

**RIFT MARGIN DEVELOPMENT, THE CASE OF
SOUTHERN AFAR, DIREDAWA AREA**

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**Rift Margin Development, the case of southern Afar
Depression, DireDawa area**

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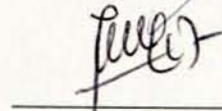
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ABSTRACT

Southern Afar Rift margin is a 25-30km wide zone separating the Somalian plateau from the Afar rift floor. It shows a complex fault pattern, characterized by the interplay of: (i) an E – W trending marginal fault system, (ii) a northwesterly major lineaments (faults) and (iii) a NE trending Nazareth fault system. The E – W oriented faults play a dominant role for the present morphology of the southern Afar rift margin and for the existence of highly tilted Mesozoic rocks.

Rifting induced late Cenozoic volcanism in the southern Afar rift margin three main types. The oldest felsic rocks, aligned parallel with the boundary faults, are formed contemporaneously with these faults. The olivine free basalts and the Rhyolites are found with in the marginal half grabens. And the youngest volcanic rocks of the area are the Afar stratoid series, erupted during further episode of rifting and tilting.

The marginal fault plane and bedding plane relationship of the area confirmed that the bed orientation is greatly controlled by the orientation of the faults. The strike of the beds and faults is nearly similar; however, their dip amount is inversely related and their dip directions lay opposite to each other.

Systematic field observations and accurate measurements of the orientation of structural elements have enabled to identify the nature of faults at depth: the presence of roll-over anticline structures together with the subsidiary normal faults led the author to conclude that the nature of faults at depth is listric normal. The general fault pattern of the southern

Afar rift margin, as well as mesoscopic fault analyses indicate the occurrence of a roughly NNE-SSW extension with small component of dextral shear motion along the Rift margin.

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CHAPTER- ONE

INTRODUCTION

1.1 General

Since the mid of 1960s, specially after the acceptance and the development (Di-Paola, 1972) of the plate tectonics theory, the interest of many Earth Scientists in Continental drift problems has strongly increased, including the study of the world's rift zones. One of the most interesting continental rift zone is the East African Rift System or broadly speaking the so called the Afro-Arabian Rift System or the Great Rift Valley (Di-Paola, 1972; Girdler, 1991). The Great rift valley is actually a long (about 4000miles), deep depression extending from the Jordan valley in the north, through the Red Sea, Gulf of Aden, Afar, East Africa and terminating in a large number of splaying faults in South Africa (Girdler, 1991). It is a major structure of the Earth affecting the whole eastern part of the African continent and some part of the southwestern Asia (Chorowicz, 1990).

Geologic information suggests that the rift began as early as the Eocene or even the Jurassic but that the current phase of extension began in the mid- Miocene, similar in time to the inception of the Basin and Range faulting (Twiss and Moores, 1992). However, it is believed that the Gulf of Aden and the Red Sea Rifts pre-date the formation of the East African Rift. The present Red Sea – Gulf of Aden could be considered as the third stage in the evolution of rifting process: the first being represented by the Ethiopian continental rift and the second by the Afar, which is a transitional from continental rifting (Berhe, 1986). The date of 13-14 Ma appears to correspond to a significant increase in the amount of rifting in E. Africa, which correlates with oceanization of the two branches (the Red Sea and Gulf of Aden) of the triple

junction (Gaulier and Huchon, 1991). Generally, it is a fascinating rift not only because of its large aerial extent but also includes an evolutionary sequence from incipient rifting in the south (Mozambique) progressing northwards to a region of fully oceanic (The Red Sea and Gulf of Aden).

Among those variably evolved regions of the Great Rift, the Ethiopian Rift System is one. It is bordering the Nubian and Somalian plateau, thought to have developed above one or two paleogen mantle plume and represents the third and northeasterly trending arm of the proposed rift-rift-rift triple junction (Ebinger et al., 1989). The Ethiopian rift encompasses moderately evolved (Main Ethiopian) to highly evolved (Afar) Rifts transecting the 1000km. wide Ethiopian plateau. A great number of step faults produce a total latitude difference of more than 1100m between the rift shoulder and its floor. All these faults are normal faults, which run for tens of km in NE – SW to NNE - SSW directions or in the case of southern Afar, in an ESE - WNW/ E - W and more rarely, in a N-S direction (southern portion of the Ethiopian Rift).

The Afar depression, which is the northern most segment of the MER, owns transitional character from continental to oceanic rifting with indication of sea floor spreading at its axial part. The structural, tectonic and lithologic differences within the Ethiopian Rift valley lead to further sub division of the rift as: Afar, Main Ethiopian and southern Ethiopian Rifts.

Afar depression is a region located in the horn of Africa at the junction of three major rift zones of the Earth's crust: the Ethiopian Rift, the Red Sea rift and the Gulf of Aden. It is

the only emerged RRR-type triple junction from which the Nubian (Main Ethiopian), Somalian and Arabian plateaus are separated (Huchon, 1989; Gaulier, 1991). The Afar Rift is distinct from that of the remaining East African Rift in the case of structural pattern, evolution and composition. The fault patterns present in the Afar depression are extremely complex as they reflect the presence, interference and superposition of the three main trends of crustal extension. Five major fault trends of different ages are recognized in the region (Berhe, 1986), however for the sake of simplicity they are categorized in to three major trends.

The outline of the faulted western scarp of the depression reflects the en-echelon disposition of the axial grabens of northern Afar. While the south eastern margin of the depression belongs to the Gulf of Aden ESE- WNW trend: i.e. the south eastern margin of Afar, which is focused in this study, has a structural trend parallel to the topographic trend of the Gulf of Aden. Towards the southwestern of Afar, a NNE-SSW (Wonji trend) exists. This fault trend extends from within the Ethiopian Rift Valley up to the curvilinear Tendaho graben in central Afar. The rate and direction of extension of Afar is comparable with that of the Red-Sea and Gulf of Aden. The 21mm a^{-1} , NE-SW directed extension in the eastern Afar, the Red-Sea, and Gulf of Aden determined from geodetic studies changes to the much slower ($3\text{-}8\text{mm a}^{-1}$) sub E-W directed extension in the MER (Ebinger et.al., 1999).

The southeastern escarpment forms the margins of Somalia plateau and consists of a 25 km wide zone of antithetically and synthetically tilted blocks of Precambrian rocks covered by Mesozoic sediments and Neogene volcanic rocks (Berhe, 1986). The normal faulting and block tilting is now highly manifested at the southern margin, near

DireDawa. It has been suggested that the southern Afar-MER transition regions is both an important physiographic and structural transition between the northern terminus of the MER and the south most Afar, and an important tectonic and magmatic link between these two distinct manifestations of East African Rifting (Chernet et al., 1998).

The study area is located in the southern Ethiopia, Dire Dawa, Gedda and north of it.

The present southern Afar rift margin escarpment is represented by E-W and ESE faults and the Northwesterly fault zones, which have acted as transcurrent faults. From the regional geological map (1:2,500,000) of Chernet and Hart (1999), the area comprises dominantly of Precambrian basement, Alaji Group Basalts and Rhyolites, the Afar Stratoid series and Alluvial and Lacustrine sediments. It also incorporates significant amount of tilted blocks of Mesozoic sedimentary rocks.

Unlike other areas, Dire Dawa is good in the north-south direction, the area is well

As evidenced from Satellite imageries and aerial photographs, previous and current works, the Rift Margin is made by short running step faults with steeply inclined fault planes at the top; however, the nature of the fault plane at depth is not yet identified. Earlier studies of the area did not tell any about the tectonic evolution and kinematics of the area.

The longest and divides the area in to four major sectors. The last two sectors are separated by a fault zone which is located only in the north-south direction. The density of the area is about 0.25 km²/km² which means that the area is densely populated. The area is well suited for vehicles to travel on during dry season. As a result, the area is well suited for vehicles to travel on during dry season. As a result, the area is well suited for vehicles to travel on during dry season. As a result, the area is well suited for vehicles to travel on during dry season.

1.2 locations and accessibility

The study area is located in the eastern Ethiopia, Dire Dawa Council and partly in the Somali Region, centered at the Dire Dawa town. It is about 520 Km from Addis Ababa and is bounded by latitude $9^{\circ} 25' 35''$ - $9^{\circ} 45' 00''$ and longitude $41^{\circ} 45' 00''$ - $42^{\circ} 00' 00''$ (Fig.1). It is found at the southern margin of the Afar depression.

The study area is accessible by about 450 km asphalted road taking to DireDawa and 70 km gravel road. The town is also accessible by railway extended for about 500 km. Unlike other areas; Dire Dawa is good in the network of roads. Generally, the area is net worked by three types of roads. The 40 km asphalted road crosses the entire southern part of the study area and terminates at the town, Dire Dawa. This road gives good exposure especially for the basement and to some extent for the sedimentary terrain. There is also an all- weather gravel road crossing the area in different directions. This road is the longest and divides the area in to four major sectors. The last road (dry weather) also provides good access to the area but is limited only for dry weather. Here what is unique is that some of the tributaries/ river channels of the area are also suitable for vehicles to move on during dry season. As roughly computed, the over all road density of the area is about 0.25 km/km^2 , which means that the area is entirely accessible to make detailed tectonic mapping.

Fig.1 Location map of DireDawa area

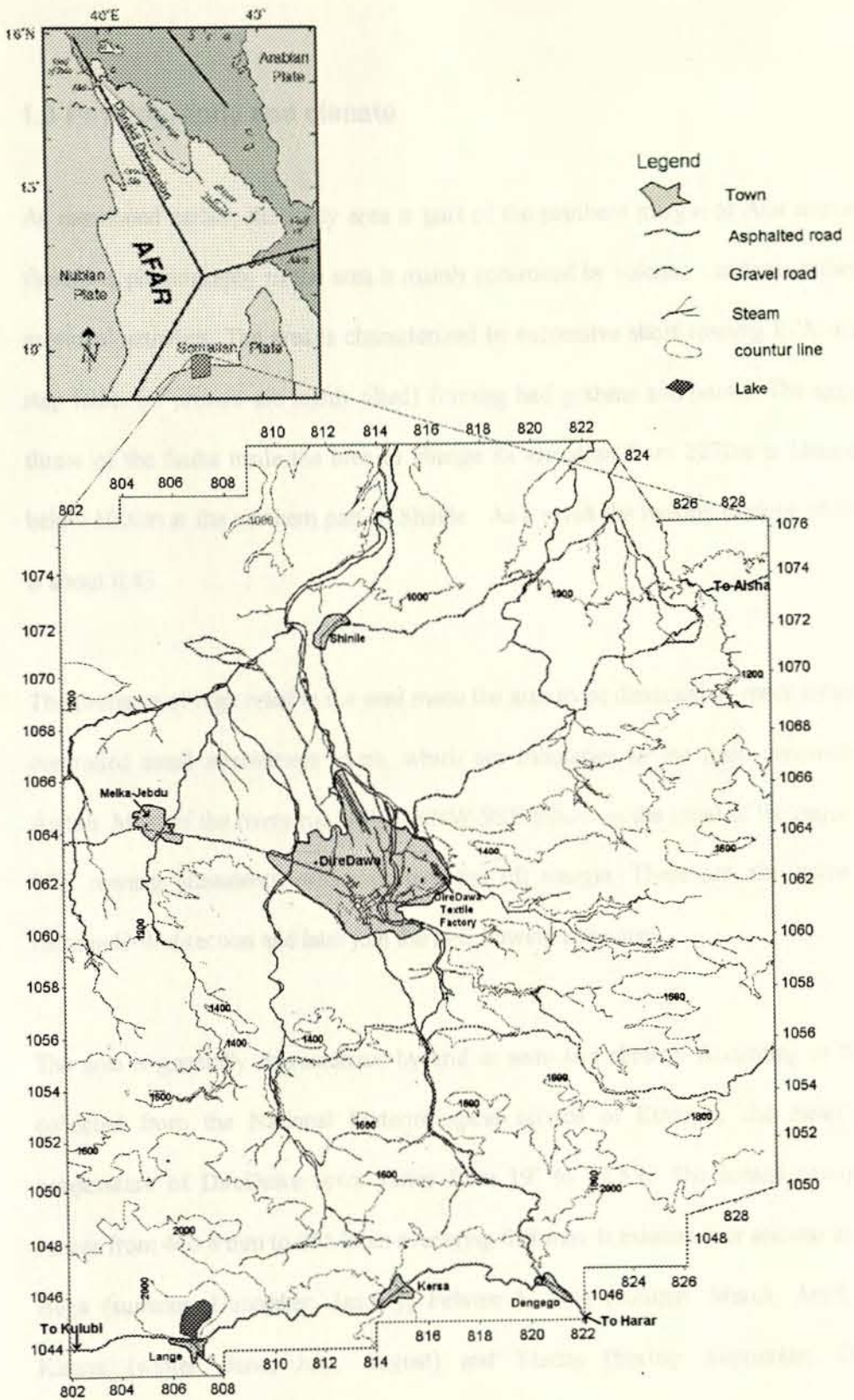


Fig.1.1 Location map of DireDawa area

1.3 Physiography and climate

As mentioned earlier, the study area is part of the southern margin of Afar depression; therefore, physiography of the area is mainly controlled by volcano - tectonic rather than erosional activities. The area is characterized by successive short running E-W oriented step faults (at present are highly tilted) forming half grabens and horsts. The aggregate throw of the faults made the area to change its elevation from 2272m at Dengego to below 1000m at the northern part of Shinile. As a result the maximum slope of the area is about 0.43.

The presence of high relief in the area made the area to be dissected by many tectonically controlled small intermittent rivers, which are tributaries to the main perennial river, Awash. Most of the rivers run N-S to NNW-SSE following the trend of the major NNE-SSE running lineaments, which crosses the rift margin. There are also some rivers running E-W direction and later join the N-S flowing tributaries.

The area is generally characterized by arid or semi-arid climate. According to the data collected from the National Meteorological service of Ethiopia, the mean annual temperature of DireDawa town varies from 19° to 32.5° c. The annual precipitation ranges from 440.8 mm to 855.2mm averaging 618 mm. It exhibits four seasons in a year: Bega (summer: December, January, February), Belg (autumn: March, April, May), Kiremt (winter: June, July, August) and Tseday (Spring: September, October, November). The highest rainfall is recorded during August with 157.9mm/month.

1.4 Objectives

The principal aim of this work is to study an area where tectonic and gravity induced block movements are well observed and to understand the process, which has led to the occurrence of highly tilted block movements, and to determine the chronological order of the structures existing in the area, and at last to come up with detail geological map of the area.

The principal objectives of this study are:

1. To decipher clearly the tectonic interaction among the different faults, in the southern Afar rift margin.
2. To evaluate block rotation and consequently determine structural evolutions of the area and study the nature of dykes using Paleomagnetic data.
3. To study secondary block movement towards the rift floor due to gravity, and finally
4. To examine in detail block tilting and associated internal structures.

1.5 Materials and Methodologies used

To accomplish the aforementioned objectives, the following materials and methodologies were used. The materials are:

1. Approximately 1:50,000 scale black and white aerial photographs of four strips, 26 in number, published in 1996.
2. 1:250,000 scale topographic map (DireDawa Sheet) published in 1979

3. 5, 1:50,000 scale topographic maps: DireDawa and Gerba Aneno sheets published in 2000; Kersa, Chelenko and Hurso sheets published in 1999.
4. Satellite imagery of landsat5 TM (thematic mapper) and related soft wares like: ENVI, Cartalnx, Arc view etc...
5. GPS (Garmin 12-Channel) for locating various geological structures, rock sampling points, contacts, hill tops etc...
6. Portable core-sample drilling machine for collecting core samples for paleomagnetic analysis (study).
7. Geological fieldwork kits such as: compass, hammer, lens, camera etc...

Having all the materials and equipments above, the field work was conducted in April 2003 and during this period, detail geological and structural mapping were done to produce a geological and structural maps on a scale of 1:50,000. The geological and structural maps were mainly proscribed by applying remote sensing applications such as *Haze correction, Georeferencing, Stretching, Spatial filtering and interpreting aerial photographs*

In all cases emphasis was placed upon systematic field observations, accurate measurements of the orientations of structural elements, careful recording of the data in the field note book, sketching and photographing of structures and preliminary analysis of structures in the field.

For the evaluation of block rotation and approximate chronological orders of the dykes, a total of 31 core samples from three separate sites were drilled in the field for paleomagnetism, and oriented in situ with a magnetic compass. As often as possible sun

orientation was also measured. At each site, at least 9 cores were collected from the basalt flow and basaltic dykes and sills, and with a distance of about 1 m between cores. Our sampling strategy was focused on the basaltic dykes and sills of the area. Back in the laboratory 2.5 cm-diameter cores were cut in to 2.2 cm-long samples, suitable for paleomagnetic laboratory of the geology and geophysics department, AAU using JR-6 Spinner magnetometer. Samples were demagnetized by alternating field. First measurement was taken at NRM (Natural Remnant Magnetization) and later with the following demagnetization steps (5mT, 10mT, 15mT, 20mT, 30mT, 40mT, 50mT, 60mT, 80mT, 100mT) (see the complete format of demagnetization step for a single specimen).

Finally, for the nomenclature of rocks in the area, 10 samples were prepared for mineralogical analyses in the Central laboratory of the Ethiopian Geological Survey (EGS). Based on the analyses rocks of the area are further classified.

1.6 Previous work

Published articles concerning the east African rift in general and the Afar depression in particular are many. However, most of them are out dated and dealt only with the petrology and geochemistry of volcanism and the extension direction of the Ethiopian rift.

Studies pertaining the geology, petrology and geochemistry of volcanism in the northern Main Ethiopian rift- southern Afar transition region are carried out by Christiansen et al. (1975), Civetta et al. (1975) and Chernet and Hart (1999).

Berhe (1986), Woldegabriel et al. (1990), Woldegabriel et al. (1992) gave a brief account on the geology and geochronology of the Ethiopian rift.

Meyer et al. (1975), Mohr (1975), Kazmin et al. (1980), Karson and Curtis (1989), Clin (1991), Gaulier and Huchon (1991), Chernet et al. (1998) and others conducted detail description on the volcano-tectonic evolution of Afar and Ethiopian rifts.

Although the extension direction in the East African Rift System is a matter of debate, many authors: Boccaletti et al (1992), Abbate et al. (1995), Boccaletti et al. (1998) and Acocella and Korme (2002) have outlined the extension direction differently.

Block tilting, rotation and continental extension of Afar has been discussed by Black and Morton (1975), Acton and Stein (1991) and Souriot and Brun (1992).

As outlined in the previous sections, it has not been clear up to now how the southern Afar rift margin has developed. There is no comprehensive understanding yet whether the margin is part of the east African rift or the Gulf of Aden. This, therefore, raises an interesting question as to how the southern Afar rift margin is related to that of the rift zones.

CHAPTER-TWO

GENERAL GEOLOGY

2.1 Introduction

The Ethiopian Rift is part of the East African Rift system and is characterized by a long history of magmatism associated with varying degrees of lithospheric extension (George and Rogers, 1999). It is a roughly NE oriented segment of the Eastern African Rift System, which extends from the Afar, across south western Afar and along the Main Ethiopian Rift valley almost to the Kenya border (Mohr and Wood, 1976; Boccaletti et al., 1998; Alula, 1990).

The Ethiopian Rift valley is an important part of this structure owing to its junction in the Afar depression, with the Red Sea- Gulf of Aden oceanic mega structure, where sea floor spreading is taking place. Though for simplicity the Ethiopia Rift is considered as a NNE-SSW oriented linear structure (Barberi et al., 1972; Berhe, 1986), it is, in reality a complex structure having orientations of N-S to NNW in the northern Afar, a nearly E-W trend in the south eastern Afar and a N-S direction in the southern Ethiopia. The Ethiopian Rift is considered to be active as compared to the other parts of the East African Rift. It encompasses highly to less evolved rift segments. As a consequence it is possible to divide it in to: the Afar, the Main Ethiopian and the Southwestern Rift zones (Boccaletti et al., 1998).

The Southwestern Rift zone is a broad structurally disturbed area containing four rift valleys which are: the northwesterly trending Kibish Rift, the north south striking Omo,

Ksno and Chew-Bahir Rifts (Alula, 1990). This Rift as part of East African Rift System is the transition zone between the Gregory Rift in the south and the Main Ethiopian/ Afar Rifts in the north (Meyer et al., 1975). A direct connection between the southern rift and the Gregory rift does not exist. The southwestern rift begins to close to the boundary of Ethiopia and Kenya. Such rift terminus is a typical site for the formation of large horsts.

Amaro horst, in this case, rises between two acutely bifurcating grabens at the southern end of the Ethiopian Rift (Bahat and Mohr, 1987; Meyer et al., 1975). This horst is not linked to one of the adjacent plateaux. Instead, horst-graben faults border Amaro on all sides, except its southern end where the horst and the bordering graben floors together merge imperceptibly in to the south Ethiopian plain.

The major rifting post-date the wide spread volcanism in the SER. Volcanism began in the late Eocene, followed by Oligocene basalts and by 12-13 my phonolite volcanism (Boccaletti et al., 1998). While major faulting pre-date the Pliocene Mursi basalts of the Omo group.

2.2 Volcano-tectonic activities of the northern main Ethiopian Rift

The main Ethiopian Rift (MER) is a graben with an average width of about 70 -80 km. It is walled to the east by the Somalian plateau and to the west by the Ethiopian plateau. Even though there is no clear limit, it starts in the north from an arbitrary Yerer- Gugu cross rift lineament and extends in the south where it bifurcates in to Ganjuli and galena (Ashenafy, 2003). In the northern section, the Rift cuts through the Oligocene Ethiopian

flood basalt and funnels out in to the Afar depression, which is characterized by modern amount of extension (β -factor about 2.5) and has a history of tholeiitic and transitional magmatism (George and Rogers, 1999). The bounding plateaus are composed of extremely deformed basement of Precambrian age unconformably overlain by horizontal-sub horizontal Mesozoic strata, which in turn are covered by tertiary volcanics.

Since the past three decades the volcano-tectonic aspect of the northern part of the MER has been topic of argument for several authors. Following the works of Mohr, Di Paola (1972) stated that the northern MER is affected by a set of north – northeast, south – southwest oriented normal faults in “en echelon” disposition which corresponds to the Wonji Fault Belt (WFB).

The successive periods of volcanic activity, according to Di Paola (1972), includes fissure eruptions with emplacement of explosive, dominantly ignimbritic products followed by volcano tectonic collapses. The youngest volcanic cycle include the building up of silicic central volcanoes on the ignimbrites followed by basaltic fissure eruptions and edification of recent mostly pantelleritic centers with associated “sub-historical” basaltic fissure eruptions.

Later Meyer et al. (1975) distinguished two main volcano tectonic units in the northern part of the rift system: an older Nazareth series and a younger Wonji series with Pleistocene – Holocene age. The two units are separated by a Nazareth faulting phase, which came in to activity many mya earlier before the Wonji fault.

The Nazareth series forms stratoid, Trachyte, rhyolites, ignimbrites and pumice. In the region of Nazareth, the succession, (Meyer et al., 1975; Alula, 1990) consists of light rhyolites and ignimbrites. Light pumice on top of Nazareth series has in some places greater thickness than normal because it accumulated in previously formed basins and grabens. Beds of tuff and yellow loam alternate in the pumice breccias.

The younger Wonji series, the, is built up mainly from large basaltic flows resulting from fissural eruptions. Trachytes, rhyolites, ignimbrites, pumice and tuffaceous materials are also found. The volcanics of this series is observed to strongly follow the north – northeast, south – southwest running faults or are erupted from fissures and vents in this direction.

From tectonic points of view the two phases are summarized as:

- “ In the first phase during the deposition of stratoid Nazareth Series with an age of 5 – 2 my a tensional stress caused the tectonic pattern with in the MER, with fractures and dykes trending NE - SW. The tectonic activity came to an end with the Nazareth faulting phase. The pattern during the Nazareth phase can be referred to as a tensional tectonics perpendicular to the direction of the MER.
- ◆ In the second and main part of the Nazareth faulting phase a Fundamental and completely different evolution began with the Wonji Fault Belt. Groups of fractures, open fissures and dykes show NNW –SSW and N – S trends. The north – northeast direction of the WFB is oblique to the direction of the MER and makes an angle of 10° – 25° with the NE – SW striking Nazareth fault series.

Christiansen et al. (1975); Kazmin et al. (1980); Berhe (1986); Chernet et al. (1998) and Chernet et al. (1999) gave a comprehensive age limit for the development of the northern main Ethiopian rift volcanics (Table.1.1). Kazmin et al. (1980) summarized the development of the rift as follows.

- ◆ The Ethiopian rift developed in stages, of which the main stages occurred at 15 to 14, 10, 4.5 to 4, and 1.8 to 1.6myr.
- ◆ At least the northern part of the Ethiopian rift was formed simultaneously with the Afar (15 to 14my).
- ◆ In the northern part of the Ethiopian Rift and in the Afar, initial down warping (14 my) was followed by intensive faulting and subsidence (10 and 4.5 my) and finally by formation of the axial zones (1.8 to 1.6 my).
- ◆ The slow rate of opening and crustal attenuation in the Ethiopian Rift provides favorable condition for the partial melting of the crust and the effusion of large volume of silicic volcanic rocks.

2.3 Volcano-tectonic History of the southern Afar Region

After the acceptance of plate tectonics theory, since the mid 1960s, several works concerning the evolution of the Great Rift Valley have been published. Some dealt on the volcanic and tectonic evolution of the newly formed young ocean basins (Red-Sea and Gulf of Aden); where as large number of publications dealt on the East African Rift, dominantly on the Afar depression. Despite of some inconsistencies, most works confirmed facts about the volcano-tectonic history of the region.

Barberi et al. (1972, 1975); Black et al. (1972); Kazmin and Berhe (1978); Kazmin et al. (1980) and others were the first to give a comprehensive summary of the development of Afar and the northern part of the Ethiopian Rift. According to Barberi et al. (1972 and 1975) the development of Afar and Ethiopian rifts started in the lower Miocene around 25 my ago. However, arguments put forward were that the oldest pre-rift volcanics (Alaji volcanics), which are best documented along the southeastern margin of the Afar, are 28-15 ma. (Morbidelli et al., 1975) and those same basalts occur in the Afar floor.

Most authors believe that the Barberi's et al. (1972) assumption was not soundly based. There was no data pointing to a sharp increase in thickness of the Miocene (Alaji) basalt in the zones of the Afar or the Ethiopian Rift escarpments (Kazmin et al, 1980). The thickness and composition of this basalt on the eastern periphery of Afar in the Aisha and Danakil uplift (Barberi et al., 1975, Kazmin et al., 1980), on the south eastern plateau and on the western margin of the Ethiopian plateau is rather uniform, while maximum thickness 2500m and more, occurs in central – eastern parts of the Ethiopian Plateaus. Therefore, there is no proof that the basalt thickness increases towards the rift but general increase to the west can be inferred from the fact that the Miocene basalts are much thicker on the Ethiopian and on the south eastern plateaux (Kazmin et al., 1980)

Kazmin and Berhe (1978) disproved the development of Afar, which was dated to 25 my that the major rifting of southern Afar and the Ethiopian Rift started at 14 my contemporaneously with formation of the Mablā rhyolites (14-11 my ago) and Anchar Basalts (11-10 my ago) along the margins of southern Afar and the eastern margin of the Ethiopian Rift. Concurrently the Jebel Sadalle and Gara Mulata basalts were developed along the rift shoulders. As cited in Berhe (1986) a basaltic unit at the base of Gara

Mulata gave an age of 13.3 my, and the base of the Jebel Sadalle Basalts has been dated at 14 mys old (Kuntz et al., 1974). This means that they correlate with the Termaber Basalt of the central Ethiopian plateau.

Following the eruptions of Alaji-Anchar-Gara Mulata basalts, another important events in the rift formation occurred in the late Miocene and early Pliocene; at this time faulted eastern escarpment was forming, west of this escarpment thick accumulation of peralkaline silicics of the Nazareth group began around 9 Ma ago (Chernet and Zewdie, 1983). They are well developed in the Main Ethiopian Rift, but absent in the northern terminus of the transition zone and in all Afar depression. As stated in Berhe (1986) the Nazareth silicic volcanics are equivalent but different in composition with the lower most Afar Stratoid Basalts dated at 7.4 my. In other words the Nazareth silicics/series or pre Wonji series forms as a stratoid series in the rift floor of the MER (Meyer et al., 1975).

Initial formation of the Afar was followed by wide spread flood basalt volcanism in the developing depression (Chernet et al., 1998). Christiansen et al. (1975) stated that the entire post rift volcanics consist of four series, which are separated from each other by periods of faulting. These series are:

1. Lower most Afar series (Lower Pliocene)
2. Lower Afar series (Lower – Middle Pliocene)
3. Afar Series (Late Pliocene – early Pleistocene)
4. Aden Series (Pleistocene – Sub recent)

Lower most Afar Series: - this volcanism started in the lower - Pliocene (that is at 11 - 10 my ago) with eruptions of fissural basalt, after an important phase of down faulting in the late Miocene which has marked the present outlines of southern Afar. They are now exposed along the foothills of the south - eastern escarpment.

Lower Afar Series: - this stage of flood basalt volcanism between 8 - 5 my (Kunz et al., 1975) can be traced nearly continuous along the Afar margins from the main Ethiopian Rift towards the Aisha and Tadjoura region. Around 5 my ago the volcanic activity again ceased and a period of faulting can be reconstructed effecting at least marginal parts of the Afar and the region of the later Wonji Fault Series.

Dating back from 5 to 1.5 my, a further episode of faulting and tilting occurred concurrently with the last volcanic phase of the rhyolites centers (Berhe, 1986; Christiansen et al., 1975). This tectonic episode, according to the authors, caused extensive eruptions of the Afar Stratoid Basalts covering large area of the Afar floor unconformably overlying the lower Afar Stratoid Basalts.

