TECTONICS OF THE WESTERN MARGIN OF THE NORTHERN MAIN ETHIOPIAN RIFT

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Abstract

Afar is a junction for the Red-Sea,Gulf of Aden and Main Ethiopian rifts.The timing of initiation of rifting in the other sectors of the Ethiopian rifts is well understood.However,there is a poor understanding of the onset of rifting in the Northern Main Ethiopian rift.The objective of the present study is to establish chronology of rifting and volcanism in the northern main Ethiopian rift,and correlate this with the other sectors of the rift to the south,Afar, Red-Sea and Aden rifts.

New Ar-Ar ages together with previous ages as well as field observations have enabled to identify five chronostratigraphic units at the western marigin:Flood basalts,Bulga basalts , Balchi group,Keradi basalt and Melka Jilo ignimbrite..Flood basalts in the northern sector of the Main Ethiopian rift are Pre-rift whereas the Bulga basalt and the Balchi group are syn-rift.Bulga basalts are early syn-rift and Balchi group is the late syn-rift. Important episodes of volcanotectonic activities at the western margin of the northern Main Ethiopian rift have been identified to occur at around 26-10 Ma,10-7Ma, 3.5-2.5 Ma at the western part and probably since 8 Ma at the eastern margin. From 1.8Ma to present their is a shift in the locus of volcanotectonic activity from both margins bounding the Northern Main Ethiopian rift to its floor.NE- trendind,NW-dipping faults rotating strata to the SE are followed by NNE-trending, ESE-dipping faults at the western margin.At the eastern margin NE-to E-trending,NW-to N- dipping faults are followed by NNE-trending, ESE- and WNW-dipping faults.The western and eastern margin of the sector has a separate rifting chronology.

The Northern main Ethiopian rift has initiated in the upper Miocene younger than the southern Ethiopian rift sectors.Measure of synchroniety of volcanism and rifting between the Red-Sea,Aden and Main Ethiopian rifts suggest Afar has evolved from a double junction to a triple junction after 10Ma.Episodes of sea floor spreading in the Red-Sea and Gulf of Aden rifts coincide with important volcanotectonic activities at the western margin of the Northern Main Ethiopian rift.

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Chapter 1

Introduction

1.1 General

Since the advent of plate tectonics and Sea floor spreading the Red Sea and Gulf of Aden basins are thought to have developed as a result of the drift of Arabia from Nubia.Afar has been accepted as a plate tectonic triple junction for the Red Sea,Gulf of Eden and Ethiopian Rifts.However,this demands tectonic and volcanic evolution of the Ethiopian rift synchronous with that of the Afar,Red Sea and Gulf of Eden(Mohr,1983).The Ethiopian rift system is on the broad Ethiopian-Yemen plateau,thought to have developed above one or two Paleogene mantle plume and represents the third and nortrheasterly trending arm of the proposed rift-rift-rift triple junction(Ebinger et al.,1989,Mckenzie,1970).Flood basalts have been erupted accross approximately 1000 Km diameter region at about 30Ma(Ebinger et al.,1989).

The Ethiopian rift valley,as part of the East African rift system,is an important part of this structure owing to its junction,in the Afar depression,with the Red Sea -Gulf of Aden rifts where transitional character to sea floor spreading is thought to be taking place.This roughly NE-oriented segment of the East African rift system can be structurally subdivided into the Main Ethiopian rift(MER) and the Southwestern Ethiopian rift(SER)(Boccaletti et al.,1998).

The Main Ethiopian Rift, northern terminus of the East African Rift system, extends from the Southen Afar margin to the lake Chamo.At a latitude of about 9^0 north the Main Ethiopian Rift starts to funnel into the Afar depression. An East -West trending extentional structure at the latitude of Addis Ababa with a possibility of passing into the Gulf of Aden has been suggested(Chernet et al.,1998).The rift floor is typically downthrown 500-1000m below the bounding plateau.It is reported that the structural margins of the Main Ethiopian Rift where not obscured by trachytic and rhyolitic centers,are normal step faults and anthitetic normal faults(Woldegebriel et al.,1990). A more recent structural feature of the Main Ethioian Rift is the Wonji Fault Belt(WFB) related to the Quaternary episodes of oblique extension passing from orthogonal to the rift shoulders(Boccaletti et al.,1998 and Boccaletti et al.,1999).

The WFB is retained within the rift margin envelope through a sequence of dextral en-echelon offsets running oblique to the rift valley margin trend(Kazmin et al.,1980).It has not been evident upto now how offsets of the WFB segments are linked.Within the Northern Main Ethiopian Rift the WFB runs close to the western marigin.Comprising Fentale and Dofan, the structure continues to Afar disposed dextrally from adjacent structure to the south around 9^0 N.The Phisiographic transition from MER to the Afar depression occurs north of Fentale volcano.

More recently,magmatic segments arranged enchelon bounded by Mid-Miocene border faults are reported in the Main Ethiopian Rift(Ebinger et al.,2001).This magmatic segments accommodate most of the the extension in the Main Ethiopian Rift being the locus of extension since 1.8Ma.A magma chamber feeds dikes that propagate laterally to form a magmatic segment.The structural relationship of this magmatic segments with the WFB is not obvious.

The rift margin envelope gently curves into the Eden rift with convex facing West at the Eastern side.On the contrary,the Western margin at the latitude of Addis Ababa is not continous.More properly it has been thought to exhibit a dextral offset by 40Km(Mohr,1983,Kazmin et al.,1980).

Evidence of the early history of the Ethiopian rift is largely buried under younger volcanics because of this the time of initiation of the Northern main Ethiopian rift and Afar has been a point of dispute(Woldegebriel et al.,1990,Barberi et al.,1972,1972,Kazmin et al.,1972,Chernet et al.,1998).In general,onset of rifting in this sector is poorly constrained.

The present study is designed in the transitional area of the southern Afar and Northern Main Ethiopian Rift margin to better understand the Volcanic successions and tectonic development of this region.

The above paragraphs enlights the volcanotectonic active rift system in Ethiopia is one of the few areas worldwide where one can acquire ongoing processes from the birth of the rift associated with/without a mantle plume upto its present transitional rift stage..The MER and the Afar also preserve a wealth of information on hominid evolution and early habitats.Consequently,knowledge of continental break up have a wide implications for Geographers and Anthropologists.

The Ethiopian rift is,therefore,an important book which has recorded a valuable information to alleviate our understanding about the tectonic and stratigraphic evolution of rift systems.Stratigraphic evolution of rifts considerably refine our understanding of the three dimensional geometries and evolution of continental rift systems.Recently,the character of rift border faults and that of the intra-rift faults,fault segmentation,displacement transfer within the fault systems of rifts have been of particular interest.

1.2. Geographical setting

1.2.1.Location

The studied area, part of northern terminus of the MER at the western margin, lies geographically between(Fig. 1) $8^{0}45'$ to $9^{0}20'$ latitude north and $39^{0}15'$ to $39^{0}45'$ east longitude.

1.2.2Accessibility

The Ethiopian plateau has been accessed by all weather roads of Addis Ababa-Sandafa-Aleltu-Sheno and some dry weather roads of Aleltu-Lizib Dingay,Sheno-Shibegi Gebriel,Debrebirhan-Kotu Gebeya and the dry weather road to Koremash.Moreover, accessibility of the plateau is also possible by Addis Ababa-Debreziet-Chefedonsa,Mojo -Balchi-Shenkora Yohannes.The study has took an advantage of the new route Areri- Debrebirhan which connects the plateau northeast and southeast of Addis Ababa passing through the upper reaches of the western escarpment.

The rift floor of the studied area has been accessed by Addis Ababa-Metehara-Metehbila and trials in the Metehbila area.Accessibility of the

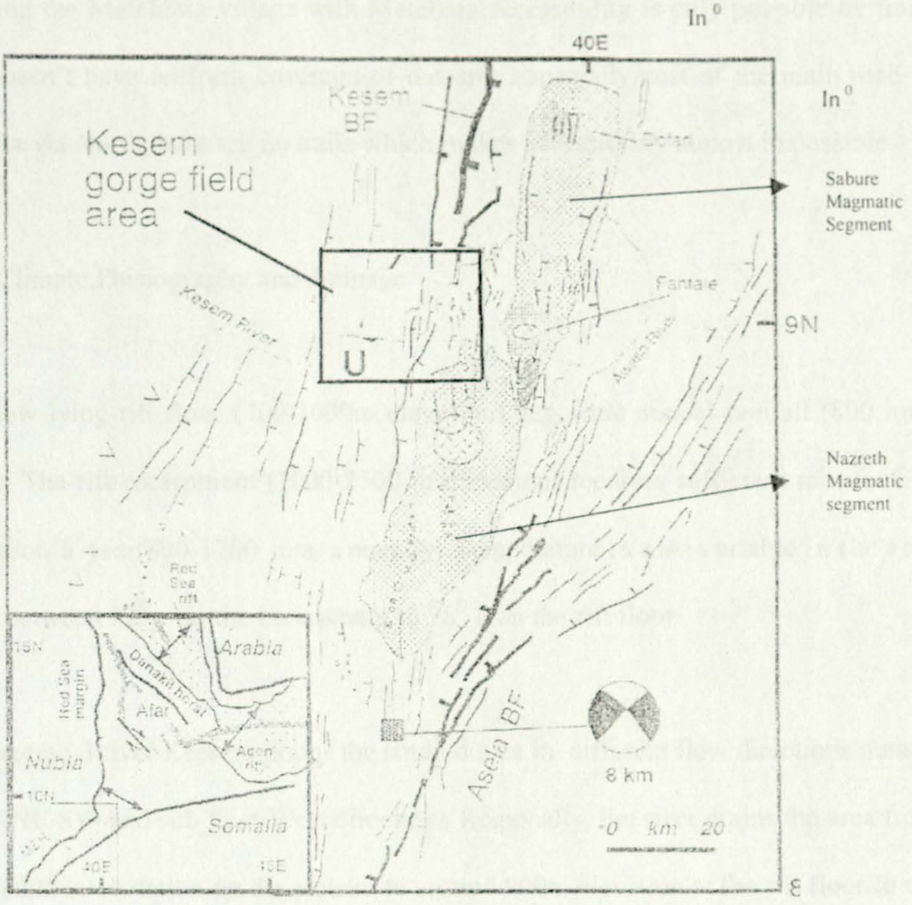


Fig. 1. Geographical location of the studied area enclosed by the box.Elongate stipple patterns are Quaternary magmatic segments of Ebinger et al.,2001.Tectonic map of the main Ethiopian rift after Ebinger et al.,2001 is also shown.Square indicates location of 1995 earthquake(Focal mechanism from Ayele,2000).U is unconformity in the Kessem gorge.Inset shows Nubia-Somalia-Arabia plate Kinematic setting, with double arrows showing direction of opening of rifts.

area in Metehbila area is generally poor.Except for the main dry weather road connecting the Metehbila village with Metehara,accessibility is only possible by trails which doesn't have uniform coverage of the area.Especially east of the main road to Metehbila via North,there are no trails which makes accessibility almost impossible.

1.2.3.Climate,Phisiography and drainage

The low lying rift floor (700-1000m elevation) gets little annual rainfall (800 mm. anually). The rift escarpment (1000-2500 m elevation) receives sufficient rain for one crop season a year(800-1700 mm. annually).Temperature is also variable in the area ranging between 22^0 c on the escarpment to 28^0 c on the rift floor.

The perennial river Kessem drains the studied area in different flow directions mainly NW-SE,NE-SW and sub East-West directions.Regionally, the river drains the area from around 2000 m elevation on the plateau to around 900m elevation at the rift floor.In the Metehbila area North of the Kessem river several streams and rivers exihibiting a parallel drainage pattern are seen to flow from a northwest direction to join the river Kessem for more than 15 Kms. Although most of them maintain their course till they drain to the Kessem, some of them are seen to deflect from their original course near it.Some tributaries of these Northwest-Southeast directed rivers are straight making contact at right angle. This is generally a feature especial to the area North of the Kessem.On the contrary,south of the Kessem,there are not as much as rivers and streams as the northern part.Although there are some,they are not so much long as the northern part and doesn't take a definite regional course.

The village Metehbila is found on a relatively flat topography of about 1,660 m elevation.From here, the area descends to an elevation of around 1000m at the bottom of the Kessem river.The 400 m elevation difference between the plateau and the Kessem river valley for nearly 6 Kms is expressed by serrated ridges and cones near the river.However, the morphology in Southern Kessem takes a different picture.The areas Gewgew and Lay Choba approximately of 1 600 m elevation are found close to the river kessem 2 Km on the average making a flat morphology .The average 2 Km span between the plateau and the river is expressed by serrated topography sharply descending to the bottom of the river.(Between 1000m and 1100m elevation).Inaddition,the plateaus are generally wider away from the Kessem.Near the Kessem ,the width of the plateau decrease with a nearly sharp tip.Infact,the Gewgew and lay choba area plateaus are nearly separate toward their tip where a stream in the middle drains to the Kessem.They generally take a roughly NNE-SSE direction whereas similar plateaus further West at Aroge Minjar and Adama show deflection to an East-West direction from a NNE trend near the Kessem river.Elevations attained by the above mentioned plateaus are between 1600m and 1700m.

Maximum and minimum elevation in the studied area are respectively more than 3000m and 1000m.Maximum elevation is found northwest of the studied area and minimum elevation is attained southeast of the studied area.

The area at the boundary between the Ethiopian plateau and the escarpment sloping down to the MER and to the Southwestern Afar,has attained an elevation between 3000m and 2000m.Morphologically,the area is formed by a series of reliefs streching on a SW-NE direction including the Entoto-Rufi-Caho mountains between Addis Ababa and Sheno located northwest of the main road.Similarly,East of Sheno the Megezez-Termaber mountains strech in a SW-NE direction(Justin-Visentin et al.,1974).The mountains generally rises to an elevation of 3000 m and more above sea level separating two plateaus of approximately the same elevation.In the vicinity of Addis Ababa, mountains Wechecha-Furi-Yerer rises also above 3000 m elevation streching in a roughly East- West direction.

In conclusion,the studied area descends from 3000m elevation in the plateau area to about 900 m elevation at the rift floor near the axial part.The prenial river Kessem drains the plateau as well as the rift floor.Tributries of Kessem in the Metehbila area at its northern part display a parallel drainage system.

1.3.Previos Works

A lot of previous works on the stratigraphic,geochronologic and geochemical works has been done in the adjacent areas of the present studied area.For the sake of simplicity,only those that could have relevance with the present study will be mentioned below in order of their chronology:-

- Stratigraphic,petrographic geochemical and radiometric dating works on the Ethiopian plateau from Addis Ababa to Debrebirhan(Justin-Visentin et al.,1974).
- Detailed Geological mapping of the Northern Main Ethiopian rift between the latitude of 8^0 and 9^0 North(Kazmin et al.,1978).

* Radiometric age determinations in the environs of Addis Ababa and the rift floor with the aim of elucidating the cause of narrowing of the volcanic zone(Morton et al.,1979).

* Identification of the main stages of rifting in the Northern Main Ethiopian rift with the aim of understanding its evolution(Kazmin et al.,1980).

* Identification of tectonic structures,volcanic centres:geochronologic and petrographic data from Yerer to Tullu Wellel(Abebe et al.,1995).

* New radiometric age determinations and tectonic insights in the Northern Main Ethiopian rift -Southern Afar transitional zone(Chernet et al,1998).

* Petrological and Geochemical works on the volcanics of the Northern Main Ethioian rift- Southern Afar transitional zone(Chernet et al.,1999).

* Examination of distribution of strain and magmatism in the Main Ethiopian Rift(Ebinger et al.,2001).

As outlined in the introduction section, it has not been clear upto now how the Northern Ethiopian Western marigin passes into the Afar margin.This ,therefore, raises an interesting question as to how the Afar western margin is related to that of the Main Ethiopian Rift.Additionaly,it has not been clear also whether the dextral transposition of the rift at the latitude of Addis Ababa is an original feature or a later dislocation(Mohr,1983).Some studies point out the importance of East-West trending weak extensional feature around the latitude of Addis Ababa with the possibility of continuing to the Gulf of Aden(Abebe et al.,1995).So,how do we explain the pattern of rifting in the Ethiopian rift valley in general and Northern Main Ethiopian Rift in particular? Unfortunately, the only detailed geological map for the Nothern Main Ethiopian Rift (Kazmin et al.,1978) with a scale of 1;250,000 ,do not cover the area further North where the Main Ethiopian Rift faults and the southern Afar faults supposedly interact.

Old researches(Barberi et al.,1972) widely accept the Northern Main Ethiopian Rift is born together with Afar 25 Myr ago.The evidence for the development of the rift comes mainly from flood basalt pile thickening and downwarping riftwards seen in tributary canyons of the Abay basin river and Addis Ababa area. This suggest that a protorift trough was already developing at that time.This trough is taught to link with Afar North but how far it extends South along the present rift valley is not known.

On the contrary, later researches(Kazmin et al,1980) are firmly of the opinion that the Ethiopian Rift together with the Afar was developed 14 Myr ago. The authors strongly argue that there is no evidence pointing to an increase in thickness of the flood basalts in the zones of the Afar or the Ethiopian Rift escarpments.They rather take a topographic containment of volcanic units 14-11 Myr in the Norhern part of the rift to be evidences of development of the rift.This volcanic units coincide closely with the present marigins of the rift.However, the authors prefer and agrees to see this episode as a further rather than initial stage of Ethiopian rift development.Morever, their interpritations about stages of rifting in the nothern Main Ethiopian rift is largely based upon observations on the Eastern side of the rift.

More recently,(Chernet et al.,1998) modern rift marigin development in the northern main Ethiopian rift and Southern Afar is reported to be at least 10 Ma.This comes from the age of the basalt from the rift floor near the eastern marigin escarpment and the assumption that the basalt is representative of a flood basalt pile present both in the rift floor and the bounding plateau.

1.4.Background

A major unconformity has been discovered in the deeply incised Kessem river gorge.In this area,an interaction between the NE- trending and NNE-trending faults are also noticeable.Overlying strata dip gently ESE whereas strata beneath the unconformity dip SE.Obviosly,variation in strata dips provide evidence for younger faults cutting sequences above the unconformity.Sequences above the unconformity includes ignimbrites,basalt flows,channel fill deposits and air fall ashes.Thus the Kessem gorge casts an insight where the structural and stratigraphical evolution of the Northern Main Ethioian rift can be determined.

1.5.. Purpose of investigation

As outlined above, the purpose of investigation is to fill important gaps that has been unclear in the Northern main Ethiopian rift so far.

Some of the works above has attempted to constrain the stages of rifting in the Northern Main Ethiopian rift.However, the lack of structural and volcanic features of interest has blocked the way to come up with a better onset of rifting.The present study looks for the structural and volcanic features of interest to arrive on the spot.

So,When did the structural evolution of the Ethiopian rift valley begin? As, noted above,the development of the Northern Main Ethiopian rift and Afar is poorly constrained.Infact ,this is because the evidence is largely buried under younger volcanics.Are there any volcanic and structural features to better constrain the onset of rifting in the Northern Main Ethiopian rift? It becomes, therefore, more convincing and clear the need of a close investigation in the Northern Main Ethiopian rift.

With the above problem at hand the main objective of the study is determining the onset of rifting in the northern main Ethiopian rift.For this purpose the methods that are followed includes:-

⇒ Map faults of the studied area from Aerial photographs,remote sensing data,and in the field.This will provide a tectonic map of the area not done so far which will enable to give a better structural outline.

⇒ Erect a stratigraphic log at the exposed sections of the area with lithological descriptions.

⇒ Conduct radiometric age determinations on units which will be valuable in the understanding of tectonostratigraphic evolution of the area.

⇒ Produce a geological map of the area with major and key units.

⇒ From cross-sections and data in the field understand the different tectonomagmatic relationshiops.

Finally ,supplementary to the main objective the study also provides how the geometry of faults look like starting from the Margin till the riftfloor.This is thought to fill an important gap because much of our knowledge on the rift is largely adhered to the marginal and seafloorspreading area.

Chapter 2

REGIONAL STUDIES

This chapter deals with previous chronostratigraphic and tectonic outlines in the northern main thiopian rift that is of importance to the present study.

2.1.Chronostratigraphic studies

Stratigraphic units identified based on K/Ar age determinations on the western and eastern margin as well as the rift floor are presented.Table 1 summarises age ranges for the western margin , eastern margin and the Rift floor.

2.1.1.Lithological descriptions

Kazmin et al.,(1980)which constrain the evolution of the northern main Ethiopian rift largely relied on the work of their predecessors (Morbidilli et al.,1975 and Kuntz et al.,1975).A general stratigraphic description of the volcanic units after (Kazmin et al.,1980) for the northern main Ethiopian rift is as follows:-

2.1.1.1. Alaji basalts

This unit is about 800m thick of predominantly aphyric basalts with very scarce silicic intercalations as observed at the southeastern plateau(Kazmin et al.,1980).The unit is also exposed at the northwestern plateau (Justin-Visentin et al., 1974) and rests unconformably on the Cretaceous sediments(Kazmin et al.,1978 and Francaviglia,1940).Thickness gradually increases to the west, as observed at the eastern escarpment.The Alaji basalts at the southeastern and northwestern plateaus are correlative. The main difference between the two is the scaricity of silicics in the southeastern plateau(Kazmin et al,1978).

Table 1

Western marigin (Morton et al.,1979)		Eastern margin (Kazmin et al.,1980)	
Age (in Myr)	volcanic units	Age(in Myr)	volcanic units
28 -23	Abbay and Sululta transitional basalts	28-15	Alaji basalts
23-22	Entoto and Kessem comendites	14	Jebel saddle basalt
16-11	Gorfu and Megezez basalts, upper Kessem Rhyolites	15-11	Arba Guracha Silicics
9-7	Northern Addis Ababa alkaline basalts	11-10	Anchar basalts
5.1-3.5	Wechecha to Yerer trachytes	9.5-3(4)	Nazret group
3.7	Southern Addis Ababa basalts	3.5-2	Bofa basalt
3.3-3.1	Managasha and Tedi Rhyolites		

Wonji group at the rift floor (After Kazmin et al.,1980)	
Age(in myr)	Volcanic units
1.6-Recent	Dino ignimbrites,Pantelleritic centers and fissural basalts

(Table 1,Contd.)

2.1.1.2Jebel Saddle basalt

It is represented by several hundreds of meters thick porphyritic basalt resting unconformably on the Alaji basalt related to shield type centers.It is exposed on the southeastern plateau near Asebe Teferi. Correlative units are Termaber basalts of the northwestern plateau(Justin-Visentin et al.,1974).

2.1.1.3.Anchar basalts and Arba Guracha silicics

The two are contemporaneous or penecontemporaneous units.Anchar basalts are flood basalts of upto 400m thick.Names like upper trap series have been coined to them in the past.Arba Guracha silicics are welded and unwelded silicic tuffs conformable on the Alaji basalt.Development of both units is restricted by the rift escarpment and thickness increases towards the rift.

2.1.1.4.Nazret Group

It represents a succession of more than 250 m thick ignimbrites,unwelded tuffs,ash flows, rhyolites and trachytes on the rift floor.On the rift shoulder, only a few meters of ignimbrites are observed.Accumulation of the unit is thought to be accompanied by the formation of shield volcanism on the rift's eastern shoulder.The upper part is correlative with the Balchi rhyolite on the northwestern plateau.(Justin-Visentin et al.,1974).Their aerial extent is restricted by mariginal faults of the rift.Thin units are observable in the escarpment and on the plateau.They overlap older rocks with slight to moderate unconformity.The latest stage of the Nazreth volcanism encompasses silicic centers as can be seen from the widerspread rhyolite domes cutting through older ignimbrite sheets.

2.1.1.5. Bofa basalts

The unit is represented by upto seven flows of fissural basalts.Its thickness attains more than fourty meters and rests unconformably on the silicic units of the Nazreth group.Being young,they are not restricted to the central part of the rift .Instead,they are rather evenly distributed over the rift floor.Because of this, they are thought to represent episodes of yonger fissural eruption.

The rift floor series that fall into the Wonji group are described as;-

2.1.1.6. Dino Ignimbrites

They cover a considerable portion of the rift floor and are represented by a number of flows of compact fiamme ignimbrites at some places intercalated with aphyric basalts and unwelded pyroclastics.Thickness of the unit varies from a few meters upto thirty meters.The unit rests unconformably on the Bofa basalt and in part can be related to older panteleritic centers like Tinish Fantale.

2.1.1.7.Pantelleritic centers

They are stratovolcanoes built mainly of peralkaline rhyolites and trachytes with some pumice,pithstone and obsidian occuring mostly at late post caldera stages. They are aligned en echelon along the segments of the Wonji fault belt.Boseti,Kone and Fentale are examples of these pantelleritic centers.

2.1.1.8.Fissural basalts

They are mainly concentrated along the Wonji fault Belt,although some exceptions are known out of it.The youngest flow of historical period is represented by fresh ‘aa’ lavas.Older basalts contemporaneous with early stages of the development of the pantelleritic volcanoes were fissural while the youngest eruptions were of central type.Alignment of well preserved volcanic cones is an expression of fractures in the Wonji Fault Belt,which in many places cut across the pantelleritic volcanic centres.

Chernet et al.,(1998) has introduced new stratigraphic nomenclature on the chronostratigraphic works adopted before them.These are described briefly below followed by a new insight gained in the transitional region.

Wechecha formation stands for the products of the Pliocene silicic volcanism on the fringes of the northwestern plateau such as Wechecha,Furi,Yerer and Menagesha.Bishoftu basalts represent basalt flows associated with numerous scoria cone found on the subdued escarpments of the Main Ethiopian Rift in Addis Ababa area.These basalts typically range in age between 2.8 and 2.0 Ma.Gara Gumbi formation represents silicic volcanoes aligned along the base of the eastern escarpment of the Northern Main Ethiopian Rift and along the Southern escarpment of the Afar depression.These alighned volcanoes are Gara Gumbi,Asebot,Afdem,Bora at,Gara Adi.

One sample on the Southeastern plateau that unconformably ovelies Mesozoic sediments yielded an age of 24 myr suggesting the time of initiation of flood basalt activity in this region.Two samples from basalt flows intercalated with the Nazreth group ignimbrites along the western escarpment(in Metehbila area) yielded ages between 6.8 and 5.8 Ma,a range which overlaps with both phases of volcanic activity inferred for the Southern Afar marigin silicic volcanoes(Gara Gumbi Formation).Two new dates on samples previously mapped as the Bofa basalt yield Quaternary ages.This new ages suggest that the Bofa basalts which were previously thought to be Pliocene might not be distinct chronologically and stratigraphically from the Quaternary basalts.

Because the studied area is part of the transitional area and also because of the reliance of age determinations on modern techniques, the chronostratigraphic synthesis by Chernet et al.,1998 is employed mostly as a base for the present study(Fig. 2).

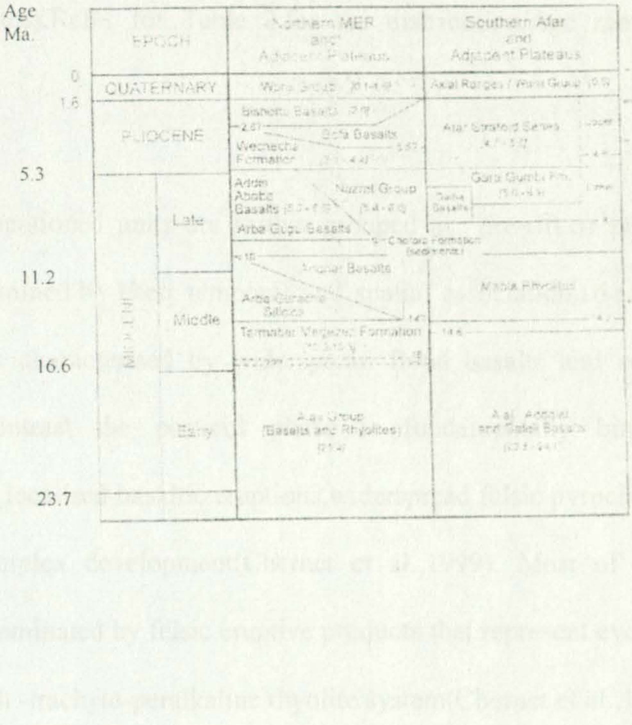


Fig. 2 Stratigraphic synthesis for the northern main Ethiopian rift.(After Chernet et al.,1998).Bracketed ages are new ages by the aforementioned author.The synthesis largely relied upon the work of Kazmin et al.,1980.See text for further description.For NMER: Wonji group(0.1-1.6),Bishoftu Basalt (2.0),Wechecha formation (3.1-4.4),Addis Ababa basalts(5.0-6.6),Termaber Megezez formation (10.3-10.6) and Alaji group(23.4).For Southern Afar: Axial Ranges/Wonji Group(0.8),Afar Stratoid Series (4.7-5.6),Gara Gumbi Formation (5.0-6.9) and Alaji,Adolei,and Galeli basalts(23.8-24.1) all in Ma.

Following Chernet et al.,(1998),volcanic products of the transitional region are subdivided into eleven chronostratigraphic units,seven basalt -dominated and four trachyte/rhyolite- dominated(Chernet et al.,1999).These are Alaji group(plateau basalts),Termaber group(plateau basalts;Termaber- Megezez formation),Nazret group basalts(western escarpment basalts),Nazret group silicics,Afar Stratoid series,Gara Gumbi formation(rift margin silicic centers),Wechecha Formation(Addis Ababa rift embayment),Bofa Basalts(young rift floor basalts),Bishoftu Basalts(Addis Ababa rift embayment),Wonji Group Basalts(young rift floor basalts),Wonji Group Silicics(young rift floor rhyolites).Refer for Table 2,for the distribution,Age range and previous nomenclature.

The above mentioned units are further grouped as pre-rift or post rift phases of activity as determined by their temporal and spatial association to rift structures.The pre-rift phase is characterised by widerspread flood basalts and subordinate felsic volcanism.In contrast the post-rift phase is fundamentally bimodal, including widerspread and localised basaltic eruptions,widerspread felsic pyroclastic deposits,and central vent complex development(Chernet et al.,1999). Most of the central vent complexes are dominated by felsic eruptive products that represent evolution within the transitional basalt -trachyte-peralkaline rhyolite system(Chernet et al.,1999).

Table 2 (After Chernet et al.,1999)

Age range	Phase	Distribution	Previous nomenclature	Type	New Nomenclature
Oligocene-Miocene	Pre-rift	NW and SE plateau	Alaji basalts, Trap Series	Basalt to Mugerite	Alaji Group
Miocene	Pre-rift	NW and SE Plateau	Termaber basalt,Arba Gugu basalt and Anchar Basalt	Basanite to Mugerite	Termaber Group
Miocene to Pliocene	Pre-rift/Post-Rift	Northern MER Escarpment	Nazreth Group or Series	Basalt to Mugerite	Nazreth Group basalt
Miocene to Pliocene	Pre-rift/Post-rift	MER floor and Escarpment :Southern Afar escarpment	Nazreth group, Balchi and Mabla Rhyolite,Arba Guracha silicics	Trachyte to Rhyolite	Nazreth group Silicics
Miocene to Pliocene	Post-rift	Afar rift floor	Afar stratoid basalts	Basalt to Muge rite	Afar StrAtoid Series
Miocene to Pliocene	post-rift	NMER marigin & Southern Afar Marigin	Gara Gumbi Trachytes	Trachyte-Rhyolite	Gara-Gumbi Formation

Table 2 (Cntd .)

Age range	Phase	Distribution	Previous Nomenclature	Type	New Nomenclature
Pliocene	Post-rift	MER escarp Ments in Addis ababa region		Benmorite To Trachyte	Wechecha formation
Pliocene	Post-rift	NMER rift floor	Bofa basalt, Wolenhiti basalt	Basalt	Bofa basalt
Pliocene-Pliestocene	Post-rift	Addis Ababa rift embayment	Bishoftu Basalt	Basanite To Hawaiite	Bishoftu basalt
Quaternary	Post-rift	MER-Sothern Afar rift floor	Wonji group	Basalt To Hawaiite	Wonji Group basalt
Quaternary	Post-rift	MER-Southern Afar rift floor	Wonji group	Benmorite To Rhyolite	Wonji group Silicics

The concept of assigning volcanic units to two domains:pre-rift and post-rift is a recent idea which is very important in understading the volcanic and tectonic evolution of the Northern Main Ethiopian Rift.The Alaji and Termaber group belong to the pre-rift phase.The Nazret group basalts and silicics belong either to the pre-rift or the post-rift phase.The remaining units belong to the post- rift phase(refer table 2).

2.2.Tectonic Outlines

2.2.1 Escarpments

The Northern Main Ethiopian rift is bounded by NE to NNE-trending faults.Progressive rift extension at mean rate of 3-5 mm/year with strain rate essentially confined within the Wonji fault belt are reported for the Northern main Ethiopian rift(Mohr et al.,1978). The main faulting is documented to be anthitetic in the eastern as well as in the western part of the escarpment.For instance,faults with amount of dip of 75-80 to the Southeast and with small displacement upto 100m are typical at the Eastern marigin(Kazmin et al.,1980,Chernet et al.,1998).

The origin of such faults is explained by block rotation in the course of crustal attenuation in the Afar(Morton and Black,1975).However,this hypothesis might not be plausable in the NMER because crustal extension is not as great as in the Afar to bring about block rotation except in parts of the margins. Downwarpping of strata from 14 to 10 Myr produced tensional fractures followed by readjustment of resulting blocks under gravity.This eventually lead to small amplitude anthitetic faults(Kazmin et al.,1980).

The Yerer-Tuluwelel extensional structure running sub East-West approximately at the latitude of Addis Ababa(9^0 N)(Abebe et al.,1995) is transversal to the Northern Main Ethiopian rift and comprises aligned volcanoes(Wechecha formation)(Chernet et al.,1998).

A rift in rift structure is developed at the eastern escarpment of the Northern Main Ethiopian Rift and Southern escarpment of Afar(Kazmin et al.,1980).The structure is a mariginal graben having ENE-WSW orientation and comprises aligned Miocene to Pliocene silicic volcanic centers(Gara Gumbi formation)(Chernet et al.,1998).

2.2.2The Rift Envelope

The western escarpment of the rift valley at the latitude of Addis Ababa is displaced 60 Km westward.Similar but smaller displacement of the eastern marigin of the rift occurs at 8^0 20^0N latitude.A linear distribution of upper pliocene centers(Yerer,Wechecha and Menagesha) marks the line of displacement at the western marigin though there are no faults on the surface(Mohr,1983 and Kazmin et al.,1980).At the Eastern marigin(Latitude of Addis Ababa) the rift has an elbow shape.This elbow configuration is thought to be determined at least in part by basement fabric.This is because easterly and ENE lineaments are common in the basement of the east Africa(Limpopo and Zambesi belts)(Kazmin et al.,1978).

Since 1.6Ma the rift floor is covered by densely spaced normal faults trending oblique relative to the bounding faults.This fault belt has typically NNE to N-S orientation and comprises volcanic centers.The belt as a whole has been named as the Wonji Fault Belt(WFB).The WFB originated because of the switch from orthogonal to oblique extension(Boccalleti et al.,1998).

