RELATIONSHIPS BETWEEN GEOLOGY, MORPHOLOGY AND SOIL ASSOCIATIONS OF BICHENA AREA (S.E. GOJAM)

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by

Teklewold Ayalew
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ABSTRACT

The study investigates the extent of influence of the geological history, essentially parent rock, topography and time, on soil formation and distribution in Bichena, Southeastern Gojjam.

Lithostratigraphy of the Mesozoic sedimentary sequence and Cenozoic volcanics is described. An attempt has been made to reconstruct the morphologic evolution of the area. Four soil mapping units in close relationship with the parent material and geomorphology have been differentiated: Vertisol, Mollisol, Alfisol and Entisol Orders. The soils are found to assume different states when the above considered soil forming factors are changed.

The vertisol development from aphanitic basalts is determined by the evolution of the structural plateau geomorphic surface through lateral planation, which has allowed for two cycles of pedogenesis. The Mollisols have developed from porphyritic plagioclase-Olivine basalt. These indicate that soil parent materials with similar mineralogy give way to soil varieties. A lateral variation in some soil properties of the Mollisol order is found to be strongly explained in terms of the slope gradient. The study shows that the Plio-Pleistocene neotectonic uplift and subsequent development of a deep canyon including morphogenetic threshold slopes has resulted in lack of sufficient time for pedogenic horizons to develop in Alfisols and Entisols.

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1. Introduction

An attempt to picture Geology in its many and varied facets is undertaken in the text. These are major soil genetic factors which present a problem in soil science and there has been no complete elucidation to date of their interdependence.

In Ethiopia, as in most underdeveloped countries, land resource appraisal and evaluation for economic development is essential. Except for very few local areas, no comprehensive scientific study of the various land resources of the country exists. This work is in the framework of the on-going activities of the Land Use Planning and Regulatory department of the Ministry of Agriculture (MOA), an organization entrusted with this responsibility, with particular emphasis on prediction of the agricultural potential of the entire country.

Agriculture is the major economic activity in the country. However, agricultural development without a systematic evaluation of the country's land resources such as geology, landforms, soils, hydrology and climate, is limited both in scope and extent, and therefore an incomplete base for development planning. In order to assist the farmers on how to best use the land, more precise soil information than presently exists is necessary and detailed soil surveys represent the best means to obtain it. However, in this study, a more general approach has been taken, one which is only a fraction of what it should be for the most effective agricultural development.

In the present study, an effort has been made to give sufficient inventory of the geology, morphology and associated soils to meet the requirements of a resource survey. A soil study proper benefits from a preliminary study of the parent material of the soils. The character of the parent rocks, their mutual relations and the relative times of their deposition, and the sequence of morphologic evolution, to some extent determine the nature and present development and distribution of the soils. The study areais believed to represent the soils formed by the bulk succession of rocks and morphologic settings of the central Ethiopian plateau. The deep river valleys together with the major Blue Nile canyon, as it passes across the length and width of the study area, exposes the geology of a considerable portion of the Ethiopian Plateau.

