of multiphase deformation of the study area.

By analyzing minerals and microstructures from the study area deformation and metamorphic history of an area was determined. Based on field observation and thin section analysis there are two metamorphic events and five deformation phases are identified from the study area.

Crosscutting relationship has been used in order to determine the relative ages of different geological structures.

7.2. Recommendation

In order to detail investigation of rock units and different geological structures, road inaccessibility, undulating topography and scattered vegetation's are some problems encountered to deal well about the area.

As the study area is part of high grade metamorphic rock, reworked parts of Precambrian geology and have more geological structures, further detailed study must be done to search many economically important minerals. From the thin section analysis of this study there are many opaque minerals. Therefore, it is recommended that the field study must be supported by polished section analysis in order to clarify opaque minerals.

For further study geochemical analysis is needed in order to understand petrogenesis and the specific paleotectonic environment.

Different generations of faults and folds of different vergence have been distinguished from their asymmetry and other geometrical characters in one outcrop. Therefore, absolute age dating for each generation is needed in order to determine the phases of those generations.

Generally the study area is interesting geological terrain for academic purpose as well as for further research; therefore I recommend the interested organizations, companies or individuals to carry on their research in the area in detail because metamorphic terrains and geological structures are usually known to host economic minerals.

References

Abdelsalam, M.G., Abdel-Rahman, M.E., El-Faki, E.M., Bushra, A., El-Bashier, F.M., Stern, R.J. and Thurmond, A. (2003). Neoproterozoic deformation in the northeastern part of the Saharan Metacraton, northern Sudan. Precambrian Res. 123, pp. 203– 221.

Abdelsalam, M.G., Liegeois, J.P., Stern, R.J. (2002). The Saharan Metacraton. J. Afr. Earth Sci. 34, pp. 119–136.

Alene, M. and Barker, A.J. (1993). Tectonometamorphic evolution of Moyale region, *Precambrian Research, 62*, pp. 272-283.

Amenti, A. (1996). The Precambrian of southern Ethiopia. EIGS, Addis Ababa, Unpub. Rep, Note No 397, pp.6.

Aspiron, H. (2015). Metamorphism and Deformation History of Precambrian Rocks of Sorobo, Konso Area, Southern Ethiopia: Addis Ababa, Ethiopia, PP.18-64

Asrat, A. and Barbey, P. (2003). Petrology, geochronology and Sr–Nd isotopic geochemistry of the Konso pluton, south-western Ethiopia: implications for transition from convergence to extension in the Mozambique Belt, International Journal of Earth science (GeolRundsch), 92, pp.873-890.

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

Barbarin, B. (1999). A review of the relationships between granitoid types, their origins and their geodynamic environments. Lithos 46, pp.605–626.

Beraki, W.H., Bonavia, F., Getachew, T., Schmerold, R. and Tarekegne, T. (1989). The Adola fold and thrust belt, southern Ethiopia: a re-examination with implications for Pan-African evolution. Geolog. Mag. 126, pp. 647–657.

Berhe, S.M. (1990). Ophiolites in northeast and east Africa: implications for Proterozoic crustal evolution. J. Geolog. Soc. Lond. 147, pp. 41–57.

Bonavia, F.F. and Chorowicz, J. (1992). Northward expulsion of the Pan- African of northeast Africa guided by a reentrant zone of the Tanzanian Craton. Geology 20, pp. 1023–1026.

Bouchez, J.L., Hutton, D.H.W. and Stephens, W.E. (eds) (1997). Granite: from segregation of melt to emplacement fabrics. Kluwer, Dordrecht.

Burke, K. and Sengor, A.M.C. (1986). Tectonic escape in the evolution of the continental crust, American Geophysical Union. Geodyn. Ser. 14, pp. 41–53.

Collins, A.S., Razakamanana, T. and Windley, B.F. (2000). Neoproterozoic extensional detachment in central Madagascar; implications for the collapse of the east African Orogen. Geolog. Mag. 137, pp. 39–51.

Davidson, A. (1983). The Omo River Project, Reconnaissance geology and geochemistry of parts of Ilubabor, Kefa, Gemu Gofa and Sidamo, Ethiopia, Ethiopian Institute of Geological Surveys, Bulletin 2, Addis Ababa, pp.18-42.