Each segment of the axial zone is 80 to 120 Km long and each one is displaced to the east for 10 to 40 Km relative to its southern neighbour(Kazmin et al.,1980).The northernmost WFB in the Northern Main Ethiopian Rift comprises Fentale volcano whereas the immediate southern segment comprises Kone and Boseti volcanoes(Kazmin et al.,1978).A prominent system of northwesterly trending faults can be traced from the eastern escarpment to the Awash Waterfalls near Karayu Lodge.Upon projection the system falls on the offset between the two parts of the above mentioned WFB segments.This offset is possibly caused by a trans-rift fracture equivalent to an incipient transform fault(Kazmin et al.,1980).

Table 3 summarises prominent tectonic phases as suggested by different authors.

Table 3

Stage of rifting and formation of volcanic units	Age(in Myr)	Inference & reference
Onset of rifting in the MER and Afar	25	A sharp increase in thickness of the Miocene (Alaji) basalt in the zones of the Afar and the Ethiopian Rift escarpments. (Barberi et al.,1972, Juch ,1975)
Onset of rifting in the MER and Afar	14-11	An increase in thickness and downwarping of the Anchar Basalt and Arba Guracha Silicics towards the MER as well as Afar Escarpment.Phase of faulting as well as tilting pre-dates accumulation of these volcanic units. (Kazmin et al.,1980)
Shield basalt formation associated sagging of the rift as a broad downwarp.	14-13	Termaber-Megezez formation on the western marigin and Jebel Saddle on the Eastern Marigin. (Kazmin et al.,1980)
Initiation of subsidence (rifting) and associated rift shoulder shield volcanism in the NMER-Afar transitional zone	10	Age of the flood basalt downthrown in the rift floor and the age of the Termaber-Megezez formation at the Western marigin. (Chernet et al.,1998)
Mariginal graben at the eastern part of the NMER and Southern Afar: Formation of alighned volcanic centers.	Around 9 : 7-5	Absence of Nazreth group in the Awash gorge section and presence of lacustrine sediments(Chorora formation) in the graben:Age of Asebot,Gara-Gumbi,Afdem,Bora at and Gara adi alighned within the mariginal graben(Chernet et al.,1998).

Stage of rifting and formation of volcanic units	Age(in Myr)	Inference & reference
Shield basalt formation on the eastern shoulder associated with mariginal graben formation	8-9	Age of Arba Gugu volcano on the Eastern shoulder(Kazmin et al.,1978)
Further subsidence and faulting of the rift floor	4-2	Lower age limit of the Nazreth group and the increase in thickness of the unit from the escarpment to the rift floor,Uniform distribution of bofa basalts on the rift floor being young deposits.(Kazmin et al.,1980)
Formation of trachytic volcanoes along the Ambo lineament associated with the episode of further subsidence	4.5-3	The age of the Alighned volcanic centers like Yerer,Wechecha,Furi along the Ambo lineament. (Kazmin et al.,1980 and Chernet et al.,1998)
Rifting prior to Wonji fault Belt(WFB)	2-1.5	Age of Dino ignimbrites possibly related to Tinish Fentale unconformably resting on the Bofa Basalt in the Awash Gorge. (Kazmin et al.,1980)
Wonji Fault Belt	1.6-Present	Lower age limit from the base of Boseti volcano and absence of the wonji belt tectonic phase for the Bofa basalt(Kazmin et al.,1978).

(Table 3,contd.)

Alignment of Pliocene volcanic centers on the Ambo lineament suggests a possible tectonic link to the Gulf of Aden and Southern Afar mariginal graben.A younger age of 0.88 Ma on a basanite flow west of Wechecha volcano along the projection of Ambo lineament suggests that volcano-tectonic activity along the Ambo lineament continued into the Quaternary(Chernet et al.,1998).An age of 0.6 Ma from Harbona rhyolite dome northeast of Boseti volcano indicated that centers(part of the WFB) are active into late pliestocene(Chernet et al.,1998).

Chapter 3

Chronostratigraphy

This chapter deals first with, providing stratigraphic framework and geochronological data obtained from best exposed sections of the rift shoulder and margin. Secondly, this is used to establish chronozones for the western margin of the Northern Main Ethiopian Rift.

The sections that are studied are described below:-

3.1.Lizib Dingay

The Germama river(one of the tributaries of Kessem) has cut a 750m gorge on the plateau(Fig 3).The topmost section in this area is represented by an approximately 4m thick ignimbrite. This ignimbrite is moderately welded containing crystals of quartz,feldspars and rock fragments including pumice.This blanketing ignimbrite is separated unconformably from underlying thick flow units each 7 to 8m thick.According to Justin-Visentin et al.,(1974),these thick flows are comprised of interbeded basalts and ignimbrites/rhyolites with basalts dominating over the ignimbrite/rhyolite based on studies conducted downstream of Kessem.The top of these thick flows is represented by an aphyric,crystal rich(with some olivine clasts) basalt.

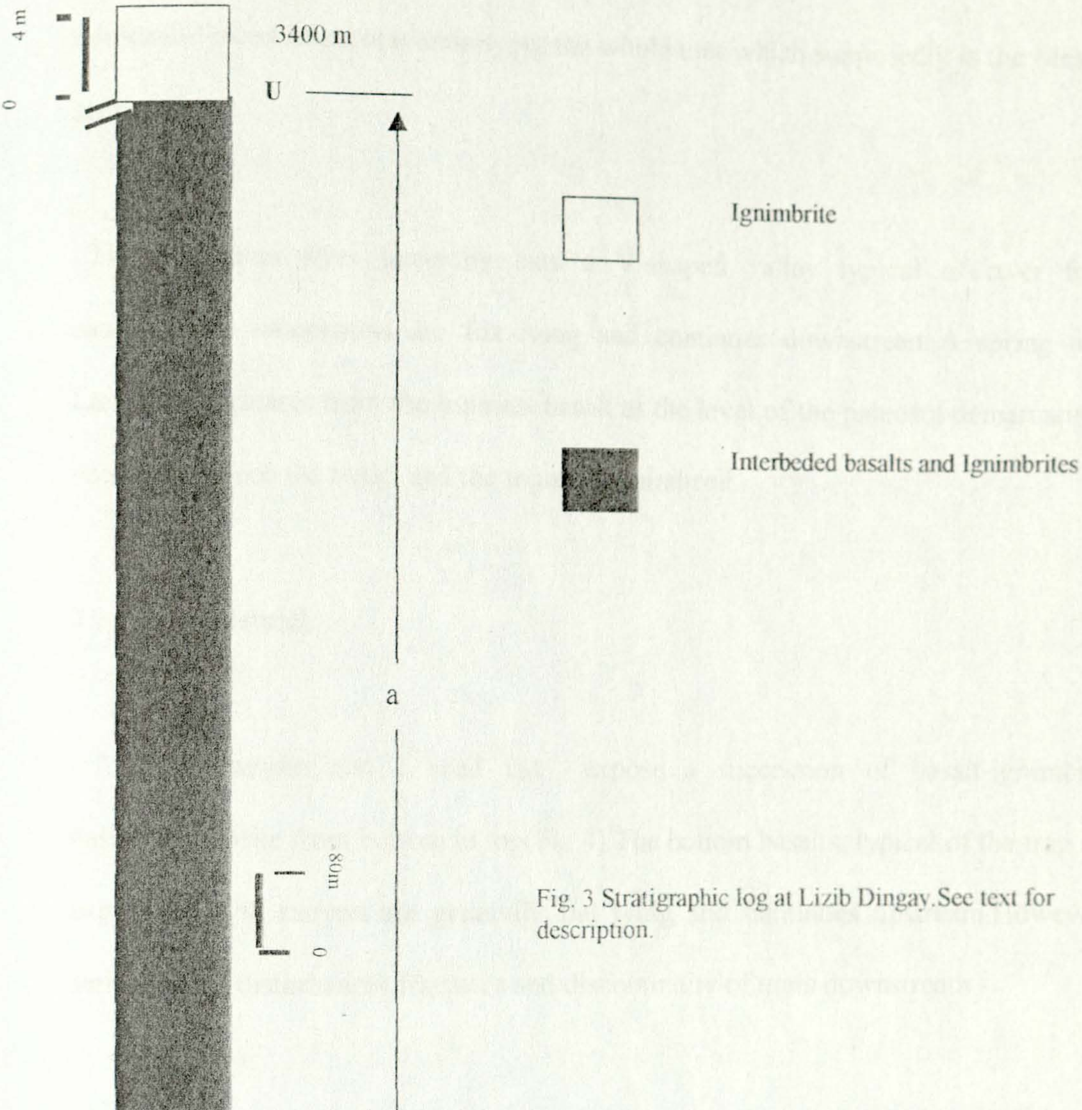


Fig. 3 Stratigraphic log at Lizib Dingay.See text for description.

According to Francavigilia's identification(1940) there is a restricted window of nonfossiliferous sandstone underlying the whole unit which supposedly is the Mesozoic sediment.

The Germama river generally cuts a V-shaped valley typical of river formed canyons.The successions are flat lying and continues downstream.A spring named Lankuso originates from the topmost basalt at the level of the paleosol demarcating the contact between the basalt and the topmost ignimbrite.

3.2.Shibeji Gebriel

A river canyon and a road cut expose a succession of basalt-ignimbrite - basalt/ignimbrite from bottom to top(Fig 4).The bottom basalts, typical of the trap series exposed at the canyon are generally flat lying and continues upstream.However,the series shows disturbances,fractures and discontinuity of units downstream.

A road cut adjacent to the river canyon exposes a 15 m thick ignimbrite which overlies the bottom approximately 1200m thick trap series. The topmost unit along the roadcut exposure is a dome shaped basaltic unit.The gnimbrite unit is an important marker for separating the lower trap series unit from the overlying plagioclase-phyric basalt.

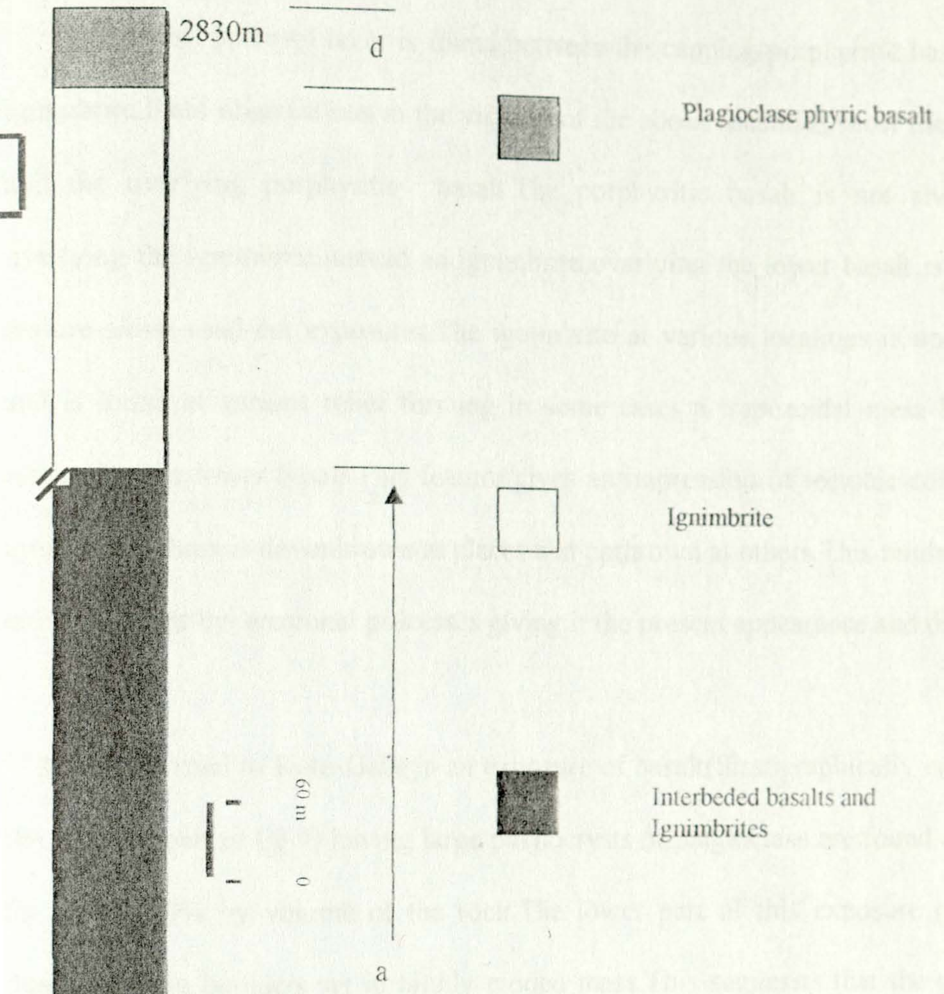


Fig. 4. Stratigraphic log at Shibeji Gebriel.See text for description.

A reddish paleosol layer is found between the capping porphyritic basalt and the ignimbrite.Field observations in the vicinity of the above localities show the ignimbrite and the overlying porphyritic basalt.The porphyritic basalt is not always found overlying the ignimbrite,instead an ignimbrite overlying the lower basalt is a common feature along road cut exposures.The ignimbrite at various localities is not continous and is found at various relief forming in some cases a trapezoidal mesa like feature resting on the lower basalt.This feature gives an impression of tectonic control on the ignimbrite which is downthrown at places and upthrown at others.This might have been later modified by erosional processes giving it the present appearance and distribution.

Along the road to Kotu Gebeya an exposure of basalt(Stratigraphically equivalent to the topmost part of fig.4) having large phenocrysts of plagioclase are found accounting for nearly 40% by volume of the rock.The lower part of this exposure represents a domain of big boulders set in highly eroded mass.This suggessts that the magma was homogenous in nature.Away from the road, the unit exhibits a gentle dip typical of shield volcanoes reflecting that the distance of flow is much greater than the height of the volcanic edifice.Large phenocrysts of plagioclase may indicate shallow level fractionation.

3.3Kotu Gebeya

Four to five thin ignimbrite units, each 5-6 m thick are intercalated with ashes (Fig. 5). The fact that there is a maximum of 30 m thick ignimbrite containing several flows makes the exposure distinct from the other areas so far encountered. The ignimbrites form steep slopes while the ashes form a gentle slope.

The observation that there are several flows of ignimbrite found on the plateau simplifies and diverts the previous impression of the ignimbrite above the lower basalt being controlled by an older tectonic phase(section 3.2). It gives now a more probable picture of erosion(denudation) process rather than tectonics playing the role. Hence, it seems that a denudation process might have removed all but two or one unit of ignimbrites at some places on the plateau as remnants to be seen at various reliefs. This last hypothesis is also strengthened by the trapezoidal mesa feature of the ignimbrite seen in the field.

3.4 Western Rift margin at Balchi

The Balchi fault scarp at the western margin of the Northern Main Ethiopian Rift with its approximately 200m height has exposed different volcanic rocks. The whole escarpment exposes alternating sequence of basalts and felsic units(Fig.6).

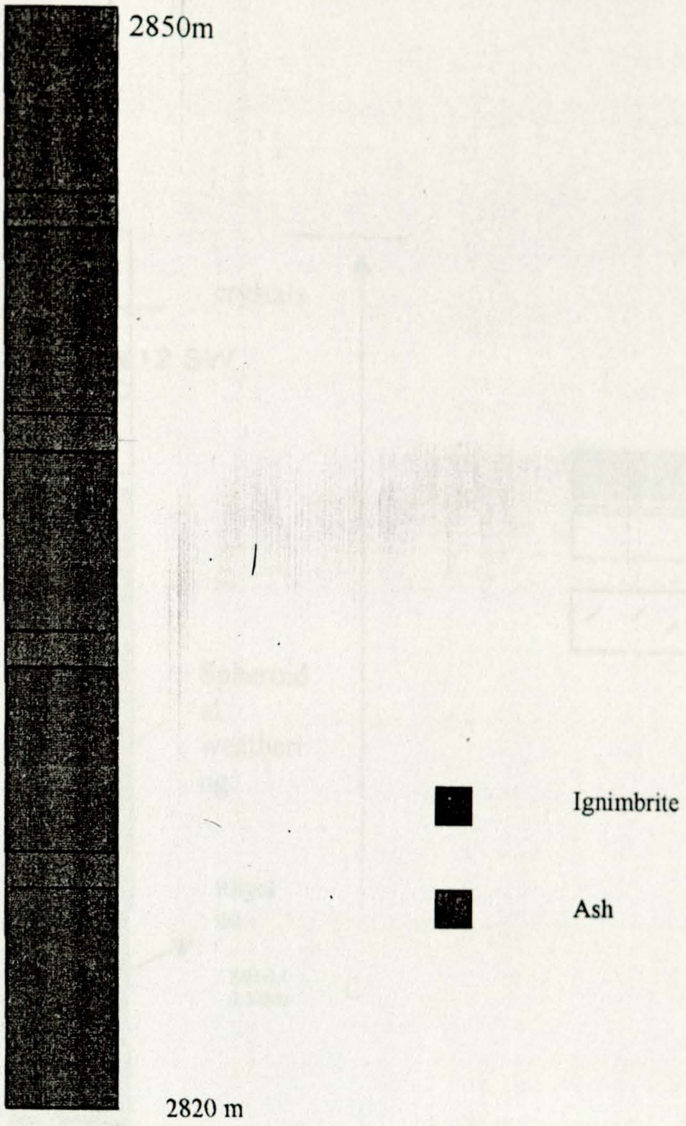


Fig. 5. Stratigraphical log at Kotu Gebeya.See text for description.

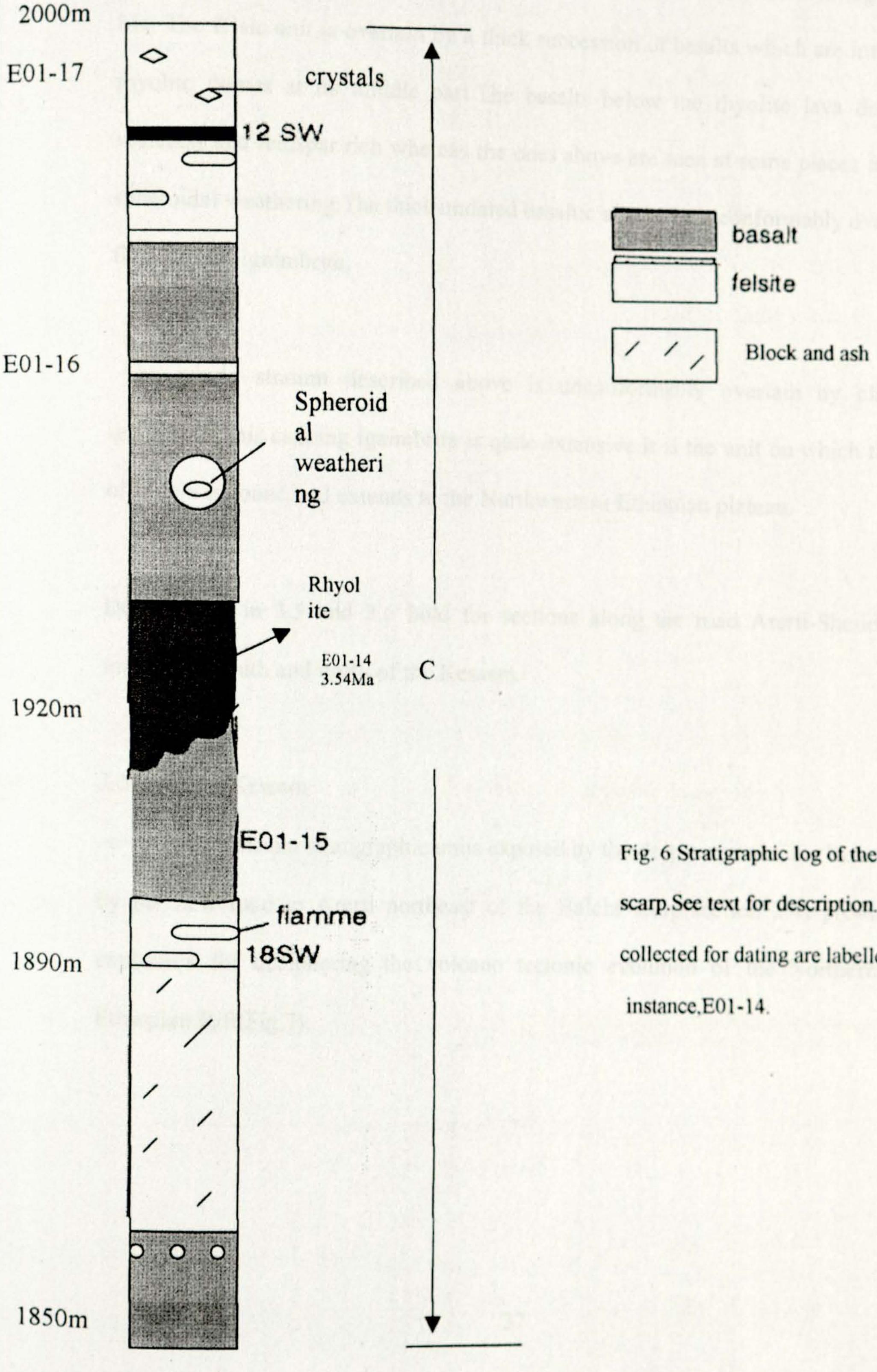


Fig. 6 Stratigraphic log of the Balchi scarp.See text for description.Rocks collected for dating are labelled for instance,E01-14.

The base of the scarp is constituted by an aphyric basalt grading into scoracious nature near the contact with the overlying felsic unit.This felsic stratum comprises rhyolites,ashes and fiamme rich ignimbrites.The later is found at the top of the felsic stratum .A rhyolite from the bottom of this felsic stratum has yielded an age of 3.54 Ma. The felsic unit is overlain by a thick succession of basalts which are intruded by rhyolite domes at its middle part.The basalts below the rhyolite lava domes are vesicular and feldspar rich whereas the ones above are seen at some places to exhibit spheroidal weathering.The thick undated basaltic sequence is conformably overlain by fiamme rich ignimbrite.

The whole stratum described above is unconformably overlain by clast rich ignimbrite.This capping ignimbrite is quite extensive.It is the unit on which the town of Balchi is found and extends to the Northwestern Ethiopian plateau.

Descriptions in 3.5 and 3.6 hold for sections along the road Arerti-Sheno in the immediate south and north of the Kessem.

3.5.South of Kessem

The volcano stratigraphic units exposed by the deep canyon of the Kessem and by the new road to Arerti northeast of the Balchi scarp(section 3.4) provide key exposures for deciphering the volcano tectonic evolution of the Northern Main Ethiopian Rift(Fig.7).

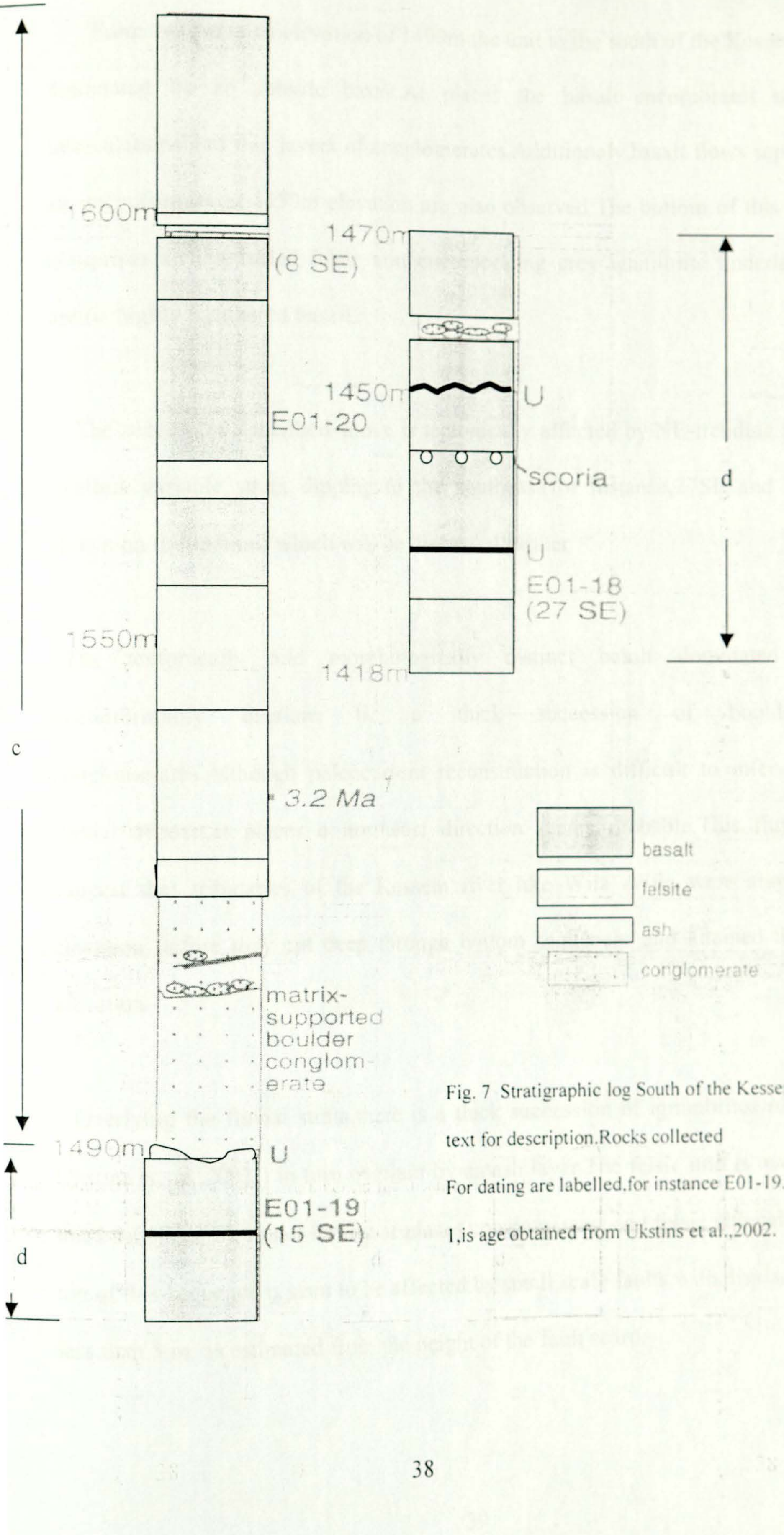


Fig. 7 Stratigraphic log South of the Kessem river.See text for description.Rocks collected For dating are labelled.for instance E01-19.

1,is age obtained from Ukstins et al.,2002.

From 1418m to an elevation of 1490m the unit to the south of the Kessem river is dominated by an aphyric basalt.At places the basalt encorporates scoracious intercalations and thin layers of conglomerates.Additionaly,basalt flows separated by an unconformity at 1450m elevation are also observed.The bottom of this sequence comprises an interbeded felsic unit encorporating grey ignimbrite underlain by an aphric highly weathered basalt.

The succession described above is tectonically affected by NE-trending faults and exhibits variable strata dipping to the southeast(for instance,27SE and 15SE are shown on the section) which will be discussed further.

The tectonically and morphologically distinct basalt dominated unit is unconformably overlain by a thick succession of boulders and conglomerates.Although paleocurrent reconstruction is difficult to infer from this fluvial deposit,at places a northeast direction seems probable.This fluvial strata suggest that tributaries of the Kessem river like Wila -Wila were above 1490m elevation before they cut deep through bottom sequences and attained the present elevation.

Overlying the fluvial strata,there is a thick succession of ignimbrites of 3.2 Ma (Ukstins et. al.,2002) in turn overlain by an ash layer.The felsic unit is overlain by a thick sequence of basalt having at places conglomerates and felsic intercalations.The top of this sequence is seen to be affected by small scale faults with displacements of less than 5 m as estimated from the height of the fault scarp.

3.6. North of Kessem

The section flanking the bottom north of Kessem canyon exposes alternating sequence of felsites and basalts(Fig 8).The base of the section is felsic unit. Sample E01-3a, an altered grey ignimbrite, has yielded an age of 10.4 Ma.The felsite is overlain by an aphyric basalt which is dated at 10.6 Ma (Ukstins et al.,2002). The current younger age, 10.4 Ma , contradicts with the 10.6 Ma due to its stratigraphic position. This might be due to the altered nature of of the sample dated which might have suffered Ar loss.Averaging the two gives an age of 10.5Ma which would be the most probable age for the units below the unconformity in Fig.8.The 10.6 Ma basalt is unconformably overlain by another felsic group.The volcanics above this felsic group is dominated by basalts and conglomerates though some of the section is concealed by talus.

The whole section described above is morphologically and tectonically distinct and is equivalent to the base of the volcanics described in section 3.5(between elevations1418m and 1490m) south of Kessem. The units are cut by NE-trending faults exhibiting variable strata dips to the SE and are approximately of 10 Ma. They are in turn overlain by a very gently dipping stratum the base of which yielded an age of 3.2 Ma. An important magmatic hiatus,therefore,exists in this area of the Northern Main Ethiopian Rift between roughly 10 and 3 Ma.

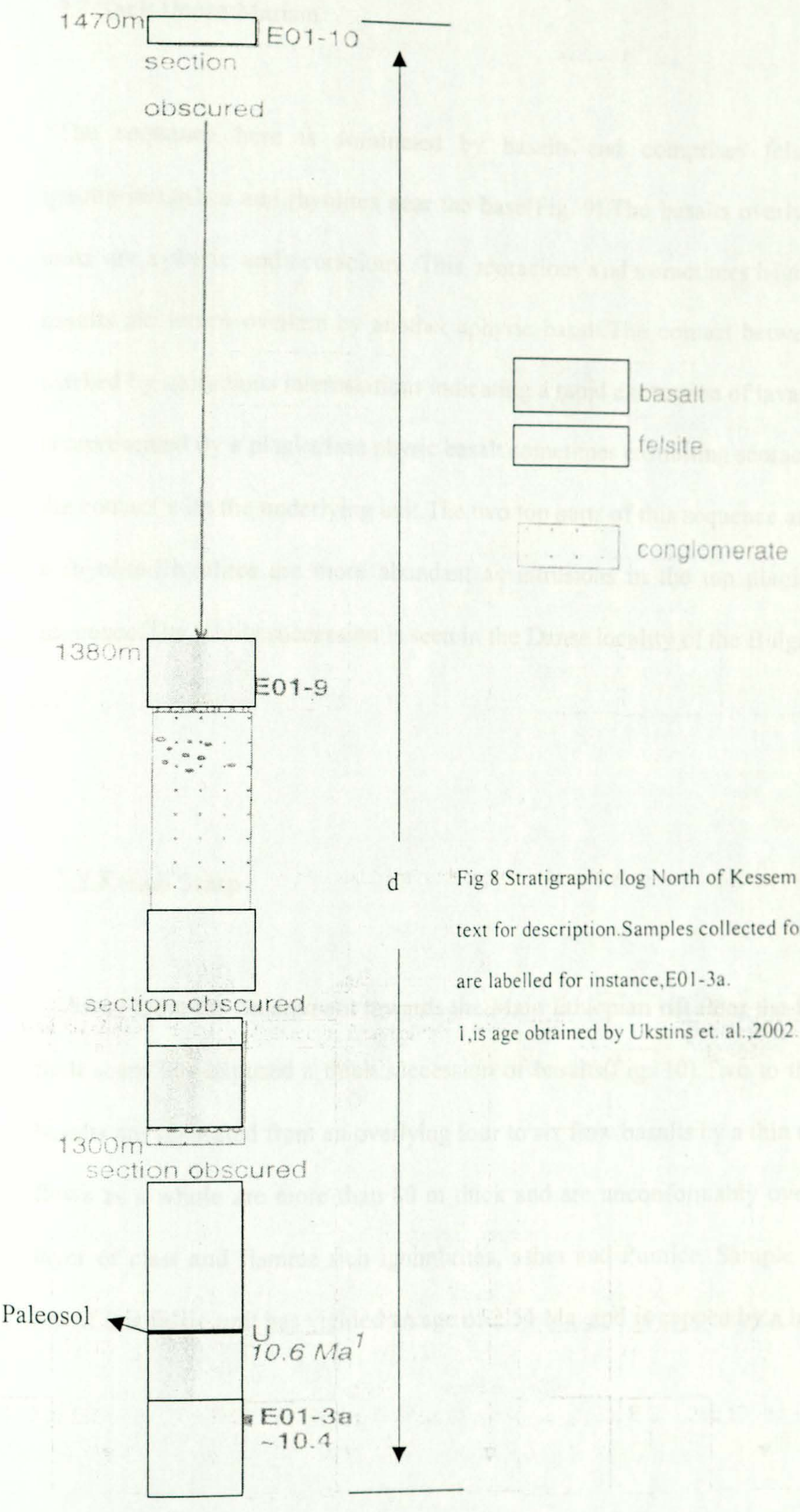


Fig 8 Stratigraphic log North of Kessem river.See text for description.Samples collected for dating are labelled for instance,E01-3a.

1,is age obtained by Ukstins et. al.,2002.

3.7 Tach Danse Mariam

The sequence here is dominated by basalts and comprises felsic units like ignimbrites,ashes and rhyolites near the base(Fig. 9).The basalts overlying the felsic units are aphyric and scoracious .This scoracious and sometimes highly weathered basalts are inturn overlain by another aphyric basalt.The contact between the two is marked by scoracious intercalations indicating a rapid exctrusion of lavas.The top part is represented by a plagioclase phyric basalt sometimes exhibiting scoracious nature at the contact with the underlying unit.The two top parts of this sequence are intruded by a rhyolite.Rhyolites are more abundant as intrusions in the top plagioclase phyric sequence.The whole succession is seen in the Danse locality of the Bulga region.

3.8.Keradi Scarp

Away from the escarpment towards the Main Ethiopian rift floor the Keradi region fault scarp has exposed a thick succession of basalts(Fig. 10).Two to three flows of basalts are separated from an overlying four to six flow basalts by a thin ash layer.The flows as a whole are more than 80 m thick and are unconformably overlain by thin layer of clast and fiamme rich ignimbrites, ashes and Pumice. Sample E-01-26 ,the top of this felsic unit has yielded an age of 2.54 Ma. and is capped by a basalt flow.

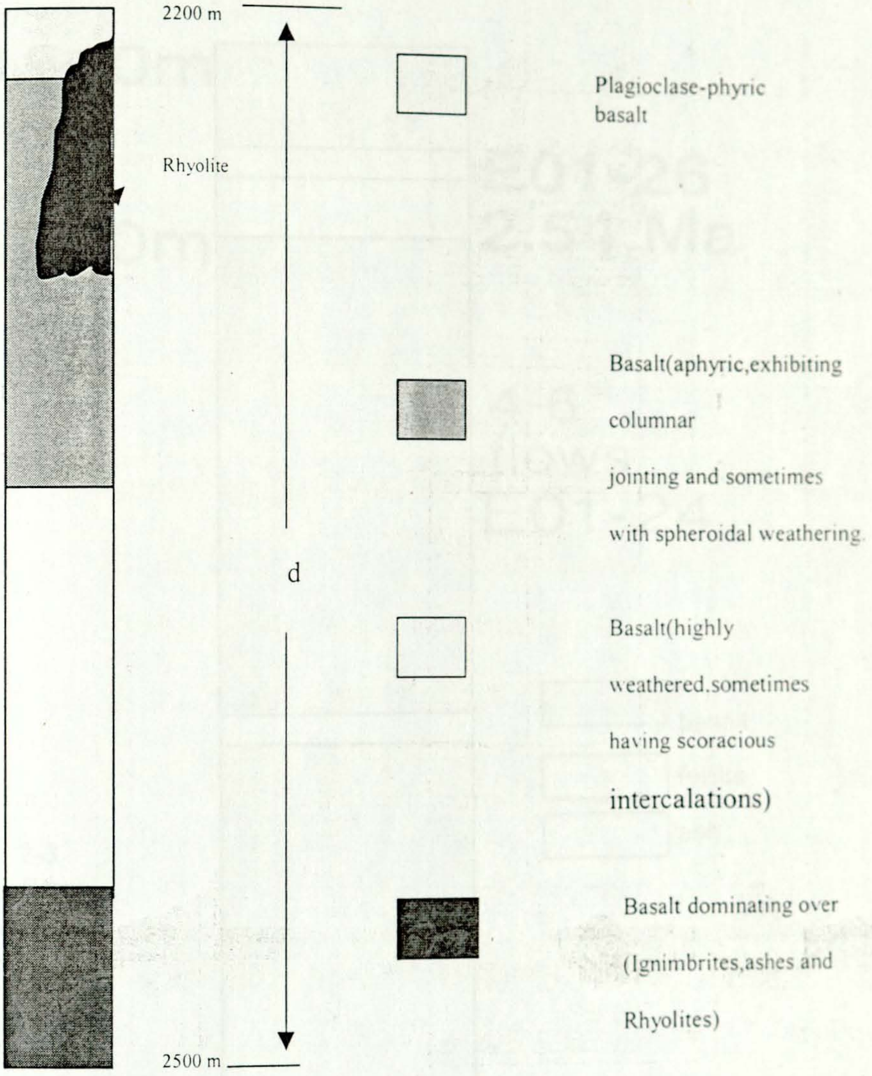


Fig. 9. Stratigraphic log of Tach Dansae Mariam.See text for description.

