STRATIGRAPHY AND CARBONATE MICROFACIES OF THE HIRNA MESOZOIC SEQUENCE.

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Master of Science in Geology

by

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ABSTRACT

The study area presents exposures ranging in age from the Precambrian (basement) through Mesozoic (sediments) to the Tertiary (volcanics) with alluvial sediments of recent age also present. The different lithological units have been mapped as well as described based on field observations.

The Mesozoic stratigraphy of Hirna area has been studied with particular reference to the carbonate lithology. Three main carbonate microfacies have been identified as being representative major constituents of these carbonates. These microfacies are distributed in a cyclic manner with time. The cyclicity has been interpreted as showing small changes of sea level in a generally shallowing up sequence.

Biostratigraphic and paleogeographic considerations show that the Lower Sandstone Unit (Triassic-Middle Jurassic) is correlative with the regionally identified Adigrat Sandstones. The carbonates on the other hand can be referred in part to the Hamanlei sequence (?Bathonian-Lower Oxfordian age in Hirna area) and in part to the Uarandab sequence (Kimmeridgian age in Hirna area). The Upper Sandstone Unit is a part of the Yesomma sequence and is of Cretaceous age in Hirna area.

Tectonically, Hirna area is only lightly deformed, with a SW-NE fault trend dominating the structures. Other trends, however, do exist with not so clear a relationship with the dominant trend. Gentle dips of local significance are shown by some of the Phanerozoic lithologies.

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I-INTRODUCTION

The study area is located approximately 375 km east of Addis Ababa along the Addis Ababa - Dire Dawa main road. It lies in the vicinity of Hirna town, within western Hararghe administrative region and is bounded by latitudes 9° 04' N and 9° 20' N and longitudes 41° 03' E and 41° 15' E (Fig.1).

A number of dry weather dirt roads are present in the area. During the dry seasons it is possible to use these roads by a four-wheel drive vehicle. During rainy periods, however, most of these roads become inaccessible by vehicle unless exceptionally strong and difficulty arises to work on some sections far from Hirna town, since all the distance should be covered on foot.

Physiographically, the study area is in the marginal parts of the south-eastern Ethiopian plateau. The chain of highlands that run along the margin of the plateau and southern Afar are known as the Ahmar mountains and include the study area.

The area is topographically very highly rugged and, although many exposures are visible from a distance, it is very difficult in many cases to reach them and make on the spot observations due to the high topographic slopes and frequent associated dense vegetation cover around.

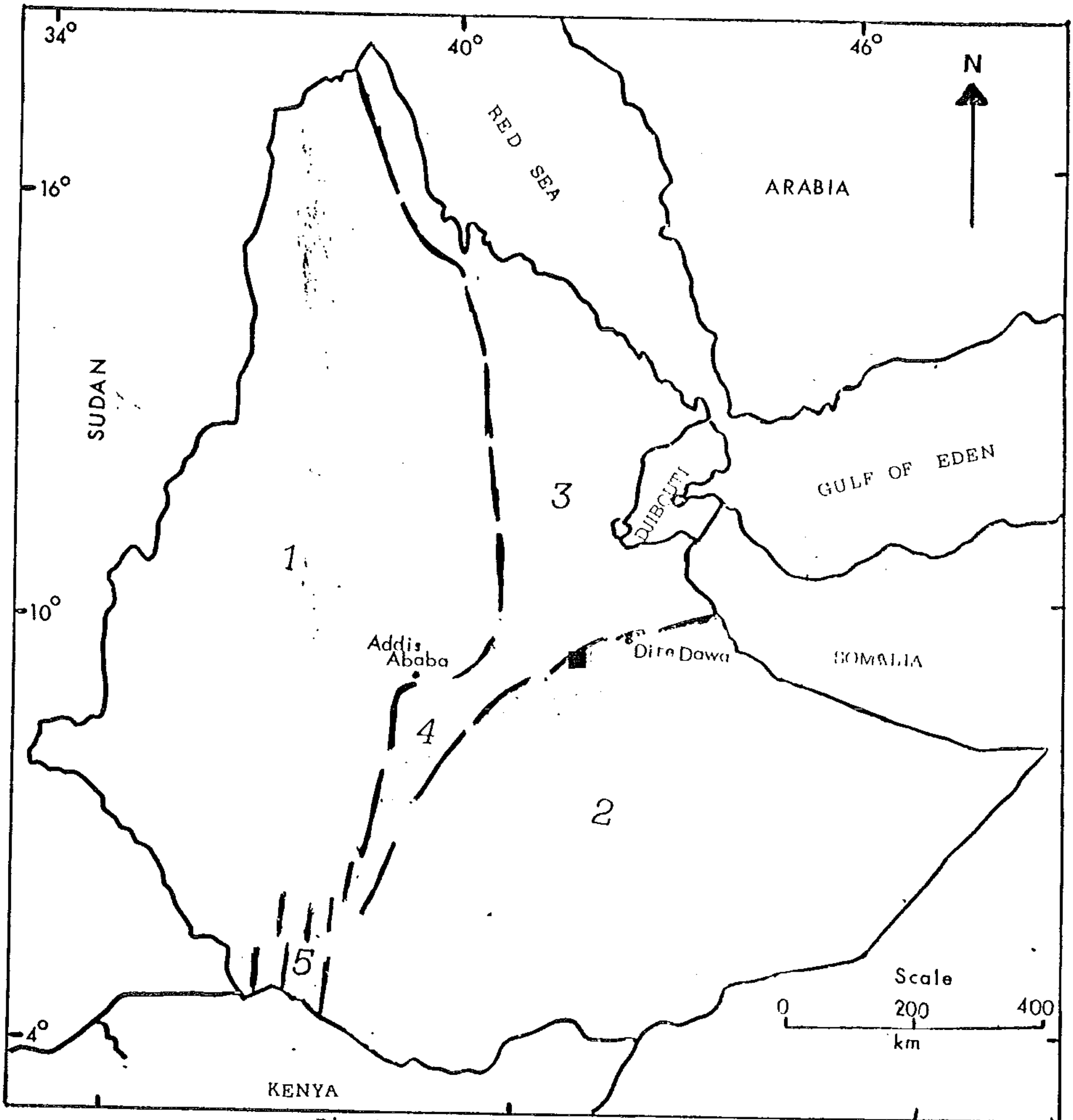

Fig.1- Location map.

1=Western Ethiopian Plateau
2=Southeastern Ethiopian Plateau
3=Afar
4=Main Ethiopian Rift
5=Southwestern Rifts
■=Study area (not to scale)

Most of the area is characterized by the presence of very steep valleys and slopy hillsides. A number of rivers flow within the area, but the largest of all is the Galleti river at the base of which is exposed the crystalline basement. Alluvial plains form quite a proportion and are particularly widespread near by Hirna town.

An elevation contrast of more than 1400 meters exists, with the lowest elevation slightly less than 1400 meters (valley bottom)and the highest greater than 2800 meters (highest peak 2835 at Gara Kufa).

Hirna is located in a temperate climatic zone and has two rainy seasons - the main one during July, August and September and another one during March, April and May.

With respect to the vegetation type, the study area is part of the coniferous forest regions of Ethiopia. *Juniperus procera* (tid, gatera) and *Podocarpus gracilior* (zigba, birbisa) trees occupy the higher elevations while *Hageira* (koso, feto) forests occupy the lower elevations.

The mean annual rainfall is about 1000 mm and the mean annual temperature ranges between 15°C and 20°C. The mean maximum temperature is about 25°C (recorded almost in all months) while the mean minimum is a bit lower than 10°C (recorded in the months of August and September).

PURPOSE

Detailed facies descriptions of sedimentary successions are necessary for understanding environments of deposition and stratigraphic relationships between various units. Microfacies analysis of carbonate rocks in particular is one of the most important methods of observation.

The sediments of the marginal parts of the South-East Ethiopian Plateau (SE Plateau), except for a few parts (which includes Dire Dawa and Harar) have not been wholly and extensively studied with respect to the above mentioned method of analysis. Such a study on a part of this region, although it may not be representative, will no doubt help in the understanding of environmental conditions and broad paleogeography of the region during the Jurassic time in the marginal parts of the SE Plateau.

This study was undertaken with the aim of attempting to come up with the composite stratigraphy of the Mesozoic sediments in the area together with an interpretation of the environmental conditions under which they were deposited, based on microfacies descriptions.

PREVIOUS WORKS

General works on the geology of Ethiopia, with some descriptions of Mesozoic sediments on the SE Plateau include that of Stefanini (1933), Mohr (1971), Kazmin (1975b) and Merla et al. (1979).

Beyond these general works Mesozoic sedimentary rocks of Harar and Dire Dawa areas have been studied by Greitzer (1970), while the coral fauna has been studied by Zuffardi Comerci (1938) and Wells (1943), and the ammonites and others molluscs by Venzo (1942). The microfacies of the Antalo Limestone in the Dire Dawa area have been analyzed by Ficcarelli et al. (1975).

Microfacies of the Antalo Limestone have also been studied in some sections of east-central Ethiopia by Turi et al. (1980) including a section near Hirna, which is part of the study area.

MATERIALS AND METHODS

Although the topo-sheets available for the area are at a scale of 1: 250,000, an enlargement from this sheet to a scale of 1:50,000 was made. The topo-map at this enlarged scale was used as a base for field mapping. Aerial photographs at the same scale were used as a supplement to the topographic map.

During the first stage of mapping the area, choice was made of stratigraphic sections to be described and sampled. The choice was based on various factors including degree of exposure and accessibility. During the field description and sampling of stratigraphic sections much use was made of the altimeter, hand lens and field hammer. The meter-tape was used in cases where measurement of beds was necessary. Representative samples were taken for different intervals and field sedimentary descriptions including color, sedimentary structures, textures and fossils were recorded.

The main method of analysis involved the petrographic decription of rock units. The carbonates, to which most of the attention was given, were microscopically studied. Microfacies descriptions and interpretations were based on such an analysis.

GEOLOGIC SETTING

The Harerghe and Ogaden basins, that occupy the SE Ethiopian Plateau, structurally belong to the well developed East African system of troughs trending NNE. The system is considered to be a rift-stage basin of the East African continental margin (Beltrandi and Pyre 1972; Kent 1974; and Purcell 1981). This margin was affected by several vertical movements that took place in a lot of different phases starting from the Paleozoic. Some of these phases were developed at the end of Jurassic and Cretaceous (Kent, 1974).The deposition of the Mesozoic sediments on the South-East Ethiopian Plateau, over the Precambrian basement was the result in part of the rifting stage heralding the Gondwana breakup and in part of the Mesozoic eustatic

Alluvium	recent
Trap Series Volcanics	Tertiary
Upper Sandstone	Cretaceous
Limestone	Jurassic (Middle – Late)
Lower Sandstone	Triassic – Early Jurassic
Basement	Archean ?

Fig. 2 Regional stratigraphy of the marginal parts of the SE Ethiopian plateau (not to scale).

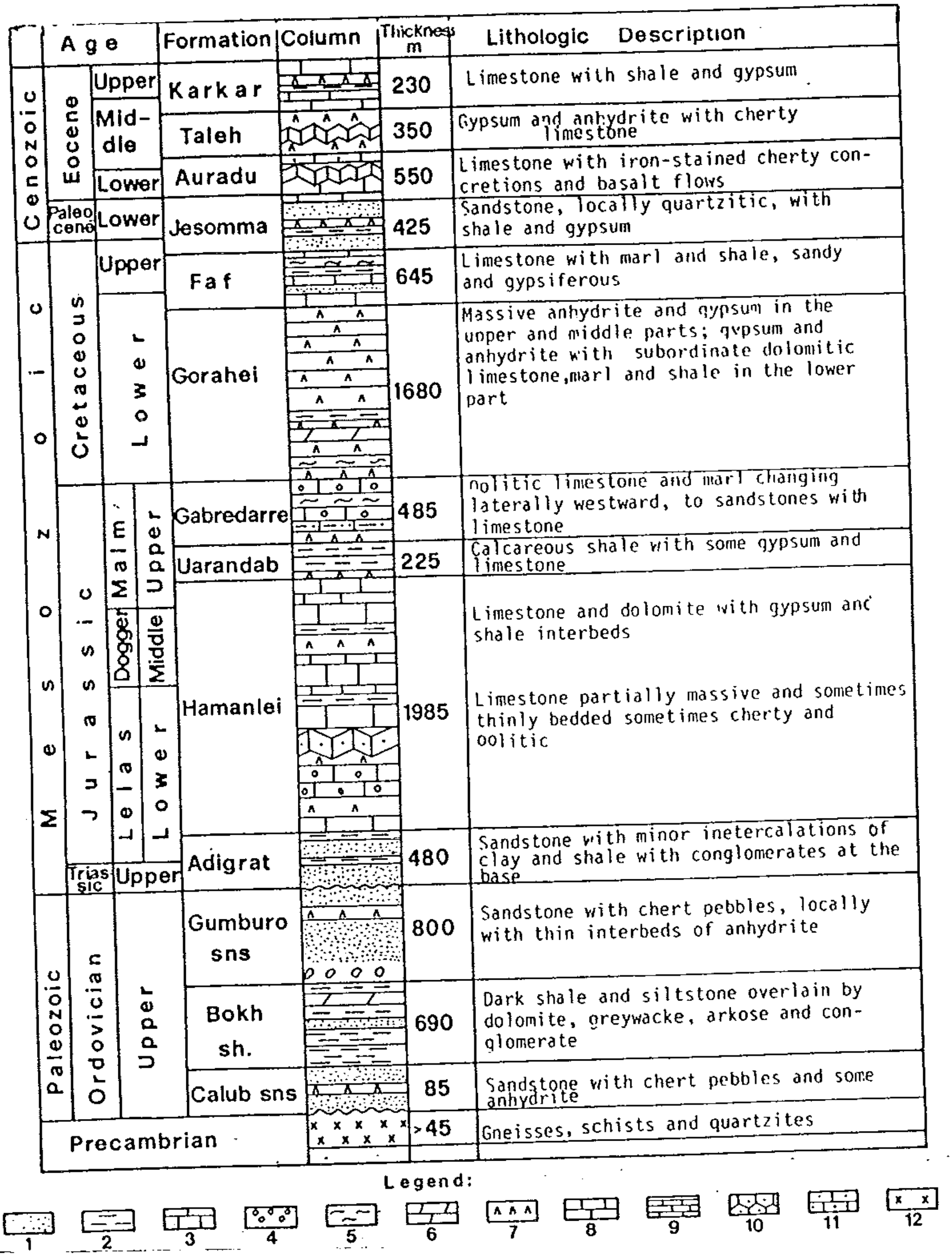

Fig.3- Generalised stratigraphic column of the Ogaden Basin. 1.sandstone; 2.shale; 3.limestone; 4.oolites; 5.marl; 6.dolomites; 7.anyhydrite; 8.massive limestone; 9.thinly-bedded limestone; 10.nodular limestone; 11.cherty, nodular limestone; 12.crystalline basement.
(After Getaneh, 1988)

II. STRATIGRAPHY AND MICROFACIES

Descriptions of units differentiated during mapping together with carbonate microfacies analysis, environments of deposition, and biostratigraphy and age will be discussed in this chapter.