Denkler, T., Franz, G. and Schandelmeir, H. (1994). Tectonometamorphic evolution of the Neoproterozoic Delgo. Zone, northern Sudan. Geologische Rundschau 83, pp. 578–590.

DeWit, M.J. and Chewaka, S. (1981). Plate tectonic evolution of Ethiopia and the origin of its mineral deposits: an overview. In: Chewaka, S., DeWit, M.J. (Eds.), Plate Tectonics and Metallogenesis: some guidelines to Ethiopian Mineral Deposits. Ethiopian Institute of Geological Surveys Bulletin, vol. 2, pp. 115–129.

Ethiopian Institute of Geological Survey (EIGS) (2010). Geological Map of Ethiopia, 2nd ed., Unpublished technical report, EIGS, Addis Ababa, Ethiopia, 129 pp.

Fentaw, H.M., Mohammed, S., Sebhat, N and Gautneb, H. (2000). The Moyale graphite deposit southern Ethiopia. Norges geologiske undersokelse Bulletin, 436, pp.169-173

Gichile, S. (1992). Granulites in the Precambrian basement of southern Ethiopia: geochemistry, P–T conditions of metamorphism and tectonic setting. J Afr Earth Sci 15 pp.251–263

Gilboy, C.F. (1970). The geology of the Gariboro region of southern Ethiopia. Unpub.rep, ph.D thesis, leeds, U.K, pp. 176, Univ.

Harms, U., Darbyshire, D.P.F., Denkler, T., Hengst, M. and Schandelmeier, H. (1994). Evolution of the Neoproterozoic Delgo suture zone and crustal growth in northern Sudan: geochemical and radiogenic isotope constrains. Geologische Rundschau 83, pp.591–603.

Harris, N.B.M. (1996). Radiogenic isotopes and the interpretation of granitic rocks. Episodes 19, pp.107–113.

Hobbs, B. E., Means, W.D. and Williams, P. F. (1976). An outline of structural Geology, Wiley, New York

Holmes, A. (1951). The sequence of Pre-cambrian Orogenic belts in south and central Africa. In: 18th Geological International Congress, Great Britain, pp. 254–269 (Part XIV).

Hussien, B. (1999). The Geology, Structure and Geochemistry of the Crystalline Rocks of the Moyale Area, Southern Ethiopia: Implication for Tectonogenesis of the Precambrian Basement, Ph. D thesis, University of Tübingen, Band 50, pp.102.

Kazmin, V. (1971). Geological map of the Yavello area. United Nation Ethiopia Mineral Surveys, Ministry of Mines, unpub.rep, Addis Ababa, pp.14.

Kazmin, V. (1972). Geology of Ethiopia, Explanatory note to the geological map of Ethiopia, 1:2,000,000, Ministry of Mine; unpub.rep, Addis Ababa, pp.182.

Kazmin, V., Shiferaw, A. and Balcha, T. (1978). The Ethiopian basement: stratigraphy and possible manner of evolution. Geologische Rundschau 67, pp.531–546.

Key, R.M., Charsley, T.J., Hackman, B.D., Wilkinson, A.F. and Rundle, C.C. (1989). Superimposed upper Proterozoic collision-controlled orogenesis in the Mozambique Orogenic Belt of Kenya. Precambrian Res. 44, pp.197–225.

Kroner, A. and Stern, R.J. (2004). Pan-African orogeny, North African Phanerozoic, Rift valley, V 1, PP.1-3.

Kusky, T.M., Abdelsalam, M., Stern, R.J. and Tucker, R.D. (eds.) (2003). Evolution of the East African and related orogens, and the assembly of Gondwana. Precambrian Res. 123, pp.82-85.

Marshak, S. and Mitra, G. (1988). Basic methods of structural geology, Prentice Hall, Englewood Cliffs, New Jersey

Melesse, M. and Demerew, Y. (2003). Report on the Geology, geochemistry and Geophysics of Konso area, southwestern Ethiopia: Unpublished, Addis Ababa, Ethiopia.