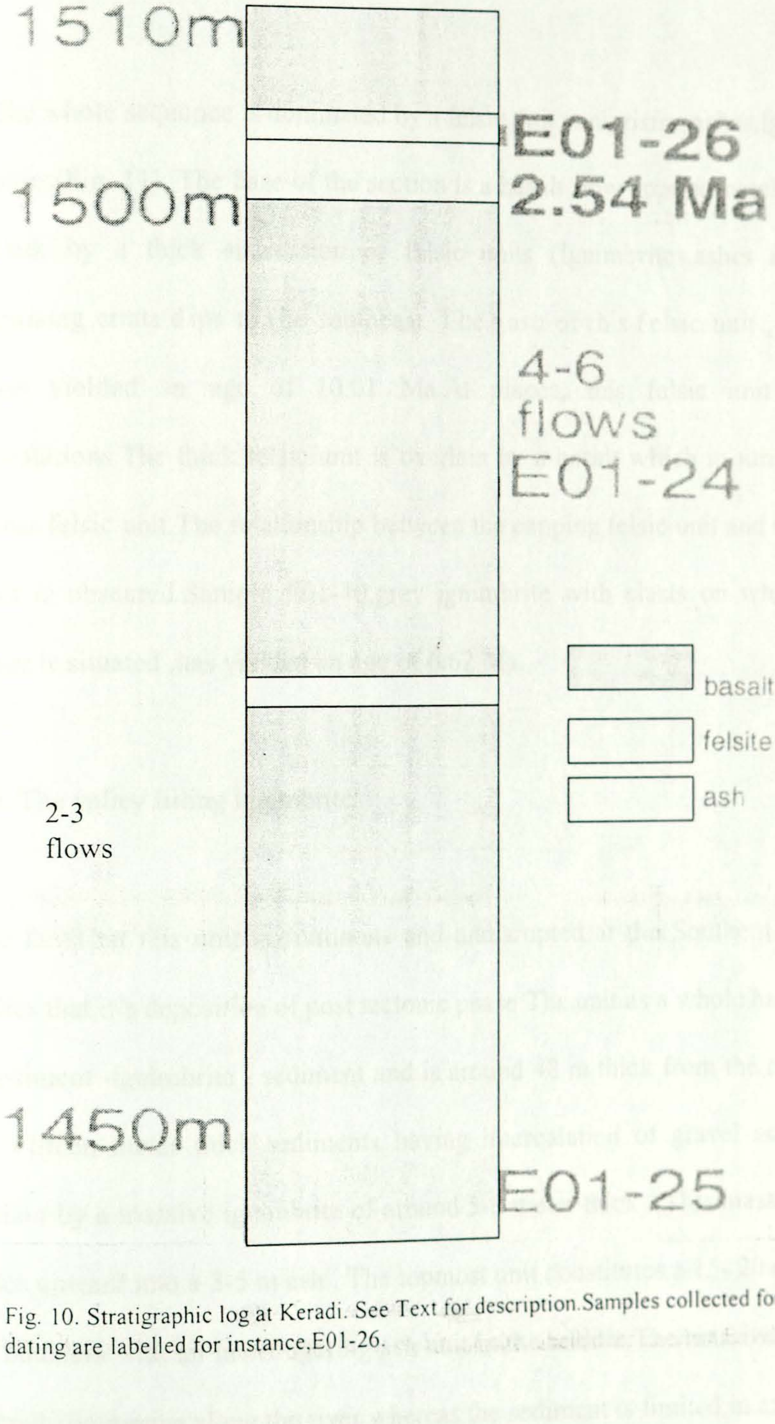


Fig. 10. Stratigraphic log at Keradi. See Text for description.Samples collected for dating are labelled for instance.E01-26.

3.9. Metehbila region (North of Kessem)

The description holds for the volcanics exposed along the road Metehara - Metehbila north of the Kessem river.

The whole sequence is dominated by a felsic unit comprising ashes,ignimbrites and rhyolites(Fig. 11). The base of the section is a basalt flow approximately 140 m thick overlain by a thick succession of felsic units (Ignimbrites,ashes and rhyolites) comprising strata dips to the southeast. The base of this felsic unit , Sample E01-42,has yielded an age of 10.01 Ma.At places, this felsic unit has basaltic intercalations.The thick felsic unit is overlain by a basalt which in turn is capped by another felsic unit.The relationship between the capping felsic unit and the underlying basalt is obscured.Sample E01-40,grey ignimbrite with clasts on which Metehbila village is situated ,has yielded an age of 6.62 Ma.

3.10. The valley filling ignimbrite

The fact that this unit is continous and undisrupted at the Southern Kessem river implies that it's deposition of post tectonic phase.The unit as a whole has a succession of sediment -ignimbrite - sediment and is around 48 m thick from the river floor(Fig. 12). Fifteen meter thick sediments having intercalation of gravel and boulders is overlain by a massive ignimbrite of around 5-8 meter thick . This massive ignimbrite grades upward into a 3-5 m ash . The topmost unit constitutes a 15- 20 m thick gravel and boulders with an interfingering ash unit in the middle.The massive ignimbrite is generally continous along the river whereas the sediment is limited in extent.

The valley filling ignimbrite doesn’t have a much lateral extent,it terminates against N-S trending west dipping fault in a westerly direction along the course of the river. way from the fault a basaltic dike of N33E , 75 SE offset N 5 E ,70 NW dike.

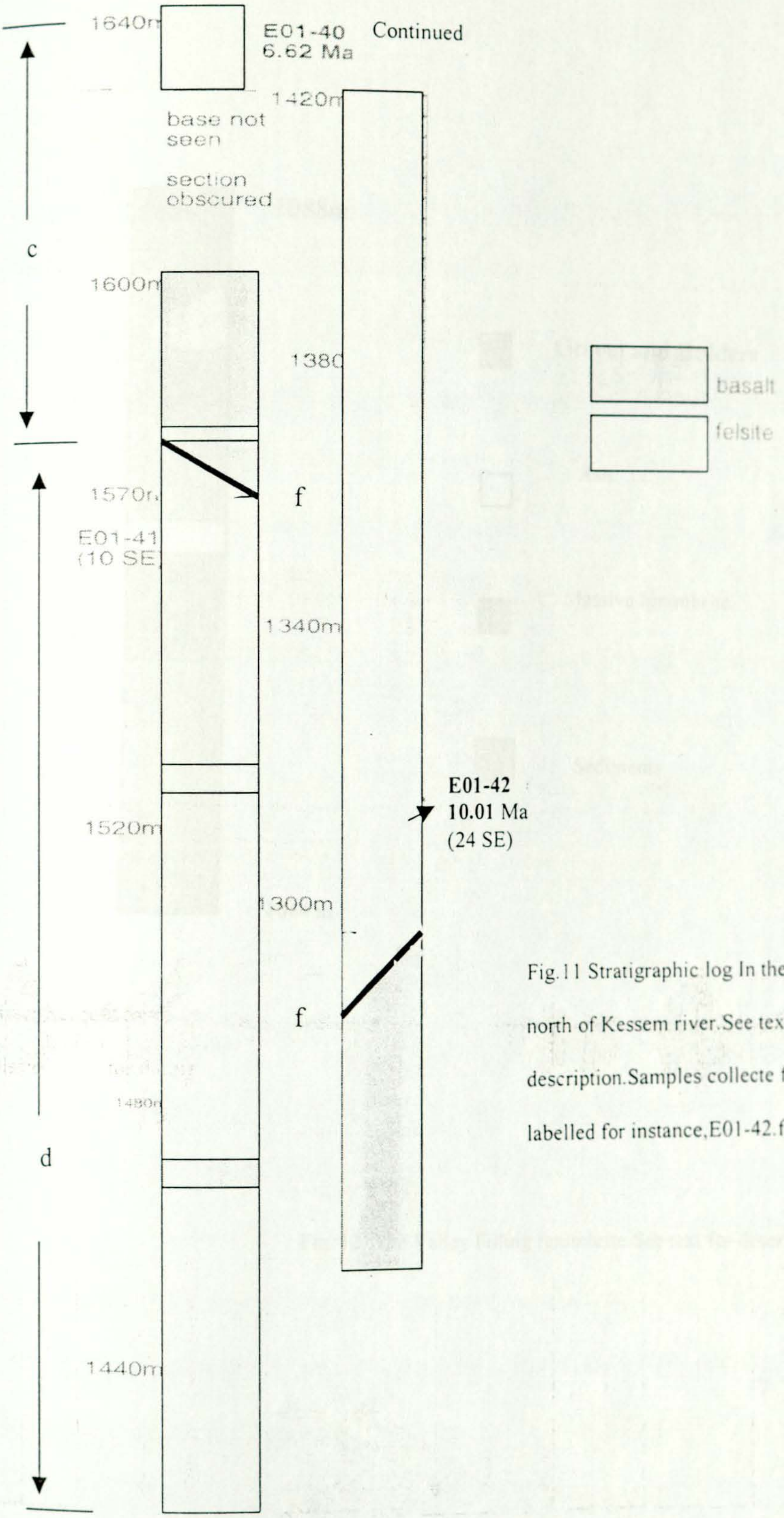


Fig.11 Stratigraphic log In the Metehbila region north of Kessem river.See text for description.Samples collecte for dating are labelled for instance,E01-42.f stands for fault.

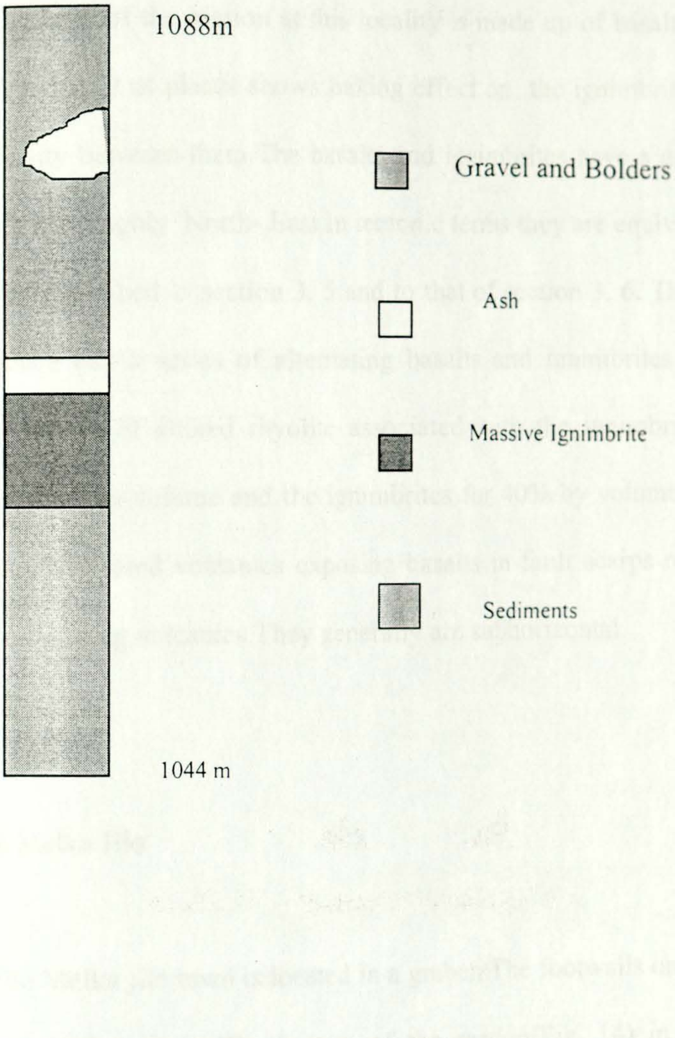


Fig. 12. The Valley Filling ignimbrite.See text for description.

3.11. Metehbila area (South of Kessem river)

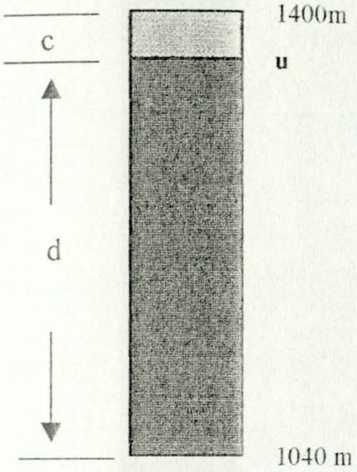
This refers the volcanic products exposed south of the Kessem river in the Metehbila area.

The base of the section at this locality is made up of basalts and ignimbrites(Fig. 13).The basalt at places shows baking effect on the ignimbrite which illustrates the continuity between them.The basalts and ignimbrites have a general tilting of 25 SE and strike roughly North- East.In tectonic terms they are equivalent to the base of the section described in section 3. 5 and to that of section 3. 6. The base of the volcanic sequence has a series of alternating basalts and ignimbrites sometimes having an intercalation of altered rhyolite associated with the ignimbrite.Basalts account for about 60% by volume and the ignimbrites for 40% by volume of the exposed rocks. Felsic dominated volcanics exposing basalts in fault scarps rests unconformably on the underlying volcanics.They generally are subhorizontal.

3.12.Melka Jilo

The Melka jilo town is located in a graben.The footwalls on either side of the town hosts small calderas.The bottom of the section(Fig. 14) in this locality is a grey medium grained pumice fall approximately 5 m thick .This grades upward into white pumice fall deposit about 50 cm thick containing clasts of upto 5 cm in diameter.The size of the pumice clasts suggests that it is erupted from the caldera situated nearby. The above units are overlain by a 15 m thick grey,highly welded ignimbrite. The ignimbrite is clast and glass rich in a roughly equal proportion.

The volcanics described above are exposed by the faults making up the graben.Within the graben the Melkajilo river has exposed a 1.5m thick weathered grey ignimbrite overlain by a 2 m thick alluvium,cobbles and pebbles.

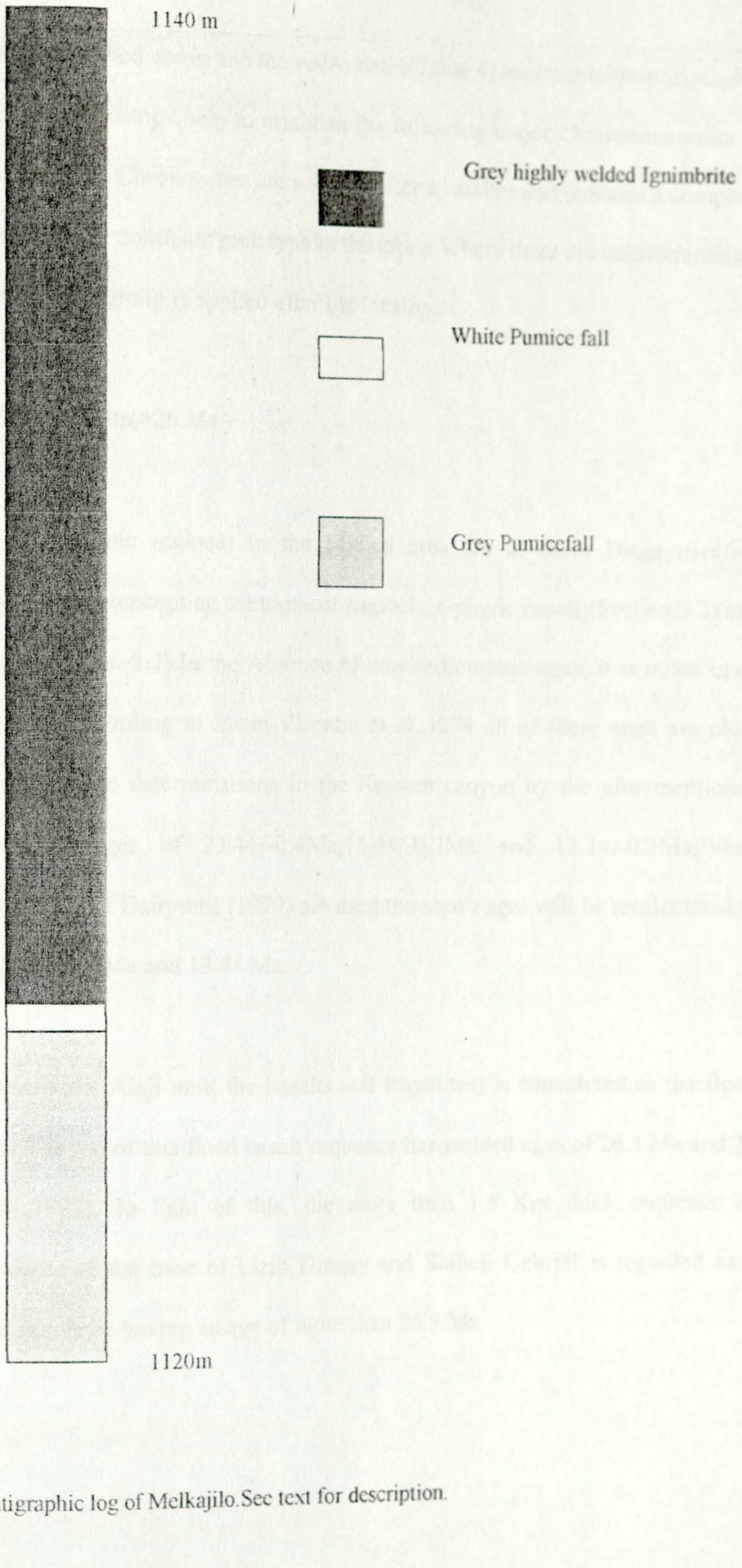


░ Ignimbrites and ashes with Porphyritic basalts in footwall to faults.

▓ Ignimbrites,ashes,rhyolites(40%) and basalt(60%),aphyric in nature and at some places exhibiting columnar jointing.

u Unconformity

Fig. 13. Stratigraphic log of South of Kessem river(Metehbila area).See text for description.



ig. 14 Stratigraphic log of Melkajilo.See text for description.

The sections described above and the Ar/Ar dates(Table 4) together with stratigraphic and lithologic relatioships help to establish the following major chronozone units of the studied area.The Chronozones are selected after a locality that contains a complete section and after the dominant rock type in the group.Where there are undifferentiated volcanics the name group is applied after the locality.

3.13.The flood basalts(>26 Ma.)

The oldest volcanic rocks(a) in the studied area are at Lizib Dingay(Section 3.1),Shibeji Gebriel (excepting the topmost pagioclase-phyric basalt)(Section 3.2) and Kotu Gebeya(Section 3.3).In the Absence of new radiometric ages, it is relied upon previous works.According to Justin-Visentin et al.,1974 all of these units are older than 13Ma.K/Ar age determinations in the Kessem canyon by the aforementioned authors yielded ages of 23.4+/-0.4Ma,15.6+/-0.3Ma and 13.1+/-0.3Ma.When conversion factors of Dalrympe (1979) are used the above ages will be recalculated to give 24.01Ma,16.01Ma and 13.44 Ma.

More recently,the Alaji unit(the basalts and Rhyolites) is considered as the flood basalt series.The top of this flood basalt sequence has yielded ages of 26.5 Ma and 25 Ma (George,1997). In light of this, the more than 1.5 Km thick sequence of basalt/ignimbrite at the base of Lizib Dingay and Shibeji Gebriel is regarded as a flood basalt sequence having an age of more than 26.5 Ma.

The base of this flood basalt sequence is exposed neither at Lizib Dingay nor at Shibeji Gebriel. However, there is a report on the presence of thin nonfossiliferous sandstone layer underlying the flood basalt sequence(Fracaviglia ,1940).

3.14.Bulga Basalts(Approximately 10 Ma)

The volcanics that fall within this chronostratigraphy are found(d) at section 3.6 ,the base of section 3.5,section3.7,the base of section3.11and the base of section 3.9.There are no radiometric ages for the base of section 3.11.But it is intended to classify it within this group because of its stratigraphical and tectonic similarity.The same is true for section 3.7.The topmost part of section 3.2 also fall within this group.The topmost part of section 3.7 and section 3.2 is plagioclase- phyric basalt.

Time correlative units are Anchar basalts of Kazmin (1980) and Guraghe basalts of Woldegebriel et al.,1990.

3.15Balchi group(6.6-3.5 Ma)

The Balchi group is represented by undifferentiated felsic units(Ignimbrites,ashes and some rhyolites) and basalts.They are exposed(C) at Balchi scarp(section 3.4),top of section 3.5 and top of section3.9.

The group rests unconformably on the Bulga basalts.The blanketing volcanics ot this group is a clast rich ignimbrite unconformably overlying the bottom fiamme-rich ignimbrite.This clast rich ignimbrite is also observed at the top of the Shenkora - Yohannes gorge northwest of Balchi.Time corelative units are Nazreth series(9-3(2) Ma) of Kunz et al.,(1975) ,Kazmin et al.,(1980) . Balchi rhyolite of Justin-Visentin et al.,(1974) and Butajira ignimbrites of Woldegebriel et al.,1990.

3.16 Keradi basalts(2.5Ma-1.8Ma)

It is exposed by the Keradi fault scarp in the keradi area.Time correlative units are Bofa basalts of Kazmin et al.,1980 and Chernet et al.,1998.

3.17 Melka Jilo Ignimbrite

The absence of radiometric age for this group makes it difficult to determine its chronostratigraphic range.Hoever,its presence on the rift floor and it's proximity to the Kone caldera gives a clue of younger volcanic activity.(probably younger than 1.8 Ma).

The flood basalt comprise basalts interbeded with felsic units(ignimbrites and rhyolites).The top of the unit is represented by an ignimbrite/ash overlain by a porphyritic basalt.The bottom of this unit is seen only in stream cut exposures which are tributaries of the Kessem river.Sometimes we find a plagioclase-phyric basalt covering an ignimbrite/ash.

The studied area in the vicinity of Koremash is mapped(fig.15) as flood basalts(99% in aerial extent).This is because at some places the Bulga basalts are seen to cover the ignimbrite.The remaining 1 %(Aerial extent) accounts for the Bulga basalts.

The Bulga basalts have a widerspread occurence in the study area(fig 15).The highest elevaton (approximately 3400m) is attained by younger plagioclase-phyric basalts of these group(Fig. 16). To the northwest and southeast of this peak(Ilehkese peak) the volcanics have an assymetrical distribution. As seen on the map(Fig 15) it covers most of the Metehbila sheet and extending as far as the Kessem canyon.

The contact between the flood basalts and the Bulga basalts is evident in most Northeast directed tributaries of the Kessem.Generally,it can be said that the group has a widerspread coverage of the studied area north of the Kessem river.

The Balchi group shows extensive exposure in the area south of the Kessem river.This doesn't mean that there are no exposures to the North of the Kessem river.There are limited pockets of outcrop in the area north of the Kessem river.Most villages of Bulga for instance,Dodota,Gobensae and the Village of Metehbila itself are located on this group(fig 15).The terminus of this flat lying pockets north of the Kessem river defines a roughly Northeast trend.

The largest felsic centre of the study area,Mt.Bokan(Fig. 17), is located outside the rift on the Balchi plateau.This centre attains a height of 2670m elevation. As seen in the Shenkora Yohhanes gorge , the top of the Balchi group thickens toward this felsic centre.

Toward the rift floor, there are other felsic centers of interest.These centers are located between the Minjar and Keradi faults.The centers are alighned roughly NNE-SSW(fig.15).

The Keradi basalt are exposed by faults in the Keradi area.The volcanic products are peculiar to the Keradi ridge and nearby faults.They are not exposed elsewhere in the studied area(fig.15).

Scoria cones are found north of the Kessem river and are seen to cover two distinct areas.One is in the southeast and the other is in the Northeast(fig. 15). The cones in the field have preserved their morphology undisturbed by any tectonic phase.

To the Northwest and Southeast of Melka Jilo town the nearby Bosena and Dobina Awile areas are felsic centers which are possible sources of the Melka Jilo ignimbrite. These centers are found on the footwall of faults found in that area..

Sample	Longitude	Latitude	Sample description	$^{40}Ar/^{39}Ar$ age (Ma)
E01-3a	39.5653	9.0393	Altered grey ignimbrite	10.4
E01-14			rhyolite	3.545
E01-26	39.6325	9.0017	Ignim-clast+ fiamme	2.54
ET01-HS02	573760	922857	Clast rich ignimbrite	7.98
ET01-HS01	574097	921736	Altered grey ignimbrite	7.807
ET01-40	39.5428	9.1783	Grey ignimbrite With clasts	6.624
ET01-42	39.7253	9.1383	Felsite clasts Below unconformity	10.01

Table4. New Ar/Ar ages in the northern main Ethiopian rift.Most of the ages are also plotted on the stratigraphic logs.

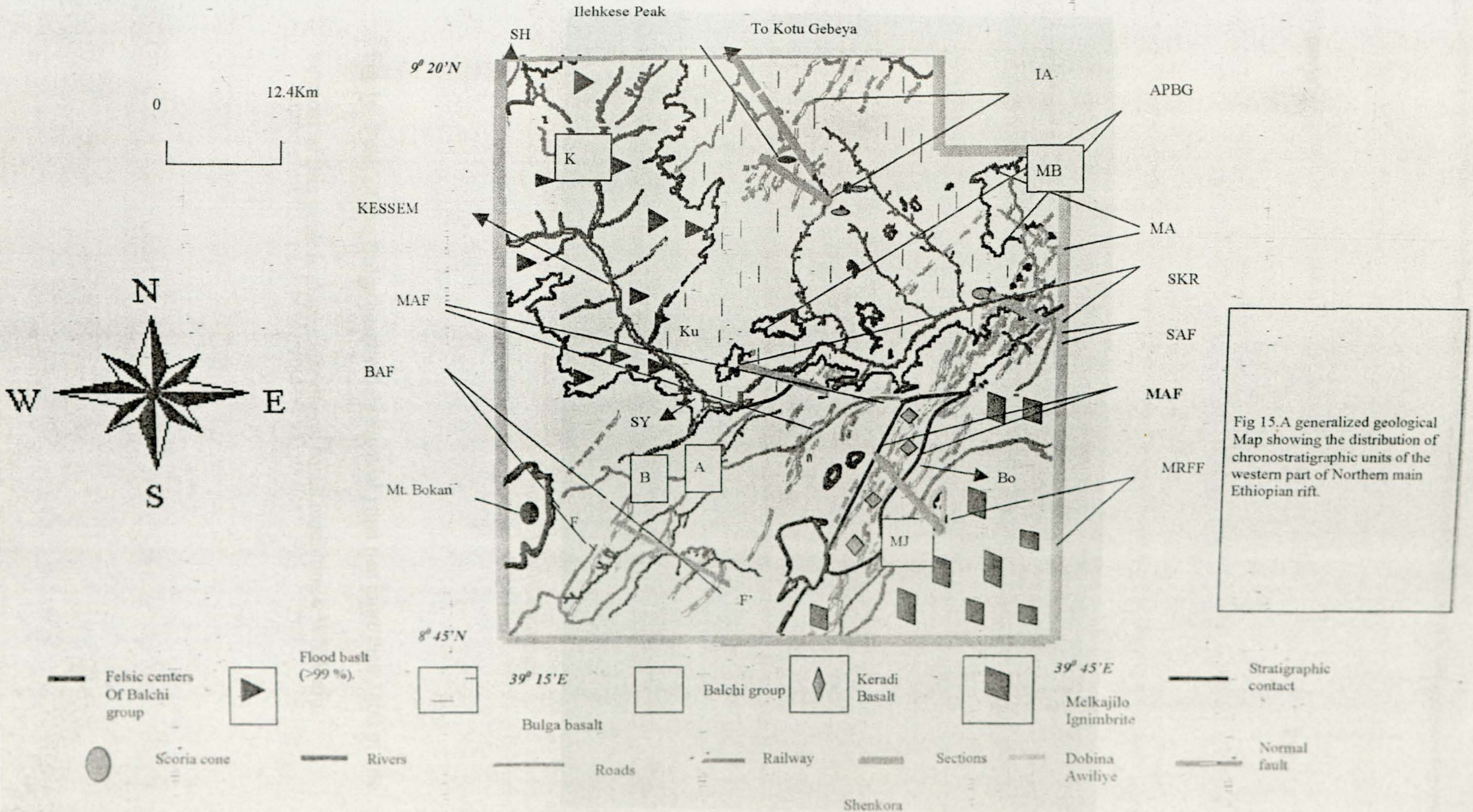


Fig 15.A generalized geological Map showing the distribution of chronostratigraphic units of the western part of Northern main Ethiopian rift.

Kurkura Stream B Balchi A Arerti MJ Melka Jilo MB Metehbila K Koremash SH Sheno SY Shenkora Yohannes gorge

Bosena

For IA, Ilehkese area;APBG,aligned pockets of Balchi group;MA,Metehbila area; SKR,southern Kessem region;SAR,Sabure area faults;**MAF**,Melka jilo area faults; MRFF,Melka jilo rift floor faults;MAF,Minjar area faults Descriptions and figures Are found in Chapter 4 and 5.BA7 is Balchi area faults.

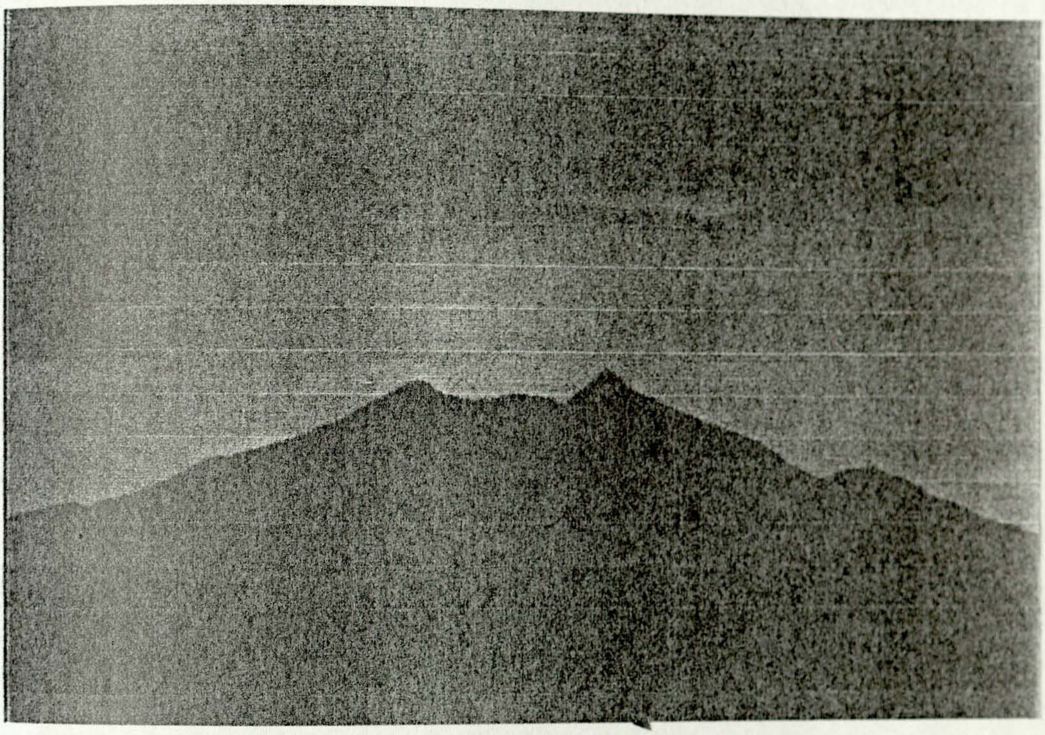


Fig.16 Peak of the Bulga basalts(Ilehkese peak) that rise more than 3400 m.The topmost of this peak is plagioclase phyric basalt exhibiting a WNW dip.

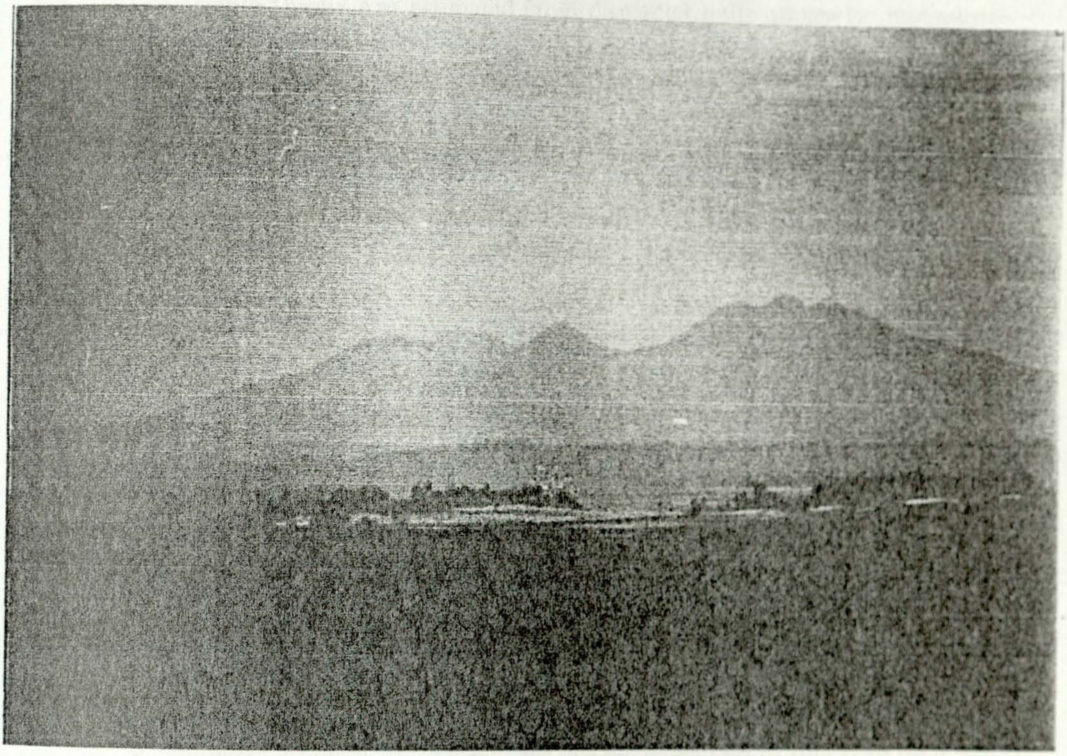


Fig 17 The Bokan felsic centre. Photo taken along the road Sheno- Arerti north of Kessem river.