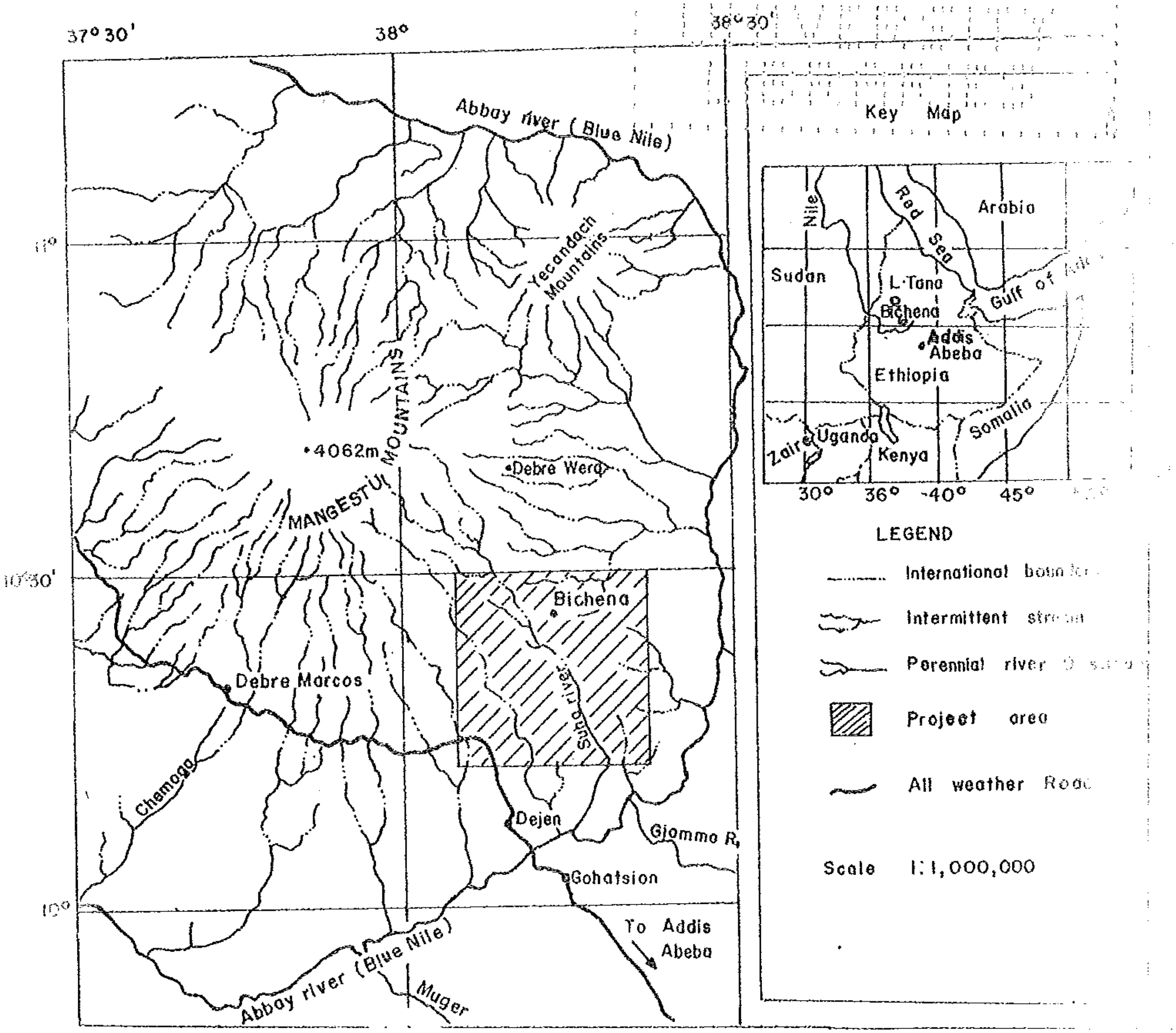
The soil behavior of any one characteristics is significantly influenced by the geological history as is shown in the subsequent discussion. In addition, previous studies on soil forming factors such as climate, vegetation and related land use is reviewed and quoted in the text.

1.1 Geographical Setting

The study area is situated, 38°05' - 38°22'E, 10°13' - 10°30'N, in the central part of the Blue Nile basin in south-eastern Gojjam administrative region, with a total area coverage of 900 square kilometers (Fig. 1). It encompasses the town of Bichena, 250 kilometers north of Addis Ababa. An asphalted road from Addis Ababa to Dejen, and an all-weather gravel road from Dejen to Bahir Dar run through the area. In addition to these roads, there are numerous trails, most of which can be traveled by four wheel drive vehicles in dry weather.