Passchier, C.W. and Trouw, R.A.J. (1998). Microtectonics, Springer-Verlag Berlin Heidelberg, New York, PP1-6

Pearce, J.A., Harris, N.B.M. and Toille, A.G. (1984). Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. J Petrol 25, pp.956–983.

Ramsay, J.G. (1967). Folding and fracturing of rocks. McGraw Hill, New York

Ramsay, J.G. and Huber, M.I. (1987). The techniques of modern structural geology, 2: Folds and fractures. Academic Press, London

Pinna, P., Jourdge, G., Calvez, J.Y., Morez, J.P. and Margues, J.M. (1993). The Mozambique Belt in northern Mozambique: Neoproterozoic (1100–850 Ma) crustal growth and tectogenesis and superimposed Pan-African (800–550 Ma) tectonism. Precambrian Res. 62, pp.1–59.

Samuel, G. (1991). Structure, metamorphism and tectonic setting of a gneissic terrane, the Sagan Afleta area, southern Ethiopia. Msc thesis, Ottawa-Carleton Geoscience center and University of Ottawa, Canada.

Santosh, M., Morimoto, T. and Tsutsumi, Y. (2006). Geochronology of the khondalite belt of Trivandrum Block, southern India: electron probe ages and implications for Gondwana tectonics. Gondwana Research 9, pp.261–278.

Shackleton (1979, as cited in Asrat and Barbey, 2003) Petrology, geochronology and Sr-Nd isotopic geochemistry of the Konso pluton, south-western Ethiopia: implications for transition from convergence to extension in the Mozambique belt. Int journal of Earth Science (Geol Rundsch), 92, pp.873-890.

Shackleton, R.M. (1979). Precambrian tectonics of northeast Africa. In: Al Shanti AMS (ed) Evolution and mineralization of the Arabian–Nubian Shield, Pergamon, vol 2. Oxford, pp. 1–6

Stern, R.J and Dawoud, A.S. (1991). Late Precambrian (740 Ma), charnockite, enderbite, and granite from Jabel Moya, Sudan: a link between the Mozambique belt and the Arabian–Nubian Shield? J Geol 99, pp.648–659

Stern and Dawoud (1991, as cited in Thige et al., 2005) Neoproterozoic-Early Paleozoic gravitational tectonic collapse in the southern part of the Arabian-Nubian shield: The bulbul belt of southern Ethiopia. Precambrian research, 138, pp 297-318.

Stern, R.J. (1994). Arc assembly and continental collision in the Neoproterozoic east African Orogen: implications for the consolidation of Gondwanaland. Annu. Rev. Earth Planet. Sci. Lett. 22, pp.319–351.

Stern, R.J. and Dawoud, A.S. (1991). Late precambrian (740 Ma) charnockite, enderbite and granite from Jebel Moya: a link between the Mozambique Belt and the Arabian-Nubian Shield? J. Geol. 99, pp.648–659.

Tapponnier, T., Peltzer, G., Le Dain, A.Y., Armijo, R. and Cobbold, P. (1982). Propagating extrusion tectonics in Asia; insights from simple experiments with plasticine. Geology 10, pp.611–616.

Teklay, M., Kroner, A. and Oberhansli, R. (1993). Reconnaissance Pb- Pb zircon ages from Precambrian rocks in eastern and southern Ethiopia and an attempt to define crustal provinces. In: U., Thorweihe, H., Schandelmeier, (eds.), Geoscientific Research in Northeast Africa. A.A. Balkema, Rotterdam, pp. 133–138.

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

Vail, J.R. (1976). Outline of the geochronology and tectonic unit of the basement complex of northeast Africa. Proc. R. Soc. Lond. Ser. A-350, pp.127–141.

Vail, J.R. (1985). Alkaline ring complexes in Sudan, In: Black R, Bowden P (eds) Alkaline ring complexes in Africa, Journal of Africa Earth science, 3, pp.51-59.

Vail, J.R. (1986). Geology of Southern Blue Nile Province, Sudan, Bull.Geol.Res. Authority Sudan, pp.32.

Vail, J.R. (1989). Ring complexes and related rocks in Africa. Journal of Africa Earth science, 8, pp.19-40

Vaughan, A.P.M. and Pankhurst, R.J. (2008). Tectonic overview of the West Gondwana margin. Gondwana Research, 13, pp.150–162.