Chapter 4

Structural outlines

Following is the description of general structural outlines that are observed in the Western marigin of the Northern Main Ethiopian Rift.For the sake of discussion , the description is divided in two parts.These are north of Kessem and south of Kessem.

Wherever possible throws are estimated from displaced units otherwise minimum estimates are given from the height of the fault scarp.All of the faults in the studied area are normal faults. Wherever there are prominent faults of significant length and/or displacement, they are named after the locality.

4.1.North of Kessem river

In this region the most prominent structure is the Ilhekese border fault. It is NNE-trending,ESE dipping and has a maximum throw of 150m. The fault developed near the peak of the Bulga Basalts which rise to 3400 m elevation(Fig. 18).Though the fault scarp is moderately eroded,the amount of dip is estimated to be $> 60^0$..It tiltes strata to the northwest with approximately 30^0. To the northwest of this fault there are very closely spaced faults with similar trends,dip directions but having throws of less than 15m each.

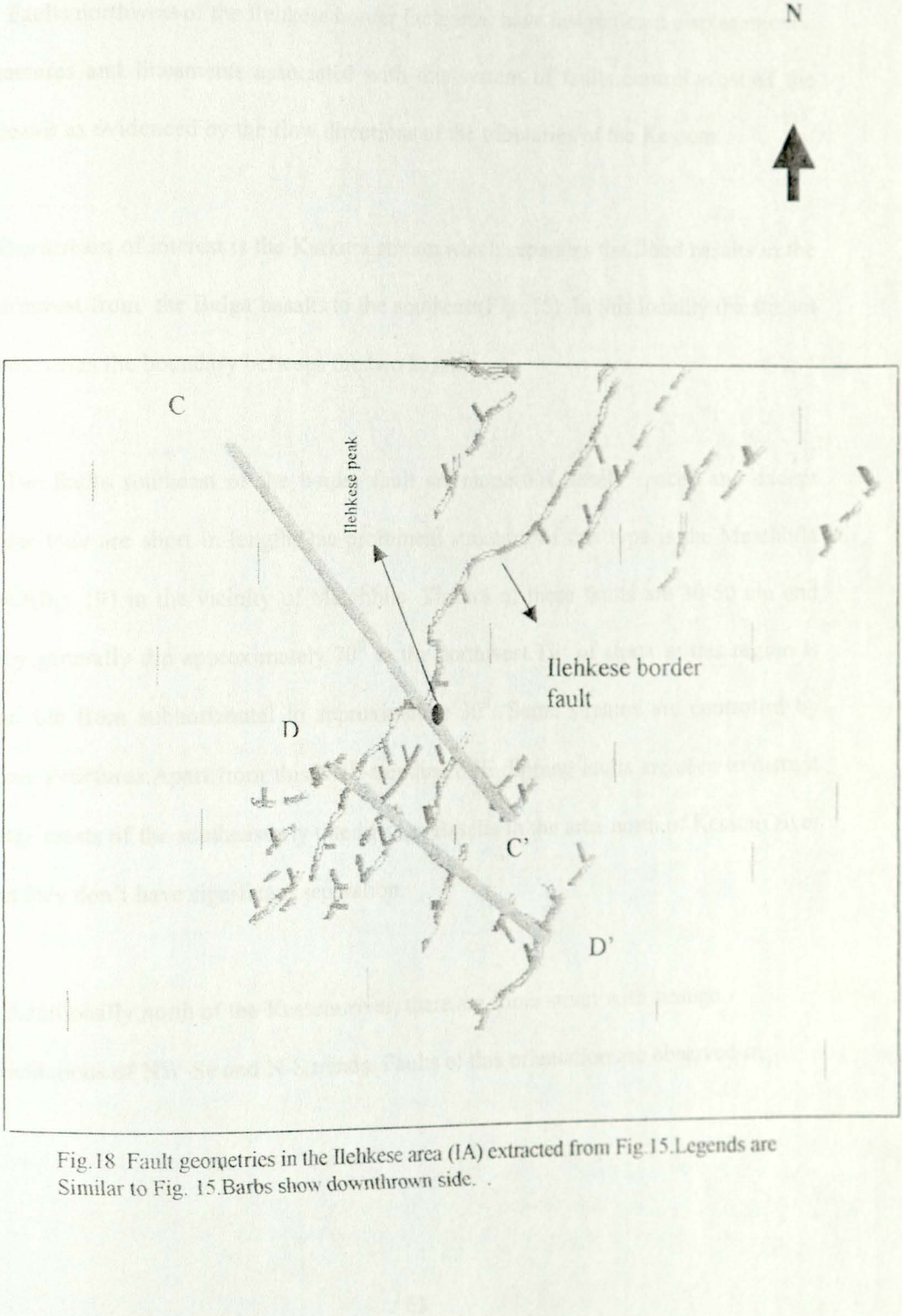


Fig.18 Fault geometries in the Ilehkese area (IA) extracted from Fig.15.Legends are Similar to Fig. 15.Barbs show downthrown side. .

In the northwest and southeast of the Ilehkese border fault,faulting persumes a different orientation. Commonly,it takes up a NE-trending ,NW dipping faults tilting strata to the SE. It is more developed to the Southeast of the Ilehkese border fault.

Faults northwest of the Ilehkese border fault area, have insignificant displacements. Fractures and lineaments associated with this system of faults control most of the streams as evidenced by the flow directions of the tributaries of the Kessem.

One stream of interest is the Kurkura stream which separates the flood basalts in the northwest from the Bulga basalts to the southeast(Fig. 15)..In this locality the stream demarcates the boundary between the two basalts.

The faults southeast of the border fault are numerous,closely spaced and except some they are short in length.One prominent structure of this type is the Metehbila fault(fig. 19) in the vicinity of Metehbila .Throws of these faults are 30-50 cm and they generally dip approximately 70^0 to the northwest.Tilt of strata in this region is variable from subhorizontal to approximately 30^0. Some streams are controllrd by these structures.Apart from this,NNE-trending,ESE dipping faults are seen to disrupt ridge crests of the southeasterly tilted Bulga Basalts in the area north of Kessem river but they don't have significant separation.

Additionally,north of the Kessem river, there are some struct with strange orientations of NW-Se and N-S trends. Faults of this orientation are observed in

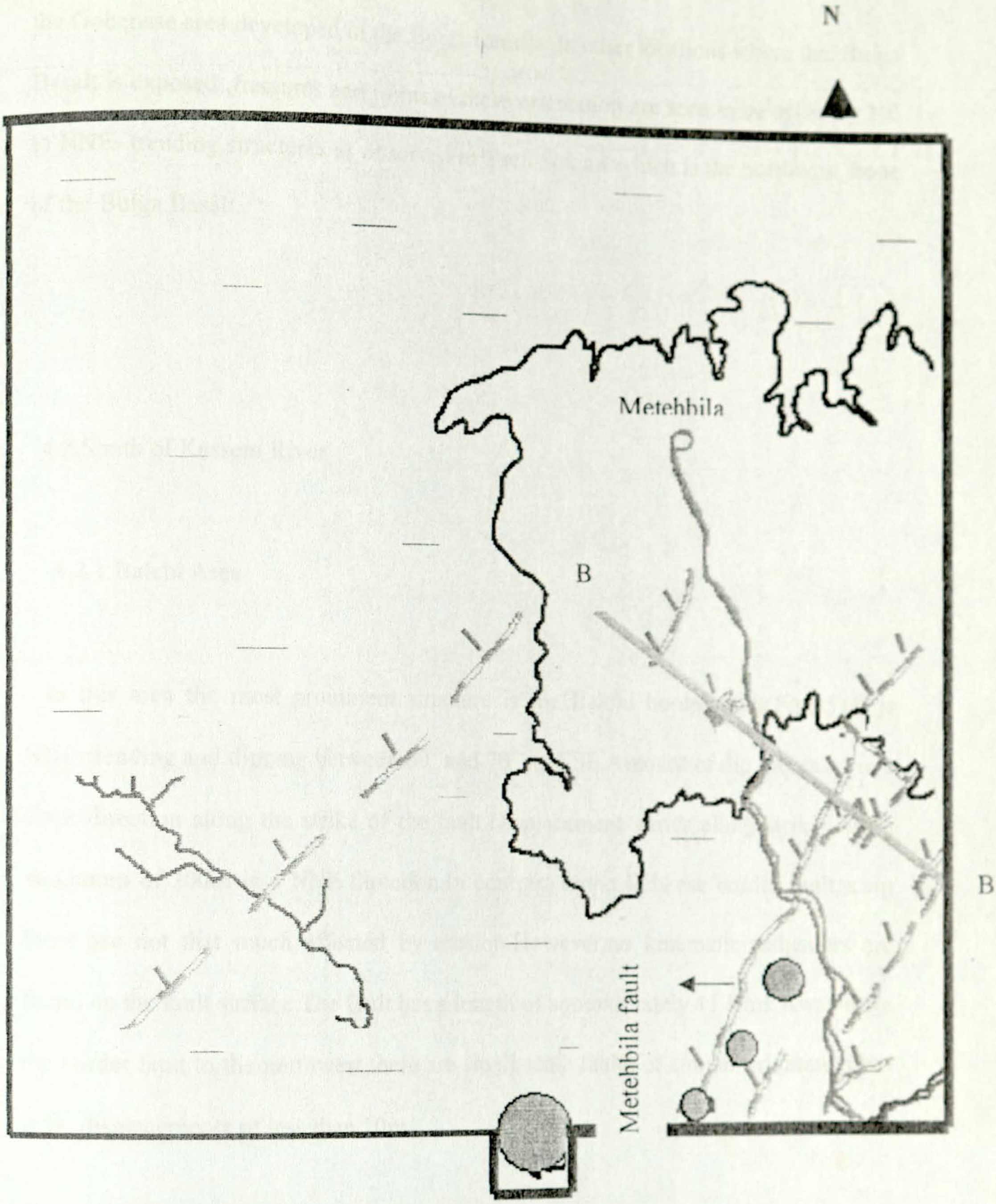


Fig.19 Geometry of faults in the Metehbila area(MA) extracted from fig.15 . Legends are the same as Fig. 15.Barbs show to the downthrown side. .

the Gobensae area developed in the Bulga Basalts. In other locations where the Bulga Basalt is exposed ,fractures and joints of these orientation are seen to be offset by NE to NNE- trending structures as observed in Tach Sokuru which is the northwest slope of the Bulga Basalt.

4.2.South of Kessem River

4.2.1.Balchi Area

In this area the most prominent structure is the Balchi border fault(Fig.15).It is NNE-trending and dipping between 60^0 and 70^0 to ESE.Amount of dip increases in a NNE direction along the strike of the fault.Displacement varies along strike with a maximum of 200m in a NNE direction.In contrast to the Ilehkese border fault,scarp faces are not that much affected by erosion.However,no kinematic indicators are found on the fault surface.The fault has a length of approximately 11 Kms.Away from the border fault to the northwest,there are small scale faults of similar orientation but with displacements of less than 10m.

In a southeast direction from the Balchi border fault ,there are three faults of similar orientation as the border fault.These three faults are each approximately 3 Km long and the intervening distance among them and the border fault is on the average 3 Km.Two of these faults, the closest and the farthest to the Balchi border fault , have a maximum displacement of 100m.On the contrary the middle one has a maximum displacement of 200m.All of the intrarift faults have a maximum displacement in the middle part with decreasing displacement toward their tips.

The stratum between the border fault and the first intrarift fault gently dips to the northwest. Other strata flanked by the intrarift faults in these area are flat lying.

4.2.2 Kessem Area

This description holds for the area south of the Kessem river of localities Aroge Minjar,Adama-Dire Michael , Gewgew and Lay Choba from west to east.

The above mentioned horst like features are found on the average 2 Km from the Kessem river.A common feature of this intervening distance is the NE-NNE-trending,NW to WNW dipping faults that rotate the strata to the ESE and SE.

The Aroge Minjar area(fig. 20) is bounded to the West by a NNE -trendng,WNW dipping fault and to the east by a NNE-trending,ESE dipping fault. Displacement on each of these two faults is less than 20m. NE to NNE-trending , WNW to NW dipping minor faults are developed between the two bordering faults.Throw on these faults is less than 5 m and gently tilt strata to the ESE. .

The Adama-Dire Michael(Fig 20) area has to the west a NNE-trending,ESE dipping fault and to the east a fault of similar orientation.The stratum dips gently to the nothwest.

The Gewgew area(Fig. 20) has to the east a NNE -trending,ESE dipping fault and to the West a fault of similar orientation.Maximum displacement on the east bounding fault is 100m and displacement increases toward the fault tip in a NNE-direction.

The western Lay Choba area has to the west a NNE-trending ,WNW dipping fault and to the east a similar orientation but oppositedly dipping fault.The eastern Lay Choba area has to the west a NNE-sriking,WNW dipping fault.To the east, the area has a segmented system of NNE-trending,ESE dipping fault.The eastern boundary descends in at least two steps.Maximum total displacement on this faults is 400 m.This fault is named the Kessem border fault(Fig. 21).Maximum displacement on the western boundary fault is 80 m.

The Lay Choba area between the bounding faults have many NNE-trending faults.The faults have variable dip directions but the WNW dipping ones dominate over the ESE dipping ones.

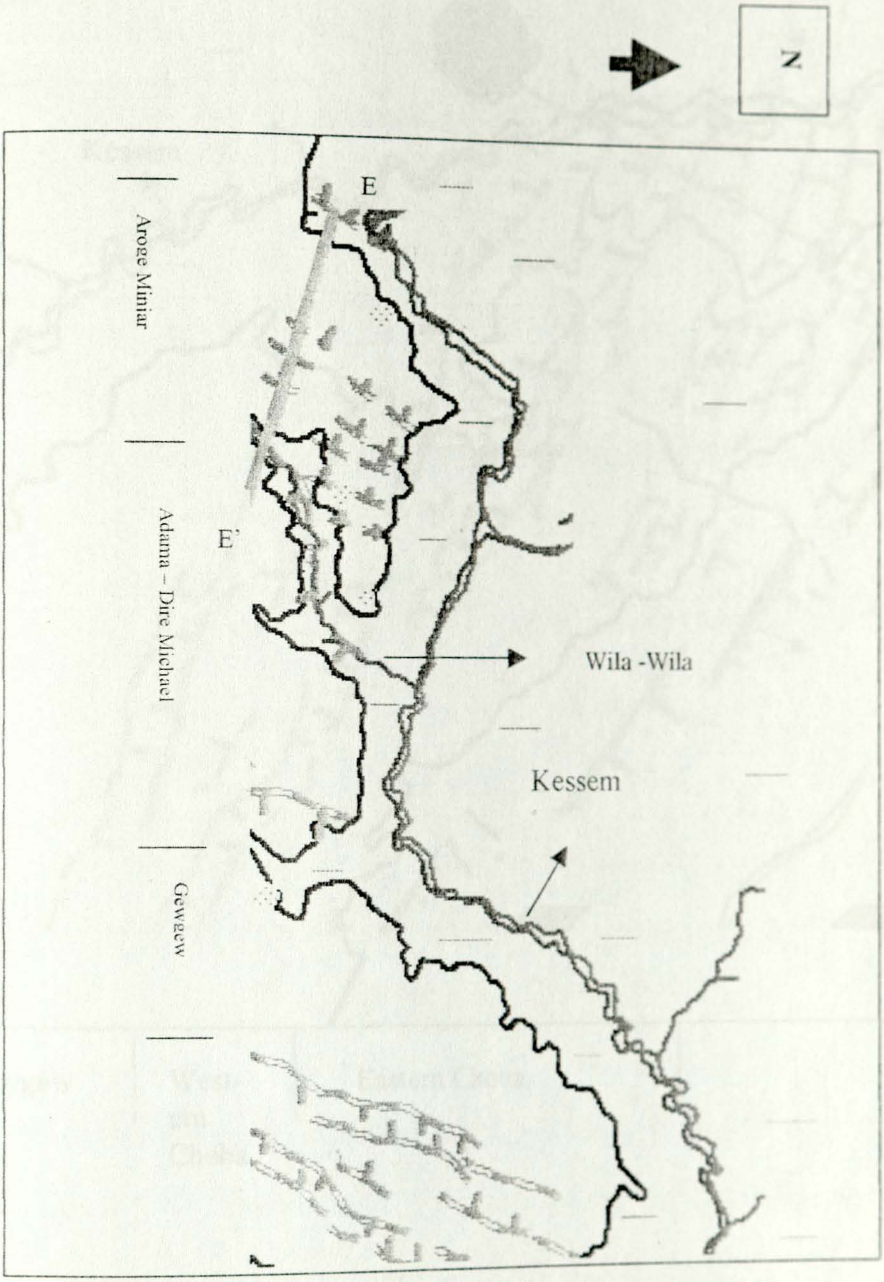


Fig.20 .Geometry of faults in Aroge Minjar,Adama-Dire Michael and Gew-Gew area extracted from Fig. 15. and represents the western part of SAR(Souther Kessem region.Legends are the same as fig .15.Barbs show to the downthrown side.

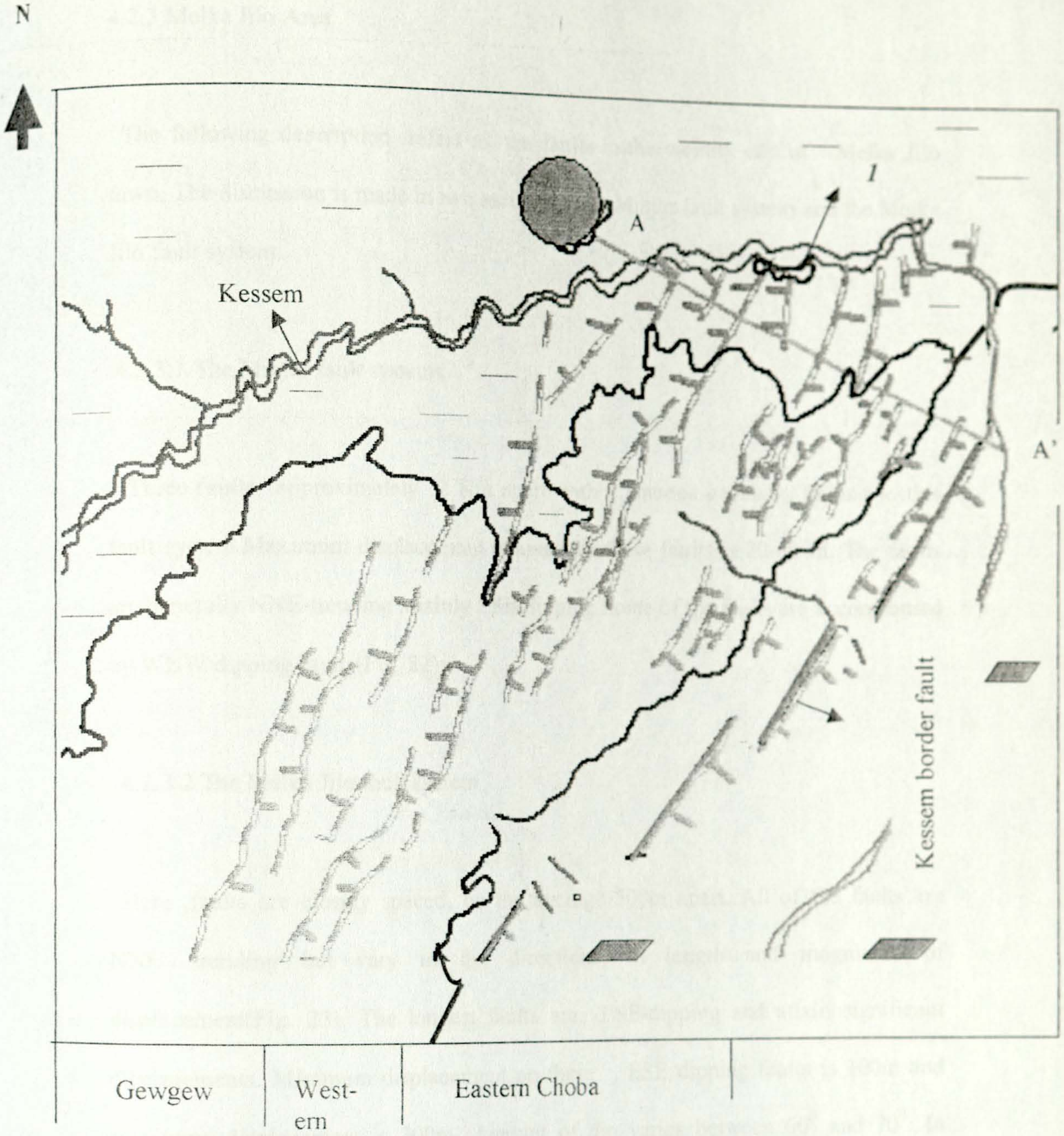


Fig.21 Showing fault geometries in the Gewgew and Choba areas extracted from fig.15,eastern part of SAR .Legends are the same as the map(Fig. 15) except *1* representing the valley filling ignimbrite not shown in fig.15 due to the scale.Yellow is alluvial fan.Barbs show to the downthrown side.

4.2.3 Melka Jilo Area

The following description refers to the faults in the vicinity east of Melka Jilo town. The discussion is made in two sections : The Minjar fault system and the Melka Jilo fault system.

4.2.3.1 The Minjar fault systems

Three faults approximately 2 Km apart with a sinuous geometry belong to this fault system.Maximum displacement attained by these faults is 20-40 m. The faults are generally NNE-trending ,mainly ESE-dipping.Some of the faults are accompanied by WNW dipping faults(Fig. 22).

4.2.3.2.The Melka Jilo fault system

Here ,faults are closely spaced, on the average 500m apart. All of the faults are NNE- trending but vary in dip directions, in length and magnitude of displacement(Fig. 23). The longest faults are ESE-dipping and attain significant displacements. Minimum displacement on these , ESE dipping faults is 100m and maximum displacement is 200m. Amount of dip varies between 60^0 and 70^0. In between these faults,there are some WNW dipping faults. These WNW dipping faults are short in length and displacements on these faults are less than 20 m.

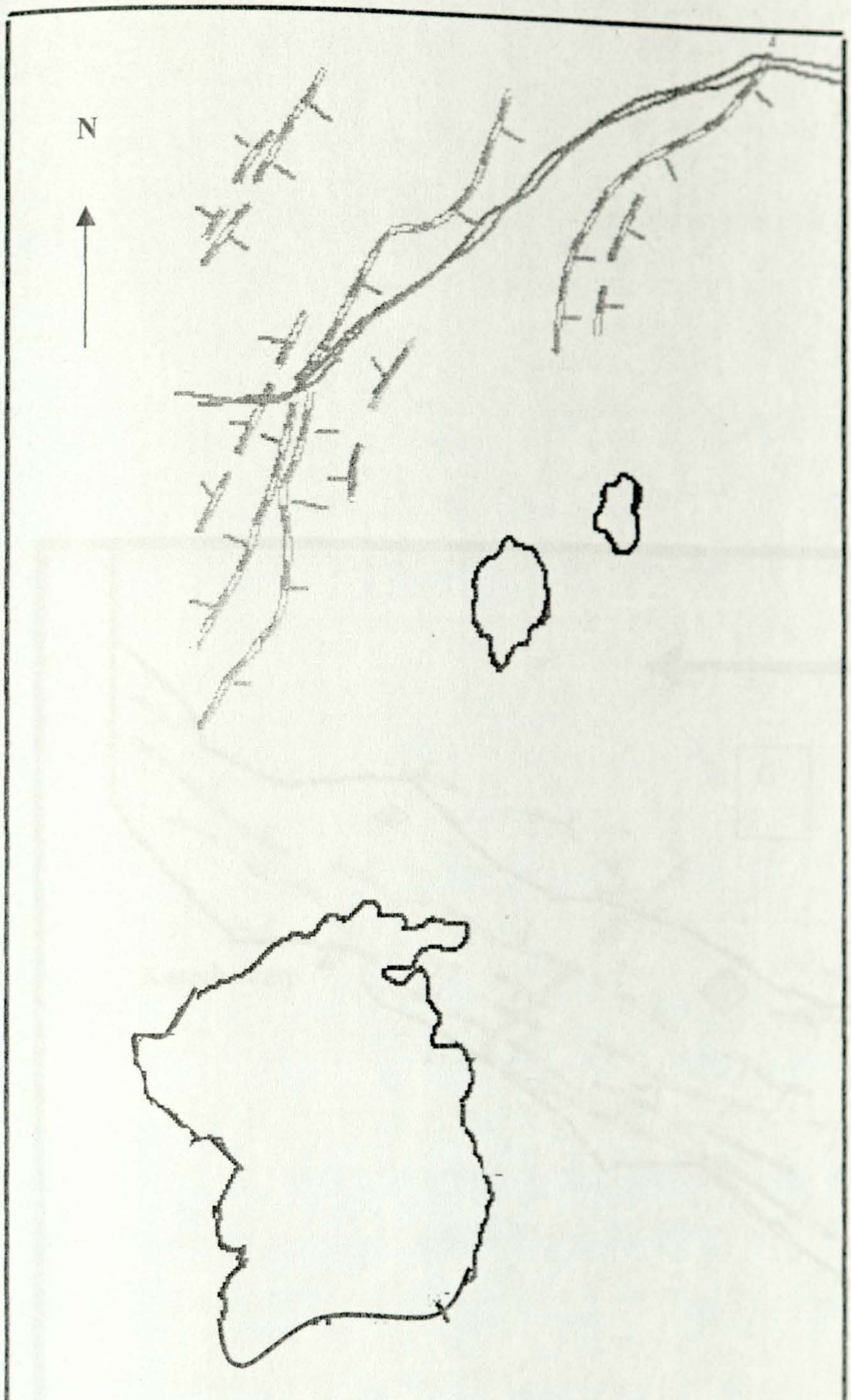


Fig.22 The Minjar area faults and aligned felsic centres extracted from Fig.15(MAF) . All are developed within the Balchi group.Legends are the same as fig.15 except black boundaries represent felsic centres within the Balchi group.Barbs show to the

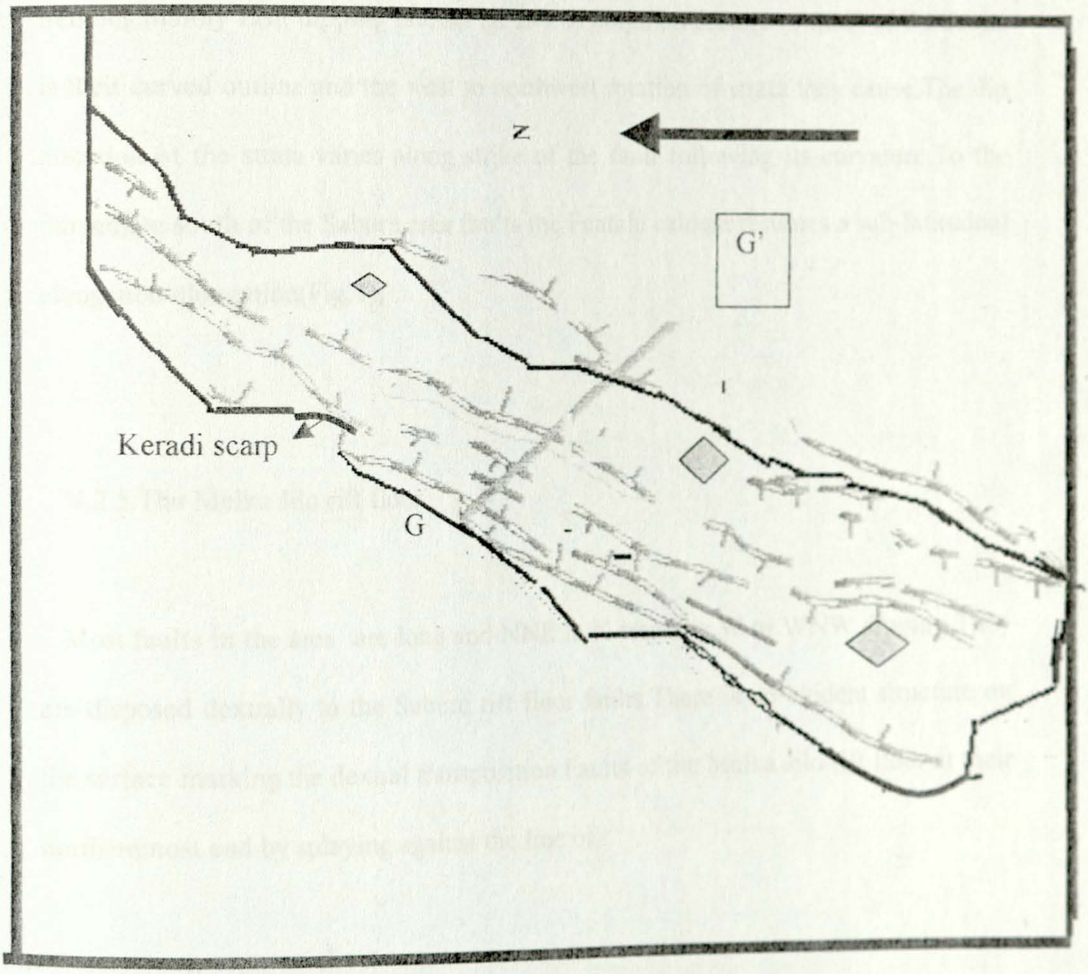


Fig.23 The Melka jilo faults extracted from fig.15.(**MAF**) .Legends are the same as Fig.15. The black boundary separates the Keradi basalts from other volcanics. Legends are the same as fig.15.Barbs show to the downthrown side.

4.2.4.Sabure area

The Western part is flanked by the Kessem border fault. In this area the fault is continous and attains maximum displacement of 100 m. It swiches from convex- to concave- facing the rift along strike. Consequently,its orientation also swiches between NNE and N trends.The structure crosses the Kessem river and embays a system of intricate faults at the rift floor.

The rift floor in this area is dissected by a dense system of N to NNE trending,mainly ESE dipping faults(Fig. 24). A common feature to most of the faults is their curved outline and the west to northwest rotation of strata they cause.The dip direction of the strata varies along strike of the fault following its curvature.To the immediate south of the Sabure area faults the Fentale caldera resumes a sub-latitudnal elongation elongation(Fig.1).

4.2.5.The Melka Jilo rift floor

Most faults in the area are long and NNE to N-trending,W to WNW dipping.They are disposed dextrally to the Subure rift floor faults.There is no evident structure on the surface marking the dextral transposition.Faults of the Melka Jilo rift floor at their northernmost end by splaying against the line of

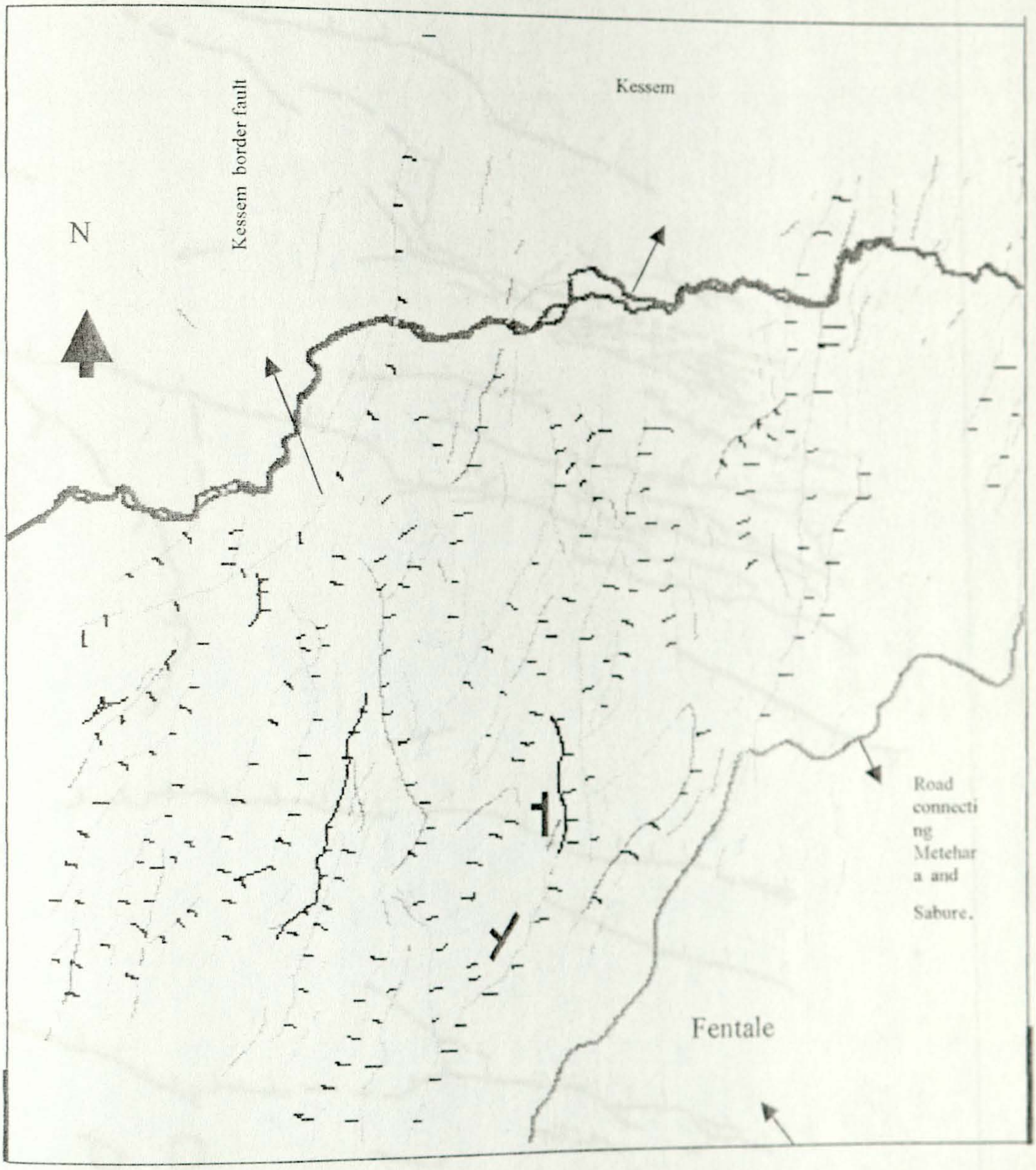


Fig.24 .Showing geometry of faults in the Sabure area.Lines with barbs are normal faults , barbs indicating to the downthrown side.Other lines without barbs are small scale normal faults.The location is indicated in fig.15.(SAR). ⊥,dip direction of strata.