The last episode of rifting took place between 1.8 my to present. As pointed out by many authors (Mohr, 1967; Meyer et al., 1975; Berhe, 1986; Kazmin and Berhe, 1978; Christiansen et al., 1975 and others), the latest volcanism in the Afar and Ethiopian Rift is related to its axial extension zone, the Aden series (Christiansen et al., 1975) in the case of Afar and the Wonji Group (Main Ethiopian Rift). Lower Pleistocene faulting affected the entire graben floor and caused a drastic change in the distribution and mode of occurrence of volcanic rocks. The distribution of the Aden series well reflects the connection of strong dilatation by normal faulting and magmatic activity which lasted from the lower Pleistocene to Historic times, and is restricted to internal graben and

marginal zones (Christiansen et al., 1975). In the southern Afar the Aden Series volcanics are known from the two segments of the Wonji Fault Belt: the Hertale and Ad Ado graben, and furthermore, from the E – W directed marginal Goflol structures east of DireDawa. The Wonji series forms the upper unit within the main Ethiopian Rift, especially in its northern part. According to Kazmin and Berhe (1978) the Wonji Group includes all rift volcanics formed after the last major episode of rift faulting which followed accumulation of the Bofa Basalts. The volcano-tectonic evolution of the region (northern main Ethiopian – Southern Afar transition zone) starting from pre-rift volcanics (Alaji basalt) to the recent Wonji group and Aden Series is summarized in

Table 1.1

Time (Ma)	Geological Event	Volcanic Series	Reference
11-12 Ma		Archaic Basalts Dora Mela Basalts Maha Kregaha	Kazmin et al. (1976) Mortelmans et al. (1973)
10 Ma	Major rift development		Chernet et al. (1978)
8-9 Ma	Faulting & Downs warping	Aden Group Basalt	
7 Ma			
6 Ma			
5-4 Ma		Neogene Group Lower Afar Strained zone	Christiansen et al. (1975)
4-3 Ma			
3 Ma	Further episode of rifting and subsiding	Afar Strained Series Bofa Basalt	Molz (1974) Meyer et al. (1971)
2 Ma			
1 Ma - Present	Last episode of rifting Wonji Fault Belt	Wonji Group Aden Series	Kazmin et al. (1978) Chernet et al. (1977)

Table 2.1 Evolutionary history of the Afar and northern Main Ethiopian Rifts

Age Range	Rift Development	Volcanic Activities	References
Oligocene-Miocene (28 – 15 Ma)	Pre-Rift (None)	Alaji Basalt	Berhe (1986) Chernet et al. (1998)
Miocene	None/Weak	Tarmaber/Jebel Saddale Basalt	Kazmin et al. (1980)
Miocene 14 Ma 14-11 Ma 11-10 Ma	Rifting commenced	Arba Guracha Silicics Anchar Basalts Gara Mulata Basalts Mabla Rhyolites	Berhe (1986) Kazmin et al. (1980) Morbidelli et al. (1975)
Miocene 10 Ma 8.5 Ma	Major stage in rift development Faulting & Down warping	Arba Gugu Basalt	Chernet et al. (1998)
Miocene - Pliocene 9.5 – 4 Ma 8 – 5 Ma		Nazareth Group Lower Afar Stratoid series	Christiansen et al. (1975)
Pliocene 5 – 2 Ma 3.5 – 2 Ma	Further episode of rifting and tilting	Afar Stratoid Series Bofa Basalt	Mohr (1974) Meyer et al. (1975)
Quaternary/Pleistocene – Recent < 1.8 Ma	Last episode of rifting Wonji Fault Belt	Wonji Group, Aden Series	Kazmin et al. (1980) Chernet et al. (1999)

2.4 Structural Elements of the Southern Afar Region

As discussed earlier the tectonic trends, styles and stages of extensional faulting are variably high, these are thought to be caused by differential spreading and propagation of Red Sea-Ethiopian and Aden Rifts, in space and time (Kronberg, 1991). Consequently the fault patterns present in the Afar Depression are extremely complex as they reflect the presence, interference and superposition of the three main trends of crustal extension.

Afar triangle is, therefore divided into two quite different structural units (Barberi et al., 1972 p.22): the Red Sea - Gulf of Aden mega structure (NNW-SSE and WNW-ESE trends respectively) and the northern end of the East African Rift (NNE-SSW). The southern sector of this region also incorporates the mentioned structural units except that the NNW - SSE oriented extensional faults of the Red Sea are substituted by the northwesterly transcurrent fault zones which cutoff the southeastern rift margin and extends northward to the rift axis.

As stated in Berhe (1986) and Meyer et al. (1975) the southern margin of Afar is characterized by a number of tectonic trends: the Gulf of Tadjoura, Nazareth and Wonji trends, and the northwesterly fault zones.

The Tadjoura fault trend E-W or ESE-WNW are restricted to the southern Afar rift margins up to the vicinity of the Gulf of Tadjoura (Berhe, 1986). Detailed structural map of Christiansen et al. (1975) has shown that the E - W oriented faults act like transform faults as they cross the axial range of southern and central Afar. During the major stage

of rifting, extension occurred in an ENE direction with a smaller component in the N – S direction (Black et al., 1975). From 7 my ago the region west of Aisha was affected by extension in a NE – SW direction (Berhe, 1986). This is parallel to the direction of plate separation along the Gulf of Aden.

The second most observable structure of the area is the NE-SW trending fault system. The Nazareth fault trend defines the margins of Northern Main Ethiopian Rift-Southern Afar transition zone. It has been described in the Nazareth area by Kazmin et al. (1980) where they are dated at 9-5 mys old by their association with volcanic rocks of the same age. This tectonic activity came to an end with the Nazareth faulting phase about 1.6 to 1.8 mys ago near the boundary of Pliocene/Pleistocene time. The pattern during the Nazareth phase can be referred to as a tensional tectonics perpendicular to the direction of Rift. However, recent studies on the main Ethiopian Rift show that the boarder faults are not purely extensional, the evidences of a strike slip component of motion has been documented (Boccaletti et al., 1992).

In the second and main part of the Nazareth faulting phase a fundamental and completely different evolution began with the Wonji Fault Belt (WFB). This Pleistocene to recent faulting generally trends NNE-SSW and is restricted to the axis of the Rift (Berhe, 1986). Groups of fractures, open fissures and dykes show a north-northeast, south-southwest an north-south directions. The NNE direction of the WFB is oblique to the direction of the MER and makes an angle of 10-25 degrees (Alula, 1990). As cited in Berhe (1986) the limited extent of this trend and the lack of intersecting faults surrounding its zone of occurrence led (Tazieff et al., 1972) to conclude that the Ethiopian Rift played a very minor rock in the formation of Afar.

The last structural unit, which is orthogonal or nearly orthogonal to the E-W trending Tadjoura, is the northwesterly fault zone. These northwesterly trending fault zones in the DireDawa area are parallel to the Marda Fault Zone, which is a major structural element in the horn of Africa. These faults pre-date the Wonji fault belt, but are thought to be rejuvenated from pre-existing structures. The Northwesterly Fault zones have displaced the southeastern escarpment by 10-15 km in the Dire Dawa area, while the Marda Fault has displaced the Aisha block by about 110km (Berhe, 1986).

Black et al. (1975) summarized that in the Dire Dawa-Aisha region, there are two separate tectonic domains, which are separated by the Bia Anot, north striking transcurrent fault. The Southern Dire Dawa domain forms the margin of the Harar-Somalia plateau and consists of a 50 km wide zone of antithetically tilted blocks of Precambrian overlain by Mesozoic sediments and trap series basalts dipping 10- 30° south, partly obscured by younger basalts and alluvium. In the northern Aisha domain a similar stratigraphy is affected by dominantly N and NNW striking faults of the Red Sea trend producing fields of blocks tilted at angles of 20°-50° W or E. The abrupt juxtaposition of these two domains is best explained by a major sinistral movement

As stated in Morton and Black (1975) the areas of pre-Miocene rocks exposed with in Afar are all intensely faulted by normal faults, and the blocks between the faults are strongly tilted. Typically, a series of faults up to a kilometer apart, all or nearly all with the same direction of throw; separate a series of tilted blocks with beds dipping in the opposite direction to the fault. Often the dip angles are similar on successive blocks, and field of tilted blocks with dip angles up to 40° are commonly observed. Locally the dip

angles are more variable from block to block and extreme dip angles of up to 90° had been recorded. In areas of strongly tilted blocks the faults may dip at only shallow angles or even show a horizontal attitude. Finally what they concluded is that on the escarpments flanking the Afar, bedding dip angles often increase progressively from the plateau towards the depression, the escarpment regions being characterized by a series of step faults rather than by the large master faults typical of many continental rift

CHAPTER-THREE

APPLICATION OF REMOTE SENSING AND PALEOMAGNETISM IN STRUCTURAL GEOLOGY

3.1 General

In the dynamically growing world, the intention of human beings to know and manage their surrounding is dramatically mounting. Peoples are able to know and exchange information about the Earth with in real time. The cause for fast information exchange is due to the availability of satellites, which are put at various orbits in space. In this topic the aim is not to see the nature and characteristics of satellites but to process and interpret the remotely sensed image of the study area.

Remote sensing is the acquisition and measurement of data/information on some properties of a phenomenon, object, or material by recording device not in physical, intimate contact with the features under surveillance/investigation. Whatever working definitions we use to describe remote sensing, the key concept is that remote sensing involves making observations remotely, or without physical contact with the object under investigation. The remote nature of these technologies allow us to make observations, take measurements, and produce images or phenomena that are beyond the limit of our senses and capabilities.

Nowadays, the application of remote sensing in the study of regional structures and geological maps (small scale) is becoming vital, because the ability of human eyes to

scene large area at a time is very limited. Before the advent of satellite imageries, geologists had used aerial photographs for decades as data bases for mapping rock units (stratigraphy), study the expression and modes of origin of land forms, determine the structural arrangements of disturbed strata (faults and folds), evaluate dynamic changes from natural events (eg. Floods, volcanic eruptions), and seek surface clues (such as alteration and other signs of mineralization) to subsurface deposits of ore minerals, oil and gas and ground water exploration (Nicholas, 1998). With the advent of space imagery, geoscientists now can extend that use in three important ways:

- the advantage of large area or synoptic coverage allows them to examine in single scene (or in mosaics) the geological portrayal of the Earth on a regional basis
- the ability to analyses multispectral bands quantitatively in terms of numbers (DNs) permits them to apply special computer processing routines to discern and enhance certain properties of Earth materials.
- the capability of merging different types of remote sensing products or combining these with topographic elevation data and with other types of information bases (eg. Thematic maps, geophysical measurements, chemical sampling surveys) enables new solution to determine interrelation among various natural properties of Earth phenomena.

These all and some other application of the satellite imageries make remote sensing as a basic tool for various disciplines. In our case, in the study of global tectonics, it would have not been plausible without the inputs of remote sensing. Lineament analyses using

space images have been particularly valuable in determining regional and continental fracture patterns that reveal some of the stress history imposed on large crustal units.

GIS:- Geographic Information Systems are computer based systems that are used to store, retrieve, manipulate and analyze geographic information. This technology has developed so rapidly over the past three decades that it is now accepted as an essential tool for the effective use of geographic information (Aronoff 1989). GIS has the ability to spatially interrelate multiple types of information stemming from different sources. As remote sensing has routinely provided new and high-resolution images of the Earth's surface, it should be intertwined with GIS as a means to constantly and inexpensively update some of the data that comprise an integral segment of a GIS.

3.2 Digital Data and Processing Technique

The satellite data scene used in this work is obtained from landsat-5 TM acquired in----- . The data was primarily used for the area of Aisha and Tadjoura, which are found in different UTM zone (zone 38). As the study area is the western extension of those areas, part of the scene is used for our purpose. The bands available are TM band1, band2, band3, band4, band5, band6 and band7. As the data was part of the Aisha block and has got inherited geometric distortion, various digital image-processing techniques have been applied to register and rectify the digital data.

3.3 Digital Image Processing

Digital image processing is an extremely broad subject, and it often involves procedures, which can be mathematically complex. It involves removing geometric distortion, to calibrate the data radiometrically and to make an image more interpretable (Image Enhancement) for a particular application. The major processing techniques applied to rectify and enhance those bands are: Haze correction, Georeferencing, Stretching and Spatial filtering.

3.3.1 Haze (Radiometric) Correction

Haze correction influences the brightness values of an image to correct for sensors malfunctions, or to adjust the values to compensate for atmospheric degradation (Aronoff, 1989). Like all other materials on Earth's surface, atmospheric particles also reflect or emit radiations that will be captured by sensors. Unless not corrected, such additional reflectance may lead to wrong image interpretation. Atmospheric scattering is high in low-lying regions like Afar. This may be due to the thermal disturbance in the atmosphere.

Atmospheric degradation can be corrected by many techniques, but the most widely used and applied in this work is by plotting DN values for a high-wavelength band usually in the infrared where scattering is at a minimum against those for a band in the visible region where scattering has a greater effect (Drury, 1993). The second way is

based upon examination of reflectance from an object of known or assumed brightness recorded by multispectral imagery. Based on the above two techniques a DN value of about 17 (cut-off or dark-pixel correction) resulting from the atmosphere has been subtracted from the DN value of each pixel.

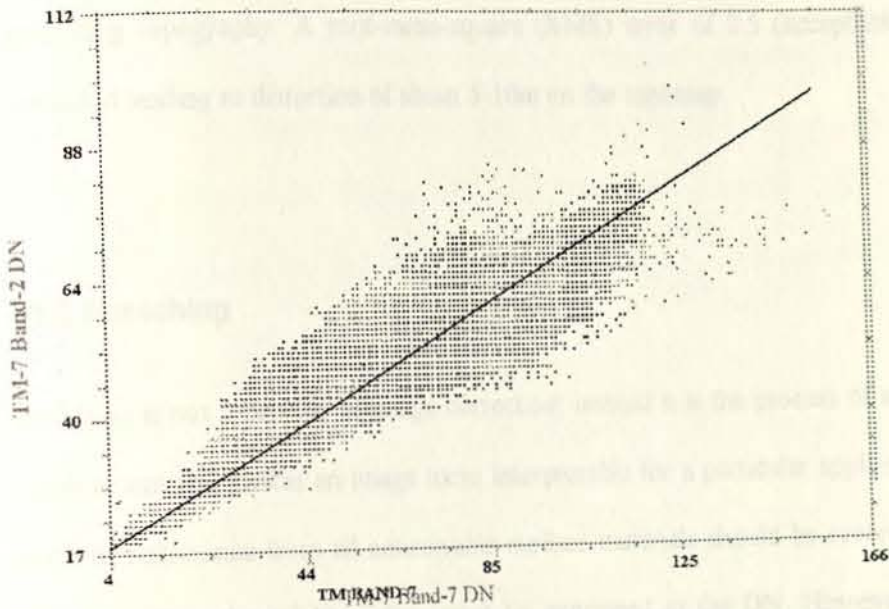


Fig.3.1 Two-dimensional scatter plot for high-wave length band (Band-7) usually in the infrared where scattering is at a minimum against those for a band in the visible region (Band-2) where scattering has a greater effect

3.3.2 Georeferencing

Raw digital images usually contain geometric distortions so significant that they cannot be used as maps. The sources of these forms of distortions range from variation in the altitude and velocity of the sensor platform, to factors such as panoramic distortion, Earth curvatures, atmospheric refraction, relief displacement, and non-linearity in the sweep of a sensor's IFOV. Although these are the principal factors for distortion, the digital image of DireDawa did not have all these problems. It was already georeferenced with respect to UTM projection of zone-38. But co-ordinate translation has been made to bring the earlier georeferenced image to the exact co-ordinate (location) of zone-37.

The translation applied is based on the existing topographic maps at a scale of 1:50000. Six ground control points (GCPs) were identified both on the topomaps and the Satellite image to be corrected. The GCPs are evenly distributed all over the area with relatively large number of points on the rugged slopes to minimize correction errors due to undulating topography. A root-mean-square (RMS) error of 2.5 (acceptable error) is computed leading to distortion of about 5-10m on the topomap.

3.3.3 Stretching

Stretching is not a process of image correction; instead it is the process of single image enhancement that makes an image more interpretable for a particular application. A full range of reflectance from all conceivable surface materials should be recorded and the dark as well as the bright surface must be expressed in the DN. However, only few Earth's surfaces have these extremes. Consequently, histograms for most images are compressed in to relatively narrower portion of the 0 – 255 range (Drury, 1993). Displaying the cumulative histogram can indicate the degree of contrast between different surface features. An image with compressed histogram appears to have a very poor contrast. Process of stretching changes DN values in an image to any of the 256 intensity levels and expands the histogram so as to occupy the full range of DN values (0 – 255). The minimum DN is set to 0, the maximum to 255. This technique (linear stretching) enables us to better visualization of the various lithologic units and structures of the DireDawa area.

The integrated result of the above three techniques provide us with well defined geological map (fig.3.2)

3.3.4 Spatial Filtering

Another processing procedure falling in to the enhancement category that often divulges valuable information for structural mapping is *spatial filtering*. This technique explores the distribution of pixels of varying brightness over an image and, especially detects and sharpens boundary discontinuities. The high frequency features such as faults, fractures and other lineaments are filtered with convolution of directional filters to enhance features such as faults and lineaments along the E – W, NE – SW and NNW directions (fig.3.4 a, b).

3.3.5 Band ratioing

Different Earth materials have their own reflectance property. Some are well registered by one band and others by the other bands. The process of dividing one band by another gives good color contrast between features. It also helps to distinguish the effect of varying illumination caused by topography. For the same material, slopes facing the sun are more strongly lit than horizontal surfaces, and those facing away from the sun receive less radiation. This problem is solved by dividing one band by another. In fig.5.2 Band7 is divided by band3, the ratio shows good color contrast between basalts and the other materials.

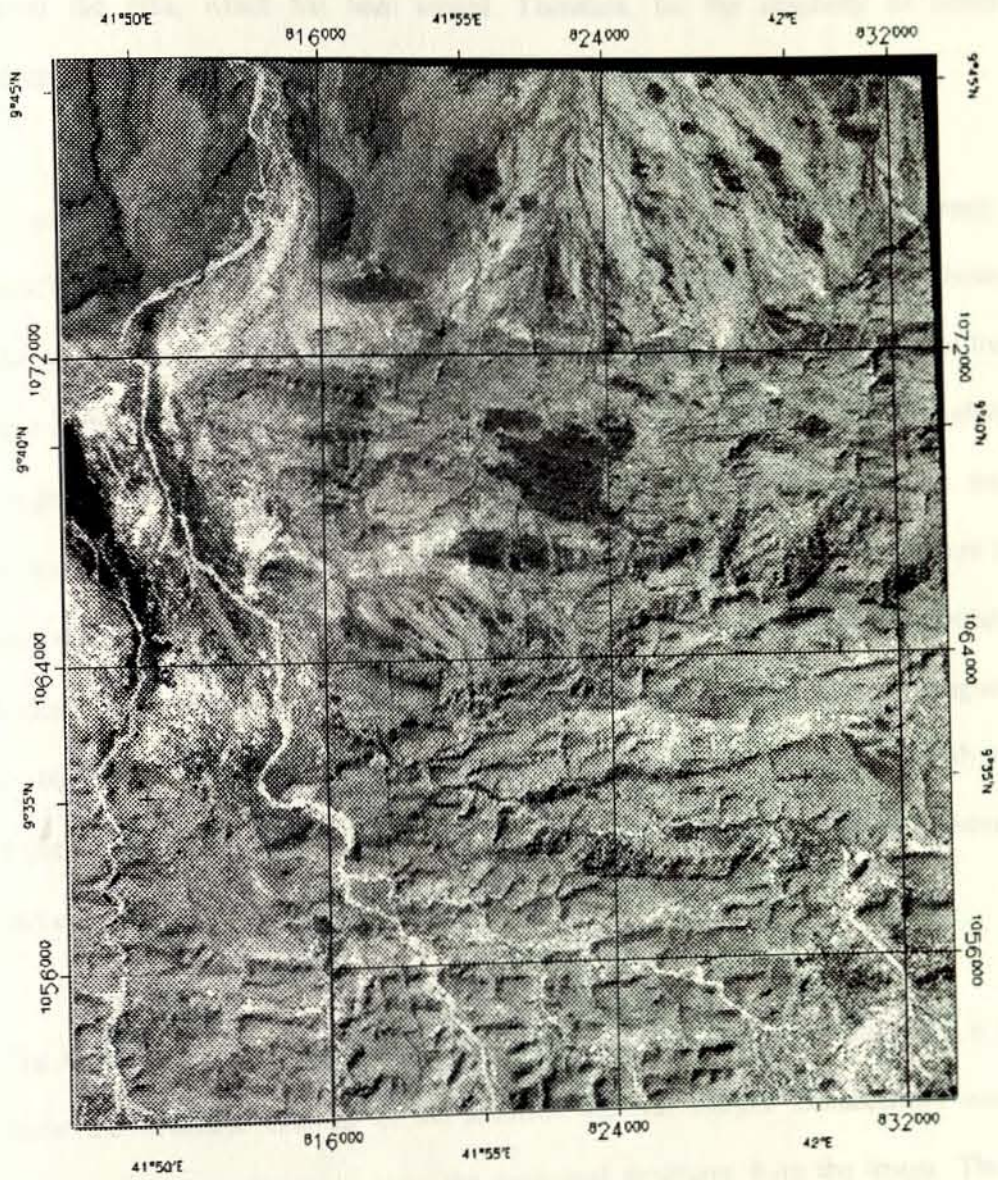


Fig.3.2 Band ratioing between band7 (nominator) and band3 (denominator)

3.4 Geological and Structural Mapping

In the aforementioned topics, we saw few of the ways/techniques of the digital image processing. Each band of the image is then corrected and enhanced with respect to the processing techniques. But most of the time a single band does not give full information about the area, which has been sensed. Therefore, for the simplicity of image interpretation, color composite images are mostly preferred.

To produce a satellite image based geological map of DireDawa, three bands (namely: band7, band5, band3) are selected. The color composite image of the three bands shows that the area is lithologically divided in to three major groups. The southern part of the area is characterized by light-green to green colored features, and texturally it is slightly rough. These are predominantly of basement rocks. While the central, eastern and western parts of the area are covered by grey to brownish-grey color. Their texture is very smooth. These colors and texture are representatives of the Mesozoic Sedimentary rocks of the area. And the northern and northwestern portions of the area are assigned by blue to brownish blue color accompanied with rough texture. These are mainly of mafic rocks (fig3.3). Scattered spots of mafic rocks are also observed in the northeastern part completely enclosed by the sedimentary rocks.

The second but most important application of the satellite imagery in this work is to study the structural interplay of the southern Afar rift margin. Enhancement using directional filters helps in mapping the geological structures from the image. Three distinct fault systems are observed in the image. The dominant structures are those running in an E – W direction. These are normal faults that constitute the rift margin. The second once are those aligned in the N – S or NNW – SSE direction. These are

major lineaments that are cut by the E – W oriented structures. Some of these structures are seen magnified by the north south running drainages. The third fault systems run in a NE – SW direction. These are mainly restricted to the northwestern part of the area.

Satellite based geological maps and structural maps are then mains for the preceding chapters to produce detail geological and structural maps of the DireDawa area.

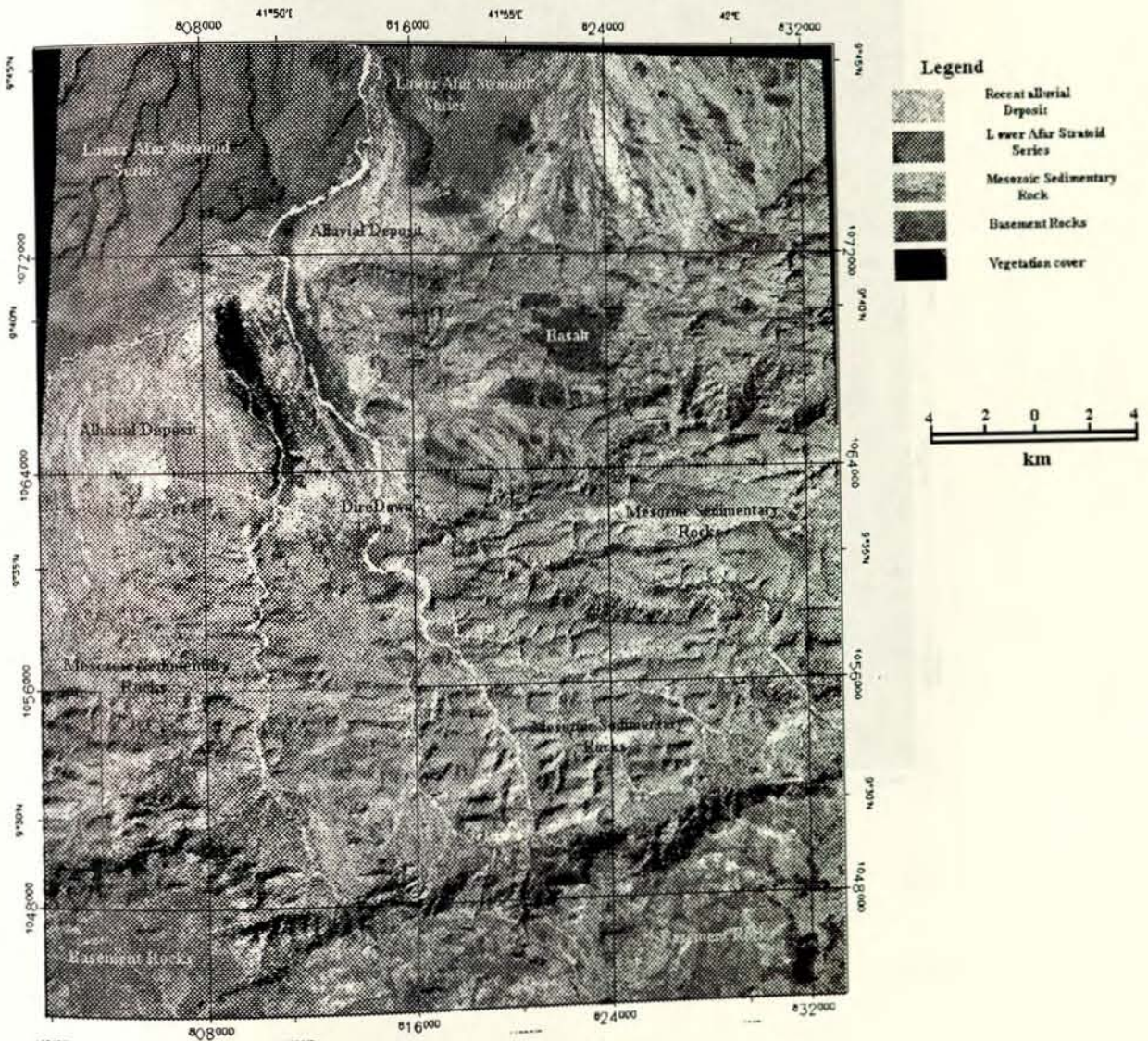
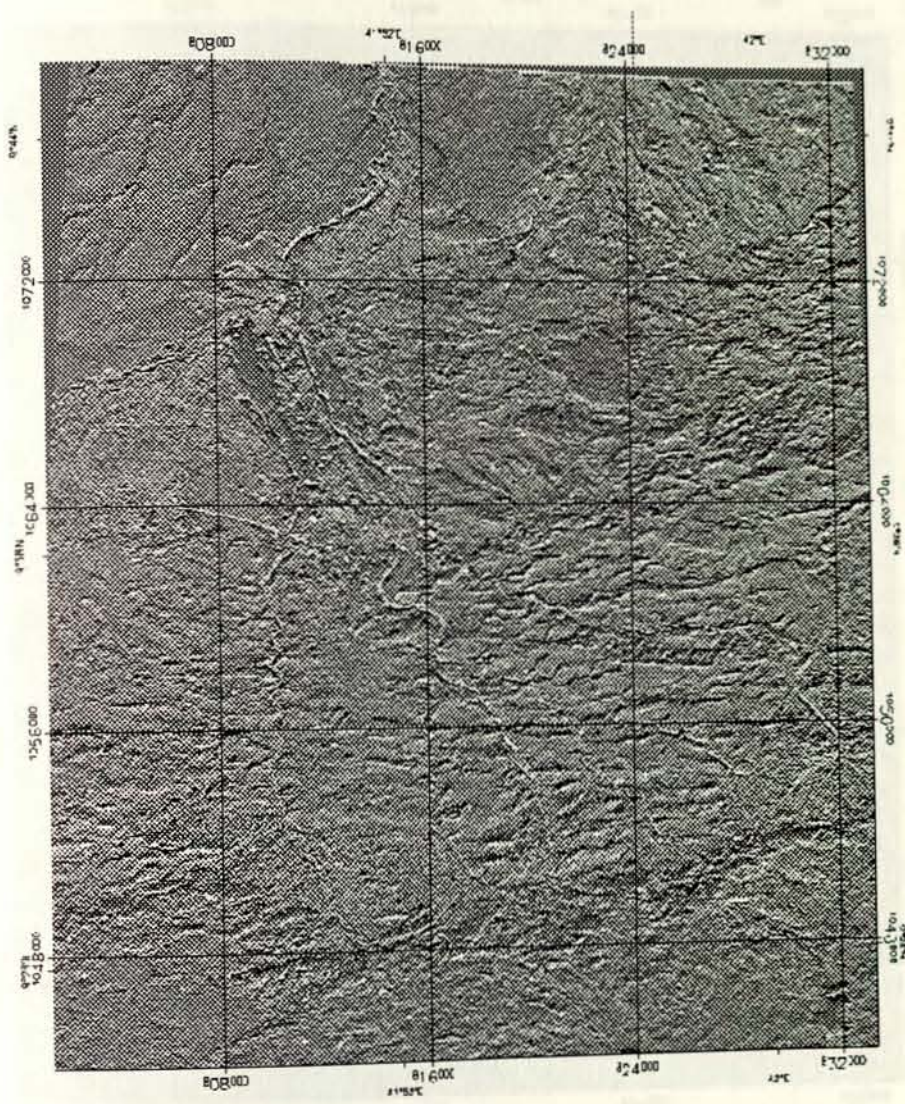


Fig.3.3 color composite image of DireDawa and its vicinity



Topographic map of the area shown in Figure 1. The map is oriented along the same axis as the photograph in Figure 1.