Warden, A.J. and Horke, A.D. (1984). The Geological Evolution of NE-Branch of the Mozambique Belt (Kenya, Somalia, Ethiopia), Mitteilungen der Oesterreichischen Geologischen Gesellschaft 77, pp.11-184.

Whalen, J.B., Currie, K.L. and Chappell, B.W. (1987). A-type granites: geochemical characteristics, discrimination and petrogenesis. Contrib Mineral Petrol 95, pp.407–419

White, A.J.R. and Chappell, B.W. (1983). Granitoid types and their distribution in the Lachlan Fold Belt, South Western Australia. Geol Soc Am Mem 159, pp.21–34

Woldegabriel, G., Nasir, H. and Tesfaye, Y. (1994). Geology of the Ageremariam area. EIGS, Unpub.rep, Addis Ababa, Memoir 8.

Woldehaimanot, B. (1995). Structural Geology and geochemistry of the Neoproterozoic Adobha and Adola Belts (Eritrea and Ethiopia). Ph.D. Thesis. University of Giessen, Germany.

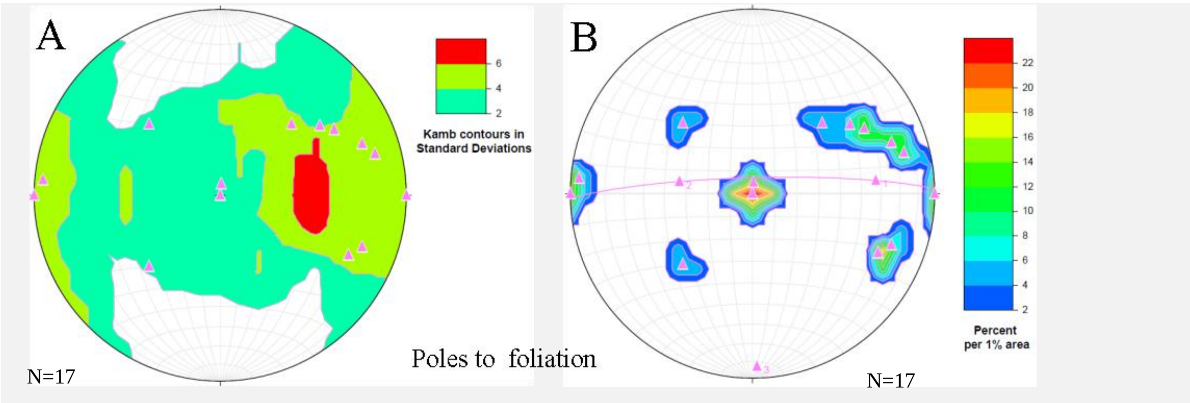
Worku, H. (1996). Geodynamic development of the Adola belt (southern Ethiopia) in the Neoproterozoic and its control on gold mineralizatio. Ph.D. Thesis. University of Berlin, Springer Verlag, Germany.

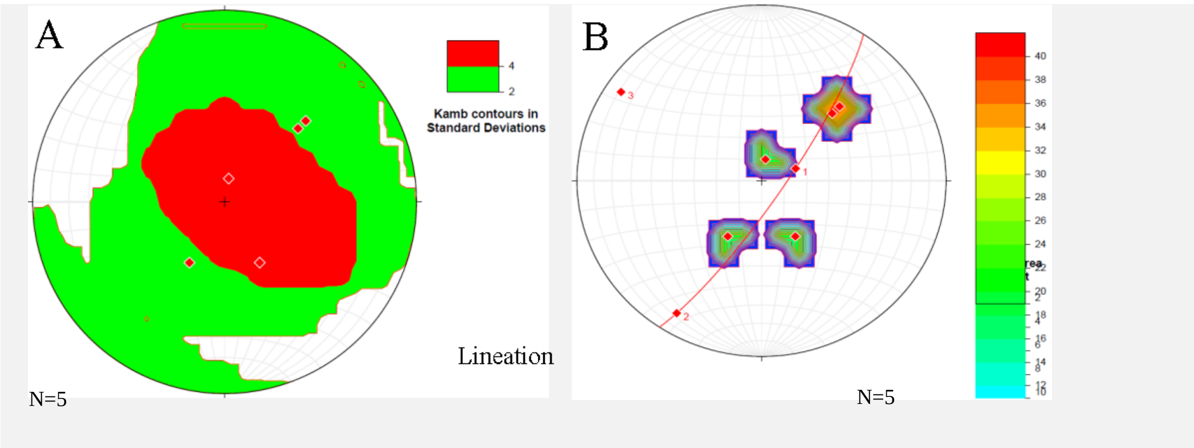
Worku, H. and Schandelmeier, H. (1996). Tectonic evolution of the Neoproterozoic Adola Belt of southern Ethiopia: evidence for a Wilson Cycle process and implications for oblique plate collision. Precambrian Res. 77, pp.179–210.