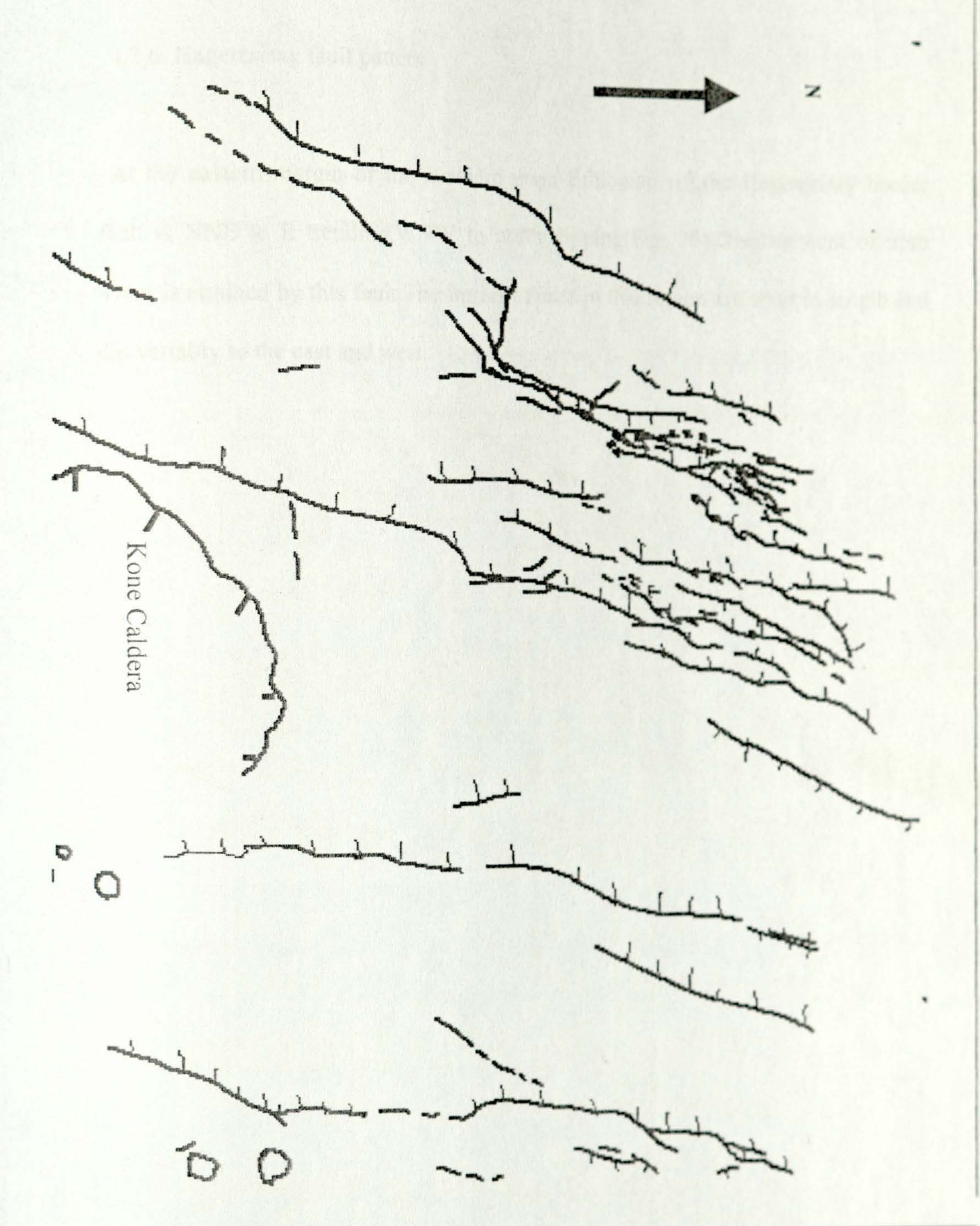


Fig.25 Melka Jilo rift floor faults.(MRFF) of Fig.15.Lines with barbs are normal faults.Other lines are small scale faults.Circular patterns at the eastern end are cones.

disposition.The Kone Caldera is found within this fault system and the caldera's western rim is breached by a N-S trending fault(fig. 25).The original geometry of the caldera seems circular.

4.2.6. Hageresisay fault pattern

At the eastern margin of the northern main Ethiopian rift,the Hageresisay border fault is NNE to E trending,WNW to north dipping(Fig. 26).Displacement of upto 400m is attained by this fault.The intrarift faults in this region are short in length and dip variably to the east and west.

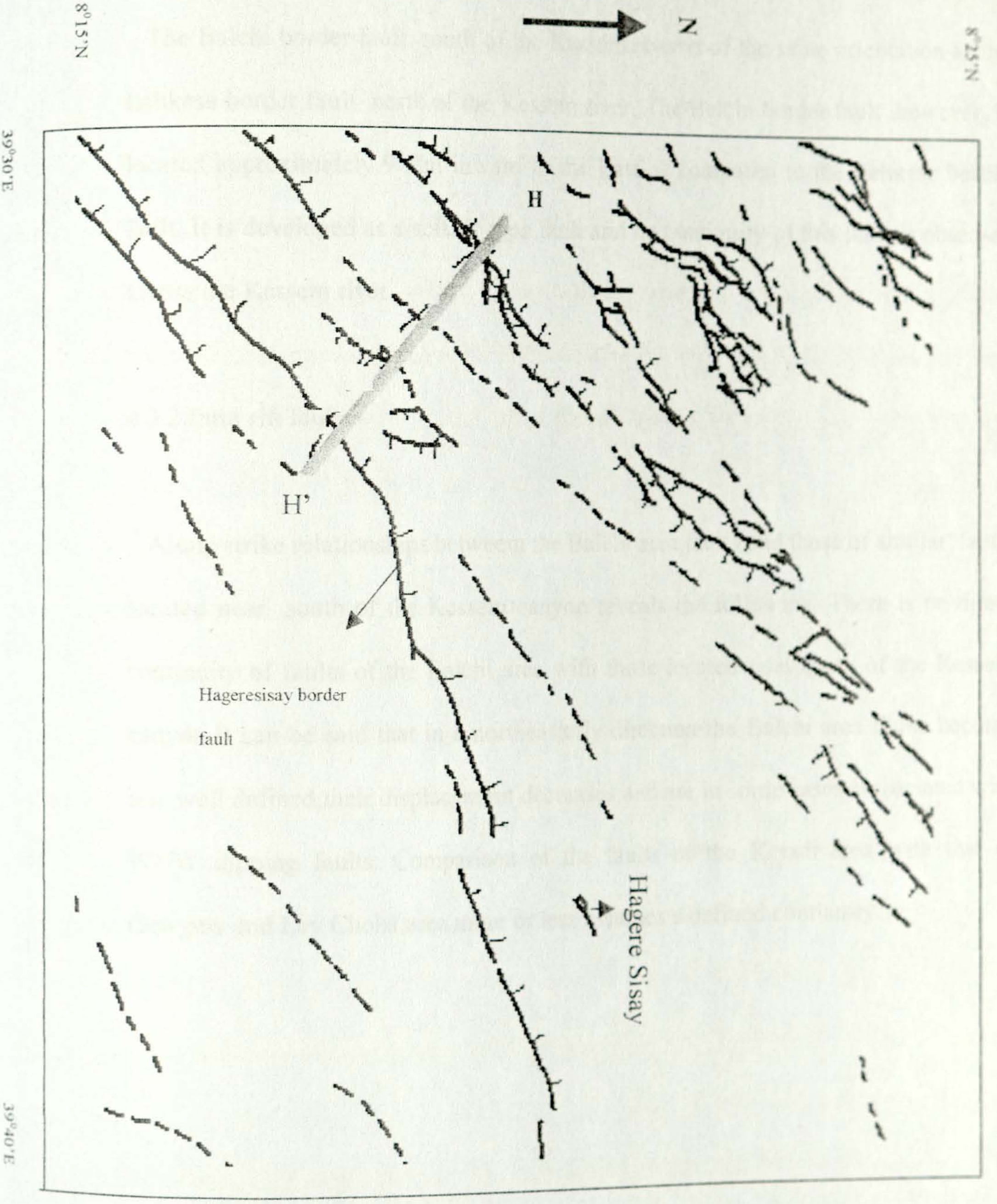


Fig. 26.Fault patterns at the eastern margin of the Northern main Ethiopian rift.Lines with barbs indicate to the downthrown side.Other lines are small scale faults.

4.3.Along strike Tectonic aspects

4.3.1.Border faults

The Balchi border fault south of the Kessem river is of the same orientation as the Ilehkese border fault north of the Kessem river. The Balchi border fault ,however, is located approximately 9 Km inward to the East as compared to the Ilehkese border fault. It is developed as a scissor type fault and no continuity of this fault is observed across the Kessem river.

4.3.2.Intra rift faults

Along strike relationships betweem the Balchi area faults and those of similar faults located near south of the Kessem canyon reveals the following. There is no direct continuity of faults of the Balchi area with those located near south of the Kessem canyon.It can be said that in a northeasterly direction the Balchi area faults become less well defined,their displacement decreases and are in some cases asssociated with WNW dipping faults. Comparison of the faults of the Keradi area with that of Gewgew and Lay Choba area more or less assumes a defined continuity.

The NNE trending,ESE dipping itrarift faults as a whole do not cross the Kessem river except some exceptions.The area north of the Kessem river is characterized by west dipping,NE-NNE -trending faults.

4.4.Across strike tectonic aspects

4.4.1.Section A-A'(Fig. 21,Fig 15)

The Bulga basalts are at the base of this section(fig. 27). As seen in the cross-section the units are tilted to the WNW and ESE by N 25 E to N 35 E striking normal fault. The basalts account for 60% and the felsic unit(Ignimbrites and ash) 40% by volume of this unit. The unit as a whole is more than 200m thick..

Unconformably overlying the Bulga Basalts, the Balchi group dip very gently to the ESE.The valley filling ignimbrite flanks the section to the north(Fig. 21). The deposit is continous and undisterbed by any tectonic movement.

A tectonically coeval unit to the north of the Kessem river is scoria cones and associated basalts(shown in the x-section)(Fig 15,Fig.21). This unit immediately north of the Kessem assume a typical cone geometry where lava flows normally from the centre undisturbed by any tectonic phase.

The WNW dipping faults are the first to be developed and affect the 10 Ma Bulga basalts and rotate strata to the ESE. Therefore, the WNW dipping faults were active after the deposition of the Bulga basalts(aproximately 10 Ma) and are the first to be developed. The ESE -dipping faults are on the other hand seen to cross-cut the WNW -dipping faults and were active during(because sometims in the field the Balchi group thickens toward the ESE-dipping faults) and after the emplacement of the Balchi group (6.6Ma-3.5 Ma).Where the two fault systems with opposite dips interact, the Bulga basalt strata dip decreases.

All fault activity in this area ceases before the valley filling ignimbrite and the scoria cone were deposited. The Lay Choba horst in the ESE extreme is bounded by the Kessem border fault.This fault has a displacement of approximately 400 m. To the extreme WNW of the section there is a WNW dipping fault.This WNW dipping fault upon projection to the north fall on the Metehbila fault which is the only WNW dipping fault that has the greatest length in the area(fig.19).This fault has been named the Metehbila fault.

4.4.2. Section B-B'(Fig 15,Fig. 19)

The older volcanics,the Bulga basalts, are tilted to the SE by N50E striking faults.Unconformably overlying the Bulga basalts in the footwall to the Metehbila fault, are the Balchi group where in some cases show growth faults into the WNW dipping faults.In the hanging wall of the Metehbila fault, there is a thick sequence of the Balchi group.The village of Metehbila is found on this group. The top of this sequence is dated at 6.6 Ma. Unconformably underlying this

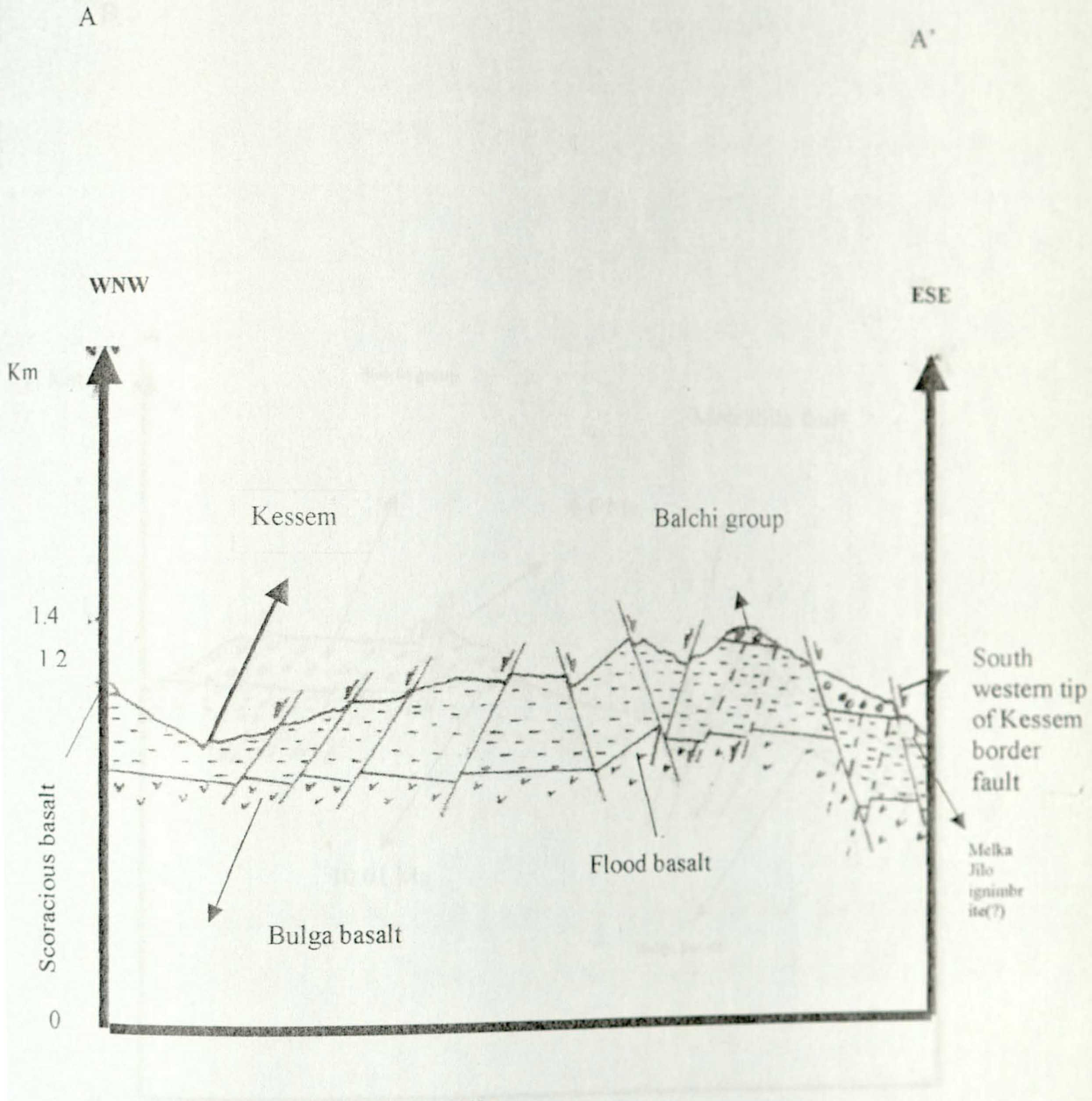


Fig27 . X- section south of Kessem river in the Metehbila region.See text for description.

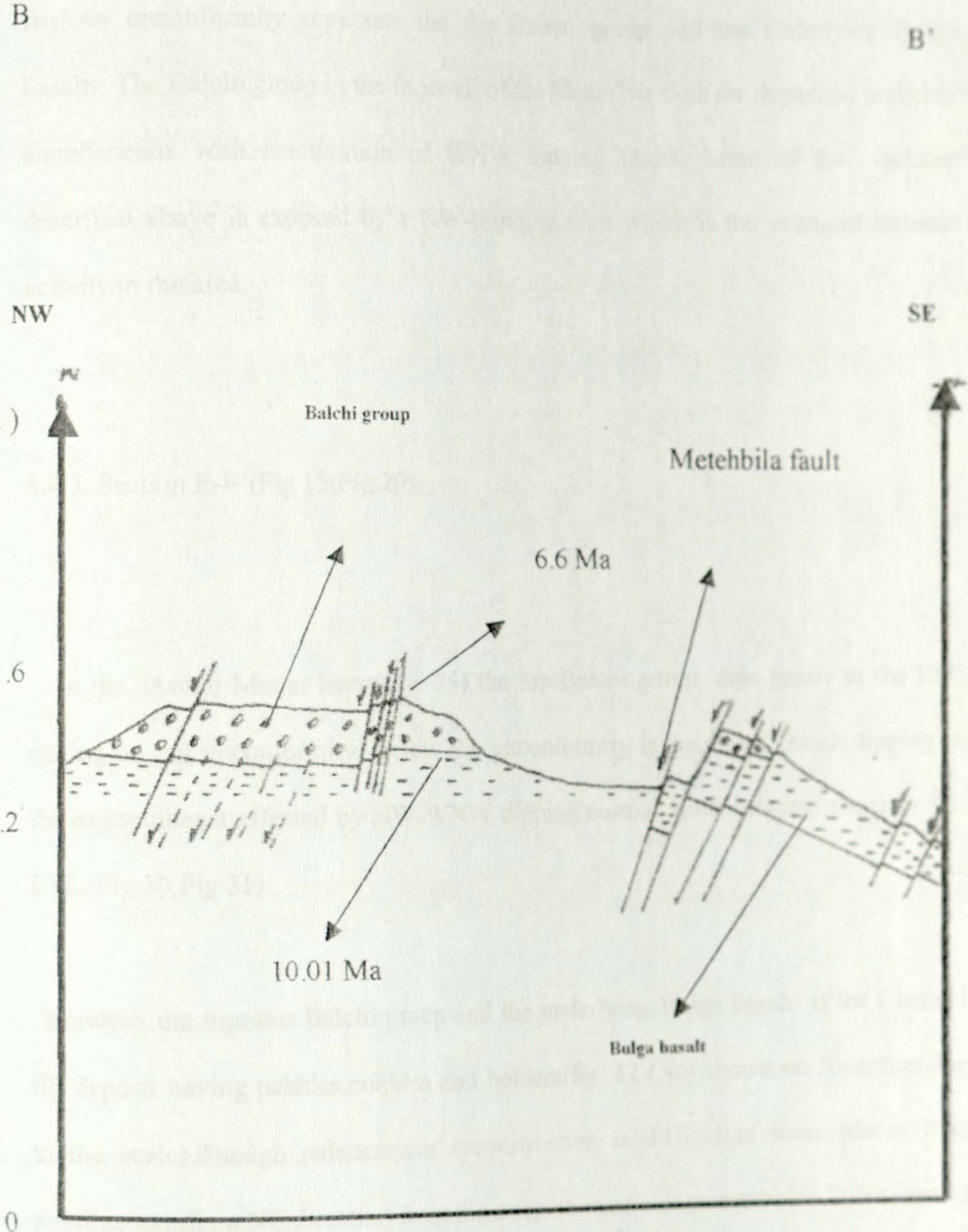


Fig.28 X- section in the vicinity of Metehbila.See text for description.

0 1km

group,the Bulga basalts are tilted to the SE.An ignimbrite from this volcanics has yielded an age of 10 Ma(fig. 28).

Volcano-tectonic relationships here suggest that the WNW dipping faults developed first.An unconformity separates the the Balchi group and the underlying Bulga basalts. The Balchi group in the footwall of the Metehbila fault are deposited probably simultaneous with reactivation of WNW dipping faults. Some of the outcrop described above is exposed by a NW-trending fault which is the youngest tectonic activity in the area.

4.4.3. Section E-E'(Fig 15,Fig.20)

In the Aroge Minjar horst(Fig. 29) the top Balchi group dips gently to the ESE resting on an unconformity. Below the unconformity is the Bulga Basalt dipping to the eastsoutheast affected by NW-WNW dipping normal faults rotating strata to SE-ESE.(Fig 30,Fig 31).

Between the topmost Balchi group and the underlying Bulga basalt is the Channel fill deposit having pebbles,cobbles and bolders(fig. 32)(Not shown on X-section due to the scale).Though paleocurrent reconstruction is difficult,at some places it is possible to infer a NE-direction from the orientation of elongate pebbles.Tributaries of the Kessem such as Wila Wila must have had elevations

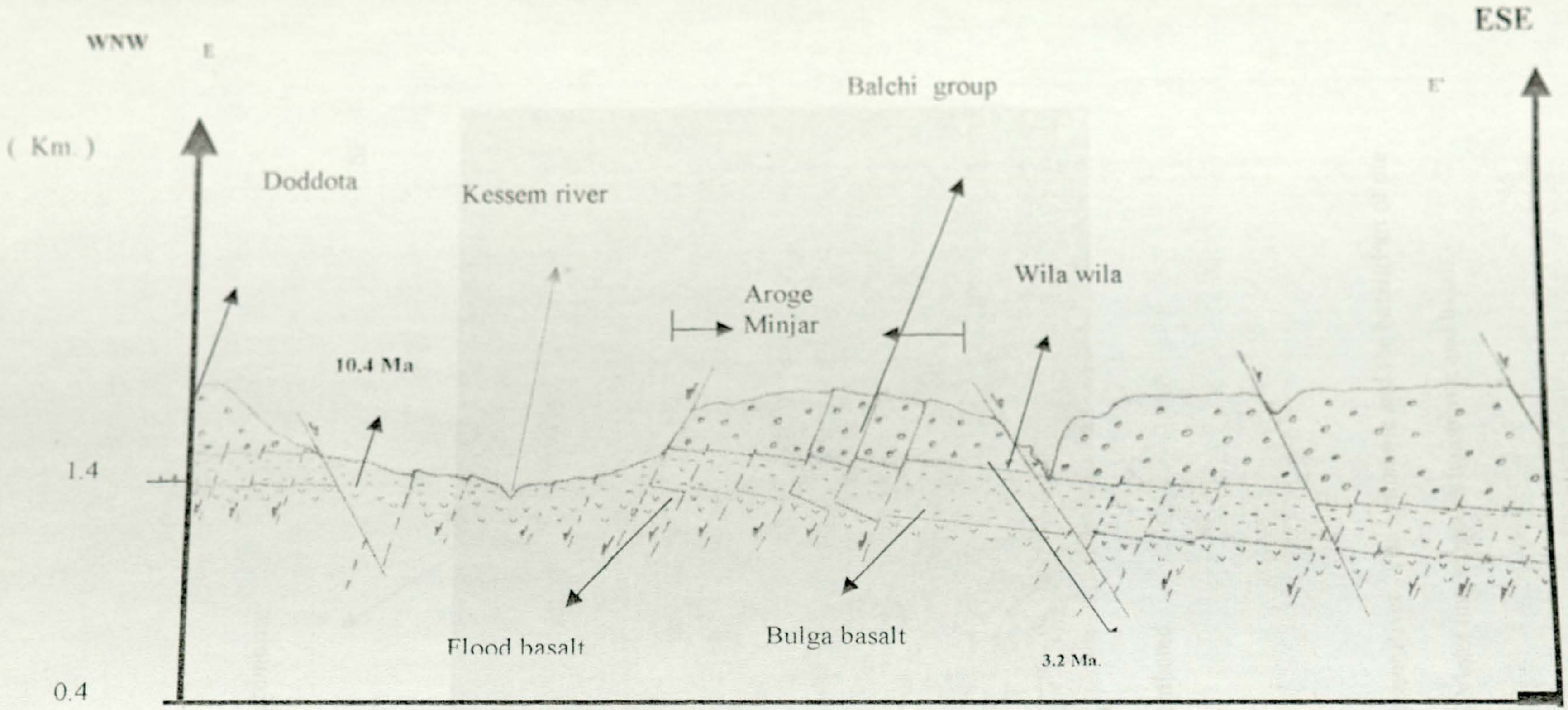


Fig.29 X- section within the northern main Ethiopian rift across the Kessem river. See text for description.

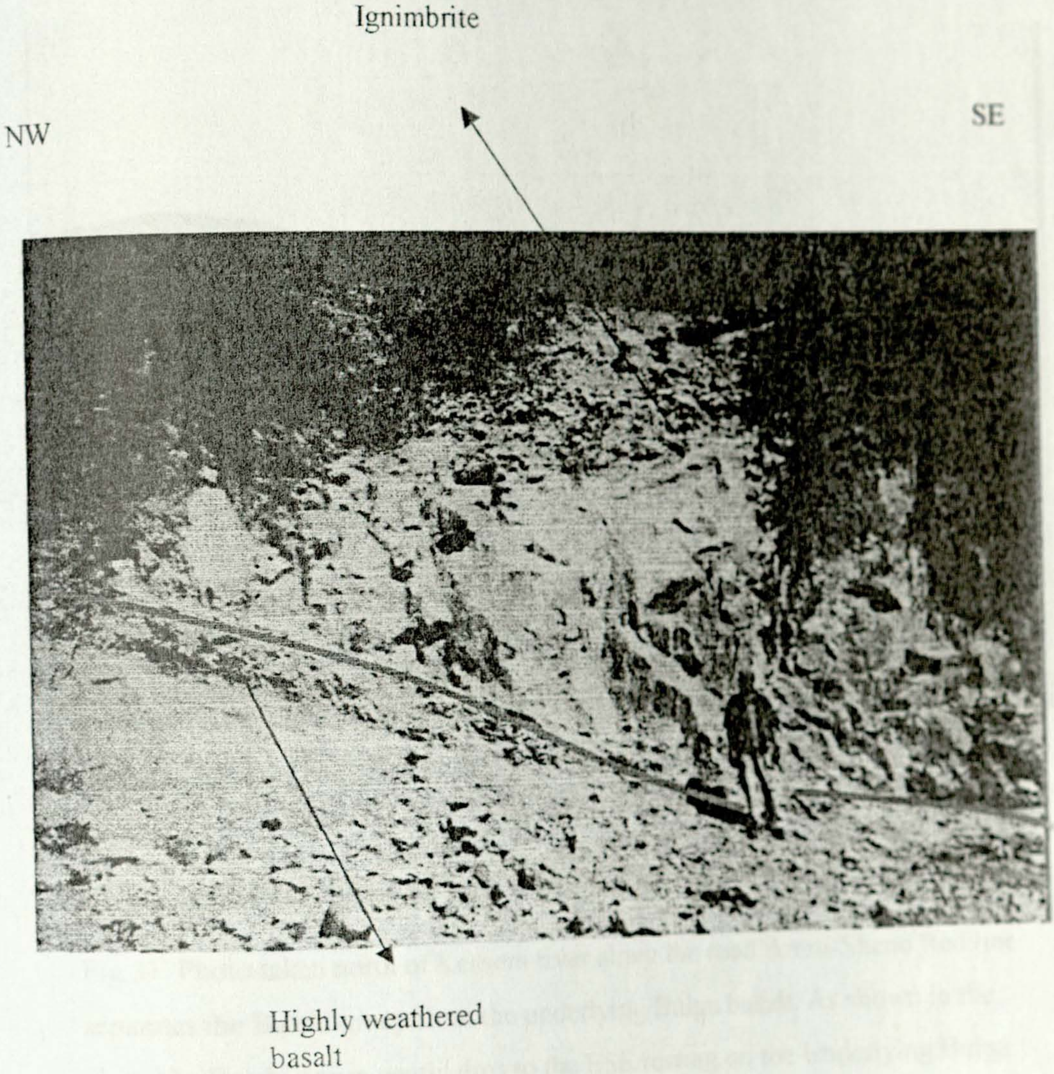


Fig.30 Photo north of Kessem River . The Ignimbrite and the basalt(Part of the Bulga basalt) dip to the SE.Violet line separates Ignimbrite and basalt.

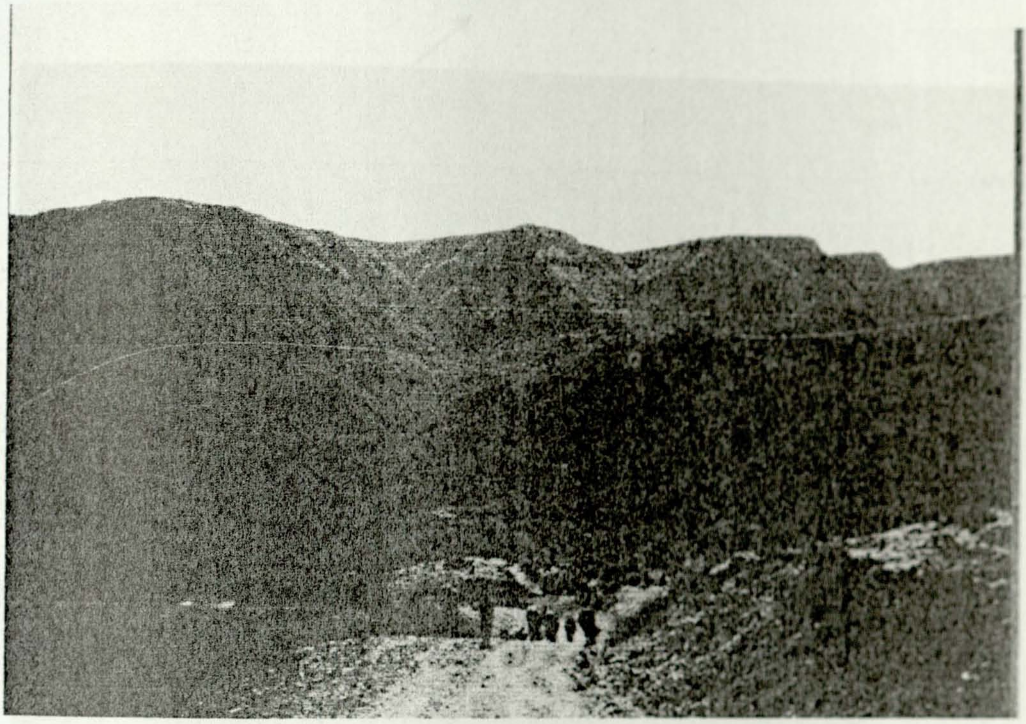


Fig.31 Photo taken north of Kessem river along the road Arerti-Sheno.Red line separates the Balchi group from the underlying Bulga basalt. As shown in the photo the Balchi group gently dips to the ESE resting on the Underlying Bulga basalt.

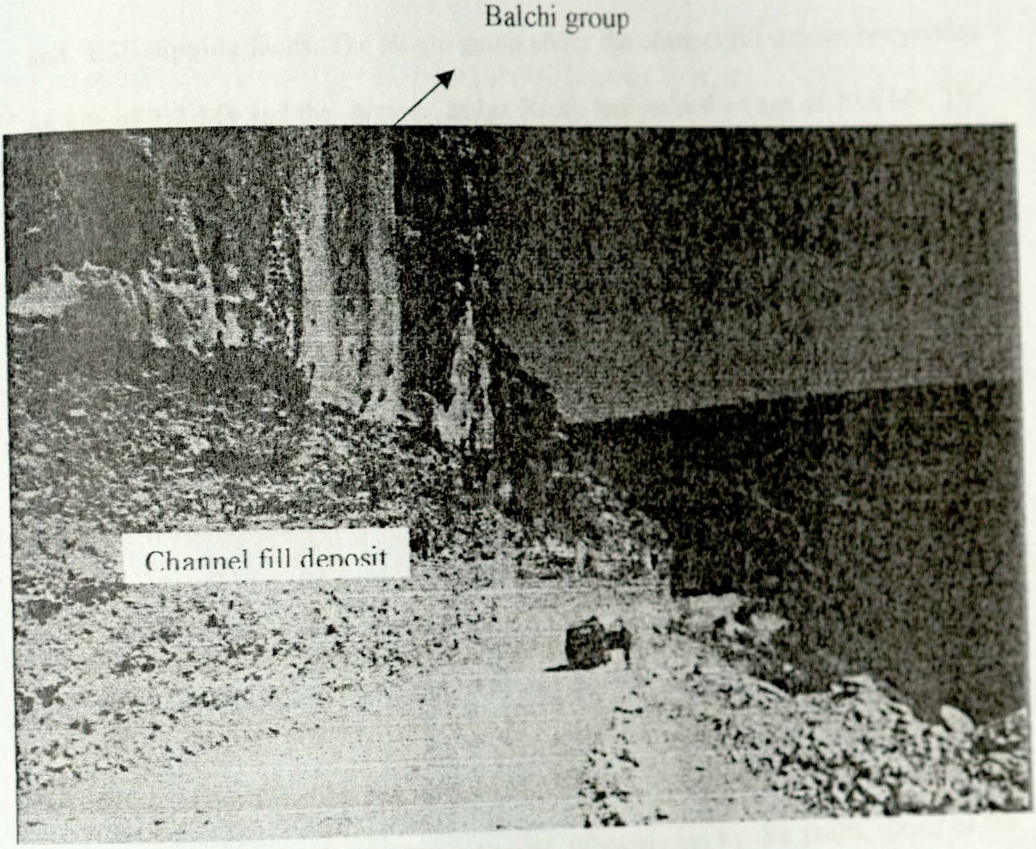


Fig.32 Photo taken south of Kessem.The Balchi group overlies the channel fill deposit.The later indicates the previous elevation of Wila-Wila(The tributary of Kessem).

upto the present day channel fill deposit before they cut through the Bulga Basalt at the bottom to reach the present level.

The Aroge Minjar Horst is flanked by two NNE-trending normal faults, by WNW and ESE dipping faults. The Balchi group above the channel fill deposit has yielded an age of 3.2 Ma and the bottom Bulga Basalt has yielded an age of 10.6 Ma. The ignimbrite belonging to the Balchi group has clasts from the channel fill deposit testifying that the deposition of the ignimbrite has taken place before the channel fill deposit is consolidated.It can be said ,therefore, that Wila-Wila has cut an approximately 60m(in the area where the x-section is taken)to 100m(north of the section) thick sequence of the Bulga basalt in the past 3.2 Ma.This is in fact assisted by a NNE-trending,ESE-dipping faults.

The topmost Balchi group at Aroge Minjar horst is affected by small scale NNE-trending , WNW dipping faults with small displacements.These faults are resulted from the reactivation(Because they have increased the tilt of the Bulga basalt) of the first faults that affected the Bulga basalts. Wherever,cut by this faults, tilting of the Bulga basalts increases.The Balchi group is also shown exposed in the section WNW across the Kessem river.

The Volcanotectonic relationships suggest that NE to NNE-trending ,NW to WNW dipping faults developed first after deposition of the Bulga Basalts(Approximately 10 Ma).These normal faults have rotated strata of the Bulga Basalts. Then NNE-trending, ESE dipping faults developed,after 3.2 Ma. The last tectonic activity is reactivation of the first tectonic phase and has resulted in increasing the tilt of the Bulga Basalt.