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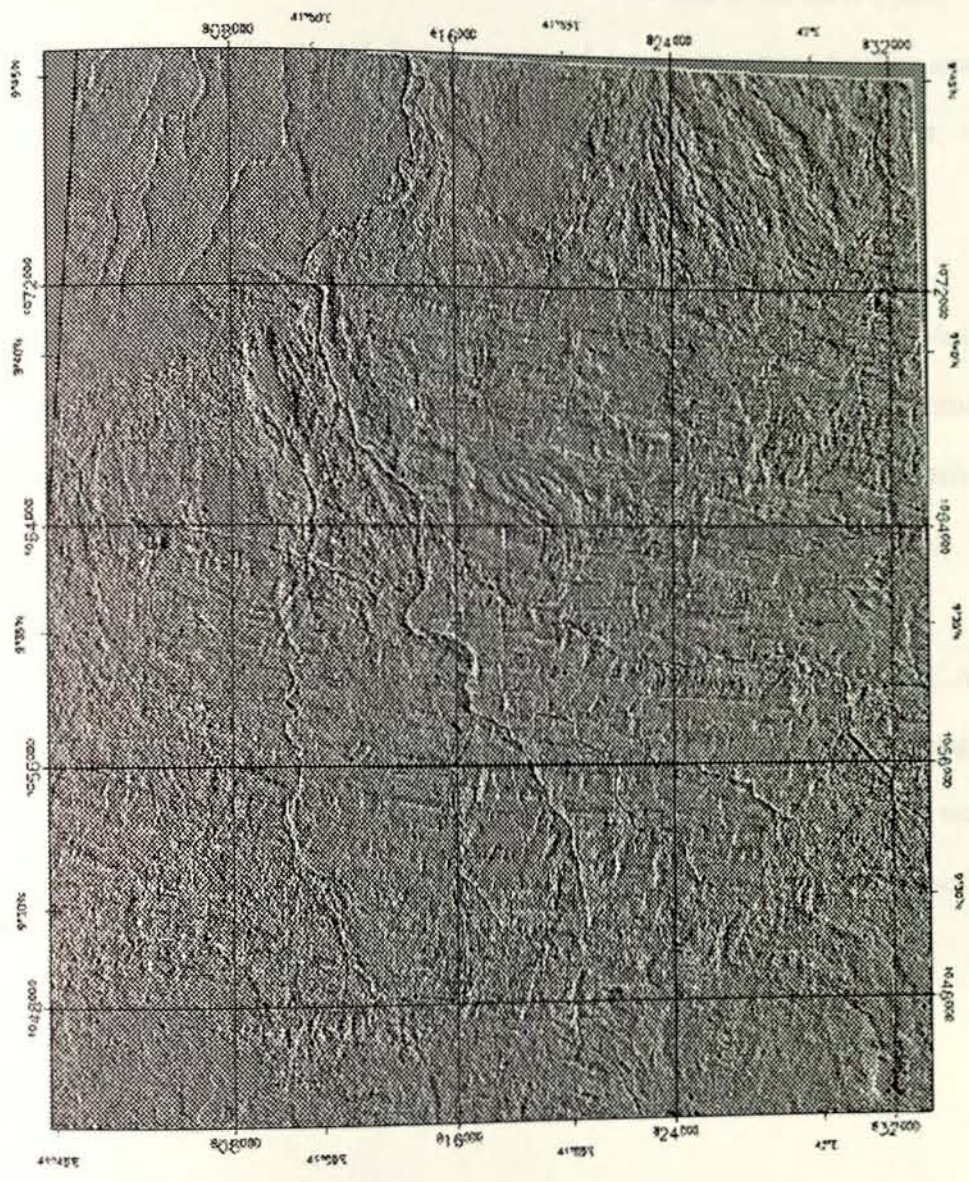


Fig.3.4 enhanced satellite image (a) Filtered along E - W (b) Filtered along S 20° E directions

3.5 Aerial Photography

Aerial photographs are the most easily available of all remotely sensed data, and have been acquired at various scales for much of the land area of the Earth (Drury, 1993). Aerial photographs are not digital images and are not as easy as Satellite images to correct their geometric errors and enhance their interpretability. However, various techniques can be applied to correct and enhance aerial photographs.

Like Satellite images, aerial photographs are also affected by large amount of distortion, especially at the peripheries of each photograph. So as to remove this distortion and make the photos more consistent, georeferencing is applied to each photograph. After then each feature in the photograph is very close to its exact geographic location.

The last procedure, which was applied to the aerial photographs, was merging (mosaicing) a number of georeferenced images to a single one. Mosaicing aerial photograph is very important in the study of structural geology. Because this technique enables us to examine in a single scene the geological structures of the earth on a regional bases.

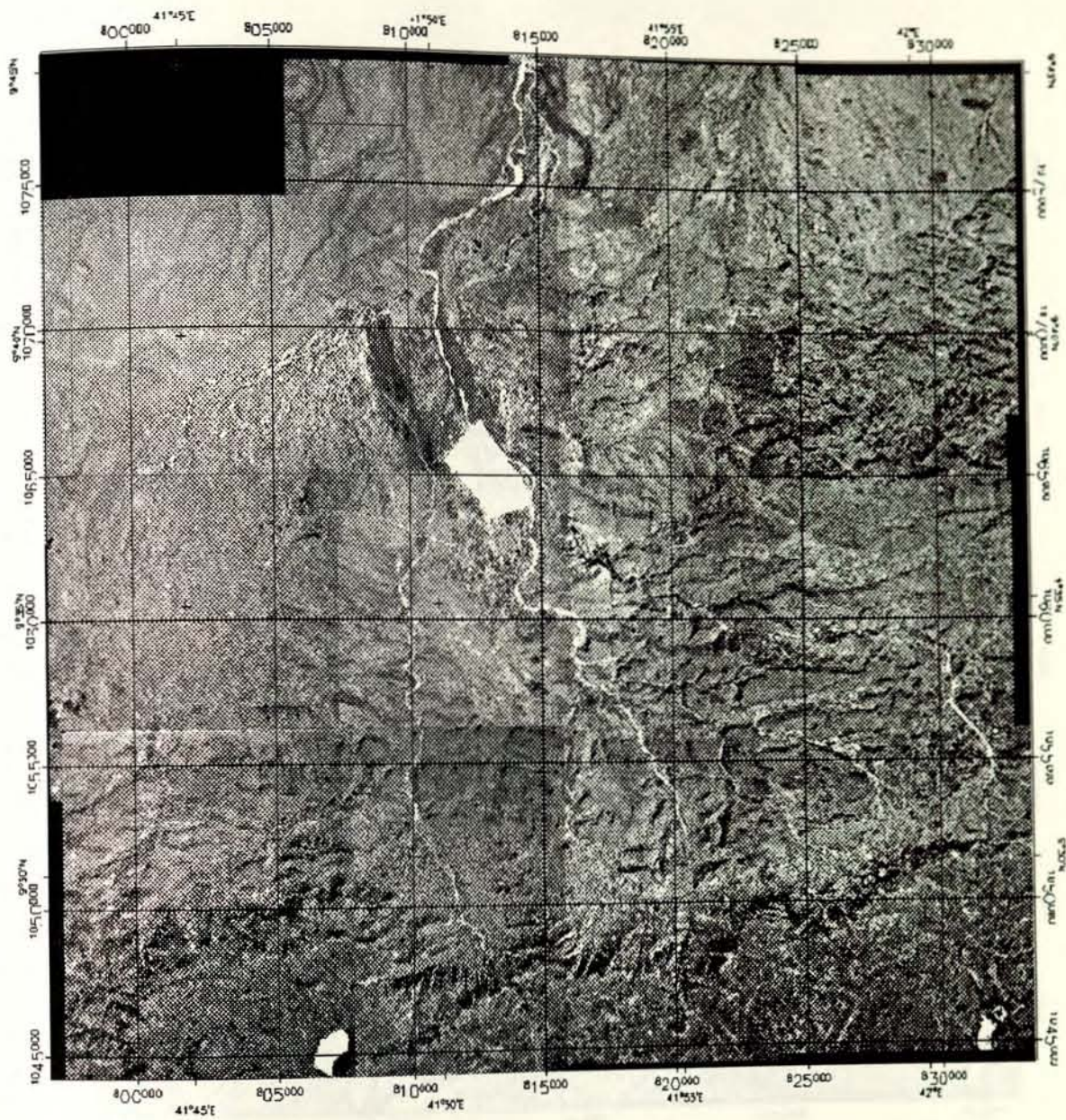


Fig.3.5 Georeferenced and Mosaicked aerial photographs of DireDawa area

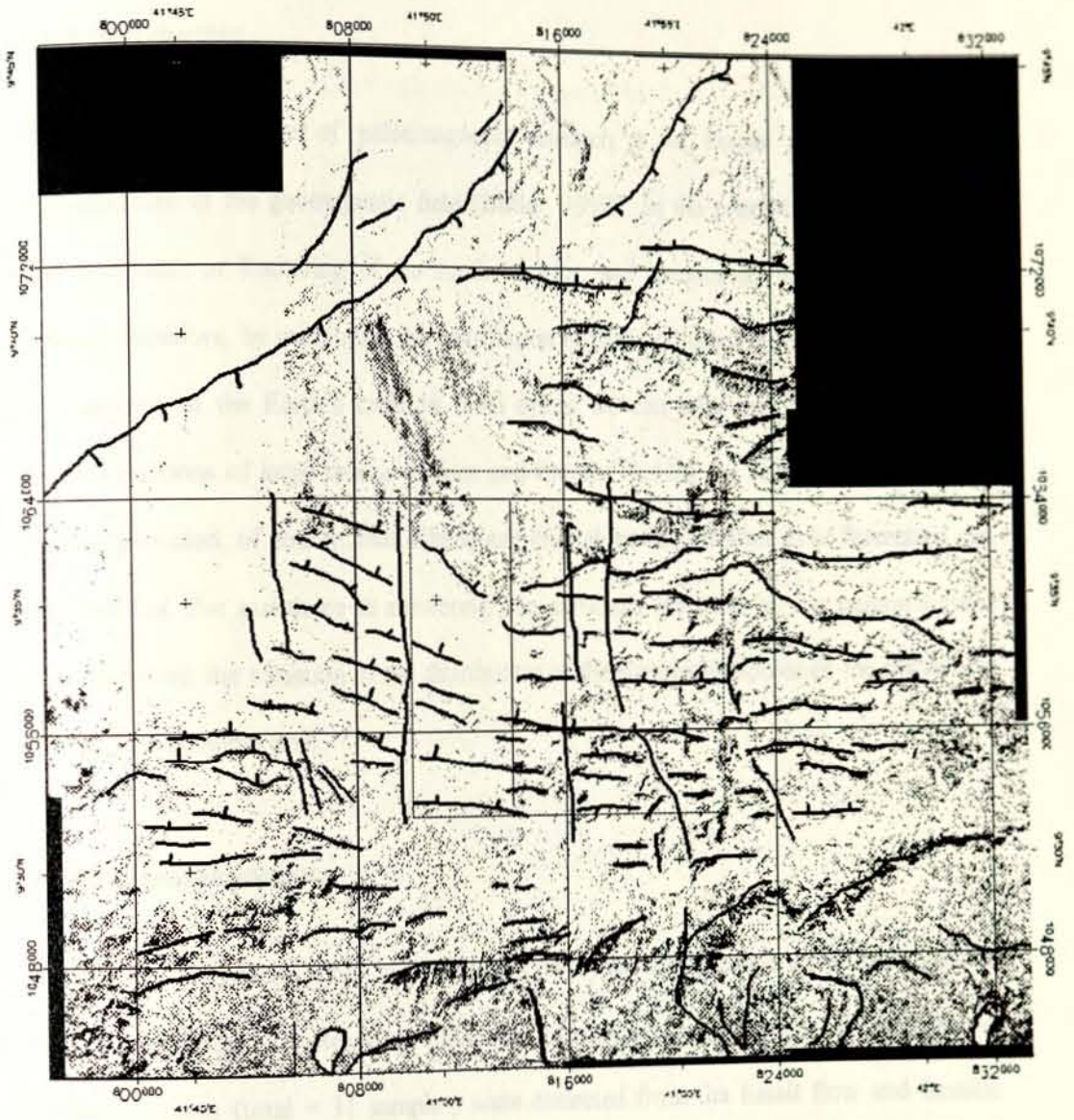


Fig3.6 *Filtering geological strictures from the mosaicked aerial photographs*

3.6 Paleomagnetism of DireDawa

3.6.1 Introduction

The primary objective of paleomagnetic research is to obtain a record of past configuration of the geomagnetic field (Butler, 1992). In the present study we assume that tectonics, or fracturing of the southern Afar, and igneous activities are intimately related, therefore, by measuring the distribution in time and space of magma intrusion in to fractures of the Earth's crust to form dykes we can infer the stress patterns and relative motions of large crustal masses and thereby deduce the tectonic history of the region, provided, of course, that subsequent crustal movement after dyke formation can be recorded. For assistance in answering this particular question we use paleomagnetic data to record the variation in the distribution of the magmatic dipoles of the dykes as a function of geologic time.

3.6.2 Paleomagnetism

A total of 3 sites were drilled in the field for paleomagnetism, and oriented in situ with a magnetic compass. As often as possible sun orientation was also measured. At each site, at least 9 cores (total = 31 samples) were collected from the basalt flow and basaltic dykes and sills, and with a distance of about 1 m between cores. Our sampling strategy was focussed on the basaltic dykes and sills of the area. Back in the laboratory 2.5 cm-diameter cores were cut in to 2.2 cm-long samples, suitable for paleomagnetic laboratory of the geology and geophysics department, AAU using JR-6 Spinner magnetometer. Samples were demagnetised by alternating field. First measurement was taken at NRM (Natural Remnant Magnetization) and later with the following

demagnetisation steps (5Mt, 10mT, 15mT, 20mT, 30mT, 40mT, 50mT, 60mT, 80mT, 100mT) (see the complete format of demagnetisation step for a single specimen).

Table 3.1 *Representative table format for a single specimen*

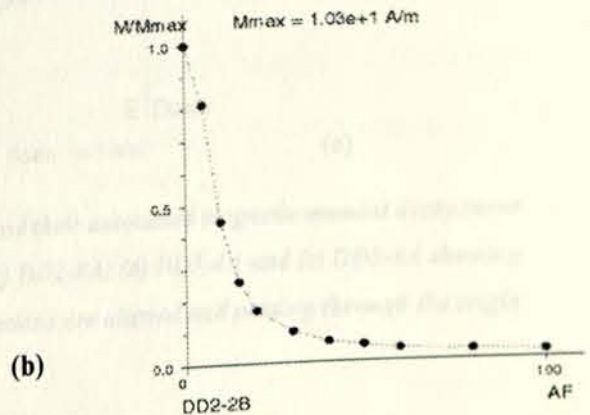
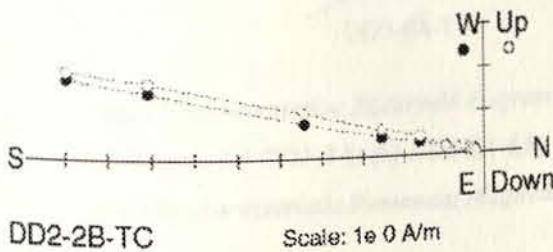
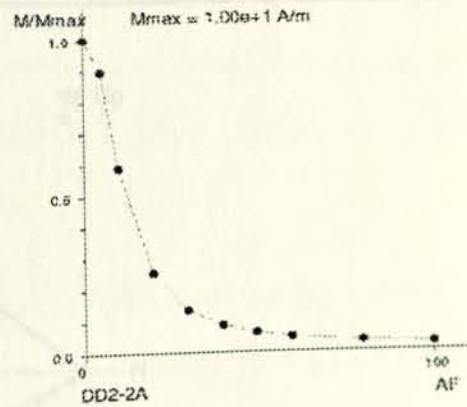
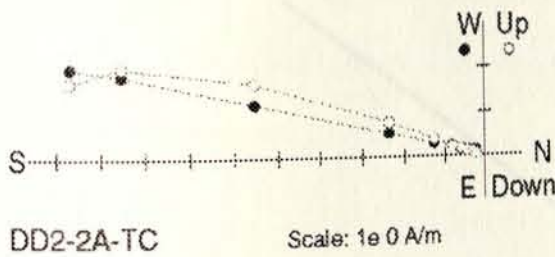
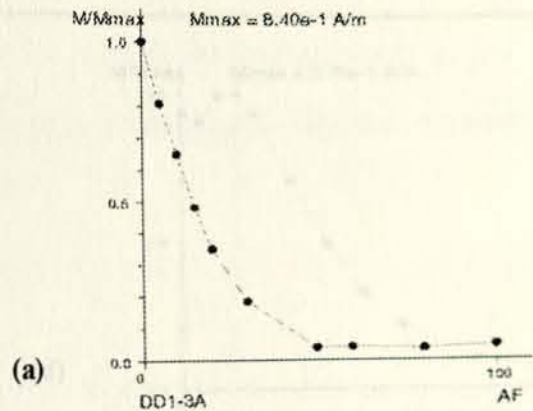
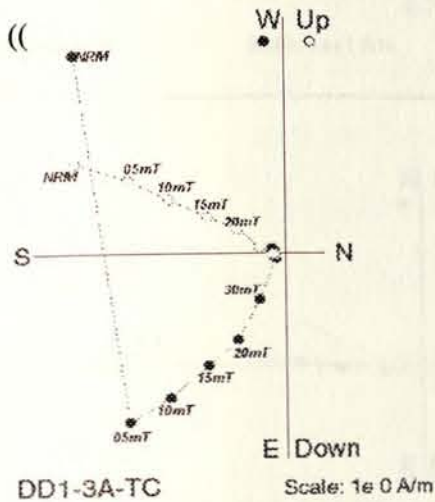
Name	Step	X	Y	Z	M	Ds	Is
DD2-2A	NRM	-9.67	-2.02	-1.7	10.02	16	29
DD2-2A	M5	-8.54	-1.84	-2.03	8.97	16	26
DD2-2A	M10	-5.54	-1.21	-1.67	5.911	16	23
DD2-2A	M15	-361	-0.78	-1.13	3.86	16	22
DD2-2A	M20	-2.37	-0.53	-0.79	2.557	16	21
DD2-2A	M30	-1.274	-0.288	-0.387	1.362	16	23
DD2-2A	M40	-0.815	-0.225	-0.203	0.8699	20	25
DD2-2A	M50	-0.589	-0.148	-0.154	0.6263	18	25
DD2-2A	M60	-0.442	-0.121	-0.103	0.4698	20	26
DD2-2A	M80	-0.3	-0.111	-0.086	0.3311	24	22
DD2-2A	M100	-0.22	-0.112	-0.05	0.2521	32	24
DD2-2A	M100	-0.22	-0.112	-0.05	0.2521	32	24

Natural remanent magnetization depends on the geomagnetic field and geologic processes during rock formation and during the history of the rock (Butler, 1992). NRM typically is composed of more than one component. The NRM component acquired during rock formation is referred to as primary NRM and is the component required in most paleomagnetic investigations. However, secondary NRM components can be acquired subsequent to rock formation and can alter or obscure primary NRM.

AF demagnetization is often effective in removing secondary NRM and isolating PNRM (characteristic NRM) in rocks. During demagnetization at steps NRM through 10 Mt and some times 15Mt, the remaining NRM rotates in direction and changes intensity as a low- stability component (viscous remanent magnetization) is removed. During demagnetization steps 15 through 100Mt, the remaining NRM does not change in direction but decreases in intensity. This high-stability component is well isolated by demagnetization to steps 15Mt. Demagnetisation steps above 15mT generates a straight

line directed to the origin. Results of progressive demagnetization steps are now displayed by using Zijderveld diagram (fig.3.7).

The AF experiment result for DD1 indicates that the demagnetisation steps above 15mT did not generate a straight line. Instead many components of magnetization are found. Such conditions most probably happened during transition environments.



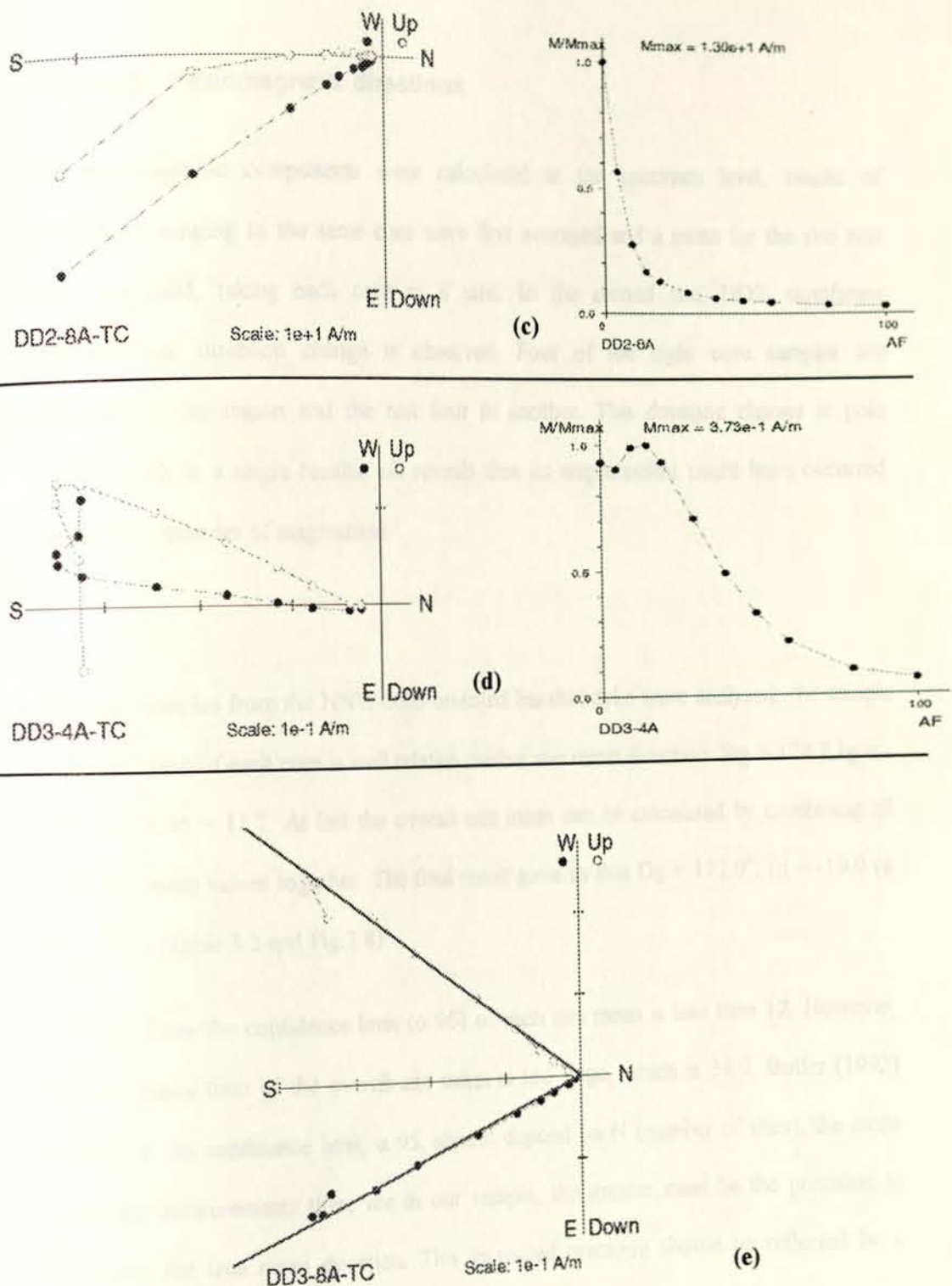


Fig.3.7 Representative Zijderveld diagram and their associated magnetic moment decay curve of samples (a) DD1-3A; (b) DD2-2A & B; (c) DD2-8A; (d) DD3-4A and (e) DD3-8A showing how the characteristic Remanent Magnetizations are aligned and passing through the origin

3.6.3 Mean Paleomagnetic directions

All paleomagnetic components were calculated at the specimen level, results of specimen belonging to the same core were first averaged and a mean for the site was then calculated, taking each core as a unit. In the second site, DD2, significant paleomagnetic direction change is observed. Four of the eight core samples are clustered in one region and the rest four in another. This dramatic change in pole position within a single basaltic sill reveals that its emplacement might have occurred during two episodes of magmatism.

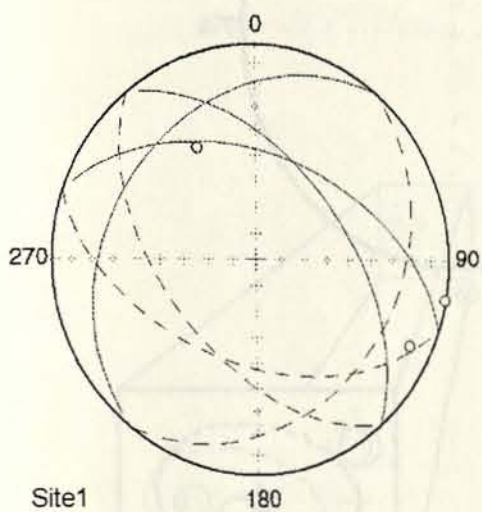
Ten core samples from the NNW-SSE oriented basaltic dyke were analysed; the sample mean direction of each core is well related with a site mean direction: $D_g = 174.2$, $I_g = -30.1$ and $\alpha_{95} = 11.7$. At last the overall site mean can be calculated by combining all three site mean values together. The final result gave us that $D_g = 172.0^\circ$, $I_g = -19.0$ ($\alpha_{95} = 34.9$) (Table 3.2 and Fig.3.8).

As seen above the confidence limit (α_{95}) of each site mean is less than 12. However, the confidence limit of the overall site mean is too large, which is 34.9. Butler (1992) stated that the confidence limit, α_{95} , should depend on N (number of sites), the more individual measurements there are in our sample, the greater must be the precision in estimating the true mean direction. This increased precision should be reflected by a decrease in α_{95} with increasing N.