II.1.Field-descriptions

Six lithological units have been distinguished during mapping. Some have further subdivisions within them. Descriptions of these together with an additional part on other igneous bodies in the area are as follows:

II.1.1. The Precambrian basement

The basement rocks outcrop on the sides of the deep gorges cut by the major rivers of the study area. These are distributed in the southern and central parts of the mapped region. The exposed thickness of these rocks is greater than 200 m.

Complex lateral and vertical relationships occur between the various lithologies of the basement. No attempt has been made to unravel these relationships in the present work. Prominent features observable in the field, however, have been recorded.

Field observations have revealed the presence of gneisses, migmatites, schists and marbles as constituent parts of the basement rocks. Clear differentiation between melanocratic and leucocratic

Plate 1- View of the basement rocks, with clear differentiation between melanocratic and leucocratic layers.

layers is visible on outcrops of gneisses and migmatites (Plate 1). The migmatites show macroscale folds of common ptygmatic nature. Foliation is the dominant feature in the schists while the marble is in most cases white and crystalline in nature. Although the marble commonly consists of large crystals, fine-medium grained varieties have also been observed. Pegmatite dykes and quartz veins have also been observed occasionally.

According to Kazmin (1975a), the Precambrian rocks of the Harar region form part of the Lower Complex and are of Archean age.

II.1.2. The Lower Sandstone Unit

The Lower Sandstone Unit is exposed mainly in the southern and central parts of the study area. Outcrops are found along the sides of valleys cut by the major rivers of the area such as the Galleti, Debeso and Midedu (Plate 2). The thickness of the unit varies between 90 m and 150 m - an average thickness of 120 m. is representative. This unit is predominantly a cliff-former (Plate 3) although in some cases parts of the unit form gentler slopes.

The vertical variations within this unit as observed from the field study of two stratigraphic sections and additional observations during mapping are as follows:

The lower subunit which has a thickness of about 90 m

Plate 2- Basement and Lower Sandstones on valley sides of the major rivers of the study area.
L sst = Lower Sandstone

development of the conglomeratic part overlying the Precambrian basement. The upper calcareous sandstones sub-unit nearby the contact, also shows differences in thickness, but no general trend of thinning or thickening is observable.

II.1.3. The Limestone Unit.

Field observations and areal photo interpretation have showed the existance of three mappable subdivisions within this unit. Later petrographic work, however, has confirmed general lithological similarity in the unit, except for some rocks in the third or uppermost subunit.

II.1.3.1. Subunit 1.

This subunit is distributed quite extensively in the study area, especially in the central and southern parts. It is exposed on hillsides conformably overlying the Lower Sandstone Unit and is clearly seen to form steep slopes, thus enabling differentiation from the other limestone subunit above it during mapping. The unit has about 140 m thickness.

At about the start of the subunit the limestones are sandy due to the transitional nature of the contact with the Lower Sandstone. Apart from these the rocks are generally allochemical to micrite limestones. In some cases some sparry calcite crystals are observable in hand specimen in addition to the micritic-allochemical nature of constituents observable in most cases. Allochems observable in the field include intraclasts and skeletal remains.

The color of the limestones varies from grey to light brown to pinkish brown. Weathering affects on the rocks are mainly chemical in nature resulting in dissolved rough irregular surfaces of dominantly dark brown color with additional whitish parts in between. Physically they are well consolidated quite hard rocks. The limestones are massive to thickly bedded, with rare dissolution grooves on outcrop surfaces and caliche observed also in rare cases.

Macrofossils are not abundant, and even these are in a poor state of preservation making identification difficult. Fossils of brachiopods and pelecypods, however, were observed.

Most of the other characteristic features are observed petrographically.

II.1.3.2. Subunit 2.

This subunit is also extensively exposed in the study area. Only the extreme northern parts of the area, covered by volcanics, lack outcrops of these limestones. Exposure is on hillsides and some hilltops, generally forming gentler slopes compared to the underlying subunit of limestone which is a cliff-former as previously mentioned.The thickness is about 300 m.

Color variations from dark grey to light brown and pinkish are observed. Generally speaking the rocks of this subunit are physically well consolidated. Weathering surfaces, are more darker in color in most cases, compared to weathering surfaces of the underlying limestone subunit. Weathering effects are dominantly chemical with very abundant dissolution grooves on the surface of outcrops. The grooves display a dendritic pattern on macroscale in many cases. Additional effects include formation of numerous large hollows and alteration to yellowish orange colors along fractures.

Lithological types include nodular limestones, oolitic limestones, and other allochemical to micritic varieties with sparry calcite crystals visible in some cases. The rocks are highly fossiliferous at macroscale in most cases.

Thick bedding is the ubiquitous sedimentary structure observed. Secondary structures include stylolites (especially in the upper part of the unit), chert nodules and chert lenses (at about the middle part) in addition to the various dissolution features previously mentioned (grooves, hollows). The chert lenses range in length from 10 cm - 80 cm and their thickness is commonly between 4 cm and 6 cm. Caliche are also present.

The mode of preservation of fossils is mainly in the form of moulds, but some casts are also observed. Macrofossils observed are pelecypods, brachiopods, stromatoporoids and corals. Extent of preservation, although allowing identification of phyla, is not good enough for more detailed identification in most cases. The corals and stromatoporoids identified were: *Stylina kachensis* (Gregory), *Actinastraea newtoni* (Gregory), *Convexastraea lortphillipsi* (Gregory), *Stylina* sp., and *Promillepora pervinquieri* (Dehorne), *Dehornella crustans* (Hudson).

Results of petrographic study give us more information on the type and variations of the Limestone unit in general.

II.1.3.3. Subunit 3.

Quite extensive exposures are found distributed in the study area, mainly in the central and southern parts. The subunit is a gentle-slope former and occurs mainly on hillsides. The thickness is about 60 m.

Color variations observed in the rocks are yellow, variegated (pink, orange, yellow) and light brown. The limestones showing yellow and variegated colors are mainly marly limestones. The light brown limestones are similar to the ones in the underlying subunit in hand specimen. Physically, the rocks of this sub-unit are consolidated to well-consolidated and of variable hardness. The different colored rocks constituting the subunit are found distributed in a vertically alternating manner. Thickness of alternating layers varies from 5-10 m.

Thick bedding with laminations in some cases, is the common primary sedimentary structure found. Secondary sedimentary structures of the subunit are stylolites, very abundant in the light brown limestones, and some dissolution grooves.

The light brown limestones are sometimes highly fossiliferous with poorly preserved brachiopods and bivalves. Ammonites were found in the yellowish and variegated rocks.

II.1.4. Upper Sandstone Unit

This unit comprises the rocks found in the stratigraphic interval between the Limestone Unit and the overlying volcanics.Two subdivisions are recognised within it and the different topography displayed by the subunits aids in field geological mapping.

II.1.4.1 Subunit I

This subunit is distributed quite extensively especially in the southern parts of the study area with additional occurrences in the central and northern parts. It is found on the upper parts of the hills in the area and is topographically a gentle slope former (Plate 5).

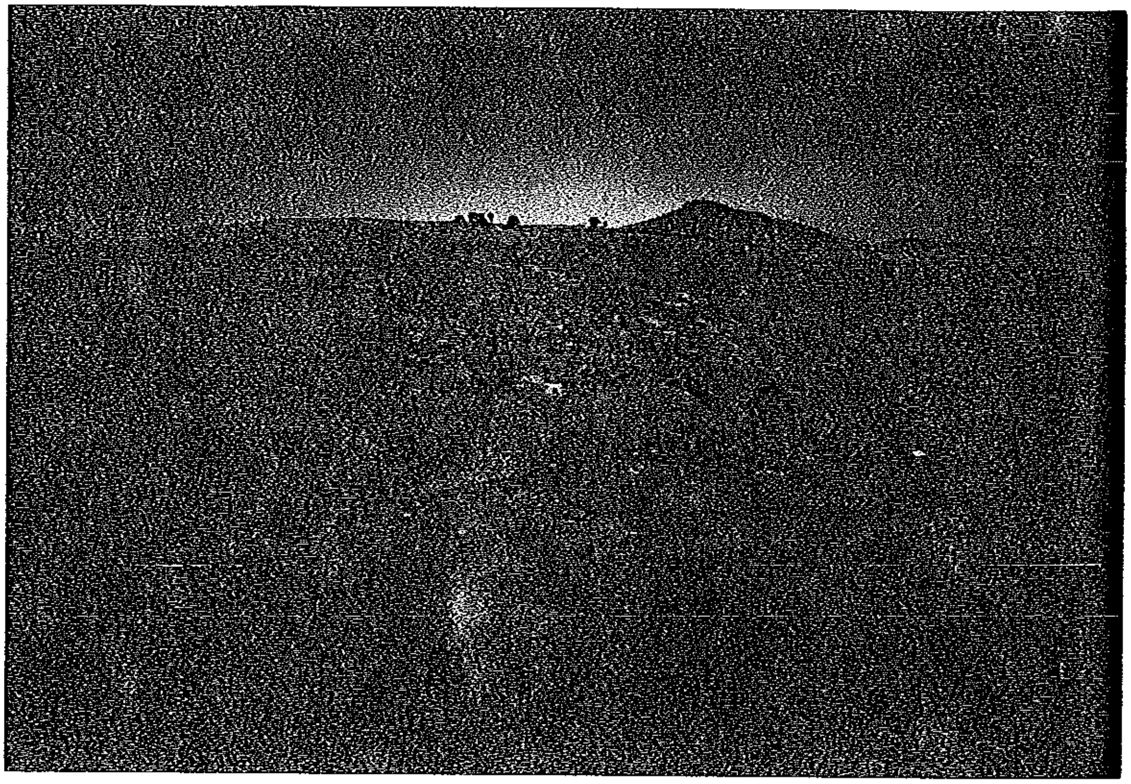

Plate 5- View of subunit I of the Upper Sandstone showing the gentle slope it forms.
I = subunit I

Outcrops commonly occur along road cuts, foot-paths and areas cut by small seasonal streams. Unlike the previously described units outcrops are not widespread, frequently being hidden by soil cover. The thickness of this subunit is about 200 m.

The subunit as a whole is lithologically made up of mudrocks, shales, siltstones, sandstones and limestones. The detrital rocks are found alternating with each other in an irregular pattern while the limestone forms a thin intercalation towards the topmost part of this subunit (Plate 6). A thick basaltic intercalation was observed within this sub-unit and will be discussed in a later part.

Although the actual contact between the underlying limestone and this subunit has not been observed in the field (being hidden by soil cover) the first lithology to be observed after the ending of the limestone unit is a thick interval of mudrocks. Other mudrock intervals continue to be seen at different levels within the subunit. The color of the mudrocks range from light brown to greyish white. Physically, they are of poorly consolidated to consolidated friable nature. The thickness of the various mudrock intervals is highly variable ranging from 1-25 m.

The shales commonly display a variegated color.A dark grey color with shades of green and some additional yellowish brown colors is a common observation (Plate 7).

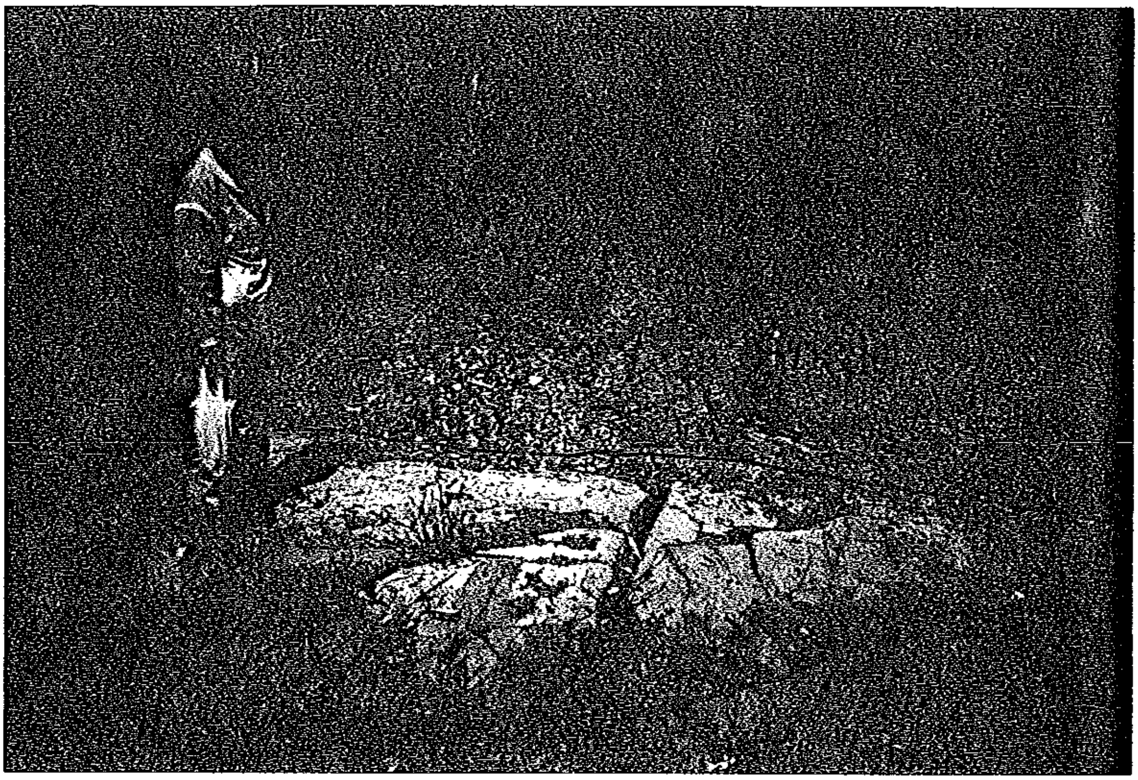

Plate 7- Variegated shale intercalation in subunit I of the Upper Sandstone Unit.