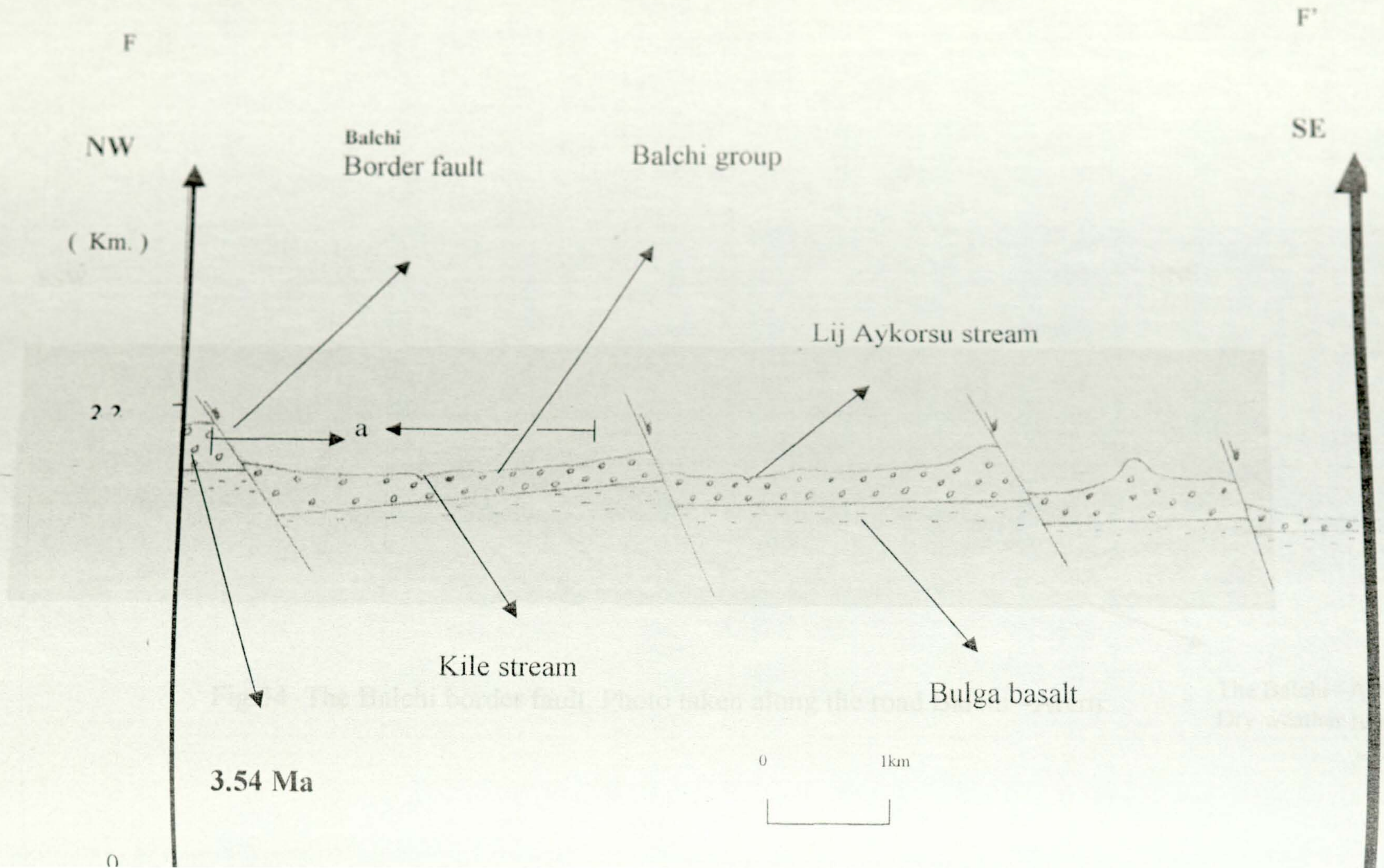
4.4.4.Section F-F'(Fig 15)

In the section(Fig. 33) four faults and four blocks are shown. Fault 1 is the Balchi border fault.All the faults are NNE-trending , ESE dipping.Fault 1 exposes basalts and felsic volcanics(Ignimbrites,ashes and rhyolites) all belonging to the Balchi group.As outlined before ,the Balchi border fault marks the boundary of the Northern main Ethiopian rift(Fig. 34).

As described before, further NW the Shenkora Yohannes gorge exposes a sequence of Bulga Basalts overlain by the Balchi Group. The Balchi group exposed at this place thickens to the SE. Further SE,along the Shenkora Yohannes river, there is a silicic centre(Mt. Bokan) which might be a source for the Balchi group volcanic products.

Block 'a' gently dips to the NW whereas the other blocks are flat.An approximate projection to the NE- across the Kessem river also reveal NW- tilted strata cut by NNE- trending and ESE dipping faults in the Ilehkese area. Approximate NNE projections of faults 2,3 and 4 to the NNE fall along the border of the blocks of Adama and Aroge Minjar near the Kessem river.

Presence of felsic centers along the Balchi border fault suggest that it has developed by 3.5 Ma(Fig.6).



X-section at the western margin of the northern main Ethiopian rift. See text for description.

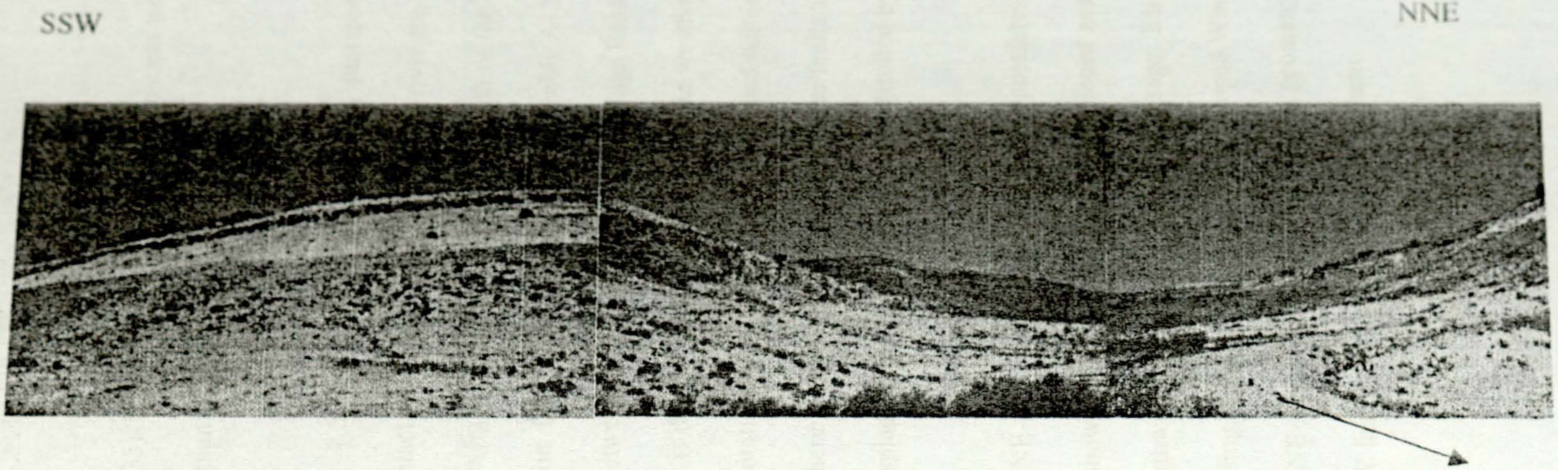


Fig.34 The Balchi border fault. Photo taken along the road Balchi –Arerti.

The Balchi –Arerti
Dry weather road

4.4.5. Section C-C'(Fig. 15,Fig.18)

Section C-C'(fig. 35) is the key area where the volcano-tectonic history of the Northern Main Ethiopian Rift can be investigated.

The approximately 1.5 Km thick flood basalt is juxtaposed with the Bulga basalts.From this contact to the bottom of the Kessem river the Bulga basalts have a widerspread coverage(fig. 15). Immediately to the South of the Kessem canyon, The Balchi group rests on the Bulga Basalts unconformably.A NE- oriented faulted contact is inferred between the flood basalts and the Bulga Basalts. Near the peak,the Ilehkese border fault is developed rotating stratas to the westnorthwest.NE-trending, NW- dipping faults rotating strata to the SE are developed within the Bulga basalts to the SE of the peak where these basalts are exposed.These faults are short in length and have mostly small displacements. Some streams are controlled by these faults.

Development of NNE-trending,ESE dipping faults postdates the aforementioned tectonic activity.As shown in the section they are developed near the peak and rotate strata to the westnorthwest.They have a limited coverage. Elsewhere in the Bulga Basalts, the NE-trending,NW -dipping faults are developed.Where the two system of faults interact ,the NNE- trending ones assume curved geometry(fig. 18). The latter also cross-cut NE-SW faults and are continous across them.

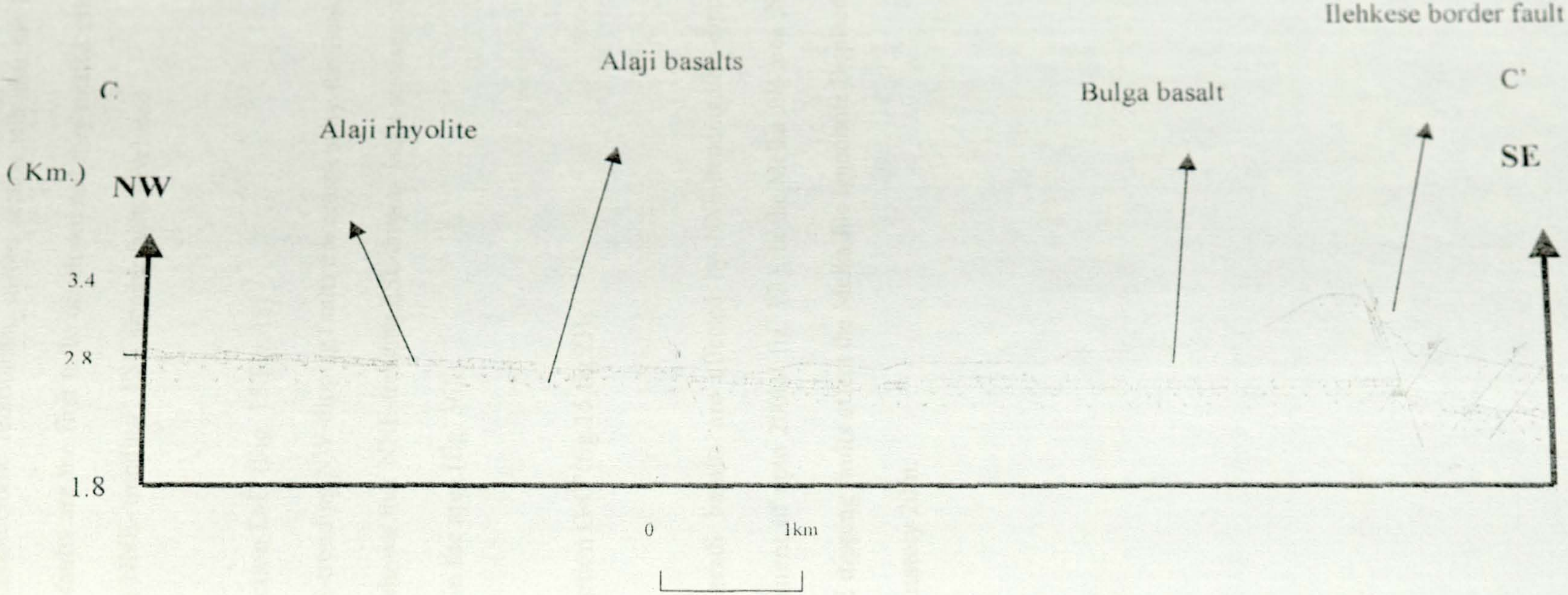


Fig.35 X- section constructed from the plateau to where the northern main Ethiopian rift starts.See text for description.

The volcanotectonic relationship in this section tells that the NE- trending , NW-dipping faults are the first to be developed and they rotated strata to the Southeast . Then the NNE- trending , ESE dipping faults developed.

4.4.6.Section D-D'(Fig. 15.Fig. 18)

The NE-trending,NW-dipping faults are cross-cut by the Ilehkese border fault.The section shows that NNE-trending,ESE-dipping faults represent the youngest tectonic activity in the area.(fig. 36).

4.4.7.Section G-G'(fig.15,fig.23)

The Keradi basalts are affected by NNE-trending,ESE-dipping faults having a displacement of upto 200m(fig. 37). In the Melka Jilo area ,NNE-trending, WNW and ESE dipping faults affect the Melka Jilo Ignimbrite.Displacement on this faults is approximately 20m.

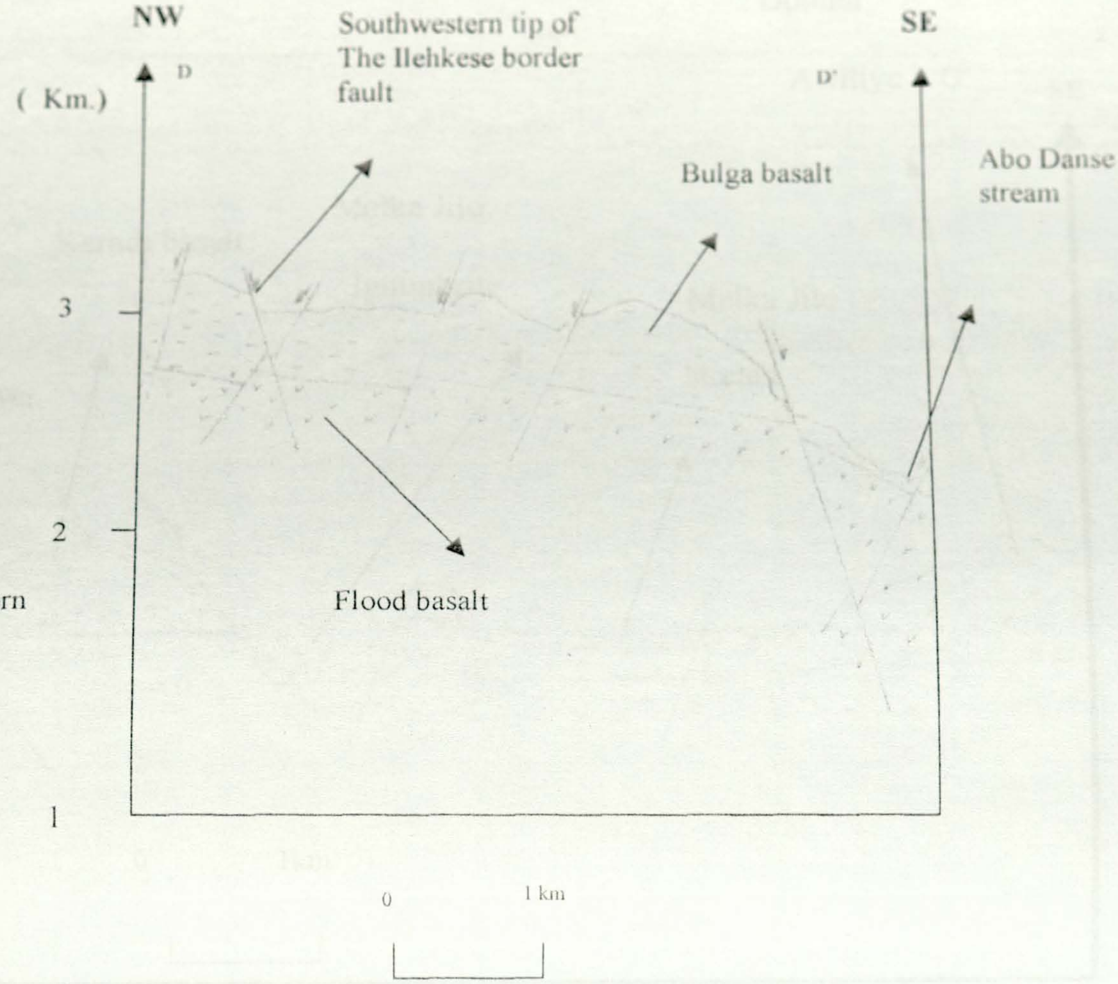


Fig.36 X- section at the western margin of the northern main Ethiopian rift.See text for description.

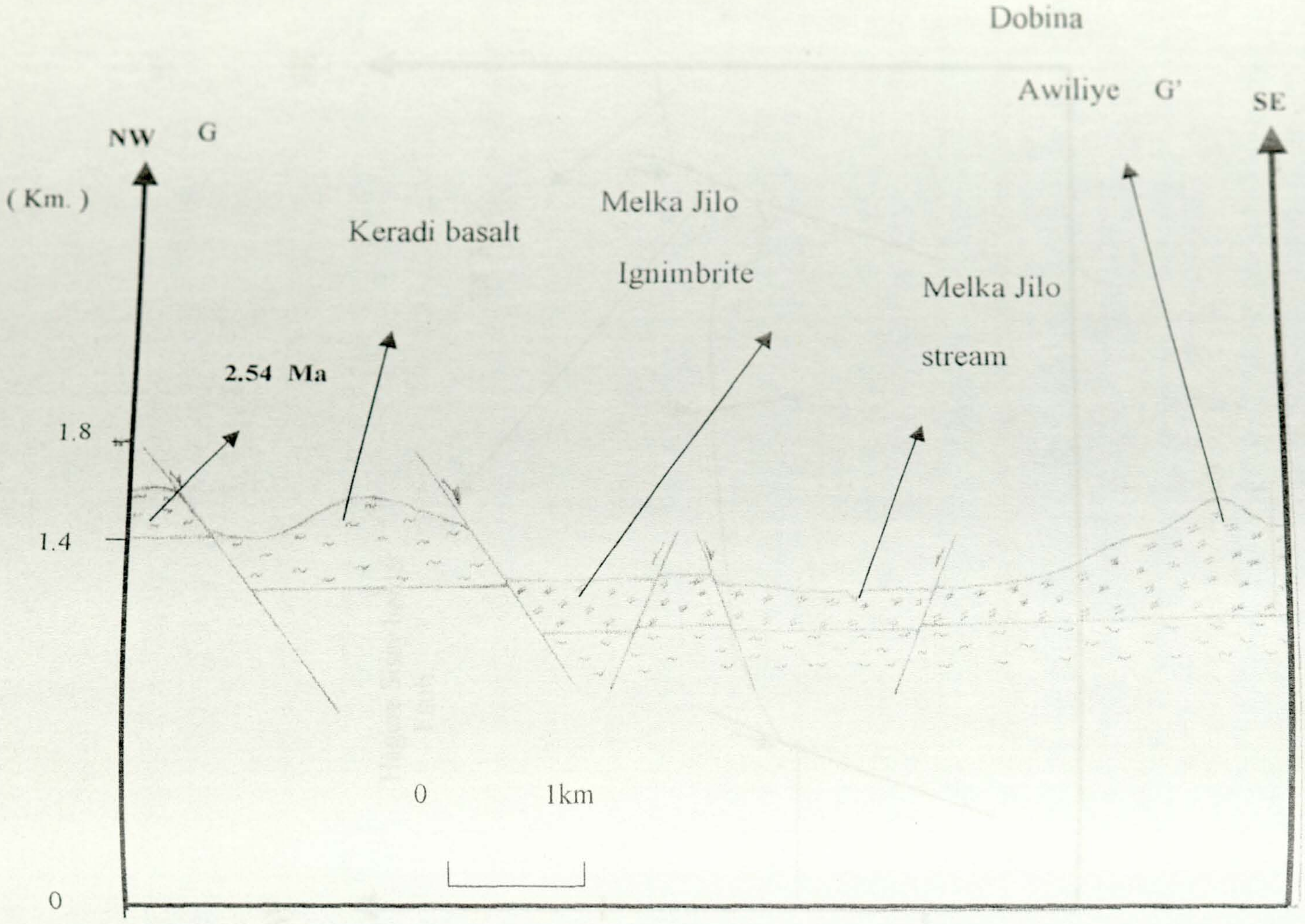


Fig.37 X-section in the floor of the northern main Ethiopian rift.See text for description.

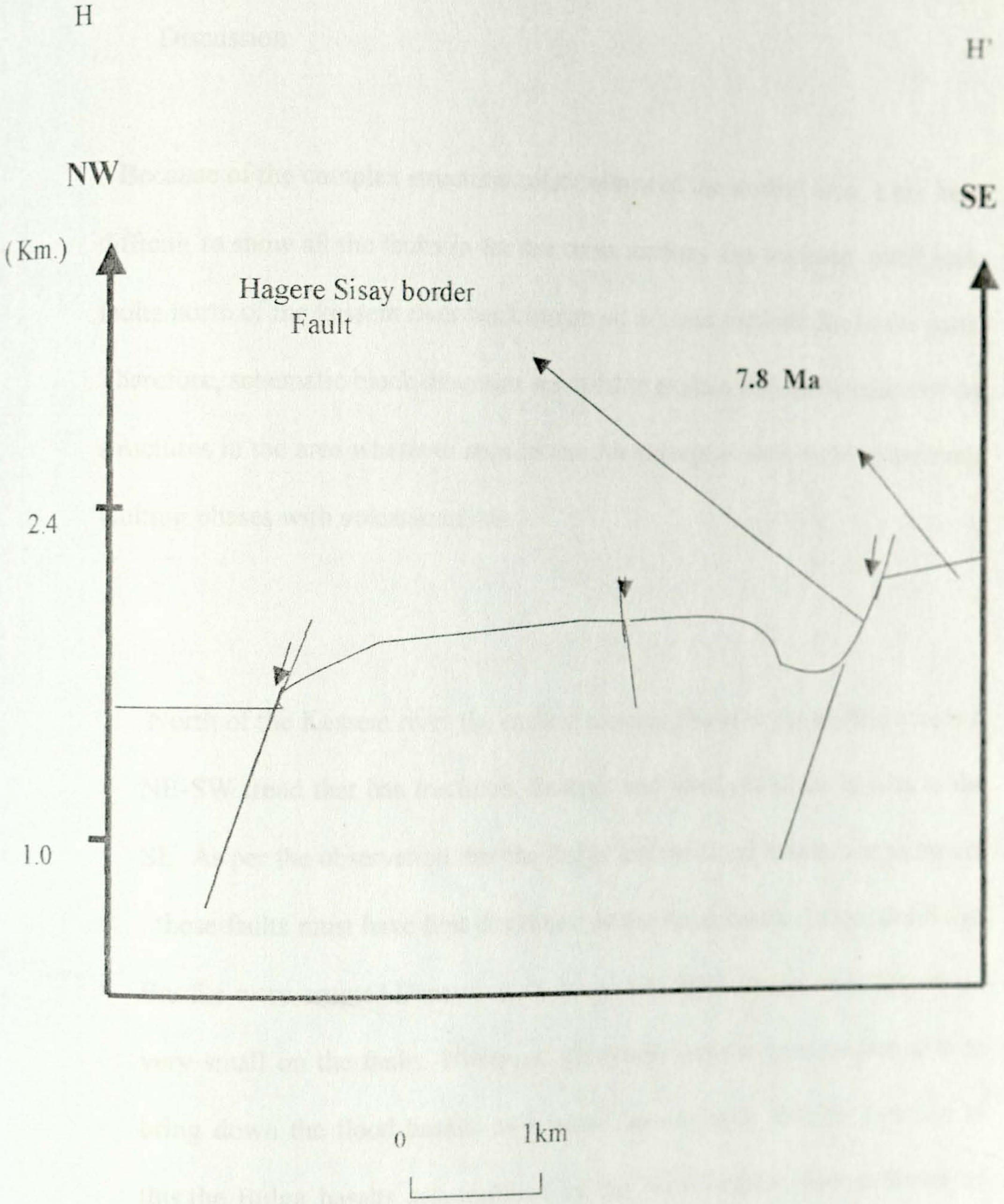


Fig.38 X- section at the eastern margin of the northern main Ethiopian rift.See fig. 26. The section shows the Hageresisay border fault at the eastern margin of the northern main Ethiopian rift is developed after 7 Ma.

CHATER 5

Discussion

Because of the complex structural relationships of the studied area, it has been difficult to show all the faults in the the cross sections. For instance, small scale faults north of the kessem river can't be shown in cross sections due to the scale. Therefore, schematic block diagrams are used to explain the relationships of the structures in the area wherever appropriate.An attempt is also made to associate faulting phases with volcanic units.

North of the Kessem river the earliest tectonic phase in the studied area is a NE-SW trend that has fractured, faulted and tilted the flood basalts to the SE. As per the observation that the Bulga and the flood basalts are juxtapsed , these faults must have first developed in the flood basalts before the Bulga Basalts were erupted.Density of faulting and displacement must have been very small on the faults. However, the whole tectonic process was able to bring down the flood basalts as a broad 'monoclined' feature. Because of this,the Bulga basalts are confined by the flood basalts. Any evidence of earlier faulting and tectonic phase in the flood basalts is attested in some deep gorges of the flood basalts seen as a 'monocline' steepening to the rift and along NE-SW directed tributaries of the Kessem. This less defined tectonic phase becomes more pronounced near the Ilhekese border Fault.

SE-of the Ilehkese border fault the Bulga basalts are affected by a NE-trending, NW dipping faults which gently rotate strata to the southeast. This is also evident in the Kessem canyon within the rift.

However, the above mentioned faulting isn't the only characterstic of the area north of Kessem.The Bulga Basalts are also in some places affected by later NNE-treading, ESE- dipping faults of small displacements. This second tectonic phase has altered the original dips of the Bulga basalts. This is to mean that when already southeasterly dipping layers are cut by these tectonic phase their dips obviously decreases by opposite rotation. Hence, the cutting of the previously titled Bulga basalts by later NNE, ESE-dipping faults has created variations in dip angles.NNE-trending,ESE-dipping faults of significant displacement are found south of the Kessem river.

The Balchi area faults,faults of the Aroge Minjar,Adama-Dire Michael,Lay Choba and the Minjar fault system all developed after the Balchi group was deposited.Most of the Melka Jilo faults developed after the emplacement of the Keradi basalts.All of these faults are NNE-trending,ESE-dipping nearly all of them with significant displacement found south of the Kessem river.

Volcanotectonic Evolution

Pre-tertiary rocks overlain by Tertiary basalt are found in the Eastern and Western Afar margin, western margin of the central MER, Amaro Horst in southern Ethiopia and the broad rifted southwestern Ethiopian rift(Barberi et al.,1977;Ebinger et al.,1993;Ebinger et al.,2000 and Woldegebriel et al.,1990).

In the studied area(western marigin of the Northern main Ethiopian rift) the base of the flood basalts is not exposed. If the discovery of Francaviglia (1940) is true , the existence of Mesozoic sediments beneath the flood basalts might ensure that doming may have preceded volcanism and rifting in this region.Similar observation is documented in the central sector of the main Ethiopian rift.(Woldegebriel et al.,1990)

The flood basalts of the studied region have been affected earlier by a not too pronounced tectonic phase. This tectonic phase have developed approximately after the flood basalts were deposited. There is no evidence that the rift had existed before the deposition of the flood basalts. The earlier tectonic phase of the flood basalts has resulted later confinement of the Bulga Basalts by the Flood basalts(fig. 39). It is not known whether the contact between the Bulga and the Flood Basalts is tectonic or not.Confinement of Miocene Volcanics by Oligocene flows is also documented in the central sector of the Main Ethiopian rift older alternating polarity faults (Woldegebriel et. al, 1990).

After the deposition of the Bulga basalts at around 10 Ma, numerous NE-treading, NW dipping faults began to act. This tectonic phase has titled the Bulga Basalts to the southeast before the beginning of the deposition of the Balchi group at around 6.6 Ma at the present south of the Kessem river. On the Bulga basalts, after the youngest plagioclase-rich basalts were erupted, the Ilehkese border fault developed(fig.40).The Anchar basalts of kazmin et. al., (1980) and Cherenet et. al, (1998 and 1999) are pre-rift. However, according to the present study the time correlative unit to the Anchar basalt,the Bulga basalt, is syn-rift.

The Balchi group is probably issued from the Bokan felsic center. The deposition, thickest at the center has extended northeast as far as Doddota, Gobensae, Akirmit Burka and Metehbila areas in the present north of the Kessem river and onlapped on the SE tilted Bulga Basalts(fig. 41).The Balchi fault scarp has already developed by 3.5 Ma and other intra-rift faults in the Balchi area developed at around 3 Ma.Tributaries of Kessem such as Wila-Wila and the Kessem river in the nearby areas begin to downcut at around 3Ma . Later intensive erosion removed the Balchi group north of the Kessem except some pockets presently found at Koste, Gobensae, Akirmit , Burka and Metehbila area(fig.42,Fig. 43,fig. 44).

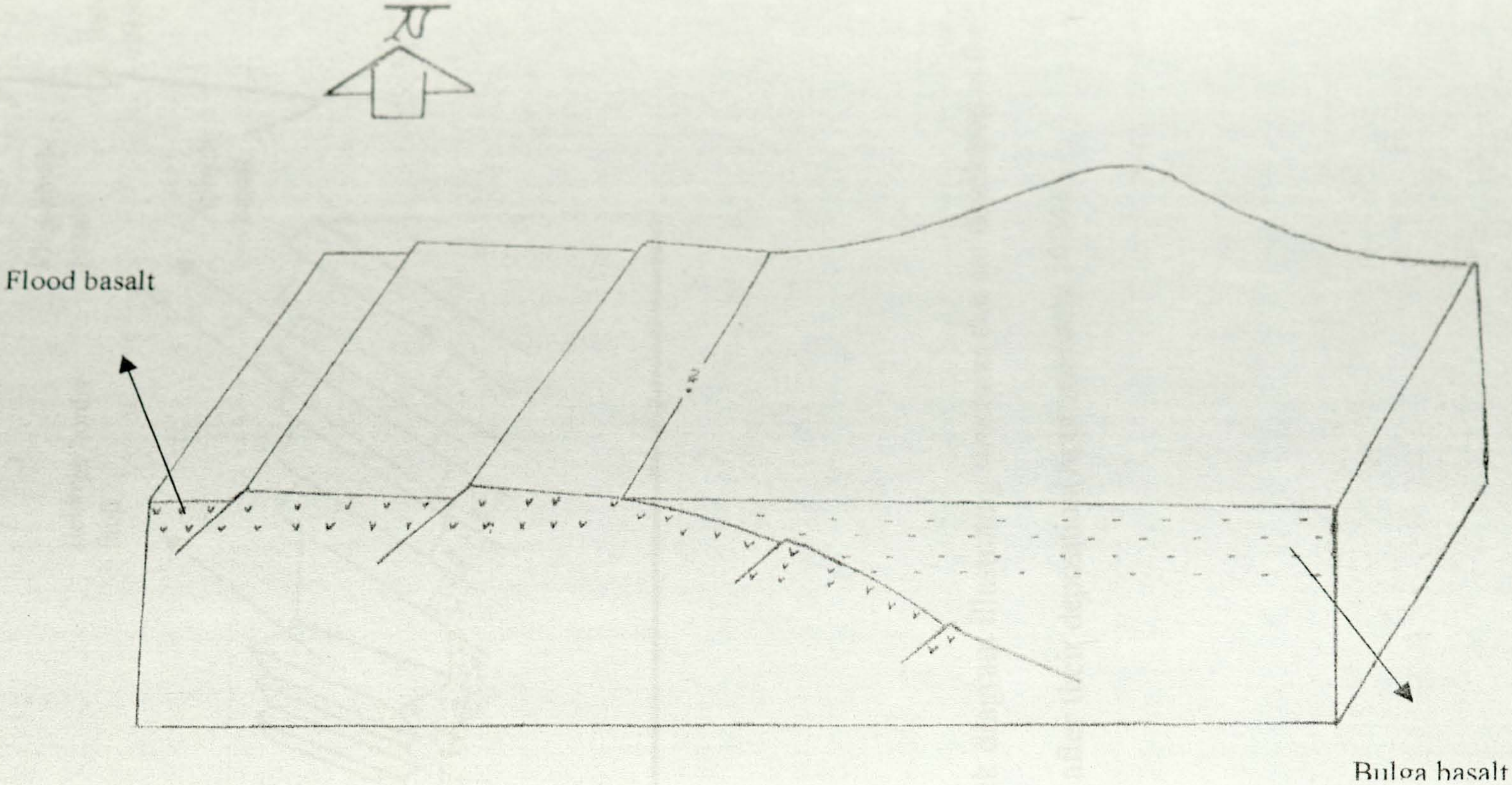
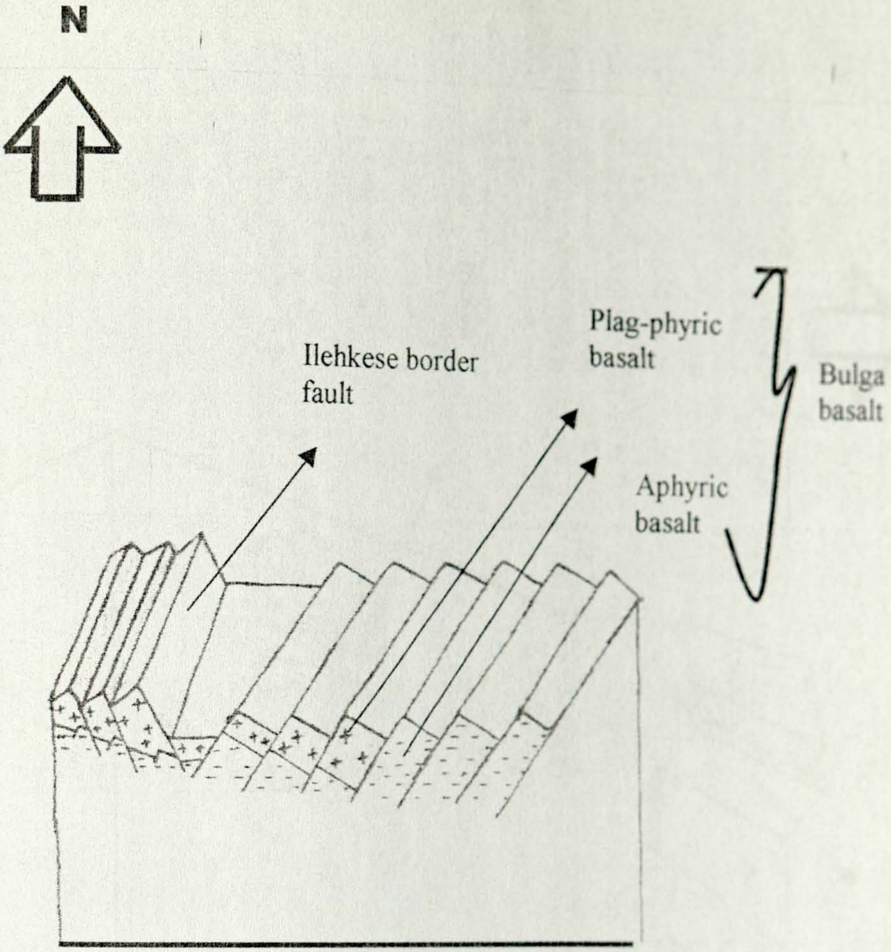


Fig.39 Block diagram illustrating the western margin of the northern main Ethiopian rift between roughly 26 Ma and 10 Ma. See text for description.



ig.40 Block diagram illustrating structures that are developed in the

ulga basalt after their deposition(Approximately 10 Ma.)