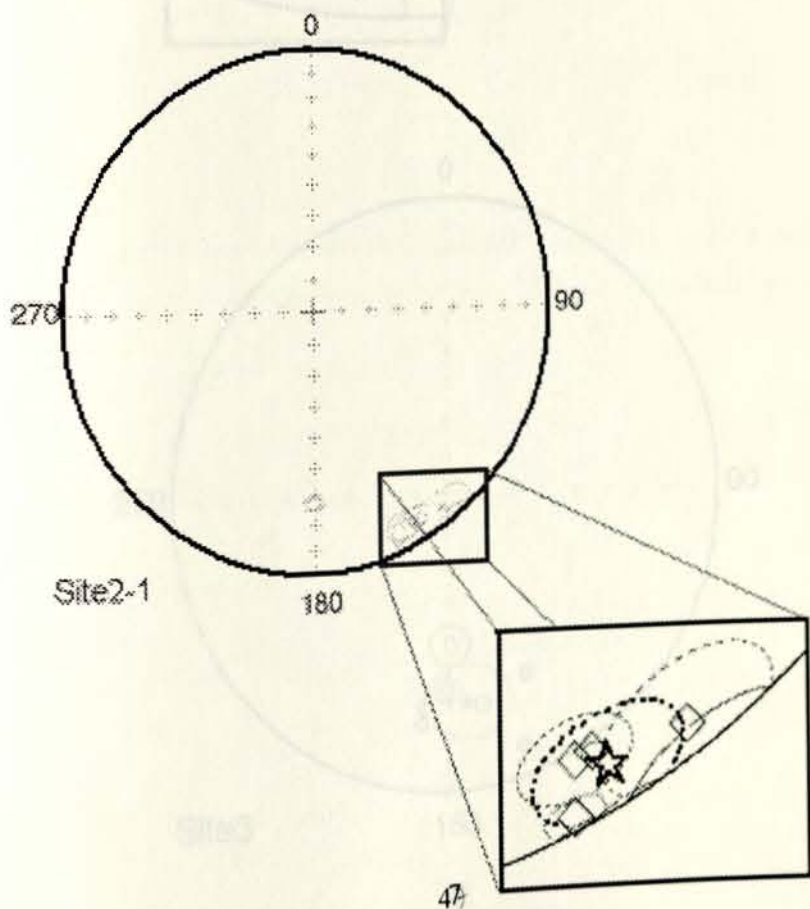
Table 3.2 *Paleomagnetic mean directions averaged after AF demagnetisation.*

Name	Direction	Steps	N	Dg	Ig	Ds	Is	k	A95
DD2-2A	DirOKir	M10 -M100	8	192.5	-16.6	192.5	-16.6	0	1.1
DD2-2B	DirOKir	NRM -M100	11	190.7	-12	190.7	-12	0	0.9
DD2-2B	DirOKir	M10 -M100	9	190.6	-13.5	190.6	-13.5	0	1.1
DD2-3A	DirOKir	M10 -M80	8	180.3	-27.5	180.3	-27.5	0	2.9
DD2-4A	DirOKir	M10 -M100	9	197.4	-16	197.4	-16	0	1
DD2-5A	DirOKir	M10 -M100	9	153.3	-8.7	153.3	-8.7	0	1.9
DD2-5B	DirOKir	M10 -M100	9	155.5	-9.9	155.5	-9.9	0	2.2
DD2-6A	DirOKir	M15 -M40	4	152.7	-9.3	152.7	-9.3	0	1
DD2-7A	DirOKir	M15 -M100	7	145	-6.4	145	-6.4	0	3.3
DD2-7B	Dir Kir	M15 -M100	7	144.3	-2.6	144.3	-2.6	0	3.3
DD2-8A	DirOKir	M15 -M100	8	156.8	-2.3	156.8	-2.3	0	2.8
DD2-8B	DirOKir	M15 -M60	6	155.8	-1.6	155.8	-1.6	0	2.6
DD2-9A	DirOKir	M20 -M100	7	190.8	-16.5	190.8	-16.5	0	2.7
DD2-9B	DirOKir	M20 -M100	6	195	-15.4	195	-15.4	0	1.8
DD2-2	rep G&S	site ave	2	191.3	-14	191.3	-14	1027.3	3.8
DD2-5	rep G&S	site ave	2	154.4	-9.3	154.4	-9.3	2105.6	5.4
DD2-7	rep G&S	site ave	2	144.7	-4.5	144.7	-4.5	904.3	8.3
DD2-8	rep G&S	site ave	2	156.3	-1.9	156.3	-1.9	8657	2.7
DD2-9	rep G&S	site ave	2	192.9	-16	192.9	-16	759.6	9.1
Mean2	rep G&S	site ave	8	170.8	-13.1	170.8	-13.1	13.3	15.7
Mean2-1	rep G&S	site ave	4	190.7	-18.5	190.7	-18.5	78.9	10.4
Mean2-2	rep G&S	site ave	4	152	-6.3	152	-6.3	167.2	7.1
DD3-10A	DirOKir	M10 -M100	9	129.3	-21.9	129.3	-21.9	0	3.2
DD3-1A	Dir Kir	M15 -M80	7	187.3	-28.6	187.3	-28.6	0	1.6
DD3-2A	Dir Kir	M15 -M100	7	180.3	-34.1	180.3	-34.1	0	3.7
DD3-4A	Dir Kir	M20 -M100	7	187.6	-23.5	187.6	-23.5	0	1.3
DD3-5A	DirOKir	M40 -M80	4	161.6	-11.6	161.6	-11.6	0	1.1
DD3-6A	Dir Kir	M40 -M100	5	169.8	-28.4	169.8	-28.4	0	2.4
DD3-7A	DirOKir	M20 -M80	5	104	21.7	104	21.7	0	5.6
DD3-8A	DirOKir	M15 -M100	8	155.1	-32.8	155.1	-32.8	0	1.4
DD3-9A	DirOKir	M15 -M80	7	179.2	-47.6	179.2	-47.6	0	5.8
Mean3	rep G&S	site ave	7	174.2	-30.1	174.2	-30.1	27.3	11.7
All Mea	rep G&S	site ave	3	172	-19	172	-19	13.6	34.9

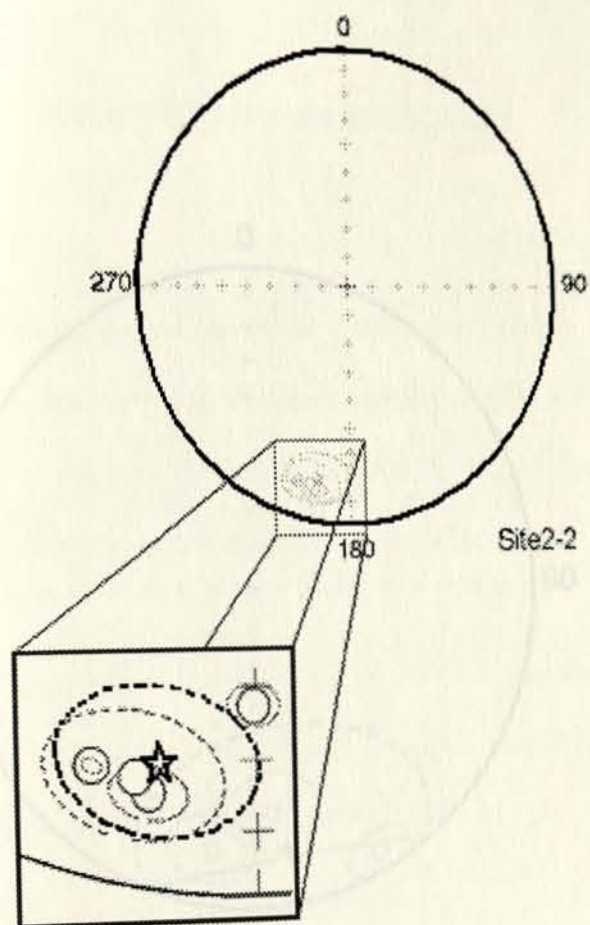
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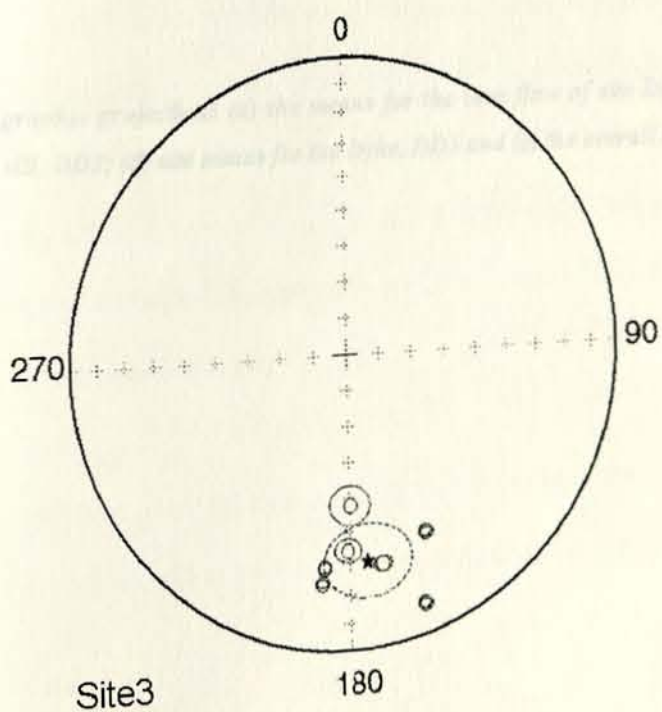
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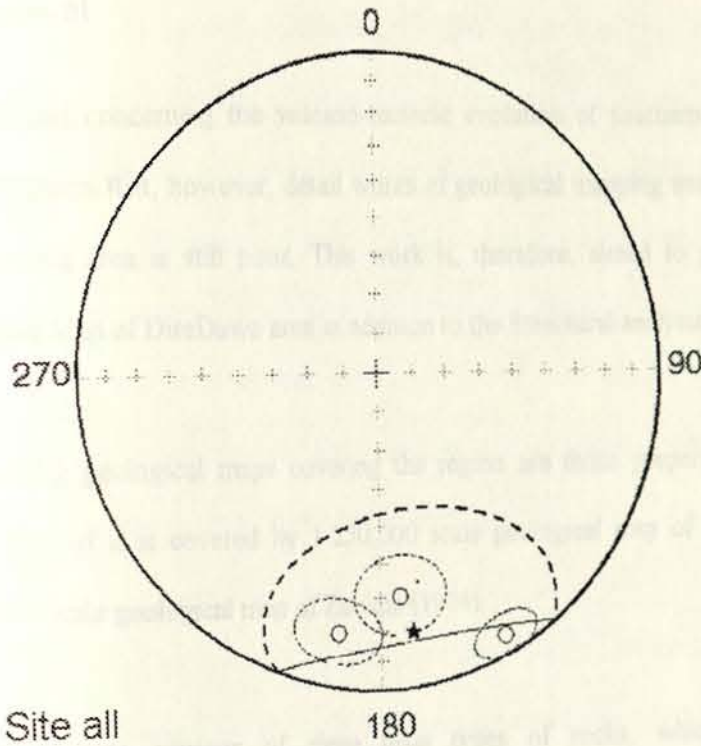
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(d)



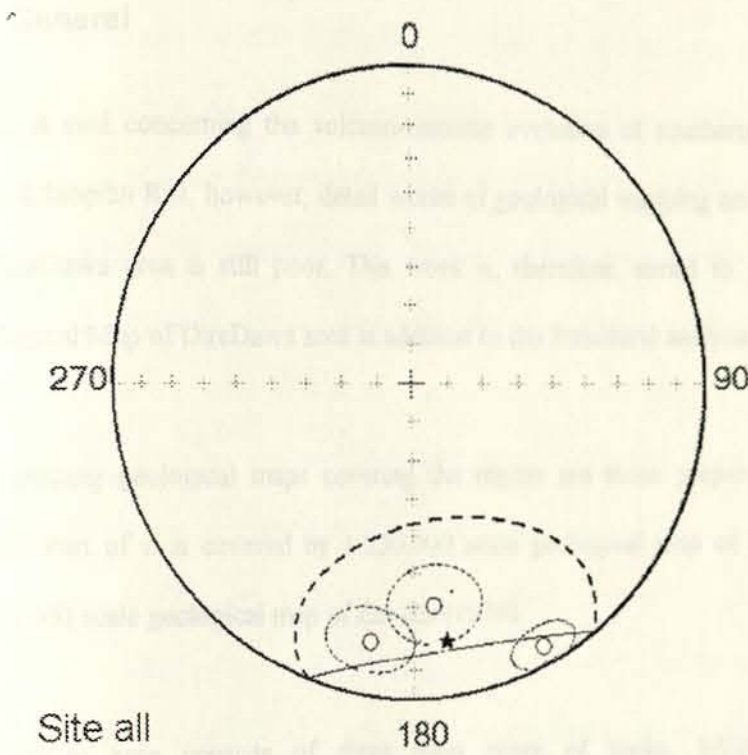
GEOLOGY OF DIRADAWA AREA



(e)

Fig.3.8 Stereographic projections (a) site means for the lava flow of site DD1; (b)&(c) site means for the sill, DD2; (d) site means for the Dyke, DD3 and (e) the overall mean directions for the sites.

GEOLOGY OF DREDAWA AREA



(e)

Fig.3.8 Stereographic projections (a) site means for the lava flow of site DD1; (b)&(c) site means for the sill, DD2; (d) site means for the Dyke, DD3 and (e) the overall mean directions for the sites.

CHAPTER- FOUR

GEOLOGY OF DIREDAWA AREA

4.1 General

Much is said concerning the volcano-tectonic evolution of southern Afar – northern Main Ethiopian Rift, however, detail works of geological mapping and lithostratigraphy of DireDawa area is still poor. This work is, therefore, aimed to produce 1:50,000 Geological Map of DireDawa area in addition to the Structural analysis of the area.

The existing geological maps covering the region are those prepared at 1:2,500,000 scales. Part of it is covered by 1:250,000 scale geological map of Berhe (1985) and 1:100,000 scale geological map of Zewdie (1974).

The study area consists of three main types of rocks, which are results of metamorphism, sedimentation and volcanism, occurred during Precambrian, Mesozoic and Cenozoic respectively. From the one-month fieldwork, the geology of the area is well identified. It consists of Precambrian metamorphic rocks, Mesozoic sedimentary rocks (comprising of lower sandstone, limestone and upper sandstone), various types of Rift related volcanic rocks (the marginal mafic rocks and some intermediate rocks), and Quaternary to recent alluvial deposits.

The metamorphic rocks cover the entire southern part of the area (fig.4.10) and in some deep river cut exposures and at the base of some fault scarps in the middle part of the

area. These rocks are unconformably overlain by the sedimentary formation of Mesozoic age and some volcanic products of recent ages.

Unlike the other Ethiopia Rift margins, which are volcanic dominate, the area is dominantly covered by full succession of highly tilted Mesozoic rocks. The oldest Mesozoic deposit in the area is the lower sandstone which crops-out in very restricted area in the middle part of the study area, specially along deep river cut and deep fault scarp exposures. The next and most dominant Mesozoic sedimentary rocks are the limestone group (some times called the Antalo limestone), which constitutes almost about 60% of the area, covers the entire middle, southeastern, southwestern and northeastern part of the region. The limestone unit is overlain by the upper sandstone unit, which outcrops as isolated patches all over the area.

The north and northwestern part of the area is covered by Pliocene volcanic rocks of recent age. These rocks are also common in areas where tectonic activities were intense. According to Chernet et al. (1998) these volcanic products are categorized with the Afar stratoid series dated between 5.6 and 4.my. Volcanic rocks of intermediate composition are also present. Some are found directly overlying the basement rocks and others erupted along the half grabens bounded by sedimentary rocks.

In order to draw a complete picture of the stratigraphy of the area, it is necessary to subdivide the rocks based on their lithology, chronology and tectonic evolution.

Based on their geochronological order, rocks of the area could be put from older to younger as follows:

1. Basement complex
2. Lower sandstone
3. Transition beds
4. Limestone Supersequence
5. Upper sandstone
6. Rift-Related volcanic rocks
 - i. Rift margin felsics
 - ii. Marginal mafic rocks
7. Quaternary-Recent alluvial deposits

N: B. The stratigraphy of the Rift related volcanic rocks is mainly based on the works of Chernet et al. (1998); Berhe (1986) and Kazmin et al.(1980)

4.2 Basement complex

These are the oldest rocks in the study area as well as the country as a whole. They are of Precambrian in age and now well exposed in the southern part of the study area, in some deep river cut exposures and along fault planes. Mostly, these rocks are overlain by Mesozoic sedimentary rocks in the area (fig. 4.1). However, in some places, around Dengogo and southern Kersa, the basement rocks are directly overlain by the marginal felsic rocks: Trachytes and Dacites (Fig. 4.2).

In the study area, the basement rocks are mainly characterized by Gneisses and Schists. Low-Grade metamorphic rocks (like Slates and Phyllites) are absent. The gneiss covers the largest portion of the basement rocks. It is pinkish grey when the rock is dominated by Microcline; otherwise, it is characterized by white and black mineral banding. The petrographic analyses show that the principal mineral constituents of the gneissic rocks (meta-granites and meta-granodiorites) are K-feldspar (Microcline), Quartz, Plagioclase and Biotite. These minerals together account more than 92% by volume of the rock sample. Plagioclase shows sericitization and calcitization, which could represent late stage of alteration. Biotite shows alteration to chlorite. Microcline is sericitized and its twin lamellae are stretched. Some plagioclase also shows myrmikite texture.

The *Chlorite-Biotite-Schist*: - these are small exposures mostly found sandwiched between the gneissic rocks. Unlike the gneissic rocks, this unit has variegated color dominated by deep brown color and consists of biotite, chlorite, chlorite-actinolite and actinolite-quartz schist.

The basement rock in general, is characterized by pre and syn-rifting structures. The per-rifting structures represent foliations, non-systematic fractures, veins and some disharmonic type of folds. The syn-tectonic structures are mainly of extensional fractures and faults, which have similar orientation with the major trend of the marginal faults and the northwesterly trending lineaments.

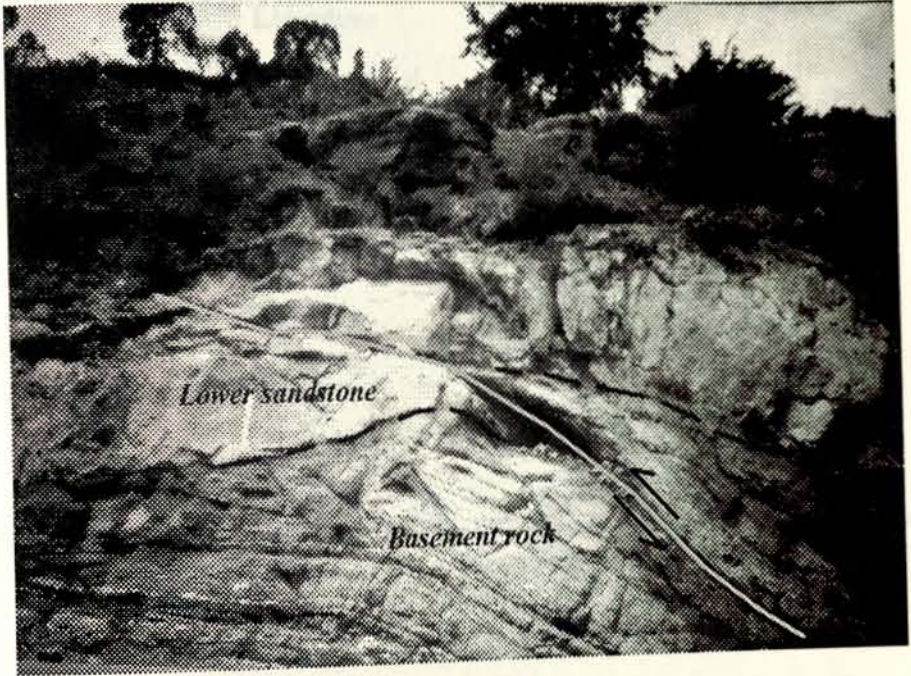


Fig. 4.1 Road exposure showing the contact between the metamorphic rocks and the lower sandstone (4 km east of Lange). The sandstone is slightly inclined

Elevation above
Sea level
in metres

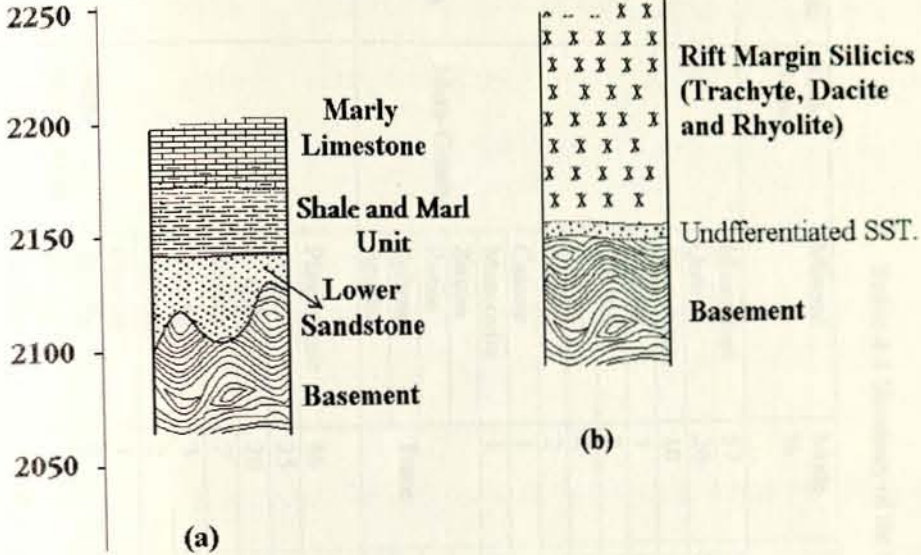


Fig. 4.2 Local Stratigraphic columns: (a) basement rocks overlain by the normal successions of Mesozoic Sediments around Lange, (b) basement complex overlain by the marginal rocks at the northeast of Dengogo and southeast of Kersa.

Table-4.1 Summary of the Mineral contents of Gneissic rocks

Sample Code	Rock Name	Mineral	Mode %	Texture	Location in UTM Zone (37)		
					Easting	Northing	Alt.
T ₁₂ -S ₂	Meta-Granite	Microcline	57	Xenoblastic	819431	1048506	1922
		Quartz	20	Xenoblastic			
		Plagioclase	10	Xenoblastic			
		Biotite	5	Flaky			
		Chlorite	2	Flaky			
		Opaque	2	Idioblastic-Xenoblastic			
		Sericite	2	Very fine			
		Calcite	1	Xenoblastic			
		Muscovite	1	Flaky			
		Zircon	Trace	Idioblastic			
		Rutile		Hypidoblastic			
		Sphene		Hypidoblastic			
		Apatite		Idioblastic			
T ₁₂ -S ₁	Meta-Granodiorite	Plagioclase	46	Xenoblastic-hypidoblastic	819840	1048236	1956
		Quartz	25	Xenoblastic			
		K-feldspar	20	Xenoblastic			
		Biotite	7	Flaky			
		Calcite	3	Xenoblastic			
		Chlorite	2	Flaky			
		Opaque	1	Xenoblastic			
		Apatite	1	Idioblastic			
		Zircon	Trace	Idioblastic			
		Sericite		Very fine			
		Sphene		Idioblastic			

4.3 Lower Sandstone

The clastic sedimentary succession underlying the Jurassic carbonate rocks and overlying the high-grade metamorphic basement is described as a single unit called the *Lower Sandstone*. Equivalent terrigenous successions in other parts of Ethiopia are referred to as Adigrat Sandstone in Mekelle basin and lower sandstone in Abay basin. Earlier writers: Stefanini (1933); Mohr (1962); Dow et al. (1971); Saxena and Assefa (1985) and others used the term Adigrat Sandstone for this formation instead of lower sandstone.

This Sandstone is yellowish-grey to red, fine to coarse-grained, well sorted and is most probably the result of reworking of the underlying basement rocks. Unlike the lower sandstone in Mekelle outlier, which is underlain by the Edaga Arbi glacial (Tillite), this unit directly overlies unconformably the basement rock (Fig.4.3). Cross bedding is common and intercalations of silt and shale occurs frequently in the upper part of the section.

Practically the grains are composed of quartz arenites cemented by silica, carbonaceous and ferruginous materials. Calcareous cemented rocks are slightly lighter and friable than the other sandstone, which are cemented by silica and ferruginous materials.

The thickness of this unit is highly variable. Even in some places, it is completely absent and the carbonate rocks are directly unconformably overlying the basement rocks. In some of the deeply cut river gorges, its thickness reaches up to 35 m. However, Getaneh (unpublished) estimated the maximum thickness of this unit to about

100m. This fairly large thickness of the Sandstone is well observed in tectonically undisturbed areas of Kulubi, which is about 5 km far from the southwestern part of the study area. The great variation in thickness of this unit is assumed to be deposition of the Sandstone in a piedmont area or non-denudated environment of the basement.

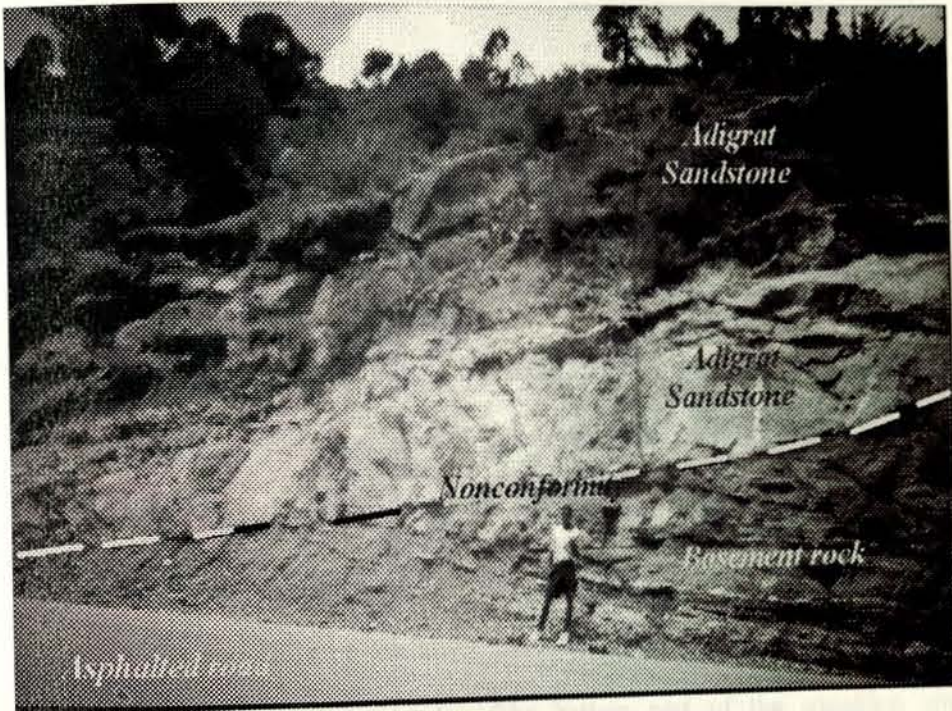


Fig.4.3 the Adigrat sandstone of DireDawa overlying the basement rocks

Bosellini et al. (1999) added that the rapid change in thickness suggest the occurrence of rough topography and gully infilling. Both the lower and upper boundaries of the Adigrat sandstone are probably diachronous. The age of the lower boundary is particularly impossible to date. The beginning of clastic sedimentation was largely controlled by the gondwana relief and can be Triassic to Early Jurassic or even Permian. The age of the Upper boundary, which, grossly speaking, should be taken as the Jurassic

rifting and by the gradual on lapping of marine sediments on to the east African continent

As the unit is generally exposed along deep river cuts and the base of steeply inclined fault scarps, it is impractical to indicate it in the geological map, however cross-sections of the area can illustrate the nature and position of this unit.

4.4 Transition beds

The boundary between the lower sandstone and the overlying carbonate rocks is characterized by a transitional zone. This transitional zone is thick, 25- 35m, and contains alternating beds of shale and marl, with some sandstone/siltstone and calcarenite beds. The transition beds show that the fluvial environment, which was the cause for the formation of the lower sandstone, has ceased, while shallow marine environment had started to develop. The bottom part of the transition zone is dominantly of sandstone intercalated with thinly bedded shale and marl. The sandstone is generally thinly bedded (5-20cm), fine-grained (siltstone), friable and greyish - yellow in color. As moving up sequence, especially along the road leading from Lange to Kersa, the sandstone diminishes in thickness and is replaced by calcareous sand, shale and marl. The shale and marl intercalations, at half way between the two mentioned towns, is well bedded with bed thickness 5 - 80cm (shale) and 0.1 - 1m (marl) (Fig. 4.4)

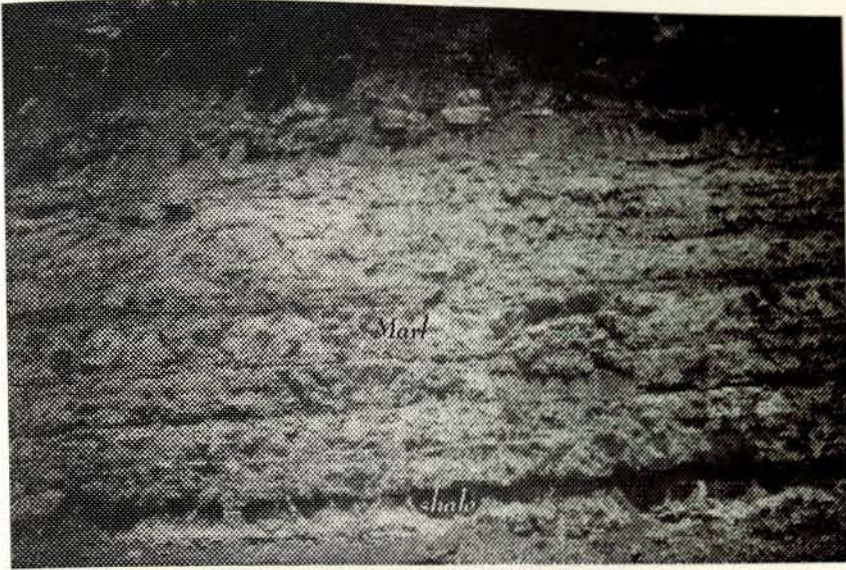


Fig.4.4 *Representative image for the transition beds; the layers of the shale are thick at the bottom and progressively decreases their thickness upwards, while the layers of marl increase their thickness upwards*

4.5 The Limestone Supersequence

The organic sedimentary succession overlying the transition beds covers the entire middle, western, eastern and northeastern part of the study area. This supersequence is the dominant rock type covering about 60% of the project area. Equivalent, non-clastic sedimentary rocks in other parts of the country are referred to as the Antalo Limestone (Mekelle outlier), the Limestone unit (Abay basin) and Hamanlie and Uarandab (Ogaden basin). Getaneh (unpublished) stated that this unit is slightly older than the Antalo Limestone in Tigray and is estimated to be *Lower – Upper Jurassic* in age. He

also added that the presence of Ammonites confirmed that this supersequence was formed under relatively deep marine environment.

The type of the limestone is not uniform as a result of inhomogeneity during its deposition (Fig.4.5). The lower part of this supersequence has a thickness of about 70m and lies on the shale and marl unit. It is dominantly of reddish grey to greyish yellow, friable marly limestone with thin beds of shale and marl intercalations. This unit is more widespread carbonate rock and is found following the southern vicinity of DireDawa to the *BekeHalo* village (southeastern DireDawa) and in some parts of the *Hula-Hulul* area (southwestern DireDawa) (Fig.4.10).

Overlying the marly limestone, there is well-developed reddish grey to black-bluish, extremely fine-grained (Crypto-crystalline) limestone beds (the middle subgroup) with well-oriented sets of joints. The thickness of each bed ranges from 50cm - >2m and an aggregate of these beds gives a total thickness of about 140m. Fossils are absent or not very common, this may tell us that this subunit was formed under deep marine environments. Despite of the fact that this portion (unit) is massive and thickly bedded black-bluish limestone, thinly bedded shale and marl (5 - 10cm.) are intercalated. As stated above, there is a remarkable facies change in this sequence, including a substantial increase of marly limestone and shale, the total disappearance of the black-bluish limestone and the occurrence of greyish-yellow marl, shale and mudstone.

A thick succession of marly limestone, shale, marl and mudstone overlies the top part of the black bluish limestone. The thickness of this unit, measured from the fault scarp, is about 60m. The major constituents of this subunit are: fine-grained, greyish-yellow

marly limestone, aggregates of loose and fragmented yellowish grey marl, light brown to dark-brown shale and thinly bedded (10 – 15cm), slightly nodular black-blush mudstone. However, 3 – 4m thick layers of reddish-grey limestone are common within this subunit. Unlike its equivalent units of Abay and Mekelle basins, this sub unit is particularly non-fossiliferous. According to Bosellini et al. (2001) this sub group is called the “DireDawa Formation” (Fig.4.7)

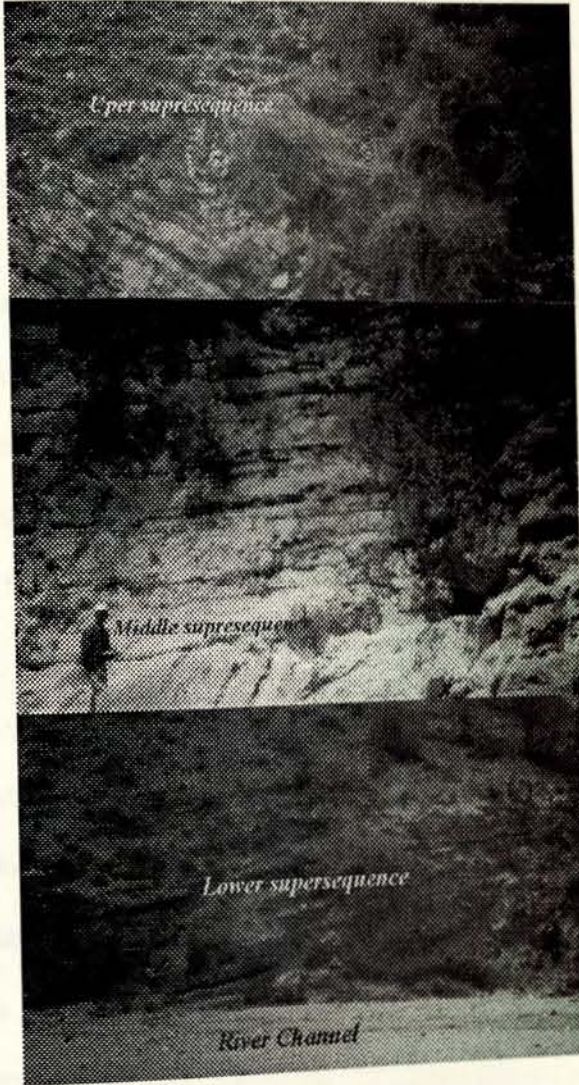


Fig.4.5 An image showing the three sub-groups of limestone: marl and shale dominated lower sub group; blue-black, massive limestone (middle) and marl dominated upper limestone.