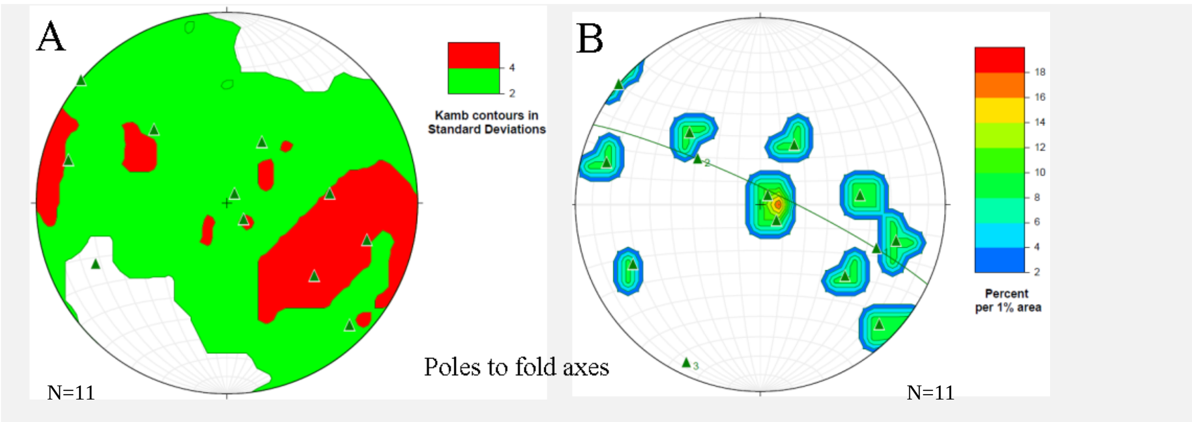
Yibas, B. (2000). The Precambrian geology, tectonic evolution and controls of gold mineralization in southern Ethiopia. Ph.D. Thesis. University of the Witwaterstrand, Johannesburg, South Africa, pp.486.

