TECTONICS OF THE PRECAMBRIAN ROCKS OF THE NEGASH AREA, TIGRAI REGION, NORTHERN ETHIOPIA

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ABSTRACT

The Wukro area is constituted by weakly metamorphosed largely Precambrian age volcano-sedimentary rock units of Tsaliet Group, Tembien Group, Didikama Formation, Matheos Formation and pebbly slate which form part of the Upper Complex of the Precambrian basement. The younger Palaeozoic-Mesozoic sedimentary cover consisting of the Enticho Sandstone, Edagga Arbi Glacials and Adigrat Sandstone unconformably overlies the Precambrian units.

Detailed structural analyses at macro, meso and microscale have revealed three generation of ductile deformational events (D_1, D_2, & D_3) and late faulting. The first phase of deformation D_1 is characterized by transposition phenomena which has obliterated the original stratigraphy and produced rootless intrafolial foldings. The intensity of transposition is greatest on the rocks of Tembien Group and Didikima Formation and is least on the rocks of Matheos formation and Pebbly slate. Associated with the D_1 deformation is the N-S trending S_1 foliation largely defined by slaty cleavage.

The second phase of deformation D_2 is characterized by the development of a (10°-20°) -->(170°-195°) plunging overturned major folds, which has folded the structural elements of the D_1 generation. It developed two synforms and two antiforms, namely North Western Synform, Western Antiform, Central Synform and Eastern Antiform from west to east. The planar fabric element S_2 produced by this generation is nearly sub-parallel to S_1 along the limbs of the D_2 folds and is nearly perpendicular to S_1 along the hinge zones of the D_2 folds.

The third phase of deformation D_3 is the last deformation event in the study area. Throughout the area its effect is a development of undulations on the previous N-S trending composite (S_0 S_1 S_2) surfaces . Its effect is greatest in the North-Western synform, where the D_2 axial plane appears to have a curvilinear trace.

Following this event is an intrusion of small granite and dykes into the rocks of the Tembien group and Didikama formation.

Metamorphism in the area is largely synchronous with the D_1 and D_2 deformations. Metamorphic conditions during these deformations were restricted to low greenschist facies.

Following peneplanation of the basement and deposition of Palaeozoic-Mesozoic sediments, numerous normal faults affected the basement and the younger sedimentary cover succession.

CHAPTER I

1. INTRODUCTION

1.1 LOCATION AND ACCESSIBILITY

The study area is located in Tigrai administrative region; in the province of Hulet Awilalo. The principal town is Wukro (latitude 13°30'N and longitude 39°30'E) and it encompasses the Negash village located some 8 km north of the town. The Negash village, being within the study area, is situated at 840 Km from Addis Ababa on the main road running from Addis Ababa to Adigrat through Mekele. The area is bounded by latitudes 13° 49'N and 13° 54'N, and longitudes 39° 34'E and 39° 44'E (fig 1.1). The southern boundary is marked by "Wukro fault belt" (Beyth, 1971). The area in general is intensively dissected by streams which provide good exposures of the rock units. Physiographically, the study area is located at the eastern margin of the western highlands of the country. Within it, the altitude generally decreases from 2900 metres above sea level (close to Astbi Bota) westwards to the western lowlands (1500 metres above sea level).

Except the all weather Addis ababa - Adigrat road passing through the western part of the study area, access by car is generally poor due to the elevated ridges and deep valleys. All traverses were, therefore made on foot.

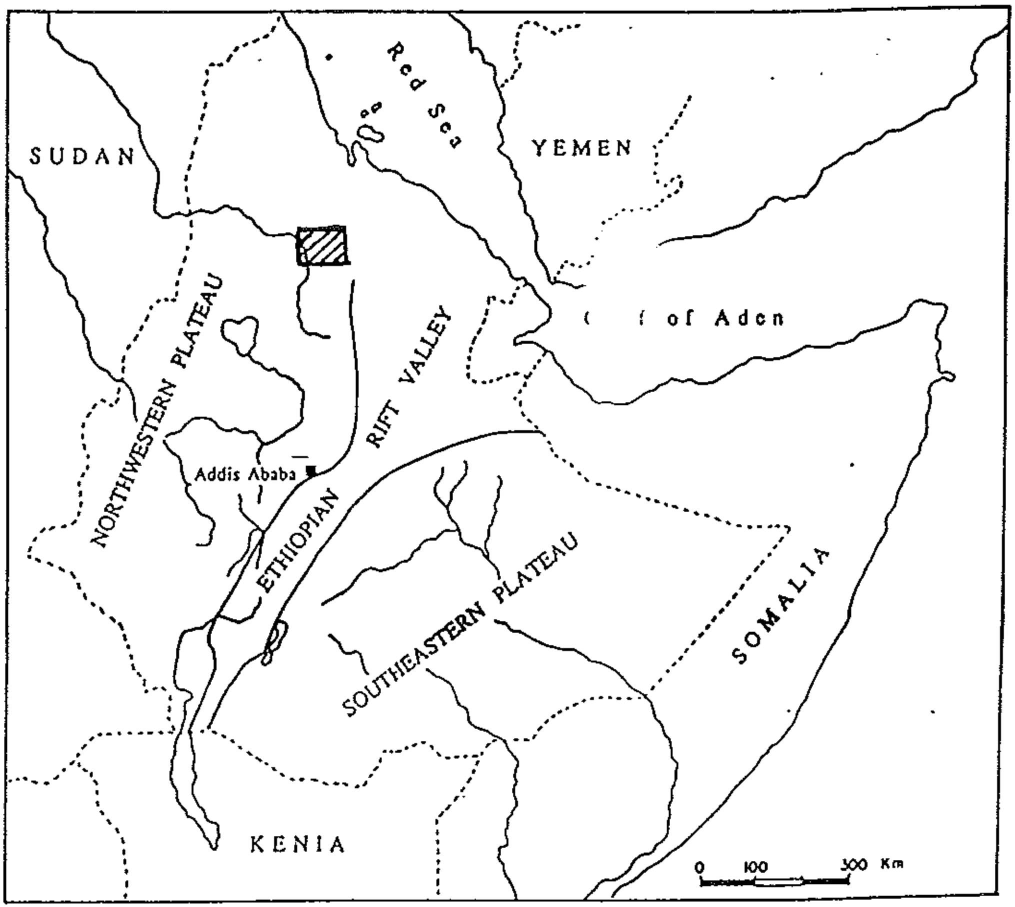


Fig.1.1 Location map of the study area, Wukro.

1.2 CLIMATE AND VEGETATION

Although the climate and vegetation of the Negash village and/or the Wukro town are not well studied, generally the area has a mean annual temperature ranging from 15°C - 20°C, and a mean annual rainfall of about 520 mm. Climatically it belongs to the temperate region. Two small rivers meet in the study area: The Genfel river and Getebhidat river. These two small rivers with their tributaries emanate from the elevated highlands of the region and flow through the area in different directions to join the Nile river.

The dominant vegetation types of the area are Bush formation and Mountain Savanna: these include, wood lands, acacia forests and ever green thickets. Associated with Savanna, a grass cover of Hetropogon and Danthonia grass is found. The area has been inhabited for long time and wherever there is sufficient soil, intensive cultivation is practised.

1.3 PREVIOUS WORKS

Although the Tigrai administrative region of Ethiopia, has received a good deal of scientific attention as compared to the rest of Ethiopia (from as early as eighteenth century); the standard reference work for the geology of the province is that of Merle and Minucci's "Missione geologica nel Tigrai" (1938). All subsequent researches were based on Merla and Minnuci's work to complete stratigraphic column, and produced a reconnaissance geologic map at a scale of 1:400,000 with accompanied reports.

Dainelli (1943), in his work on the geology of the eastern Africa, gave an account on the basement complex and the sedimentary sequence of the area (from Garland 1980).

Mohr's, (1963) text book entitled "The Geology of Ethiopia" is a compilation and modification of data from Dainelli, with much new detailed information of his own. In this work, he tentatively divided the Precambrian rocks of Ethiopia into an older, more metamorphosed, and a younger, less metamorphosed group separated by an unconformity.

Many other works undertaken on the Tigrai region did not include the present study area. The most important studies on the immediate vicinity of the studied area includes the works of Beyth (1971). He recognized the different lithologies, with particular attention to the basement rocks, giving a detailed account on the classification, mapping and stratigraphy of basement rocks. He divided the basement rocks broadly into two big groups, one of which is further subdivided into four different formations. (see section 2.2)

Levitte (1970), mapped the region systematically and subdivided the basement into four formations (see section 2.2).

Arkin *et al.* (1971) produced Geological map of the Mekele sheet including the study area at a scale of 1:250,000 with accompanying explanatory notes (after Beyth, 1971).

Garland (1980), in his geological map of the Adigrat area, gave the stratigraphy of the study area (which is 15km below the southern limit of his map). According to him, the basement rocks of the study area are divisible into two groups and two formations (see section 2.2).

1:4 OBJECTIVES OF THE PRESENT WORK

Even though studies on the geology of Tigrai commenced early in eighteenth century, the details of the Precambrian rocks of the region are only known through the works of Beyth *et al.* (1971), Levitte *et al.*(1970) and Garland (1980). These and other previous works on the geology of the Tigrai region have only mentioned the structure of the Precambrian rocks briefly. Thus, the main purpose of the present work is studying and describing the structural details, (i.e, including geometrical analysis of the study area) in order to:

1. *Produce detailed structural map at a scale of 1:12,500*
2. *Determine the kinematic significance of deformation phases, and*

3. Elucidate the relative tectonic history of the region

1.5 MATERIALS AND METHODS

A topographic map at a scale of 1:250,000, aerial photographs at a scale of 1:50,000, 1:12,500, and a geological map at a scale of 1:250,000 were available. Brunton compass, altimeter, pocket stereoscope, camera, overlays, hammer, rucksack, hand lenses and Hcl acid were the field equipment packed to the site of the study area. The field work commenced with a reconnaissance surveying on the potential map area to get a general knowledge of on the quality of exposures, the type of rocks present, the general distribution of lithologies and structures. This was followed by geological mapping of the area which is about 100 sq. km at a scale of 1:12,500. Rock samples were collected for microscopic analysis. Most important structural details of the area were measured. This includes structural elements (such as lineations, fold axes, foliations) which are presented on the structural map (see back wallet).

Equal area plots of structural measurements were made in the laboratory to determine the mean orientation of planar and linear fabric of different generations and to determine mean orientation of fold axes and axial planes. Finally,using these plots the orientation and description of the large folds in the area were made.

CHAPTER II

2. REGIONAL GEOLOGY AND STRATIGRAPHY

2.1. GENERAL

The basement rocks of Ethiopia with ages over 600 ma are exposed in parts of Hararghe, Sidamo, Bale, Illubabor, Gojjam, Wollega, Gondar, Tigrai and Eritrea provinces (Kazmin, 1971). According to Kazmin (1971), Precambrian rocks were subjected to several orogenic episodes since their formation. The basement rocks contain a wide variety of rocks of sedimentary, volcanic and intrusive origin. These are metamorphosed to varying degrees.

At the end of Precambrian, uplift occurred which was accompanied by prolonged period of erosion. Any sediment deposited above the basement rocks during the Palaeozoic have been largely removed by erosion except some shales and deposits of glacial origin laid down in the northern parts of Ethiopia (Kazmin, 1971). During the Mesozoic, subsidence occurred. Subsequently, marine transgression have deposited a thick unit of sandstone, mudstone and limestone on the old erosional land surface.

Extensive fracturing of rocks accompanied by widespread volcanic activity which occurred during Cenozoic largely determined the form of the landscape in the western half of Ethiopia (Kazmin, 1971).

2.2 PRECAMBRIAN BASEMENT ROCKS

Kazmin (1971, 1972a, 1975) subdivided the Precambrian of Ethiopia into:

- **The Lower complex** oldest
- **The Middle complex**
- **The Upper complex** **youngest** and

described them as follows.

2.2.1. The Lower complex

The Lower complex is comprised of various coarse grained and foliated gneisses, mainly of granitic and, migmatitic, in places grading into metamorphic granites. The metamorphic grade is largely amphibolite facies and **in places granulite. Broad and gently dipping synforms** and antiforms characterize the structural styles of the complex.

2.2.2. The Middle complex

It is represented by metamorphic sandstones and quartzites with various schists which formed a "cover" sequence over the granitic gneisses of the Lower complex. According to Kazmin (1971), this complex is recognized only in southern Ethiopia (Sidamo region)

2.2.3. The Upper complex

The Upper complex consists of rocks that have been tightly folded but subjected to only the lowest grade of metamorphism. As a result, original sedimentary features such as, ripple marks, graded bedding and slump structures are preserved; thus, each rock type may be traced back to its origin. They are mainly shales and metavolcanics.

2.3 GEOLOGY AND STRATIGRAPHY OF THE REGION

The regional geology of the northwestern Ethiopian plateau, with the exception of the Mekele outlier and Adigrat ridges, is characterized by extensive exposures of steeply dipping basement rocks. The study area is situated between the Mekele outlier in the south and Adigrat ridges in the north, and it is mainly constituted of Precambrian crystalline rocks.

Except limited outcrops of the lower complex in Eritrea and in areas north of Adigrat, (Garland, 1980), the Precambrian rocks of Tigrai area constitute part of Upper complex (Kazmin, 1971, 1975). Kazmin (1971, 1975) described the complex as a series of thick, inhomogeneous units of volcanic rocks and greywackes.

Although researchers involved in the Tigrai region (such as, Beyth, 1971; Levitte, 1970; Garland, 1980) described the basement rocks in similar manner, they did not come up with a single or unique generally accepted Precambrian Stratigraphy of the region. But, a general framework of the Precambrian stratigraphy of the region was first outlined by Beyth (1971). According to Beyth (1971), two different stratigraphic succession were possible for the whole of the Tigrai region. One is for the Maikenetal type area and was considered representative for most of Tigrai region (fig 2.1. b). The other one is for the Negash district and applicable to the present study area (fig 2.1. c).

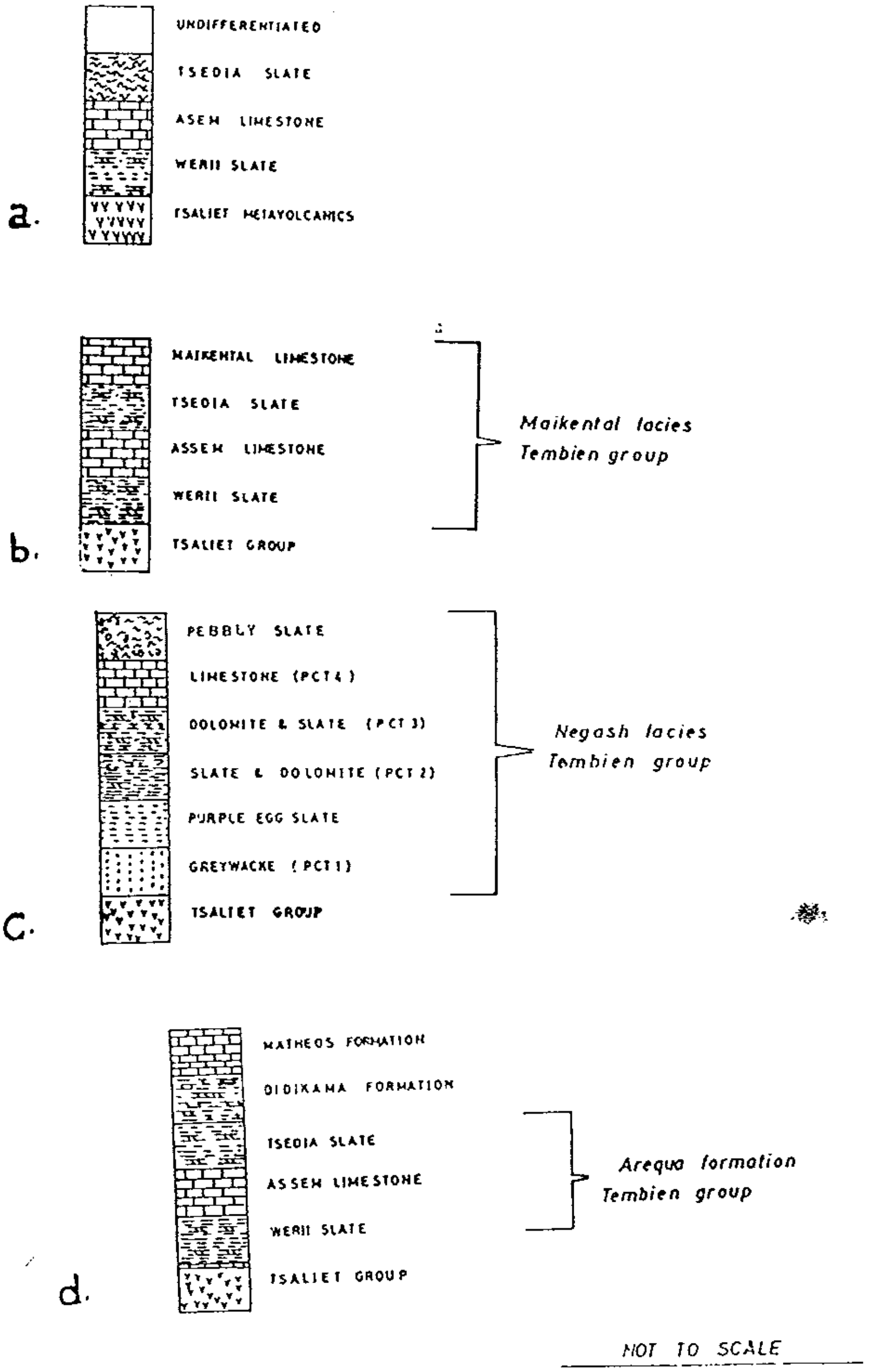
In the Maikenetal area, rock groups found from oldest to youngest were, respectively termed Tsaliet group and Tembien group. The Tembien group was further subdivided, from oldest to youngest, into Werii slate, Assem limestone, Tsedia slate and Maikenetal limestone (fig.2.1 b).

In the Negash area rock units found from oldest to youngest respectively belong to the Tsaliet group and Tembien group. The Tembien group was divided into greywacke, purple egg slate, slate and dolomite, dolomite and slate, limestone, and pebbly slate. They were collectively termed Negash facies of the Tembien group and were considered to be the equivalent of the Maikenetal facies (fig. 2.1. c).

The stratigraphy produced by Levitte (1970) is entirely based on the work of Beyth (1971). According to Levitte (1970), the basement rock units found from oldest to youngest were Tsaliet metavolcanics, Werii slate, Assem limestone, Tsedia slate, and Undifferentiated basement rocks. This stratigraphy is similar with Beyth's (1971) Precambrian stratigraphy in the Maikenetal type area, except that the Maikenetal limestone is missing.

Garland (1980), who mapped the Adigrat area attempted to generalize the Precambrian stratigraphy. According to Garland (1980), the Precambrian rock units from oldest to youngest were divisible into Tsaliet group, Tembien group, Didikama formation, and Matheos formation (fig. 2.1.d). Here, the Tembien group include the Werii slate, Assem limestone, and Tsedia slate. This generalized stratigraphy was based on the work of Beyth (1971). Compared to the stratigraphy by Beyth (1971), it has some similarity and differences. The Tsaliet group and Tembien group exactly corresponds with the Beyth's (1971) stratigraphy in the Maikenetal type area. Garland (1980) quoting the work of Temesgen in Shiraro area (Tigrai region) concluded that the Negash facies described by Beyth (1971) is not part of the Tembien group but is a new unit above it. This new unit was previously named Didikama formation by Temesgen (after Garland, 1980).

Fig.2.1 Regional Precambrian stratigraphy of the study area (see text for details). a). Precambrian stratigraphy according to Levitte (1970) .b and c.Precambrian stratigraphy for Maikental and Negash type area respectively, according to Beyth (1971). d). Precambrian stratigraphy of the study area according to Garland (1980).


a.
UNDIFFERENTIATED
TSEDIA SLATE
ASEM LIMESTONE
WERII SLATE
TSALIET METAVOLCANICS
b.
MAIKENTAL LIMESTONE
TSEDIA SLATE
ASSEM LIMESTONE
WERII SLATE
TSALIET GROUP
Maikental facies
Tembien group
c.
PEBBLY SLATE
LIMESTONE (PCT4)
DOLOMITE & SLATE (PCT3)
SLATE & DOLOMITE (PCT2)
PURPLE EGG SLATE
GREYWACKE (PCT1)
TSALIET GROUP
Negash facies
Tembien group
d.
MATHEOS FORMATION
DIDIKAMA FORMATION
TSEDIA SLATE
ASSEM LIMESTONE
WERII SLATE
TSALIET GROUP
Arequa formation
Tembien group
NOT TO SCALE

2.3.1. METAMORPHOSED BASEMENT ROCKS

As was described in the earlier paragraphs all the three workers, despite the difference in nomenclature of the stratigraphy, gave a generally similar description to the lithologies. This is summarized as follows.

Tsaliet Group

The "Tsaliet group" is named after the Tsaliet river in the central Tigrai (Beyth, 1971). It is formed mainly of bedded intermediate to acidic tuffs, welded tuffs, volcanic greywackes, lapilli tuffs, agglomerates, and limestones at the upper part. Due to their considerable lateral variations, their lithologies were mapped as a single unit (Group) throughout northern Ethiopia. The rocks of these group posses a regional strike and dip of beds ranging between north 40°-55° W, 30°-55° (Levitte, 1970). The age of these rock group is Upper Proterozoic, Riphaen (Kazmin, 1970).

Tembien Group

The name "Tembien group" derived from Tembien Awraja in the central Tigrai province. The rocks of these group conformably overlie the rocks of the Tsaliet group, the nature of the boundary is gradational and the contact is locally marked by thin beds of limestone (Garland

1980).

The group includes four members first recognized by Beyth and Dow (1970) in the Maikental type area. These are:

- **The Werii slate** **oldest**
- **The Assem limestone**
- **The Tsedia slate**
- **The Maikenetal limestone** **youngest**

The former three were named the Arequa formation by Tsegaye (1971). This rock is exposed in the Maikental, Tsedia and the east of Edagga Hamus area as recognized by Beyth (1971). The age of this rock group is Upper Proterozoic, Riphaen (Kazmin 1970, 1971).

Werii Slate

Its name is derived after Werii river in Tigrai region (13° 58' N and 38° 54' E). It comprises mainly of black slates and pyllites which are partly graphitic. The unit in general is well laminated showing small asymmetric ripple marks and also contains fine grained, thinly bedded black limestone. At the top of the section it is cut by quartz-biotite-diorite dikes and quartz veins. Its upper boundary is marked by the predominance of fine and well bedded black limestone, and its lower boundary is arbitrarily placed where metavolcanics of the Tsaliet group become dominant (Beyth, 1971). The unit is extensively exposed in Maikental in Tigrai province effects. The dolomite is locally shelly, with talc, and in other places it contains mica in waxy crystals of calcite one centimetre across. Elsewhere it is changed to coarsely crystalline aggregates in which dolomite rhombs reach three centimetre long.

Matheos Formation

The top of the Didikama formation is seen overlapped by the top most limestone of Matheos formation. This unit is thought to be the youngest Precambrian formation in Ethiopia (Garland, 1980) and an angular unconformity separates it from the underlying dolomites and slates (Beyth, 1971; Garland, 1980). According to Garland, (1980) this formation is only known at the "Negash Syncline". It is well bedded black limestone occurring as micritic, oolitic (?), and fragmental (0.5 cm grain size) varieties. Towards its top it becomes light greenish grey limestone and marly, partly well laminated and cut by quartz and feldspar veins (Beyth, 1971).

Pebbly Slate

This unit is only mapped and described by Beyth (1971). It is a light grey to brownish pebbly slate and black phyllite containing very small greenish quartz and sericite crystal, with rounded and elongated pebbles parallel to the foliation of the muddy matrix. The pebbles are composed of limestone, granite, quartzite and metavolcanics unconformably overlying the limestone (Beyth, 1971).

Undifferentiated Basement

This unit is exposed mainly on mountains or along the foot of hills or along the faces of escarpments in Eritrea (Garland, 1980), and also on the eastern part of the Mekele area mapped by Levitte (1970). According to Levitte (1970) this rock sequence dips generally eastward. Main rock types are greywacke and basic to acidic metavolcanics (Levitte, 1970).

2.3.2. PRECAMBRIAN INTRUSION

Forstega Diorite

Named by Beyth (1971) after the village Forstega (13° 55' N and 39° 56' E). It formed a large elongated stock in the escarpment area around Forstega, which is associated with, and migmatized by, the Mareb granitic stocks of the plateau. It is black and white spotted diorite and quartz diorite intruded by black-andesite, light brown dacitic and rhyolitic dikes which are slightly foliated and partly chloritized. The Forstega diorite intruded the Tsaliet metavolcanics and the

Tembien group (Beyth, 1971). According to Kazmin (1970, 1971) the age of this diorite is Upper Riphean.

Mareb Granite

Named after the Mareb river in Tigrai province by Beyth and Dow (1971). This granite intruded the Tsaliet metavolcanics and Tembien group. It is characterized by pink to grey colour, porphyritic with microcline phenocrysts up to 5cm long. The characteristic petrography is microcline perthite, Na-plagioclase with clear zoning, biotite, and green pleochroic hornblende. This granite is cut by aplitic dikes which contain quartz microcline, orthoclase, albite, biotite and apatite. The field evidence suggests that the Forstega diorite intruded before the Mareb granite. In all the intrusions, the intermediate types between granite and diorite were discovered (Beyth, 1971). K/Ar age dating of the granite yielded around 650 m.a (Kazmin, 1971).

CHAPTER III.

3. LOCAL GEOLOGY

3.1. INTRODUCTION

The geology of the study area is constituted by two main rock types; the Precambrian basement (metamorphic rocks and intrusive), and the Palaeozoic-Mesozoic sediments which outcrop systematically in the area. The metamorphic rocks and associated intrusives are restricted to north of the "Wukro Fault Belt" whereas, the Palaeozoic-Mesozoic rocks are exposed south of the fault belt. The basement rocks can be broadly classified into two "groups": metavolcanics and metasediments.

3.2. METAVOLCANICS

The rocks of this group, despite the occurrences of some isolated rock units at the south western synform (fig.3.1), are generally exposed in the western and eastern boundary of the study area. They always have a sharp contact with the metasedimentary units. This contact has a mean orientation of 55°-->280° in many localities. The contact is offset by northwesterly oriented fault at the southern limit of the North-Western synform (fig.3.1). These rocks on the eastern boundary of the study area form an elevated topography with flat tops and steep slopes at the contact. Similarly, the contact in the western side [illegible] steep as the eastern part) with flat tops, especially in the southwestern part of the study area.

Fig. 3.1 Geological map of the Negash area, Wukro (Appended in pocket)

Though the dominant lithologies within this group are metavolcanics, some thin beds of metagreywacke and slate of sedimentary origin also occur. Because the metavolcanic and metasedimentary rocks are interbedded at different scales within this group, and are not traceable laterally, they are lumped and mapped together.

In detail, the unit comprises of:

- Aphanitic metavolcanics
- **Meta breccia**
- Metavolcanics with visible crystals
- Metasediments
    - Slate
    - **Metagreywacke**

3.2.1. Aphanitic Metavolcanics

This rock unit covers the largest portion of the area mapped as metavolcanics. It is a greenish grey coloured, fine grained rock exposed in both eastern and western boundaries of the study area. Rocks grouped here include meta-andesite, metadacite, chlorite schist, and metarhyolite.