Generally, the lower and upper parts of the supersequence are more alike except that the upper part possesses thin beds of mudstone. Since these two subgroups own significant amount of shale and marl, they are highly susceptible to erosion and sliding. Therefore, their morphology/topography is gentle as compared with the cliff forming middle part of the supersequence. Moreover the fault scarps that pass through these units are highly modified by erosion and this time they can't reflect the exact fault geometry.

4.6 Upper Sandstone

The youngest siliciclastic Mesozoic sediment, overlying unconformably the upper Jurassic sedimentary succession of Harar, is named as the '*Upper Sandstone*'. Equivalent siliciclastic sediments occur in central Ethiopia (Blue Nile; Assefa, 1991); Tigray (Mekelle outlier, Bosellini et al., 1997) and Eritrea (Denakil Horst, Hutchinson and Engels, 1970).

This unit consists of three types of well-layered sandstone (Fig.4.6). The first one is whitish to greyish-yellow in color. It is coarse-grained and commonly associated with quartz conglomerate lenses. The existence of quartz conglomerates with in this unit enables to distinguish it easily from the lower sandstone in stratigraphically disturbed environments. The second layer, which is very fine-grained and relatively softer than the above two, is light blue to pale-blue in color. Unlike the above two, this layer is thinner and devoid of those quartz conglomerates.

The third layer, which is relatively finer, well sorted and cemented, is light red in color. This layer also consists of quartz conglomerates but not as much and large as the first layer.

The above sequence is common in the central and southern part of the area, but as moving from the rift margin towards the rift floor, one major change occurs. In most exposures of the western and northern part, it is ordinary to observe whitish (sugary texture), massive boulders imbedded with in the sandstone. This shows transformation (slight metamorphism) of the sandstone in to the so-called quartzite. The main factor for the recrystallization of this sandstone may be the existence of anomalous heat during dyke injection and an elevated temperature due to emplacement of granites and other intrusive bodies in such environments.

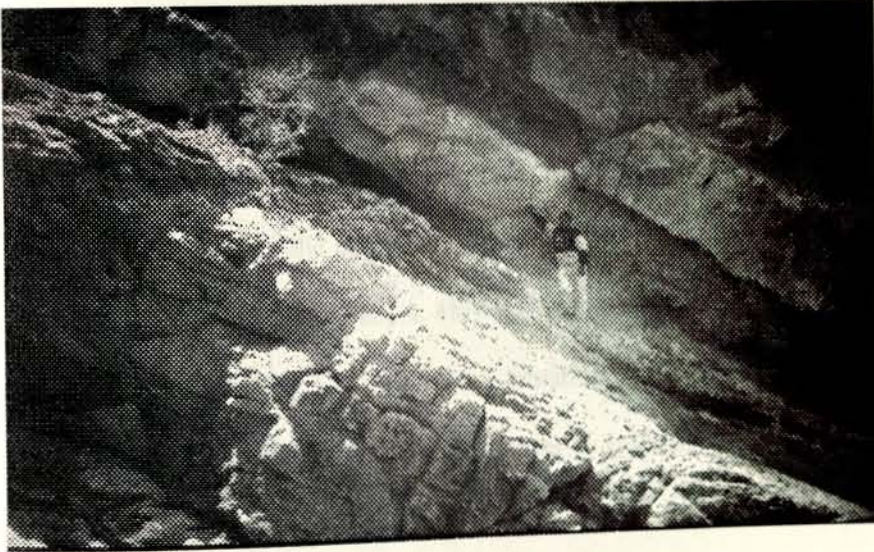


Fig.4.6 Steeply inclined upper-sandstone. It is variegated in color: well-sorted light-red sandstone at the top; light-blue to purple, soft sandstone (middle), and white to grey conglomeratic sandstone at the bottom.

In the study area, the complete stratigraphy of this unit is disturbed; therefore the entire thickness of this unit is assessed five kilometres away from the southwestern side of the mapped area, around Kulubi town. At this locality the stratigraphy is well preserved, the trap series and the carbonate rocks are found overlying and underlying this unit respectively and thickness of the sandstone is estimated to be about 120m. However, Getaneh (Unpublished), stated that the thickness of this unit is about 300m, which is most comparable with the Ambaradom formation of Tigray. Recent publications (Bosellini et al., 1999,2001) stated that the Ambaradam Formation of DireDawa area is 150 – 200m thick mainly consists of fluviatile sandstone and minor shale, and is overlain by trap basalt.

From the Stratigraphic point of view, it is not heavy task to estimate the relative age of the Upper sandstone of Harar and DireDawa, but to group it to which period it belongs, it needs some paleontological evidences. As cited in Bosellini et al. (1997), the paleontological dating of the '*Upper Sandstone*' of Harar, Chercher and Arussi is Aptian-Albian (Lower Cretaceous) (Gortani, 1973; Silvestri, 1973; Beauchamp, 1977), which is a bit younger than the upper sandstones of Abay and Mekelle. Generally, the upper sandstone is undated in Ethiopia. However, at Graua and Gara Mulata, some 50km south of DireDawa, a 15 – 20m thick limestone intercalation, rich in various species of Orbitolina and pelecypods, clearly indicates an early Aptian age for that tract of the formation (Bosellini et al., 1999)

4.7 Rift Related Volcanic Rocks

Following the major episode of rifting, the continental crust of Afar is highly attenuated. Significant decrease in thickness of the crust leads to substantial amount of decompression melting beneath the thinned continental crust. Eruption of those molten materials to the surface result to those various rift related volcanic rocks. The chemistry of these rocks is diverse as they are results of different parental magmas. In this topic the aim is not to discuss the geochemistry of these rocks but to understand the nature and type of the volcanic rocks of the area and to construct their lithostratigraphy.

As mentioned earlier, there are two types of Rift Related volcanic rocks in the specified area. These are:

- i. Rift margin felsics
- ii. Marginal mafic rocks

4.7.1 Rift Margin felsics

Based on their physical appearance as well as their petrographic analysis, the rift margin silicics are further subdivided in to two major groups.

The first group (Trachytes and Dacites) are exposed in the southern periphery of the area, aligned parallel with the boundary faults directly overlying the basement rocks. These are dominantly of grey to greyish-white, fine to medium grained massive rocks forming a circular domes along the road of Lange to Dengego (Fig.4.10). According to Kazmin et al. (1980) these rocks are related with the Arba Guracha Silicics and Mabl Rhyolites, which were formed contemporaneously with the emergence of the Afar depression about 14 my ago.

The petrographic analysis of the unit points that the dominant minerals are: K-feldspar and plagioclase, which together constitute 80% of the rock. Pyroxene and other opaque minerals (Fe-Oxide) constitute about 5% of the rock sample and Quartz about 5%. The K-feldspar (Sanidine) and the plagioclase show parallel to sub parallel alignment. Volcanic glass shows devitrification to chalcedony. The texture of the minerals is in most cases is anhedral.

The second group of silicic rocks (Rhyolites) are exposed only in the lower part of the margin, confined within the major half-graben passing through the southern part of the DireDawa town. These rocks are dominantly of grey in color and fine to medium-grained in texture. They are characterized by well-developed spheroidal weathering (fig.4.8).

The petrographic data reveals that the major minerals constituting the rock are: plagioclase, K-feldspar and quartz. These three minerals constitute about 94% of the samples. Opaque minerals and pyroxene constitute the remaining 6%. The ground mass is dominantly made of tabular plagioclase, anhedral K-feldspar and quartz. Some large crystals of plagioclase are seen as phenocrysts. The shape of the crystals is dominantly tabular, lath tabular to anhedral. Detail mineral contents of the three samples are tabulated in Table 4.2.

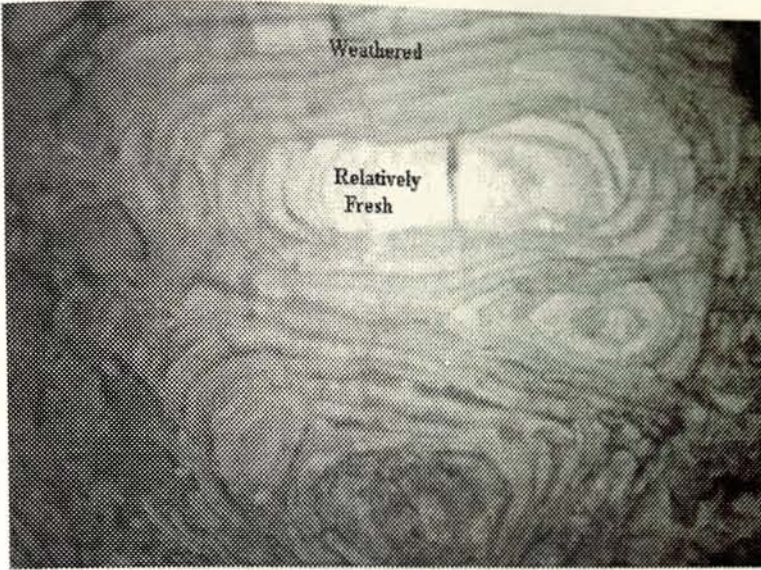


Fig. 4.8 *Spheroidal weathering developed on the Rhyolitic rocks.*

In the regional volcano-tectonic framework, this late Miocene–Pliocene Silicic volcanics are aligned along the base of the southern escarpment of the Afar depression (Chernet et al., 1998). Kazmin et al. (1980) suggested that these silicic centres developed in a marginal graben 7-9 km. wide (rift – in – rift structure), which formed along the foothills of the eastern escarpment of the northern main Ethiopian Rift and the southern escarpment of the Afar depression.

In this particular area, absolute age dating has not been conducted. However, ages were determined from the silicic rocks of Asebot-Karajote eruptive centres and from GaraGumbi volcanoes, which have similar composition and tectonic histories with this unit. These results indicate that the Asebot-Karajote centres were formed between 5.6 and 5.0 Ma, while the later volcanic centre was erupted 6.87my ago (Chernet et al.,

1998). Therefore, it can be speculated that the Rhyolitic rocks of the area might have been erupted at the same time with the aforementioned rocks.

Table 4.2, Summary of Mineral contents of the silicic rocks

Sample Code	Rock Name	Minerals	Mode %	Texture	Location in UTM Zone (37)		
					Easting	Northing	Altitude
T ₁₁ -S ₂	Trachyte	K-feldspar	60	Anhedral	815981	1045462	2073masl
		Plagioclase	20	Lath anhedral			
		Devitrified volcanic glass	10				
		Quartz	5	Anhedral			
		Pyroxene	3	Anhedral			
		Opaque (Fe-Oxide)	2	Anhedral			
T ₄ -S ₄	Rhyolite	K-feldspar	45	Tabular	814470	1058830	1290masl
		Plagioclase	30	Anhedral			
		Quartz	20	Sub-Anhedral			
		Opaque	5	Anhedral			
XX ₄	Dacite	Plagioclase	54	Lath Tabular	814798	1058407N;	1358masl
		K-feldspar	20	Lath Tabular			
		Quartz	18	Anhedral			
		Opaque	5	Anhedral			
		Pyroxene	3	Anhedral			
		Calcite		Trace			

4.7.2 Marginal Mafic Rocks

These rocks cover a broad exposure on the northern and northwestern portion of the area and as patches on the northeastern side. As seen from satellite imageries and some regional maps, it is traced nearly continuously along the Afar margins from the northern main Ethiopian rift through the Aisha and Tadjoura region

Basically, these mafic rocks are of two types: olivine rich basalts and olivine poor once. The olivine rich basalts are mainly found on the northern and northwestern side of the area and are called '*Afar Stratoid Series*'. They cover the largest part of the volcanic products attaining a maximum thickness of about 150m. These rocks are assumed to be characteristics of well-evolved rift zones. The Age determination carried out by Chernet et al. (1998) defined that the Afar Stratoid series is dated at 4.68 my, which is nearly the same as with the age dated by Christiansen et al. (1975) for the whole series. However, recent publication (Kidane et at., 2002) modified the name to Lower Stratoid Series.

Petrographic analyses of these rocks show that the dominant minerals are plagioclase, pyroxene and olivine. These three minerals account about 83%. The ground mass is mainly composed of anhedral laths of plagioclase, pyroxene and olivine. The interstitial space between plagioclase is filled by pyroxene, olivine and opaque (magnetite) minerals. Some empty and partially calcite filled vesicles are also evident.

The second type of rocks, olivine poor basalts, are commonly found on the northeastern side of the area. These are in general black in color and very fine grained in texture.

They are mostly emplaced in the well-developed half grabens aligned nearly parallel with the major marginal fault trends of the area and outcrops surficially directly above the faulted and tilted block intersections. Their thickness is variable but in some places a thickness of about 30m is evident.

The leading minerals in these rocks are plagioclase and pyroxene. Lath microlithic plagioclase, anhedral pyroxene and euhedral opaque minerals are the main components of the groundmass. Pyroxene and opaque minerals fill the interstitial space between plagioclase crystals.

From the above two mafic rocks, it can be inferred that the olivine poor basalts are erupted earlier as a result of the major marginal fault development, whereas the olivine rich ones are resulted from further episode of faulting and tilting occurred concurrently with the last volcanic phase of the Rhyolitic centres (Berhe, 1986).

Table 4.3 Summary of the Mineral contents of Mafic Rocks

Sample Code	Rock Name	Minerals	Mode %	Texture	Location in UTM Zone (37)		
					Easting	Northing	Altitude
T ₆ -S ₁	Olivine basalt	Plagioclase	48	Lath anhedral	814400	1079050	965asl.
		Pyroxene	20	Lath anhedral			
		Olivine	15	Subhedral - Anhedral			
		Opaque (Fe-Oxide)	10	Subhedral - Anhedral			
		Calcite	7	Anhedral			
T ₅ - S ₃	Amygdaloidal olivine Basalt	Plagioclase	48	Lath anhedral	828964	1075612	1008asl.
		Olivine	25	Anhedral			
		Pyroxene	10	Euhedral - Subhedral			
		Calcite	10	Euhedral - anhedral			
		Opaque	7	Anhedral			
T ₅ - S ₂	Basalt	Plagioclase	55	Lath	821890	1068732	1119asl.
		Pyroxene	25	Anhedral			
		Opaque	15	Euhedral			
		Volcanic glass	5	-----			

4.8 Quaternary – Recent alluvial deposits

This unit outcrops in all or nearly all of the deeper parts of the half grabens as well as along the gently laying major river courses. However, it is dominantly found laying on the 5 – 7 km wide marginal grabens. This unit was formed as a result of the end product of weathering of the three rock types. Therefore, various colours and size of soils are characteristics of the alluvium. In some places it is fine-grained, dark to dark brown in color and is most probably the result of reworking of the mafic rocks, where as the others are fine to coarse – grained, grey to light brown soils. As seen from some boreholes in the area the thickness of the alluvium reaches about 40m.

4.9 Stratigraphic Column of the Area

As mentioned at the beginning of this chapter, the aim was to show lateral extent and vertical thickness of the various rock types and to construct the lithostratigraphy of the units. From the regional point of view and some radiometric dating, rocks of the DireDawa and its vicinity are reconstructed as the sketch below.

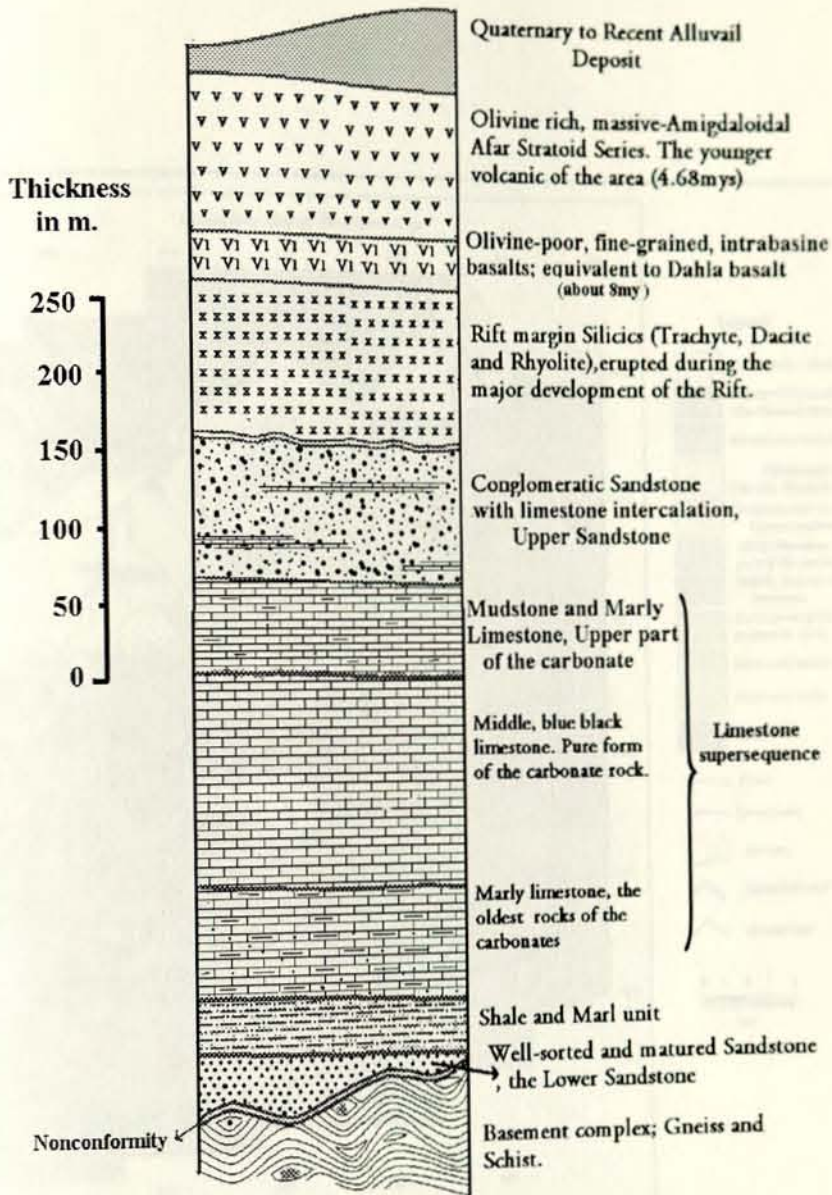


Fig.4.9 Reconstructed Stratigraphic column of DireDawa area and its vicinity.

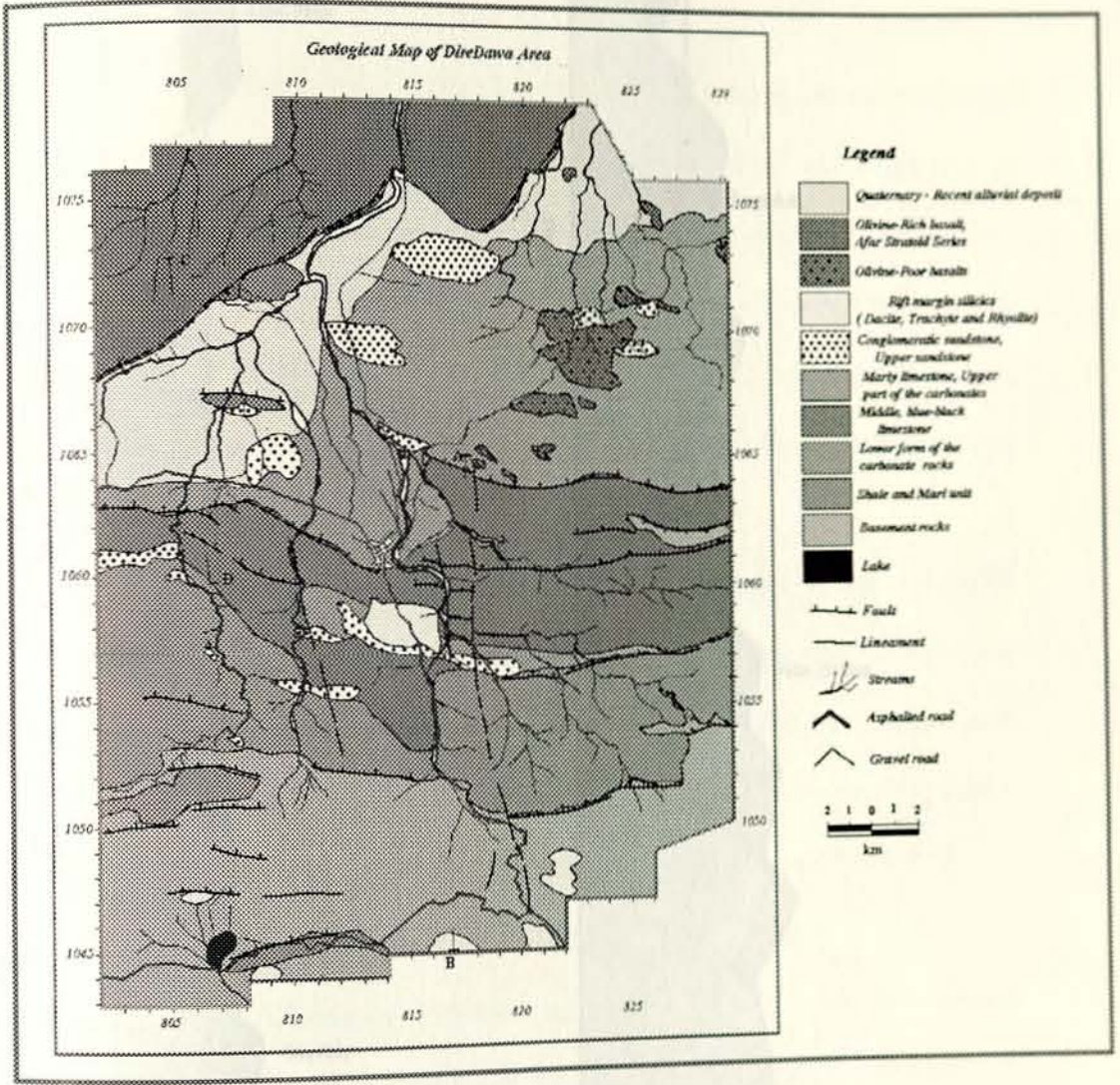


Fig.4.10 Geological map of DireDawa

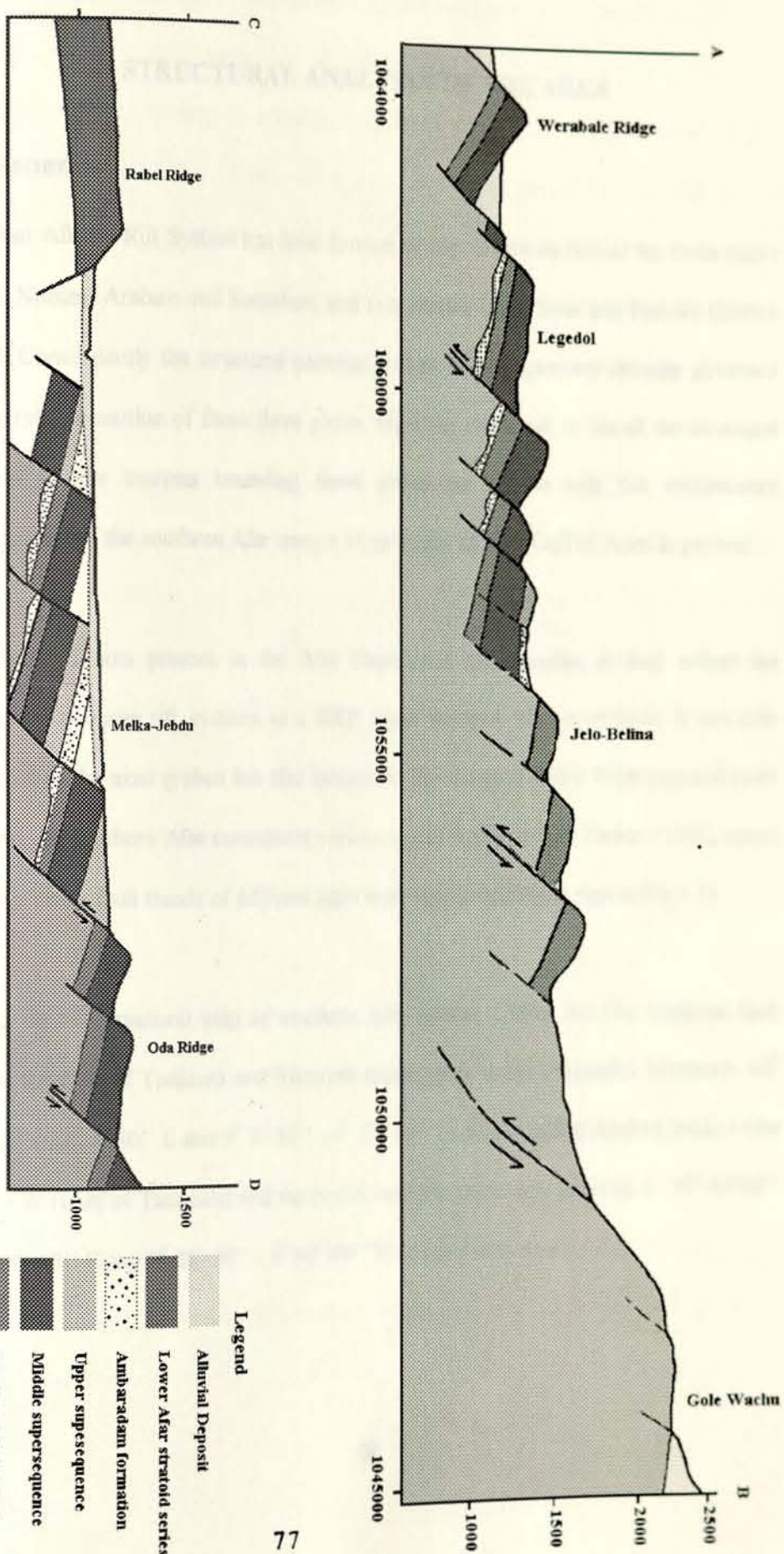


Fig.3.11 Geological Cross-section

CHAPTER – FIVE

STRUCTURAL ANALYSES OF THE AREA

5.1 General

The East African Rift System has been formed by the relative motion of the three major plates; Nubian, Arabian and Somalian, and two smaller ones, Sinai and Danakil (Berhe, 1986). Consequently the structural patterns present in the region are strongly governed by the relative motion of these three plates. Here the aim is not to see all the structural patterns of the margins bounding these plates but to see only the evolutionary development of the southern Afar margin in particular and the Gulf of Aden in general.

The fault patterns present in the Afar Depression are complex as they reflect the interaction of three rift systems in a RRR triple junction. This complexity is not only restricted to the axial graben but also extends to the marginal faults. From regional point of view, the southern Afar constitutes various types of fault trends. Berhe (1986) stated that five major fault trends of different ages were recognized in the region (fig. 5.1).

Based on the structural map of southern Afar (Berhe, 1986), the two marginal fault trends, the Gulf of Tadjoura and Nazareth trends meet at the geographic locations: $40^{\circ} 52' 30'' - 41^{\circ} 7' 30''$ E and $9^{\circ} 7' 30'' - 9^{\circ} 37' 30''$ N, locally called **Asebot**, mean while the E - W (Gulf of Tadjoura) and the North westerly lineaments intersect at: $41^{\circ} 45' 00'' - 42^{\circ} 00' 00''$ E and $9^{\circ} 22' 30'' - 9^{\circ} 40' 00''$ N or DireDawa area.

The southeastern escarpment forms the margins of the Harar - Somalia plateau and consists of a 25 - 30km wide zone of Antithetically and Synthetically tilted blocks of Precambrian rocks covered by Mesozoic sediments and Tertiary volcanic rocks (Black and Morton, 1975). The present rift margin of the escarpment is delimited by NE trending fault (Nazareth trend) and E -W oriented faults, which could be continuations of the Ambo fault on the northwestern Ethiopian plateau. The rift margin appears to have been affected by north- westerly lineaments, which might have acted as transcurrent faults.

The structural style of the escarpment changes rapidly west and east of **Kulubi** either side of the Gara Mulata fault zone (Berhe, 1986). West of **Kulubi** the beds dip towards the rift and fault planes dip away from the rift; whereas east of **Kulubi** the reverse is true. The fault planes dip towards the rift while the bedding planes dip away from the rift. In the **Kulubi** area fault sets with opposed hade are observed to interfinger. This is a transition zone where rotation of bedding and fault planes change from antithetic to synthetic.

When we narrow the area of study to a particular site, DireDawa and it's surrounding, it does not necessarily mean that this area gives a complete solution for the tectonic style and evolution of the southern Afar rift margins. However, structural analyses of the area will give imminent for the rift margin development and will strengthen the idea about inhomogeneity of tectonic style and direction of extension of the region. Moreover, it will give the chronological order of structures by analyzing the various orientations of Dykes of the area.

The analysis is mainly based on the faults, Dykes, Bedding planes, folds and other features associated with these major structures.