Generally, the Ethiopian highlands rise to altitudes in excess of 2000 meters forming an extensive uplifted plateau, bisected by the main Ethiopian and Afar rift escarpments in the east, and by lower and less defined escarpments in the west which decline gently to the Sudan plain. The study area generally slopes to the East and Southeast towards the major river valley of the Abbai. It is bounded on the northern and western limits by a degrading shield volcano, mount Mangestu, and the eastern and southern limits by river valleys which open into the Blue Nile river valley with vertical and precipitous cliffs developed from Tertiary basalts and Mesozoic sediments. Generally, it is a submature upland valley which has been strongly influenced by water erosion.

Figure I LOCATION MAP



1.2 Climate

Insufficient data limit the precise determination of the volume and intensity of rainfall, and variations in air temperature in the study area. Nevertheless, the best approximation is here forwarded with reference to other areas having more complete records and similar climatic patterns.

Daniel Gamechu (1977), recognized eight rainfall regimes in Ethiopia each with a characteristic seasonal distributions of rainfall. Accordingly, the study area is designated as Regime ID, where there are seven rainy months from April to October; and small rains at the beginning and the end of the rainy season. The heavy rains are from May to September, with a high concentration of rainfall in July, August and September. The seasonality of rainfall outlined above indicates the likely timing of the rainfall. The type of precipitation of the regime is graphically represented in Fig. 1. The mean annual rainfall amount recorded for the regime is 1400-1800 mm.; and a humid moisture region is recognized.

The volume and season of water surpluses, deficits, soil moisture recharge and soil moisture utilization is significant in particular from groundwater, hydrology and soil conservation points of view. A water budget calculation and climatic data established for Debre Marquos, the closest station to the study area, is given in Table 1.

Table 1. <u>Climate and Water Budget Data for Debre Marqos. (After Daniel Gemechu, 1977)</u>

		J	F	M	A	M	J	J	A	S	O	N	D	Average Annual	Average per day
Debre Marqos	Temp.	15.5	16.5	17.3	15.9	14.2	14.4	13.2	13.2	14.1	13.2	13.4	13.3	–	14.5
IM = +61	RF	2.34	1.76	5.7	7.7	6.16	18.44	31.72	31.74	22.25	7.65	0.76	1.81	138.03	–
10.21N	PE	7.80	7.74	9.48	8.24	7.13	7.21	6.48	6.42	6.73	6.12	6.08	6.14	85.57	–
2411m	Deficiency	5.46	5.98	3.78	0.54	0.97	–	–	–	–	–	–	0.35	17.08	–
	Surplus	–	–	–	–	–	1,23	25.24	25.32	15.52	1.53	–	–	68.84	–

Legend:

Legend:	PE	– Potential evapotranspiration according to Thornwaiite formula
	Temp.	– Temperature in °C; other data in centimeters
	IM	– Moisture index
	N	– Degrees & minutes North latitude
	m	– elevation above sea level in meters

The difference between rainfall and potential evapotranspiration is noted for each month as water surplus or deficiency, taking into account an average soil field capacity of 10 cm. There is a total water deficiency of 17.08 cm. from the last week of December to the end of May. From the end of May to the end of June, there is soil moisture recharge. The total water surplus is 68.84 cm., with highest surplus in August, when streams come to peak flow. There are six months of surplus water with considerable soil moisture available for ideal plant growth. The high water surplus reflects the high rainfall and/or low potential evapotranspiration. This fact together with the existing suspended shallow water table account for the wetness or waterlogged nature of the soils in the area.

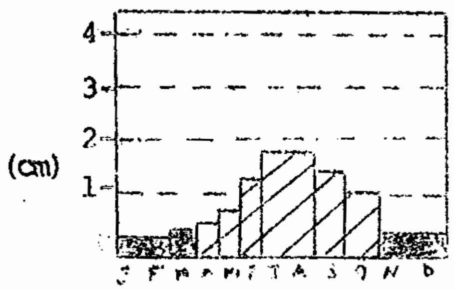
Fig. 2. Precipitation of Regime ID (After Daniel Gamechu, 1977)

Legend: Rainy months

Relatively dry months

Ordinates of graphs are coefficients of precipitation.