Thin section analysis shows that it is a low grade metamorphic rock with clear relics of well preserved porphyritic texture in a recrystallised matrix. The phenocrysts in most of the samples are plagioclase and some amphiboles (tremolite). In some of the samples, quartz is also found as a phenocryst. In addition to the above minerals epidote, muscovite and chlorite occur as newly formed minerals. The groundmass in most cases is completely recrystallised while in some others recrystallisation is partial.

The plagioclase grains are mostly altered to epidote and sericite (muscovite). In some instances the alteration is so intense that one can only see the phantoms of plagioclase. The abundance of plagioclase is between 47-75% with euhedral grains reaching 3mm in diameter. The mafic minerals appear to be completely transformed to tremolite, chlorite and some epidote without leaving any trace of relict texture. Tremolite in many of the samples occur both as phenocrysts and as a fine grained mass in the recrystallized matrix, in form of acicular crystals elongated fibrous needles. It forms a significant percentage in some samples, while in many others it makes up between 3-7% and is visible only under higher objectives, where it forms part of the recrystallized groundmass. When it occurs as phenocrysts, it has grain diameters reaching 1mm.

Quartz is found locally in small amounts in most of the studied samples as a recrystallisation product from the groundmass. However, the metavolcanic rocks outcropping in the northwestern synform contain around 35% of primary rounded quartz phenocrysts.

Epidote is present as a secondary phase almost in all of the sections in variable proportions. Commonly it occurs as irregular aggregates and makes up to 10% of the rock. Muscovite is present as a minor constituent .

Chlorite occurs in different proportions in different samples, i.e in some rocks it is completely absent, whereas in others it forms around 60% or more. It occurs as an alteration product of ferromagnesian minerals. Finally opaque minerals such as magnetite and accessory minerals of apatite and zircon are present.

The mineralogy as given above is plagioclase, amphiboles, chlorite, epidote, muscovite and in some of the samples quartz phenocrysts.

It is believed that chlorites are low grade alteration products of pyroxene and other ferromagnesian minerals, while epidote and sericite are alteration products of plagioclase. The mineral association suggests that the original rock is probably an intermediate volcanic rock, possibly andesite. (fig. 3.2, 3.3, 3.4, 3.5, 3.6). For the samples which bear quartz phenocrysts, dacitic as well as rhyolitic origin is suggested.

Associated with these rocks, especially in the eastern part of the study area, are some fine grained massive ashes without any visible foliation, and significant recrystallization. In hand specimen it is fine grained rock with light green colour. The above features indicate that the original rock type might have been pyroclastic.

3.2.2. Metabreccia

It is black, green-grey, sometimes faint blue in colour with grain sizes of angular blocks with average diameter of 15cm but, in places it reaches upto 1m . In outcrop the rock is extremely compact. The colour of individual block varies from black to reddish brown. However the reddish brown colour is dominant though compositional implications are not determined. This unit is observed sporadically exposed on the western side of the study area, on the hill tops, and along stream cuts.

Petrographic analysis of the rock thin section, shows that, the rock is mainly composed of quartz, epidote, plagioclase, and sericite with a significant amount of iron oxides.

The phenocrysts are dominantly quartz and plagioclase while the groundmass is almost exclusively constituted by quartz and sericite. The phenocrysts have two groups of size distribution; the plagioclase phenocrysts are euhedral to subhedral grains with size greater than 3mm, mostly untwined and being altered to aggregates of epidote and sericite.

Fig.3.2:- Photomicrograph (crossed polarizers) of an aphanitic metavolcanic rock with relict porphyritic texture and highly recrystallized groundmass. The phenocrysts are plagioclase (pl) and newly formed minerals of epidote (ep).

Fig.3.3:- Photomicrograph (crossed polarizers) of an aphanitic metavolcanic showing a clear relict porphyritic texture with phenocrysts of plagioclase (pl) and quartz (qz). The groundmass is highly recrystallized quartz, epidote, sericite, and plagioclase.

Fig.3.4:- Photomicrograph (plane light) of an aphanitic metavolcanic rock composed mainly of chlorite, epidote, plagioclase and opaque minerals.

Fig.3.5:- Photomicrograph (crossed polarizers) of an aphanitic metavolcanic rock with relict porphyritic texture, composed of phenocrysts of highly altered plagioclase (pl) to epidote, and muscovite. The groundmass is largely quartz crystals.

Fig.3.6:- Photomicrograph (crossed polarizers) of aphanitic metavolcanics containing Tremolite (Tr) and epidote (ep) minerals.

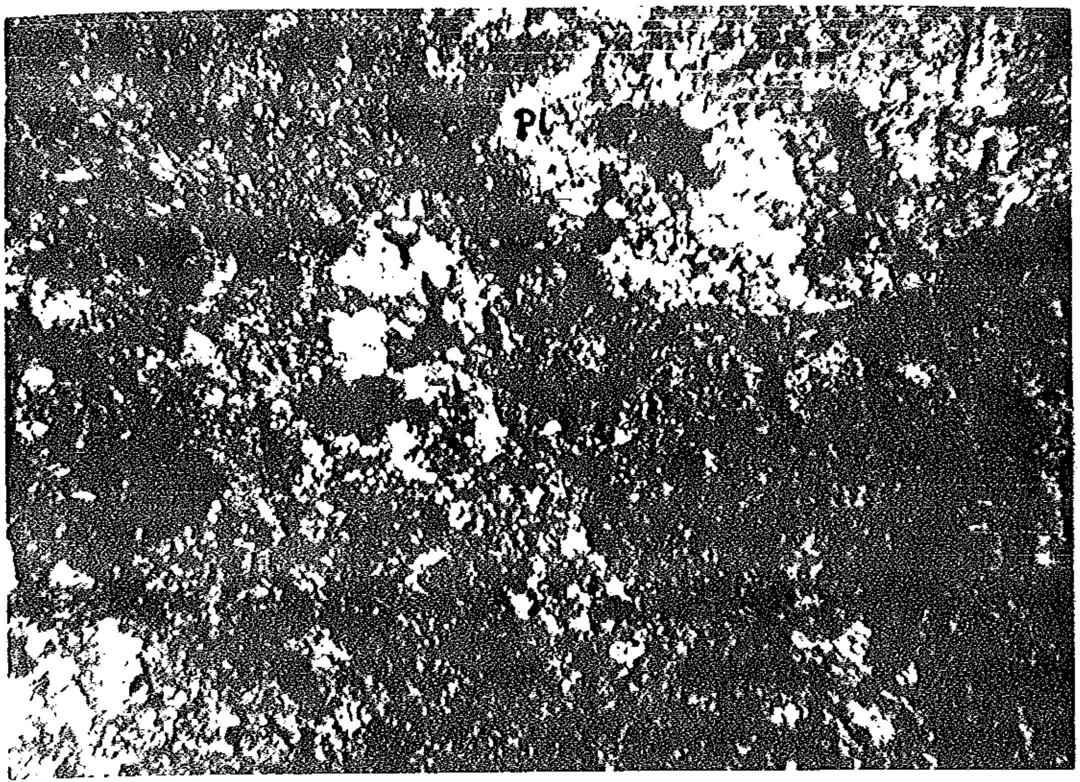


Fig. 3.2

Fig. 3.3

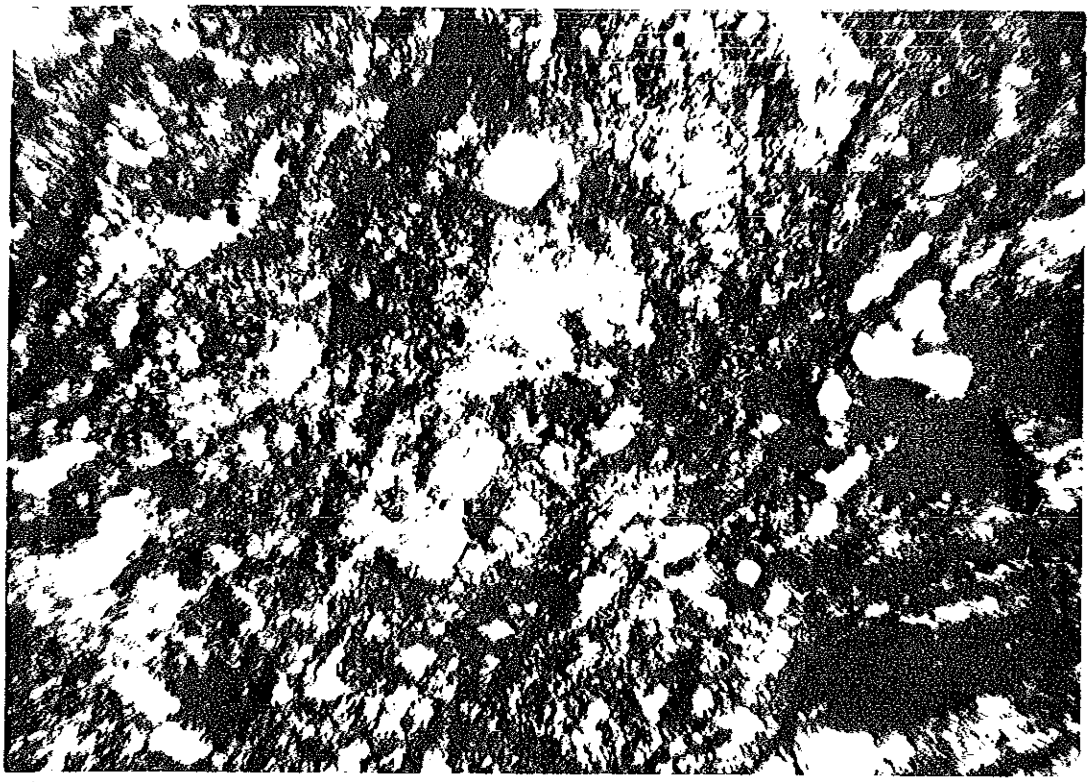


Fig. 3.4

Fig. 3.5

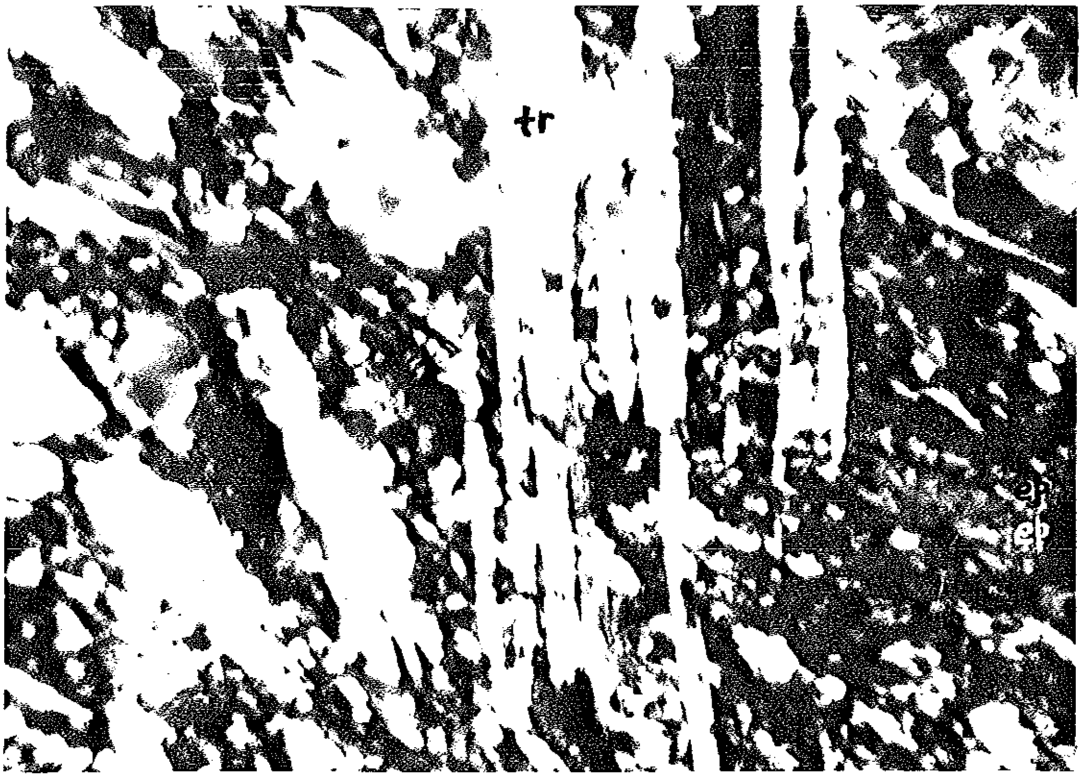


Fig.3.6.

The quartz grains occur as microphenocrysts genetically belonging to the ground mass. They commonly occur as aggregates and exhibit typical wavy extinction. Epidote mainly occurs as smaller aggregates as alteration product replacing plagioclase. Iron oxide occur as weak bands alternating with quartz and plagioclase.

The fact that the blocks are of different colours implies difference in composition and the original igneous glassy groundmass transformed into a recrystallized matrix suggests volcanic origin for the rock and hence the original rock is breccia.

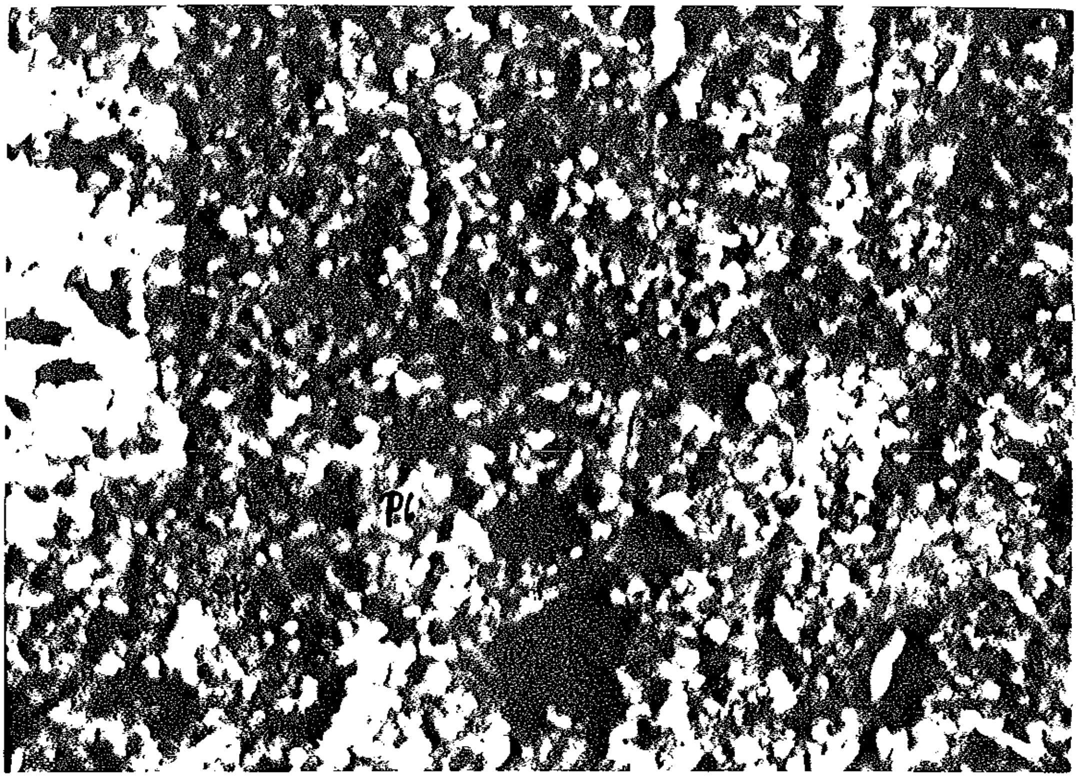


Fig.3.7:- Photomicrograph (crossed polarizers) of metavolcanic rock with the field of view covered by single plagioclase mineral partially transformed to epidote.

3.2.4. Slate

This unit has greyish to light bluish colour. It is highly friable with persistent fine bedding and is found interbedded with the metavolcanics. In the northern part of the study area, it is intensively dissected by quartz veins of differing widths having mean orientation of

75°-->235° which is subparallel to the regional foliation.

It is friable, soft and highly weathered that not even a single sample can be obtained for thin section analysis. In some cases it is found inter-stratified with metagreywacke.

3.2.5. Metagreywacke

This unit is found on the western boundary of the study area, mostly along road cuts, interbedded with the slates and acidic metavolcanics. It is oriented parallel to the regional trend of the foliation.

It is grey to black, weakly metamorphosed greywacke composed of relics of angular to subangular grains of quartz and plagioclase as major constituents in a fine grained matrix. Newly formed minerals include epidote, chlorite and accessory opaque minerals. These grains are generally fine grained (rock flour size) interlocked with recrystallized quartz and plagioclase.

Microscopic analysis shows that the plagioclase accounts for around 40% of the constituents, most of which are untwined with grain sizes less than 0.2 mm. In most cases, the plagioclase is slightly altered to fine sericite and epidote.

Quartz is the next dominant mineral found in the rock, forming around 20%. It occurs both as fine angular grains and as recrystallized matrix material.

Since the predominant mineral is feldspar the original rock is arkosic greywacke (fig.3.8).

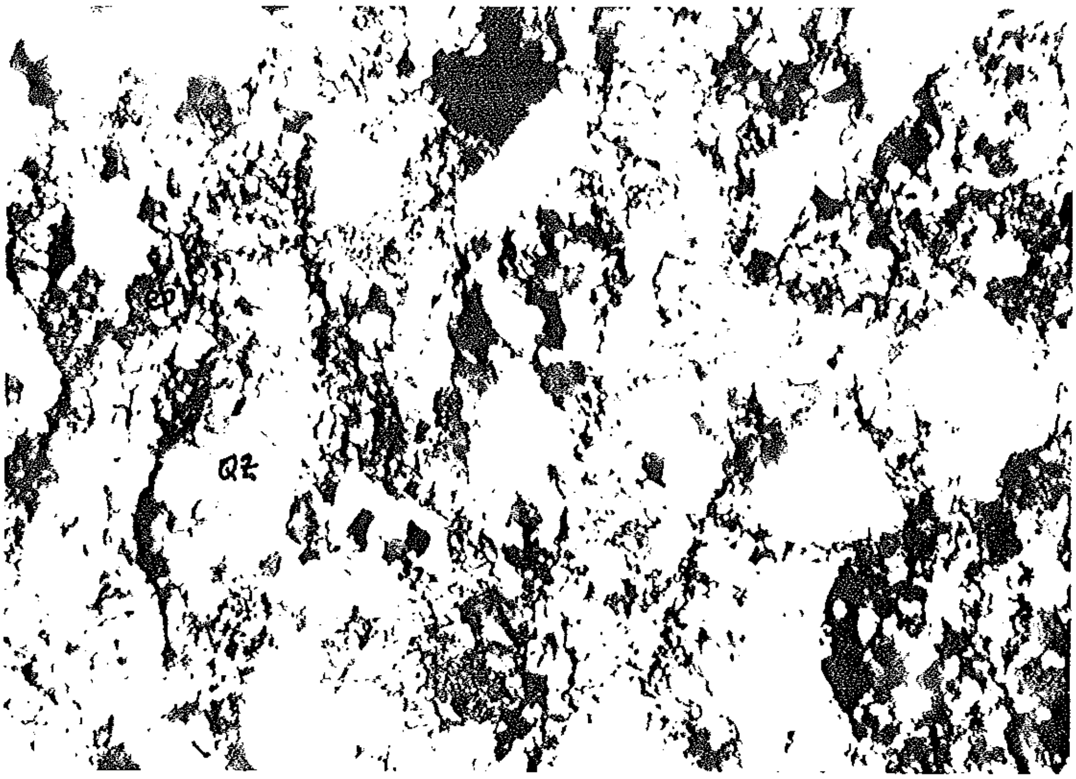


Fig.3.8:- Photomicrograph (crossed polarizers) of metagreywacke with grains of quartz (qz) and plagioclase in a sheared matrix. The groundmass is constituted of recrystallized quartz and newly formed epidote

Concluding remarks

The metamvolcanic rocks which are correlative to the Tsaliet metavolcanics of Beyth (1971) (see section 3.4) are composed of an originally volcanic rocks of andesitic, breccia, tuffs, dacitic, and rhyolitic composition. Though not clearly observed in the study area, Beyth (1971), documented that these rocks throughout the Tigrai region show primary sedimentary structures such as bedding, and graded bedding. Moreover, within these metavolcanic associations, there are some thin interbedds of slate and greywacke. For the above reasons, it is concluded that the metavolcanic rocks of the area were deposited under water, in a deep basin. The same conclusion was given by Beyth (1971) and Garland (1980).

3.3. METASEDIMENTARY ROCKS

The metasedimentary rocks as a whole occupy the central part of the study area, bounded to the east and west by a sharp contact with the metavolcanics.

This group include the following lithologies:

- Slate
- White fine marble
- White coarse marble
- Graphitic phyllite
- Quartzite
- Metaconglomerate
- Fine black marble
- Black marble and slate intercalation
- Pebbly slate

The above listing and foregoing description of each lithology does not have any stratigraphic implication, as most of the lithologies are non continuous across the folds; except for the last three units which have lithologic continuity across the fold.

Morphologically the area occupied by the metasedimentary units can be divided into three: Ridges, flats, and irregular ups and downs. The ridges in most cases are formed by intercalations of quartzite, thin beds of slates, fine to medium marbles, especially in the western and part of the south eastern flank of the central synform (fig.4.3); white coarse marble, metaconglomerate, and graphitic phyllite in the limb of the eastern antiform; fine black marble, found at the centre of the synform.

The flats are exclusively occupied by slates and are largely found on the western and part of the southeastern flank of the central synform; whereas the ups and downs are constituted by pebbly slate which forms the core of the central synform.

3.3.1. Slate

Slate in the metasedimentary succession is found forming thin beds, interbedded with other ridge forming units, in the western and part of the south eastern flanks of the central synform. However, it dominantly occupies topographically flat regions of the study area.

It is a light grey, light yellow, sometimes bluish grey coloured, partly graphitic and is very soft rock. It exhibits fine bedding commonly less than 1cm. The strike of the layering is parallel to the regional trend of the foliation, but in some instances (100m SE of the hill formed by Enticho sandstone), the bedding is found with an orientation 75°--> 285°; whereas the layering direction is found to be 80°-->120°. The thickness of the units is variable in different parts of the study area. Although, the rocks are too fine grained for microscopic identification of mineral grains, samples taken from near the intrusion showed its composition to be quartz, sericite, feldspar, and some opaque minerals (fig. 3.9).

The rock units underlying and overlying it are quite different in different parts, this unit is observed having a sharp contact with the metavolcanics of the Tsaliet group and metasedimentary units.

3.3.2. White fine marble

It is a white to light yellow coloured rock which outcrops mainly in the western and part of the southeastern flank of the central synform (fig. 3.1.). Small outcrops are found in the eastern parts of the eastern antiform. This is the dominant lithology among the ridge formers and is intensively cut by quartz veins of various width, reaching 15cm. The layering is parallel to the regional foliation.

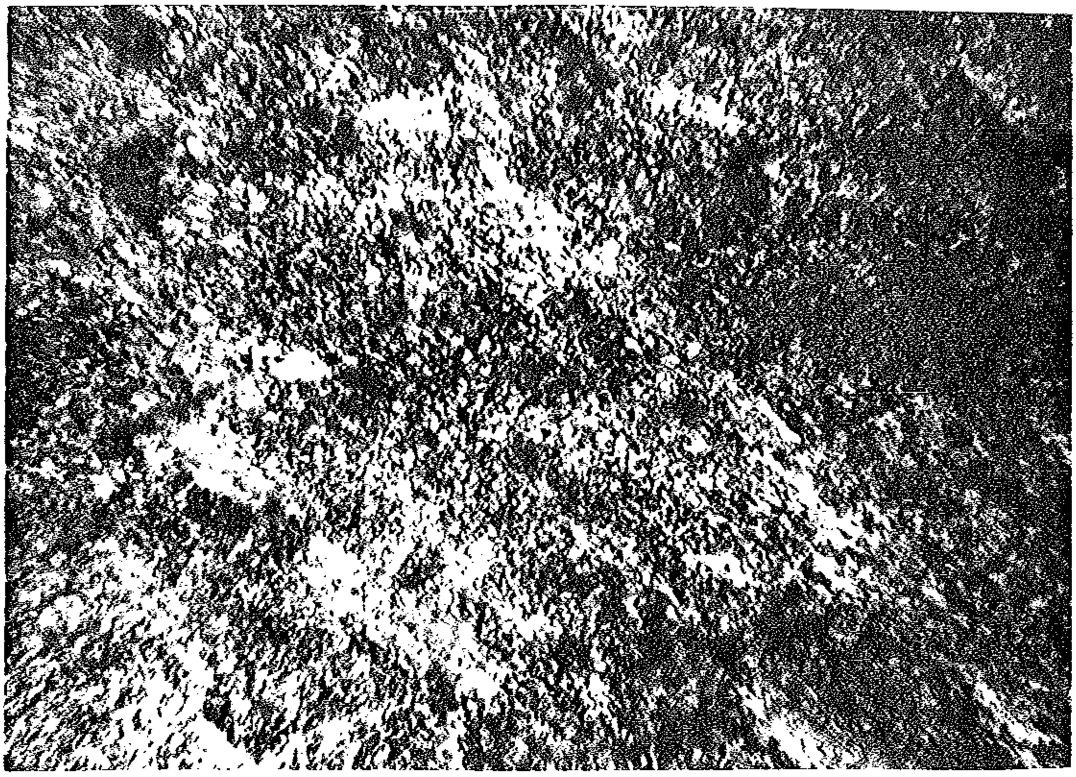


Fig.3.9:- photomicrograph (crossed polarizers) of slate near the granite composed of feldspar, quartz, and sericite grains.

According to Beyth (1971), the original rock is dolomite with a range of composition: detrital quartz grains 5%-90% with 0.2mm grain size, alkali feldspar and Na-plagioclase >5%, and prismatic chlorite >5% (foliated).

It is mostly found intercalated with other ridge forming metasedimentary units and sometimes, especially north of the Negash village, it is found in contact with the metavolcanic rocks.

Thin section studies of this rock showed that the rock is dominantly composed of calcite and dolomite (about 70%). Plagioclase accounting for (15-20%) and quartz (10-15%) occurs in bands of two size groups: one group of the bands formed by coarse grained quartz and plagioclase. The other band is constituted by very fine grains of quartz and plagioclase. The proportion of the quartz and plagioclase minerals given above approximates the maximum value for the impurities that exist in the white fine marble (fig. 3.10).

3.3.3. White Coarse Marble

It outcrops mainly on the western flank of the eastern antiform, where it covers a wide portion of the flank. It is white coloured, and compares with the white fine marble. It is coarse, crystalline, with calcite and big pebbles of quartz visible to the naked eye.

Microscopically the rock is composed of calcite with a very small percentage of plagioclase, quartz and muscovite.