5.2 Faults

As mentioned earlier the study area, located in the southern part of Afar Depression, is characterized by well marked nearly E-W oriented boundary normal faults at the southern periphery, by well-defined marginal graben at the north and poorly defined, N 10° W oriented transcurrent faults bounding a 25 - 30 km wide rift margin. This region is generally good in preserving almost all the tectonic activities, which have taken place since the initiation of rifting to the Miocene- Pliocene periods. It comprises of older (~14 my) faults along the periphery of the rift to faults of relatively younger (< 5 my) age at the northern part. The development of the marginal graben is considered as recent

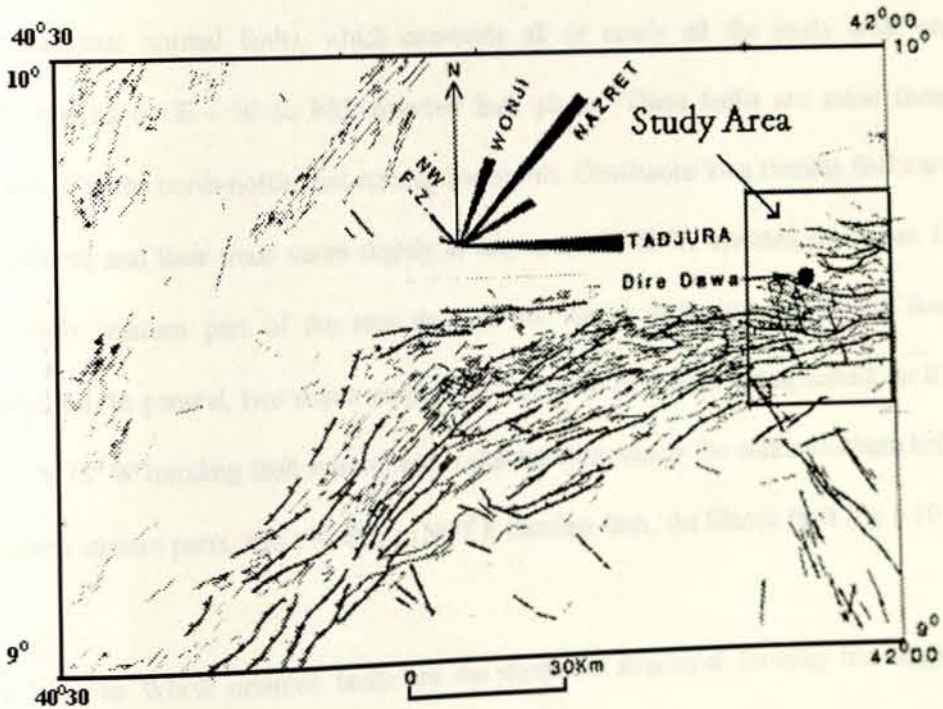


Fig5.1 Structural map of the Dire Dawa area (modified after Berhe, 1986)

activities of the rift margin. More over, middle age volcano tectonic activities are also preserved along the well-developed half grabens or the rift margin in general.

The boundary faults, which separate the Somalian plateau from the rift, are constituted by several short running E - W to ESE - WNW oriented faults. These faults have discontinuous right-stepping en-echelon disposition. The maximum throw of the boundary faults measured from the topographic map reaches up to 500m. In other parts of the boundary there are a series of synthetic faults up to 300m apart, all or nearly all with the same direction of throw, constitute the fault scarp. On traversing such areas, the same geological sequence may be repeated on each successive fault block. These normal faults are generally older as they are reflected by the older felsic centers along these faults.

The marginal normal faults, which constitute all or nearly all the study area, are characterized by E - W to ESE oriented fault planes. These faults are some times dissected by the north-north-west running lineaments. Continuous long running faults are not evident and their trend varies slightly as they cross the NNW oriented structures. In the north western part of the area there is one major fault showing unique fault orientation. In general, two major marginal fault systems have been distinguished: an E - W to N 78° W trending fault system, which characterizes mainly the entire southern half, the north eastern parts, and a N40° E to N60° E trending fault, the Shinile fault (fig 5.10).

The E-W to WNW oriented faults are the dominant structures forming the largest portion of the rift margin. The rose diagram (fig.5.3) shows that the fault trends of this system vary from S 80° W - N 60° W. The northeastern, central, southern and

southeastern parts of the area are characterized by S 80° W – N 75° W trending fault scarps. The throw of the faults range from 40m to about 150m. The fault scarp cuts the Mesozoic rocks of the area and the top part of the Precambrian basement. The magnitude of dip of the fault planes is variable. In areas where there is high block tilting, the magnitude of dip of the faults reduce greatly and a dip angle of about 45° N is measured, while in areas of gently dipping blocks such as: around Lange and Kersa, its dip amount reaches up to 70° N.

At the western and southwestern part of the area (Melka-Jebdu, Dujuma), the marginal faults are constituted by several N 80° W to N 60° W oriented fault planes. Their dip amount ranges from 70 - 40° NNE and their maximum throw was estimated to be about 100m, which is almost similar with the E-W oriented faults. However, this area is devoid of any intra-basin volcanic products.

Well-developed fault scarps are observed in the north and northwestern part of the study area in particular along the northwestern border of the Shimile town. In this particular area distinct fault patterns, trending NE to ENE (N 40° E - N70° E) and dipping to about 70° SE are evident. The second and most important distinguishing feature of these faults is that they cut the recent volcanic product (Afar stratoid series) of the area, which is dated to 4.68 Ma. (Chernet et al., 1998). There fore, it can be suggested that these faults are the youngest of all marginal faults present in the area.

The north-northwest trending faults or lineaments in the DireDawa are aligned N20° W to N5°W. These faults are particularly evident in DireDawa and its vicinity. Tectonic structures associated with these faults occur on many scales. Small faults are traceable up

to the rift margin (Berhe, 1986) where they offset the escarpment, and continue to central Afar (fig.5.1). As he stated more, these faults have extended histories dating well back in to the Mesozoic or even the Precambrian. Therefore, it is promising to say that these faults (lineaments), which are evident in the study area, have two tectonic histories. The main evidence for this is the crosscut nature of the structures. Most of the structures are cut by the E -W running marginal normal faults. This shows that the NNW trending faults pre-date the marginal faults. While the second group of structures cut the marginal faults, meaning that these lineaments (shear zone) post-date the marginal faults. Therefore, this indicates that the structures might have been rejuvenated from the pre-existing NNW oriented faults.

In the project area, dextral senses of movements are observed. The nearly N - S trending lineament that passes through the eastern side of the town, DireDawa (DireDawa Textile factory) shows a dextral sense of movement. This sense of movement was confirmed from the detail measurements of the bedding plane orientations (Fig.4.2). But in most areas (such as along Lege-Oda river and Hula-Hulul) this sense of movement is justified from aerial photographs and satellite imageries.

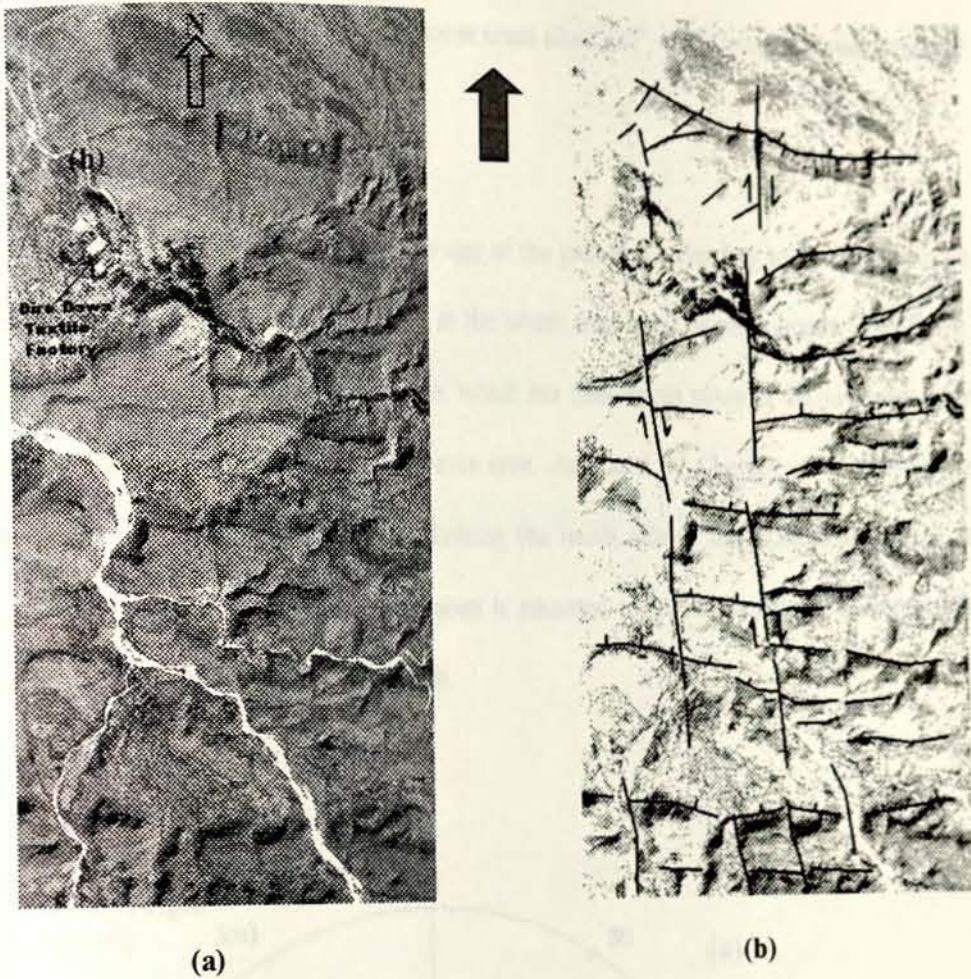
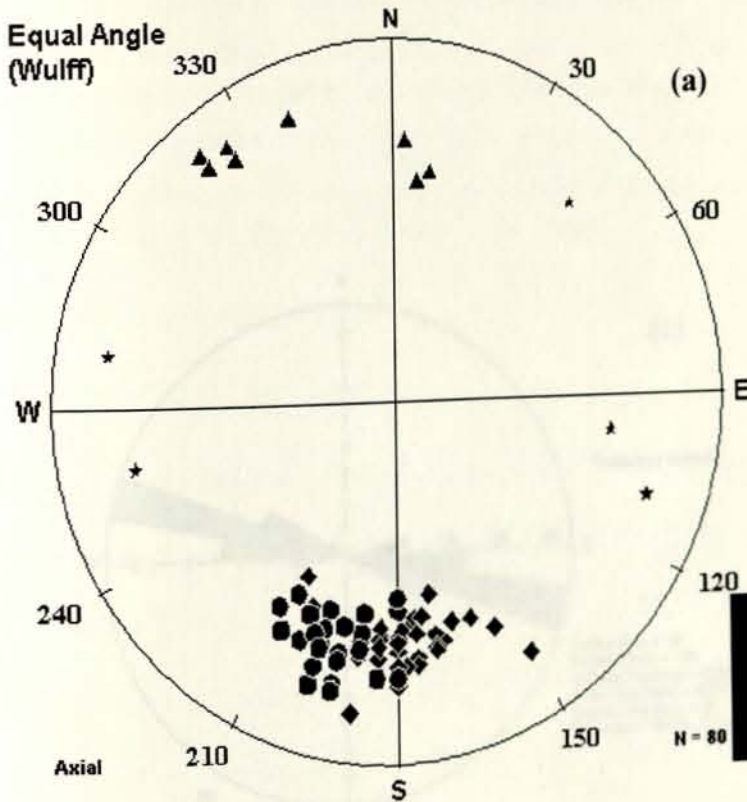


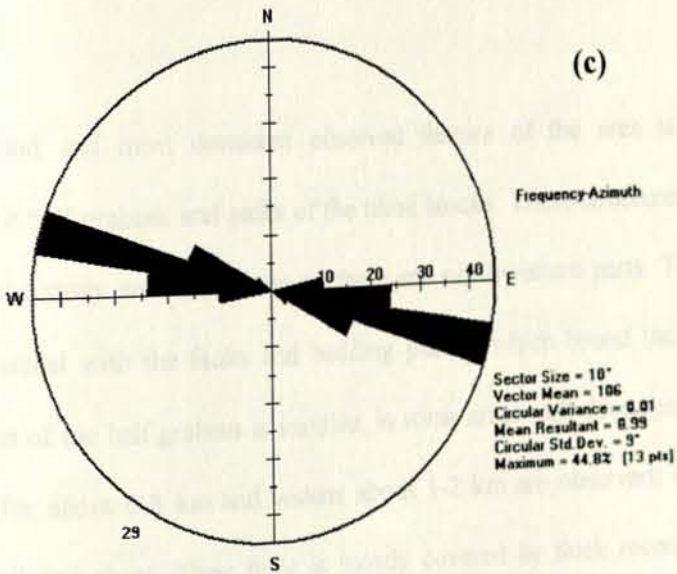
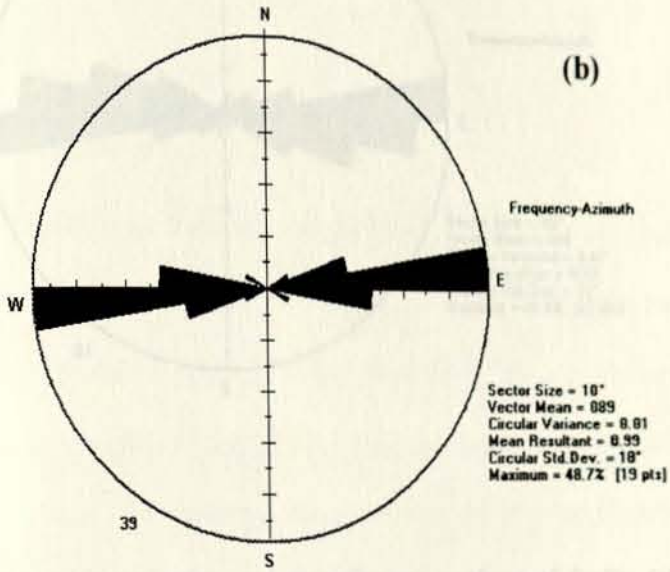
Fig.5.2 Post-rift, dextral north-northwesterly transcurrent faults on the eastern side of the Dire Dawa town (a) Aerial photograph and (b) schematic structural map of eastern DireDawa

The other fascinating feature of the area is the development of marginal depression (Graben) at the north-north-east side of the area. This is a continuous graben extending from Asebot passing through Melka-Jebdu to Shinile, bounded at the north by the $N 40^{\circ}$ E to $N 70^{\circ}$ W trending Shinile Fault and at the south by successive steps of the marginal faults (fig. 4.11b). The maximum width of the depression is about 7km and is 140m deep from the northern flanking plateau (Rebal and Rerjashebeley Ridges). Thick alluvial

deposits mostly cover its floor but in some areas tilted (27° - 28°) layers of limestone and sandstone are present.

Kazmin et al (1980) estimated that the age of the graben is extending to Miocene (about 9my). However, the marginal graben in the study area is by much younger (<4.68 my). This graben may be the recent episode, which has been taken place in the southern Afar margin particularly around the DireDawa area. As stated by Chernet et al. (1998) the rocks, which constitute the plateau flanking the north side of the graben, are dated at 4.68 Ma. Therefore, this marginal graben is assumed to be developing post-dating the Afar stratoid series and the Shinile fault.





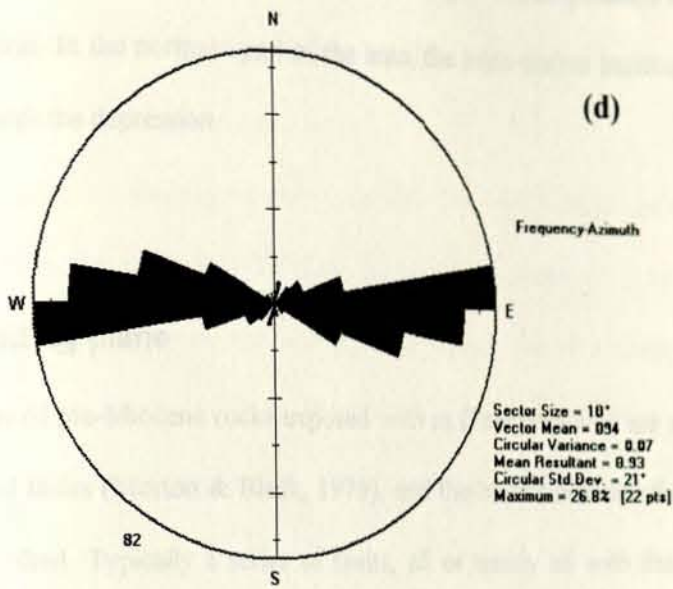


Fig.5.3 Stereographic projection and rose diagram analyses of faults: (a) Stereographic projection of the various fault planes; the pole positions with “◆” symbol represents the orientations of the southern and south-eastern portions of the study area, “●” symbols are pole positions of the south-western and western sides of the area, “▲” are pole positions for the Shinile and other south dipping faults; whereas, “φ” represents for the locally oriented fault planes; (b) is a rose diagram for the “◆”; (c) is a rose diagram for “●”, and (d) is a general rose diagram for the whole fault system.

The second and most dominant observed feature of the area is the existence of successive half-grabens and picks of the tilted blocks. These structures are found almost all over the study area except the northern and northwestern parts. They run parallel or nearly parallel with the faults and bedding planes, which bound the half-grabens. The dimension of the half grabens is variable, in some areas well-developed half grabens that extends for about 6-8 km and widens about 1-2 km are observed; whereas others are very small and short. Their floor is mostly covered by thick recent alluvial deposits.

However, in some places, the floor is covered by volcanic products of mafic and felsic composition. In the northern part of the area, the intra-graben basaltic rocks are aligned parallel with the depression.

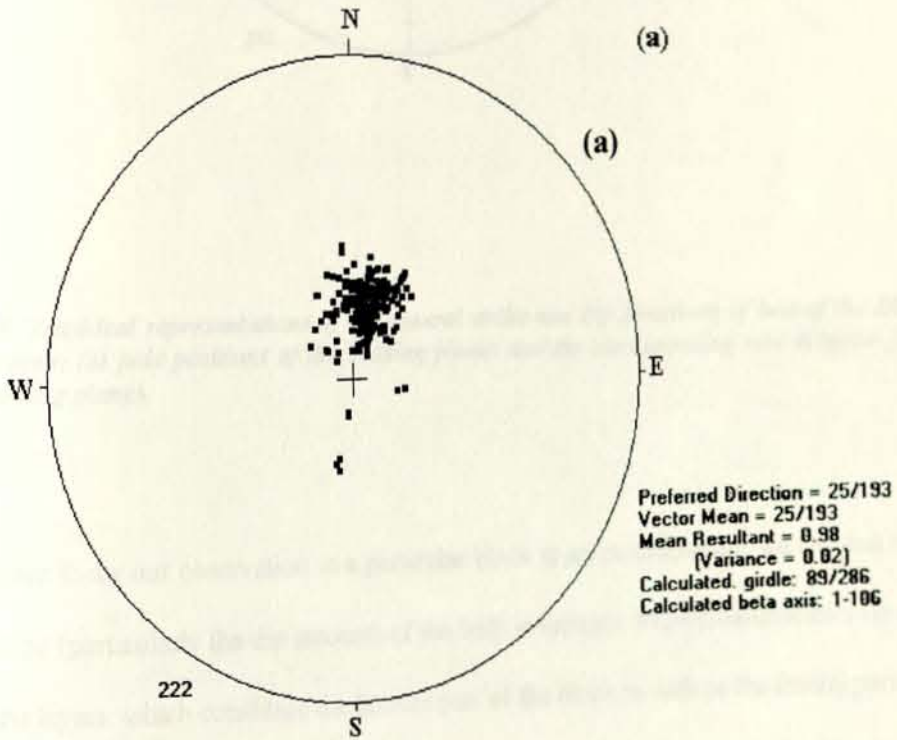
5.3 Bedding plane

The areas of pre-Miocene rocks exposed with in DireDawa area are all intensely faulted by normal faults (Morton & Black, 1975), and the blocks between the parallel faults are strongly tilted. Typically a series of faults, all or nearly all with the same direction of throw, separates a series of tilted blocks with beds dipping in the opposite direction to the fault. The fault and bedding relationship of the area confirmed that the bed orientation is greatly controlled by orientation of the faults. The strike of the beds and faults is nearly similar, however, their dip amount is inversely related and their dip direction lies opposite to each other. The dip amount of the bedding plane increases with progressive increment of block rotation about horizontal axis, while the dip amount of the faults planes decreases with progressive increment in block rotation. The orientation of the strike of beds range from $S80^{\circ}W - N60^{\circ}W$; however, the strike of the beds vary locally and trends of $S45^{\circ}W - S80^{\circ}W$ and $N60^{\circ}W - N40^{\circ}W$ are observed. Moreover, the dip amount of the beds varies from nearly horizontal to about 45° s.

As stated above the strike of the beds is not uniform through out the area. Some localities show E-W oriented beds, while the trend of the beds in other localities are slightly deviated towards north. In general, the southeastern, eastern, central and northeastern part of the area are characterized by $S85^{\circ}W - N75^{\circ}W$ oriented bed strikes,

while, the southwestern western (Melka-Jebdu) and around the NNW running lineament are manifested by $N75^{\circ}W - N60^{\circ}W$ oriented bed strikes (fig.5.10).

On the escarpment flanking the region, bedding dip angle often increases progressively as moving from the plateau (rift margin faults) towards the rift floor. At the southern periphery of the area, along the road of Kersa- Lange, the dip amount of the sedimentary rocks range from horizontal to about 10° s, while, as moving downwards to the north the dip amount progressively increases and bedding dip of about 45° s is measured.



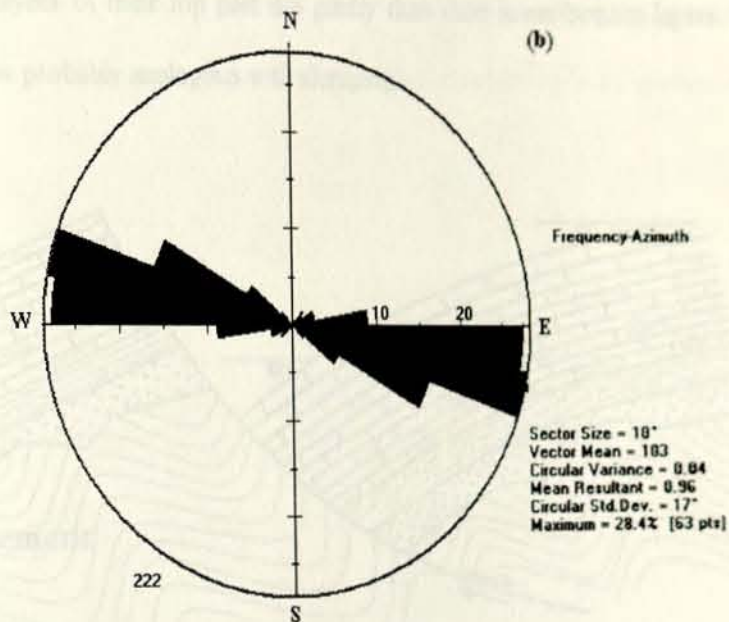
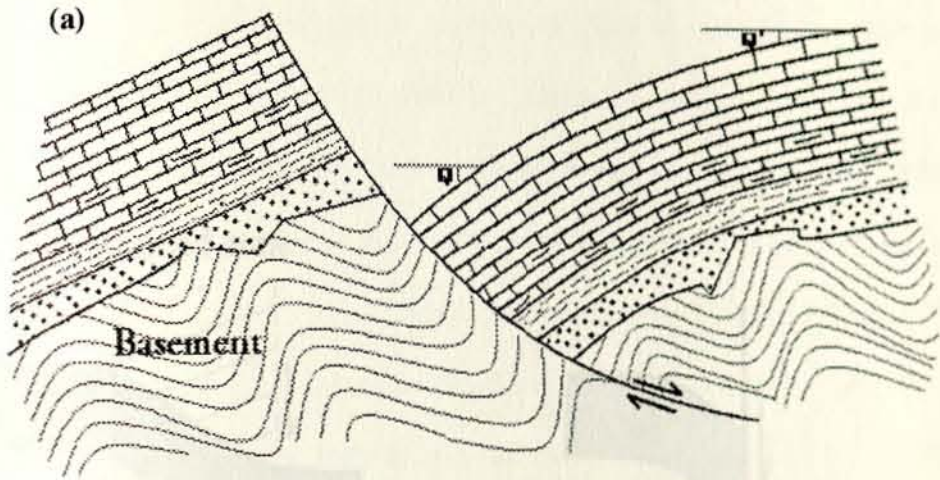


Fig.5.4 Graphical representations of the general strike and dip directions of beds of the Dire Dawa area: (a) pole positions of the bedding planes and (b) corresponding rose diagram for the bedding planes.

When we focus our observation to a particular block at an outcrop scale, we see that the geometry (particularly the dip amount) of the beds is variable. Most measurements reveal that the layers, which constitute the bottom part of the block as well as the frontal part of the top layers, are gently dipping, while as moving up sequence the layers dip steeply. In that case a dip difference of about 23° is observed between the frontal and backsides of the top layer (fig.5.5a). Such block geometry is analogous with blocks formed by roll-over anticline. The second way that modifies the dip amount of a single block is

development of subsidiary normal faults on the hanging wall. These subsidiary normal faults change the dip of the bed by about 20° (fig.5.5b). Some steeply dipping blocks also show that the layers of their top part dip gently than their lower/bottom layers. Such geometry is most probably analogous with slumping.



(b)



Fig.5.5 Representative Sketches and photographs showing variations in dip amount of a single layer or block (a) Schematic Cross-Section showing block tilting accompanied with roll-over anticline structures (b) highly tilted block accompanied with antithetic normal faults.

Some blocks adjoining the NNW-SSE trending lineaments commonly exhibit open folds or flexures, which appear to be related to the fault movement. Park (1997) explained that normal drag is used to describe a fold that bends in the opposite sense. Such structures predominantly define the sense of movements of the transcurrent faults present in the area (fig.5.6).

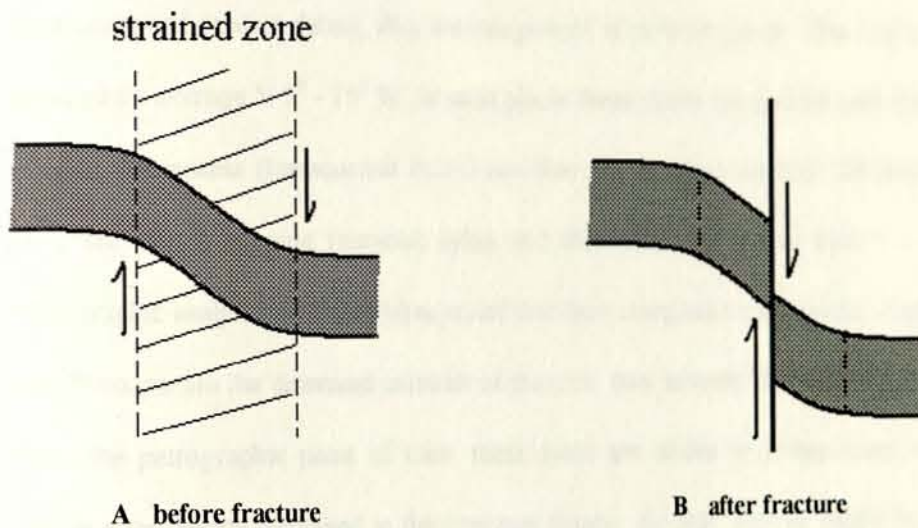


Fig.5.6 Association of faults and flexures. Normal drag ductile bending in a strained zone (A) may precede fault movement (B) causing flexure in the rocks adjacent to the fault.

5.4 Dykes

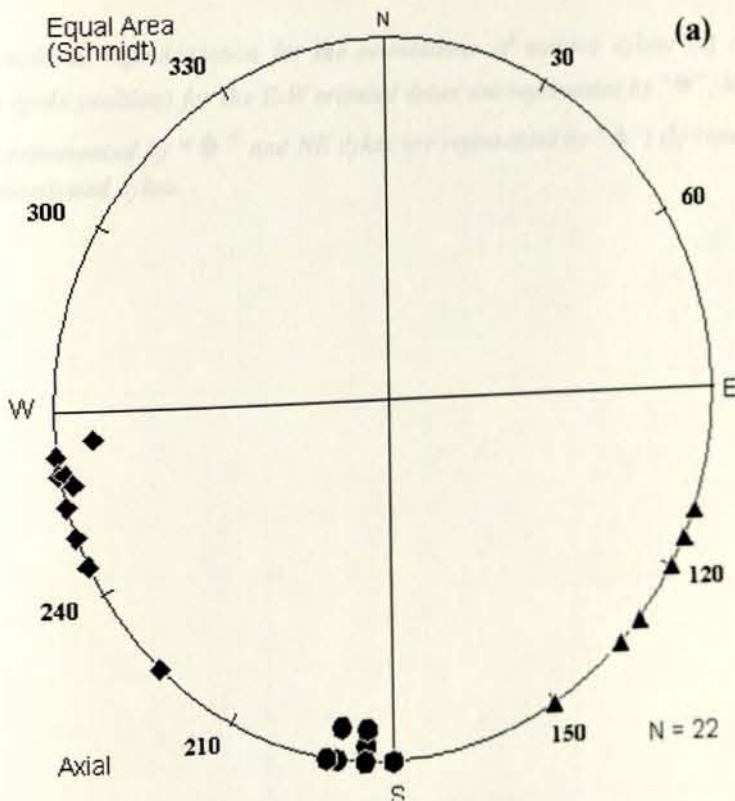
Chernet et al. (1998) stated that the southern Afar rift margin volcanic products are subdivided in to five chronostratigraphic units, three basalt-dominated and two Trachyte/Rhyolite-dominated. These units are grouped as either belonging to pre-rift or syn-rift phases of activities as determined by their temporal and spatial association to rift structure (Chernet et al., 1999). However, in the study area only few of the volcanic

products are practically examined, the rest are preserved only in the form of dykes and sills injected to the basement and Mesozoic sedimentary rocks. Therefore, to assess the volcano-tectonic evolution of the rift margin, detail structural analyses of the nature and orientation of dykes is very crucial.