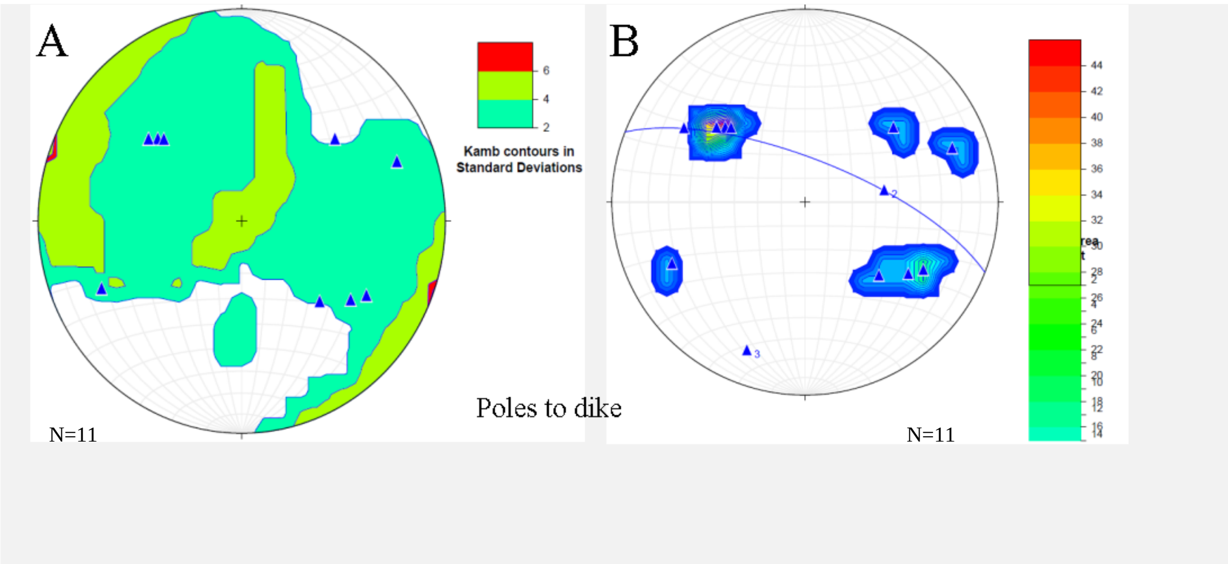
ANNEX I

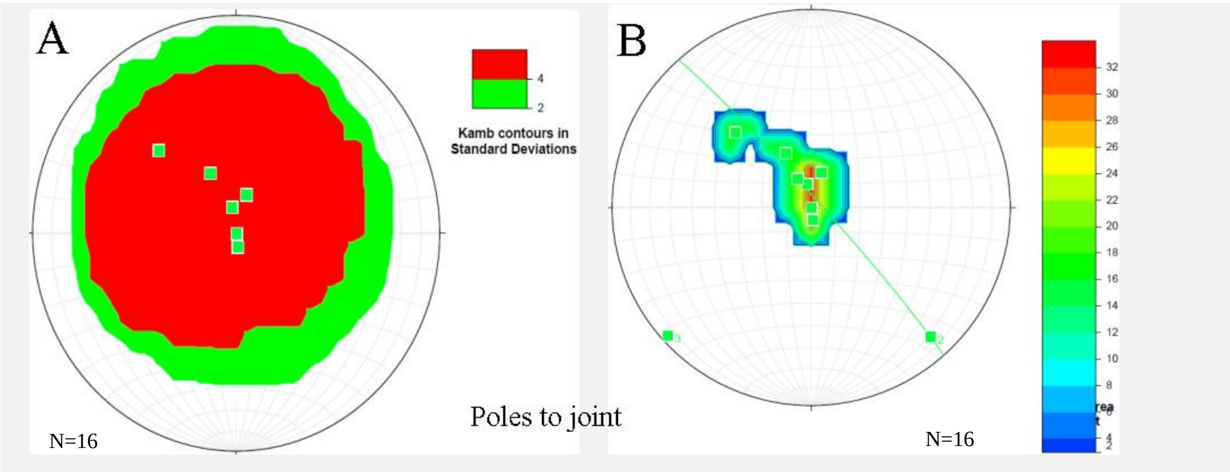
Kamb Contouring method and 1% Area Contouring method: these are practiced for a small numbers of data sets. They allow graphic analysis of the statistical significance of point concentrations on an equal-area plot. The observed densities of different fabric element data points have preferred orientation in the area of study. The characteristics and descriptions are shown in ANNEX table 1 below.