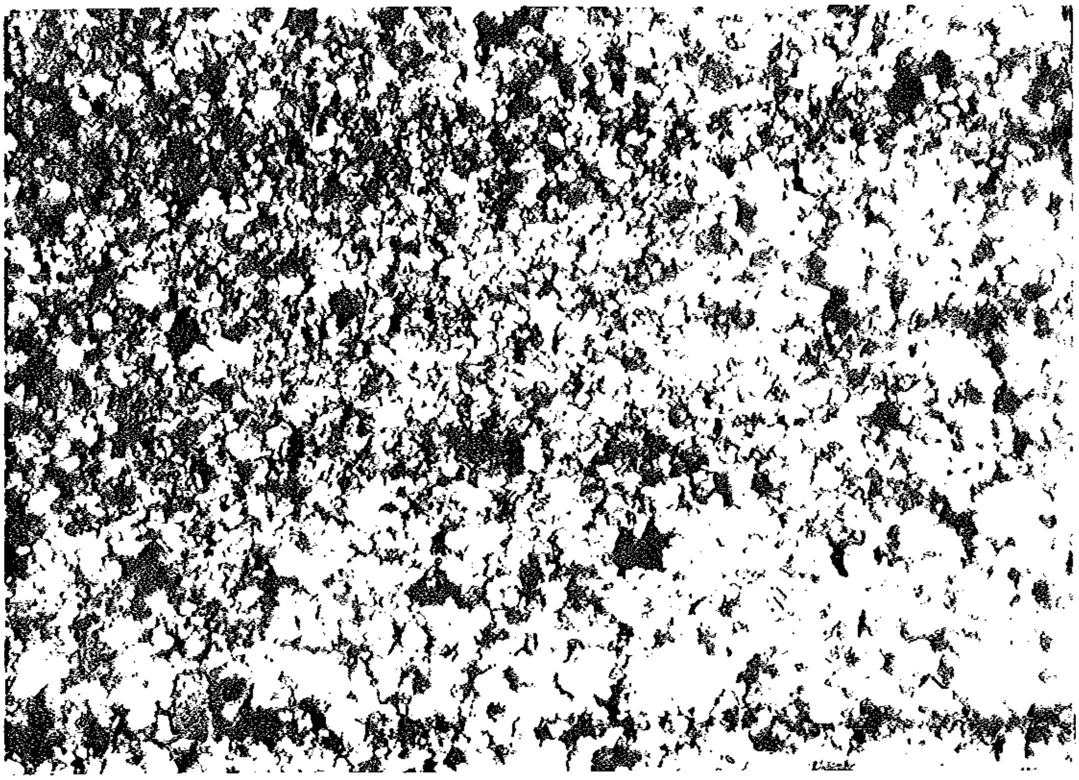


Fig.3.10:-photomicrograph (crossed polarizers) of white fine marble containing minor quartz and plagioclase.

In the rock, calcite makes up to 60-90% of the composition with grain size reaching 3.5mm. Muscovite showing preferred dimensional orientation makes upto 30-35% in some thin sections. In this rock plagioclase and quartz make up a maximum of 10% (fig. 3.11, 3.12).

Fig.3.11:-photomicrograph (crossed polarizers) of coarse marble containing minor quartz and plagioclase.

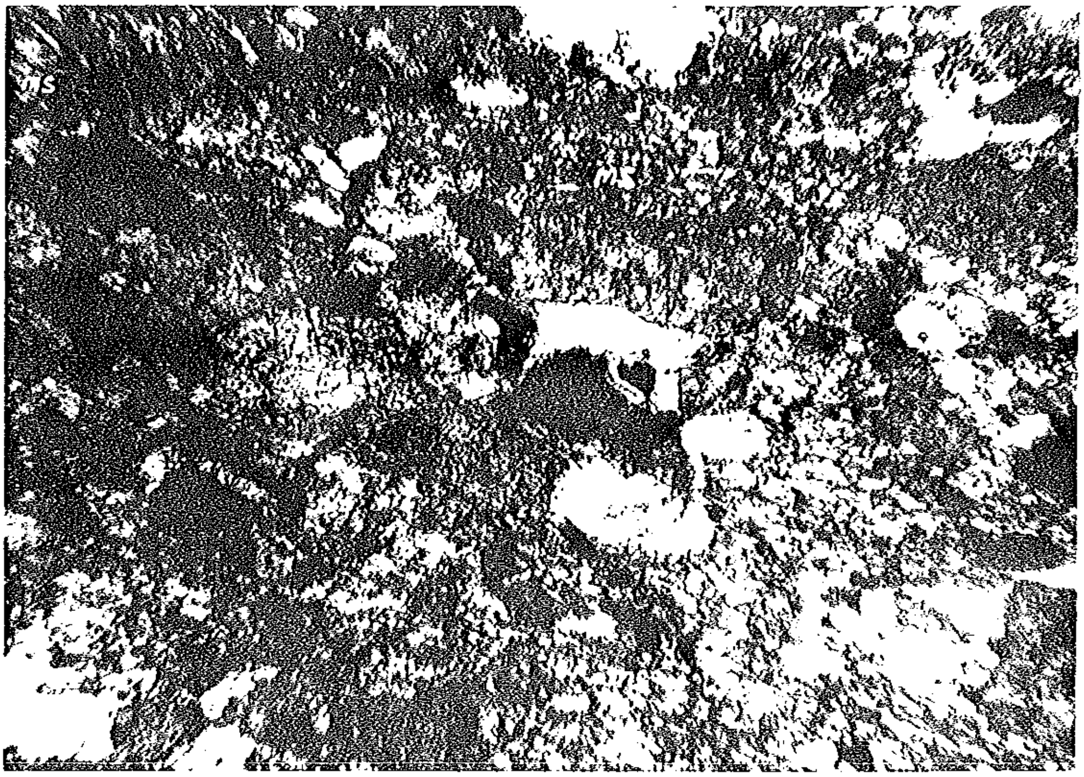


Fig.3.12:-photomicrograph (crossed polarizers) of coarse marble containing 30-35% muscovite which shows preferred orientation.

3.3.4. Graphitic Phyllite

Graphitic phyllites outcrop in the eastern and western flanks of the north western synform, eastern antiform and on the western flank of the central synform (fig. 3.1); wherever it occurs, it forms narrow ridges.

It is exposed in different parts of the study area making clear contacts with other basement rocks (especially with the metavolcanics, white fine marble and slate units). This unit in the study area found within depression, ridges, and sometimes small hill (especially at the western boundary of the north western synform.

It is a variegated rock with green, purple, reddish brown, yellowish and black colours with layering parallel to the regional foliation. In thin section the rock is very fine grained. The slaty cleavage is defined by alternating bands of the same minerals with variable degree of compaction. Minerals found are feldspar, graphite, quartz, and some slightly crystallised micaceous material (fig.3.13).

3.3.5. Quartzite

This unit largely outcrops on the western side of the central synform together with the white fine marble, and on part of the northwestern side of the eastern antiform with the white coarse marble.

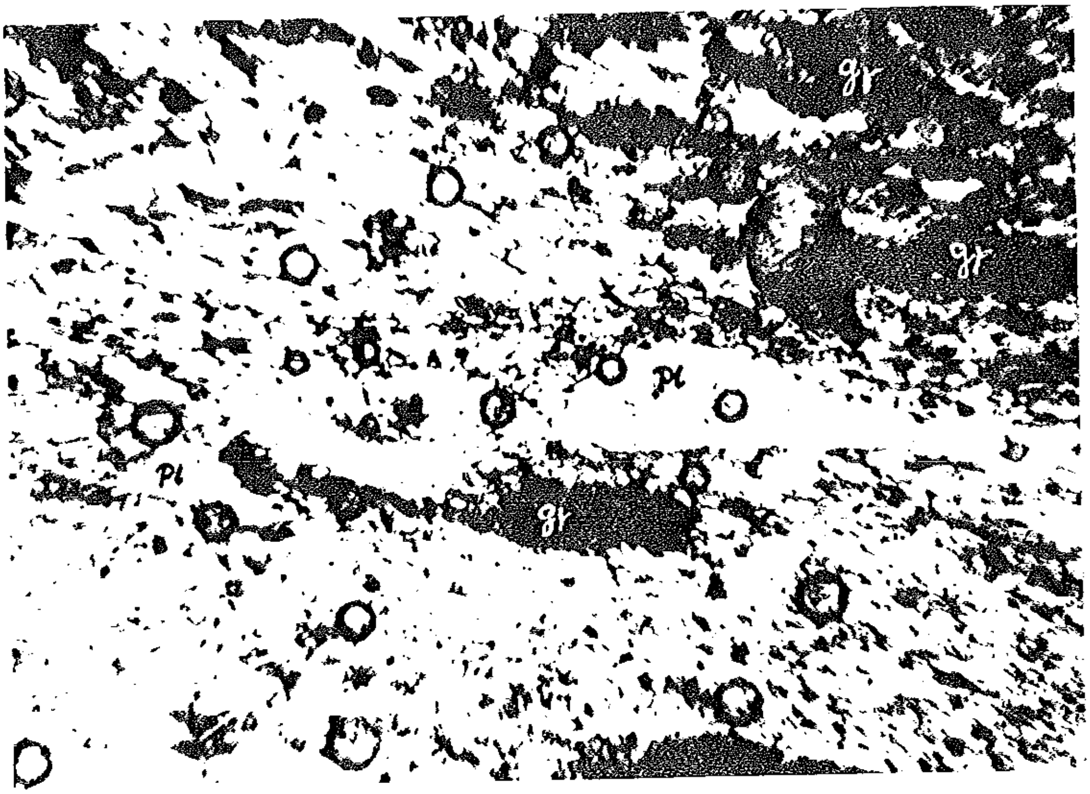


Fig.3.13:-photomicrographs (plane light) of graphitic phyllites. Dark minerals are graphite, white minerals are plagioclase and quartz.

In both areas, it is a ridge forming, and occur as thin beds repeated in an irregular manner from ridge to ridge. It is white to very light blue coloured and compact. It is found intercalated with white fine marble and slates in the central synform. The orientation of the layering is parallel to the regional foliation.

Although in most of the exposure it is found sandwitched between the rocks forming the ridges, in some instance it is found making sharp contact with the metavolcanic rocks.

Under microscope study, it is composed of about 90% quartz, all recrystallized with its typical wavy extinction, and 10% calcite grains. The grain size of quartz reaches, 2.5mm, but the average size is about 1mm. It is often cut by calcite veins of variable thickness (fig. 3.14).

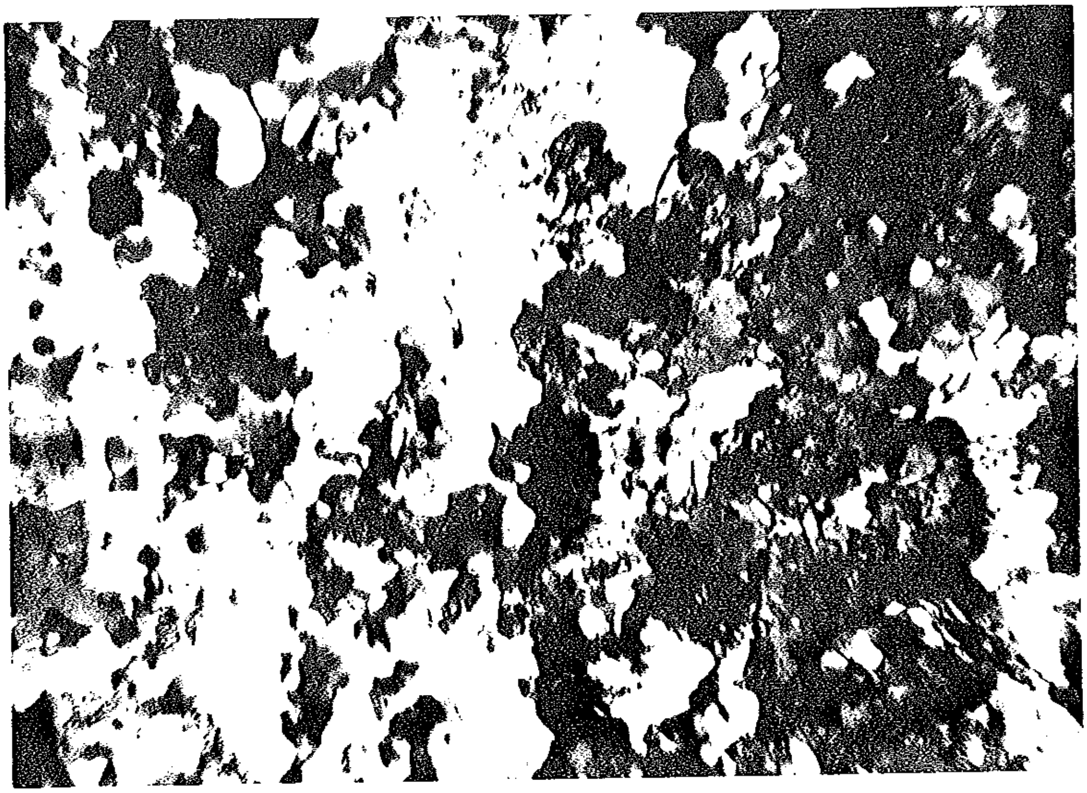


Fig.3.14:- photomicrograph (crossed polarizers) of quartzite showing strained mineral of quartz.

3.3.6. Metaconglomerate

It is a black to brown coloured, very hard rock, which occur as a very thick layer. It is bedded with orientation 42°-->125°, having approximate thickness of 250m measured in the northern part along the eastern flank of eastern antiform. In hand specimen, the grains of quartz are rounded and in average 1cm in diameter. Microscopic analysis reveals that it is composed of quartz, muscovite and chlorite (fig. 3.15). Quartz forming 80-85% occurs both as a coarser grain with grain size of 5mm and as finer groundmass, recrystallised from the matrix between the coarser stuff. Muscovite, on the other hand, occurs as a fine grained mass replacing previous euhedral minerals which left traces of their outline (mostly of plagioclase). It forms 7-10% of the rock and shows a preferred orientation. Chlorite constitutes about 5% (fig.3.15).

3.3.7. Black fine marble

Black marble outcrops entirely near the axis of the central synform (fig 3.1). It is massive with approximate thickness of 250m. It is intensively cut by three sets of joints all filled with calcite which are oriented 70°-->160°, 82°-->025°, and 30°-->100° . As the name implies it is black in colour, finely crystalline, composed entirely of calcite with minor quartz and plagioclase.

Within the southwestern neighbouring ridges of this unit, there are thin beds of black marble unit which is coarse grained, dominantly composed of calcite with again minor quartz and feldspar.

In this rock neither allochems nor fossils are found, which might be attributed to recrystallization effect. Thus, the rock is recognised as marble instead than limestone.

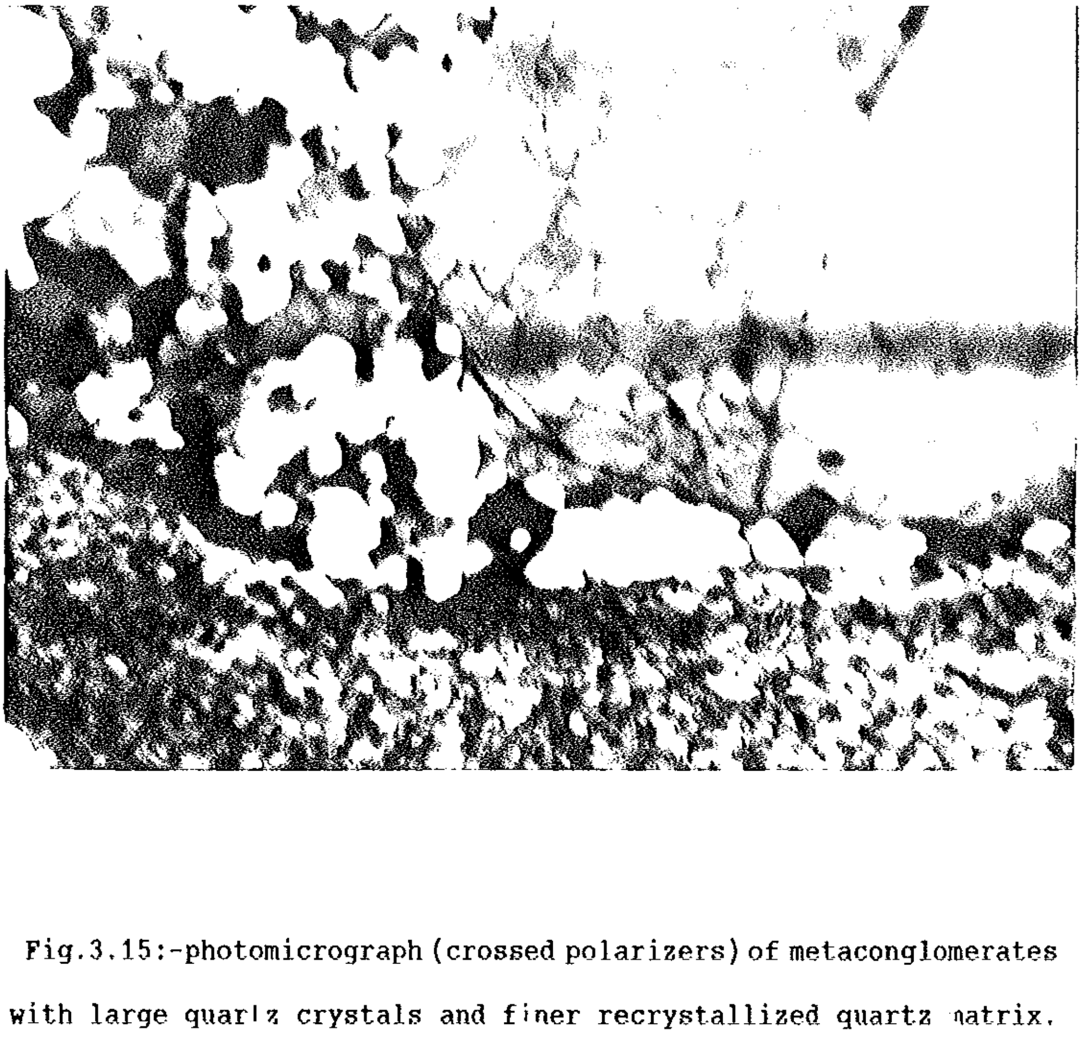


Fig.3.15:-photomicrograph (crossed polarizers) of metaconglomerates with large quartz crystals and finer recrystallized quartz matrix.

3.3.8. Black Marble and Slate Intercalation

The black marble unit grades into intercalations of banded slates (i.e bands of white thinner stripe and greyish thicker stripe), thin beds of yellowish brown mud rocks, fine green slates, thin beds of metamorphosed marl, and thick black marble units (fig. 3.16). These intercalations have an approximate thickness of 300 m. This rock crops out along the central part of the area outlining the central synform. It is characterised by the best development of intersection lineation along the hinge zone of the central synform.

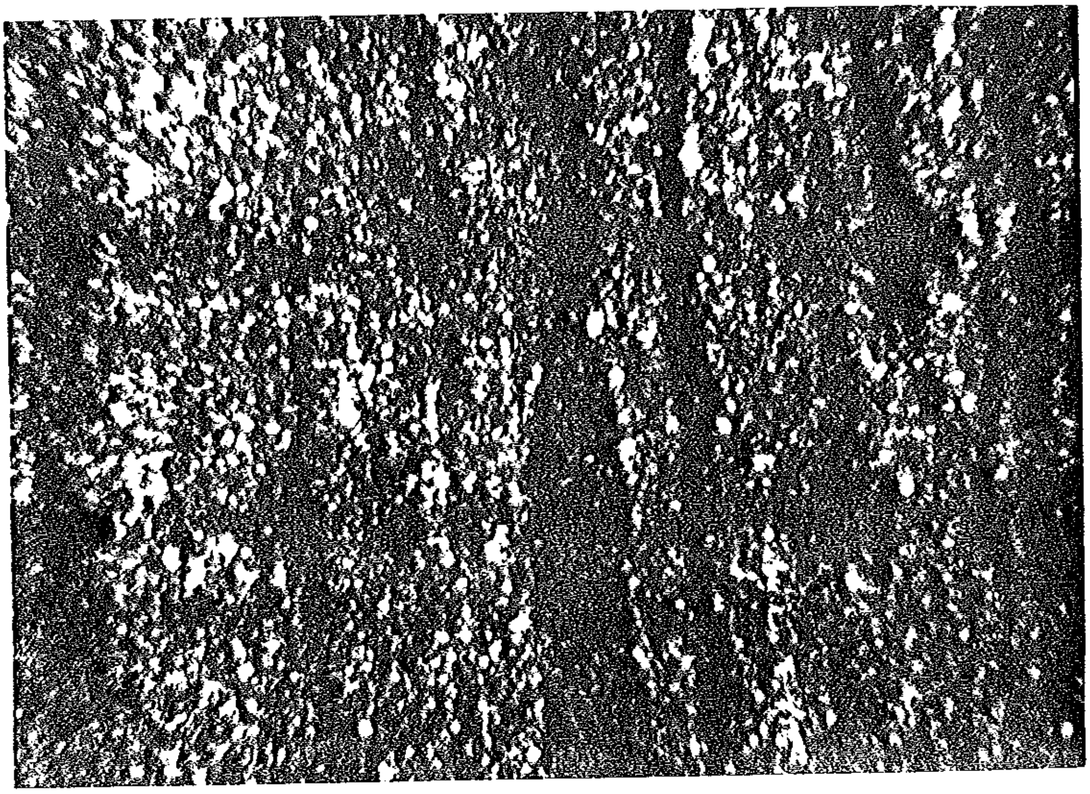


Fig.3.16:-photomicrographs (crossed polarizers), showing slaty cleavage within the thin marl unit found intercalated with the black marble.

3.3.9. Pebbly Slate

The rocks crops out along the core zone of the central synform. It forms a unique rugged topography. It is very friable and very susceptible to weathering and not good for making thin sections. In hand specimen it contains rounded pebbles of different colours originating from limestones, granite, quartzite and metavolcanics (Beyth, 1971). According to Beyth (1971), who has also made personal communication with Dow, there is a slight possibility that this pebbly slate is a result of an intraPrecambrian glaciation.

Concluding remarks

The metasedimentary rocks in the study area (see section 3.3 for detail) clearly were of marine origin. These sediments all being marine in origin, the black colour of some of the slates and the presence of graphitic phyllite in the sequence suggests that they were deposited under low energy and reducing environment. The deposition of the metaconglomeratic layers is indicative of a relatively higher energy environment during its formation. The marble unit found interbedded and overlying the slate unit indicates a change from terrigenous to chemical sedimentary conditions.

3.4. Correlation of the basement stratigraphy

In the study area, the basement rocks are broadly divided into metavolcanics and metasedimentary rock units (section 3.2 and 3.3).

The metavolcanic subdivision as described in section 3.2 is constituted by metamorphosed; breccia, lavas and thin beds of pyroclastics. In places, interbedded slate and metagreywacke are observed.

On the basis of lithological association, mineralogy, colour, mode of exposure, and metamorphic grade the unit can be correlated with the Tsaliet Group described by Beyth (1971), Levitte (1970), and Garland (1980) (fig 3.1). The following features of the metavolcanic of the Wukro area are particularly similar with that of Tsaliet Group: lateral variation of lithologies, rocks are acidic to intermediate in composition, and there are associated metagreywacke and slate.

The metasedimentary unit includes (see section 3.3): slate, white fine marble, white coarse marble, graphitic phyllite, quartzite, metaconglomerate, black fine marble, black fine marble and slate intercalation, and pebbly slate.

The Werii slate of Beyth (1971), is basically consisting of variegated slates which are commonly friable. At the base, it contains some calcareous sandstone and intraformational conglomerate (Garland, 1980). Thus, the quartzite, slate and metaconglomerate in the study area can be correlated with the lowest part of the Werii slate (fig. 3.1.).

The Tsedia slate, in the whole of the Tigrai region, is characterized by its purple slate at the base. The top of the section closely resembles the Werii slate (Garland, 1980). Therefore, the graphitic phyllite in the study area is probably correlative with the base of the Tsedia slate (fig. 3.1, fig. 3.17).

Garland (1980) reported that, the Didikama formation which consist largely of fine to coarse grained dolomite, and in outcrop it forms an elevated ridges. Since the white fine marble and the white coarse marble of the Wukro area are of the same rock types and form ridges, it can be said that they belong to the same rock unit as the Didikama formation (fig. 3.1.).

The black fine marble was previously described as Matheos formation by Garland (1980). In the Wukro area, however, the black fine marble and slate intercalation is recognised as a separate unit above the Matheos formation.

Finally the youngest Precambrian rock is the pebbly slate found at the core of the central synform.

3.4.1 Concluding comments

In the present study area, the metavolcanic rocks which are correlative with the Tsaliet group are found making sharp contact with the slate, graphitic phyllite, and white fine marble which are correlative with the Werii slate, Tsedia slate and Didikama formation respectively at different localities. Moreover, the graphitic phyllite (correleble with Tsedia slate) is found above the white fine marble and slate (which are correleble with the Didikama formation and Werii slate respectively) at the western flank of the Central synform (fig.3.1). Garland (1980) who observed the Didikama formation resting in places on the Tsaliet Group and in others on the Arequa formation explained the existence of an unconformity. But, in the study area there is no clear evidence for the existence of unconformity. Therefore, the stratigraphy produced by the previous workers in the study area is not strictly applicable at least not for the Werii slate, Tsedia slate, and Didikama formation.

Furthermore, the study area is characterized by the development of complex structures such as transposed layering (see chapter 4.) which complicated the local stratigraphy. This calls upon making a revised version of the previously established "simple" stratigraphy of the area.

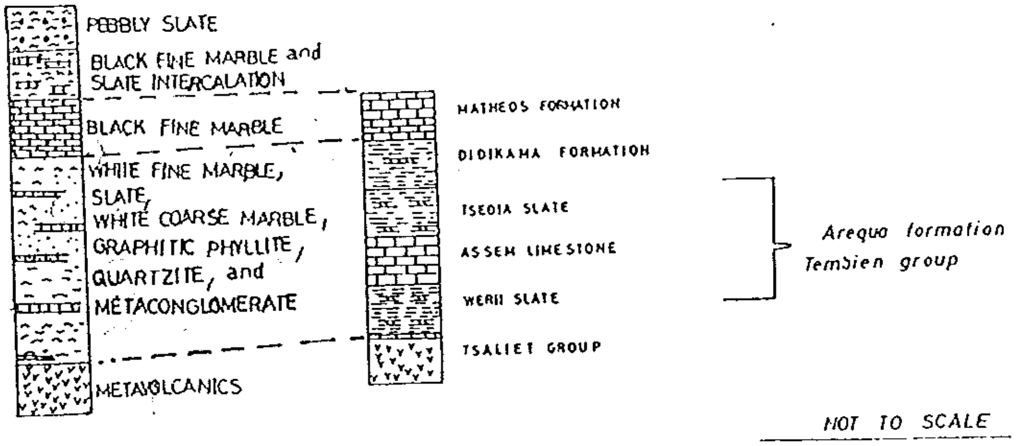


Fig. 3.17. Correlation of local stratigraphy with the regional stratigraphy produced by Garland (1980).

3.5. INTRUSIONS

3.5.1. Granite

East of the northwestern synform (fig.4.3) there is a small granite intrusion at around 13° 53' N and 39° 39' E (Beyth, 1971). The granite is elongated parallel to the marble-slate layering or the regional foliation, and forming relatively elevated topography. It is 2.5 km long and 880m wide.

It is pinkish in colour and is medium grained. The unit is frequently cut by pinkish aplite dikes having a dominant orientation of N 25° E. Some spherical to oval patches of crustal inclusions, with concentric layers of differing composition are found in this granite. At the margins of the granite some blocks of quartz-diorite is found.

Microscopic analysis shows that this granite has suffered slight degree of metamorphism. It is comprised of plagioclase (30-35%), alkali feldspar (perthite) (30-40%), quartz (approx.20%), muscovite (5%) and biotite (5%).

The plagioclase has composition of oligoclase some of which is altered to muscovite. Alkali feldspar occurs as perthite containing few scattered lenses of albite. The grain size of this feldspar reach 3.5mm in diameter. Quartz is not much altered.