The thickness is also variable here,ranging from 50cm-5m. The fissile nature of the shale is well developed in this subunit relative to the shale of the Lower Sandstone Unit. They are also physically more indurated, hard rocks unlike the commonly friable shales of the Lower Sandstone.

The siltstone shows colors such as light brown, light red and greyish white. This lithology is not abundant relative to the other types and thus constitutes a minor proportion of the subunit.

Fine-medium grained sandstones dominate the sandstones present, but coarse - grained varieties were observed in rare instances. Color variations are from red-white with yellow and light brown colors present as weathering effects. Sometimes mottled color distribution of the mentioned colors is observable on outcrops. The induration of the sandstone lithology in this subunit in general is best described as being friable although exceptions of hard, well cemented sandstones were observed in very few cases.

Sedimentary structures displayed by these clastic rocks are thin-thick horizontal bedding , laminations, rare cross-bedding (in the sandstones), and dessication cracks (in fine sandstones).

The limestone intercalation is 15-20 m thick and its continuity can be visually followed by observation from a distance in many cases. In other cases, where the continuity cannot be controlled by observation from a distance (due to poor exposure) assumption was made regarding its lateral continuity based on previous observations at a number of selected localities. The limestone has a light-dark grey fresh color with yellowish brown weathering colors frequently occuring in mottled form. In most cases it is highly fosiliferous at macroscale, although one can distinguish between outcrops of low and high concentration of fossils laterally and vertically. In outcrops, the macrofossils have size of 2cm on the average with good sorting observed on isolated exposures. Macrofossils present include broken shells of pelecypods, brachiopods, <u>Nerinea</u> sp., and ammonites.

II.1.4.2. Subunit II

This sandstone subunit is of limited extent in its distribution relative to the other units described. It generally has a scattered distribution occupying some central, western, southern and south-eastern parts of the study area. It usually occurs in the top parts of hills below the volcanics. Topographically, it is a steep-slope former and the slope-difference with the underlying Subunit I, allows its distinct mapping in the field (Plate 8). Outcrops are commonly found along road cuts, foot paths and following small seasonal streams. Although exposures of this subunit are greater than the underlying one, it is still not

Plate 8- Topographic difference between subunit I and subunit II of the Upper Sandstone Unit.
I = subunit I
II = subunit II

comparable with the abundant cropping-outs, in the Limestone and Lower Sandstone units. The thickness of the subunit is about 60 m.

Lithologically, the rocks of this subunit differ from the subunit I in that these are sandstones proper, without any significant finer intercalation within them. The sandstones are mainly medium - very coarse grained, with some fine sandstones occasionally observed. Some conglomeratic sandstones (with quartz pebbles small in proportion) are also present, eventhough they are very rare.

The color of the sandstones is red and white, the red types slightly dominating over the white ones. Weathering effects especially on the whitish sandstones, result in brownish colors superimposed on the fresh color. The rocks within this sandstone sub-unit are physically hard to friable. The grains, as seen from observations in the field are angular-rounded. Variable degrees of sorting were also observed, again from estimations of sorting in the field.

Sedimentary structures displayed by these sandstones are massive to horizontal bedding (beds being thin-thick) and cross bedding. The size of the forsets are generally smaller in this sandstones, compared to those in the Lower Sandstone Unit.

The topmost beds of the sandstone, show baking effect of the volcanics overlying them.

II.1.5. The volcanics

The most extensive outcrops of the volcanic rocks occur in the northern part of the mapped area. In addition, they are also found on the topmost parts of some of the hills, in parts of the study area other than the northern ones. The extreme northern parts are almost wholly covered by volcanic rocks, except for some sandstones occupying the bottom part of the hills. This rock unit commonly forms a gently sloping topography.

The sandstones are unconformably overlain by these rocks. Lithologically they are dark grey-black basalts, which in some cases show brownish colors as a result of weathering. Both aphanitic and porphyritic basalts were observed in outcrop.

II.1.6. Alluvium and travertine.

The alluvium, which covers a significant proportion of the study area, are distributed mainly around the town of Hirna and some other west-central parts. In the vicinity of Hirna town they form low-lying plains, while in the west central part they form terraces. The thickness of the alluvial cover, as seen from seasonal river cuts is at least 3-4 m.

The alluvial sediments are formed of unconsolidated layers of gravels, sands and clays. Field observations have also shown the presence of a clearly developed alluvial cone at the basal part of a hill.

The travertines were observed in a small area along the start of the Hirna-Mesela road. They are creamy in appearence with dark and whitish bands observable. Another case of occurrence of travertine in the study area is nearby the Lower Sandstone-Limestone contact. Here numerous caves are formed displaying travertines in the form of stalactites.

II.1.7. Other Igneous Bodies.

Besides the volcanic rocks previously described, other groups of igneous rocks have been observed within the study area. Lithological subdivision of these igneous bodies can be made into those of basaltic and those of trachytic composition.

II.1.7.1. Basaltic intrusives.

Subunit-I of the Upper Sandstone has shown a thick basaltic sill occupying its upper part. This body has been met in a number of occasions. The greatest thickness recorded was in the central parts of the study area (SE mountains facing Hirna town). The thickness was 60-70 m. The interpretation of this igneous body as an intrusive is based on the rare field evidences of baking effect on the sandstones. Although not very clearly developed, frequently being covered by soil and highly affected by weathering, it occurs on both the bottom and top parts of the intrusion.

Numerous other basaltic dykes, although not very large, occur in the Lower Sandstone, Limestone and Upper Sandstone Units. One sample within the Lower Sandstone Unit, has revealed an evolved basaltic mineralogical composition (? Hawayite) when analyzed petrographically.

The basalts are highly weathered, showing brownish colors on their surface. Spheroidal weathering effects have also been developed in outcrops.

II.1.7.2. The trachyte

This body is found in the upper part of the Lower Sandstone Unit. It attains a thickness of 15-20 m. Outcrops have been observed along a number of the traverses taken, but the present field work was not deep enough to be sure of the continuity of the trachytes.

The rocks are physically compact and generally light colored with spots of dark colored minerals also present. No attempt was made to classify the rock in the field except for noting its acidic nature.

A single thin-section studied showed a trachytic composition affected by later silicification.

Begashaw (1987) has put forward stratigraphic evidence for the presence of Lower Mesozoic trachyte lavas and tuffs along the Southern Afar-Plateau margin.

It is probable that the trachytes of this study area could be correlated with these lavas and tuffs. But, more intensive field and laboratory investigations are recommended, to come up the true nature of the trachytes in the study area.

The trachytes are light colored, compact rocks.

II.2. CARBONATE MICROFACIES ANALYSIS

Analysis of carbonate thin-sections, of samples collected during the study of four stratigraphic sections has revealed the presence of three main microfacies repeating themselves in a cyclic manner. As seen from the stratigraphic columns constructed (Figs.5,6,7,8) the pattern of cyclicity differs from one section to the other. So does the extent of development of the different microfacies. Following this, the description of the three main microfacies will be given. Photographs of some thin sections are given in the Appendix.

Microfacies A

This microfacies is, by far, greater in proportion than the others distinguished during the analysis of samples from stratigraphic sections within the study area. It is predominantly represented by mudstones. Using Folk's terminology, these are mainly micritic microfacies - fossiliferous micrites in most cases.

The dominant allochemical constituents of the microfacies, when present, are obviously skeletal grains as the name indicates. In rare cases, however, peloidal allochems have been observed (G2). Sample B10 shows a microscopically intercalated packstone within the mudstone and it is interpreted as being a debris-flow which resulted from syn-depositional reworking. A clear size difference in skeletal grains is observed between those in the mudstone (fossiliferous micrite) and packstone (biomicrite) within it. The packstone consists of fossils of pelecypods, gastropods, echinoid spines and plates and corals. The identifiable skeletal grains in the micritic microfacies in general include pelecypods, ostracods, echinoid spines and plates, crinoids, gastropods, foraminifera, radiolaria and spicules. As seen from a number of samples (B23, B24, G1) spicule abundance reaches large proportions. Micrite envelopes have developed around some skeletal grains as seen from sample G10. The quantity of skeletal grains in different samples is quite variable ranging from scarce fossil remains in relatively pure micrites (sample B13) to quite abundant fossils in the occasionally met mudstone whose allochemical proportion is near the wackestone boundary (B8, G10).

A very small percentage (< 5%) of fine detrital quartz grains is seen in some samples. In a few samples (B13, G14) stylolite structures have been observed.

A common feature of this microfacies, is the presence of either rhomboidal dolomite crystals or rhomboidal voids.

Microfacies B

This microfacies is mainly represented by wackestones (Folk's biomicrite). Allochemical proportions are quite variable.

Skeletal grains which are the dominant allochemical constituents are quite abundant in most of the analyzed samples. Peloidal allochems are also present in some cases (G3, B18). The sample A15 shows a wackestone with intercalated debris-flow containing oolites. Intraclasts are also observable in some cases (G10).

Identifiable fossils within the samples of this microfacies are foraminifera, pelecypods, brachiopods, bryozoa, spicules, radiolaria and gastropods. The spicules show variations in abundance from sample to sample ranging from complete absence - presence in very large proportions (B21, B22). Fragments of stromatoporoids are also present.

A number of samples show a significant proportion (10 - 15 %) of terrigenous component (G3, G11, G17).

Extensive dolomitization sometimes resulting in dolostone (A11, G17) is observed. In other cases dolomite rhombohedra may be rare or entirely absent

(G11, G12). An additional diagenetic effect observable is micrite recrystallization. Samples G15 and B18 show that micritic constituents are represented by neomorphic sparite and microspar.

Microfacies C

This microfacies is represented by packstone and grainstone. Skeletal grains and other allochemical constituents are in some cases coated by micritic envelopes (B7, B19, G13). Pseudo-oolites are also frequent (B7, B12, B21, H6, A3, A12). Sample B19 shows clear oncolitic allochems.

Detrital quartz present in packstones show variations both in size and abundance (1-10%).

Microstylolites are also present. Several samples are affected by extensive dolomitization and / or recrystallization which gives rise to the presence of microspar and neomorphic sparite.

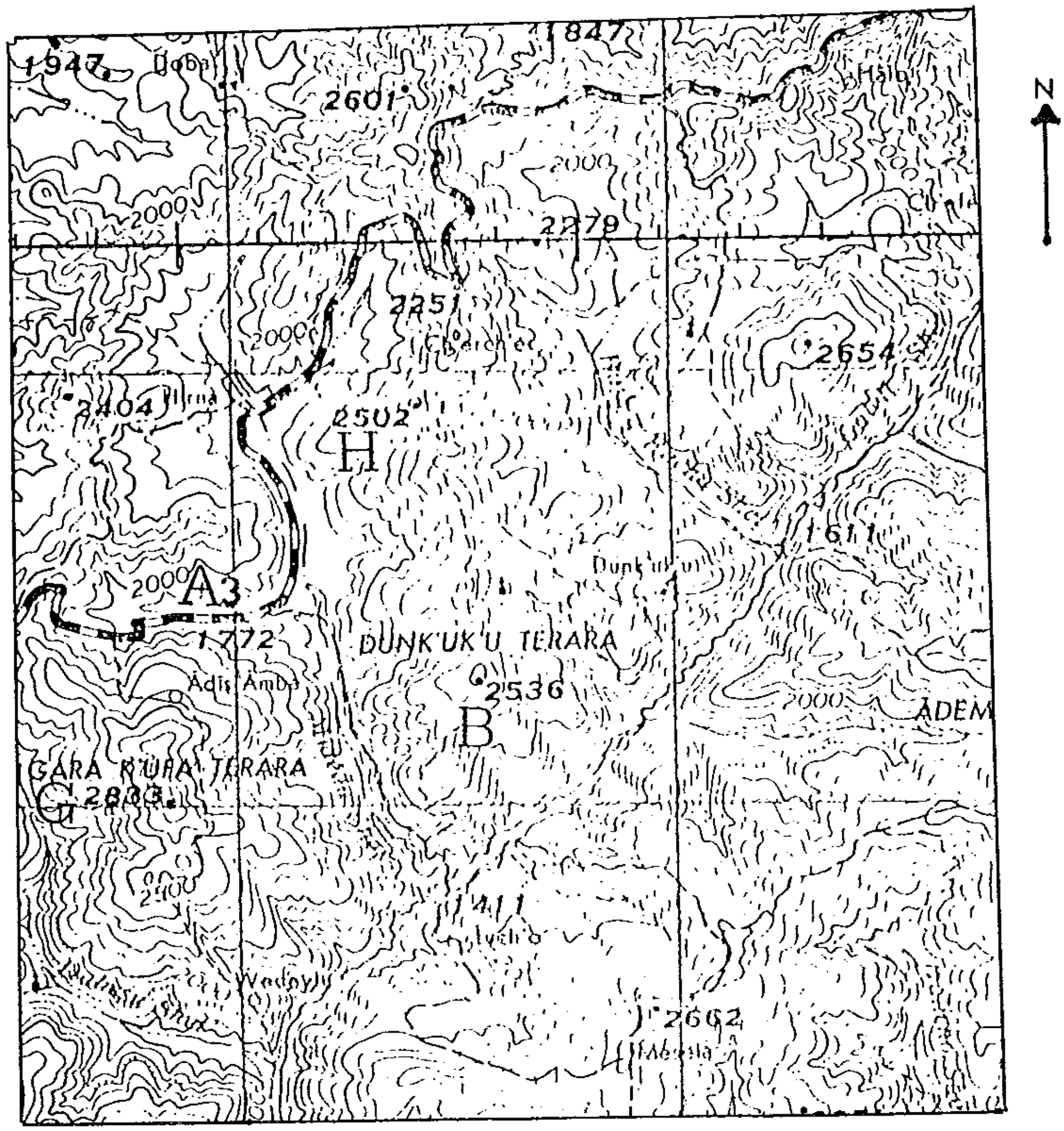

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Fig.4- Location of stratigraphic sections
(A , B , G and H)