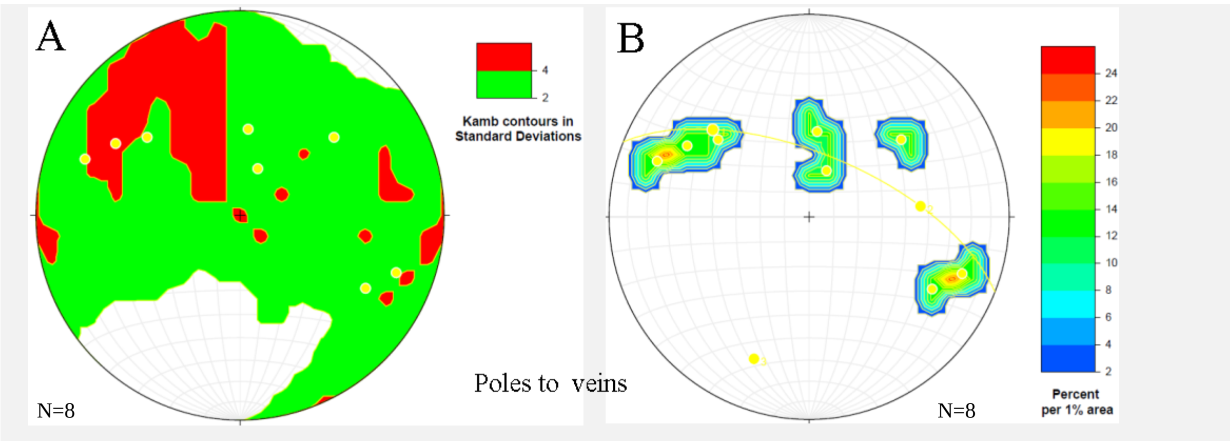







A
B
Kamb contours in Standard Deviations
6
4
2
Poles to dike
N=11
N=11


A
B
Kamb contours in Standard Deviations
4
2
Poles to joint
N=16
N=16


A
B
Kamb contours in Standard Deviations
4
2
Poles to veins
N=8
N=8
Percent per 1% area

ANNEX fig 1 Best fit great circle for different fabric elements using an equal-area projection; (A) Kamb Contouring method. (B) 1% area Contouring method. The pole to foliation indicates that the rock is folded about a steeply southwest-plunging axis and the fold axes indicate that the rock is folded about S-W-plunging axis. Generally, all the structures indicate that the rock is folded about S-W.

Structures	**Figure A**			**Figure B**			
	Kamb contouring			**Best fit great circle (strike, dip RHR) in 1% area contours**			
	Contour interval	Counting area	Significant number	Stress field	Trend (°)	Plunge (°)	(strike, dip RHR) (°)
Poles to foliation	2σ	34.62% of net area	3σ	σ_1 σ_2 σ_3	084.0 279.2 178.5	32.5 56.6 07.0	268.5,83.0
Lineation	2σ	64.29% of net area	3σ	σ_1 σ_2 σ_3	069.4 211.4 303.6	74.0 12.8 09.6	033.6,80.4
Fold axes	2σ	45% of net area	3σ	σ_1 σ_2 σ_3	110.6 305.7 205.3	33.4 55.7 07.1	295.3,82.9
Poles to dike	2σ	45% of net area	3σ	σ_1 σ_2 σ_3	301.4 081.8 201.3	27.5 55.9 18.5	291.3,71.5
Poles to joint	2σ	60% of net area	3σ	σ_1 σ_2 σ_3	333.9 137.4 228.3	76.7 12.7 03.6	318.3,86.4
Poles to veins	2σ	52.94% of net area	3σ	σ_1 σ_2 σ_3	311.8 084.3 201.7	35.3 43.6 25.8	291.7,64.2

ANNEX table 1 Different fabrics description table of Kamb and 1% Area Contouring method

ANNEX II

ANNEX fig 2 Field photograph of A and D) shows dextral (right lateral) strike-slip fault, photo taken looking N; B) shows oblique fault, C) indicates normal dip-slip fault E) shows the difference in curvature of inner arc and outer arc of folded layer, the curvature of inner arc is less than the curvature of outer arc and F) shows the arrow shows detached fold which shows fold transposition; B, C, E and F photo taken facing NW.

ANNEX fig 3 Field photograph shows A, B & D) tourmaline mineral concentration in pegmatite dike, and veins and garnet minerals in D, C) indicates sinistral shear sense, E) weakly deformed xenoliths of amphibole within amphibole gneiss rock shows dextral reverse fault and F) shows crosscutting relationships (Inclusion - pieces of older rock trapped within younger rock).

D E C L A R A T I O N

I hereby declare that the thesis entitled "Reconstructing Deformation history by using microstructural and petrographic analysis of Sorobo, Konso area, southern Ethiopia" has been carried out by me under the supervision of Mulugeta Alene (PhD), Department of Geology, Addis Ababa University, Addis Ababa during the year 2018 as partial fulfillment of the requirements for the Degree of Masters of Science in Structural geology. I further declare that this work has not been submitted to any other university or institution for the award of any degree or diploma, and also that all sources of materials used during the thesis work have been properly acknowledged.

………………………. ……………..…….…

Muluken Fanta (Candidate) Date

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

…………………………… ……………………

Dr. Mulugeta Alene (Advisor) Date