Dyke intrusions of different ages and types are widespread through out the southern Afar margin, particularly with in the basement and Mesozoic sediments flanking the rift floor. In most parts of the area, the dykes are oriented in three major trends. Based on their orientation and relative dating, they are categorized in to three groups. The first group is oriented on average $N 5^{\circ} - 15^{\circ} W$. In most places these dykes run parallel with the NNW trending lineaments (transcurrent faults) and they are synchronous with the lineaments. They are steeply dipping (vertical) dykes and their thickness ranges from 1.5 - 40m. Petrographic analyses of these dykes reveal that their composition is basaltic. Plagioclase and Pyroxene are the dominant minerals of the rock, they account about 89% by volume. From the petrographic point of view, these dykes are similar in composition with the olivine poor basalts discussed in the previous chapter. So their activity might be related to the emplacement of this olivine poor basalt of the Dahla Age.

The second groups of dykes are those oriented $N 80^{\circ} - 90^{\circ} W$ or exactly parallel with the trends of the marginal faults. Most of the dykes are vertically dipping, but some are slightly inclined ($10-30^{\circ}$) from vertical towards north. Like the first group, their mineralogical composition is mainly governed by plagioclase and pyroxene. These two minerals together consist of about 86% by volume. But these dykes slightly differ from the first group that they are olivine free, porphyritic in texture and relatively older (Table 5.1).

The third types of dykes are those running N 20° E to N 50° E. These are independent dykes, which are not related with any of the major structural elements of the area. These are evident mainly along the road cut exposures of DireDawa – Dengego and Dengego – Lange. Such dykes are mostly thin (0.5 – 1.5 m thick) and friable as compared with the above two types. As referred from the work of Megrue et al. (1972), these dykes are very old dating back to 11 - 35 my. Therefore, these dykes might have been developed contemporaneously (concurrently) with the pre-rift volcanic products, Alaji and Jebel Sadalle basalts.



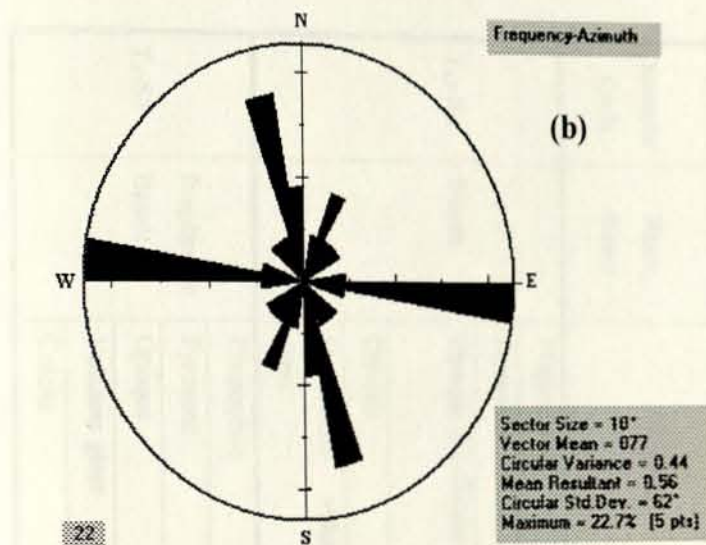


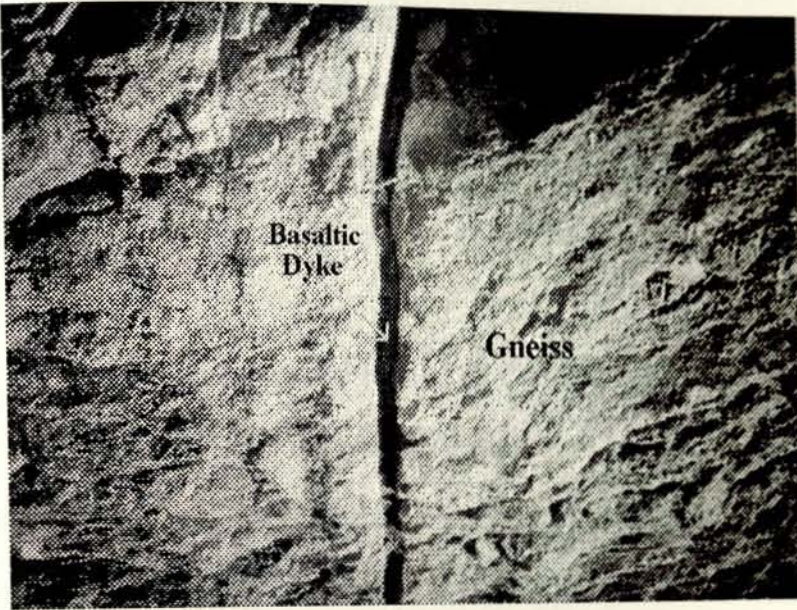
Fig5.7 Graphical representation for the orientations of various dykes: (a) stereographic projection (pole position) for the E-W oriented dykes are represented by “●”, NNW oriented dykes are represented by “◆” and NE dykes are represented by “▲”;

(b) rose diagram for the aforementioned dykes.

Table 5.1 Summary of the mineral contents of the Dykes

Sample Code	Rock Name	Minerals	Mode %	Texture	Location in UTM Zone (37)		
					Easting	Northing	Altitude
T ₁₂ -S ₃	Basalt	Plagioclase	55	Lath-Anhedral	819500	1050040	1737asl
		Pyroxene	34	Anhedral			
		Opaque (Fe-Oxide)	8	Euhedral-Subhed			
		Olivine	2	Subhedral			
		Devitrified volcanic glass	1				
T ₄ -S ₂	Porphyritic Basalt	Plagioclase	56	Tabular-Lath	807347	1053196	1460asl
		Pyroxene	30	Anhedral			
		Opaque	7	Subhedral-Anhed			
		Volcanic glass	5	-----			
		Calcite	2	Anhedral			

(a)



(b)

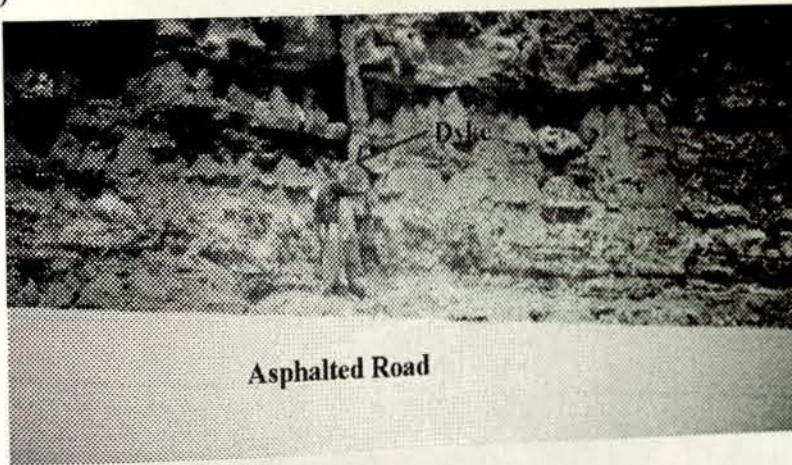


Fig.5.8 Basaltic dykes (a) a dyke intruded with in the basement complex, (b) E-W oriented dyke intruded with in the Shale and Marl unit.

5.5 Folds

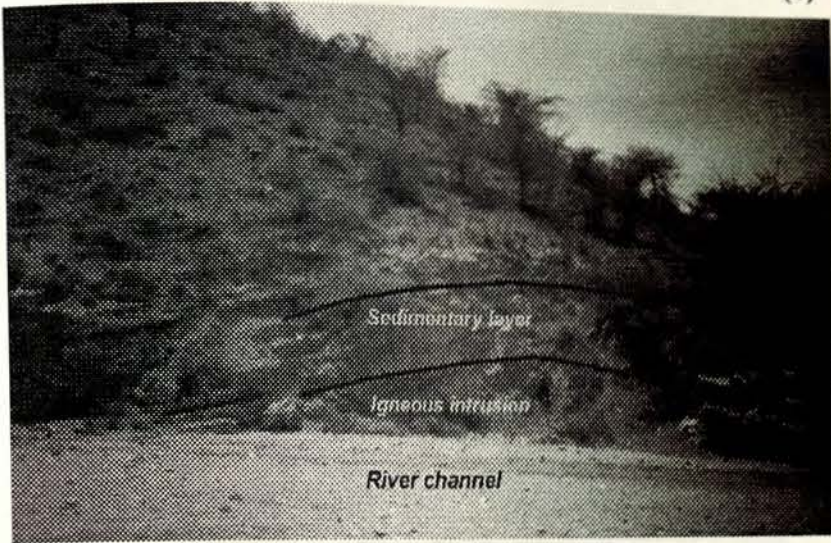
The study area or the southern margin of Afar depression in general is an area showing extensional tectonics. Consequently large-scale (Megascopic) folds are absent in the area. However, locally induced mesoscopic folds and some pre-rift folded structures are observed within the limestone group and the basement rocks. The folds formed by basaltic intrusions are predominantly of Dome-shapes (fig.5.9.a &b), whereas some other folds formed by the compressional effect of the transcurrent faults are open folds. The second types of folds, which are commonly observed within the Gneissic rocks are very small-scale folds. Such type of folds are mostly irregular in geometry (disharmonic type folds) and do not have any measurable structure (fig.5.9.c). These folds are assumed to develop pre-dating the rift formation.

(a)



Fig. 5.9. Folded structures developed as a result of basaltic intrusions (a) and (b) and (c) fold developed during the reorganization of the basement complex (c).

(b)



(c)



Fig.5.9 Folded structures developed as a result of basaltic intrusions (a) and (b) and those folds formed during the recrystallization of the basement complexes (c).

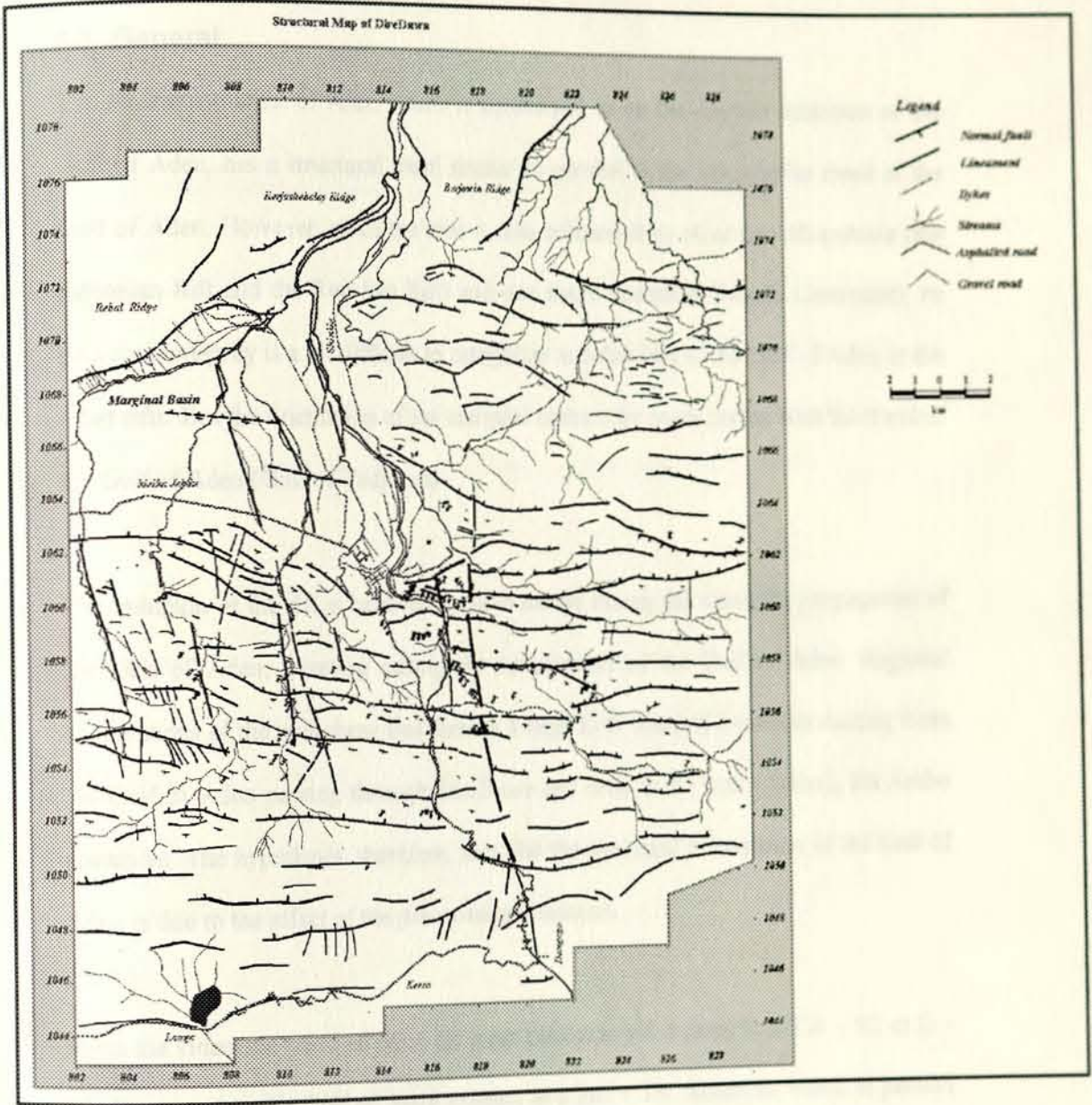


Fig5.10 Structural map of DireDawa area

CHAPTER-SIX

TECTONICS OF DIREDAWA AREA

6.1 General

The southern margin of Afar, which is considered to be the western extension of the Gulf of Aden, has a structural trend similar or parallel to the topographic trend of the Gulf of Aden. However, since the area is also influenced by other two rift systems (the Ethiopian Rift and the Red Sea Rift) and one major lineament (Marda Lineament), its structural integrity is a bit difficult to categorize as either part of the Gulf of Aden or the other rifts. But the orientation of the marginal faults is by much similar with the trend of the Gulf of Aden (Gulf of Tadjoura).

The initiation of the rift is believed to have started during the westward propagation of the Gulf of Aden, meaning during the oceanization of the Gulf of Aden. Regional observations of the area show that there is a large E-W oriented lineament starting from the Gulf of Aden passing through DireDawa and ends at the west (Ambo), the Ambo lineament. The hypothesis, therefore, says that the westward propagation of the Gulf of Aden is due to the effect of the pre-existing lineament.

From the kinematic point of view, the main Ethiopian rift extends in a NW – SE or E – W direction, but the Gulf of Aden extends in a NE – SW direction, which is parallel with the transform faults of its ocean basin. The southern Afar margin on one hand has an extension direction towards $N 23^{\circ} E \pm 10^{\circ}$. This extension direction is closely related with that of the Gulf of Aden. Therefore the E – W structures in the study area might represent the extension of the Gulf of Aden ridges. Between the time interval of (22-13my) the Gulf of Aden ridge (GAR) in its westward propagation encountered the

Shukra El Sheik discontinuity and at that period it is believed that the GAR jumped westward and penetrated the southern Afar depression for the first time forming the E – W oriented structures we see in DireDawa, Alisabieh and Ambo areas (Audin et al. in press, 2003)

6.2 Block rotation/tilting and Internal structure of faults

While it is evident that fields of normally faulted and tilted blocks are formed by extensional processes, the manner in which the faults are accommodated at depth and the cause for tilting of blocks remain a problem. From a geometrical viewpoint two solutions have been put forward for the cause of block tilting.

Firstly, if the fault planes are essentially fixed and strongly curved; the block movement is the analogous to a landslide due to removal of support in front of the block. In this case small blocks (the hanging walls) rotate about a horizontal axis fixed at the centre of the curve (fig.6.1). Such blocks although not common are observed at around Dengogo and northern part of Kersa town. These blocks are supposed to be developed by gravitational sliding.

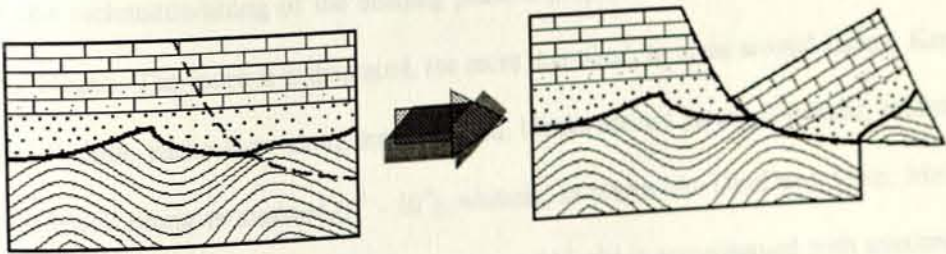


Fig.6.1 Rotational block tilting along fixed fault plane; such block rotation is common in gravity induced block movements

Second, if faulting takes place on a series of sub parallel straight or curved fault planes, progressive movement causes rotational tilting of both the blocks themselves and the faults bounding them. In this case normal faults in the hanging wall block may form (Twiss and Moors, 1992) a set of imbricate faults, which are closely spaced parallel fault of the same type that either terminate against or merge with the detachment fault (fig.6.2)

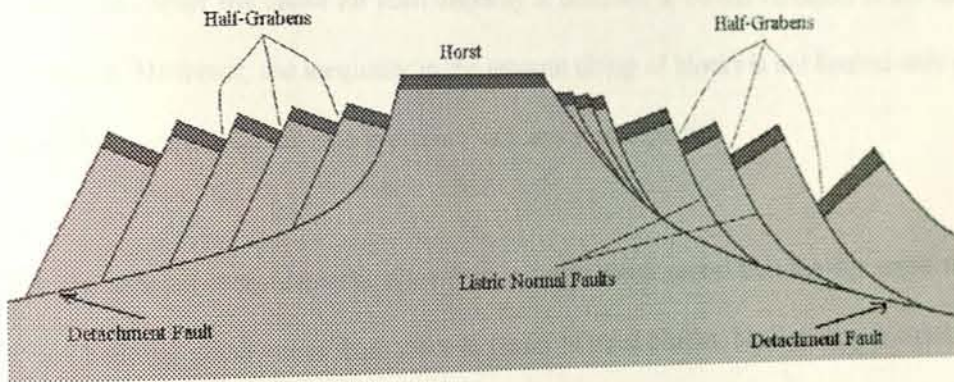


Fig.6.2 System of normal faults commonly are characterized by a main fault with associated subsidiary faults and by low-angle detachment faults with imbricate fault blocks in the hanging wall block (modified after Twiss and Moors, 1992).

Whatever the shape of the faults at depth is, one fact is observed in the study area. That is the inclination/tilting of the bedding plane is proportional with the displacement of the blocks. The more it is displaced, the more it is tilted. In areas around Lange, Kersa and Kulubi, particularly along the main road, blocks are not greatly displaced, meaning that block tilting is minimal ($0^{\circ} - 10^{\circ}$), whereas, in places like DireDawa town, Melka Jebdu and Halo Busa the large displacement of blocks is accompanied with maximum tilting. In these areas blocks are tilted to about 43° .

To determine the nature of the faults at depth, whether the fault planes are listric or planar, geophysical techniques especially Seismic Reflection was more convenient than any other technique. However, due to its limitation, the nature of the fault plane was assessed by analysing the orientations of the bedding planes.

In the study area almost all blocks are tilted to some angle. Some are highly inclined (to about 45°) and some are less inclined and even few blocks are free from tilting. As mentioned earlier the cause for such disparity is believed to be the variation in the state of motion. However, the inequality in the amount tilting of blocks is not limited only on those different blocks but also is evident with in a single block.

The dip amount measurements taken from a single block reveal that the dip angle of a single bedding plane varies from place to place. In most blocks, block tilting is minimal at the top of the frontal part of the block, while as moving backward to the depression, block tilting significantly increases (fig.6.3). This leads to about 20° dip difference with in a single layer or block in general.

The general observation of the layers, which constitute the block, shows that such geometry is typical of roll over anticline structures. These structures are therefore, developed when the fault plane separating the two blocks (hanging and foot walls) is predominantly of listric normal fault (fig.6.3).

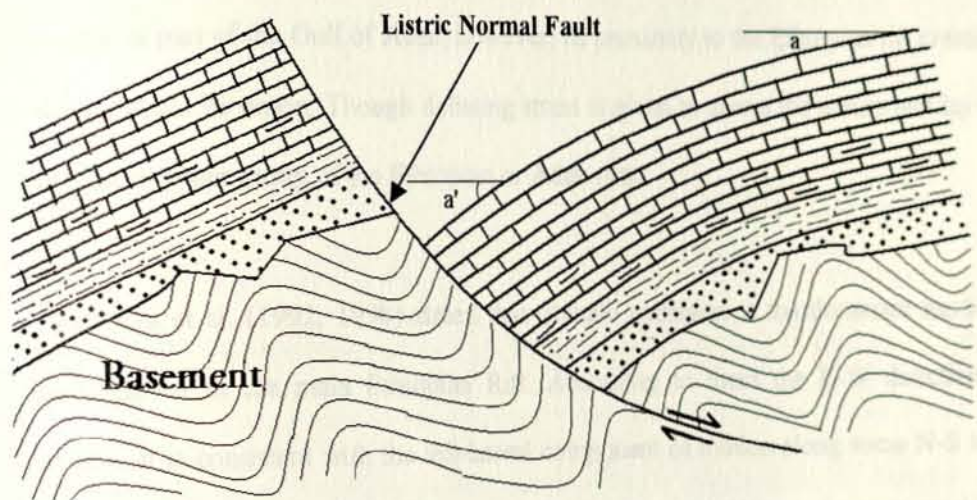


Fig.6.3 Model for the geometry of the fault planes: " a " represents the frontal part of the dip amount of the plane, which is gently inclined, while " a' " is the steepest part of the bedding plane.

6.3 Extensional tectonics in the southern Afar Rift Margin

The southern Afar rift margin is a roughly E-W ($N 87^{\circ} W$) oriented segment of the Gulf of Aden Rift. Unlike the Afar rift floor and the northern main Ethiopian rift, which have been the subject of numerous geological and structural observations, this sector has been less investigated. The lack of detailed structural analyses led to different tectonic interpretations regarding its development. It is not yet certain that whether this sector is part of the Gulf of Aden or the East African rifts. Its structural trend resembles that this margin is part of the Gulf of Aden; however, its proximity to the Ethiopian rift creates a debate about its origin. Though debating stress is given to assess the nature and lay the margin as either group of the Ethiopian or Aden rifts.

Boccaletti et al. (1992, 1998) stated that oblique extension is the dominant mode of deformation in the main Ethiopian Rift. According to them the E-W direction of extension is consistent with the left-lateral component of motion along some N-S to $N 40^{\circ} E$ trending faults affecting Quaternary volcanic rocks. However, recent works of Acocella and Korme (2002) stated that even though the mean extension direction ($N 52^{\circ} W \pm 20^{\circ}$) is perpendicular to the mean main Ethiopian Rift trend ($N 40^{\circ} E \pm 11^{\circ}$), the extension direction is slightly oblique (with a component of dextral shear) with regard to the extension fractures of the Wonji Fault Belt (mean trend $N 23^{\circ} E \pm 13^{\circ}$).

Like the Main Ethiopian Rift, the Gulf of Aden also shows well-defined oblique extension. But the direction of extension is by far different from the main Ethiopian rift. Its extension direction is nearly NE-SW or $N 30-40^{\circ} E$ (with a component of dextral share).

We saw that the extension direction of the two rift systems (the Ethiopian Rift and the Gulf of Aden) is different. The Ethiopian rift extends in the E-W to N 52° W $\pm 20^{\circ}$, while the Gulf of Aden extends in the NE-SW direction, which is orthogonal or nearly orthogonal to each other.

In order to evaluate the Miocene – Pliocene extension direction of the southern Afar Rift margin, measurements were made on the striations/slickensides of the fault planes. These striations are linear features of fault planes indicating the direction of relative movement of faulted blocks.

A total of 11 measurements were made on the Slickensides of the fault planes. These Slickensides or Striations are analysed with their respective fault orientation using the geological softwares: Spheristat and Georient. The preferred Striation direction (extension direction) and the vector mean directions are the same, which is $48-026^{\circ}$ (fig.6. 4). As the mean direction of the faults is $49/010^{\circ}$ (dip amount/dip direction), the associated mean Striation direction ($48-026^{\circ}$) indicates that a component of dextral shear is present along the faults. Therefore, the area is not manifested by pure extensional deformation; instead lesser amount of dextral shear is synthesized modifying the pure extensional tectonics.

As evidenced from the previous works, the extension direction of the main Ethiopian Rift is E-W to N 52° W $\pm 20^{\circ}$ but the extension direction of the southern Afar rift margin (DireDawa area) is nearly perpendicular to it.

Table-6.1 Summarized orientations of faults and their respective striations.

<i>Easting</i>	<i>Northing</i>	<i>Symbol</i>	<i>Group</i>	<i>Weight</i>	<i>Azimuth</i>	<i>Inclination</i>
817134	1060691	33	-1	1.0	273	45
		76	5	1.0	30	42
817021	1060989	33	-1	1.0	278	50
		76	5	1.0	40	45
828964	1073612	33	-1	1.0	280	32
		76	5	1.0	30	29
829013	1073600	33	-1	1.0	285	54
		76	5	1.0	32	52
828982	1073110	33	-1	1.0	285	50
		76	5	1.0	23	49
815440	1071514	33	-1	1.0	275	34
		76	5	1.0	355	33
815386	1070865	33	-1	1.0	290	37
		76	5	1.0	0	36
821025	1057270	33	-1	1.0	275	65
		76	5	1.0	35	62
820295	1057783	33	-1	1.0	280	60
		76	5	1.0	41	56
816969	1060285	33	-1	1.0	283	58
		76	5	1.0	22	58
816778	1060337	33	-1	1.0	279	55
		76	5	1.0	28	54

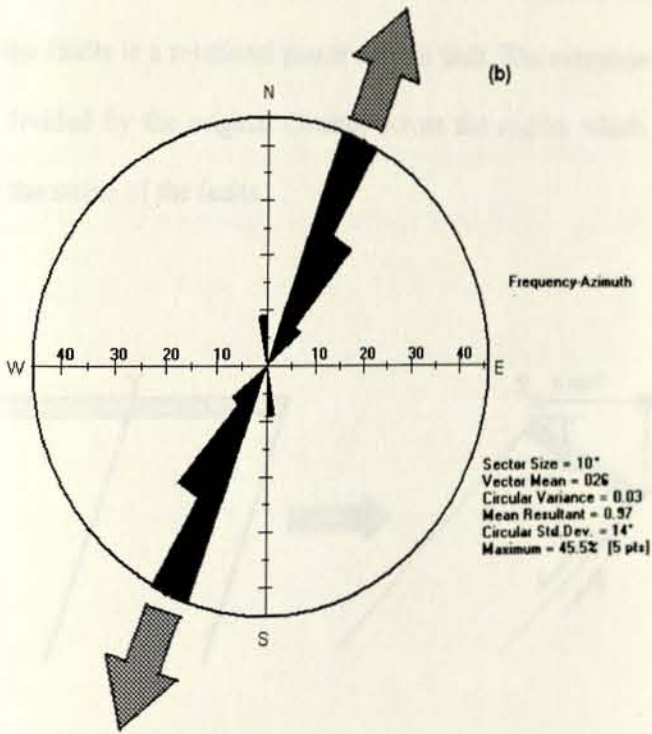
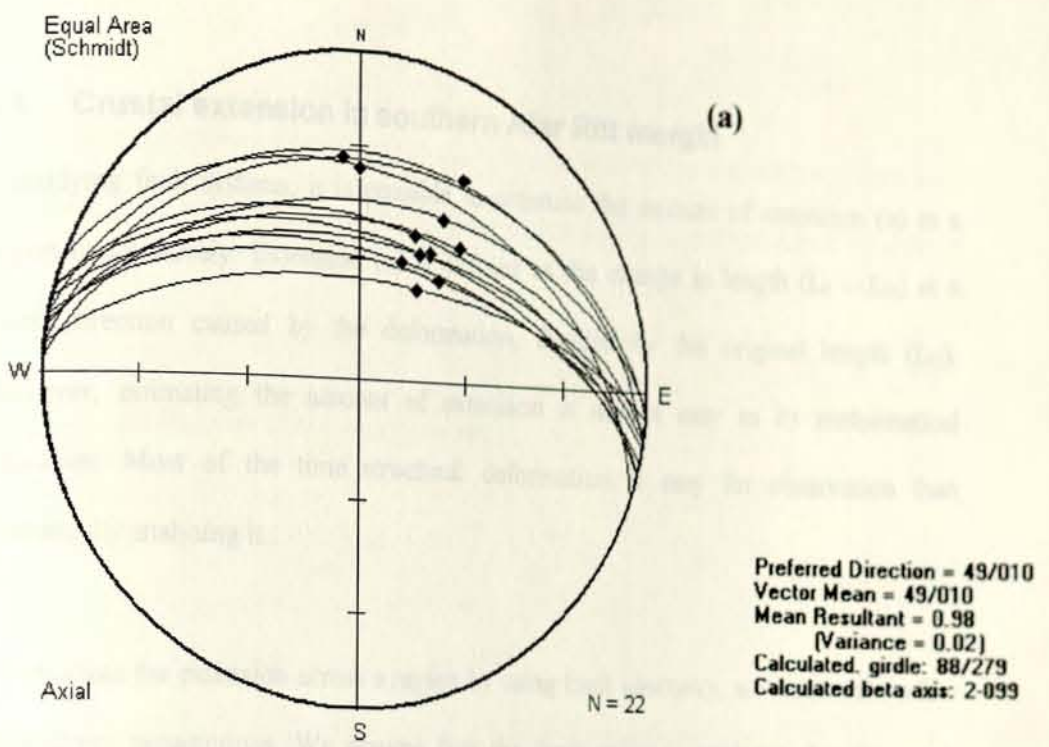


Fig.6.4 Stereographic projection (a) and rose diagram (b) showing the direction of striations.