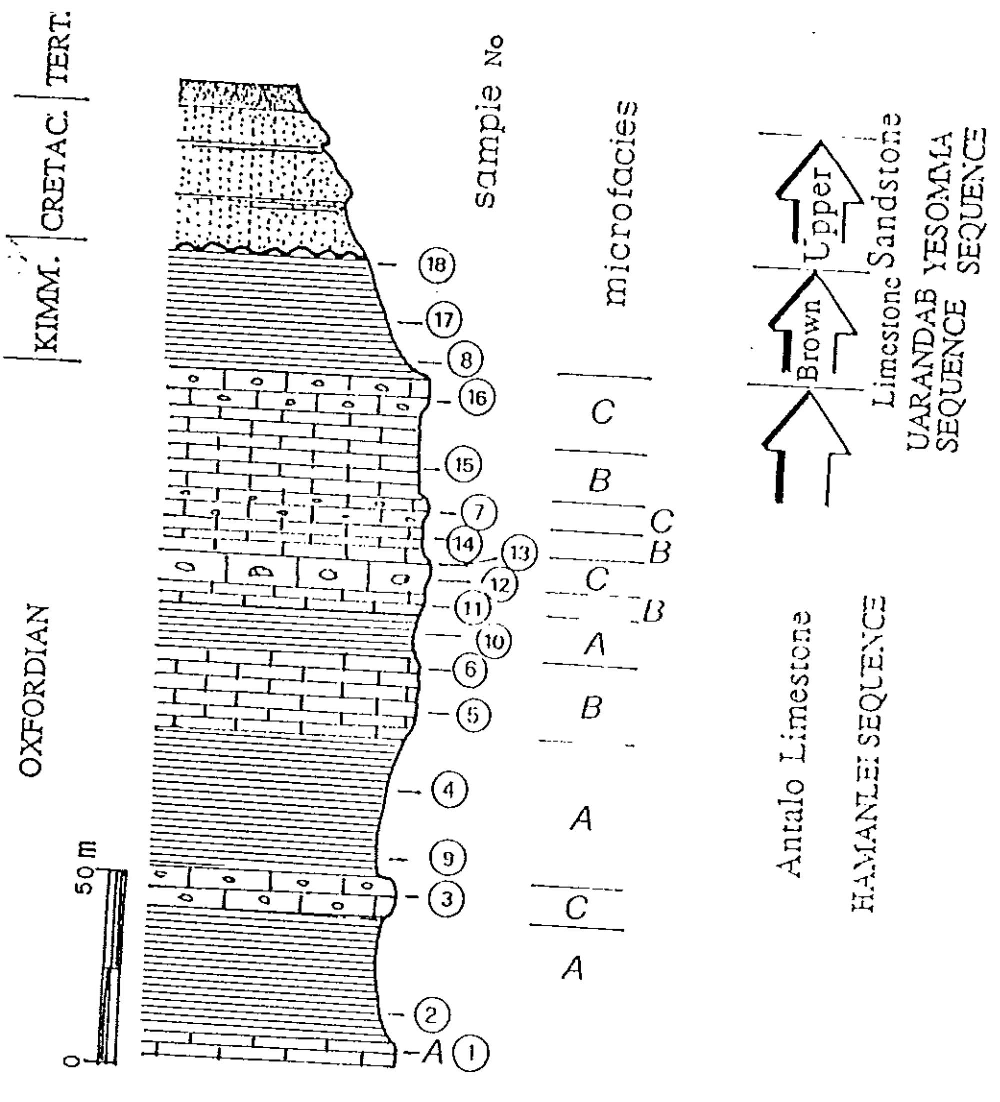

Fig.5- Stratigraphic section A

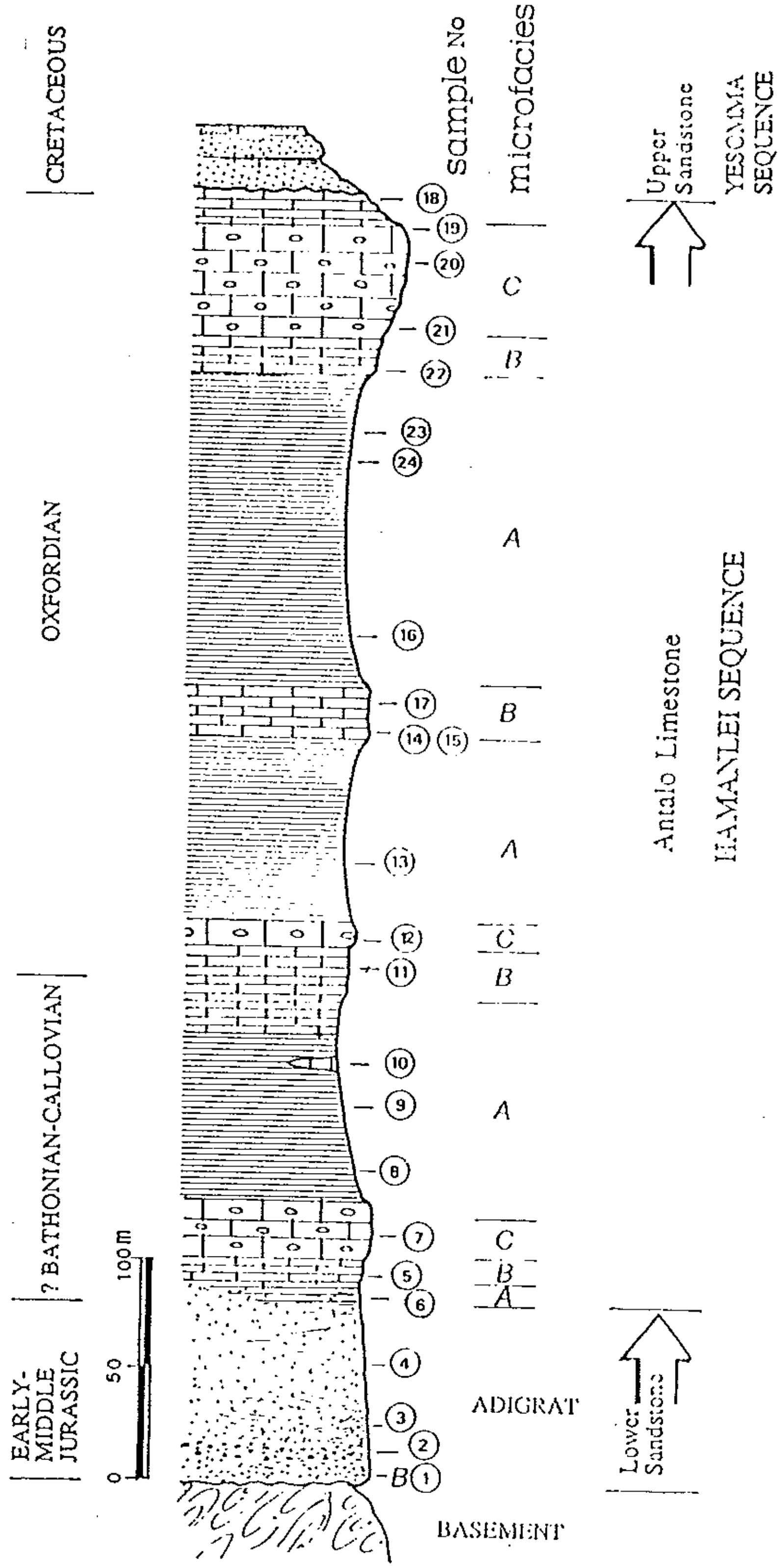

Fig.6- Stratigraphic section B.

COMPOSITE SECTION IN HIRNA AREA

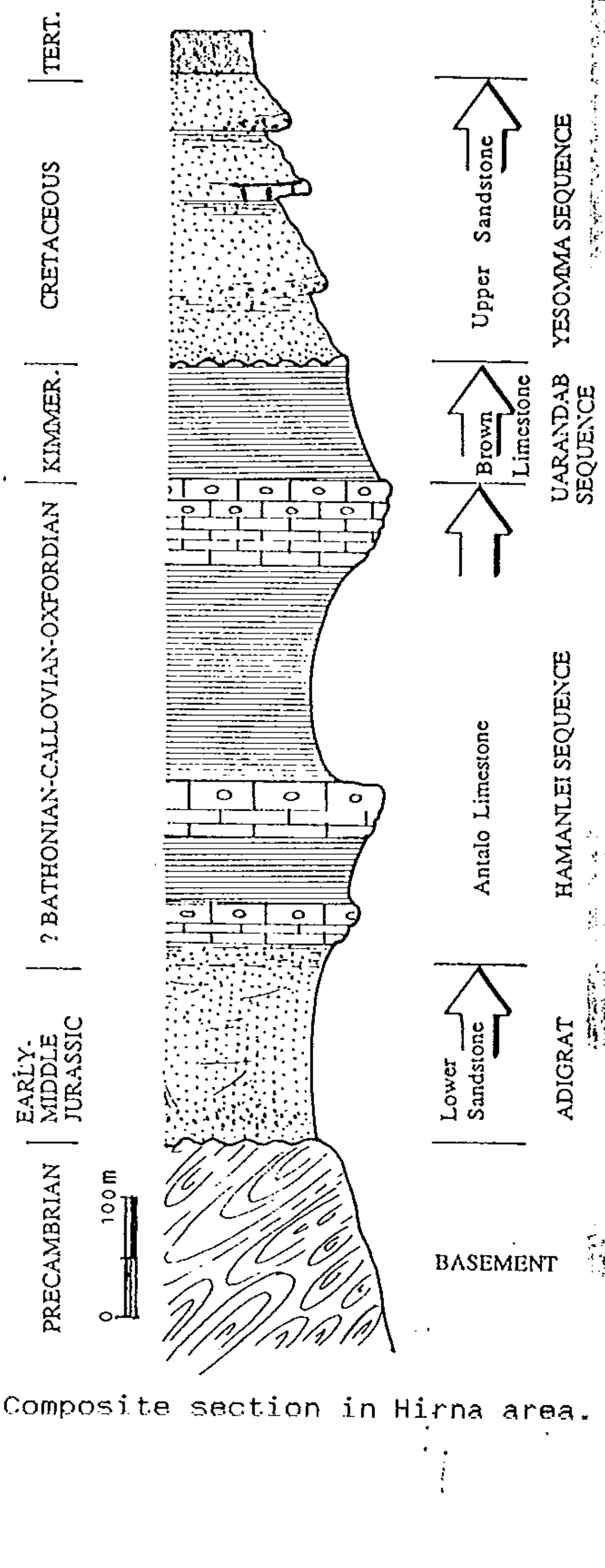

Fig.9- Composite section in Hirna area.

II.3. ENVIRONMENTS OF DEPOSITION

The Limestone unit in Hirna area was a result of a cyclic deposition on a shelf environment. The cycles are shallowing up, and they are constituted by three facies, which are repeated many times. Each cycle starts with a mudstone (facies A),continues with a wackestone (facies B) and ends with an oolitic packstone- grainstone (facies C). We interprete these cycles as being related to small variations of the sea-level.

As mentioned before the facies A (represented principally by mudstone) is more developed in the lower part of the Limestone unit, while in the upper part the oolitic packstone and grainstone (facies C) are thicker. This suggests a shallowing up general trend of the unit as a whole.

The presence of detrital quartz grains in a significant number of samples analyzed, suggests a source area nearby. The high proportion of detrital quartz sands at the base of the unit marks a transitional passage with the Lower Sandstone and it is indicative of a transition from a continental-fluviatile environment to a marine one.

In conclusion, the occurrence in this unit of the three microfacies in a more or less cyclic pattern suggests that water energy (turbulence) was changing from calm to turbulant also in a cyclic manner, related to small changes of sea-level. The presence of more developed packstones-grainstones towards the top of the sections also indicates that the whole succession is shallowing up.

It is not possible to make a full interpretation of the depositional environments under which the Lower and Upper Sandstones were deposited (from the present work). This is due to lack of sufficient information on petrography, paleocurrent data, texture and geometry regarding these units. General remarks, however, can be made based on available field observations and comparison with previous works on similar units.

The lower sub-unit of the Lower Sandstone unit was deposited in a fluvial environment. This is suggested by the presence of conglomerates at the base; the normal graded bedding <fining upward (FU) sequence> recognized at various levels; and sedimentary structures such as cross-bedding, horizontal bedding and lamination. The Upper Sandstone was also a result of a similar sedimentary environment. The presence of one layer of limestone very rich in marine fossils in the Upper Sandstone testifies to the vicinity of the sea.

II.4. BIOSTRATIGRAPHY AND AGE

With the absence of fossils in the Lower Sandstones of Hirna area, it is difficult to assign a sure age for the unit. But, noting that these sandstones are equivalent to the Adigrat Sandstones in nearby regions approximate age limits can be given.

A Lower-Middle Jurassic age is assigned by Greitzer (1970) for the Adigrat Sandstones in Dire Dawa and Harar areas. In Kersa area, a bit west of Harar and Dire Dawa, Getaneh (1987) has identified dinosour footprints in the sandstone which point to an Upper Triassic age. Thus, a broad age interval of Triassic-Middle Jurassic is possible for the Lower Sandstones in this area.

The Limestone Unit ranges in age from ?Bathonian-Kimmeridgian. The stratigraphic columns drawn for the different sections studied shows the ages of different portions of the limestone unit (Figs. 4,5,6,7,8).