The ferromagnesian minerals present in the rock are euhedral grains of biotite. Some of it is altered to chlorite. The muscovite minerals seen in these rocks are of two types: primary and secondary; the primary muscovite occurs in euhedral separate grains being crystallised out from the original melt; whereas, the secondary ones are found within and replacing the surfaces of the plagioclase.

The above mineralogy clearly indicates that the original rock is a muscovite-biotite granite which has attained a low degree of metamorphism (fig. 3.18).

The mineralogy of the quartz diorite block seen at the margin of the small granite is more or less the same as the mineralogy of the muscovite-biotite granite. But in here, (1) the abundance of biotite grains reaches around 10% (partly transformed to chlorite) with few, hornblende, and sphene making up about 3%; (2) the proportion of alkali feldspar is diminished while the proportion of plagioclase increases. In addition to the chlorite, it has secondary muscovite and epidote which are products of the low grade metamorphism of the quartz diorite (fig. 3.19).

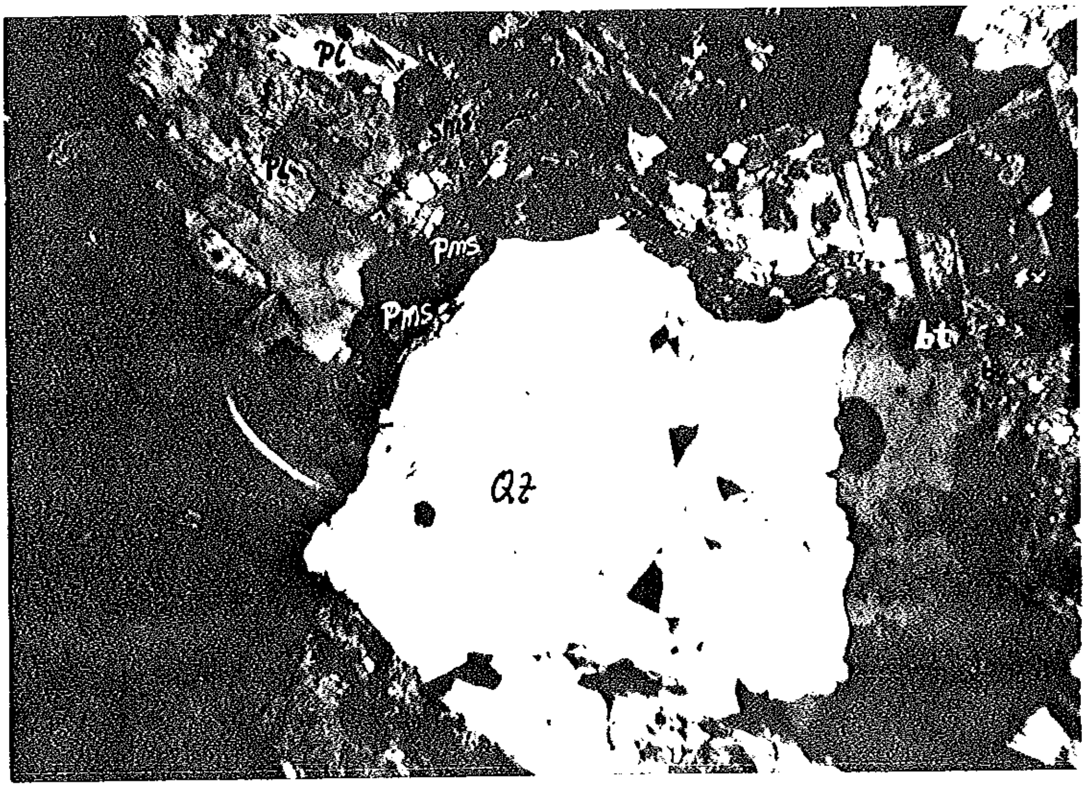


Fig.3.18:- photomicrograph (crossed polarizers) of meta muscovite-biotite granite, with grains of quartz (qz), plagioclase (pl), primary and secondary muscovite (pmv,smv) and biotite (bt)

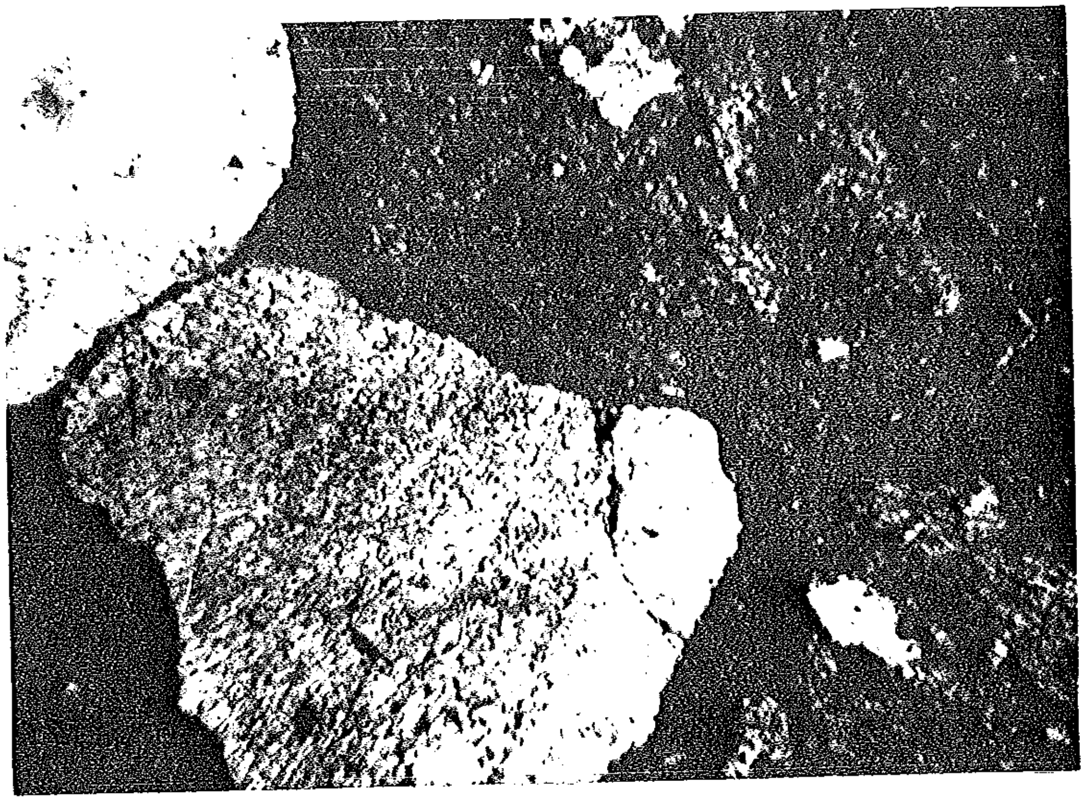


Fig.3.19:-Photomicrographs (crossed polarizers) of quartz-diorite with crystals of plagioclase, biotite, and quartz

3.5.2. Aplite

Aplites occur as grey, pink to yellow dikes mostly about 5cm-10cm thick cutting the metamorphic rocks. The aplite intrudes the granite and represent the latest of the basement magmatism. They are granitic in composition with fine to medium grain size, consisting mostly of equal amounts of quartz and feldspar; with minor constituents of biotite or muscovite. According to Levitte (1970), in places there are outcrops of mafic rocks composed of 75-80% mica most of which is muscovite, small amounts of plagioclase, quartz and alkali feldspar.

3.6. PALAEOZOIC – MESOZOIC SEDIMENTS

3.6.1. General

After the deposition, folding, tilting, intrusion, and faulting of the Precambrian basement a period of erosion and peneplanation occurred. In northern Ethiopia the levelling was followed by a hiatus in the geological sequence with the Edagga Arbi glacials or Mesozoic sediments being the next successive formations.

These sediments in the study area are characterized by clastic successions, mainly of sandstones, which are classified into:

- White sandstone (oldest)
- Shale
- Brown sandstone (youngest)

3.6.2. White Sandstone

It is found resting unconformably over the peneplained basement morphology (fig.3.20). It is exposed largely on the southern parts of the area and as an outlier in the northern part of the study area. Wherever it outcrops, it forms a hill. This unit is composed of white, medium grained, highly friable sandstone with a very good sorting. At the base, it is partly conglomeratic. It is laminated, where each laminae is separated by an encrustation of iron which is believed to be due to weathering which also resulted in the formation of grooves on the encrustation surfaces. The ferruginous encrustation surface interrupts the individual sets of laminae. In some places it shows graded bedding. This unit forms a gentle dipping (14°-->215°).

In this rock the only sedimentary structures observed are grooves, graded bedding, and small laminae. Within this dominant lithology, there is another unit containing large angular pebbles approximately 5cm in diameter within the matrix. This angular pebbles are of granitic, metavolcanic, and marble origin.

The textural and structural features of this sandstone unit is indicative of either fluvial fan or lacustrine deposit (Boggs, 1987). But it does not indicate unique features to exactly decide its environment of deposition.

On the basis of general lithological similarities and stratigraphic position this sandstone unit is correlable with the Palaeozoic Enticho Sandstone described by Dow *et al.* (1971), and Beyth (1971).

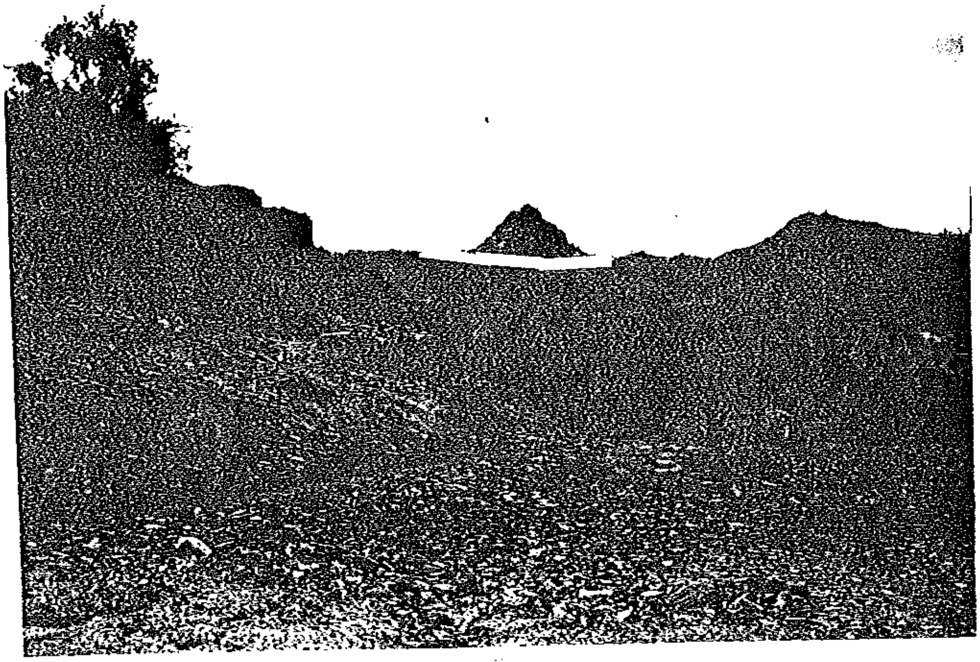


Fig. 3.20. Contact between the Palaeozoic sandstones (Enticho sandstones) and the underlying folded basement rocks.

3.6.3. Shale

At the southern boundary of the study area, in a small quarry, there is a silty clay unit containing some pebbles overlying the white sandstone. It is highly laminated with varve structures. At the base of each laminae, one can recognise coarser white silty material and finer grey material. Varves are believed to form mainly in lakes and are the more diagnostic characteristics of lake sediments (Boggs, 1987). The varved nature of the shale and the stratigraphic position of this unit can correlate it with the Edaga Arbi glacials described by Dow *et al.* (1971) and Beyth (1971) which is Palaeozoic in age. Therefore, this unit might have been deposited in a glacial lake. Thus, the varved shale is the product of changes in the climate which determined the volume of water input into the lake.

Overlying this shale unit is a white to grey rock containing boulders and pebbles of various sizes, and hence, extremely poorly sorted. The pebbles and boulders are different in composition. The largest seen is 1m. of granite boulder, but these larger boulders are widely scattered within the fine matrix. It is poorly consolidated and is highly friable with poorly developed sedimentary structures. This unit might have been deposited in a fluvial system developed as an outwash fan infront of a deeply melting ice in the glacial period and is not a tillite, because:

a) there are only rare angular fragments and

b) the boulders are very scattered, a high proportion of these found only on the top part of the section.

3.6.4. Brown Sandstone

This unit overlies the Palaeozoic Edagga Arbi glacial and is about 100m thick. It is best exposed along a fault scarp in the southernmost part of the study area. It generally dips to the SW which is tilted by the major fault of the "Wukro Fault Belt" of Beyth (1971), fig.3.21.

In the study area, the unit has yellow, red to brown colour. It is fine to medium grained sandstones with fine laminae. The sandstone contains ferruginous silt and in most places the sandstone is laterized. It is often cut by normal faults, which are antithetic to the major "Wukro Fault Belt" (fig. 4.2).

The colour, texture, and stratigraphic position of this sandstone correlates it with the Adigrat sandstone defined by Dow *et.al* (1971), Beyth (1971), with an age of Triassic (?) to Upper Jurassic.

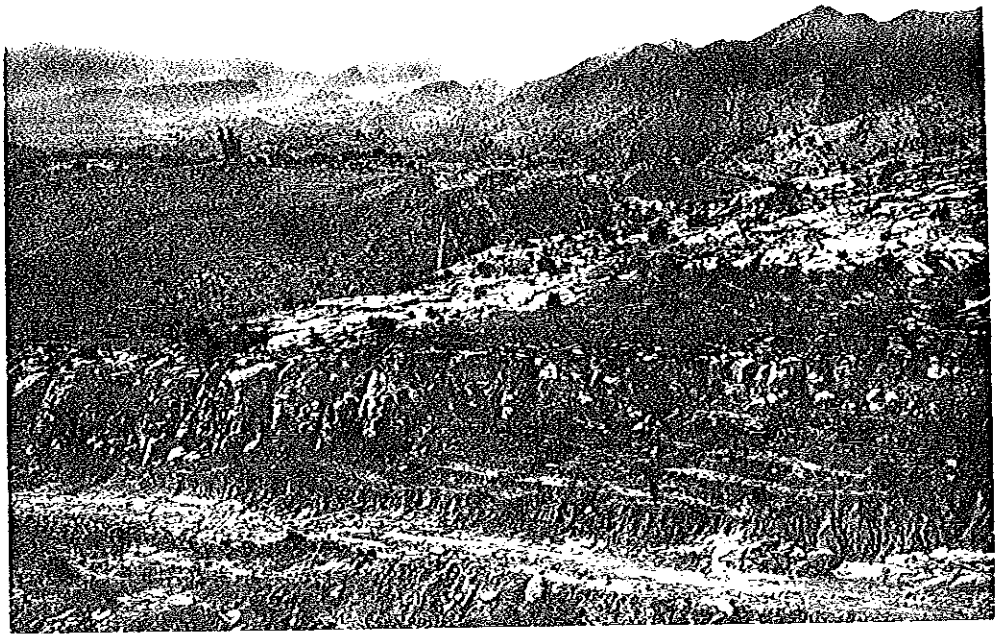


Fig. 3.21. Panoramic view showing the horizontal Mesozoic sequence overlying the Precambrian rocks

3.7. Doleritic Dyke

This dyke is observed intruding the metasedimentary rocks of the study area. It has an orientation parallel to the regional foliation. It is black holocrystalline rock with crystals of oligoclase, pyroxene, olivine, and opaque minerals.

The oligoclase occurs as a lath shape and is twinned, making upto 50% of the rock with euhedral crystals of 1mm. size.

Olivine makes upto 35% of the rock and occurs as fine euhedral grains. The pyroxene is hypersthene making around 10% and occurs as fine euhedral grains. The remaining proportion is constituted by iron oxide and apatite (fig.3.22).

This dolerite is affected by onion weathering. No trace of metamorphism effect is observed in the rock implying that it is a younger dyke which has intruded after the Precambrian deformation event. This dolerite closely resembles the Mekele dolerite described by Beyth (1971). The age of the Mekele dolerite is Tertiary probably comagmatic with the Trap volcanics (Beyth, 1971).

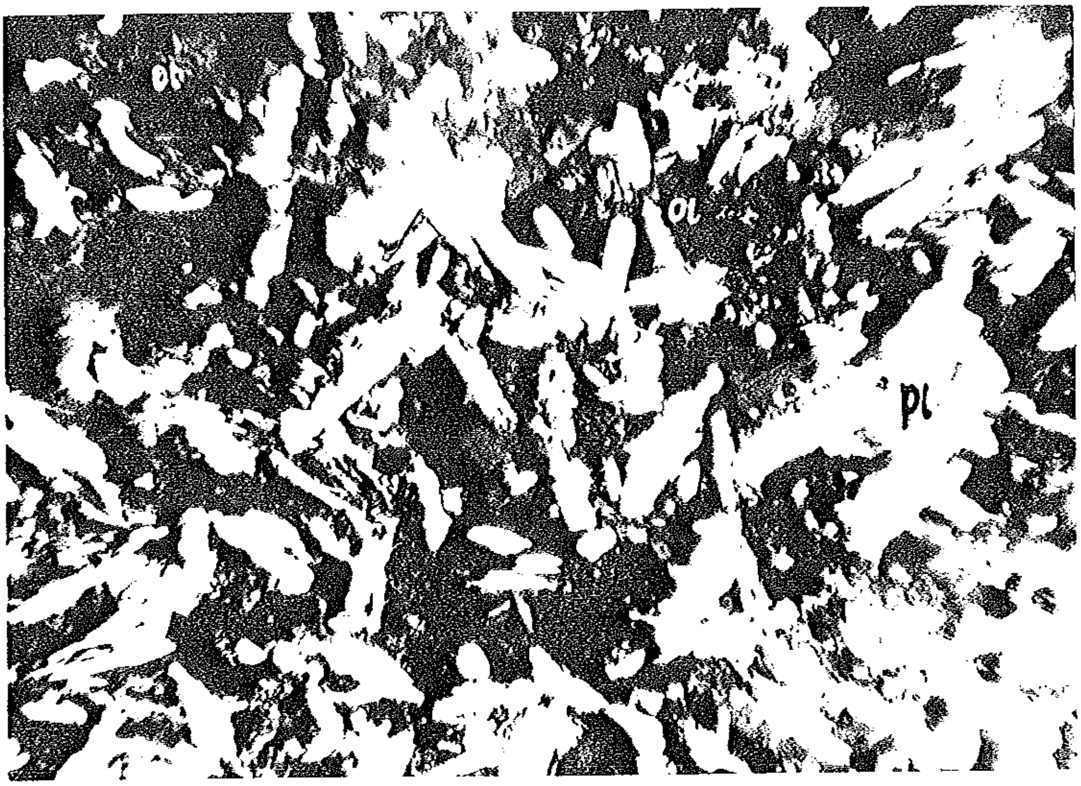


Fig.3.22:- photomicrograph (crossed polarizers) of an ophitic textured dolerite. The mineral grains are lath shaped plagioclase (pl), olivine (ol), and hypersthene (hy)

CHAPTER IV.

4. STRUCTURE AND TECTONICS

4.1. INTRODUCTION

4.1.1. PREVIOUS WORKS

Beyth (1971) mapped the Mekele sheet and indicated that the Precambrian rocks of the area were affected by folds of gently dipping symmetric and/or asymmetric major synclinorium and anticlinorium, all arranged in en echelon manner. According to this work, the major structures in the Mekele Sheet from west to east are:- the Maikental synclinorium, the Tsaee anticlinorium, the Tsedia synclinorium, the Chemit synclinorium, the Bereh anticlinorium, the recumbent anticline in the area around Hauzein, and the Negash synclinorium.

The "Negash synclinorium" is formed of two anticlines, one syncline, and a few smaller fold structures arranged in en echelon style with average plunge 15° NE in the north and 15°SW in the south oblique to the eastern fault line (Beyth, 1971), (fig. 4.1).

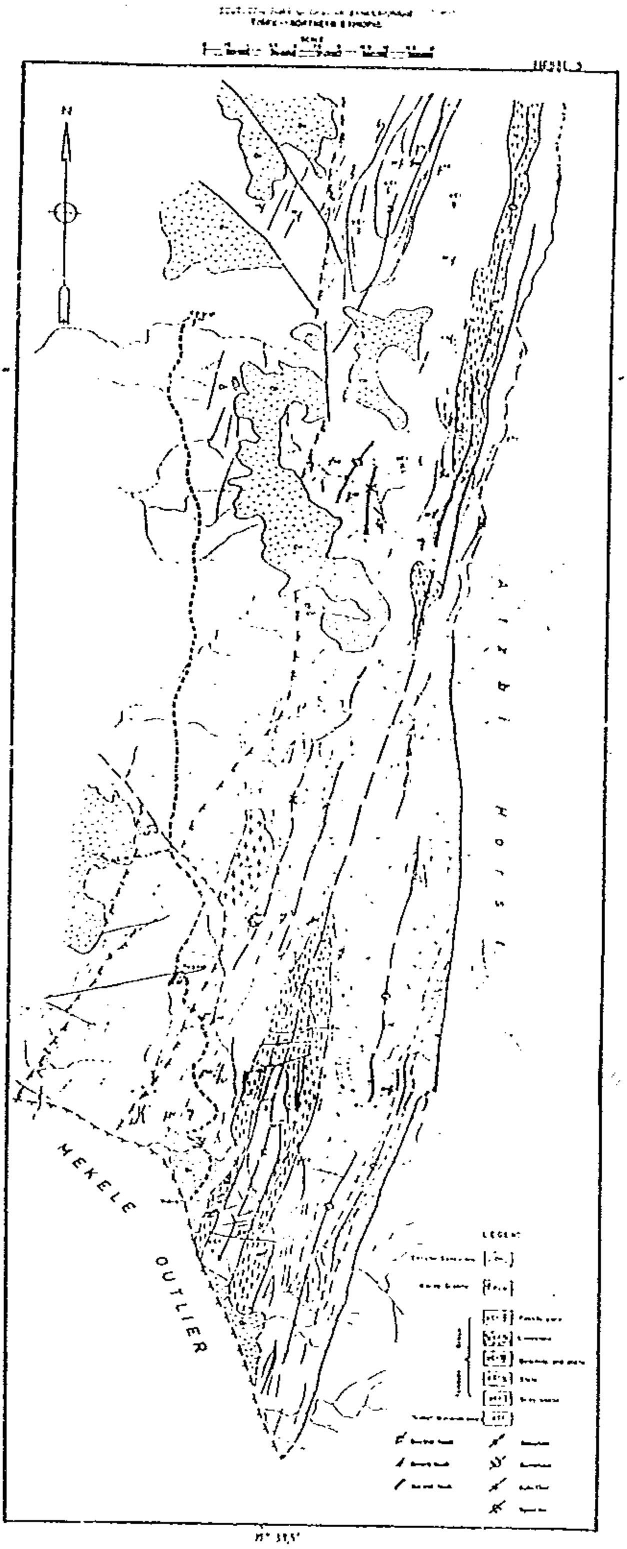


Fig.4.1 map showing the major structures found within the "The Negash synclinorium" (after Beyth, 1971)

The "Negash synclinorium" is bounded to the east and west by two en echelon faults running N-S which are normal and reverse type respectively (Beyth, 1971; Garland, 1980) (see fig. 4.1). These faults, with steep planes showing downthrows up to several hundreds of meters, are believed to be Precambrian in age and post-date the folding phases (Garland, 1980). According to Garland (1980), these faults are very clear in a satellite image and form a lineament extending for 70 to 80 kms.

Other younger faults observed by the worker are: ENE-WSW trending short dextral strike slip faults which offset the "limestone of the overturned syncline"; and ENE and WNW trending normal faults. These normal faults displace the Enticho Sandstone, the limestone and the Adigrat Sandstone of the Mekele outlier.

4.1.2 UNSOLVED PROBLEMS

What is presented so far is a short summary of the geology and structure of the region as described by the various researchers involved in the geological mapping program launched by EIGS.

Although there are differences in the use of terminology and nomenclature, all previous workers basically identified the same lithologic units in and around the study area. The rock units recognized by the workers from "oldest" to "youngest" are : "Tsaliet group

"; "Tembien group"; "Didikama formation":- slate, slate-dolomite, dolomite-slate; "Matheos formation" and Pebbly slate.

In the study area one can clearly observe the following:

1. an irregular N-S trending alternation of ridges and flats. The ridges are dominantly constituted by marble, quartzite and slates. Whereas the flats are constituted exclusively by slates.(fig.4.2)

   These ridges outcrop as lenticular features which cannot be attributed to original sedimentary facies changes, because:

   a. very thick (approximately 50m.) lenses end abruptly along the regional foliation trend.
   b. the ridge flat combination retaining a uniform thickness, the number of ridges counted across the regional foliation trend in a different intervals is quite different.
   c. rock units found on one limb of the synform are missing on the other limb of the synform.

2. Very common isolated tight folds (i.e.rootless intrafolial folds), with an axial plane parallel to the main foliation, are observed within all lithologies in the study area.

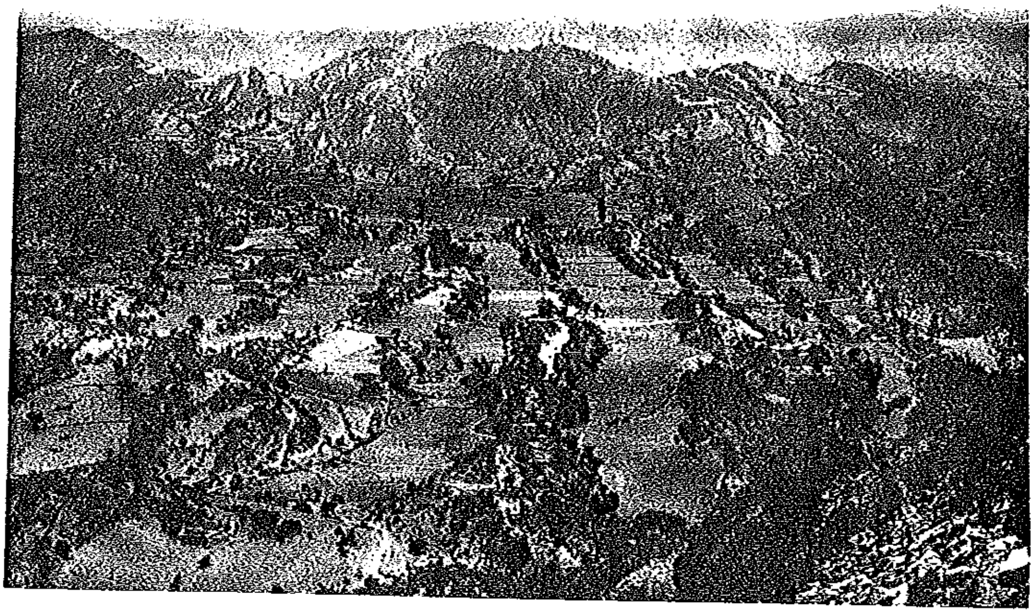


Fig.4.2 Panoramic view of the N-S trending Precambrian synform with an alternation of ridges and flats

For previous workers the structure was simple, the area was considered to have occupied limbs of an anticline and syncline only. They did not recognize the rootless intrafolial folds. Where they recognized a few folds, they interpreted them as micro or *"drag"* folds related to the major structure and the layering was interpreted directly as bedding. Repetition of the ridges and flats was interpreted as a product of sedimentary facies variation.