Coefficient of rainfall define the dry and rainy months.



1.3 Vegetation and Land Use

Extensive cultivation and deforestation have left a sparse cover of natural vegetation of grass, shrubs, and small trees. Generally, Savanna type vegetation associations are present. The plant species as studied and recorded by Le Houeron (1980) for the eastern portion of Gojjam administrative region are: Ficus salicifolic, Euclea schimperi, Acacia etbaica, Acacia abyssinica in the deep river valleys; Stereospermum kunthianum, Croten macrotachys, Cordia abyssinica in the plateau surface; and on higher surface Podocarpus gracilor and Juniperus procera on higher surfaces.

The area has a humid temperate climate and supports a variety of crops; the major ones being Eragrostis tef (teff), Triticum spp. (wheat), Bicolor spp. barley, Hordeum vulgare (sorghum), Gizotia abyssinica (noog), Lathyrus sativus (sweet peas). Lens esculenta (lentils), and Cicer aristinum (chick peas). The vast gently sloping surface and the adjacent, near level plain are the major agricultural sites. These are cropped once or twice a year. Soil erosion is active in these areas as is evident from comparisons of the present observations with the evidence of aerial photos of 1957 Gregorian Calendar. Teff cropping has spread over much of the low lying but not permanently waterlogged areas. Crops requiring a well drained friable root zone are grown on the hillslope. A considerable portion is devoted to pasture, usually in places where it is too wet for cropping. Livestock plays an important part in the farm economy. Except where some shrubs and Eucalyptus occur, the inhabitants use dried dung and plant residue as firewood.

On the benched slopes of the river valleys some sorghum and teff are grown, and the rest of the valley is barren except for the presence of scattered small trees here and there. The edges boardering the valleys known as "Ambas" were historically chosen as places of settlement due to their strategic positions.

1.4 Previous Work

The main expusures of the Mesozoic sequence in relation to the succession and classification of the sediments in the Abbai valleys and its tributaries was worked out by Blanford (1870), Aubry (1886), H. Donville (1886), Futterer (1897), Krenkel (1926), Stefanini (1933), Jepson & Athearn (1961), Elwerath Oil Co. (1967), Getaneh A. (1975), and Beauchamp (1977). The stratigraphic, petrographic and sedimentologic analyses of Getaneh A. (1975) provide a basis of recognition of five informal rock units.

Studies pertaining to the Cenozoic rocks of the plateau including chronology, petrochemistry, petrogenesis and nomenclature, have been done by Grasty et al., (1963), Abbate et al (1968), Gass (1970), Mohr (1972), Zannetin et al (1974), Beauchamp and Lemoigne (1975), Kazmin (1975) and Merla et al (1979) are the most valuable. The aforementioned works quote various names and age limits to these extensive rock units.

Systematic studies on morphology and soil associations of the area are scarce. However, fairly general attributes from Abul Haggag (1961), Dainelli (1970), Merla et al (1979) and Williams (1980) offer clear insights into the morphologic history of the region. A cross country study of the soils of Ethiopia has been done by Murphy (1959), and a subreconaissance level study of the Blue Nile river basin was undertaken by the Bureau of Reclamation, US Department of the Interior (1959-1962). The latter survey was meant to identify and classify irrigable areas within the river basin.

1.5 Materials and Methods

A Geological and Morpho-pedological map of the area was made from aerial photographs having a scale of approximately 1:50,000. The photos were badly distorted as subsequent studies of the area using topographic maps were larger than indicated. Thus,base maps were corrected for the distortions present in the original photos. The photo centres are shown on the morpho-pedological map. A photogeological study of the geology, morphology, and soils was undertaken.

In this investigation rock samples were collected from sites most suitable to provide complete geological information. Petrographic study of selected samples representing the outcropping formational units was undertaken. The carbonate rocks & sandstones were described using the rock clan designation scheme of Folk (1962) and PettiJohn (1975), respectively.