Subunit 3 is present in all four stratigraphic sections (A, G, B and H). The age of this subunit is Kimmeridgian as indicated by the occurence of Lenticulina and Epistomina (Greitzer, 1970). Subunit 3 can be correlated with the Uarandab sequence in the Ogaden area.

The remaining lower part (subunit 1 and subunit 2), known also as Antalo Limestone, ranges from ?Bathonian to Oxfordian and probably reaches the Early Kimmeridgian. The ?Bathonian-Callovian is present only in stratigraphic section B, where it is documented by the occurence of Pfenderina sp. This species was found a few meters above the Adigrat Sandstone in sample B10.

Some authors (Crescenti & Sartoni,1962; De Castro,1962; Crescenti,1971, in Flugel,1982) indicate a Middle Jurassic age for Pfenderina, which disappears within the Callovian. Jaffrezo, 1990 (in Flugel,1982) shows a different range of Pfenderina, from Middle Bathonian to Early Oxfordian.

The Oxfordian is documented by the presence of Kurnubia palastinensis. Jaffrezo,1980, extends the range of this species to Early Kimmeridgian, associated with Alveosepta jaccardi.

In the present study I never found Pfenderina associated with Kurnubia. On the contrary, in the upper part of subunit 2, Kurnubia is associated with very rare specimens of Alveosepta jaccardi.

Additional benthic foraminifera in the observed samples include Nautiloculina oolithica, Ataxophragmidae and Valvulinidae. As mentioned before, Alveosepta jaccardi is present only in the uppermost part.

The presence of a limestone intercalation within the Upper Sandstone allowed the recognition of some specimens of Orbitolina, which indicates a Cretaceous age. Unfortunately, the absence of oriented sections, including embryonic chambers, prevented the specific identification, and consequently, a more precise dating of the rocks. However, Gortani(1973) dates the Upper Sandstone of Gara Muleta, 60 km. east of the study area, as Aptian-Albian. His dating was based on a fauna contained in a similar intercalation of limestones in the Upper Sandstone.

The volcanic rocks of the area are of Tertiary (Oligocene-Miocene) age. This is based on a number of absolute age determinations on the SE Ethiopian Plateau (Merla, 1979).

III. TECTONICS

From the tectonic point of view the area under investigation is lightly deformed. The sedimentary succession outcropping in the area is affected by gentle dipping (about 5°) towards south-east (Plate 9). Only a few fault-structures affect the terrains of the study area.

The prominent of these structures trends in a NE-SW direction extending from Adis Amba to the hill located in the north - eastern corner of the study area, having an altitude of 2654 m above sea level (Plates 10,11,12). This structure, morphologically marked by a small fault-scarp, is represented by a NW dipping normal fault which displaces all the sedimentary succession. It is characterized by a total throw of about 500 m, putting in contact the whole succession (from the basement to the Tertiary basalts), outcropping on the footwall, with the Upper Sandstone and the Tertiary basalts which outcrop on the hanging wall.

Along the valley where the Hirna town is located, another smaller structure trending in a direction similar to the previously mentioned prominent fault occurs. The presence of this structure is actually inferred by the distribution of different levels of the sedimentary succession along the opposite sides of the

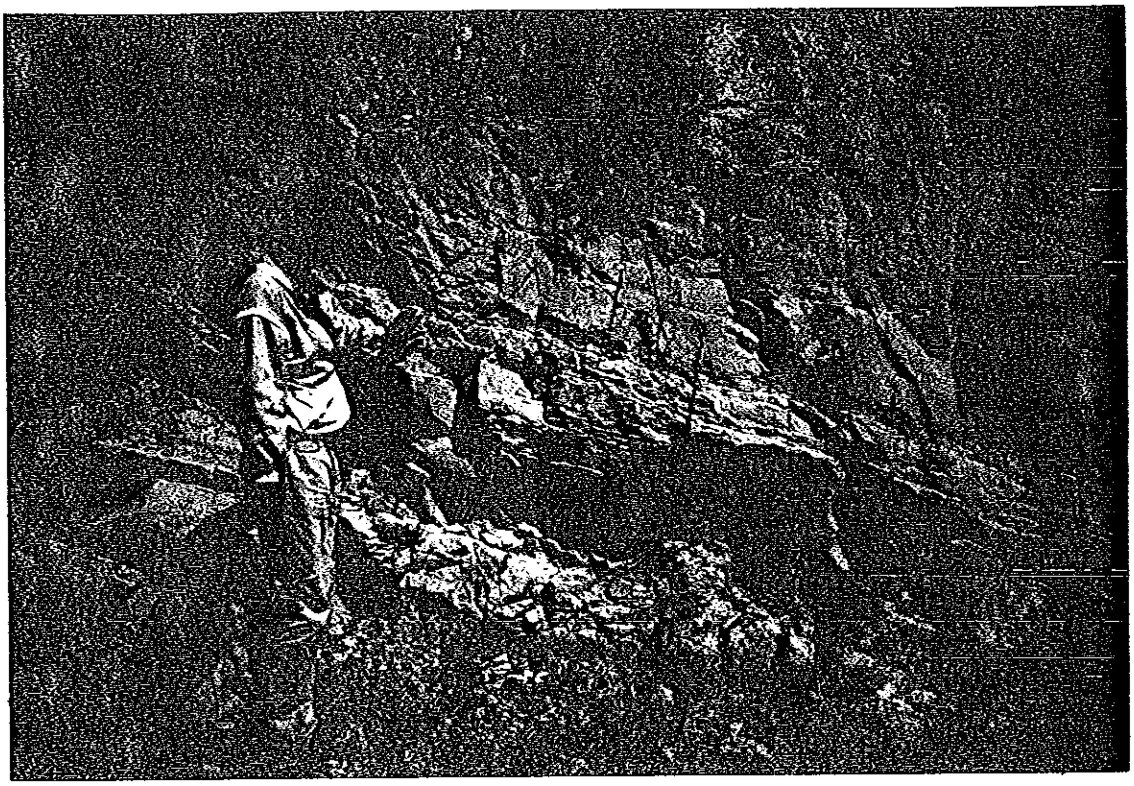

Plate 9- Gentle local dipping of the Upper Sandstone.

valley. Along the eastern slope, representing the footwall of the structure, most of the sedimentary succession outcrops while on the western one, representing the hanging wall, only the Tertiary basalts and a small part of the Upper Sandstones are exposed.

On the south-western border of the study area small N-S trending fault structures also occur. These are represented by westernly dipping normal faults showing throws of about 50 m.

Regarding the exact age of the fault trends occuring in the area it can not be accurately defined. The NE-SW trend has been activated after the Tertiary basalt flooding and we suppose that the tectonic event responsible for the development of this trend, is similar to the tectonic event which formed the E-W rift border extending up to Dire Dawa. Hence, the event may be related to the rift formation. Regards the north - south trend we do not know if it has been developed by the same tectonic event or not, because no relationship between the two trends has been observed.

The tectonic features occurring in the study area suggest that this sector of the SE Ethiopian Plateau was mostly influenced by epeirogenic movements. Following this, it was involved in the rift process responsible for the development of the NE-SW trending fault-structures occurring in the area.

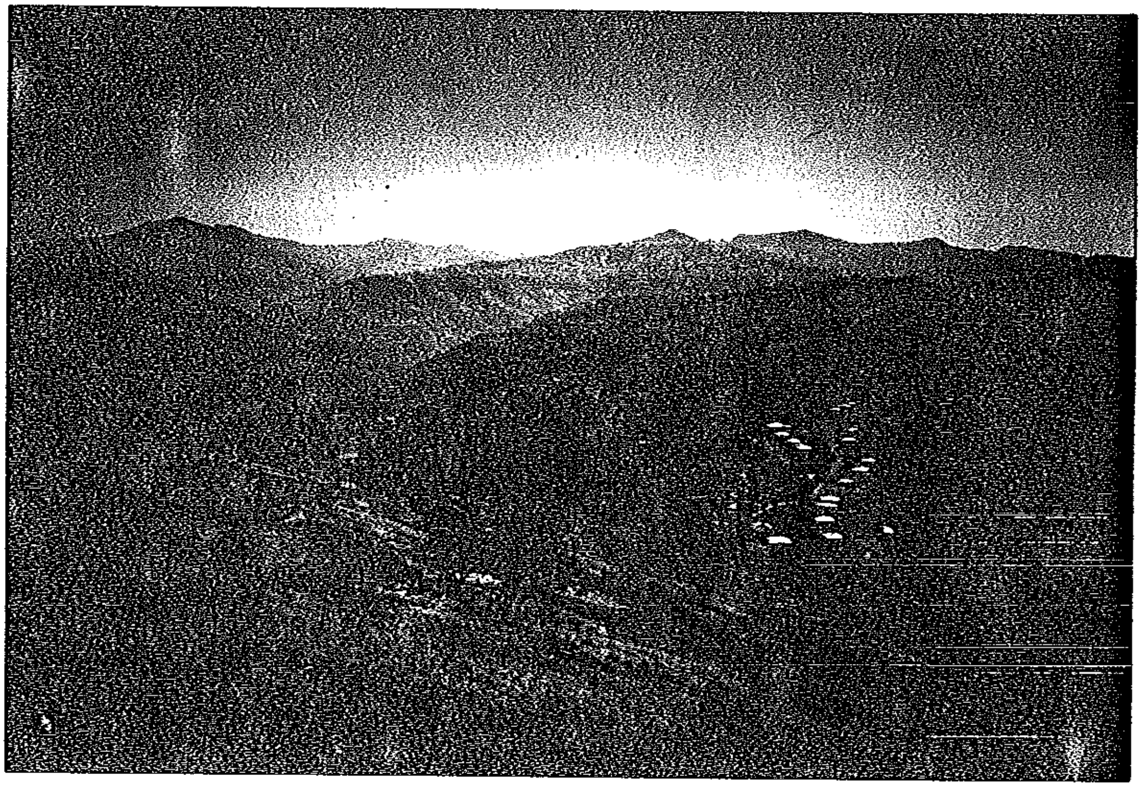

Plate 10- View of the prominent fault of the study area
(arrows point to fault scarp)

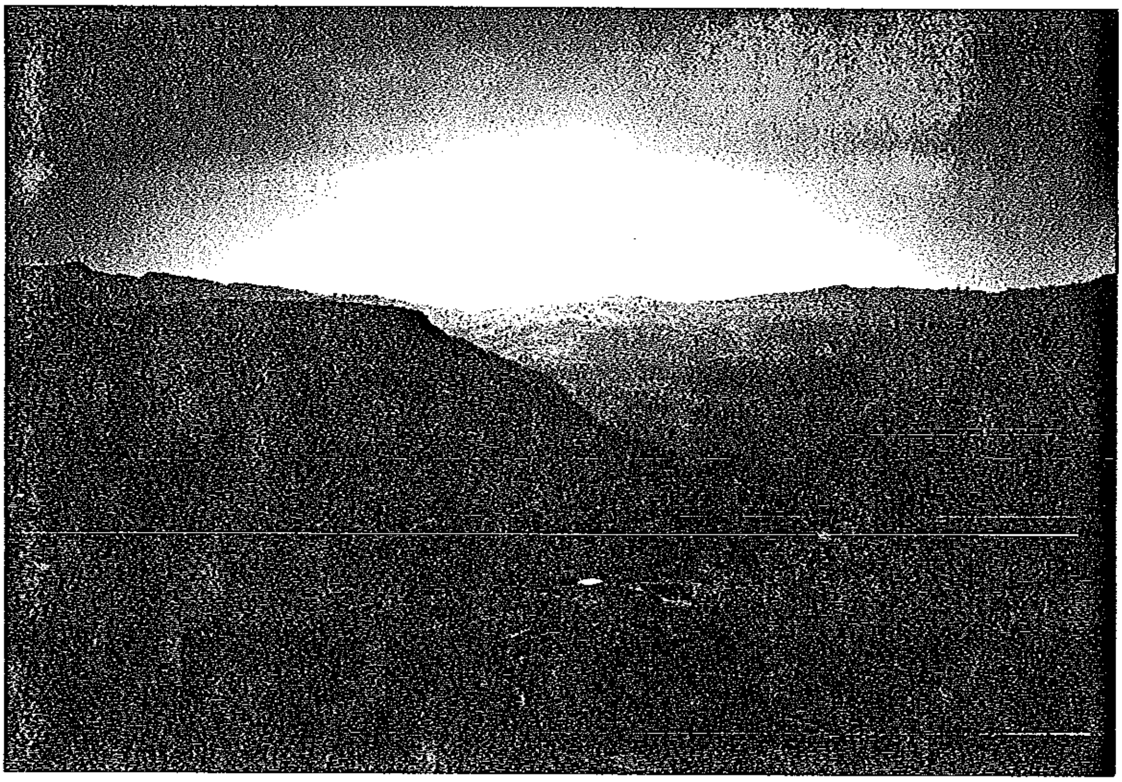

Plate 11- View of the prominent fault of the study area (arrows point to fault scarp)