However, the observations reported on the above two points suggested that the rocks are involved in a number of fold generations. So, detailed structural studies for the area is vital and it was decided to undertake a research work in this particular area.

4.2. STRUCTURAL ANALYSIS

4.2.1. METHODOLOGY

In areas of poly-deformed terrains superimposed ductile deformation are often accompanied by metamorphism. The coupling of metamorphism and multi-phase deformation can produce distinctive rock fabrics, fold geometries, fold interference patterns, overprinting relations and fold styles which are powerful tools for unravelling complex geological problems (Ramsay, 1967; Hobbs *et al*, 1976; Marshak and Mitra, 1988).

In this study the geometrical pattern of the different terms of the lithostratigraphic sequences has been precisely defined through a detailed structural mapping at the 1:12,500
scale.

A relative chronology of the different folding generations has been reconstructed on the basis of the direct superimposition between planar and linear geometric characteristics of tectonic origin (mesoscopic fabric) and of regional significance. The interference between folds and foliations associated have been the guide-lines for the individuation of structures at different scales and for understanding of their present geographic orientation.

When the sedimentary origin of lithological surfaces is evident due to conservation of sedimentary structures, they should be considered as real original sedimentary surfaces (S_0) only very near the locality where such structure have been found. When such evidences do not exist, thick lithological layering can not be always generally considered as sedimentary surfaces. In fact, the thickness of the layering could be obtained through a differentiation during the deformational processes. This is testified by the presence of intrafolial folds which indicate transposition phenomena.

Based on the above geological facts, in the study area overprinting relationships have largely been used in conjunction with orientation and style of minor structures to group the folds into generations.

4.2.2. STRUCTURAL DETAILS

From structural studies point of view, the studied area is characterized by mega structures formed by antiforms and synforms (Fig.4.1).

Using the classical methodology for geometrical analysis of poly-deformed terrains described above, three(3) generations of foldings (D_1, D_2, D_3) were recognized at all scales, and are described below.

4.2.2.1. The D_1 deformation

The D_1 phase of deformation is recognizable mainly at meso scale. It is characterized by transposition of the primary (bedding) structures (fig. 4.3). The phenomena intensively affected the marble, quartzite, slates, and metavolcanic units.

The D_1 mesoscopic fabric elements are schistogenetic isoclinal rootless intrafolial folds, with sharp or very sharp hinges; they are almost always intrafolial. Their size ranges from centimetres upto decimeters. Asymmetries of B_1 folds are more or less equally distributed, but do not allow to reconstruct the main structures to which they are related.

The distribution of the various lithologies in the study area shows that except the black marble and other units found in the core of large D_2 fold, which outcrop in both sides of the limbs, the remaining units do not show a symmetric distribution (i.e, rock units found on either sides of the fold are different except the sporadic occurrences of some similar lithologies, fig.3.1). Therefore, the transposition phenomena at all scales is well represented in areas where slate, quartzite, and white fine marble units are exposed. The phenomena resulted in thin layering of most competent rocks namely, quartzite and white fine marble randomly distributed within the incompetent slate. In these layers, some sedimentary structures, such as graded bedding, lamination, slumping and convolute lamination, are preserved though not persistently seen throughout the units (fig. 4.4 a and b).

Within the black marble unit, the transposition is not well represented and the outcrop of this is continuous and intact in both sides of the limb of major D_2 fold (i.e the central synform). Where slate is found intercalated with the black marble and impure marble, isoclinal folds are observed (fig. 4.5 a and b).

Foliation associated with the D_1 (S_1) on a meso scale is represented by slaty cleavage and has been folded by the D_2 generation (fig. 4.6 a and b). S_1 has a more or less similar amount of dip and orientation at all places except near the hinge zones of the folds of D_2 generation. At the hinge zones its amount of dip rapidly decreases to a minimum value and shown a change in dip direction. S_1 slaty cleavage is generally parallel with the actual lithological layering, and often give rise to a new lithological assemblage within the main lithoformations.

Microscopic examination of most pelitic and semi pelitic rocks exhibit a well developed slaty cleavage. In samples where the spaced S_2 fabric is developed (example.in metagreywacke) the S_1S_0 composite fabric is only preserved in the microlithons with typically rotated minerals and showing sigmoidal shapes (fig. 4.7).

Fig.4.3 Structural map of the Negash area, Wukro, showing all structural elements (Appended in pocket).

Fig.4.4 Pictures showing some sedimentary structures found within the competent layers forming ridges. a) shows graded bed at the base, which continues upward into plane lamination and convolute lamination b) small slumping in the coarse graded bed.

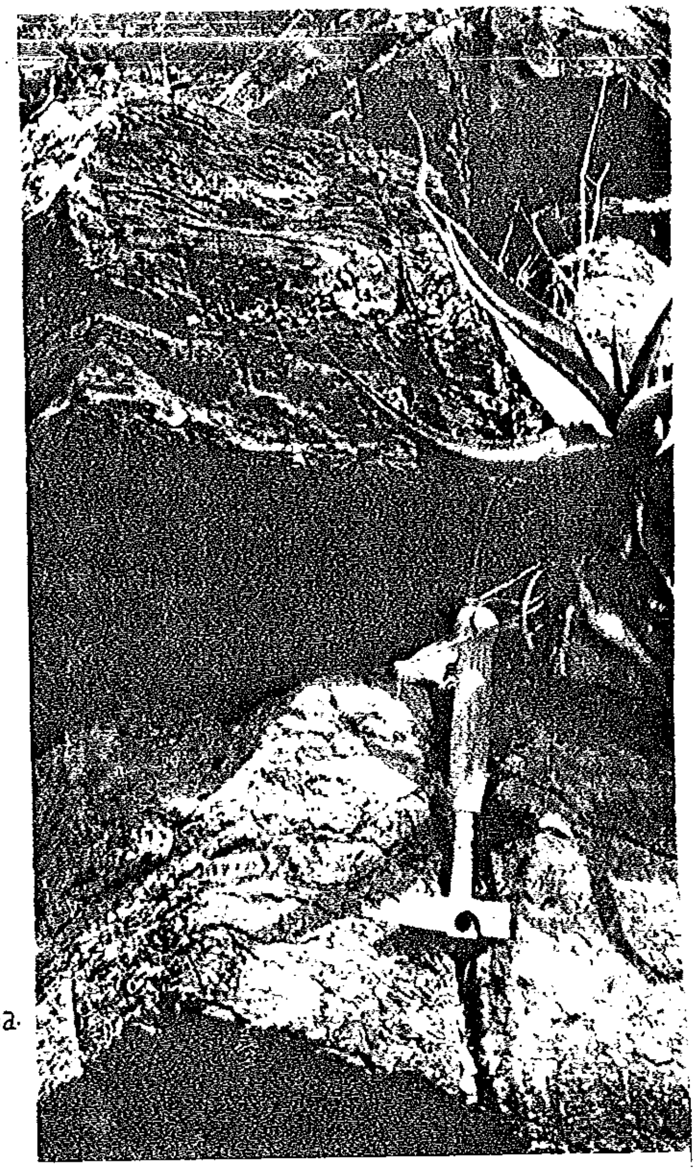
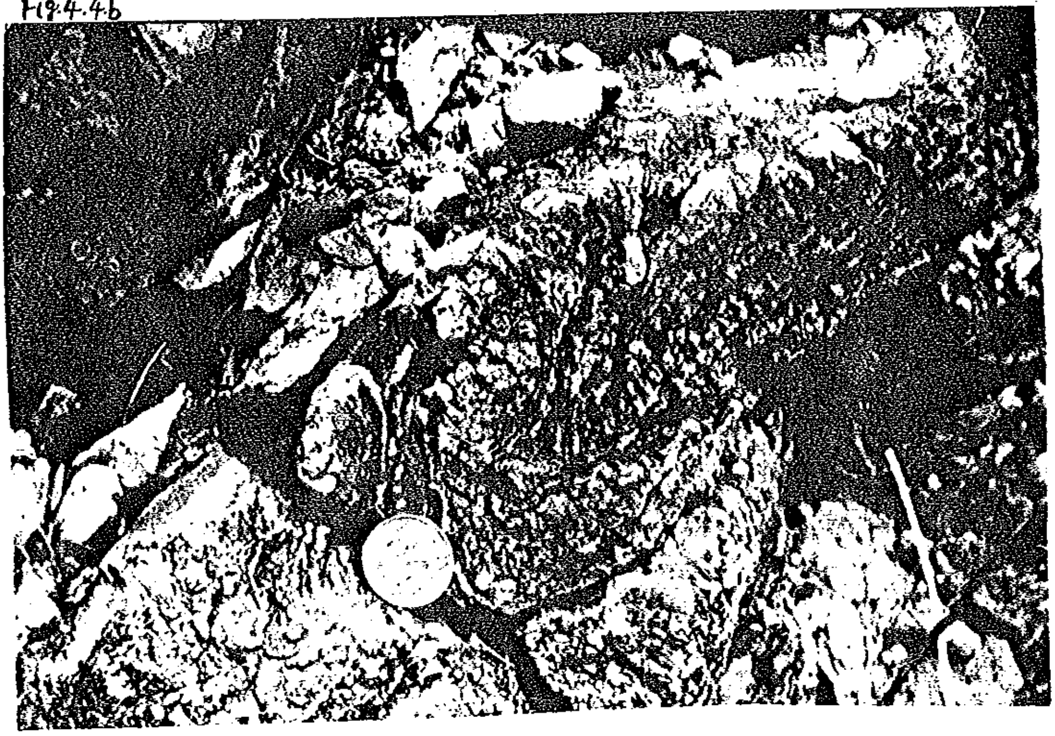


Fig.4.4a.

Fig.4.4b



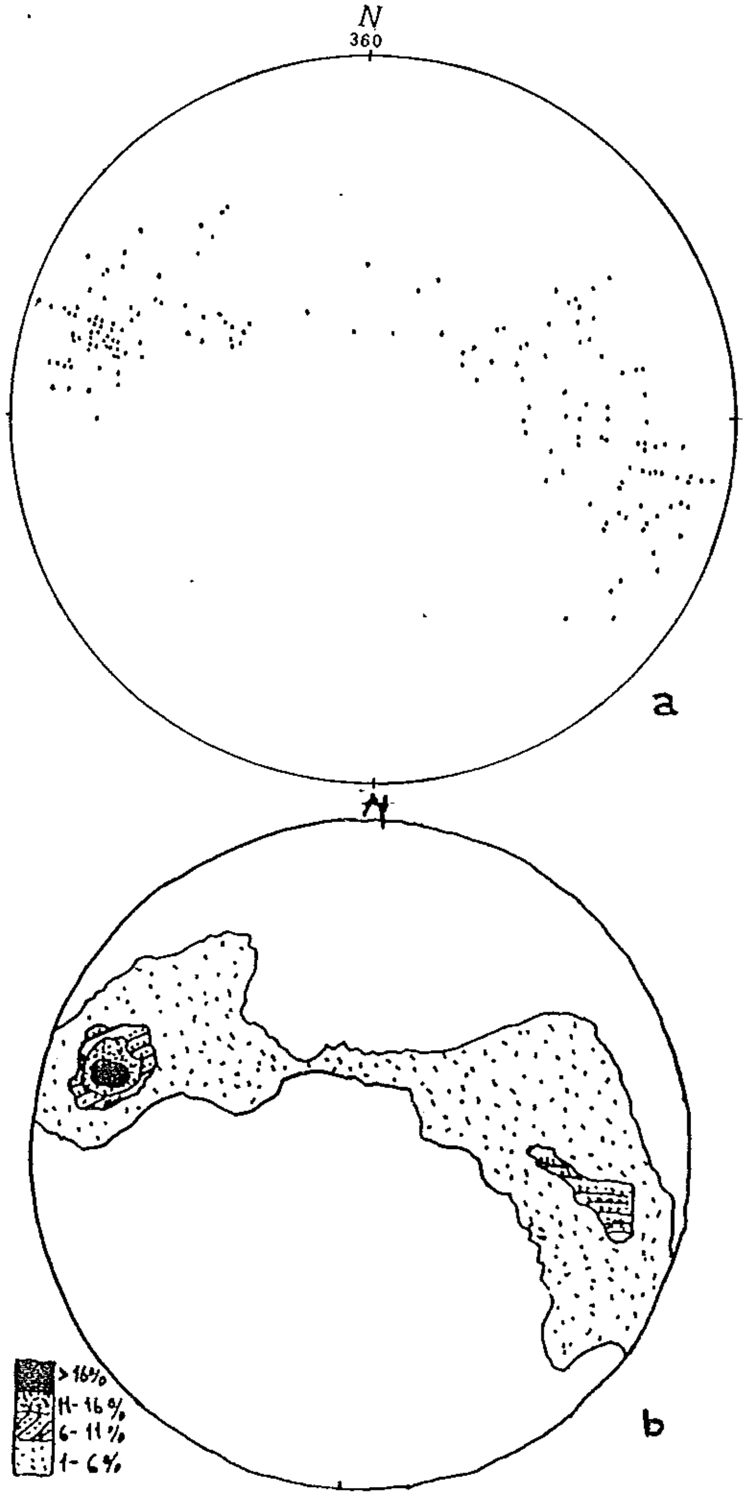


Fig.4.6a. Lower hemisphere equal area projection of 167 poles to S_1 foliation.b) Contoured version of the point diagram of the S_1 foliation, contours at 1, 6, 11, 16%.

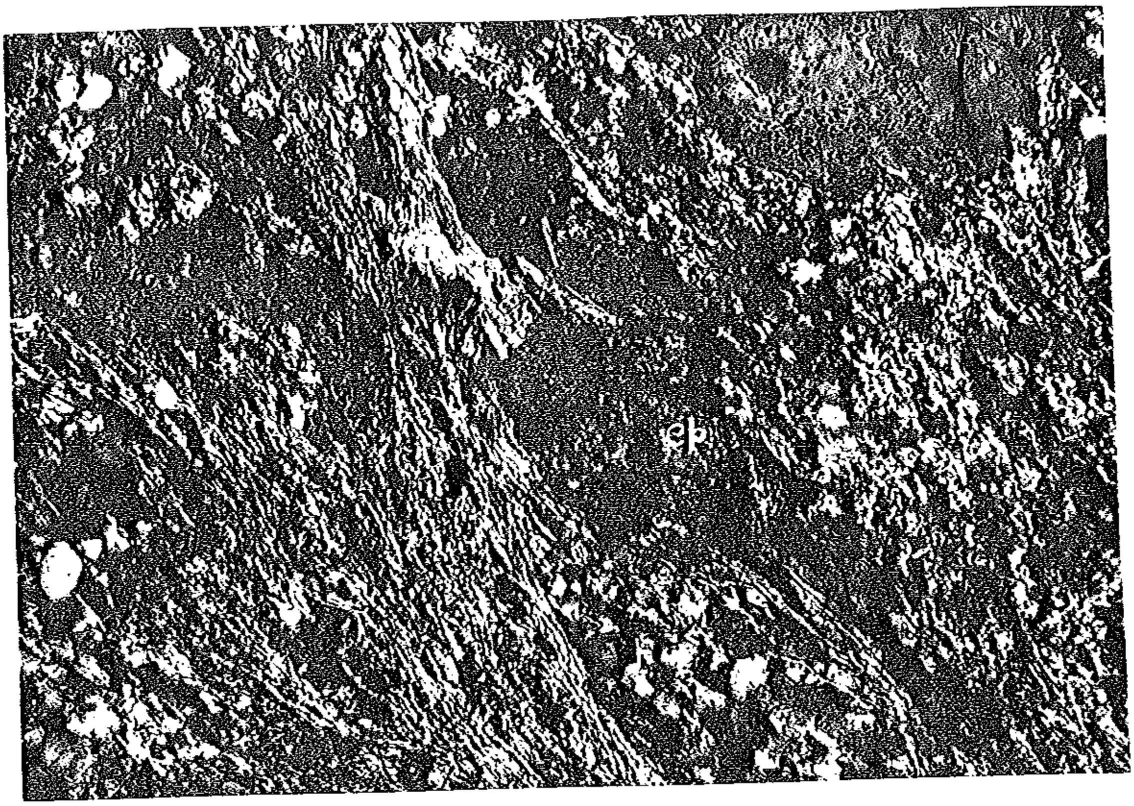


Fig.4.7.Within the main S_2 asymmetric zonal crenulation cleavage, microlithons of S_1 slaty cleavage, and asymmetric and rotated epidote (Ep) porphyroblast may be replacing feldspar with a sigmoidal shape.

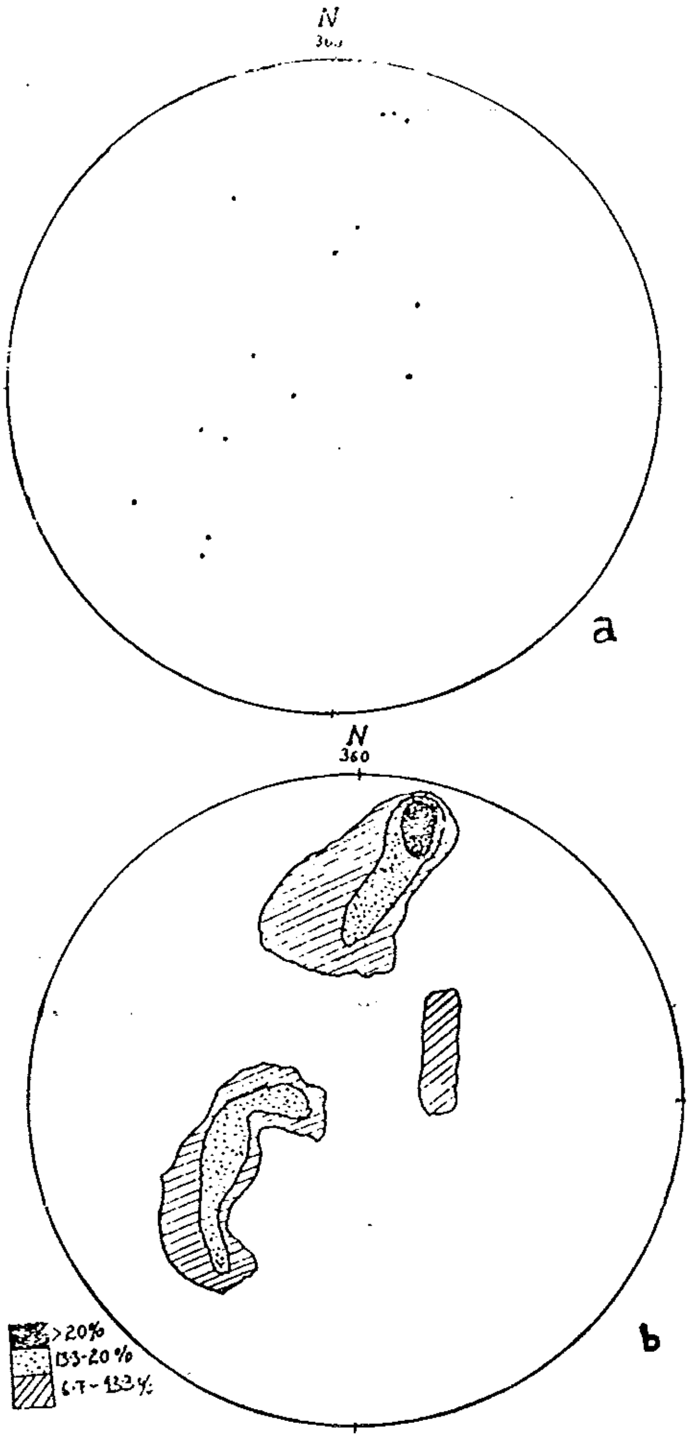


Fig.4.8a. Point diagram of 15 rootless intrafolial fold axes.b) contoured version of the point diagram above and showing two regions of concentration, contours at 6.7, 13.3, 20%.

For the above mentioned discrepancy in orientation and plunge of the rootless intrafolial D_1 folds two possible explanations are proposed:

i. The presently NNE-SSW and ENE oriented rootless intrafolial folds at once might have belonged to the same D_1 deformation and might have had the same E-W orientation. They might have attained this orientation due to the re-folding of the previous folds by the subsequent D_2 deformational event (fig. 4.9). If this assumption is correct then the plotted structural data should have described one continuous great circle on the schmidt net. In the plot, though points lie more or less in one great circle there is no continuity (fig.4.8); i.e there exists a gap between maxima. This intern might be attributed to the absence of sufficient data, as the rootless intrafolial folds are not well developed in the lithology of the terrane.

ii. The rootless intrafolial folding might also have been formed by two generations of folding D_{1a} and D_{1b}. Where D_{1b} represents the ENE oriented rootless intrafolial folds, and D_{1a} representing the NNE-SSW oriented rootless intrafolial folds. If this assumption is correct then the opposite in plunge of the D_{1a} rootless intrafolial folds could have been due to re-folding effect by the later D_{1b} deformation event. However, in the study area, the folds of both D_{1a} and D_{1b} generation have the same shape (they are seen parallelized in the same axial plannar cleavage) and in the present situation it is impossible to distinguish, them using their style. Moreover, no overprinting confirming their relationship is found throughout the area.

Macro scale studies on aerial photographs seem to support the first explanation in that large scale foldings with clear closures having an earlier E-W axis perpendicular to the B_1 have been mapped in most of the area (fig.4.3). The abrupt termination of thick ridges in the area also suggests an earlier transposition phenomena perpendicular to D_1 generation.

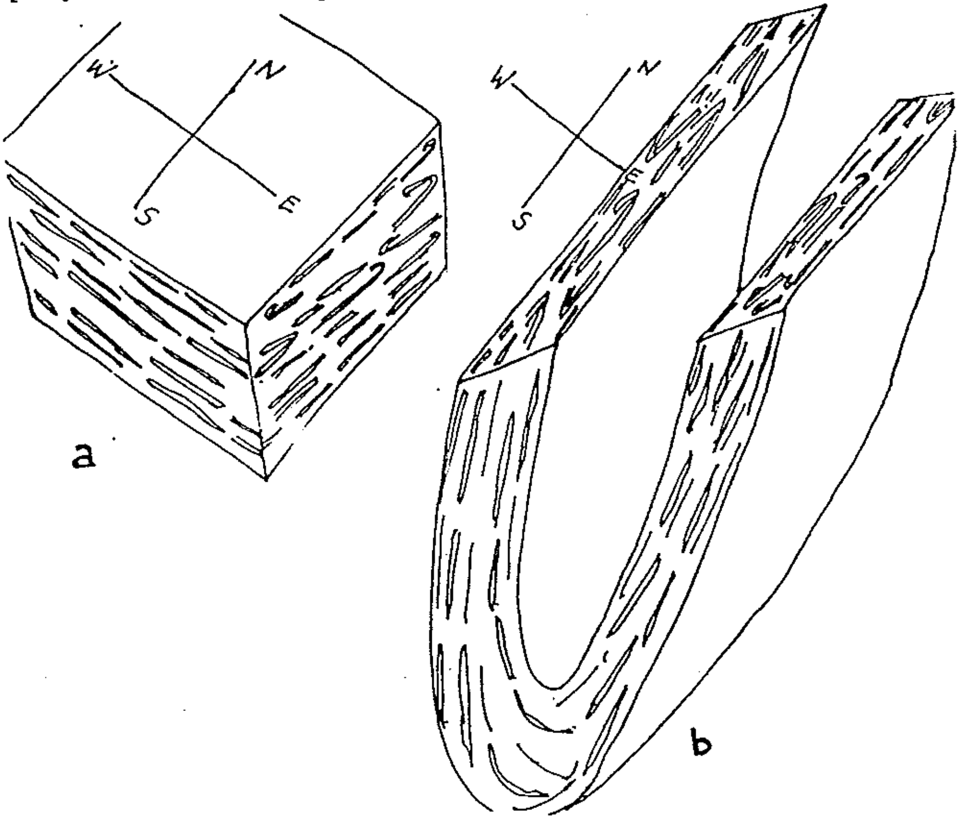


Fig.4.9. Sketch showing a) the previous east-west trending rootless intrafolial folds. b) re-oriented rootless intrafolial folds by the subsequent deformational event.

4.2.2.2. The D_2 deformation

Evidences of the D_2 deformation occurs in mega, meso, and micro scales. D_2 is characterized by large tight to isoclinal folding with sub-horizontally SW plunging axes with an approximately N-S orientation. This folding phase has folded the previous S_1 foliation and/or layering which in some case define the bedding S_0.

In the area the D_2 deformation produced two major synforms and two major antiforms namely from west to east:

- **North western synform**
- **Western antiform**
- **Central synform, and**
- **Eastern antiform.**

i. The North western synform

The north western synform is located in the north western side of the study area, just at the western boundary of the granite (Fig.4.3). It is a small synform showing a clear closure.

The axial trace is oriented N 15^0 E. In the south, its axis disappears at an oblique angle when it reaches the contact between the metasediments and the metavolcanics (fig.4.3).

Along its core a lens shaped metavolcanic rock is exposed, whereas at the limbs it is comprised by intercalation of slate, white fine marble and quartzite.

Meso structural evidence related to this fold are rare. In one place (at the southern end of the eastern flank) one minor "Z" fold is observed indicating that the fold closing southwards. The minor fold plunges 10°-->170°. In general the fold axial plane is undulating which may be attributed to the superimposed third deformation. The composite S_0S_1 fabric is folded around this synform. Plots of poles to these composite fabric reveals that the synform has mean fold axis orientation of 17-->194° (fig.4.10).