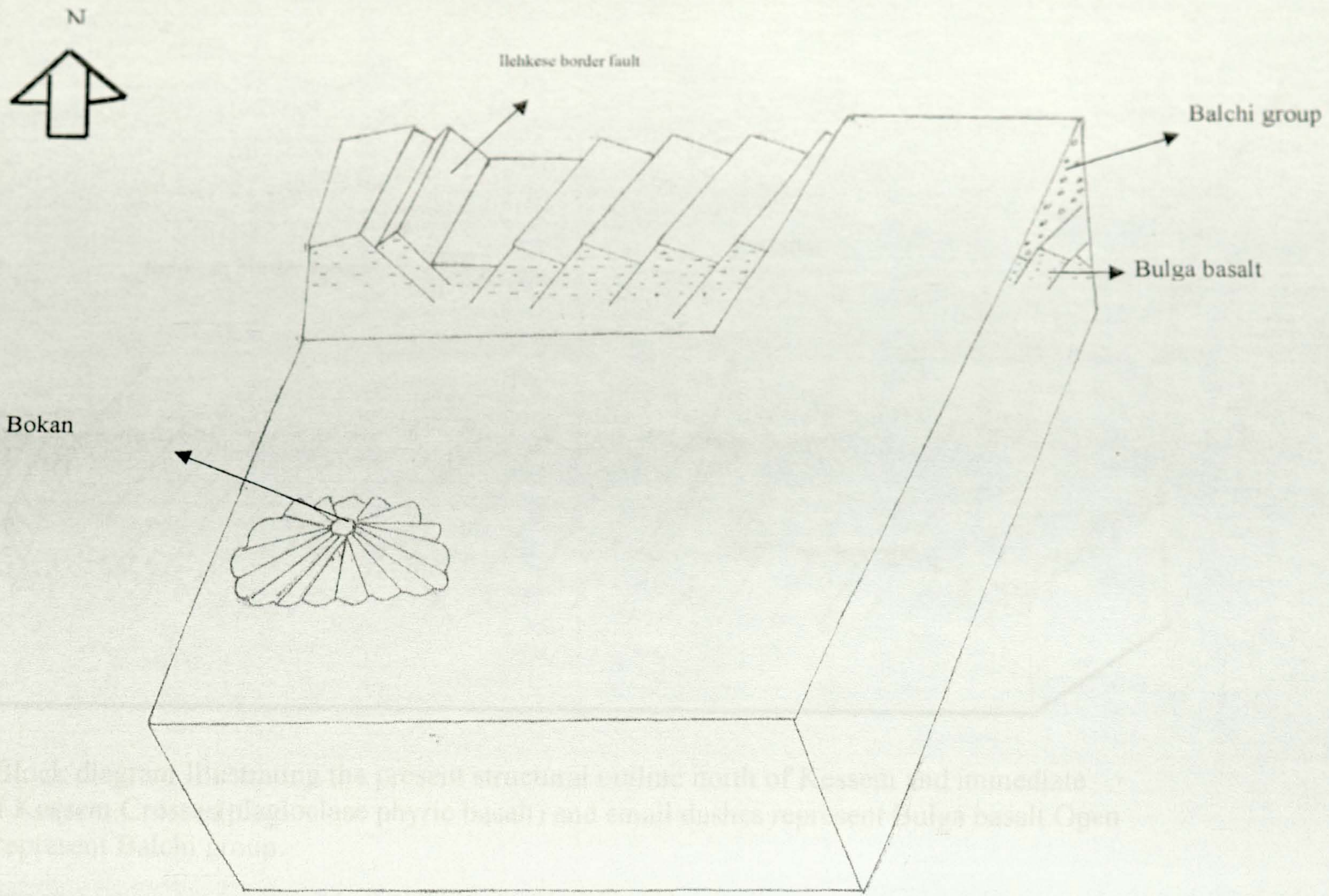


Fig 4.2 Block diagram illustrating the present structural outline north of Kessem and immediate south of Kessem Cross (plagioclase phyric basalt) and small dashes represent Bulga basalt Open circles represent Balchi group.

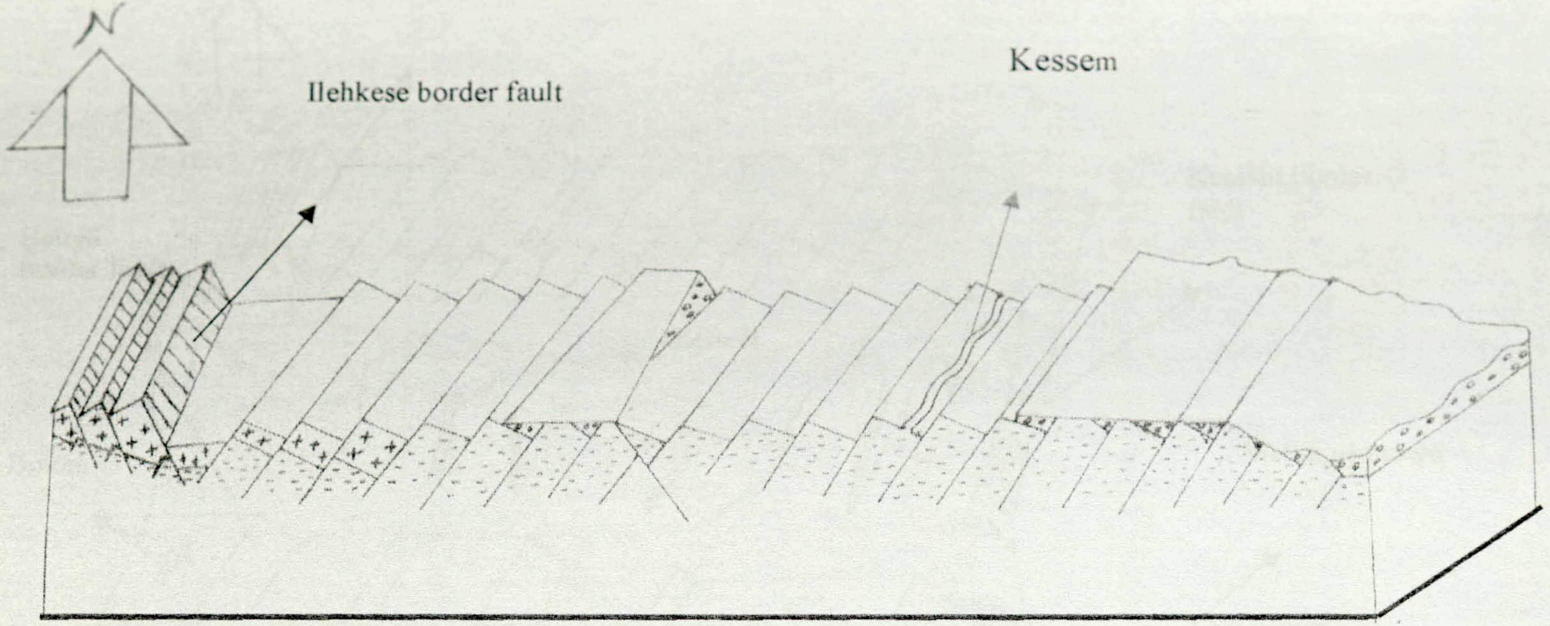


Fig.42 Block diagram Illustrating the present structural outline north of Kessem and immediate south of Kessem.Crosses(plagioclase phyric basalt) and small dashes represent Bulga basalt.Open circles represent Balchi group.

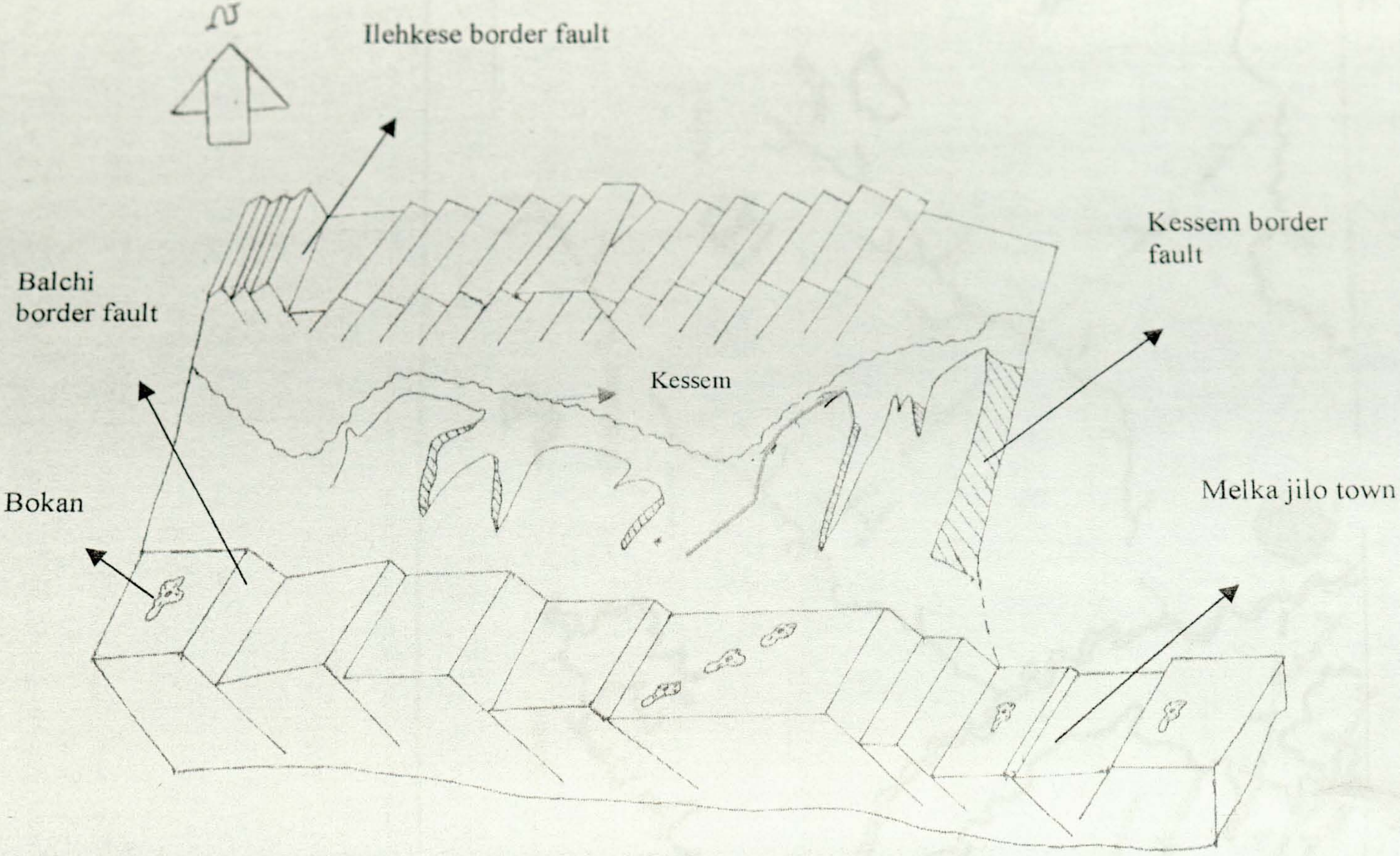


Fig43. Block diagram illustrating present western part of the Northern main Ethiopian rift.Only prominent structures are shown for simplicity.See text for description.

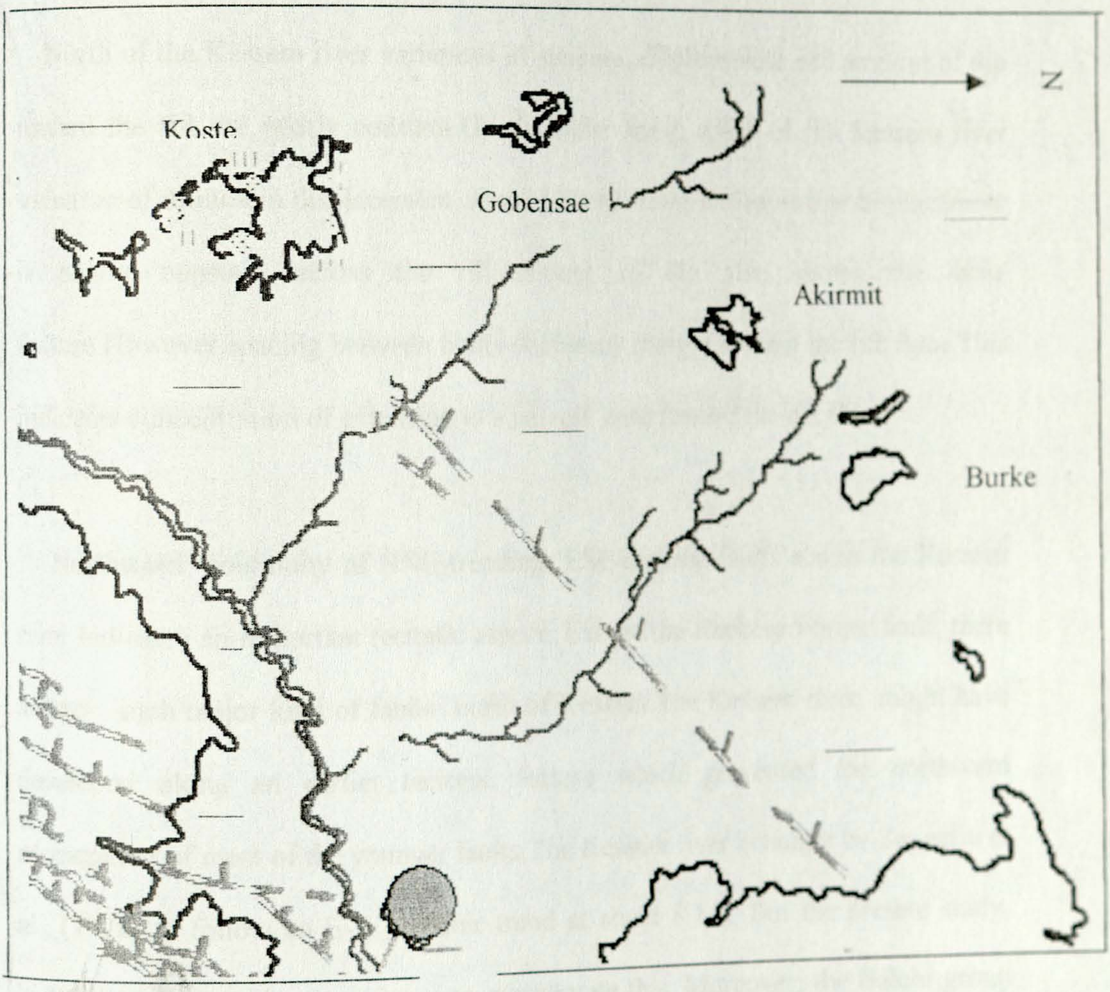


Fig. 44 showing alignment of pockets of the Balchi group north of the Kessem river s extracted from fig.15(APBG). Legends are the same as fig.15,barbs show to downthrown side.

Volcanism and faulting migrated toward the rift as evidenced by younger flows of the Keradi basalts. In the Southern Kessem, this younger faulting after 2.5 Ma is characterized by development of longer and large displacement NNE- treading, ESE dipping faults and some short, small displacement WNW dipping faults in between them. The last tectonic phase(WNW dipping fault) is probably due to reactivation of a former tectonic phase and is responsible for some horst like features flanking the Southern Kessem canyon as Aroge Minjar(fig. 43).

North of the Kessem river variations of spacing, displacement and amount of dip toward the rift are nearly constant.On the other hand, south of the Kessem river variation of minimum displacement toward the rift floor indicates that displacement is nearly constant across the rift.Amount of dip also shows the same feature.However,spacing between faults decreases sharply toward the rift floor.This indicates concentration of extension in a narrow zone toward the rift floor.

Northward continuity of NNE-trending, ESE-dipping faults across the Kessem river indicates an important tectonic aspect. Except the Ilhekese border fault, there are no such major kind of faults north of Kessem.The Kessem river might have developed along an earlier tectonic feature which prevented the northward propagation of most of the younger faults.The Kessem river is taught by Zannetin et al., (1978) to follow an E-W tectonic trend at about 8 Ma. But the present study, indicates that there is no evidence to corroborate this. Moreover, the Balchi group which began to be deposited at 6.6 Ma is observed across the Kessem river further north.However, some segments of the Kessem river follow an East-West line.If this is due to a structural control in the past , a roughly bracketed age of 6 Ma and 3 Ma for its development is suggested.An East-West transversal structure named Yerer-Tuluwellel further west of the Kessem and a rift in rift structure further East of the Kessem lie about the same latitude(Approximately 9^0 N) where the Kessem follows an East -West trend(Abebe et al.,1995;Chernet et al.,1998).

From 1.8Ma to the present there appears to be concentration of younger volcanotectonic activity on the rift floor comprising silicic centers.This belt has been named the Wonji fault belt(Mohr et al.,1983).The Melka Jilo floor and Sabure area faults described in the previous chapter fall within this group.Though given a common name(Wonji fault belt) ,there are significant geometric differences between the Sabure area and the Melka Jilo floor faults.These faults also fall within the Nazret magmatic segments(Melka Jilo floor faults) and Sabure magmatic segments(Sabure area faults) identified recently in the Main Ethiopian rift(Ebinger et al.,2001).

The curvature of the Minjar faults, the WNW-ESE flow direction among a different alternating courses taken by the Kessem,the WNW-ESE deflection of horst like features(Aroge-Minjar and Adama-Dire Michael) where the Keseem takes a WNW-ESE direction of flow and the dextral sense of shear exhibited at the southwestern tip of the Kessem border fault all suggest a dextral sense of shear.This might be the effect of a WNW-ESE structure that is responsible for disposing the Quaternary Wonji Fault Belt in this area.Within the Yerer-Tuluwellel there are also sinous faults where the same sense of shear can be inferred.(Abebe et al.,1995).

In the Central Sector of the MER, faulting on the floor of the northern part of the sector is progressively younger toward the margins (Woldegebrial et. al., 1990). In the Norhern Main Ethiopia rift, faulting becomes progressively younger toward the axis.

In the central sector of MER, rifting has been proposed to have begun with an alternating polarity rifting at the Oligocene-Miocene to a symmetrical rifting by Pliocene time (Woldegberial et. al, 1990). In the Western margin of the Northern main Ethiopian rift a pronounced rifting phase has taken place during the Miocene time as evidenced by the development of the Ilehkese border fault.Between 7 and 2 Ma the eastern margin has developed.The Balchi border fault formed slightly inward from the Ilehkese border fault south of the Kessem river.This later tectonic phase has established the initiation of the present rift architecture at the western margin.

Another important question to raise is the structural evolution in the northern main Ethiopian rift related to magmatic influence.

In considering magmatism , there is the Bulga basalts and the Bokan centre which are equivalents in terms of along strike postions but within significant different ages. The Ilehhkese border fault is developed after the eruption of the Bulga Basalts and the Balchi border fault after the Bokan felsic centre. Moreover, the Balchi border fault is found East of the Bokan felsic centre. In the Minjar area closely spaced faults of the Keradi group are found east of the alighned Felsic centers of the Minjar area.

So, at least in the Balchi to Melka jilo area it can be said that probably magmatic activity has disrupted pre-existing fault planes causing strain hardening and shifting of faulting (similar displacement) toward the East. This is especially evident from alignment of felsic centers in the Minjar area which probably seal pre-existing weakness planes. In Kenya migration of faults with high displacement and amount of dip toward the East is also reported (Morley et al.,1992). However, the mechanism for this cause is suggested to be rotation of pre-existing fabric into less prefered orientation thereby causing strain hardening. There is no evidence found in the Northern main Ethiopia rift to support such a suggestion.

The concentration of closely spaced faults also coincides with the abundance of Keradi basalts. This might indicate the importance of magmatic activity in addition to the far field stress in changing widely spaced faults to a closely spaced ones where the hot weakened crust becomes the preferential site for extension.

Volcanism in the western margin of the Northern Main Ethiopian Rift not only becomes younger toward the rift floor but also an earlier younging of volcanism SSW along the Ilehkese border fault is also observed. Again, magmatism may have been important in shifting the border fault location toward the SSW of the Balchi border fault in addition to possible influence of far field stress fields.

When did the structural evolution of the Western margin of the Northern main Ethiopian rift begin?

The present study indicates that onset of rifting between 10 Ma and 7 Ma is definite as evidenced from the faulted Bulga basalts onlapped by the Balchi group.Hence, the Bulga basalts and the Balchi group are associated with rift initiation.It would be more appropriate to assighn an early syn-rift domain for the Bulga basalts and late syn-rift domain for the Balchi group. Presence of some Plagioclase- phyric basalts on the plateau outside the rift might indicate subsidence rate must have been small during the earlier formation of the rift.

Volcanic rifted margin : Worldwide implication

Volcanic rifted margins are produced where continental breakup is associated with the eruption of flood volcanism during pre-rift and / or syn-rift stages of continental separation(Menzies et al.,2002).The following sections tries to establish the characterstics of one of the volcanic rifted margins worldwide: The western margin of the Northern Main Ethiopian rift.This will be done by comparing and contrasting with other volcanic rifted margins worldwide.

The pre-rift to syn-rift transition is marked by a structural change,in some cases a magmatic hiatus,erosion of newly formed rifted mountain,formation of high velocity lower crust(HVLC) and a seaward dipping reflector series(SDRS) (Menzies et. al.,2002).

In the western marigin of the Northern Main Ethiopian rift the present study highlights the sructural changes during the pre to syn rift stages.The pre-rift flood basalts are characterised by the absence of or less pronounced NE- trending tectonic phase.The early syn-rift Bulga Basalts record an inner SDRS. Simillar inner SDRS are documented as a diagnostic characterstic for volcanic rifted marigins(Menzies et. al.,2002). The other structural change that we find here in the Northern Main Ethiopian Rift is between the early and late syn-rift volcanics. As the late syn-rift volcanics are charactereised by riftward dipping widely spaced faults of the Balchi group which is in marked contrast with the structural styles of the early syn-rift volcanics.

The topmost of the flood basalts of the western marigin of the Northern Main Ethiopian Rift is dated at 26.5 Ma (George ,1997). The bottom of the early syn-rift Bulga basalts is dated at 10.6 Ma (this study) . So, a magmatic hiatus characterises the pre- to syn- rift transition. A magmatic hiatus for the pre- to syn -rift transition is also documented for other volcanic rifted margins(Menzies et. al.,2002).

Additionaly as the early syn-rift volcanics is 10.6 Ma and the late syn-rift volcanics is of 6.6Ma- 3.5 Ma, there exists also a magmatic hiatus between the early and late syn -rift transitional stage.

Passive(Plate driven) and active (Plume-driven) rifting processes are documented for the generation of non- volcanic and volcanic rifted marigins respectively.Plate -driven model requires that rifting be initiated by far field extensional forces followed by surface uplift and magmatism related to upwelling of asthenospheric material.Melts would be generated by shallow decompression melting processes. On the other hand, the plume -driven models require deeper melt generations and interactions with the continental lithosphere. In this case uplift will precede volcanism and rifting.

The presence of thin Mesozoic sedimentary layer beneath the flood basalts in the Northern Main Ethiopian Rift as well as in the central sector of the Main Ethiopian Rift may suggest that uplift has preceded volcanism and rifting in this sectors of the rift.(Woldegebriel et al.,1990 and Francaviglia ,1940).

Pre-rift flood basalts of the studied area appear to be derived from the decompression melting of Pyroxene-rich shallow mantle(Chernet et al.,1999). This is on the side of a passive rifting model.However,little or no tectonic movements have accompanied the flood basalts arguing against decompression melting.Additionaly,the study of peridotite xenoliths favours a model of active rifting in Afar(Roger et al.,1997).A model intermediate between active and passive rifting is suggested(Report on the international symposium flood basalts,rifting and paleoclimates in the Ethiopian rift and Afar depression,presented by Courtillot et al.,1997).

Whereas basaltic volcanism dominates the evolution of the LIP(Large igneus province) , silicic volcanism may have contributed significantly to the total volume of the volcanic pile(Menzies et al.,2002). The flood basalts of the studied area are interbeded with silicic products (Justin -Visentin et al.,1974). LIPs which characterises all volcanic rifted marigins are rarely thicker than 2 Km because they represent the erosional remnant of earlier sequence estimated to have been as much as 2-3 times thicker than present time eruption(Menzies et al.,2002). The pre- rift flood basalts of the studied area are approximately 1.5 km thick in consistence with the worldwide documentation.

The erupted thickness differs from the actual melt thickness , so volcanic rifted marigins must include igneous intrusives added to the continental crust(Menzies et al.,2002).This may be evident as overthickened HVLV. Presence of HVLC (7.4 Km/s) is reported in the northern Main Ethiopian Rift (Berkhemer et. al.,1975)

In majority of the volcanic rifted marigins, basaltic and silicic volcanism occured over a short period of time ranging from 1- 4 Ma(Menzies et al.,2002). The pre- rift flood basalts of the studied area interbeded with silicics have been probably extruded within short period of time(Cherenet et al.,1999 and George 1997).

Silicic volcanism appears early during the main basaltic episode or after the main basaltic eruption in LiP formation. In the studied area silicic volcanism occured after a basaltic volcanism but the whole sequence contains an interbeded silicic and basaltic volcanics(Justin-Visentin et al.,1974).

Reflector packages within the SDRS diverge downward and dip oceanward 20^0 or more. (Menzies et al.,2002). However, in the Northern Main Ethiopian Rift dip angle of 60^0-70^0 is observed. In the Yemen marigin , a significant proportion of the SDRS (at least 50 %) is constituted by a sedimentary nature.This is thought to be due to removal by erosion of basaltic and silicic rocks from the volcanic rifted marigin during syn-rift extension(Menzies et al.,2002). However, in Ethiopia the inner SDRS is constituted by plagioclase-phyric basalt that is highly eroded.This nature of the basalts indicates a shallow level fractionation process after a decompression melting . This is because of synrift extension that causes mantle upwelling.

SDRS typically post date flood basaltic volcanism and the rifted marigin, and their formation may be synchronous with a haitus in magmatism, a change in magmatic source area , and a peak in denudation(Menzies et al.,2002). Also in the Northern Main Ethiopian rift, this suggestion seems to hold true. It is likely that strain localisation and focused extension accelerated melt generation during formation of SDRS(Menzies et al.,2002). Hence, the Balchi group in the Northern Main Ethiopian Rift is indicative of a change in magmatic source area and its extensive nature probably shows an accelerated melting due to focused extension.

he relationship between magmatism and faulting is complex. Magmatism may post- dated rifting as in some of the central Atlantic volcanic rifted marigins , addled the pre-rift to syn-rift transition as in the North Atlantic volcanic rifted ins of the Greenland-UK(Menzies et al.,2002). In the Northern Main Ethiopian magmatism has preceeded rifting. Extension has been initiated after the flood ts were extruded .

nost of the volcanic rifted marigins no kilometer scale mountain range existed to rifting and magmatism . So an important part of the evolution of volcanic d marigin is mountain building and erosion(Menzies et al.,2002). In the tern Marigin of the Northern Main Ethiopian Rift, the Bulga Basalts rise to an ation of approximately 3400m elevation. There is no doubt that their formation lated to evolution of the volcanic rifted marigin.

Chapter 6

An Outline of the Afro-Arabian rift system.

6.1.Overview

The Eastern African rift system is connected to the Red-Sea and Gulf of Aden in Afar.It is,therefore,critical to compare chronology of rifting in the Gulf of Aden,Red Sea,Afar and the Ethiopian rift in order to understand how break up occurs.The Red-Sea at its Northwestern tip joins the gulf of Suez and Dead Sea-Aqaba at Sinai.Following a brief description of each of the rift systems will be given.The descriptions focuses on chronology of rifting,Sea floor spreading and to some extent on segmentation in the Ethiopian rift.

The Dead Sea is a transform fault ,seismically active, and comprises left lateral shear.Two major phases are supposed to take place in the displacement with significant pause.The first took place in the latest Oligocene to early Miocene and the second in the plio-pliestocene time and still is continuing to the present.(Girdler,1990:Girdler 1991).

The gulf of Suez is an extensional graben with little or no crustal extension.Rift movements commenced at the end of the Eocene(about 35M.Y.) and continued to the oligocene with a major unconformity at the beginning of the Miocene.Dykes intrude Mesozoic and Eocene units and terminate at the base of Miocene.Subsidence at 25-15

Ma and 5Ma to the present is observed but there is no igneous activity since the lower Miocene.(Girdler,1991).

Earliest rifting in the gulf of Aden dates back to the Middle/late Eocene.Main sea floor spreading occur in the early Miocene followed by a rejuvenation in the Plio-pliestocene.(Girdler et al.,1990).

Extension in the Red-sea commenced in the Oligocene time.Movements in the Dead Sea rift are responsible for sea floor spreading in the Red-sea rift during Oligocene/early Miocene and Plio-Pliestocene.Only the northern part of the Red-Sea is underlain by oceanic crust.In the southern part continental crust still exists.(Girdler,1991).

From the work of Girdler(1991) major geodynamic changes have occured in Afro-Arabian plate during Oligocene,Miocene and Plio-Pliestocene.The last two are also important in the Ethiopian rift as will be outlined later and probably in the whole of the Eastern African Rift.Basins bigan to form in the Ethiopian Rift during the Miocene.The Plio-Pliestocene time is most important in the formation of symmetrical rifting.

About 30 Ma the area shared by Northern Ethiopia and Yemen was flooded by basalts as a result of the impact of the Afar mantle plume.In less than two million years basalts cover more than 600,000 km2 ,covering Northrn Ethiopia and Western Yemen with 1-2 Km thick traps.(Coulie,2001;Ukstins et al.,2002).

From the onset of the breakup of Arabia and Africa till 20 Ma the Eden rift propagated toward Afar along the Arabia Somalia boundary.Around 18 Ma the Red-Sea rift tip had reached the gulf of Zula.The Danakil and Ali Sabih Aysha blocks must have been detached from the Nubia and Somalia plates,respectively around 20 Ma after which the formation of Afar triangle becomes much more pronounced.At later times the Danakil microblock has rotated countersclockwise facilitating the penetration of the Red-Sea ridge into Afar by jumping westward from its southward propagation.(Report on the international symposium on Flood basalts,Rifting and paleoclimates in the Ethiopian Rift and Afar depression,1997 hereafter abbrevated as FRP report,1997).

Much of the Miocene and Pre-Miocene history of Afar is difficult to study because much of the Afar depression is covered by recent flows.(Barberi et al.,1977). Though we have a poor understanding of the development of the Eastern boundary of Afar, the Western boundary is developed by 26 Ma (E. Wolfenden,2003).

Between 20 and 10 Ma the Red Sea ridge has made its first appearance in the central Afar.Afterwards it has propagated southeastwards alternated by southward jumps creating NNW-NW trending volcanic rift segments(Ert ale, Tat'Ali,Alayta and Manda Hararo).(FRP report,1997).

At about 18 Ma, when the Red-Sea ridge has already reached The Gulf of Zula the WSW propagating Eden rift encountered Shukura- el- Shiek discontinuity which prevented it to penetrate into Afar for 13 M.y. At 5 Ma the Eden ridge makes its first appearance in Afar.(Manighetti et al.,1998)

Since then the Northwestward propagation alternated by northward jumps of the Eden rift has given rise to two NW-trending volcanic rift segments.(Asal Ghoubet and Manda Inakir).Rifting has started approximately 900ka ago in the Asal Ghoubet and approximately 200ka ago in the Manda Inakir.Both of them are presently active.(Manighetti et al.,1998). Holocene and historic basaltic eruptions associated with fresh normal fault scarps and open fissures occur in both of the continuation of the propagating Eden and Red -Sea Rifts in Afar.(FRP report,1997).

A rapid attenuation of the crust occurs at the eastern edge of the Ethiopian plateau where over a distance of 80 Km the continental crust thins from 40 km to only 25-20Km.This zone also coinsides with an elongate, N-S gravity minima some 140 Km wide extending for some 200 Km from Addis Ababa northwards.(Makris et al.,1987). A zone of high volcanic lower crust is reported to underlie this zone of thinning.(Berckehemer et al.,1975).Gravity values in the Ethiopian plateau are strongly negative with a minimum value of -240mGal. Over the Southeast plateau gravity values increase gradually.These areas of negative anomalies on the plateau are separated from the Afar depression by steep gravity gradients, gravity values increasing sharply over a relatively short distance to -50mGal.The Afar depression is transitional between a continental crust and an oceanic crust.It is greately attenuated and is underlain by a low velocity(7.4-7.5Km/s), high temperature upper mantle material.Thickness of the crust within Afar itself decreases sharply to the northeast and to the east towards the Red-Sea and Gulf of Aden, respectively. The two main gradients coinciding more or less with the border escarpment, particularly the N-S gradient is readily seen in gravity maps.The gravity trend of the Ethiopian rift reaches southern Afar where the trend of crustal thinning changes and becomes parallel to that of the Red Sea trend.The spreading area of the Red-Sea is marked by gravity maxima.Similarly, The Gulf of Aden gravity maxima continues west towards the Ethiopian rift.The gravity trends coincide with areas of maximum crustal thinning and might suggest a poosible triple junction in development. (Makris et al.,1987).

The Ethiopian rift is divided into four sectors: The Northern,Central,Southern and Southwestern sectors.(Boccalleti et. al.,1998).

In the northern Main Ethiopian Rift faulting has commenced between 10 and 7 Ma at the western marigin.Evidence is found from the faulting of the Bulga basalt(approximately 10 Ma) onlapped by the Balchi group(approximately 7 Ma).There are also alighnment of felsic centers along the Ilehkese border fault similar to that documented in the central,southern and southwestern part of the rift.These rhyolites can give the minimum age for the development of the boundary fault when dated.The present eastern marigin of the northern main Ethiopian rift is formed after 7 Ma.

At the Western margin of the Northern Main Ethiopian Rift chronozone units that are identified in the present study are:

Flood basalts(.> 26 Ma.),Bulga Basalts(Approximately 10 Ma),Balchi group(6.6-3.5Ma) , Keradi basalts(2.5-1.8 Ma) and Melka Jilo ignimbrites(younger than 1.8 Ma.).(Fig. 45).

In the Northern Main Ethiopian Rift from 1.8Ma to the present there is a shift in the locus of tectonomagmatic activity toward the axis with creation of magmatic segments(Ebinger and Casey,2001).

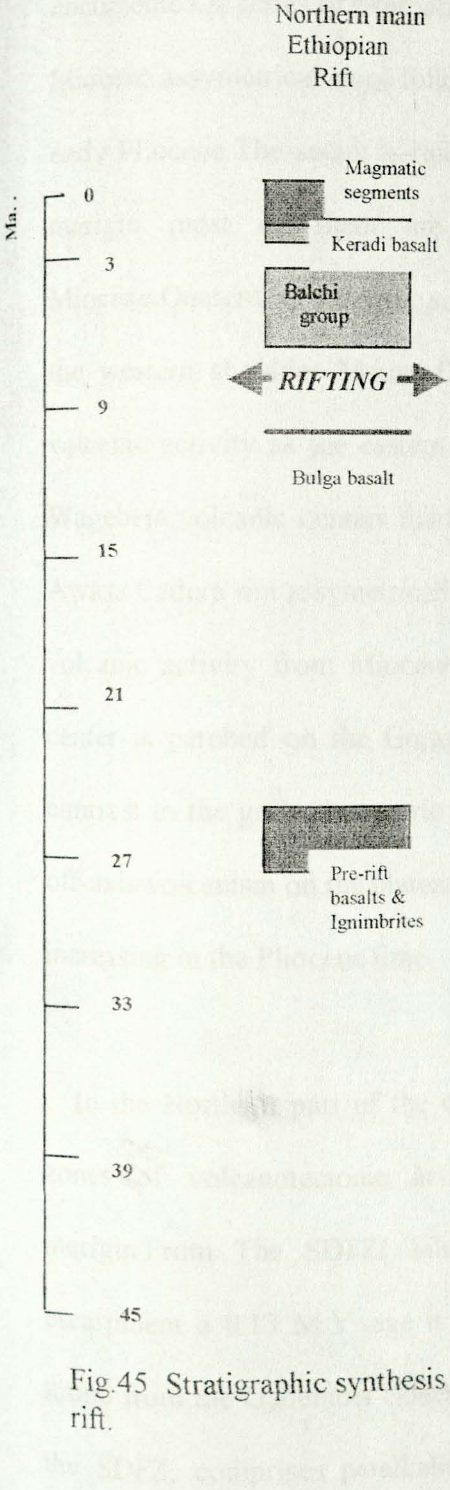


Fig.45 Stratigraphic synthesis for the western margin of the Northern main Ethiopian rift.

In the central sector of the main Ethiopian Rift a two stage rift development is documented.A series of alternating half grabens suppossedly of late oligocene or early Miocene assymetrical stage followed by a symmetrical rifting stage in late Miocene or early Pliocene.The sector is rich in off axis volcanoes.At the shoulder of the eastern marigin most of them are mid-Pliocene in age except Chike which is Miocene.Quaternary volcanic activity is also observed among this volcanic chains.At the western shoulder Mount Damot of mid-Pliocene age seems to have similar volcanic activity as the eastern rift shoulder volcanoes.North of Mount Damot, the Wagebeta volcanic centers mark the tip of the Bonga lineament on the plateau.The Awasa Cadera rim assymetrically designs part of the eastern marigin and has spanned volcanic activity from Miocene to Quaternary.The Gash Megal Miocene rhyolitic center is perched on the Guraghe Plateau.(Woldegebriel et al.,1990).Therefore ,in contrast to the general scenario younging of volcanism toward the rift axis,we have off-axis volcanism on the plateau from Miocene to Quaternary with intensity of pulse increasing in the Pliocene time.