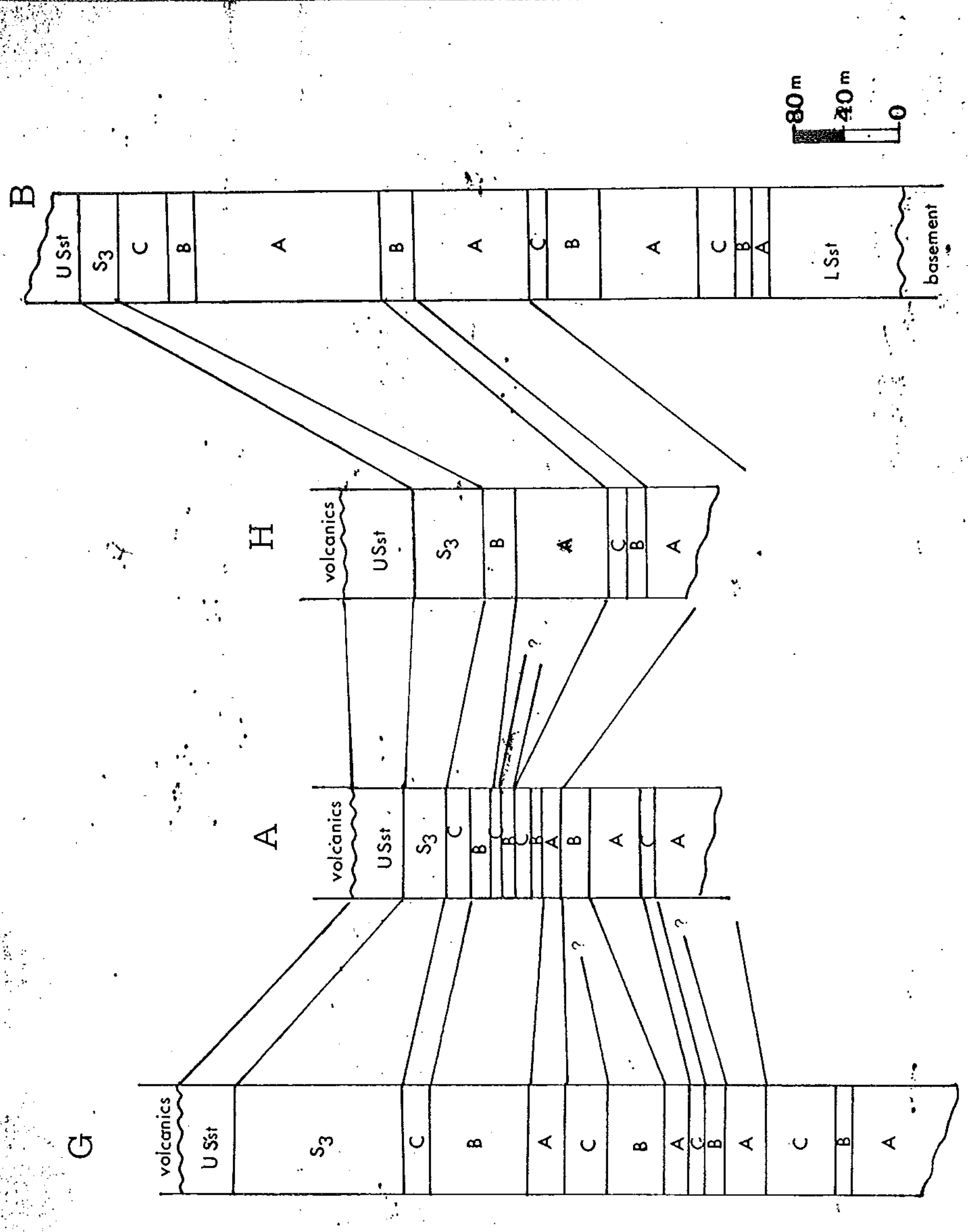

Fig.10 - Correlation of stratigraphic sections A, B, G and H.

A = Microfacies A L Sst = Lower Sandstone
B = Microfacies B U Sst = Upper Sandstone
C = Microfacies C S_3 = Subunit 3

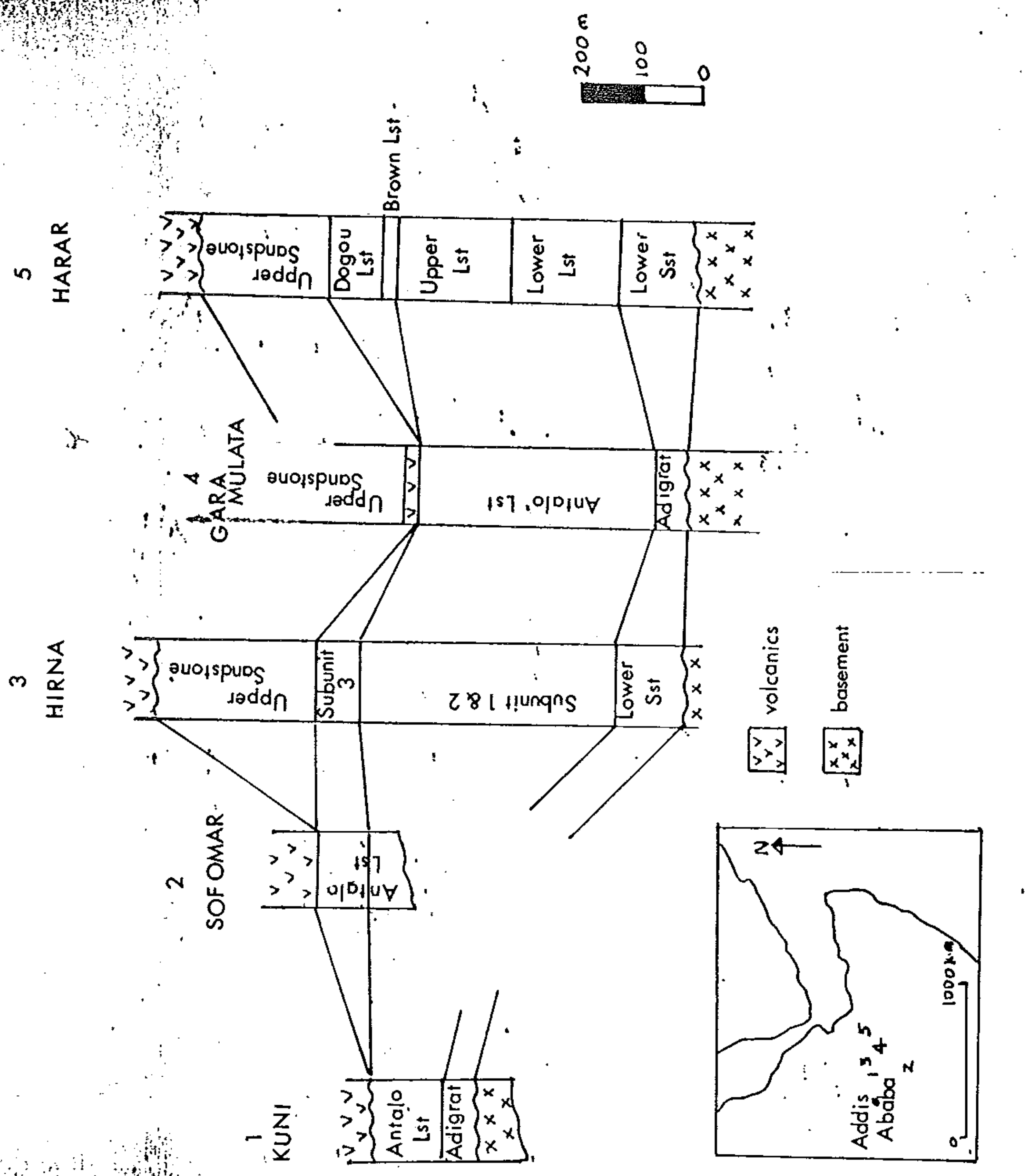

Fig.11 - Correlation of four successions from the SE Plateau with the Hirna stratigraphic sequence (the present work)
Harar region from Greitzer (1970)
Kuni, Sof Omar and Gara Mulata from Turi et.al (1980)

top is: Lower Sandstone - Lower Limestone - Upper Limestone - Brown Limestone - Dogou Limestone - Upper Sandstone (Greitzer,1970). The Brown Limestone and Dogou Limestone (Kimmeridgian) which are mainly composed of limestones and marly limestones are correlative with subunit 3 while the Lower limestone and Upper Limestone (Bajocian-Oxfordian) are equivalent to the remaining lower part of the Limestone Unit in the study area.

Turi et.al (1980) have studied the stratigraphy of a portion of the limestone unit (Antalo) in Sof Omer area. They have distinguished a lower part of dolomitic limestones (followed by layers of calcarenite, calcisiltite and calcilutite), a middle portion of yellowish dolomitic limestones (with macrofossils of corals, gastropods and pelecypods) and an upper part of pale brown calcareous dolomites. The upper part according to the authors is Kimmeridgian-Tithonian? and is correlable with subunit 3 of the study area while their middle and lower parts represent the upper portion of the Bathonian-Oxfordian limestones in my study area.

At Kuni, the Antalo Limestone overlies reddish sandstones (Adigrat). It is mainly made up of calcarenites and, to a lesser amount, calcisiltites and calcilutites, often extensively dolomitized (Turi et.al, 1980).It is of Bathonian-Oxfordian age and is equivalent to subunit 1 and subunit 2 of the study area.

The Antalo Limestone in the Gara Muleta section studied by Turi et.al (1980) overlies the Adigrat Sandstone. Lithologically it is made up of limestone, dolomite, calcarenites, calcisiltites and calcilutites. The rocks are at times marly. This limestone unit which is of Bathonian-Lower Kimmeridgian age is correlative with subunit 1 and subunit 2 of the study area.

In the Arsi Highland (stratigraphic sequence not presented in Fig. 11), which is in the western part of the SE Plateau, a Mesozoic succession of up to 1000 m. thickness is reported by Mohr (1971). The succession at Mt. Abulcassim, Mt. Jillet and Mt. Abunas is as follows:

5. Upper sandstone facies with Aptian fossils
4. Limestone with Neocomian fossils
3. Kimmeridgian marly limestone
2. Upper Oxfordian yellow limestone
1. Lower Oxfordian reef limestone

The Kimmeridgian marly limestones recorded by Mohr (1971) are probable equivalents of subunit 3, while the lower two units recognized here are the equivalents of the upper part of the Bathonian-Oxfordian limestones in my area.

V. PALEOGEOGRAPHY

The sediments outcropping in the study area can be referred to the terrigenous basal clastics or Adigrat Sandstone (Trias-Middle Jurassic), the marine limestone or Hamanlei sequence (?Bathonian - Oxfordian), the marlstone or Uarandab sequence (Kimmeridgian), and to the Upper Sandstone or Yesomma sequence (Cretaceous).

V.1. The basal clastics or Adigrat Sandstone.

The Adigrat Sandstone or Lower Sandstone of Greitzer (1970) represents the basal clastics overlying the peneplained Precambrian-Early Paleozoic basement. These terrigenous sediments are responsible for levelling the Late Paleozoic topography,and consequently thickness, facies and age is variable.

The thickness is about 700 meters in Tanzania, Madagascar, eastern Kenya, southern coastal Somalia, northern Ethiopia (Tigrai and Danakil) and western Yemen, whereas it is missing or extremely thin in western and southern Ethiopia, southern Yemen, northern and central (Bur Acab High) Somalia and north-eastern Kenya.

The depositional environment of the Adigrat Sandstone was mainly alluvional. The facies pass from fanconglomerates to lacustrine, deltaic or even to shallow marine sediments, as in Harar area where teeth and bones of Lepidotus fish (Muhlen, 1931) and marine molluscs (Clift, 1957) have been found.

The age of this basal clastic is referred to Triassic - Middle Jurassic.

Regarding Ethiopia, the Adigrat Sandstone, 200-300 m thick, outcrops in the Blue Nile basin. It overlies unconformably both basement and Paleozoic sediments, and extends from Shoa to Sudan border region.

In the Harar plateau, the Adigrat Sandstone is 30-200 m thick, and is represented by classic point bar sequences with marine influence in the upper part. The fossils found by Clift (1957) are Pseudomonotis sp., Pteria sp., Leda sp., Cardinia sp., Posidonomya sp., Ceratomya cfr Matagoiensis, Pholadomia sp., Thracia cfr. Incerta, Pleuramia sp., and Astarte sp.

Gortani and Bianchi (1937) proposed to assign these fossil assemblages to Upper Liassic. Recently, Getaneh (1987) assigns the lower unit of the Adigrat sandstone, outcropping near Kersa (Harar area), to Upper Triassic based on the record of Dinosaur footprints of the genus Anchisauripus. In northern Ethiopia (Mekele area), the Adigrat Sandstone overlies glacial rocks (Dow et.al., 1971) and has a maximum thickness of 670 m., whereas westward (Tekeze river) it is 80 m. and north of the Adigrat - Axum road disappears completely. The Adigrat Sandstone and the overlying Jurassic limestone probably were never deposited farther west of 37 (Lake Tana) or farther north of 17 N. (Bosellini, 1989).

In the northern Danakil Horst, Hutchinson and Engels (1970) observed a progressive increase in thickness of the Adigrat Sandstone from the Ethiopian Plateau (Tigrai) to the Red Sea coast; at Ras Adedda the sandstone is 1775 m. thick.

As pointed out by Bosellini (1989), at the beginning of the Jurassic most of Ethiopia and adjacent areas (Somalia, southern Arabian peninsula, Kenya, India and Madagascar) were in subaerial conditions. Facies and thickness patterns of the Adigrat Sandstone suggest deposition by braided or low-sinuosity streams.

The morphology of the basement was extremely variable, as testified by the difference in thickness of the Adigrat Sandstone deposits. Structural "lows" and intermontane basins were surely present among the "highs".

V.2. The Hamanlei sequence.

The ?Bathonian-Lower Oxfordian Limestone outcropping in the study area has been included by Turi et.al. (1980) in the Antalo Group (described also for the Blue Nile, north Ethiopia < Mekele area > and Dire Dawa and Harar regions), while Greitzer (1970) called it Lower Limestone.

In terms of sequence stratigraphy, these Jurassic limestones belong to the same depositional sequence known as the Hamanlei sequence, described by Bosellini

(1989) for the Somalia and Ogaden basins. Generally the Hamanlei succession overlies the Adigrat Sandstone. It lies directly on the basement only in some occasions (Danakil Alps, western Ogaden, Nogal uplift in Somalia, Yemen). The Hamanlei represents the transgressive surface of the Jurassic sea during its flooding of the continent. As the transgression was time-transgressive, the lower boundary is not coeval. This transgression was the result in part of the rifting stage heralding the Gondwana break-up and in part of the Mesozoic eustatic sea level rise (Bosellini, 1989). As pointed out by Bosellini (1989), the sea flooded the land from north-east, ie. from the paleo-Tethyan margin (Oman, Pakistan, northern India), following the most depressed pathways and initially forming a series of long and branching "fjord"-like marine sound. The initial flooding occurred in Early Liassic time (Hettangian - ?Simurian) along the Mandera-Lugh basin, whereas the Hirna and Harar areas were flooded in the ?Bathonian-Callovian time. The upper boundary is Callovian in Somalia, but reaches the Oxfordian in the Harar area.