The attitude of the fold axis and the position of the contoured pie circle girdle on the equal area net indicate the fold to be plunging overturned (Marshak et al, 1988; Ramsay et al, 1987).

ii. The western antiform

This antiform occupies the west-central part of the study area. The axis of this antiform is identified on the basis of: (1)- Opposite dip direction of the pre-existing plannar fabrics (i.e S_0S_1 composite layering) (2)- Minor fold closures observed along the main road cut near St. Marry church. In this location a sub horizontally (10°-15°)-->210° plunging intersection lineations are common

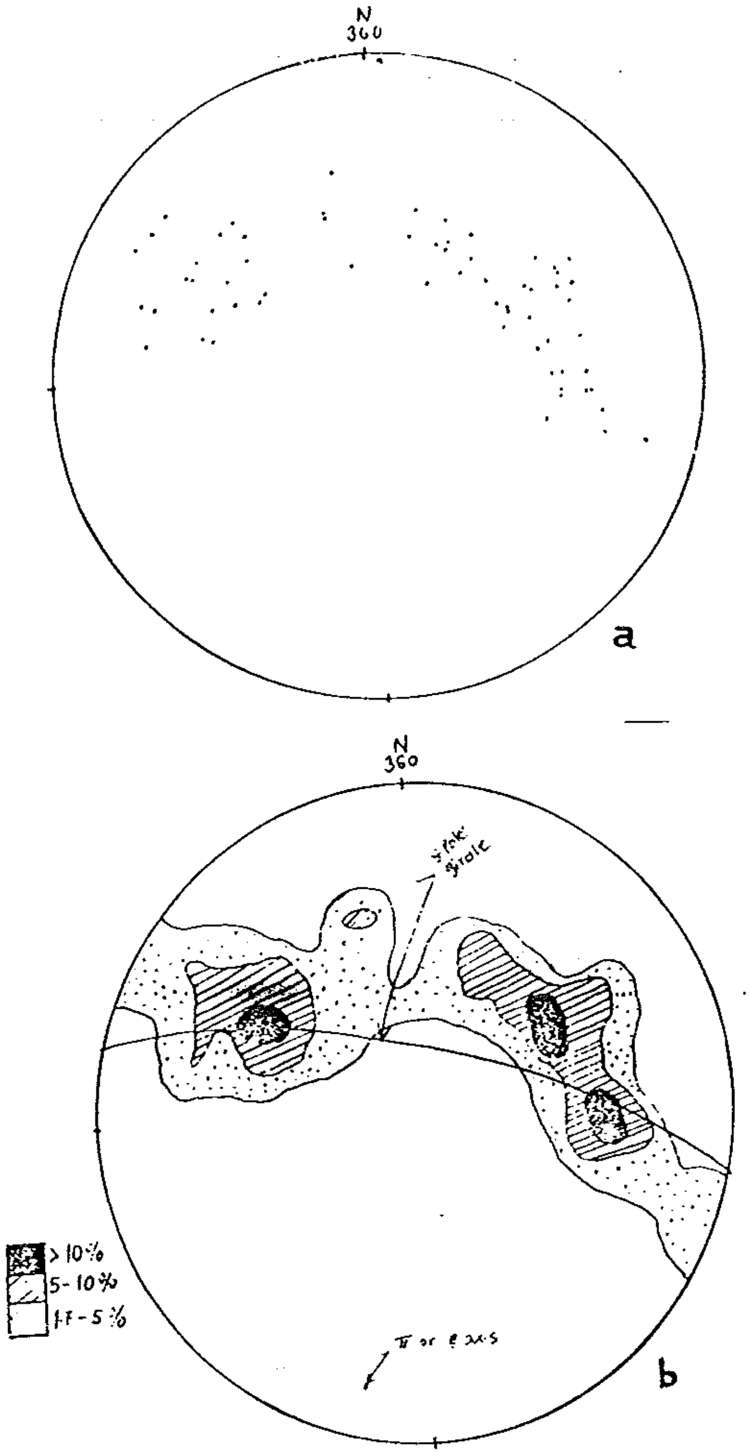


Fig.4.10 a. Point diagram of poles to the composite S_0S_1 fabric around the north western synform. b) Contoured version of the poles to the composite fabric, contours at 1.7, 5, 10%.

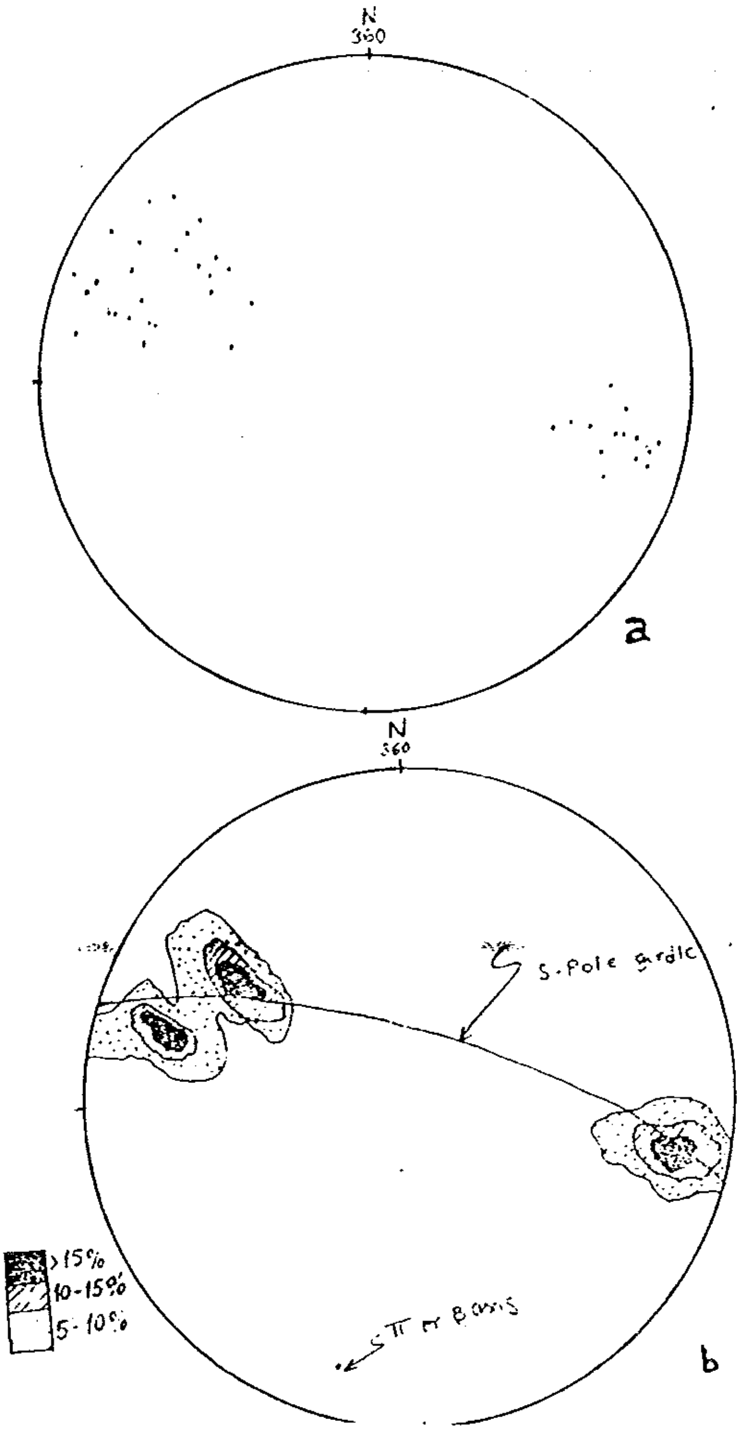


Fig.4.11 a. Point diagram of poles to the composite S_0S_1 fabric around the western antiform. b) Contoured version of the poles to the composite fabric, contours at 5, 10, 15%.

iii. The central synform

The central synform is situated in the central part of the study area and is the largest of all the mapped folds. It can be seen from aerial photographs with its distinct "bowl" shaped basin at its centre formed of pebbly slate. It has originally been referred to as "Negash syncline" (Beyth, 1971). The axial trace of this fold can be traced from the Northern limit of the mapped area to the south where it disappears beneath the Palaeozoic cover sediments after been faulted out by the "Wukro Fault Belt" (fig.4.3).

clearly three mappable units (namely black fine marble, black marble and slate intercalation, and pebbly slate) are well observed closing around this fold. Other units (example white fine marble, slate, graphitic phyllite, and quartzite) which occupy the limbs of this fold do not show a clear repetitive pattern. This can be attributed to: (1)- The transposition phenomena of D_1 and (2)- The effect of the accompanying D_2 folds which might have complicated the already mispositioned lithostratigraphic units. Nevertheless, broad lithlogical repetition can be seen in much larger scale. As a result of such unique appearance of this fold in aerial photos and at all other scales, much attention was given in the field to analyze the nature of this fold and associated meso and micro structures.

S_2 cleavage is invariably developed throughout the area but varies significantly in type from place to place and from lithology to lithology throughout the area.

For example, the S_2 fabric varies from fracture cleavage (in quartzite), differentiated crenulation cleavage in metagreywacke to typical slaty fabric in fine grained rocks such as slate, impure marble or graphitic phyllite. The fabric is commonly parallel to the composite metamorphic layering S_0S_1 along the limbs. When traversing to the hinge zone, the S_2 fabric is found at an angle with the composite layering S_0S_1 (fig.4.12, 4.13, 4.14, 4.15). This angular relationship becomes nearly perpendicular along the hinge, this is particularly clear on the black marble.

The S_2 fabric plotted on equal area net shows that it is uniformly dipping towards WNW with a mean attitude of 48°-->282° (fig.4.16).

Meso structures associated with this fold include some crenulation lineation and a well developed intersection lineation (fig. 4.17) exposed along the hinge zone. Measurement of the intersection lineation in the hinge zone was plotted on an equal area net. From the plot the mean orientation of the lineation is determined to be 27°-->192° (fig.4.18).

Measurement of the composite fabric (S_0S_1) folded around this major fold are shown on equal area net. This plot indicates that the mean attitude of the fold axis is 20°-->198° (fig.4.19) and is more or less consistent with the attitudes of the north western synform, and western antiform.

Microstructural studies show that the S_2 foliation is represented by slaty cleavage and crenulation cleavages. The slaty cleavage are developed largely on the limbs (fig.3.10, 3.13, 3.16). The crenulation cleavages are developed near the hinge zones of the central synform.

In the study area, the two morphologic crenulation cleavage types of Gray (1977) are observed. These are discrete and zonal crenulation cleavage. The discrete crenulation cleavage is defined by thin, dark and smooth but irregular linear traces (fig.4.20b, 4.20c). This cleavage truncates the original composite S_0S_1 fabric and enveloped the spatially associated microfolding of the pre-existing fabric (fig.4.21). The composition of the mineral constituent of the dark trains can not be determined with the help of optical microscope.

The zonal crenulation cleavage is defined by zones of microfolding of the original composite S_0S_1 fabric (fig.4.20a, 4.7). The pre-existing composite S_0S_1 fabric are continuous across the zonal crenulation cleavage, compared to the microlithons, are characterized by enrichment of micas relative to quartz (fig. 4.7).

The attitude of the fold axis and the position of the contoured pie circle girdle on the equal area net indicates the fold is plunging overturned (Marshak et al, 1988; Ramsay et al, 1987).

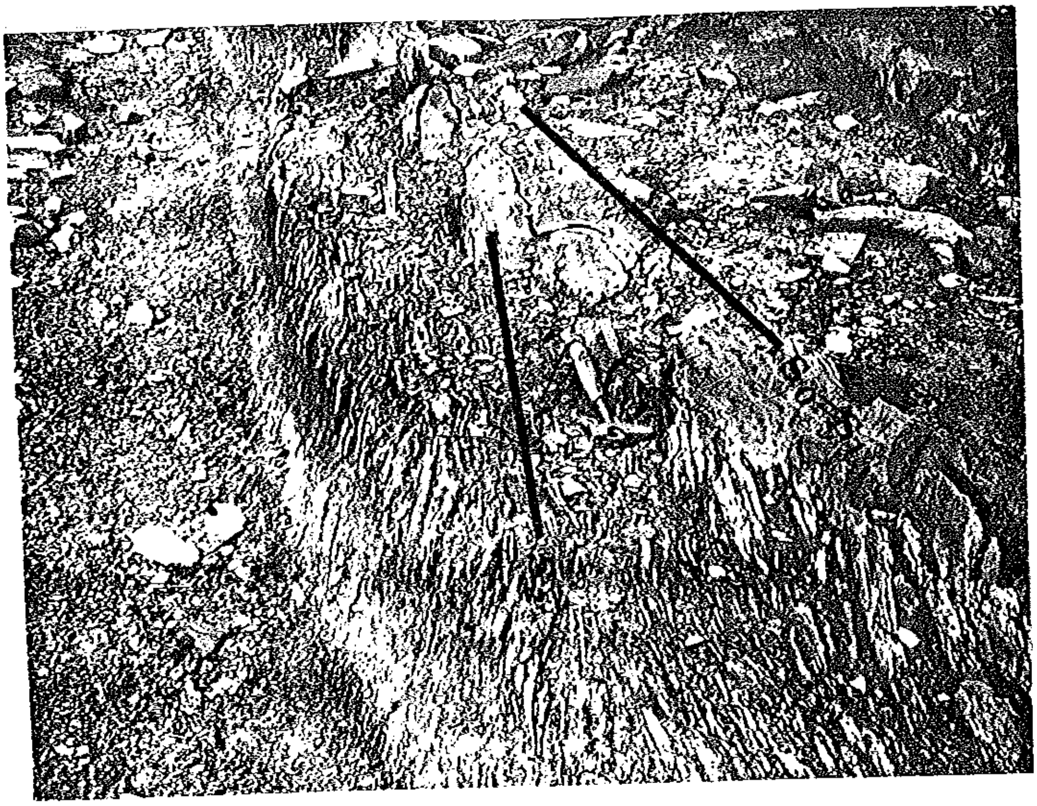


Fig.4.12 Picture showing S_2 cutting S_1 at an outcrop scale

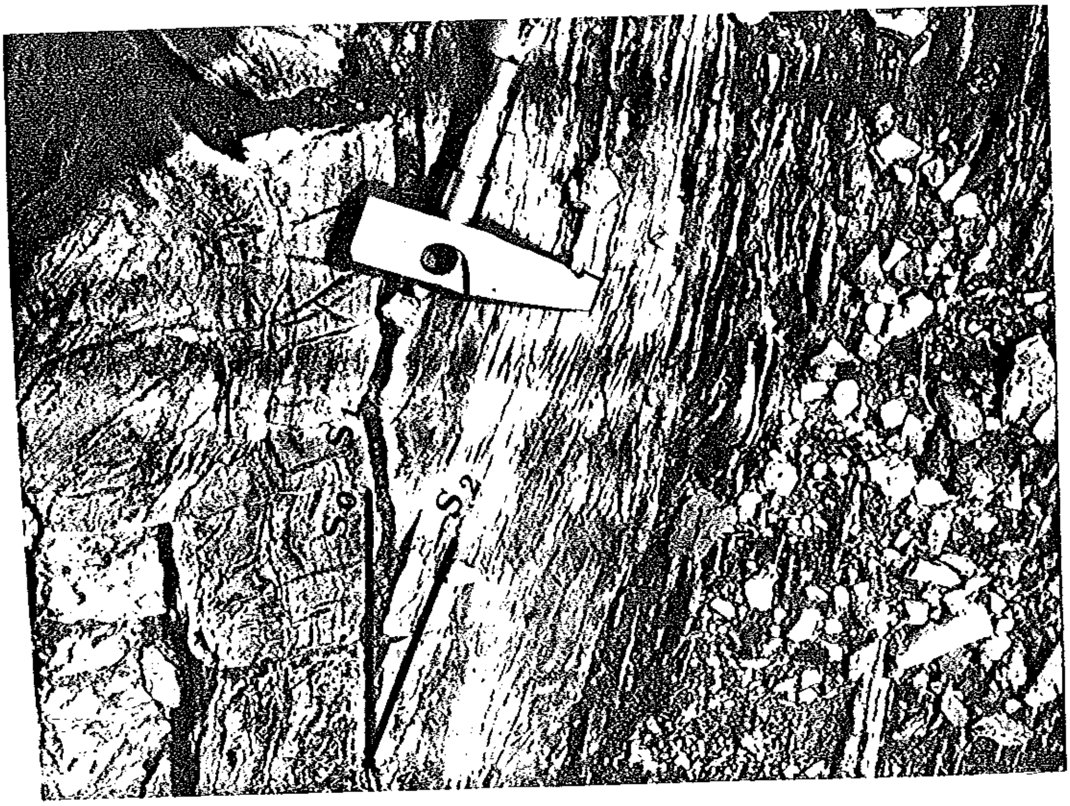


Fig.4.13 Picture showing angular relationship between S_2 and $S_1=S_0$

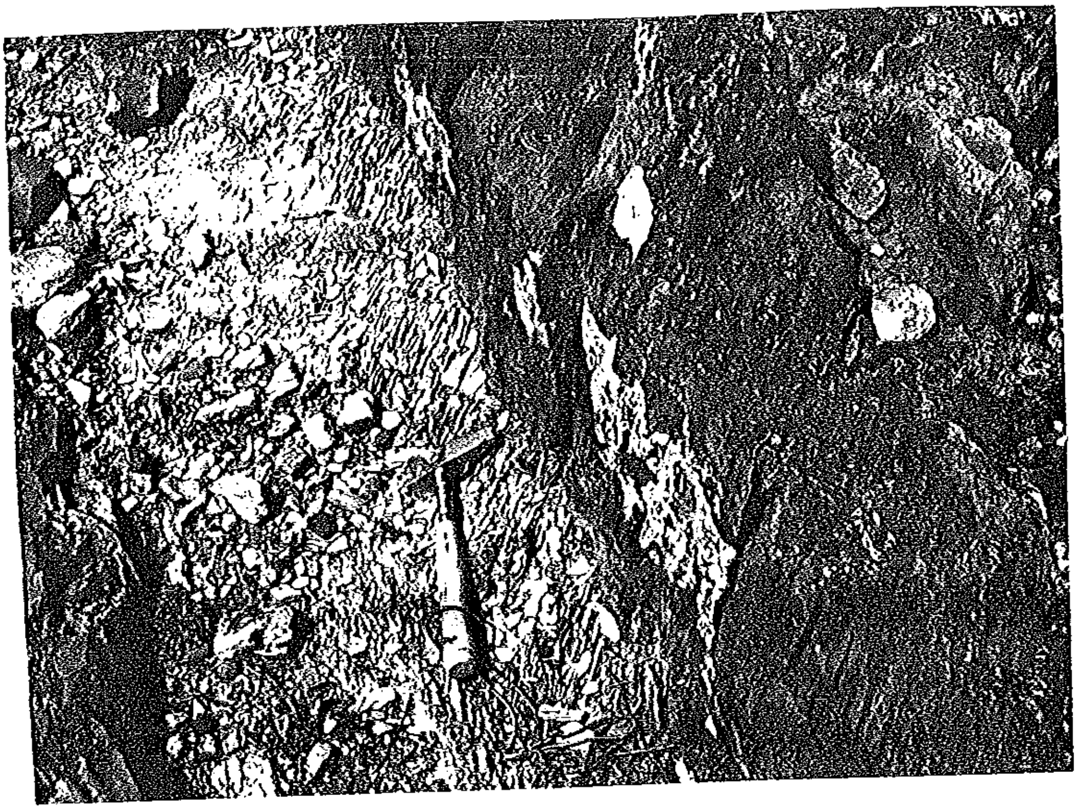


Fig.4.14 Picture showing spaced S_2 on S_1 in the fine marble unit

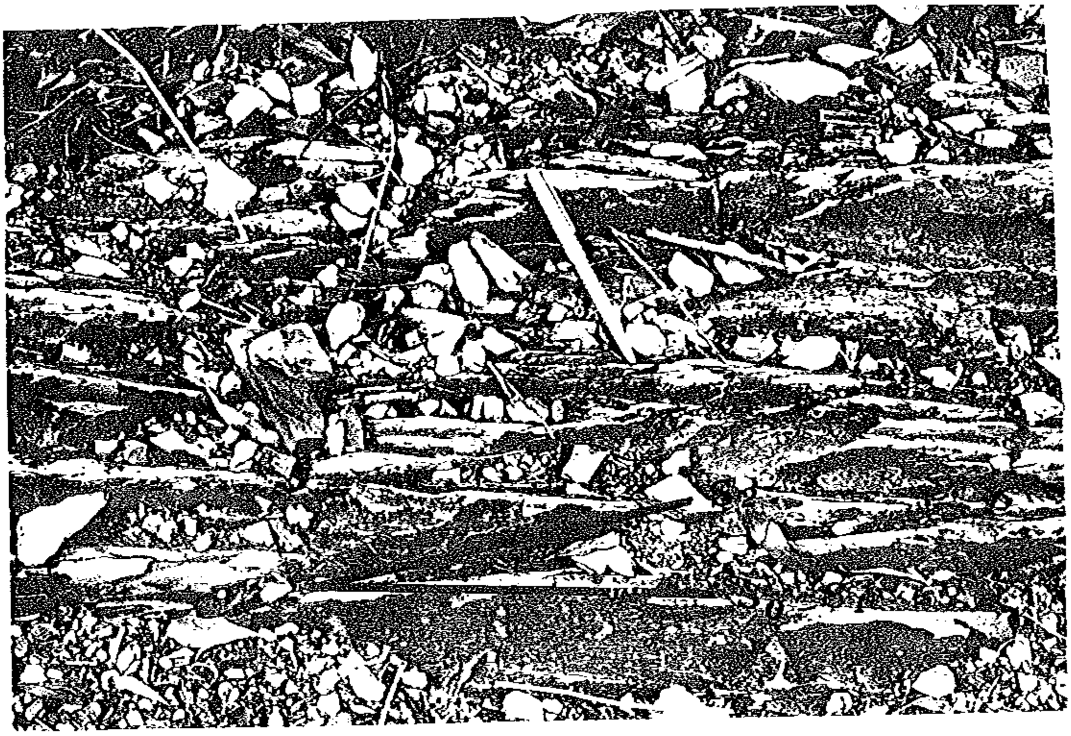


Fig.4.15 Picture showing S_2/S_1 intersection, in the slate unit very near to the Western antiform, produced intersection lineation.

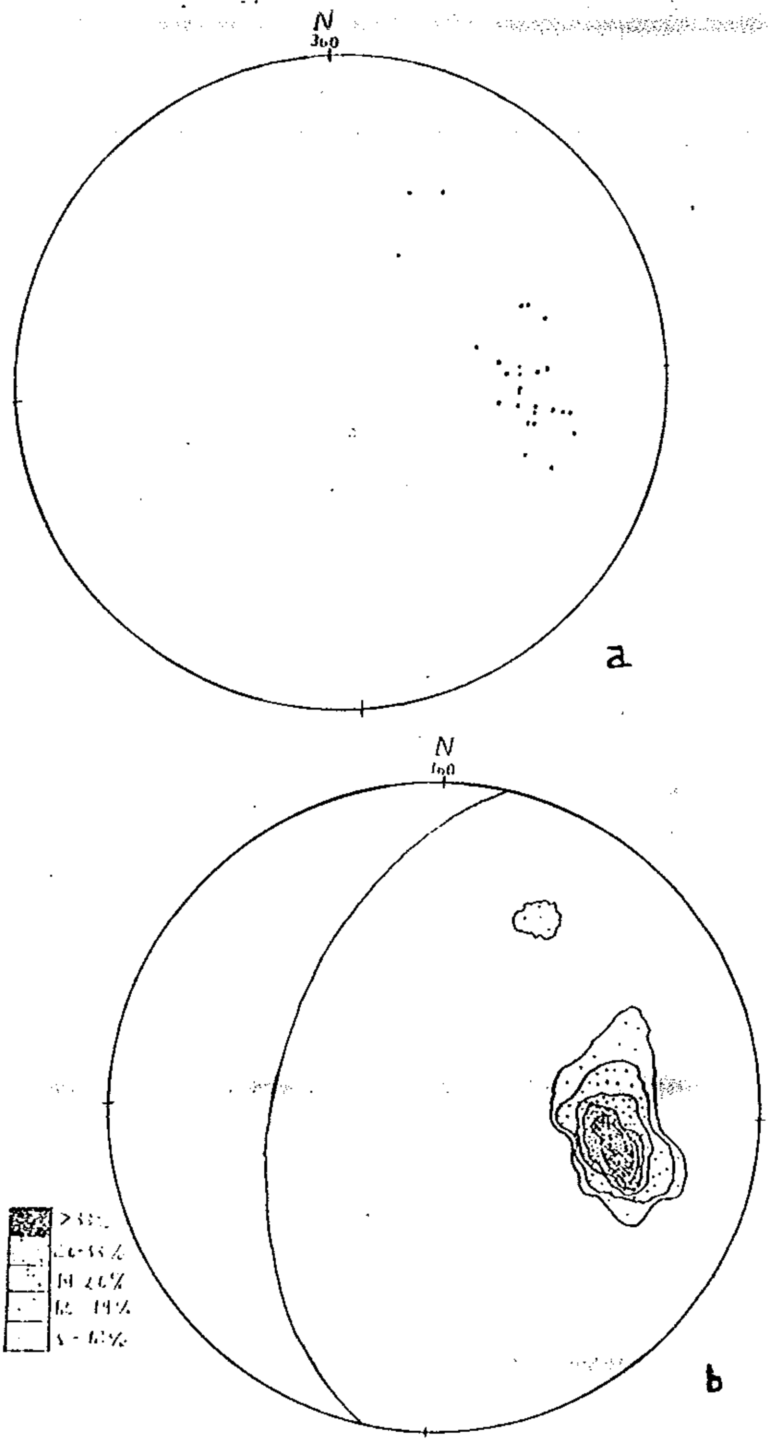


Fig.4.16a. Point diagram of 27 poles to S_2 foliation. b) Contoured version of the poles to S_2 foliation showing one region of point concentration, contours at 5, 12, 19, 26, 33%.

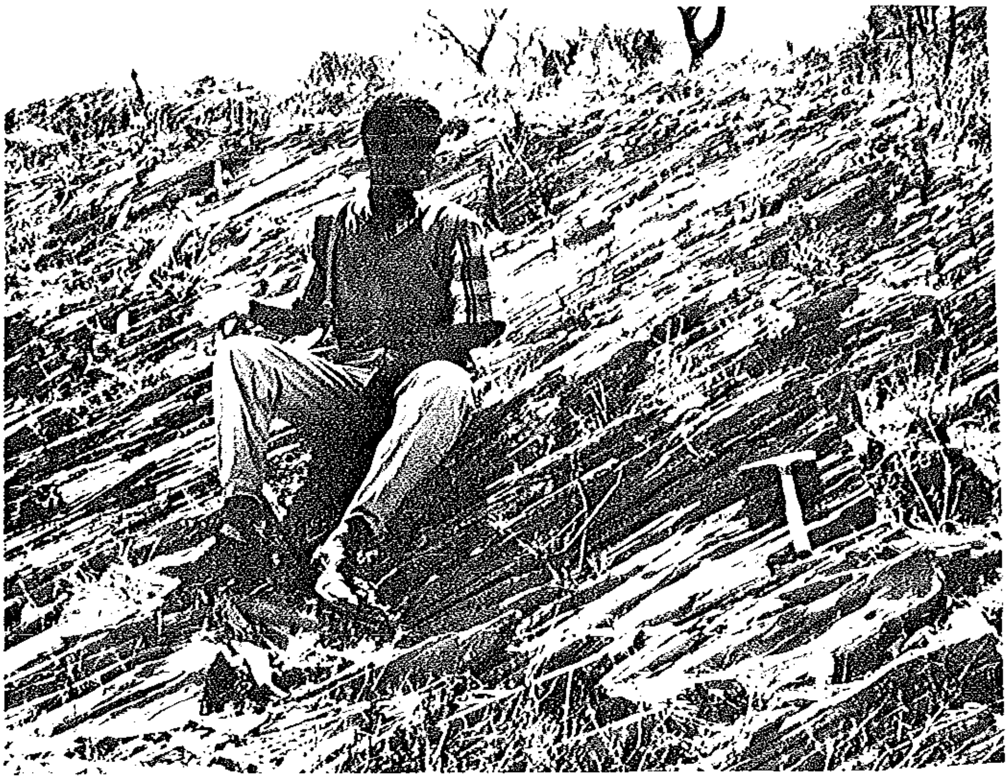


Fig.4.17 :- Photo showing intersection lineation found at the axis of the central synform

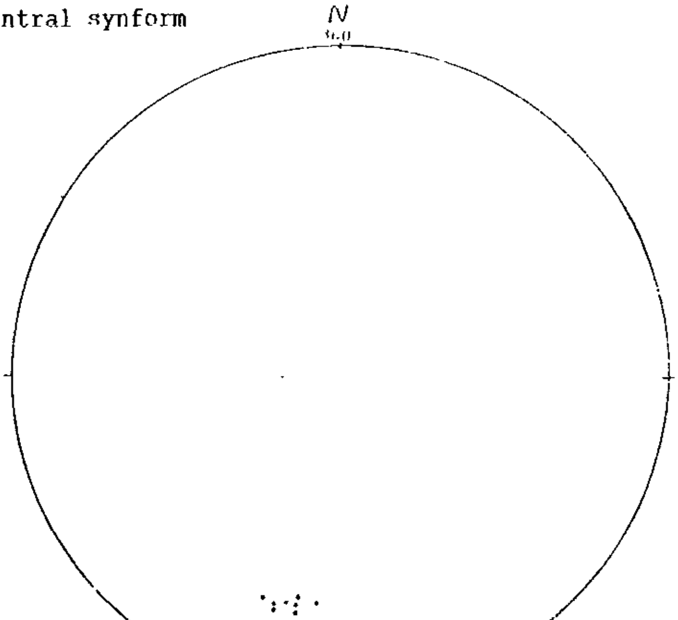


Fig.4.18. Point diagram of 8 intersection lineations on an equal area plot.