In the Northern part of the central sector of the Main Ethiopian rift Quaternary zones of volcanotectonic activity are disposed to the western and eastern marigin.From The SDFZ(Silti Debreziet fault zone) adjacent to the Guraghe escarpment a 0.13 M.Y. age is reported.Along strike to the south a 1.3 Ma age is found from the Gademota caldera.The Wonji fault Belt at the eastern marigin unlike the SDFZ, comprises peralkaline silicic centers.Lava production in this area has started about 0.83 m.y. ago.Aluto and Shala calderas within this fault zone might have formed contemporaneously at about 0.28-0.24M.A. Ages for Aluto rocks range from 0.27-0.021 m.y.. An age of 0.023 m.y. is documented from the Coribetti caldera south of Shala along the WFB.(Woldegebriel et al.,1990)

So,From the above reported ages it is difficult to infer a younging direction for the WFB.Calderas situated along it might have erupted contemporaneously and continue their activities to the recent. On the other hand the SDFZ seems to have younging direction to the North as evidenced by the age and presence of elongated fissural basalts and nested scoria cones north of the Gademota caldera.

Six chronozone units are identified in the central sector of the Main Ethiopian rift.Kella Basalt(26-32 Ma),Shebele trachyte(12-17Ma),Guraghe Basalt(8.3-10.6 Ma),Butajira Ignimbrite(3-4.2Ma), Chilalo Trachyte(3.5-1.6Ma) and Wonji group(<1.6 Ma).From the eastern and western margin the youngest sections are the Asela and Damot- Sodo comprising Quaternary ages.(Woldegebriel et.al.,1990)

From focal mechanisms,fault slip data and geometry of faults a roughly E-W extension swiching from a NW-SE direction at the Pliocene-Pliestocene boundary is inferred in the central sector(Boccalleti et. al.,1999;Ayele,2000).

Two distict magmatic phases at 45-35Ma and 19-12Ma are present in the Southern sector of the rift.(George et. al.,1998).Mid -Miocene eruptions are as much as or more than the volume of magmas erupted during Eocene to early Oligocene period prior to extension in the Amaro Horst.Little or no extension accompanied the first phase of magmatism and a small amount of extension during the second stage.Alignment of mid-Miocene felsic centers along the border fault,presence of granular textures together with absence of associated trachytic flows, presence of lacustrine sediments, absence of the pre mid-Miocene basalts in basins indicate faulting and subsidence in the Southern rift commenced between 18 and 14 Ma.Late Pliocene-recent extension lies at the foot of the Chamo border fault,where volcanic centers and fissural flows are cut by N 10^{0}E striking faults.(Ebinger et al.,1993).From focal mechanisms,alignment of volcanic centers and fault slip data the regional extension direction is WNW-ESE.(Kebede and Kulhanek 1992,Asfaw 1992).

There exists,therefore, a magmatic and tectonic hiatus between mid-Miocene and Pliocene times.During this hiatus faulting and magmatism have continued in the central and northern sectors of the Main Ethiopian rift.

The initiation of magmatism in the southern Ethiopian rift approximately 15 m.y. earlier than the northern provinces is a problem.The second magmatic phase is associated with development of a basin with beta-factor of 1.2(Ebinger et. al.,1993).The very small amount of the Beta-factor can't explain the short duration of eruption and the volume of extrusives which calls the need of a mantle plume.Topographic and gravity data from East africa suggest the current existence of two mantle plumes beneath Afar and Kenya(Ebinger et. al.,1989).The geochemical characterstics,the eruption rates and the earlier magmatism in southern Ethiopia have been attributed to the Kenyan plume influence when the Southern Ethiopia was positioned close to lake Victoria around 50Ma.(George,1997; George et.

al.,1998).This evidence is supported by the Northeast motion of the African plate at a rate of 1-3cm/yr over the past 50 m.y.(Gordon and Jurdy,1986)

The broad rifted zone of southwest Ethiopia contains N-S and NE-SW trending basins.Alignment of mid-Miocene felsic centers along border faults and the presence of mid Miocene lacusrine strata indicates that faulting and subsidence had occured by ca.14 Ma in the Southwestern rift.Similar to the Southern Ethiopian Rift,an approximately 10 m.y hiatus separated the mid Miocene volcanism and faulting from more localised early Pliocene volcanism and faulting in the broadly rifted zone.(Ebinger et al,2000).The regional extension direction is WNW-ESE from focal mechanisms(Asfaw,1992).Quaternary volcanic centers are restricted in the Omo-Turkana rift.The anomalous breadeth of the Southern rift is due to rift migration and rift propagation.In this sector of the rift, there is also an earlier phase of magmatism than the northern rift provinces(Ebinger et al.,2000).

The Southern and Southwestern sectors of the rift are similar in geometry of faults(with N-S mid-Miocene basins),in having earlier magmatism than Afar, containing tectonomagmatic haitus between mid-Miocene and Pliocene time and having restricted occurrence of the Quaternary Wonji fault belt.

In the Central and Northern sectors of the Ethiopian Rift, Miocene basins are NE-NNE trending.The Southern and Southwestern sector of the rift having an approximately similar onset to the central sector to the north,assume a different geometry of older basins.The problem becomes more aggravated if we assume a NW-SE regional extension direction in the Miocene period.Some points of regional interest might resolve the problem.In the Red-Sea and Gulf of Aden the onset of rifting is at 34 Ma.(Omar and Steckler,1995).Onset of extension in the Red-Sea predates by as much as 20 Ma rifting in the southern and southwestern sectors of the Ethiopian Rift.The western margin of afar is developed by 26 Ma(Wolfenden,2003).So,it seems impossible that faulting in these areas is trigerred by Red-Sea extension.Geological observations in these areas support a more or less passive origin for rift formation(Ebinger et al.,1993:Ebinger et al.,2000).Cenozoic structures cross cut pre-existing N-S fabric avoiding a reactivation mechanism.There are,however,N-S trending Paleogene rifts in Kenya at the Subsurface with small beta-factor as the southern rift(Hendrie et. al.,1994). Southern sectors of the rift might have gathered N-S thinned and weakness regions affected by the Kenyan plume in the last 50-30Ma.This thinned regions might have favoured the development of N-S trending basins in the Mid-Miocene.There exists alsoa north-south hotter,thinned mantle lithosphere south of the broadly rifted zone along the Ririba volcanic line(Ebinger et al.,2000).

The Southern and Southwestern sectors of the rift also contain tectonomagmatic hiatus between mid-Miocene and Pliocene time.During this time faulting and magmatism had continued in the central and northern sectors of the rift.Narrowing of extensional provinces occurs in the southern and southwestern rift after a period of widerspread volcanism at 4 Ma throught the Ethiopian rift.On the contrary,in the central and northern sectors of the Ethiopian rift valley after the widerspread volcanism,a symmetrical stage commences.While in the central and Northern sectors the Wonji fault belt has a widerspred occurrence ,in the southern and Southwestern rift it is limited.

Since the discovery of the Wonji Fault Belt(WFB) in the Ethiopian rift it has been known that young volcanotectonic activities have been concentrated in it.This young volcanotectonic activity runs NNE oblique to the trend of the rift Valley .It is, however, not a continous pattern but is disposed dextrally in en-echelon pattern(Mohr,1983).Their oblique nature to the rift envelope has led various authors to describe the incidence of the Wonji fault belt as due to the counterclockwise rotation of the Somalia plate with respect to Nubia.This was supported by kinematic data and geometry of faults.(Boccalleti et. al.,1998;Boccalleti et. al.,1999).Additional evidences come also from focal mecahanism solution of earthquakes(Ayele,2000).In the Northern Main Ethiopian Rift the WFB comprising the Kone caldera to the South is disposed dextrally to the same belt comprising Fentale to the North.The construction of silicic centers, for example, Gedemsa coincides with the disposition of the WFB.It might be probable that the intersection of this transversal structure with a zone of lithospheric thinning generate these centers.The upper stream channel of the Kessem river follows a NW-SE trend upon projection on the plateau.This is not only the characterstic of the Northern Main Ethiopian Rift alone but a counterpart is also available in Afar.The Southern Afar WFB is bounded by Yangudi and Ayelu Quaternary volcanoes possibly marking burried transfer faults(Hayward et al.,1996).

From the above discussion, it is evident that the Ethiopian rift shows along axis tectonic and magmatic segmentation.Explanations to account this includes:Periodic asthenospheric upwelling,control by pre-existing structures and inherited fandamental length scale in the rifting plate itself.Hayward et. al.,(1996) demonstrated that the segmentation in the Ethiopian rift from south to north is a consequence of decreasing crustal thickness,decreasing effective elastic thickness and increasing magma supply.Following this, there occurs in the Ethiopian rift from south to north a decrease in border fault length,decrease in width of rift basins and decrease in the relief of uplifted flanks.Large volume of quaternary basaltic magmatism in northern Afar,without the development of rift valley lead to magmatic rift segmentation.

As pointed out above,the Quaternary Wonji fault belt in the Northern part of the central sector of MER is disposed to the west and east at the Guraghe and Munesa-Asela margins respectively.In the southern part of the central sector of the MER,however,it follows a median line.(Woldegebriel et al.,1990).The widerspread eruption that gave rise to the Butagira ignimbrite during the Pliocene time is supposed to originate from a caldera now burried in the floor of the central sector(between Guraghe and Asela-Munesa margin) of the MER according to the lastmentioned authors.This magmatism might be associated with underplating giving rise to thickening of the crust.Mohr,(1992) has already outlined underplating as one of the mechanisms that could modify the cratonic crust beneath the Ethiopian rift.Hence,it looks more likely that the Quaternary WFB in the Northern sector of the central main Ethiopian rift has followed the thinnest crust at the western and Eastern margin foregoing its axial zone.

The origin of the transversal structures in the Ethiopian rift is unclear.However there is no doubt the role they play in the segmentation of the Ethiopian rift particularly the Quaternary WFB.There seems to be three possible probabilities.First its possible connection with the border faults.In the absence of subsurface data,border faults at the surface might have listric nature thereby imposing an oblique slip movement.For instance,the Balchi border fault has a northwest dipping bed infront of it.Behind the Ilehkese border fault plane beds dip northwest whereas having flat beds infront of the fault plane.The effect is that during the formation of the WFB they have undergone dextral movement due to rejuvenation.

The second is the role of pre-existing basement fabric.It is imposiible to asses its role in the northern Main Ethiopian rift because of the absence of basement exposure.However, it coudn't be completely ignored because the reactivation of a dextral NW-SE tectonic wedge of a basement during Pliestocene time will give rise to a central type volcanism(cinder cones,spatter cones etc....) in a NNE direction.Assesment of Precambrian structures in the Southern Ethiopia(Mega area) completly fits the aforementioned suggetion(Atnafu and Bonavia,1991).

Lastly,the Quaternary segments could be connected by a non-transform discontinuity.Ebinger and Casey, (2001) identified magmatic segments which are the locus of extension(accomodating >80% of the strain across the rift),with readily magma supply but without coherent sea-floor spreading anomalies.These magmatic segments are arranged en-echelon running NNE along the rift.

A transversal structure in the Northern Main Ethiopian rift is the sub E-W running Yerer-Tulu Welel Volcanotectonic Lineament(YTVL).The structure has associated fractures trending NW,NE and E-W.The NW- fractures are the oldest cross-cut by NE-ones while the relation between the E-W and the NE ones is complex.Calderas with an E-W elongation grew at the intersection of the NW and NE-fractures.Main magmatic activities are a widerspread phase of 10 Ma and a progressive shift from west to east at 7 Ma, 5 Ma and 3 Ma. Volcanic rocks also tend to show strongly evolved compositions from west to east(Abebe et. al.,1995).

At the eastern margin of Afar volcanic centers situated within a rift in rift structure yielded ages between 7 and 5 Ma.(Chernet et al.,1998).As already pointed out in earlier chapters, in the Northern Main Ethiopian Rift, the Kessem river follows some E-W directions which might be due to a structural control between 6 and 3Ma.However, there are no aligned E-W volcanic centers.

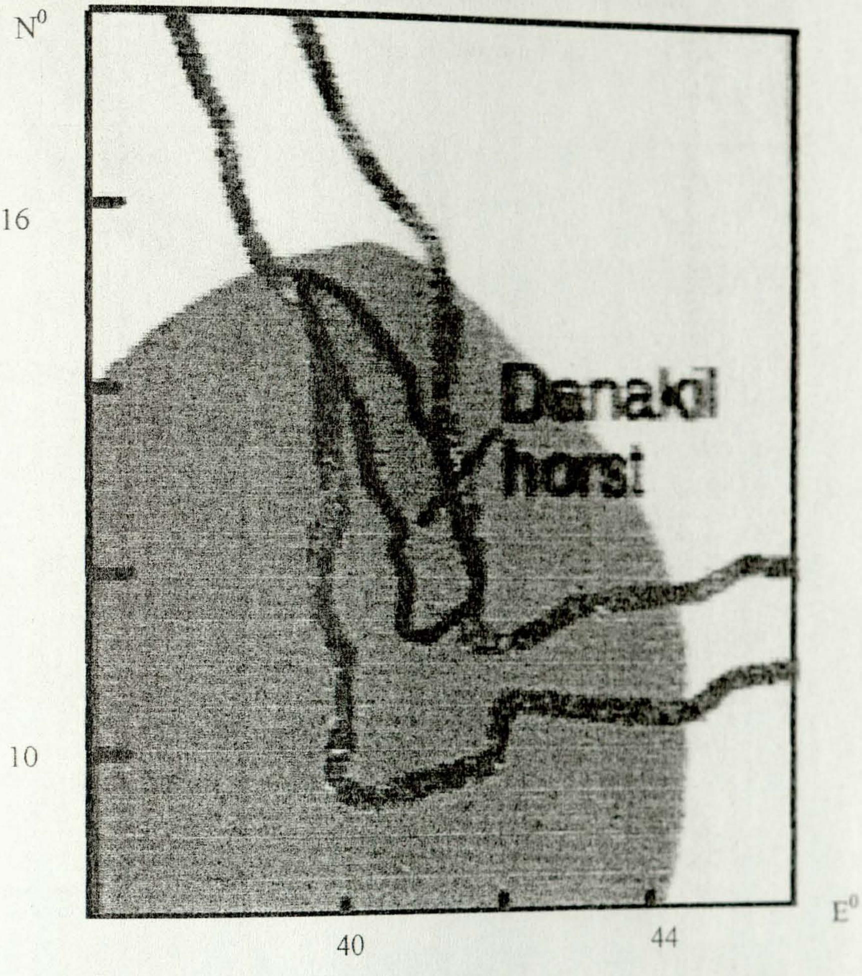
The NE-fracture patterns,the age of the Magmatism and the elongation of the calderas within the YTVL suggest its evolutional linkage with the Northern Main Ethiopian Rift.For instance, according to the present study major volcanotectonic activities coincide with important magmatic stages in the YTVL.Abebe et al.,(1995) have interpreted the incidence of this transversal structure as a result of the combined effect an older kinematics related to the the YTVL and the opening of the Gulf of Aden.

In addition , As the northern Main Ethiopian Rift is developed after Afar the superimposition of stress fields of the former on the later might have given rise to a sub E-W structures.NW-fractures might be related to the opening of Afar and NE-ones to the opening of Northern Main Ethiopian Rift.So,Wenever there are important volcanotectonic activities in the Northern Main Ethiopian Rift this is also recorded in the YTVL.The YTVL is,however, a weak zone probably because its extensional stress fields are dependent on that of Afar and The Northern Main Ethiopian Rift.

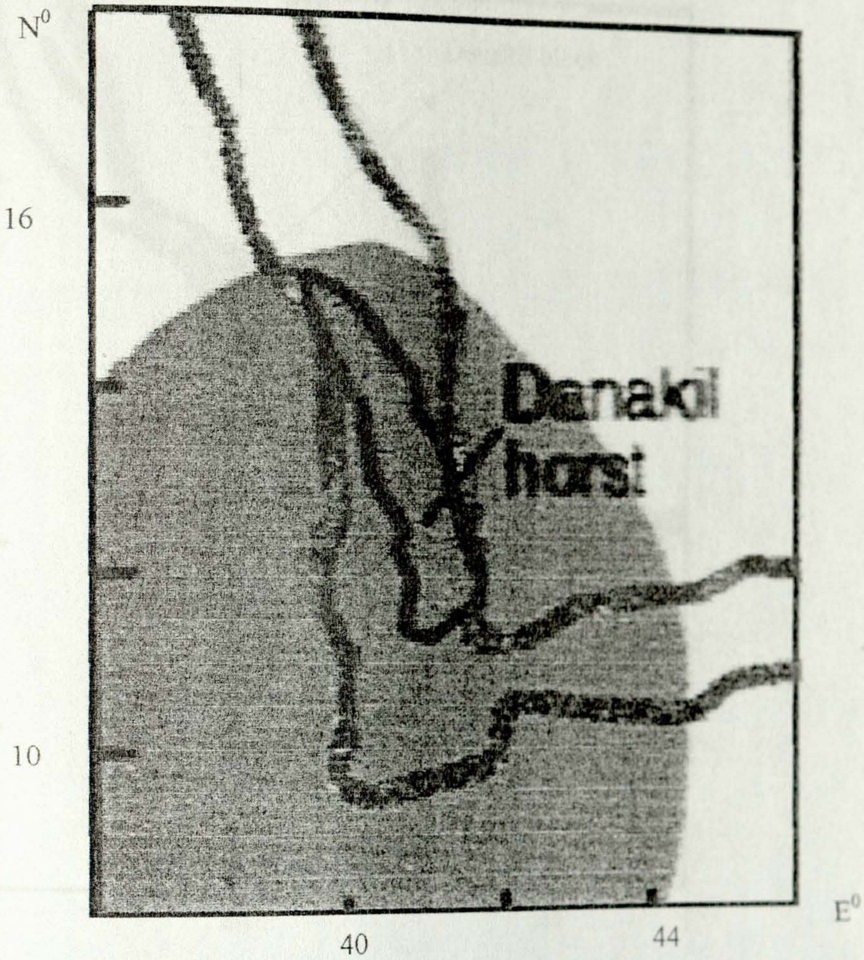
6.2.Summary

At about 45Ma the future site of the Southern main Ethiopian rift began to be flooded by basalts as a result of the impact of the Kenyan plume.At that time the African and Arabian plate were still joined together.The real break up of Africa and Arabia seems to have started around 34 Ma at the eastern edge of the Gulf of Eden whereas rifting was concentrated at the northern tip of the future Red-Sea rift.From then onwards rifting in the Gulf of Aden and Red-Sea propagated towards each other to the future site of Afar.At about 30 Ma the area shared by Ethiopia and Yemen was flooded by basalts as a result of the Afar Plume(Fig. 46).Between 30 and 20 Ma the Afro Arabian plate bigan to separate with the beginning of the birth of Afar(Coulie,2001;Ukstins et al.,2002).The western margin of Afar has developed by 26 Ma.SDR sequences infront of the border fault mark a zone of highly extended and intruded crust as evidenced by geophysical data(Wolfenden,2003).At around 20 Ma(Fig. 47), the Danakil microblock begans to detach from the Ethiopian plateau and rotate counterclockwise facilitating the penetration of the Red-Sea ridge.Between 20 and 10 Ma the Red-Sea ridge was first located between the Ethiopian plateau and the Denakil microblock..During this interval of time the southern and alternating polarity rifts in the central sector of the Ethiopian rifts had developed.In early Miocene sea-floor spreading has began in the Gulf of Aden and some part of the Red-Sea.Between 10 and 7 Ma the western marigin of the Northern Main Ethiopian Rift has developed thereby starting a triple junction development(Fig. 48).Magmatism and strain might have shifted eastward from the western marigin of Afar creating magmatic segments at around 8 Ma(Wolfenden,2003).At about 5-4 Ma the Aden ridge has arrived in Afar.The Pliocene time marks widerspread volcanism in the whole of the Ethiopian rift after which a symmetrical rifting stage in the central and probably in the Northern Main Ethiopian Rift has to place.In The Southern and Southwestern rifts narrowing of basins has taken place after the widerspread volcanism.During Plio-Pliostocene time sea-floor spreading in the Red-Sea has took place.

In Afar since the arrival of the Red-Sea and Eden ridge the propagation of both has given rise to NW-NNW trending volcanic rifts whose activities can be traced to the recent time.In the Northern Main Ethiopian Rift volcanotectonic activity systematically youngs toward the floor since its birth.From 1.8Ma to present there is a creation of magmatic segments arranged enechelon in a NNE-direction which accomodate most of the strain and probably marking the continental-oceanic boundary.Jumps between each magmatic segment is marked by a continental crust(Fig.49,Fig 50).



Showing the area now shared by Nubia.Somalia and Arabia was flooded by basalts(blue) as a result of the impact of the ne approximately 30 Ma.Future Denakil block and rift margins are shown for comparison.



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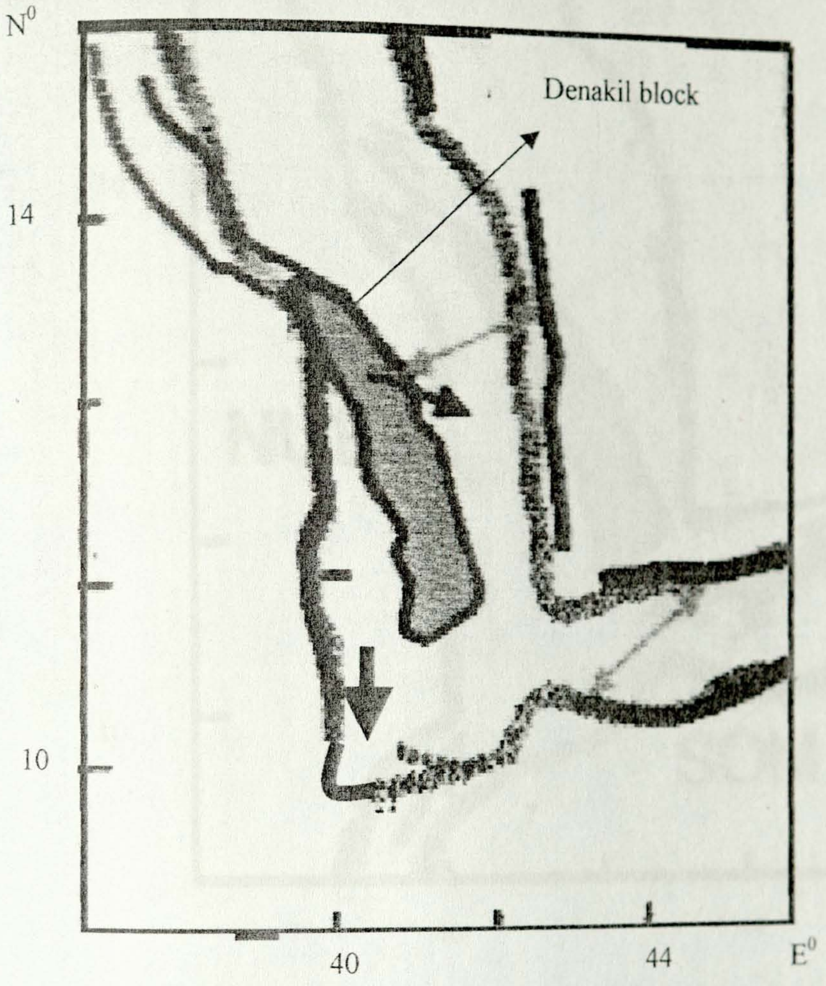

Fig.47 Approximately 20 Ma. By this time the western margin of Afar has already developed and the Denakil block begins to rotate counterclokwise.Rifting along the western margin of Afar becomes younger toward south.Blue double arrows indicate extension direction.Afar at this time was a double junction.

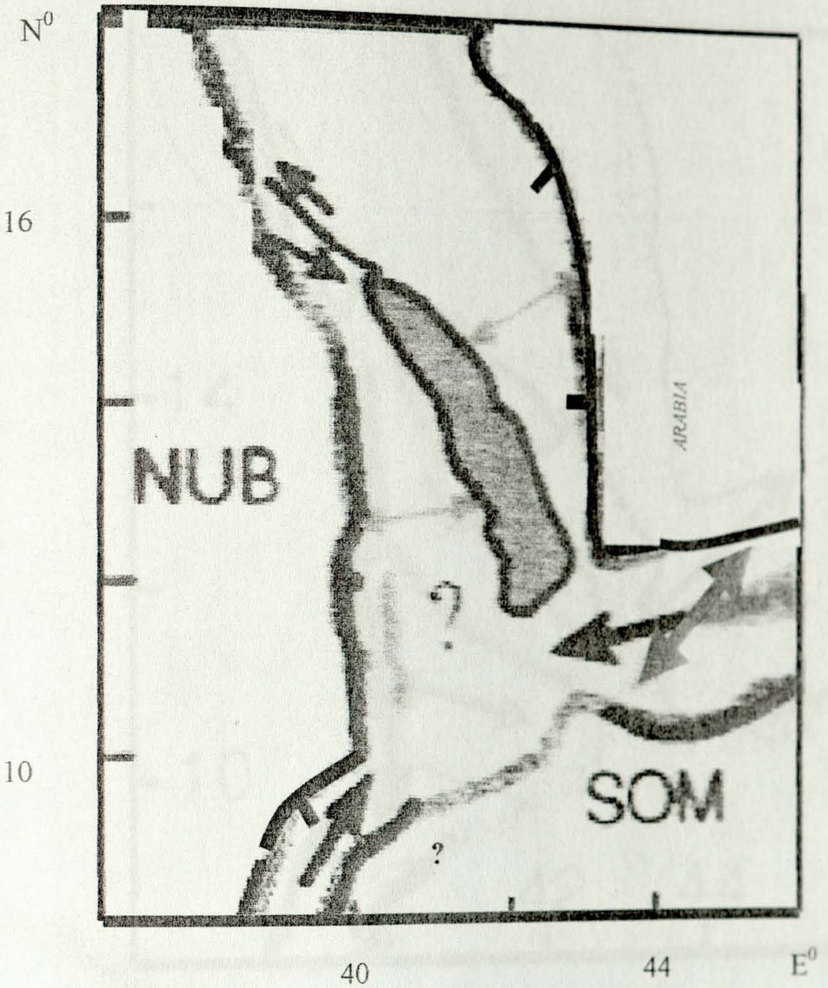

Fig.48 Between approximately 10 Ma and & 7 Ma.Light blue double arrows indicate extension direction.Oranges are magmatic segments.Red is sea floor spreading in the Gulf of Aden propagating to Afar.Rifting in the Ethiopian rift becomes younger from southern sectors to the north and a triple junction development is most probable during this time.See text for further description.

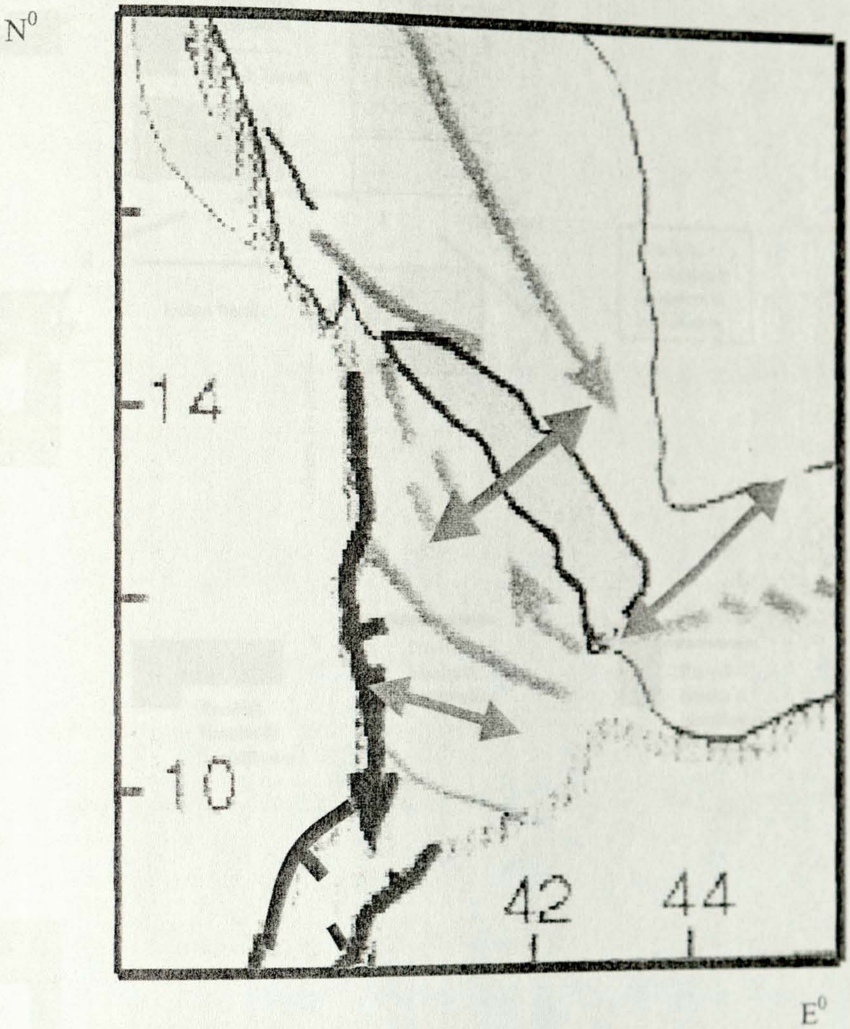

Fig.49 At present. Light blue double arrows indicate extension direction.Red arrows are sea floor spreading and their propagation direction.Oranges are magmatic segments.See text for further description.

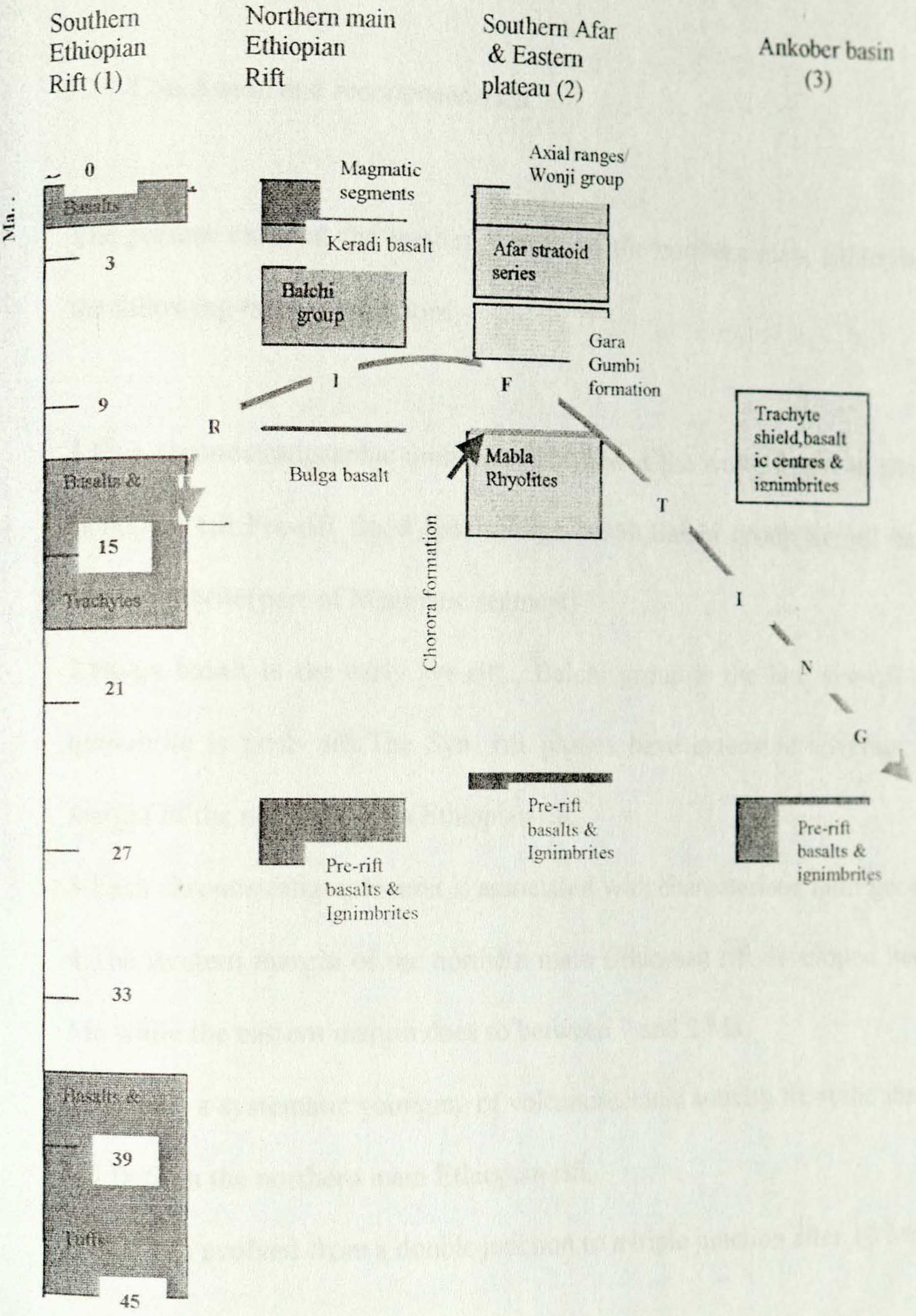

Fig.50 Comparative stratigraphics for the southern Ethiopian rift (1) after Ebinger et al.,1993; Northern main Ethiopian rift (present study); Southern Afar margin and western plateau (2) after Chernet et al.,1998 and Ankober basin (3) after Wolfenden., 2003.

Chapter 7

Conclusion and recommendation

The present study at the western margin of the northern main Ethiopian rift arrives at the following main conclusions:-

1.Five chronostratigraphic units are identified at the western part of the Northern main Ethiopian rift:Pre-rift flood basalt,Bulga basalt,Balchi group,Keradi basalt and Melka Jilo ignimbrite(part of Magmatic segment).

2.Bulga basalt is the early syn-rift , Balchi group is the late syn-rift and Melka Jilo ignimbrite is post- rift.The Syn- rift phases have extensive coverage at the western margin of the northern main Ethiopian rift.

3.Each chronostratigraphicunit is associated with characteristic fault geometry.

4.The western margin of the northern main Ethiopian rift developed between 10 and 7 Ma while the eastern margin does so between 7 and 2 Ma.

5.There is a systematic younging of volcanotectonic activity from the margin toward the rift floor in the northern main Ethiopian rift.

6.Afar has evolved from a double junction to a triple junction after 10 Ma.

Recommendations

1.Geochemical analysis of each chronostratigraphic units will help to understand the origin and evolution of the volcanics in the area.

2.Correlation of seismic epicentres with fault geometries will help to understand about fault propagation and linkage of the Northern main Ethiopian rift with other sectors of the rift.

3.Siesmic refraction studies will help to image the geometry of subsurface faults which combined with the previous one will give a better picture of the geodynamics of the area.

4.Finally, a combined structural,geophysical and geochemical studies on the Yerer-Tuluwelel structure is important to better understand its incidence and linkage with the northern main Ethiopian rift.

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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 all sources of materials used for the thesis have been duly acknowledged.

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