The thickness is 210 m. in the type section outcropping near the village of Hamanlei in the Ogaden region, about 850 m. in south-west Somalia where it is known as Iscia Baidoa Formation and reaches 1558 m. in the El Kuran 1 well (Ogaden Basin). In northern and north-eastern Kenya an equivalent shallow water succession is called Didimu Bur Majo and Murri Limestone (Joubert, 1960). In the Blue Nile valley, north Ethiopia (Mekele area) and Harar plateau it is included in the Antalo Limestone Group.

Generally, the Hamanlei Formation is subdivided into three units: Lower Hamanlei, Middle Hamanlei and Upper Hamanlei. This subdivision, based only on vertical lithological facies changes, is evident in north Somalia, Ogaden and probably in the Blue Nile. In the Harar area and Yemen only the Upper Hamanlei is present (Fig.12).

The Lower and Upper Hamanlei succession is principally a carbonate unit associated with siltstone and calcareous shales. The limestones are mainly wackestones and mudstones with skeletal debris (lamellibranchs, brachiopods, gastropods, echinoderms, foraminefera, ostracods), reflecting deposition in low-energy, shallow marine environments. Some oolitic grainstone and skeletal packstone intercalations testify to the presence of episodes of very shallow-water environments with strong hydrodynamism. Generally, the Upper Hamanlei succession is organized in shallowing up cycles starting with mudstone and ending with packstone-grainstone units, sometimes including corals and/or sponges.

The Middle Hamanlei is principally constituted by

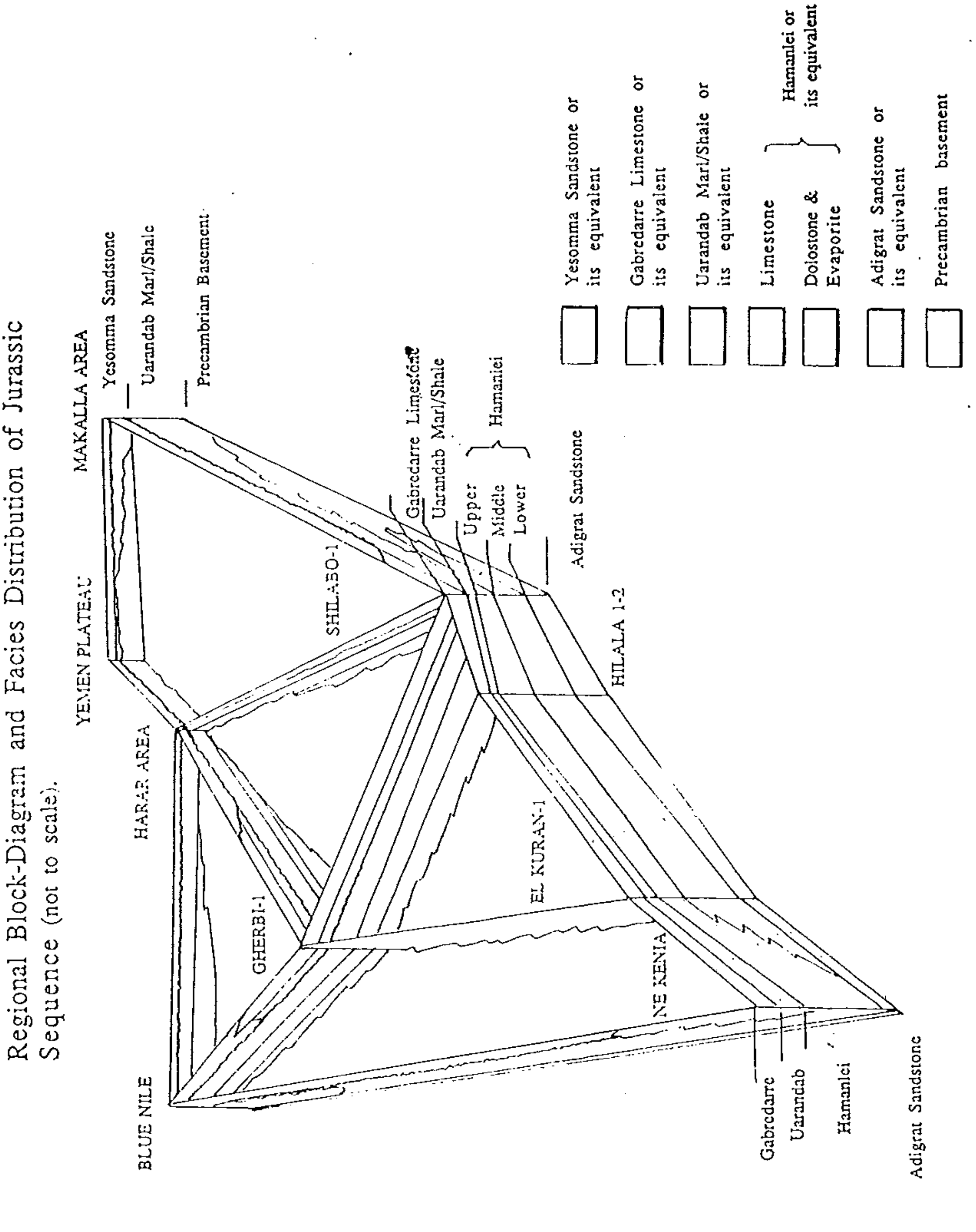

Figure 12- Regional fence - diagram and facies distribution of Jurassic sequences (not to scale).

anhydrite, dolomite and black argillaceous mudstone. Anhydrite commonly occurs as distinct beds, but it is also present as nodules and blebs within the dolomite. The dolomite is very finely crystalline where the original texture was unfossiliferous pellet mudstone or wacketone.

This carbonate platform passes with a gradational transition to a sequence of black, argillaceous lime mudstones, called Meregh Formation by Bosellini (1989), which directly overlie the Adigrat Sandstone, as it is possible to see from several well controls of the Mudugh Basin (Fig.13). These sediments, rich in pelecypods, gastropods, echinoderms, and sponge spicules, about 2500 m. thick, were deposited in low-energy, relatively deep and poorly circulated marine conditions. The Meregh Formation, which is the correspondant basinal facies of carbonate shallow water Hamanlei Formation, is confined to the Mudugh and Mandera-Lugh basins, and to the distal Indian Ocean continental margin.

In conclusion, the Jurassic flooding of East Africa, including north Ethiopia, Harar plateau and south Arabia was a time-transgressive event which protracted from Hettangian to Oxfordian. The timing of flooding was related to initial topography, timing of Gondwana rifting and gradual onlapping on to the craton. The intial flooding of the deep rift basins of Somalia

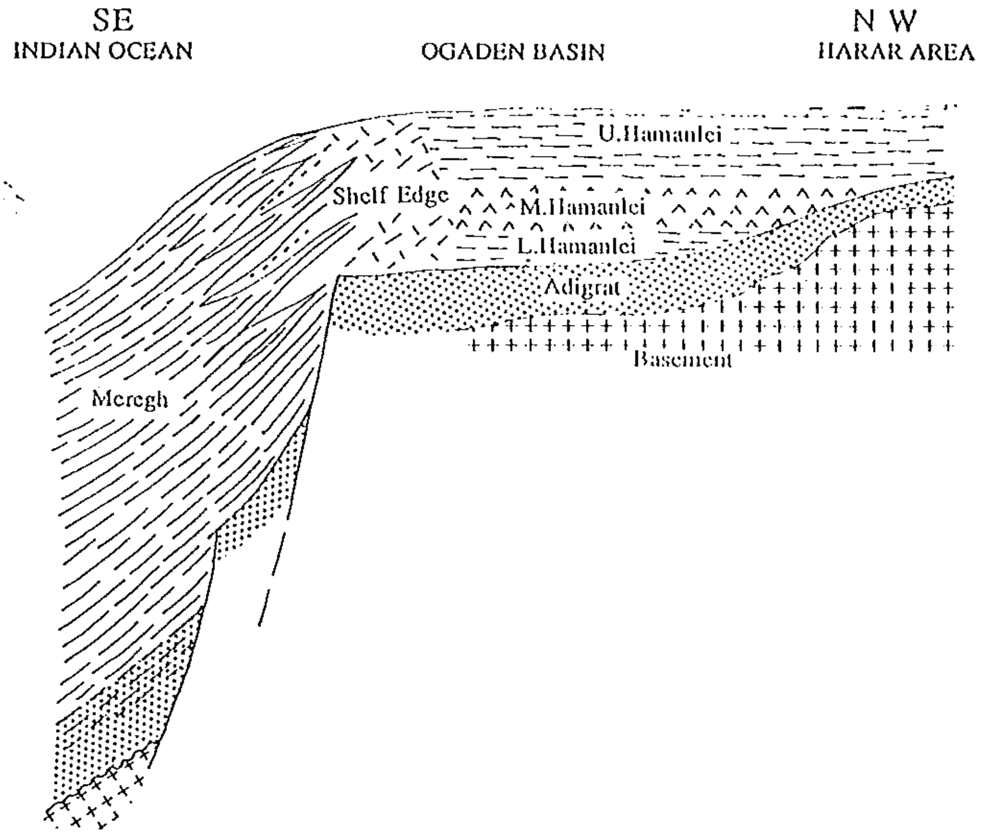

Figure 13.- Schematic cross-section from SE-NW showing the lateral variation of facies during Jurassic time.

occurred in Early Liassic time. Later, during the Pliensbachian, the Jurassic sea also flooded the adjacent shelves and "highs", and finally during Toarcian time, the entire Horn of Africa, except north-west Somalia and the adjacent Arabian block, was probably submerged (Bosellini, 1989).

To the north, on the Harar plateau and on the Arabian side of the Gulf of Aden, the carbonate Hamanlei sequence is Callovian to Early Oxfordian in age on the basis of fossil evidence, but with the Oxfordian, the transgression was general.

V.3. The Uarandab Sequence.

The Lower Kimmeridgian marlstones and mudstones outcropping in the study area, called Brown Limestone by Greitzer (1970), belong to the same depositional sequence known as the Uarandab Sequence and described by Bosellini (1989).

The Uarandab Sequence, which is mainly composed of shaly or marly mudstones and siltstones, overlies the thick-bedded oolitic packstone-grainstones of the upper most Hamanlei (Lower Limestone of Greitzer, 1970). The thickness varies from about 70 m. near Uarandab village, and about 100 m. in the Dire Dawa area, to about 1050 m. in En Dibirre-1 well (Somalia).

The age is Late Callovian-Oxfordian in Somalia and Kimmeridgian in north Ethiopia.

The Uarandab is widely distributed in Dire Dawa area, Ogaden, Somalia and east Kenya. Generally it is shallowing up, with greenish calcareous shales at the base followed upward by quartz siltstones and sandstones with parallel and ripple lamination.

Along the Indian Ocean continental margin, the Uarandab sequence is constituted by greenish grey shales and micrites. In north-western Somalia and north Ethiopia (including Dire Dawa area), the sea flooded the Adigrat landscape for the first time during the Bathonian (Antalo Limestone) and no major changes in lithology are observed through at least the Kimmeridgian.

In conclusion, as pointed out by Bosellini (1989), the major transgression occurred over most of East Africa in Late Callovian-Kimmeridgian, and is related to the final breakup of this area (Africa-Madagascar separation) and subsequent steady phase of regional subsidence.

V.4. The Yesomma Sequence.

The Cretaceous Upper Sandstone outcropping in the study area, which lies unconformably on the Uarandab Sequence, belongs to the depositional event represented by the Yesomma sequence (Greitzer, 1970).

It may partly be equivalent also to the Nubian Sandstone of Sudan and Egypt, the Marhan Sandstone of north-eastern Kenya, and Mukalla Formation of Yemen (Mohr,1962; Beydounn,1966). The Mukalla Formation, 100-300 m thick, is a siliciclastic succession constituted by cross-bedded sandstone with sparse thin layers of fossiliferous limestones, like the Upper Sandstone outcropping in the study area.

The Yesomma sequence is well defined and unconformity bounded all over southern Somalia and Yemen. In Ethiopia and proximal areas of the Mudugh and Mogadishu basins, it is represented by typical fluviatile facies.

The Yesomma sequence overlies progressively older formations toward the north, reflecting its position above a broad regional truncation. The Yesomma sequence gradually changes its lithology from west to east, and four general facies can be recognized:

i. a fluviatile facies

ii. a marginal, shallow marine belt of shale, sandstone and carbonate

iii. a zone of shallow-water carbonates

iv. a block-faulted basinal area with deep water claystone and shale (known as Sagaleh Formation), (Bosellini, 1989)

VI. CONCLUSION

The sedimentary succession studied is primarily composed of limestones and sandstones with subordinate amounts of mudrocks, shales and marls. The sedimentary units differentiated can be correlated with the regionally identified depositional sequences, namely, the Adigrat Sandstone, the Hamanlei sequence, the Uarandab sequence and the Yesomma sequence.

In age the sediments occupy a large part of the Mesozoic Era. The Lower Sandstone Unit (Adigrat Sandstone), lacking fossil remains in the study area, is assigned a probable Triassic-Middle Jurassic broad age limit. This is based on comparison with other works on the SE Ethiopian plateau. The Limestone Unit as a whole is ?Bathonian - Kimmeridgian. Age determinations were based on the forams contained within the samples studied. The part correlated with the Hamanlei sequence is ?Bathonian-Oxfordian while the Uarandab sequence is Kimmeridgian. The Upper Sandstone Unit (Yesomma sequence) is of Cretaceous age as shown by the fossils in a limestone intercalation within the unit.Comparison with a similar intercalation in a nearby region (Gara Muleta) suggests an Aptian - Albian age.

The sandstones range from fine to very coarse in grain size while the shales and mudrocks exhibit various degrees of consolidation. The limestones, on which particular attention was paid, are of three main microfacies (designated microfacies A, B and C).

The microfacies distinguished may conveniently be described as

- a mudstone microfacies (microfacies A)
- a wackestone microfacies (microfacies B)
- a packstone and grainstone microfacies (microfacies C)

the various particular aspects of each having been described in the relevant chapter. The rocks have been diagenetically affected to various extents. The main diagenetic processes involved were dolomitization, de-dolomitization and micrite recrystallization.