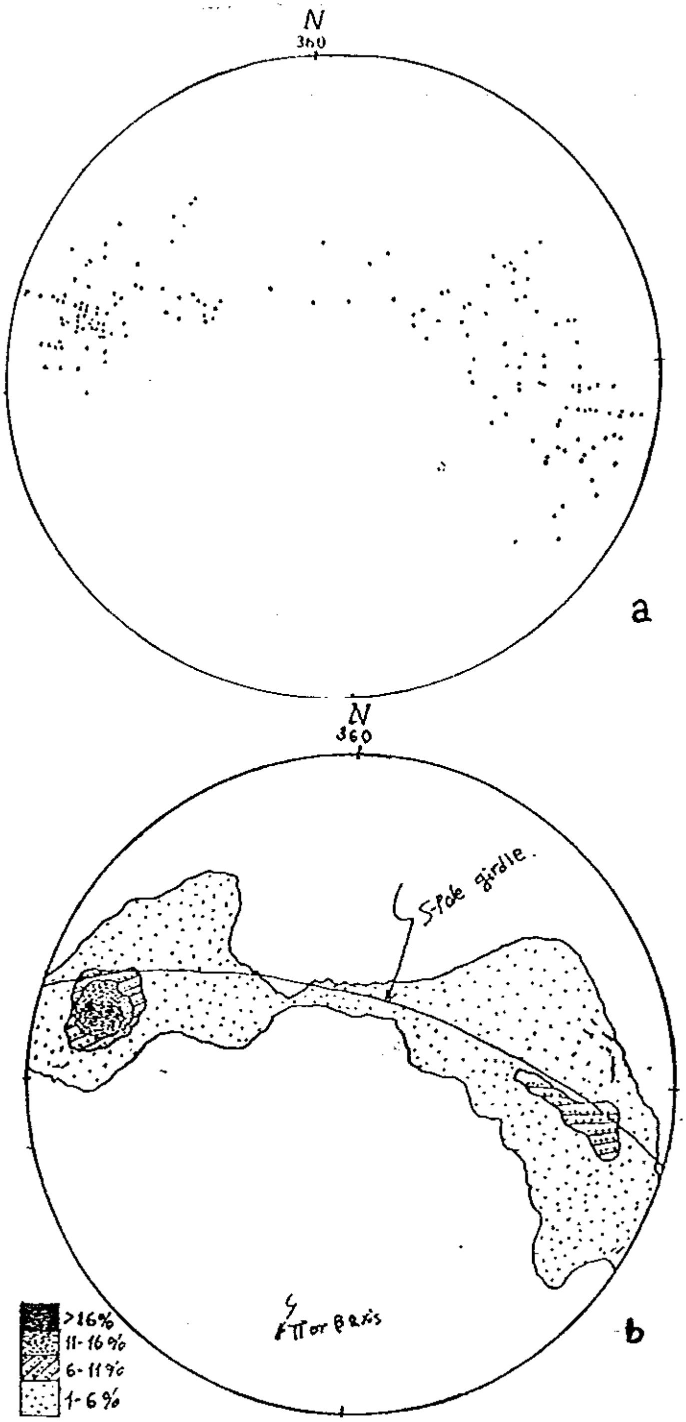


Fig.4.19 a. Point diagram of 167 poles to composite S_0S_1 fabric around the central synform. b) Countered version of the point diagram of above and showing orientation of the axial plane of the central synform, contours at 1, 6, 11, 16%.

Fig.4.20.Photomicrographs showing the relationship between microstructures. (Photo taken in crossed nicols; magnification 2.5 x 1.25 x 2)

a).The spaced S_2 zonal crenulation cleavage crenulated the composite S_0S_1 layering defined by white micas and quartz crystals. b). The S_2 discrete crenulation cleavage cutting the composite S_0S_1 fabric. The S_0S_1 fabric as a result of S_2 are microfolded. c). Discrete crenulation cleavage due to the spaced S_2 on S_1 slaty cleavage in the slate unit near the hinge zone.

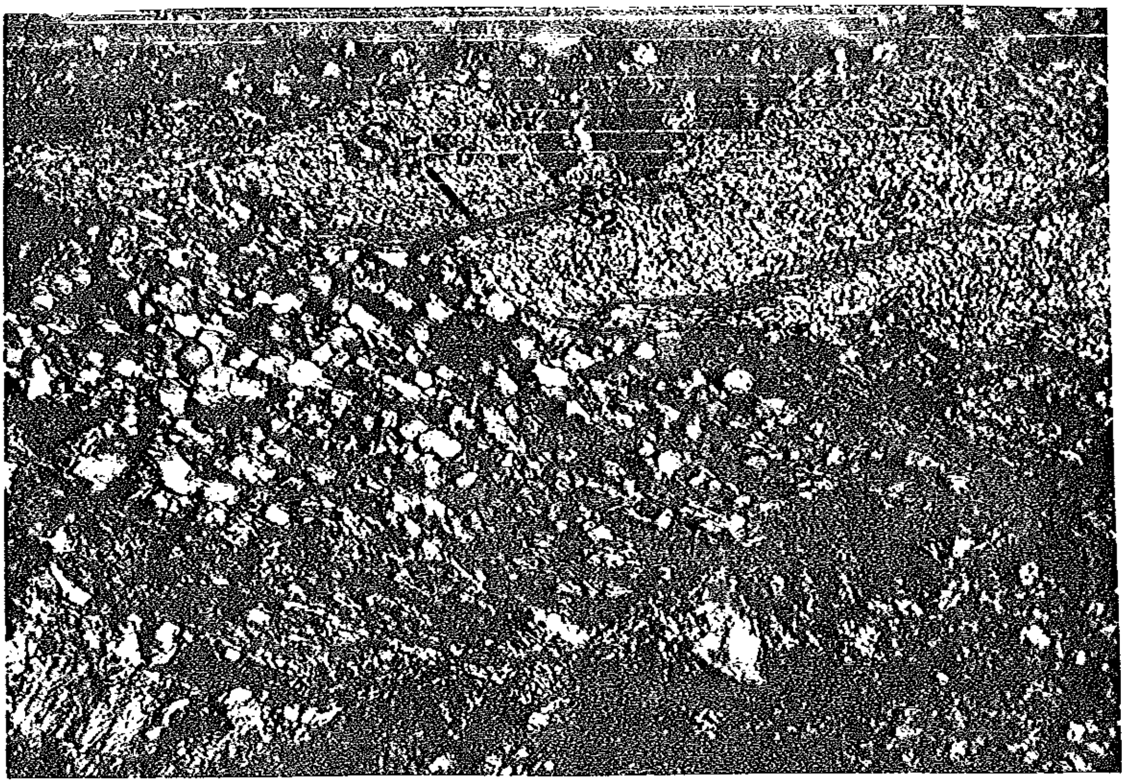


Fig. 4.20.a

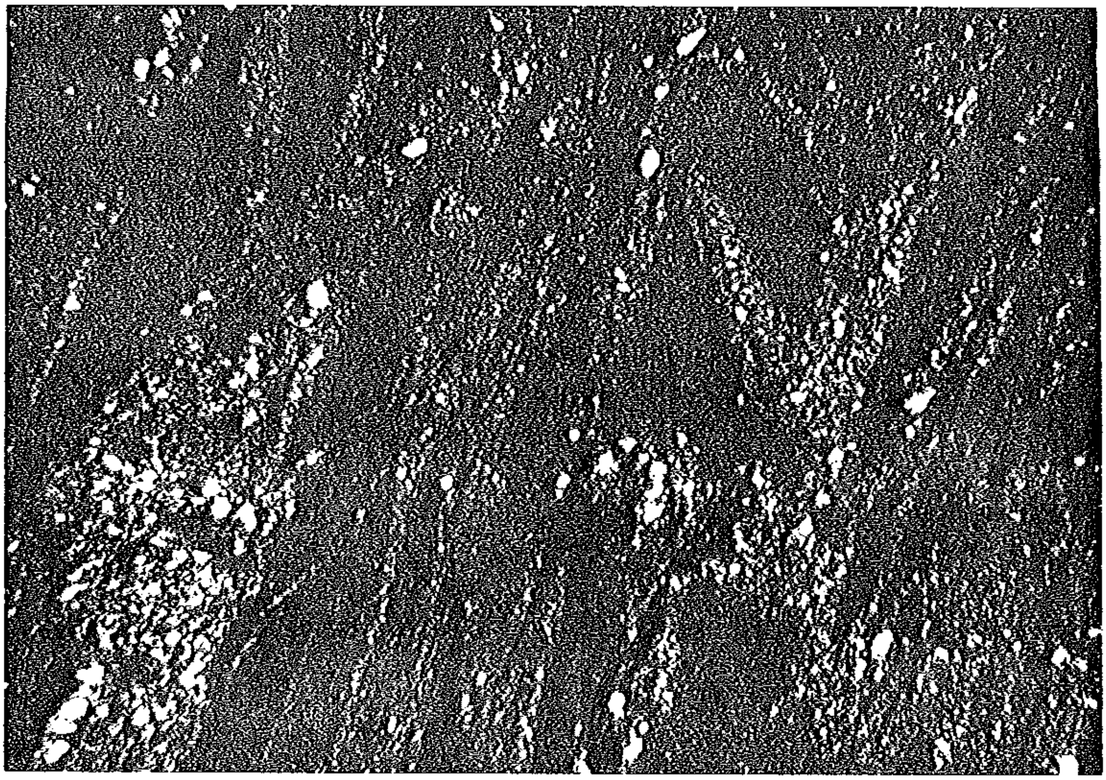


Fig. 4.20.b

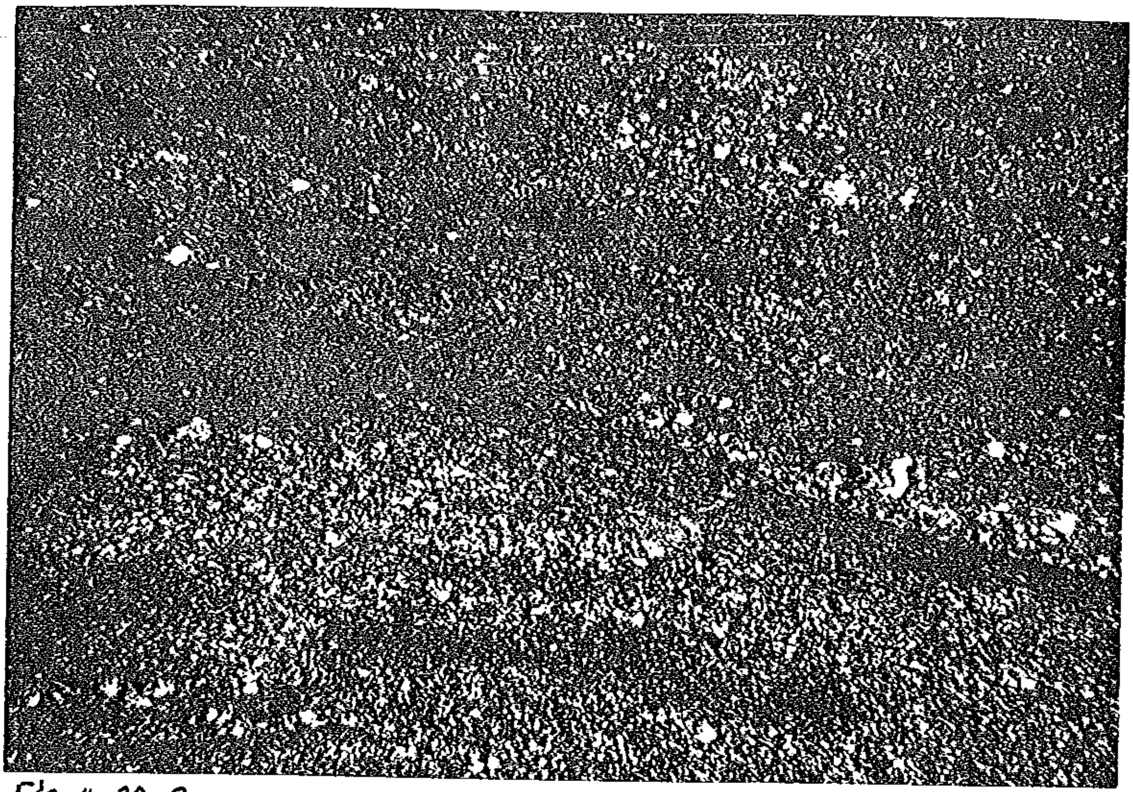


Fig. 4·20·C

iv. The eastern antiform

The eastern antiform is situated towards the eastern boundary of the study area. It is identified by its dome shaped morphology and repetition of some units (example white fine marble). No closure of this antiform is observed. The axis of this antiform disappears southwards before reaching the "Wukro Fault Belt"

Lithologic units such as metaconglomerate and white coarse marble are found only in this antiform. This antiform was originally been described as an "anticline" which is complementary to the "Negash syncline" (Beyth, 1971). Field work in the study area reveals that determination of younging direction is impossible because the older and younger rock units are found one upon the other in an irregular fashion. This may be due to transposition phenomena. Minor structure associated with this antiform are rare.

Measurements of the S_0S_1 composite fabric around this antiform plotted on the equal area net and revealed that the mean attitude of the fold axis is 20°-->187° (fig.4.21).

The attitude of the fold axis and the position of the contoured pie circle girdle reveals the synform is plunging overturned (Marshak et al, 1988; Ramsay et al, 1987).

4.2.2.3. The D_3 deformation

D_3 is the last folding event which has developed almost perpendicular to D_2 and resulted in a gentle undulation of the regional foliation in an east-west direction.

In most of the study area the effect of this undulation is not homogeneous in that very thick lithologies are seen undulating only in some parts of the study area, on a mega scale. But, observation at meso scale shows that some thin units of marble and slate within the competent layers appear to be undulating. These undulations (open folds) have a mean wavelength of 60 cm and an amplitude of 15 cm.

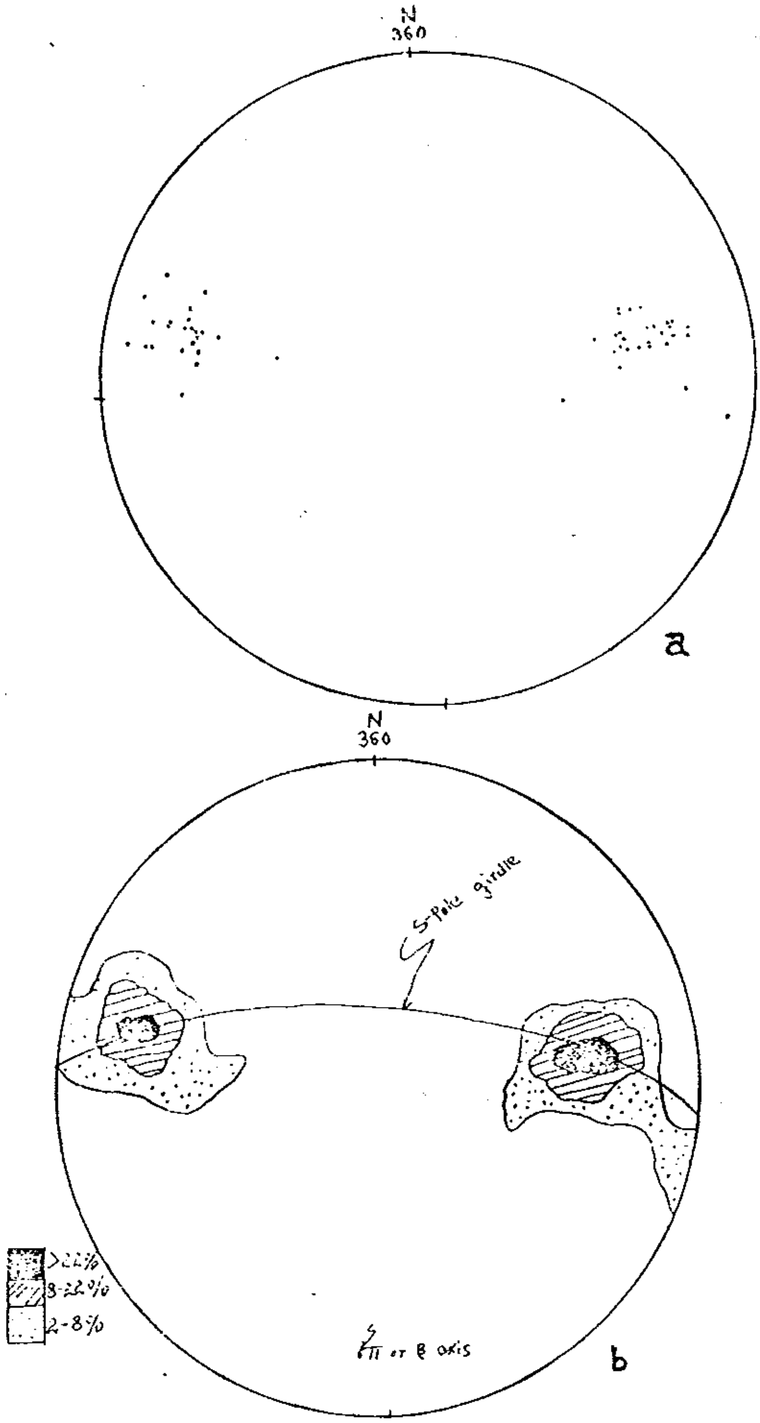


Fig.4.21. a. Point diagram of poles to composite S_0S_1 fabric measured around the eastern antiform.b) Contoured version of the point diagram of the composite fabric, contours at 2, 8, 22%.

Large scale observation on the north western synform clearly shows that the axial trace of the north western synform is undulating due to this phase of deformation (fig.4.3).

Equal area plot for a very few measurements shows the mean orientation of the F_3 fold axis to be 58°-->248° (fig.4.22).

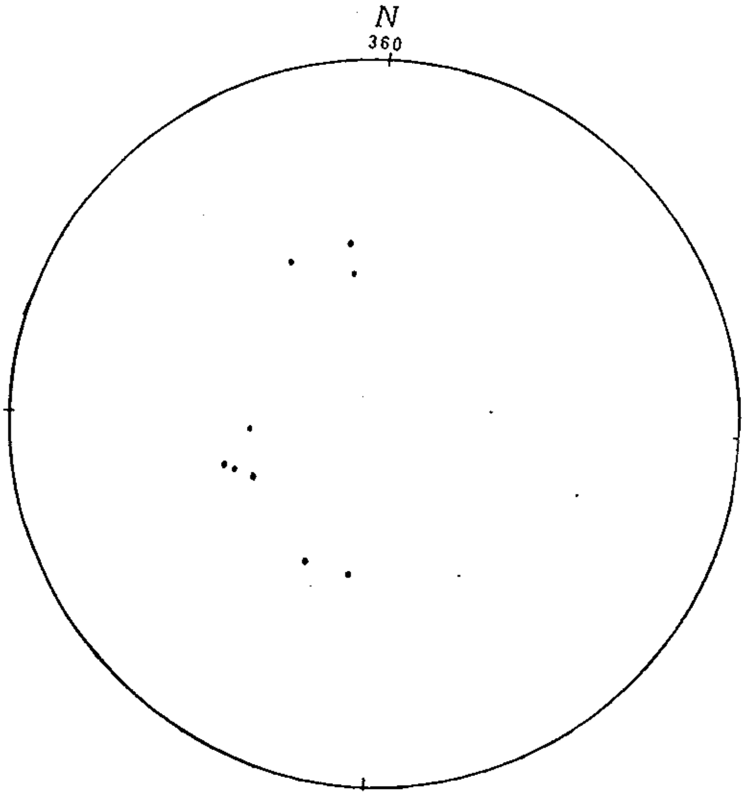


Fig.4.22. Point diagram of 9 fold axes of the D_3 generation measured in the study area.

4.2.3. FAULTS

In the study area two types of fault systems are observed (fig.4.2), these are:

- -short dextral strike slip faults
- -normal faults

4.2.3.1 The short dextral strike slip faults

These faults are, very short with length not more than 600m. They mainly affect the white fine marble, Slate, black fine marble, black fine marble and slate intercalation, and the pebbly slate found at the core of the central synform (fig.4.3, 3.1). These faults, in many places found displacing the above rock units in a dextral sense. The displacement is mostly small, about 30m, but in the extreme case it reaches around 55m. Minor structures (such as, slickensides) related to these faults recording the direction of movement are not found. So, determination of the components of displacement is not possible. However, the present field evidence suggests the faults to be pure dextral strike-slip faults with a vertical fault plane. Measurement of the fault plane attitude in the field gave a consistent and dominant orientation of 080° , however, in addition to these major pure dextral strike slip faults one pure sinistral strike slip fault with the same orientation is mapped in the present study area (fig.4.3).

4.2.3.2. The normal faults

These normal faults are the most prominent system and are well developed in the southern boundary of the study area. The white sandstone unit, the dominant rock outcropping in the southern boundary, is intensively cut by this fault system and preserved a fresh fault plane surfaces. Though the outcrops of the brown sandstone is also extensive in the southern part, it is not highly affected by this fault system. Moreover, some of these faults displacing the white sandstone are observed displacing the brown sandstone. From this one can conclude that this fault system is younger than the brown sandstone.

In the study area they form belts of normal faults which limit the northern boundary of the Mekele outlier. North of this fault belt the sediments abruptly terminate, and the sediments start to outcrop immediately south of this fault belt.

The length of the individual fault is variable, ranging from less than 20cm up to 1.2km. However, the belt continuous even as far as 65km outside from the present study area (see Beyth, 1971).

In the southern boundary region, where the metamorphics and the brown sandstone are found juxtaposed, there is a wide marshy land, indicating the wide weakness zones due to the "Wukro Fault Belt". This weakness zone has a mean orientation of WNW-ESE in the north and a mean orientation of NNW-SSE in the south. In two instances the brown sandstone is seen lying over the metamorphic rocks and the contact appears tectonic defining the fault plane of the major fault belt. Within the brown sandstone unit, there are a well developed normal faults which are antithetic to the major normal faults. These faults have a throw of about 30m. On the basis of the above observation the trace of the WNW-ESE oriented segment of the "Wukro Fault Belt" is traced and shown on the map as a solid line. Whereas, obtaining the orientation of the NNW-SSE segment of the fault belt is impossible and as a result on the map it is shown by a broken lines. From the above two paragraphs one can say that the fault belt is younger than the brown sandstone.

Associated with these normal faults there are slickensides on the fresh fault planes. These slickensides show the direction of movement to be largely of normal and sometimes normal with components of sinistral motion. So, strictly speaking, these faults are normal and normal-sinistral faults. The age relationship between the normal and the normal-sinistral movements is not exposed. However, examination of fig.4.25 reveals that faults with mean orientation of WNW-ESE, and ENE-WSW are largely pure normal faults with a very small sinistral component and the faults mean orientation of NNW-SSE are largely normal-sinistral faults. The WNW-ESE and ENE-wsw normal faults might be antithetic and syntethetic to each other and might be related to the

WNW-ESE oriented segment of the "Wukro Fault Belt". Whereas, the NNW-SSE normal sinistral faults might be related to the NNW-SSE oriented segment of the "Wukro Fault Belt".

A contoured equal area plot for this fault system gave two areas of concentration with orientation values of 46°--> 025° and 65°-->327° (fig.4.23). From this and from (fig.4.24) it is evident that the mean orientation of the faults is WNW-ESE and ENE-WSW.

4.2.3.3. Concluding comments

In the present study, two sets of faults are observed. One set is pure dextral strike-slip fault with 080° orientation. The other set is dominantly normal and minor normal-sinistral faults with orientation of WNW-ESE, ENE-WSW and NNW-SSE. The same systems of faults were observed and described by (Beyth, 1971; Garland, 1980). According to Beyth (1971), the age of the normal and the normal-sinistral fault belt ranges from Upper Malm to Lower Cretaceous, while no age for the pure dextral strike slip fault is suggested, but from the present field evidence it is suggested that they are younger than the peblly slate though their relationship with the Palaeozoic sandstone is not clear. In addition to the above fault systems, in the study area, another system of faults (normal and reverse) with north-south orientation and forming several lineaments extending 70 to 80kms are observed by Beyth (1971).

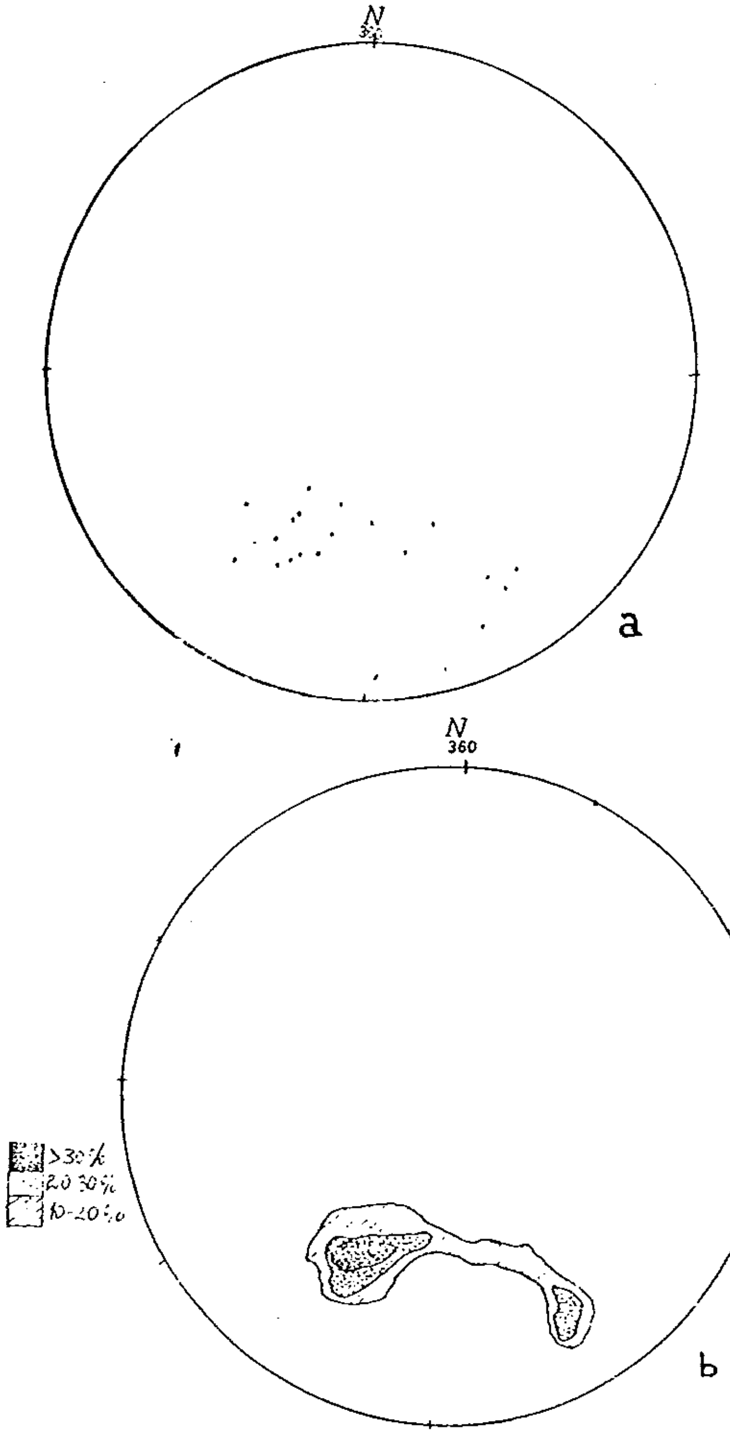


Fig.4.23. a. Equal area plots of 20 poles to Normal fault planes. b. contoured diagram of the 20 poles to the Normal fault planes. Contours at 10, 20, 30%.