6.4 Crustal extension in southern Afar Rift margin

In studying fault systems, it is possible to estimate the amount of extension (e) in a region quantitatively. Extension (e) is defined as the change in length ($L_F - L_0$) in a given direction caused by the deformation, divided by the original length (L_0). However, estimating the amount of extension is not as easy as its mathematical operation. Most of the time structural deformation is easy for observation than numerically analysing it.

To evaluate the extension across a region by using fault geometry, we must make a few simplifying assumptions. We assume that the fault strike is uniform; the change in length of the region is the sum of the horizontal extensions on all the faults, and the nature of the faults is a rotational planar normal fault. The extension is then this change in length divided by the original distance across the region, which must be measured normal to the strike of the faults.

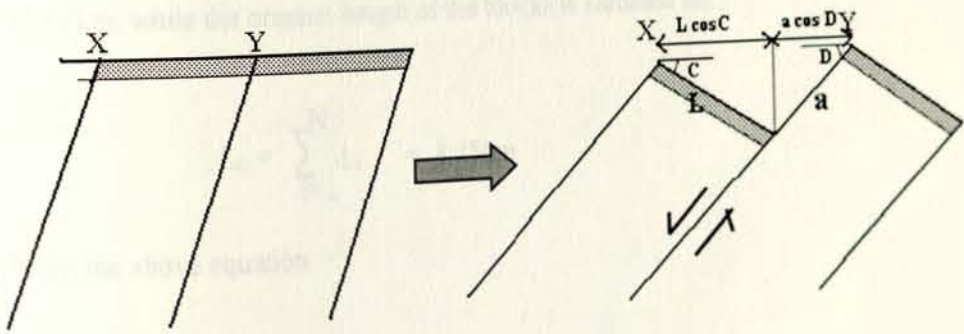


Fig.6.5 Model that shows the amount of extension

For a model of rotating planar normal faults (Fig.6.5), it can be easily derived a relationship among the extension, e, the dip of the rotated bedding C, and the dip of the rotated fault plane D.

Mathematically, this can be expressed as:

$$e = \frac{L_{\text{FINAL}} - L_{\text{ORIGIN}}}{L_{\text{ORIGIN}}}$$

$$e = \frac{L \cos C + a \cos D - L}{L}$$

which is equivalent to

$$e = \frac{\text{Sin}(C+D)}{\text{Sin}C} - 1$$

$$= \text{Sin}((25+50)/\text{Sin}50) - 1 = \mathbf{0.260}$$

One representative cross-section (Fig.6.6), 11 km long, is taken from the eastern side of DireDawa town. The cross-section constitutes nine blocks and nine fault planes. The average spacing of the faults is about 1.4 km. the final length of the cross-section is 11.13km, while the original length of the blocks is summed as:

$$L_0 = \sum_{i=1}^N L_i = 8.75 \text{ km}$$

From the above equation

$$\text{Extension (e)} = \frac{L_F - L_0}{L_0}$$

$$= \frac{11.13 \text{ km} - 8.75 \text{ km}}{8.75 \text{ km}}$$

$$= \mathbf{0.275}$$

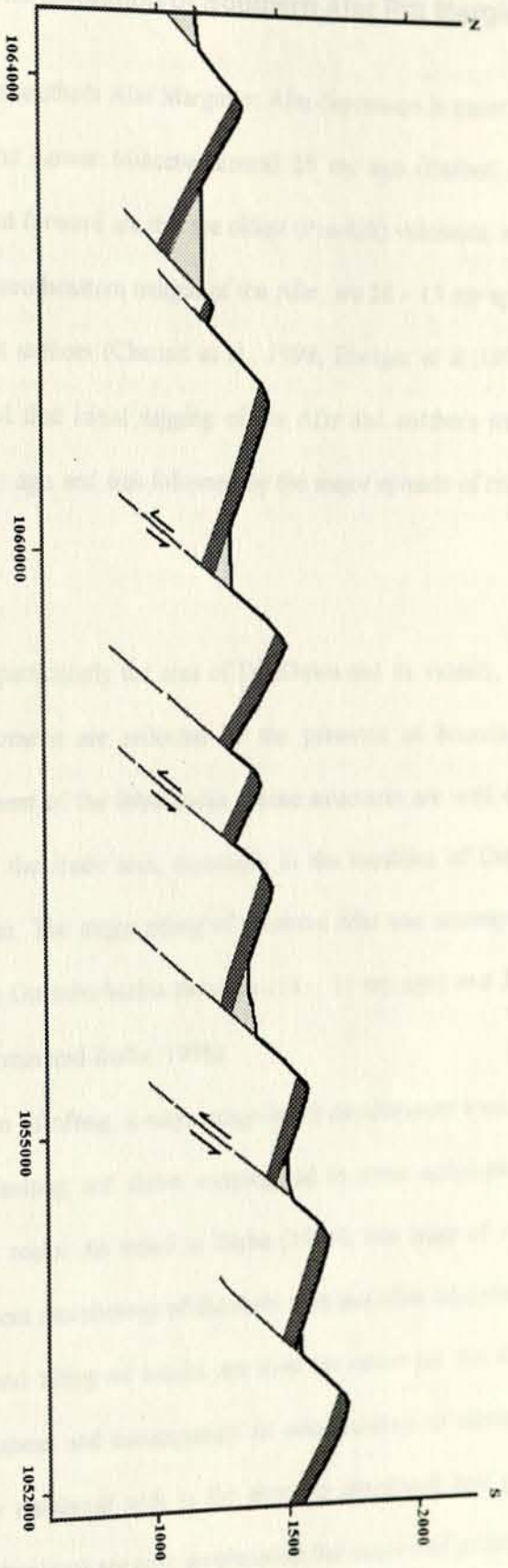


Fig.6.6 Representative cross-section along which the crustal extension of the margin is measured

6.5 Volcano-Tectonic Evolution of Southern Afar Rift Margin

The development of the southern Afar Margin or Afar depression in general is accepted as having started in the Lower Miocene around 25 my ago (Barberi et al. 1975). However, arguments put forward are that the oldest (Pre-Rift) volcanics, which are best documented along the southeastern margin of the Afar, are 28 – 15 my ago (Kazmin et al., 1980). The present authors (Chernet et al., 1998; Ebinger et al., 1997) therefore, believed and confirmed that initial sagging of the Afar and northern main Ethiopian Rifts began 14 – 15 my ago and was followed by the major episode of rifting at 10 Ma (Kazmin et al., 1980).

In the southern Afar, particularly the area of DireDawa and its vicinity, the oldest rift related tectonic phenomena are reflected by the presence of boundary faults and synchronous development of the felsic rocks. These structures are well exposed in the southern periphery of the study area, especially in the localities of Dengego, Kersa, Lange and Kulubi areas. The major rifting of southern Afar was accompanied with the formation of the Arba Guracha/Mabla rhyolites (14 – 11 my ago) and Anchar Basalts (11 – 10 my ago) (Kazmin and Berhe, 1978).

Following the initiation of rifting, a major stage in rift development took place. During this stage, intensive faulting and down warping led to some accumulation of silicic volcanics and basaltic rocks. As stated in Berhe (1986), this stage of rifting played a major role for the present morphology of the study area and other adjoining rift margins. Continuous faulting and tilting of blocks are then the cause for the development of intra-marginal half grabens and consequently an accumulation of olivine free basaltic rocks, which are now emplaced within the properly developed half grabens. Silicic rocks (Trachyte and Rhyolites) are now emplaced in the major half grabens located five

km south of DireDawa town. These are recent volcanic event because the layers are nearly horizontal; this shows that intensive faulting and tilting has not occurred after eruption.

The petrographic analyses of the E-W and the NNW oriented basaltic dykes give an idea that the dykes formed concurrently with or a bit earlier from the olivine free basalts. From the crosscutting relationship of structures, it is confirmed that the E-W oriented dykes predate the northwesterly dykes. Mean while, the E-W (N 75° W) oriented faults are older than the reactivated NNW trending lineaments (transcurrent faults). But what should be clarified here is that the northwesterly faults have extended histories (Berhe, 1986) dating well back in to the Mesozoic. Some of these structures are cut by the E-W running marginal faults and show en-echelon disposition. So the younger NNW trending faults might have been revitalized from the pre-existing lineaments.

The youngest volcanic products of the area are the "Afar Stratoid Series" or in our case the Olivine-Rich basalts. They cover the northern and northwestern portion of the area and extend to the floor of the Afar depression. These rocks are relatively older (4.68 my ago) as compared to the other rift floor basalts, therefore, these rocks are considered to be a transition from the Lower to the Upper Stratoid Series.

The last volcano-tectonic event of the area is justified by the presence of NE-SW running normal faults, the Shinile fault and the contemporaneous development of the marginal graben. This fault is relatively young (less than 4.7 my) and tectonically different from the other marginal faults. It is young because it cuts the younger volcanic

rocks of the area and tectonically different since its orientation is by much deviated from the E-W oriented marginal faults. As moving northwards, towards the rift floor, the fault orientation progressively changes and orientations similar with the northern Main Ethiopian Rift predominate.

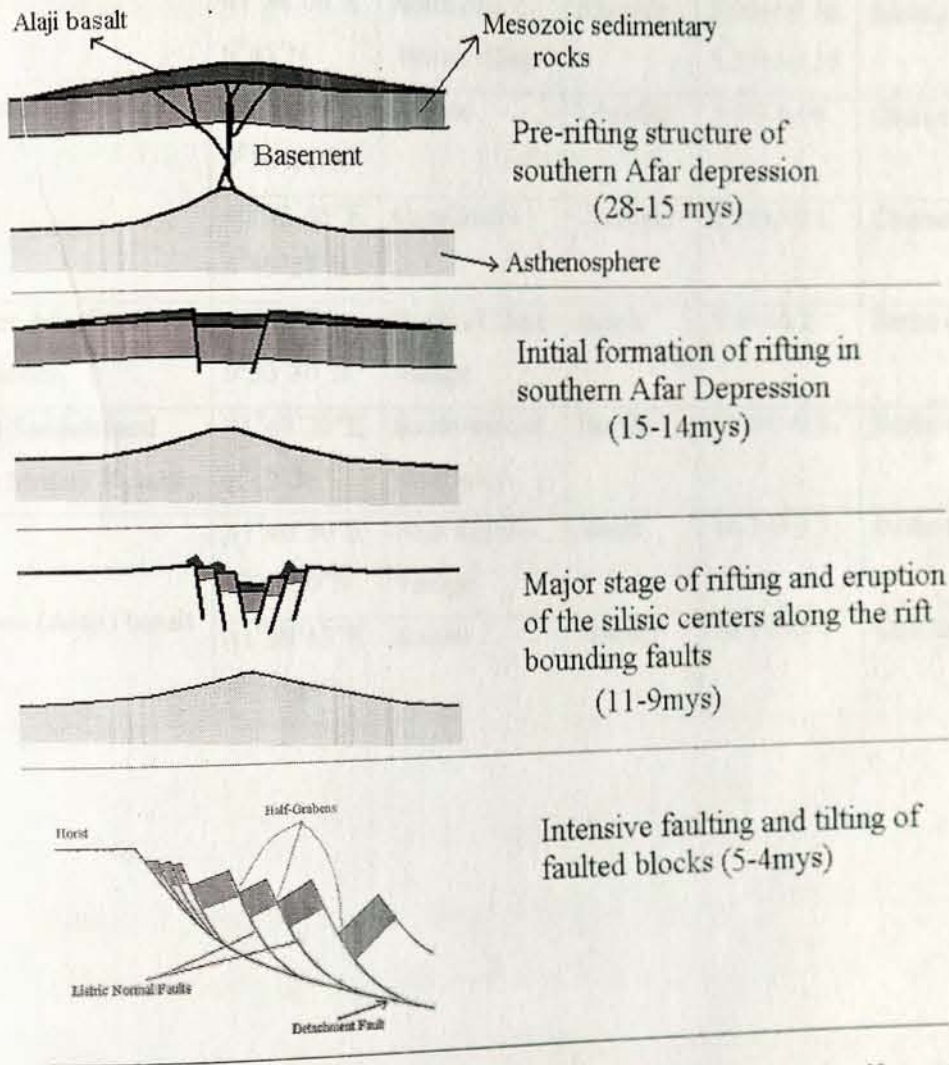


Fig.6.7 A sketch showing the volcano-tectonic evolution of the southern Afar rift margin

Table-6.2 K-Ar age determination for Southern Afar and Southeastern escarpment

Unit	Location	Locality	Rock Type	Age (Ma)	Reference
Lower Afar Stratoid Series	41°51'41"E 9°44'35"N	DireDawa	Basalt	4.68 +/-0.1	Chernet et al. (1998)
Rift margin silicics	41°34'00"E 9°45'N	North of Hurso village	Rhyolite	5.06 +/-0.16 5.33 +/-0.17	Berhe (1986)
	40°34'46"E 9°16'14"N	Asebot	Obsidian	5.6 +/-0.09	Chernet et al. (1998)
	40°13'05"E 8°49'27"N	GaraGumbi	Trachyte	6.85 +/-0.1	Chernet et al. (1998)
Lower Afar Stratoid Series	41°17'E 9°33'30"N	North of Gota Village	Basalt	7.4 +/-0.2	Berhe (1986)
Jebel Saddale and Gara Mulata Basalts	41°48'30"E 9°12'30"	South-west of DireDawa	Basalt	13.3 +/-0.4	Berhe (1986)
Plateau (Alaji) basalt	41°40'30"E 9°25'30"N	Near Kulubi Village	Basalt	18.3 +/-0.5	Berhe (1986)
	41°39'15"E 9°25'35"N	Kulubi	Basalt	24.1 +/-0.4	Chernet et al. (1986)

CHAPTER-SEVEN

Discussion and Conclusions

7.1 Discussion

Prior to commencement of rifting in the transition zone, wide spread flood basalt volcanism initiated in response to the thermal and physical effects of the Afar mantle plume (Schilling et al., 1992). Products of this continental flood basalt volcanism are exposed through out the northwestern and southeastern Ethiopian plateaus (Jones and Rex, 1974; Zanettin et al., 1980).

The Afar triangle is an area of active extensional tectonics and basaltic magmatism (Abbate et al., 1995) from which the Gulf of Aden, the Red-Sea and the Ethiopian rift systems radiate. Normal faults and open fissures are the principal elements of the Afar tectonics. However, strike-slip faults are also recognized in this area. Surprisingly, it is the only area where various tectonic activities and continental rift-rift-rift triple junction occurs.

The study area comprises the three main rock types. The basement rocks (mainly of Gneiss and Schist) covers the southern part of the area and is also exposed as an outcrop in some deep river cut exposures around DireDawa town and Beke-Halo village. They are high-grade metamorphic rocks; low-grade metamorphic rocks such as: slates and Phyllites are absent.

The Antalo super sequence of DireDawa represents the marine colonization of the East African craton. The Mesozoic succession of DireDawa can be correlated with other well-known successions of the Horn of Africa and southern Arabia, namely the Mekelle outlier of Tigray (northern Ethiopia), the blue Nile Basin of central Ethiopia, the Danakil horst of Eritrea, the Ogden basin central Somalia and the southern coastal Yemen. In terms of sequence stratigraphy, the Jurassic succession of DireDawa consists of two depositional sequences: a lower, second order Antalo supersequence, spanning the Late Bathonian to Late Oxfordian (Bosellini et al., 2001); and an upper, second order Uarandab supersequence of Kimmeridgian-Tithonian age.

A fluviatile sandstone (Ambaradam, upper sandstone) rests unconformably on the underlying upper Jurassic unit. Its age according to the limestone intercalation present near Harar and adjacent highlands (Graua, Gara Mulata, Hirna), should be Barremian-Aptian, thus documenting an early cretaceous deformation episode (Bosellini et al., 2001), which affected the entire horn of Africa and southern Yemen (fig.7.1)

The last rock type, rift related volcanic rocks, are those erupted during the major rift development. They are of two in types: the Late Miocene-Pliocene silicic volcanoes aligned along the base of the eastern escarpment of the northern MER and along the southern escarpment of the Afar depression (Chernet et al., 1998). Kazmin et al. (1980) suggested that these silicic centres developed in a marginal graben 7-9 km wide (rift in rift structures), which formed along the foothills of the eastern escarpment of the northern MER and southern escarpment of the Afar. However, there are some felsic centres appear to be aligned along the southern bordering faults

of the area which in turn parallels the Gulf of Aden structural trend. They are of Trachytic – Rhyolitic in composition. The mafic rocks are exposed in the northern and northwestern part of the mapped area. Chernet et al.(1998) stated that these rocks are more related with the Afar Stratoid series.

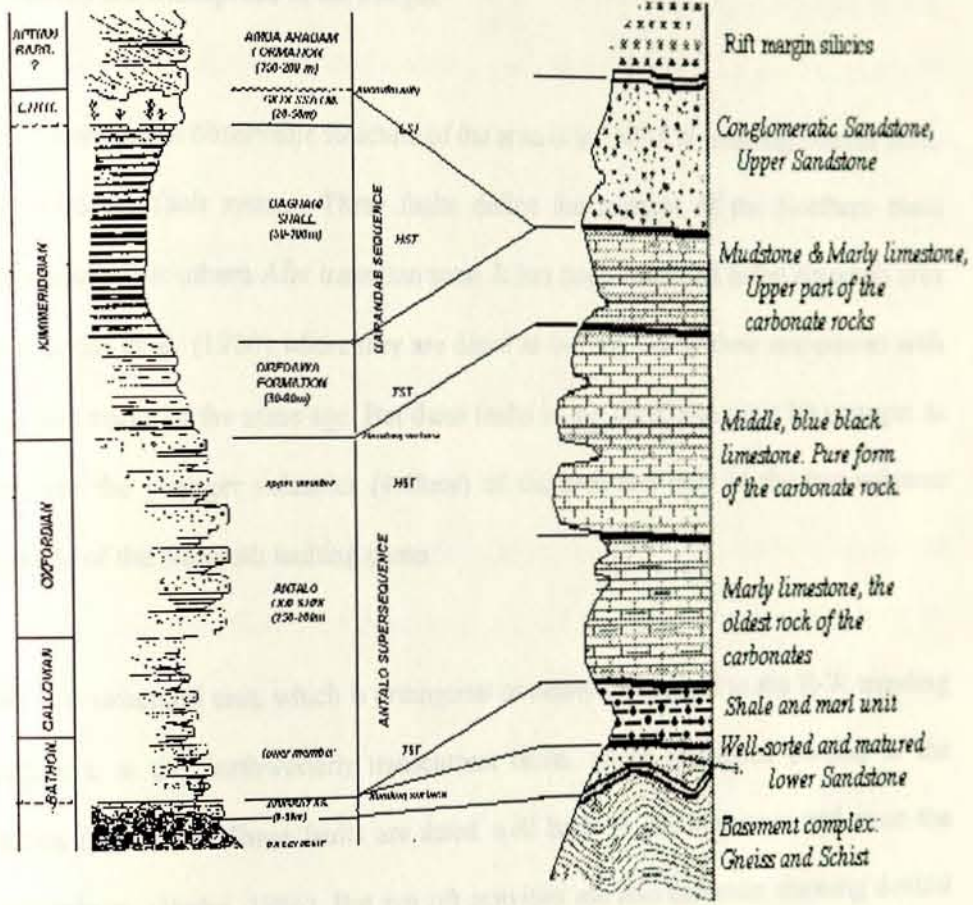


Fig.7.1 Local Correlation of the Mesozoic successions of DireDawa area

Many important structural features in the transition zones are manifestations of the Gulf of Aden structural trend. These include the southern escarpment of the Afar and the Ambo lineament. This structural trend was initiated during early-middle Oligocene rifting along the present-day Gulf of Aden (Fantozzi, 1996), the effects of which may have propagated westward as rifting progressed to ocean basin formation

in the Gulf at about 11my. This westward propagation, most probably, might have been the cause for the development of the E-W trending southern Afar marginal normal faults. The E-W oriented faults are the dominant structures covering the largest portion of the rift margin. Contemporaneously developed E-W oriented dyke intrusions are widespread in the margin.

The second most observable structure of the area is the NE-SW trending normal fault, the Nazareth fault system. These faults define the margins of the Northern main Ethiopian rift-southern Afar transition zone. It has been described in the Nazareth area by Kazmin et al. (1980) where they are dated at 9-5 my old by their association with volcanic rocks of the same age. But these faults in the DireDawa are a bit younger as they cut the younger volcanics (4.68my) of the area and may be the last volcanic episode of the Nazareth faulting phase.

The last structural unit, which is orthogonal or nearly orthogonal to the E-W trending Tadjoura, is the northwesterly transcurrent faults, which is aligned parallel to the Marda fault zone. These faults are dated well back to the Mesozoic and even the Precambrian (Berhe, 1986). But syn rift activities are also common showing dextral sense of movement in the study area.

Unlike the other rift margins, the southern Afar (particularly DireDawa area) is characterized by highly tilted blocks of the Mesozoic rocks (Morton and Black, 1975). The trend of the tilted blocks/layers is much alike with the trends of the marginal faults but their dip direction is opposite with the dip direction of the faults and their dip amount is inversely proportional with that of the faults. One fact is observed in the

area that block tilting progressively increases as one traverses from the rift shoulder towards the rift floor.

Three different types of dykes are recognized in the area. The first group are those oriented on average $N 15^{\circ} W$. They are steeply dipping (vertical) dykes and mostly run parallel with the NNW-SSE trending transcurrent faults. The second group of dykes are oriented E-W to $N 80^{\circ} W$ or exactly parallel with the trends of the marginal faults. Mostly they are vertical but in some places they are tilted from vertical by about $(10 - 30^{\circ})$ towards north. The cross cut behaviour of the dykes reveal that the second group of dykes (E-W oriented) are older than the first once. The third types (the northwesterly) of dykes are those running $N 20^{\circ} E$ to $N 50^{\circ} E$. these are independent dykes, which do not depend with any of the structures of the area. They are considered to be pre-rift dyke injections. Megrue et al (1972) computed crude date estimation (11 –35Ma ago) of these dykes and are believed to be injected during the eruption of Alaji basalt.

On the basis of both the general fault patterns of the Afar triple junction and structural analysis of the DireDawa area, the Miocene – Pliocene evolution of the southern Afar rift margin is consistent with a nearly $N 26^{\circ} E$ extension. This direction of extension is slightly oblique (with components of dextral shear) with regard to the marginal faults (mean trend $N 81^{\circ} W$). This direction of extension is nearly orthogonal with the extension direction of the Main Ethiopian rift, which is E-W (Bocaletti et al., 1998) or NW-SE (Acoccella et al., 2002); but nearly parallel with the extension direction of the Gulf of Aden ($N30^{\circ}$ - $40^{\circ}E$) (fig. 7.2)

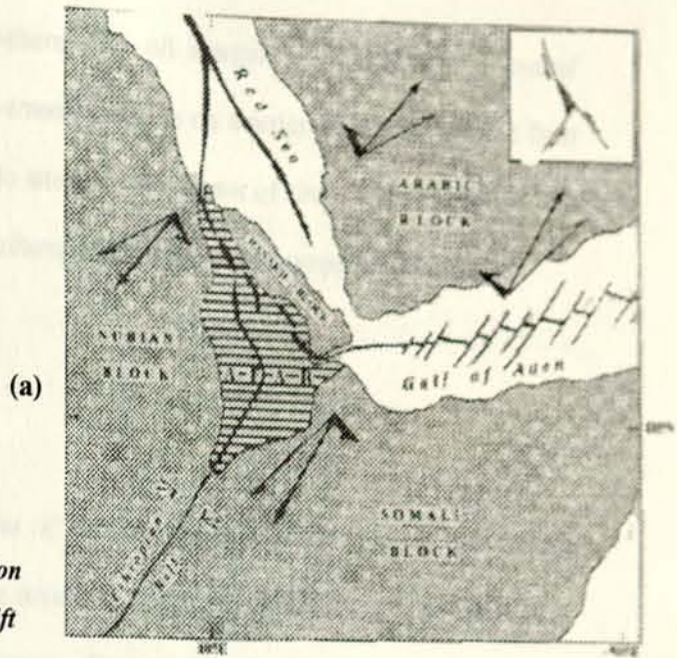
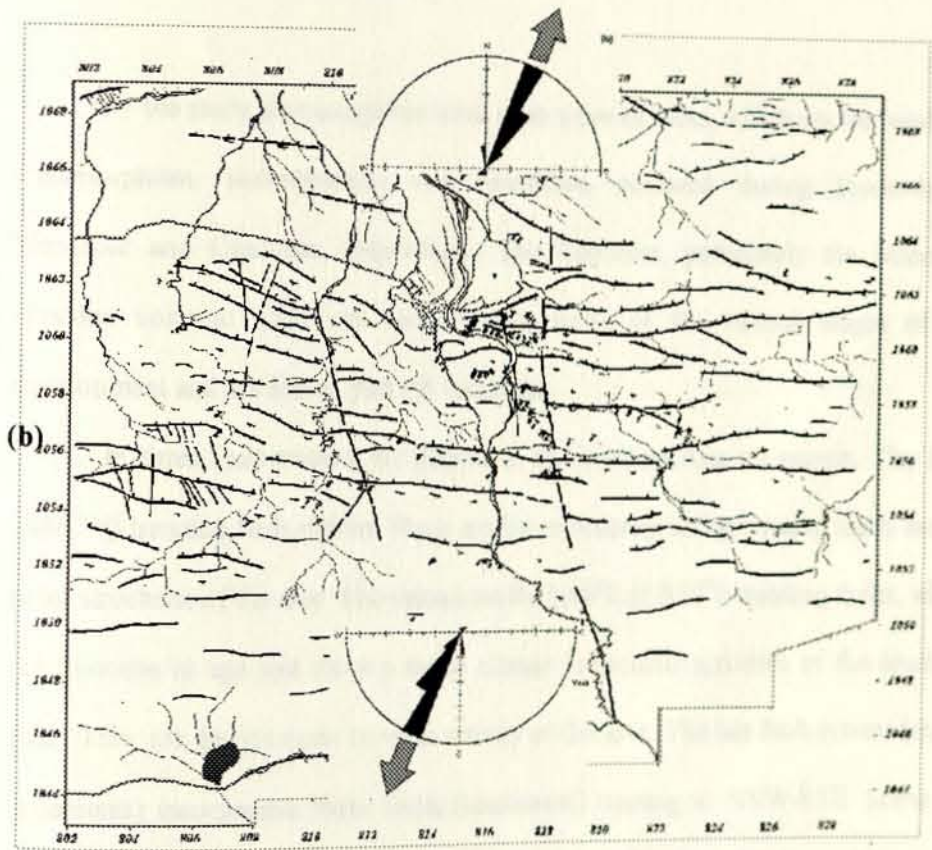


Fig.7.2 Extension direction of the three rift zones (a), and extension direction of the southern Afar rift Margin (b)



Like all other rift zones the southern Afar rift margin is also affected by crustal attenuation. The progressive movement of blocks on a series of parallel, curved fault planes causes the marginal crust to attenuate by a factor of about 1.27. Therefore, the amount of extension (e) in the southern Afar rift margin is computed to be 0.27.

7.2 Conclusions

Southern Afar Rift margin, a site of enthusiasm and keenness, is an area where tectonic and volcanic activities are intimately related. Most activities might have been taken place during the Upper Miocene – Pliocene Periods. The general viewpoint on the study area leads to conclude that:

- ▶ the study area comprises three main types of rocks, which are the results of metamorphism, sedimentation and volcanism, occurred during Precambrian, Mesozoic and Cenozoic, respectively. The Cenozoic, particularly the Miocene-Pliocene volcanic rocks are formed as a result of the various stages of rift development and are Syn to post rift volcanics.

- ▶ three fault systems are present in the southern Afar rift margin. The E-W ($N86^{\circ}W$) trending fault system. These are the commonest and governing faults are the older structures of the area. The second are the $N40^{\circ}E$ to $N70^{\circ}E$ trending faults, which are Pliocene in age and show a major change in tectonic activities of the southern Afar. They are the youngest tectonic activity of the area. The last fault system (major lineaments) incorporates those faults (lineaments) running to NNW-SSE. Some are very old dated well back to the Mesozoic and some are young; syn rift activities.

▶ three sets of dykes are also present; the two sets of dykes, oriented in E-W and NNW-SSE, are closely related with their respective faults, while the third set is unique and is not related with any of the structural elements of the area, but these dykes might have been developed during the eruption of Alaji basalt.

▶ the southern Afar rift margin is unique. It is an area where significant amount of block tilting is observed. The Mesozoic sedimentary rocks and the Upper part of the basement rocks are tilted to about 45° averaging to 25° S.

▶ from the structural point of view the nature (internal structure) of faults is assumed to be listric normal fault.

▶ southern Afar rift margin is not manifested by pure extensional tectonics; instead lesser amount of dextral shear is synthesized modifying the pure extensional tectonics.

▶ the crustal extension of the rift margin is computed using the domino model and from direct measurements across the fault planes. Both computations gave a very close result with crustal extension of about **0.267**.

▶ most volcano-tectonic activities of the area had been taken place before 4.6 my (million years) except the Shinile fault, which is not well known (< 4.7 my).

▶ from the geometric and kinematic point of view, southern Afar Rift margin has similar tectonic history with that of the Gulf of Aden. This might have strengthened the idea of "westward propagation of Gulf of Aden towards Afar Depression".

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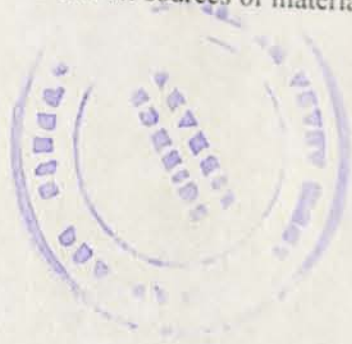
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DECLARATION

I, the undersigned person, declare that this thesis is my original work, has not been presented for a degree in any other University and that all sources of materials used for the thesis have been duly acknowledged.



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