Generally speaking, the Limestone Unit in Hirna area was deposited in a shelf environment in which cyclic deposition occurred due to small changes in sea level. A number of cycles, each made up of the three microfacies identified, are evident from the analysis of samples from stratigraphic sections. The cycles are interpreted as being a result of small variations of sea level in a shallowing up sequence. The whole succession made up of these small cycles also has a shallowing up trend. This is observed from the proportional increase of microfacies C as we go from bottom to top of a section.

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APPENDIX

(Thin - Section Photographs)

Plate 13- Sample B-7
Magnification x50 ; Plane light
Packstone showing bioclasts with micrite envelopes; micrite envelope around echinoid plate (a); molluscan fragments (b)

Plate 14- Sample B-7
Magnification x100 ; Plane light
Packstone; brachiopod shell (a), dolomite rhomb (b)

Plate 15- Sample B-12
Magnification x100 ; Plane light
Packstone with peloids; peloids (a), sparite (b)

Plate 16- Sample B-19
Magnification x50 ; Plane light
Packstone with clear oncolites; large oncolite seen at center of plate with two others below it at the right and left

Plate 17- Sample B-10
Magnification x50 ; Plane light
Packstone showing foram ; Pfenderina at the center of the plate.

Plate 18- Sample G-21
Magnification x100 ; Plane light
Dolomite crystals replacing calcite; rhomboidal form of the dolomites clearly developed

Plate 19- Sample H-1
Magnification x50 ; Plane light
Mudstone with forams; Kurnubia palastiniensis (a & b) within a carbonate mud (c)

Plate 20- Sample H-1
Magnification x100 ; Plane light
Mudstone showing forams; Kurnubia palastiniensis (a) covering most of the field of view, gastropod shell fragment (b)

Plate 21- Sample H-7
Magnification x50 ; Plane light
Mudstone showing forams; _Kurnubia palastiniensis_ (a) shell fragments of pelecypods (b)

Plate 22- Sample H-7
Magnification x100 ; Plane light
Mudstone showing forams; _Kurnubia palastiniensis_ (a)

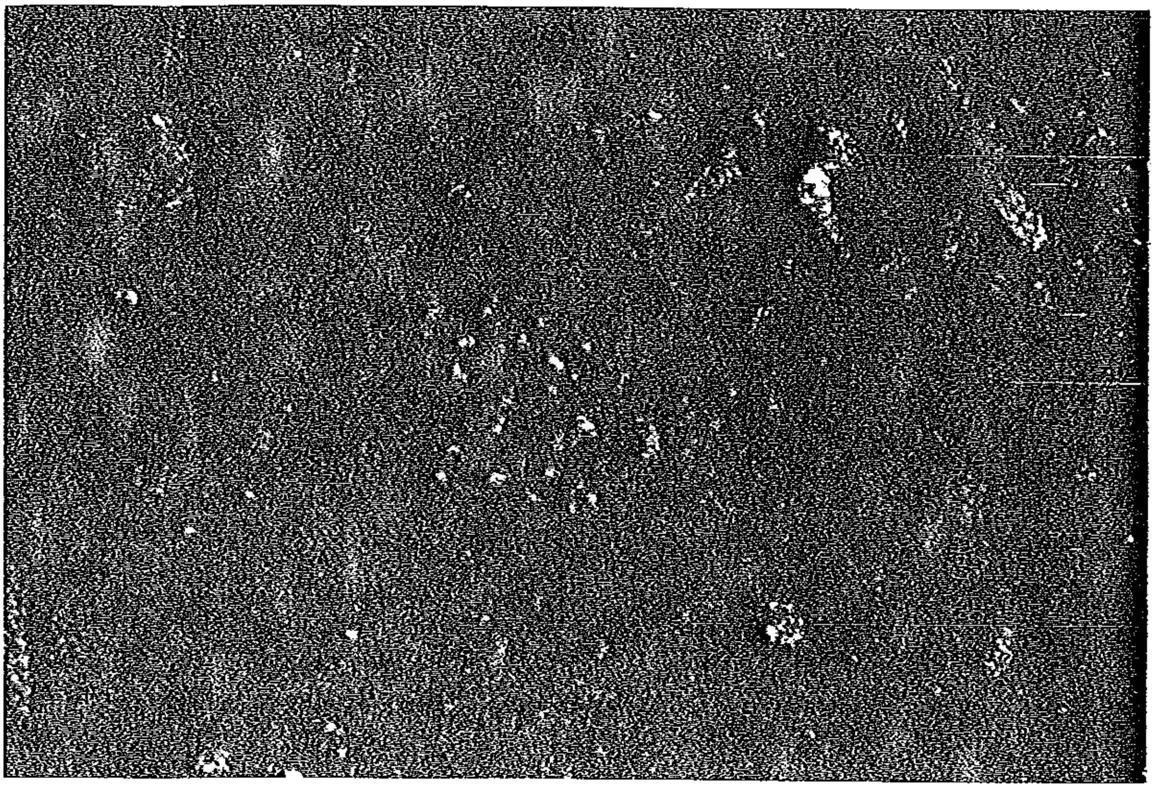

Plate 19 ×50

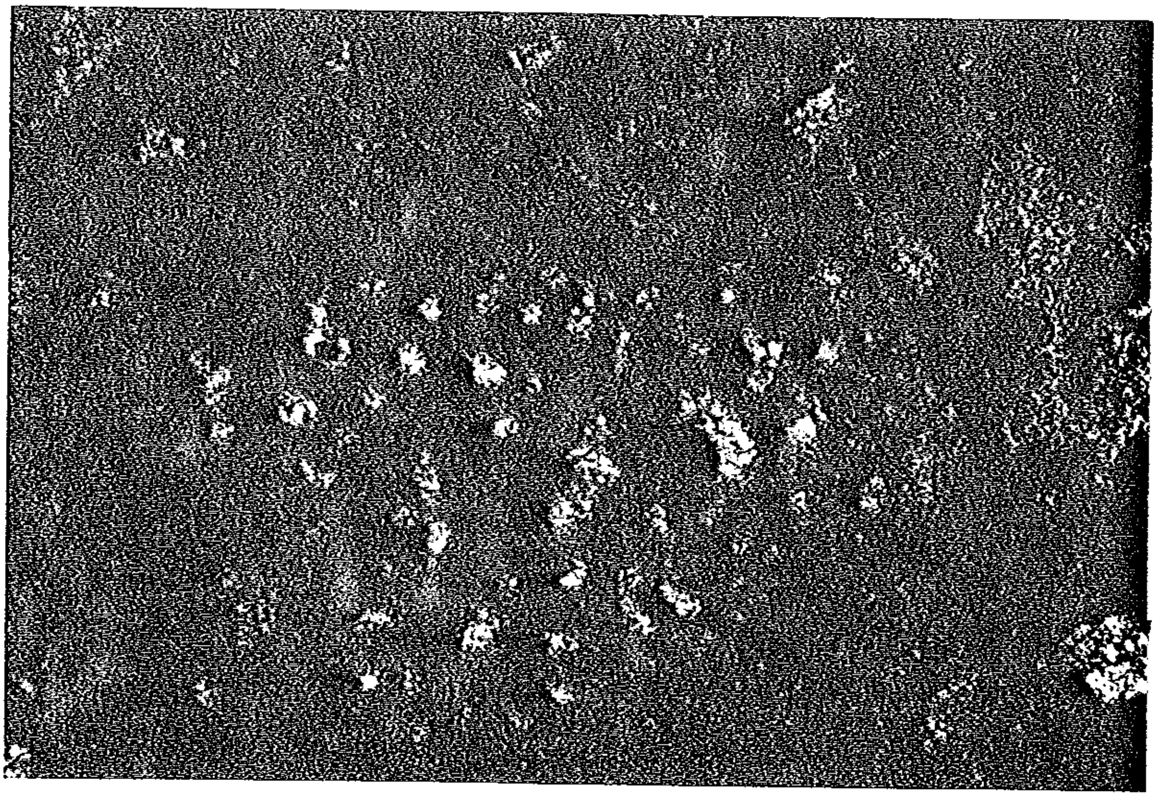

Plate 20 ×100

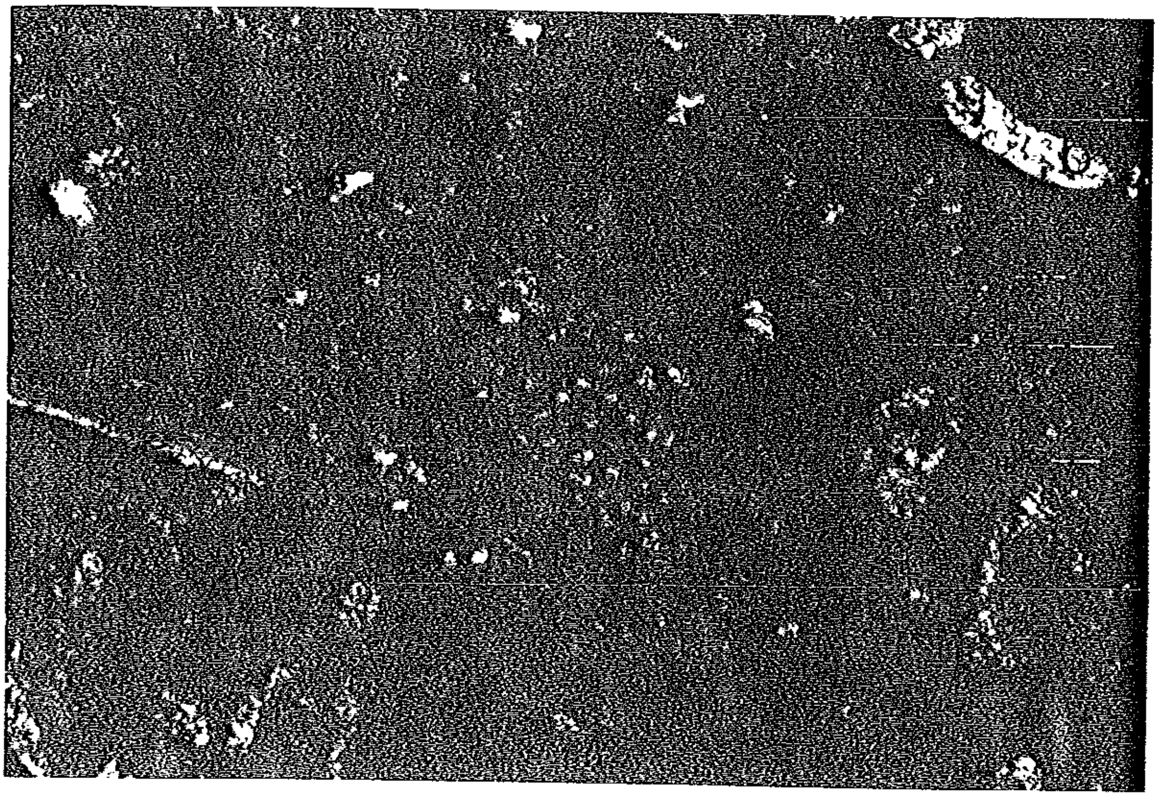

Plate 21 ×50

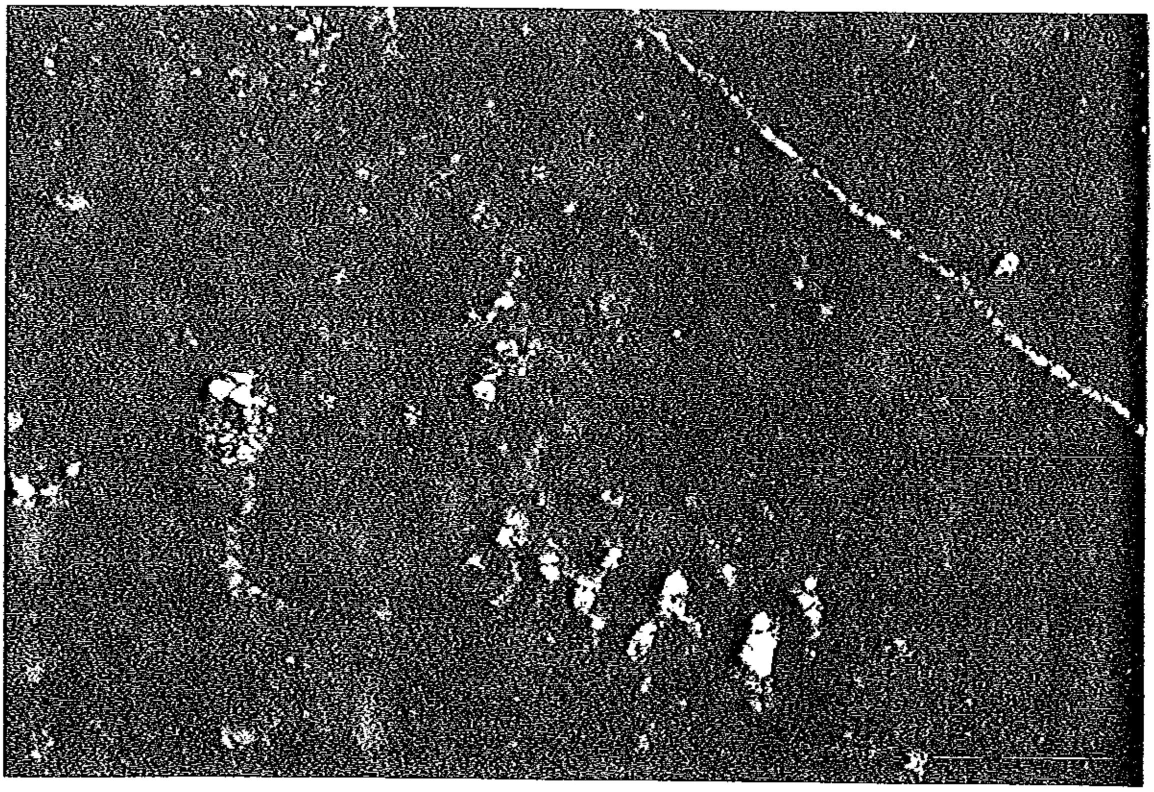

Plate 22 ×100