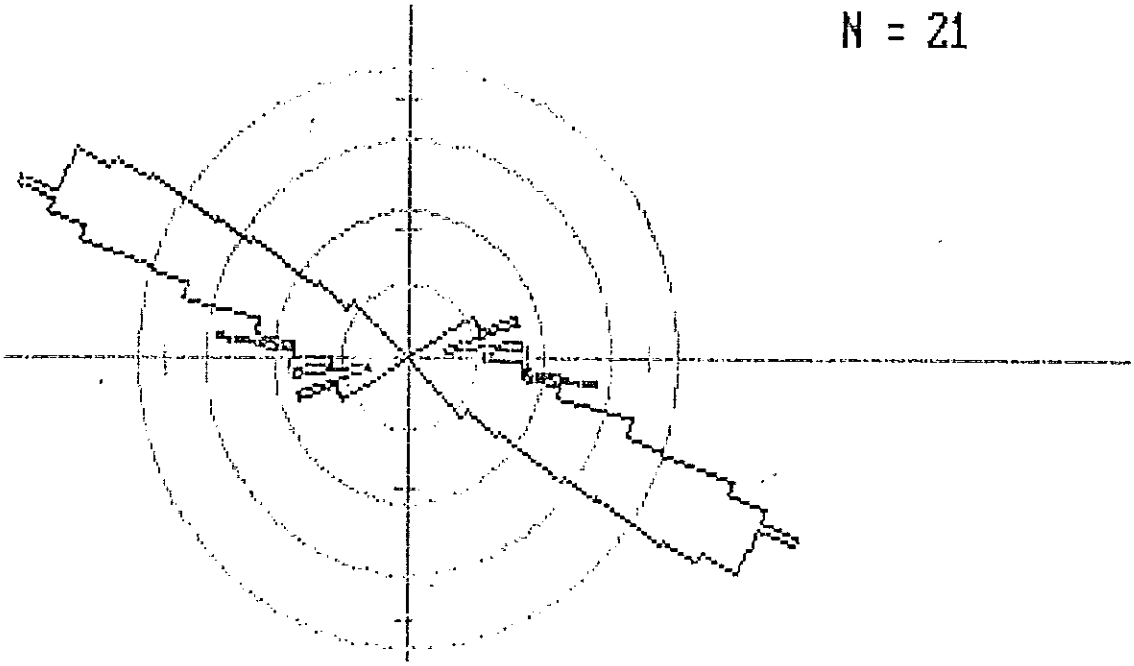


Fig.4.24. Completed rose diagram of 21 fault planes showing WNW-ESE orientation.

These faults only affect the basement rocks and post-date folding (Garland, 1980). According to Garland (1980), this belt runs along the eastern and western borders of the "Negash syncline" ; the eastern fault is normal while the western fault is reverse. However, the study area being located in the Negash area, no field evidence is found to confirm or reject the conclusion of the previous works.

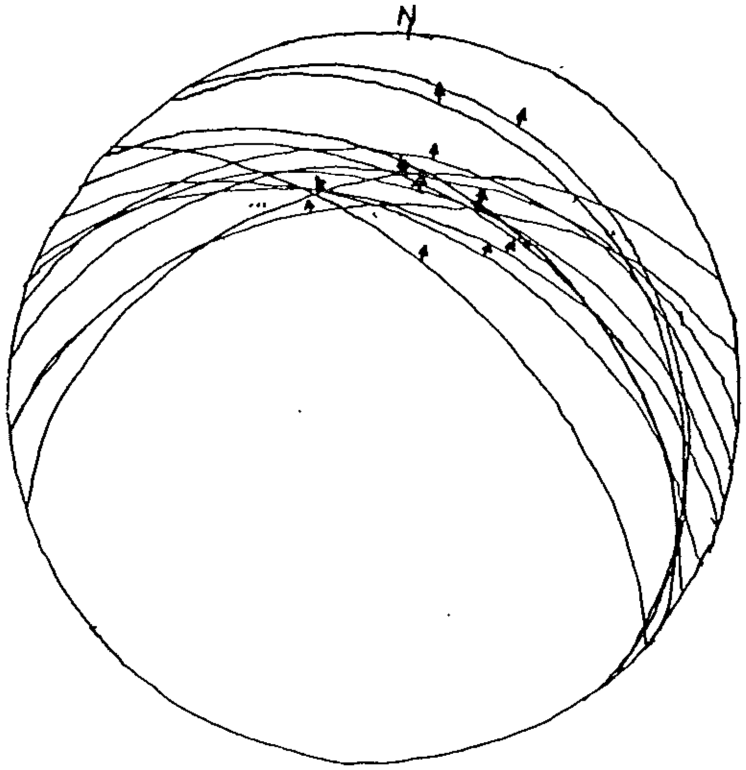


Fig.4.25. Cyclographic equal area plots of 12 faults with their associated slickensides indicating a normal and normal sinistral sence of motion.

CHAPTER V

5. METAMORPHISM

5.1. INTRODUCTION

In the study area two types of metamorphism can be distinguished. These are:

- Regional metamorphism
- Contact metamorphism

In addition to these there are patchy alteration products of the regional and contact metamorphic association perhaps indicating retrograde metamorphism. The regional metamorphic effect is of wider extent whereas the contact metamorphism is restricted to the aureoles of the granite exposed in the north-western part of the study area. In general, the lithologies exposed in the area are affected by regional low grade, greenschist metamorphism (see section below for details). However, it varies from place to place. The metamorphic grade reaches up to upper greenschist facies; in the area near the eastern antiform and in the aureole of granite (see later). Metamorphism in the area is recognized either only by the recrystallization or by recrystallization accompanied by neomineralization, depending on the original material.

5.2. Regional Metamorphism

5.2.1. Metamorphic mineral assemblages of metavolcanics

As listed in (chapter 3), the unit comprises of aphanitic metavolcanics (andesitic, dacitic and rhyolitic in composition), metabreccia, and metavolcanics with visible crystals. For the purpose of this section average composition of the major lithologic unit (aphanitic metavolcanics) will be considered, noting the variation from place to place and sample to sample. The metamorphic mineral assemblages of this metavolcanics varies in the range of the following three lists.(mineral names in decreasing order).

a) plagioclase(albite-oligoclase) + tremolite + **epidote**
± chlorite ± quartz ± muscovite.

b) Plagioclase (albite-oligoclase) + epidote + quartz + chlorite ± tremolite ± muscovite

c) **Chlorite + epidote + tremolite ± plagioclase ±** quartz ± muscovite

These assemblages are typical of low-grade metamorphism and diagnostic for the chlorite zone of greenschist facies (Winkler, 1976 pp74; Miyashiro, 1979 pp243). Microstructural details of this rock group are given in chapter 3 (section 3.2).

5.2.2. Metamorphic mineral assemblages of metasediments

This unit comprises of: a) slate, b) white fine marble, c) white coarse marble, d) graphitic phyllite, e) quartzite, f) metaconglomerates, g) black fine marble, h) black marble and slate intercalation, and i) pebbly slate (see chapter 3). Petrographic analysis is not made for the last two units, but for the remaining all other units the mineral assemblages are presented below.

a) quartz + plagioclase + muscovite + iron-oxide ± chlorite
b) calcite + dolomite + plagioclase + quartz
c) calcite + muscovite + quartz
d) quartz + graphite + plagioclase ± muscovite
e) quartz + plagioclase ± calcite
f) quartz + muscovite + chlorite ± plagioclase
g) calcite ± plagioclase ± quartz

Regional metamorphism of pelitic rocks, in the study area present a relatively complete picture of metamorphic paragenesis in the lower range of metamorphic grade in the greenschist facies. The mineral assemblages of (a), (d), and (f) are those of chlorite zone of greenschist facies, in the absence of biotite (Turner, 1968 pp277).

Calcareous assemblages (b) and (g) in the study area are characterized by persistency of calcite-dolomite-quartz-plagioclase and absence of talc, tremolite, diopside and forsterite. Long ago this type of peculiarity was noted by White and Billings (1951, pp691, after Turner,1968) who stated that "the reason may be is very high confining pressure that reduced the permeability and prevented the escape of carbon dioxide". These assemblages of unaffected calcareous rocks characterize very low-grade metamorphism (Winkler,1976 pp112). The same mineral assemblages are considered to be low-grade greenschist facies (Turner, 1976 pp277). In the assemblage (c), the presence of abundant muscovite is attributed to reaction between carbonates and clay impurities which given rise to muscovite, and minor chlorite, epidote along with quartz in the marble assemblages (Turner, 1968 pp284). According to Turner (1968,pp284), this assemblage characterize the biotite zone of greenschist facies.

As is mentioned in the introductory part of this chapter the metamorphic effect on these units is not uniform throughout the study area. Metamorphism on the ridge forming rock units outcropping along the limbs of central synform (see chapter 3 and 4), is characterized by low metamorphic grade with poor development of metamorphic minerals. The metamorphism can only be understood through the incipient recrystallization effect imposed on the above rock units (see chapter 3 for petrographic details). On the other hand, the metamorphic grade in the flank of the eastern antiform (where white coarse marble outcrops) appears to be a bit higher. On the eastern antiform, the calcite, quartz, and plagioclase of white coarse marble are coarse grained (see chapter 3). New metamorphic mineral formed is muscovite.

5.2.3. Relationships between metamorphic mineral growth and deformations

As discussed in chapter 3 and 4, in the study area a number of constraints exist to fully evaluate the metamorphic mineral growth which define the fabric related to certain phase of deformation. These include the following:

1) Due to the low grade nature of metamorphism, the grain size is very fine to fine which precludes precise evaluation of the constituents.

2) The S_1/S_2 fabrics (the main regional foliation) are in many cases parallel except near the hinge zones of D_2 folds where they occur at an angle. At the hinge zone, though they occur at an angle, due to the tight nature of the fold the exposure is small.

3) The absence of any coarse grained porphyroblasts which may preserve the record of fabric as an inclusion pattern.

However, despite these constraints there are a number of indications which suggest matrix mineral growths during the D_1 and D_2 deformation events. These include:

muscovite, tremolite, quartz, graphite, and some of the chlorites and epidotes. These minerals are synchronous (syntectonic) with the D_1 and D_2 deformation, because their preferred orientation define the S_1 and S_2 fabric (see fig.4.7, 4.20, 3.6, 3.9, 3.12, 3.13). The alteration products such as some chlorites, some epidotes, and sericite probably post-date main fabric forming deformation (i.e, D_1 and D_2). However, there is no significant change in conditions of metamorphism during the D_1 and D_2 deformations.

5.3. Contact Metamorphism

The effect of contact metamorphism is observed along the contact between the granite and metasedimentary rock units. Along the immediate contact with the granite, there are calc-silicate hornfelses, slates and spotted slate which are mapped as intercalation of white fine marble, quartzite, and slate unit (fig.3.1). The contact effect shows significant variations as one traverses outwards from the immediate contact between the metasediments and the intrusive.

Calcareous rocks near the contact are typically composed of :

calcite + wollastonite + diopside + chlorite.

These minerals are randomly distributed unlike the regional metamorphic minerals and do not define the fabric (fig.5.1, 5.2). However, in outcrop the fabric is clear and therefore it shows that the regional fabric is obliterated by contact effect in microscopic scale only. The above silica deficient assemblages are characteristic minerals in the hornblende-hornfels facies (Turner, 1968 pp204). This facies represent the middle region of the contact metamorphic zonation produced in aureoles (Turner, 1968 pp193).

The spotted slate outcrop in a weakly developed aureole, recrystallization tends to be imperfect, and listing the mineral assemblages is difficult due to the fine grained nature of metamorphic products. Careful investigation under higher objective microscope revealed that it is composed of:

quartz + plagioclase + epidote + sericite.

These mineral association typifies the pelitic hornfels and spotted slate in the albite-epidote-hornfels facies (Turner and Verhoogen, 1974 pp510).

5.3.1. Alteration

The rocks of the study area are also affected by a later weak alteration. In the metavolcanics and metasediments, this effect produced minerals such as: chlorite, epidotes, and sericite. This alteration minerals are easily identified from the same minerals of regional metamorphic origin in that; they are randomly distributed within the mineral they are replacing, and do not define the fabric

Fig.5 :- Contact-metamorphic mineral assemblages around the granitic intrusion

Fig.5.1:-photomicrograph (crossed polarizers) of calc-schist with mineral grains of Diopside (Di), Wollastonite (Wo), and Calcite (Ca).

Fig.5.2 :-photomicrograph (plane light) of calc-schist containing Wollastonite (Wo), Chlorite (Ch), and Calcite (Ca)

Finally the granitic intrusion has attained a very low degree of alteration with a well preserved previous panidiomorphic-granular texture. The effect is recognized by the development of secondary muscovite + chlorite + epidote, which are randomly distributed on the surfaces of the host minerals such as plagioclase and biotite. Hence, they are not a result of regional metamorphism. Therefore, the cause for this alteration of both the basement rocks and the granitic intrusive must be the same. The following reasons are most probable:

1) The temperature effect of a big pluton found very close to the study area, in the north-western boundary. This pluton might have intruded later than the small granite and affected both the basement and the small granite.

2) The temperature effect during cooling of the small granite itself probably has altered itself and the basement rocks in its surrounding.

or 3) The result of regional uplift and erosion which exposes the entire rock mass to a relatively lower temperature and pressure. This effect also allowing easy access of circulating meteoric water during which the "primary" metamorphic assemblages tends to adjust themselves to the new conditions.

CHAPTER VI

6. DISCUSSION AND CONCLUSIONS

6.1 The Pan-African tectonics and the Mozambique Belt in Ethiopia

Northern Ethiopia is considered to be a region where two major Precambrian structures meet: the Red Sea fold belt of Northeast Africa and the Mozambique belt of East Africa (Kazmin, 1978) (fig.6.1).

The Red Sea fold belt extends from about the Nile in the west to the Phanerozoic cover in the east (Black, 1984; Shackelton, 1986). Results from several recent research work undertaken in this region related the Pan-African event to the Precambrian shield of northeast Africa and Arabia and considered it as being the youngest, best preserved Late Proterozoic orogenic belt (Kazmin, 19798; Black, 1984; Kroener, 1985; Shackelton, 1986). The Red Sea fold belt can be described as an arcuate system in which fold strike gradually changes from northeast in the east to northwest in the west (Kazmin, 1978). This is especially clear when Arabia is restored to its pre-drift position (fig 6.1). A characteristic feature of this fold belt is the development of northwesterly striking shear zones some of which display sinistral motion (Kazmin, 1978; Black, 1984; Shackelton, 1986). The lower part of the Late Proterozoic Red sea fold belt includes altered ultrabasic and basic rocks with associated metasediments. Detailed work in recent years has led to the identification of linear ophiolite complexes in neighbouring countries (Saudi Arabia, Egypt, Sudan and Kenya). Similar occurrences of ophiolites have also been reported from Ethiopia (Kazmin, 1978; Warden et al., 1984; Wolde, 1987; Ayalew, 1988; Berhe, 1990). The ophiolites within this regional belt outcrop as a linear suture, isolated blocks, and as extensive but separated masses in huge ophiolitic melange in different countries (Shackelton, 1986). These rocks are followed by a sequence of acidic to intermediate metavolcanics and associated volcaniclastic metasediments (Kazmin, 1978; Black, 1984). The latter rocks are intruded by post- to syn-tectonic granitoids with age ranges of 800 to 500Ma (Black, 1984) and 900-650Ma (Kazmin, 1978) respectively. Though all the geophysical and geological characteristics of the crystalline basement of northeast Africa and Arabia suggest a continental crust origin (Gass, 1977), the field, petrographic and trace element evidence indicate an intraoceanic island arc environment (Gass, 1977; Wolde, 1987; Shackelton, 1986; Ayalew, 1988; Berhe, 1990).

The Northeast branch of the Mozambique belt, a major Proterozoic structural metamorphic unit of Eastern Africa, extends from Kenya through Ethiopia and the horn of Africa into southern Arabia (Warden et al, 1984). According to Warden et al (1984), a bifurcation in Southern Ethiopia separates a northeastern branch extending from Southern Kenya in the horn of Africa and southern Arabia, from the main belt which continues into Western Ethiopia and Sudan (fig.6.1).

Though available geochronological data show similar ranges of late Proterozoic ages in northeast Africa and in the Mozambique belt of Kenya and Tanzania, there are profound differences between the low grade (greenschist facies) island arc assemblages of northeast Africa and the high grade metasediments and granitoid gneisses of the Mozambique belt in east Africa (Shackelton, 1986). According to Warden et al. (1984) the structural and metamorphic evolution of the Mozambique belt is related to rifting and subsequent closure of the rift systems and basins. The few geochronological evidence suggests that the sedimentation and major metamorphic events probably occurred during the time interval of 1400-850Ma (Warden et al, 1984).

In Ethiopia the Precambrian rocks have been divided into Lower, Middle, and Upper complexes (see section 2.3 for details). Based on the tectonic framework proposed for the Precambrian rocks evolution by Kazmin et al. (1978), Wolde (1987) recognized three tectono-stratigraphic domains. These are from west to east Gambella, Konso and Adola domains respectively. According to Wolde (1987), the western and central domains i.e Gambella and Konso, respectively, represent island arc systems older than 700Ma, while the eastern Adola domain is considered to be a rifted and drifted continental mass at about 1200Ma. On the other hand (Berhe et al., 1990; Gore-Gambella Geotraverse, 1986; Ayalew, 1988) subdivided the Precambrian rocks of western Ethiopia (from west to east) into Baro domain of high grade granitoid gneisses and paragneisses; Birbir domain of metavolcanic and metasedimentary succession of greenschist facies; Geba domain consisting of high grade gneisses and migmatites. According to Ayalew (1988) the Baro and Geba domains are part of the Mozambique belt, whereas the Birbir domain constitute part of the Pan African rocks (Red sea fold belt)

Gilboy (1970) and Chater (1971) made the first important contributions to the geology of the crystalline basement of southern Ethiopia, and described four phases of deformation. The major folding phase resulted in a N-S trending system, with tight to isoclinal and upright or steep westerly inclined folds (after Beraki et al, 1989). According to Beraki et al. (1989), in the Adola fold and thrust belt two thrusting events (D_1, D_5) and three folding phases (F_2, F_3, F_4) have been documented. The F_2 folds are subvertical with N-S striking axial planes; the F_3 axes have N-S trend and are doubly plunging; the last folding event, F_4, developed almost perpendicular to F_3 and resulted in a curvilinear feature of the regional foliation (Beraki et al., 1989; Tolessa et al., 1990).

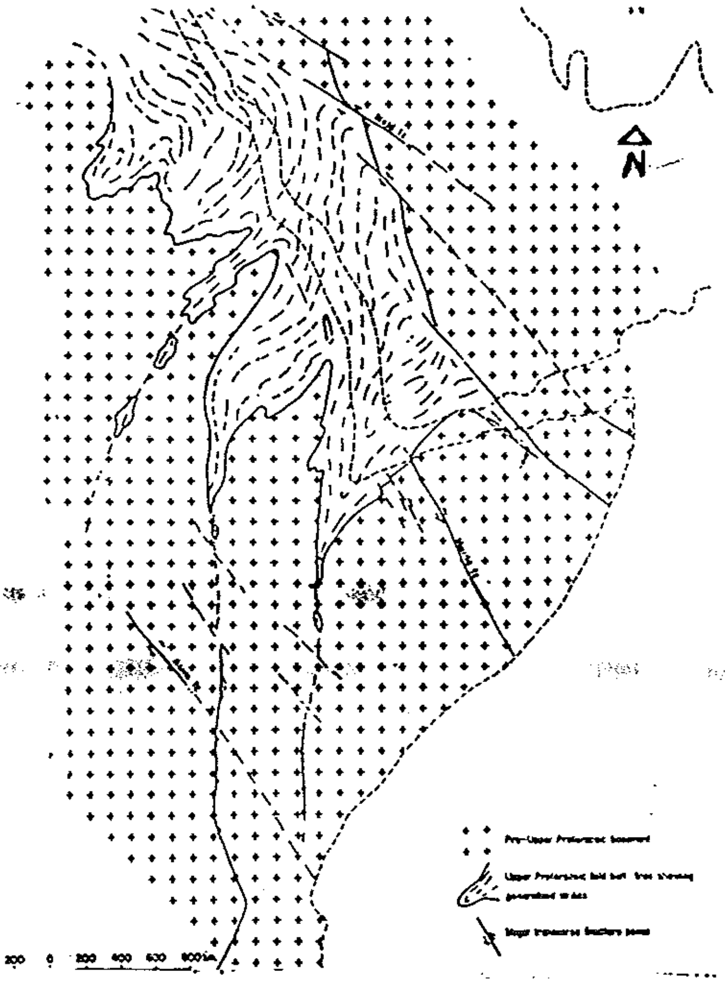


Fig.6.1. Configuration of the Red Sea Fold Belt (after Kazmin, 1978)

Research work undertaken in the Moyale area, Southern Ethiopia, (Alene, 1991) has revealed four phases of deformation. The first deformation was responsible for transposition phenomena and is characterized by rootless intrafolial folds. These folds appear to have had earlier E-W axes, which were refolded by subsequent D_2 major phase of deformation. Due to this, measured orientation data of the rootless intrafolial folds, plotted on an equal area net, are scattered along a belt oriented in a NNE-SSW direction(see section 4.2.2 for details). This folding phase is similar and may be correlatable with the D_1 deformation described in western Ethiopia (Ayalew, 1988; Teklay, 1986).

The second phase of deformation developed a 10°-20° Plunging towards-->(170°-195°) oriented major synforms and antiforms. The distribution of the various lithologic units in the study area now appears to be controlled by this fold system. This phase of deformation may be correlatable with the, deformation that produced F_3, folds described in the Adola area (Beraki et al, 1989), and with the second phase of deformation described in Moyale area (Alene, 1991) and in western Ethiopia (Ayalew, 1991; Teklay, 1986). The third and weakest phase of deformation is Probably correlatable with the F_4 folding event described in Adola area (Beraki et al, 1989).

The volcano-sedimentary rock association in the area now metamorphosed to greenschist facies represents deposition of clastic, terrigenous and chemical sediments contemporaneous with volcanism in a stretching and subsiding basin. This association belongs to the Middle-

Upper part of the Upper Complex of the Ethiopian basement rocks (Garland,1980; Kazmin, 1978). According to Garland (1980) and Kazmin (1978) these rocks belong to the younger Red Sea Fold Belt. On the other hand, Levitte (1970) and Beyth (1971), consider the basement rocks of Tigrai and Eritrea as part of the younger Basement Complex of Ethiopia, and suggest that these rocks (in northern Ethiopia) are possible extension northwards of the Mozambique fold belt succession, but recommended further detail work to confirm this conclusions. In the present study sufficient evidence has not been found to indicate an oceanic or continental origin. The unravelling of the tectonic environment and associated magmatism needs detailed geochronological, petrological, geochemical (major and trace elements) and isotopic studies, all of which are beyond the scope of this research. The age of these rocks is not known. However, Kazmin (1978) made a tenuous attempt of age correlation with similar rock units in Saudi Arabia, Egypt, and Somalia and concluded that they range between 700-1000 Ma, while the minimum age for the deposition and subsequent deformation is deduced from age dating of some oldest post orogenic granite which yielded 670-690 Ma (Kazmin, 1978).

6.2 CONCLUSIONS

On the basis of available field and laboratory data, obtained from this study the following conclusion may be drawn:

1. Structural detail in the area reveals that there are three phases of ductile deformation and a late phase of faulting. The first two deformation events are synchronous with the regional metamorphism, while the third phase is weak and has no associated metamorphism. The first phase of deformation is related to strong and pervasive transposition . This deformation is considered to have resulted in strong reshuffling of the stratigraphy which possibly mispositioned the units from their relative original stratigraphic orders. Some of the rock units, mapped in the area may be correlated easily on gross lithological similarities, with those described in the existing stratigraphic order in northern Ethiopia (see fig.3.17). However, caution must be exercised in following such a simplified approach. Primary structures which may indicate the stratigraphic way-up direction may be significant only locally. The distribution of the rock units in the area now appears to be controlled by large scale D_2 folds, while the geometry of D_1 deformation is clearly obscured and remains to mere speculation. Therefore it is suggested that the establishment of an exact stratigraphy should be given high priority for

future research. As this being the case, the stratigraphy adopted and described in this thesis is tentative and remains open to modification.

The faults mapped in the area are of two types: pure dextral strike slip, and normal faults. The pure dextral strike slip faults offset the basement rock units only at the hinge zone of the central synform, and possibly represent a post D_2 deformation event. The normal faults in most of the cases show components of sinistral motion. These faults are observed displacing largely the white and brown sandstone units in the area, and possibly are related to the "Wukro Fault Belt". These faults represent the latest brittle deformation event in the area.

2. Metamorphic mineral assemblages of the mapped units in the area are typical of low-grade greenschist facies. This conclusion agrees well with the conclusion drawn by earlier workers (example: Beyth, 1971; Garland, 1980). The fine-grained nature, and the lack of porphyroblast growth in the assemblage precluded detail examination of metamorphic mineral growth with respect to the phases of deformation described in the area. Nonetheless, from existing data, it may be concluded that the growth of all matrix-forming minerals is synchronous with the D_1 and D_2 deformations. The similarities in the mineral assemblages defining both S_1 and S_2 fabrics suggest that there were no significant changes in the conditions of metamorphism during both D_1 and D_2 deformations. The relatively

coarse-grained nature of some contact metamorphic minerals around the aureole of the granite intrusion suggests that grain coarsening was the result of heating by the intrusive mass and clearly indicates that the granitic intrusion occurred after the climax of regional metamorphism (i.e, post D_2). Since the third deformation , D_3, is weak and of local importance, its relationship to the granite emplacement is not possible to evaluate.

3. The Palaeozoic-Mesozoic sediments which were deposited on the peneplained surface of the basement rocks clearly reveals angular unconformity at their base.

The Palaeozoic clastic deposition (white sandstone and varved shale) began during Upper Palaeozoic in a channel-like, north-south trending basin as deduced by (Beyth, 1971; Garland, 1980). There are only remnant patches (outlier) of the white sandstone unit in the main map area, but are widespread in the southern parts of the study area

The Mesozoic, brown sandstone unit, in the study area is found in limited exposures at the southern boundary but becomes more extensive and thicker immediately south of the *"Wukro Fault Belt"*. This may suggest that either the depositional basin was deeper in the south, perhaps controlled by the system of faults which are part of the *"Wukro Fault Belt"*, or the area underwent significant subsidence soon after deposition to preserve a thick sequence in the Mekele outlier. Though, the present study supports the latter conclusion, it is not definitive. In fact for the definitive conclusions detailed stratigraphic and structural studies are essential including basin analyses accompanied by sedimentary facies analyses.

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