Grain size distribution for the various dispersion measures of the sandstones were evaluated and interpreted according to Folk's (1962) techniques of grain size analysis. Discrimination between terms assigned to thickness of strata and those which describe splitting properties is in accordance to the terminology of Mckee & Weir (1953). The igneous rock nomenclature is based essentially on mineralogical and textural criteria as adopted from the work of Harker, Shand & Bowen (Carmichael, Turner, Verhoogen, 1974).

The morphological analysis is based on the separation and definition of various morphologic units, and the reconstruction of their evolution by an appraisal of the landform type, the degree of dissection, drainage pattern, nature of slopes and lithology. A soil survey was conducted at a detailed reconaissance level (Soil Survey Staff, 1967). Traverses were made at spacings of less than 2 kilometers. Soils were sampled with the aid of an auger and tilling spade. Soil profiles under uncultivated conditions were described and sampled by the standard procedures of the Food and Agriculture Organization of the United Nations (FAO, 1977). The soil profiles were randomly spaced in some instances 3 to 4 kilometers apart. Locations were chosen on the basis of observed changes in either of the genetic factors. Samples were collected for each apparent horizons on a total of 34 sites. Groupings of soils by physical appearance and inferred soil properties were made and modal samples were chemically analyzed at the laboratory of Land Use Planning and Regulatory Department of the MOA. The procedures required by soil taxonomy (Soil Survey Staff (1975)), a basic system of soil classification for making and interpreting soil surveys, were followed. A full report on the analytical methods used is given in appendix I.

2. Geology

2.1 General Statement

The rocks forming the central Ethiopian plateau are mainly Mesozoic sediments and Cenozoic volcanics. Moreover, the inclusion in the study area of deep river valleys, a tributary of the Abbai river, where part of the Mesozoic sedimentary section crop out, allows to reconstruct the geological history and to examine the relations between the volcanic series and the sedimentary formations.

The Mesozoic sequences in Ethiopia are deposited by the sea advancing inlands as a result of the activization of the Gondwana platform which caused the development of a number of sedimentation basins filled with sediments of Marine, Lagonnal and continental facies. Kazmin (1972) has attempted to reconstruct the palaeogeography of the areas involved in this sedimentation which expresses two marine transgressions and regressions of a sea in a general direction of southeast and northeast. This left a thick succession of Mesozoic sediments. Various early works on the sedimentary section of the Abbai basin, lead to recognition of different types of lithostratigraphic units and terminology. The stratigraphic sequence established by Getaneh (1975), provides the basis for recognition of five informal units, These are:

1. Lower sandstone unit ....Permo-Triassic-Liassic
2. Abbai Shale & Gypsum unit...Toarcian (?)- Bathonian
3. Limestone unit..............Bathonian - L. Kimmeridgian
4. Shaly sandstone unit.........L. Kimmeridgian - Aptian (?)
5. Upper sandstone unit.........Aptian - Cenomanian

Following a long period of tectonic stability, the domal uplift of the Arabian-Ethiopian region started in the Tertiary. Since then, this region has become the site of intense tectonics and magmatic activity. According to Abul Haggag (1961), the various phases of uplift in the Ethiopian plateau, which includes the study area, took place between Cretaceous and Upper Eocene. This seems to have caused the erosional levelling of the Mesozoic sediments and the onset of volcanism. The stratigraphic series and subdivisions of the Ethiopian plateau volcanics has been set by Kazmin (1972) as follows:

1. Ashangi group (consists of Alkali Olivine basalt & tuff that erupted from fissures)	Plaeocene-Oligocene-Miocene
2. Shield group (consist mainly of Alkali basalts erupted from central vents)	Miocene

3. Basaltic flows and related spatter cones (consist of younger volcanics of an Alkaline Olivine basalts)	Pleistocene-Recent

Stratigraphic Outline of Bichena area:

The stratigraphic succession of the area includes a thick succession of Mesozoic sedimentary rocks followed by Cenozoic volcanics. Following is a generalized sequence:

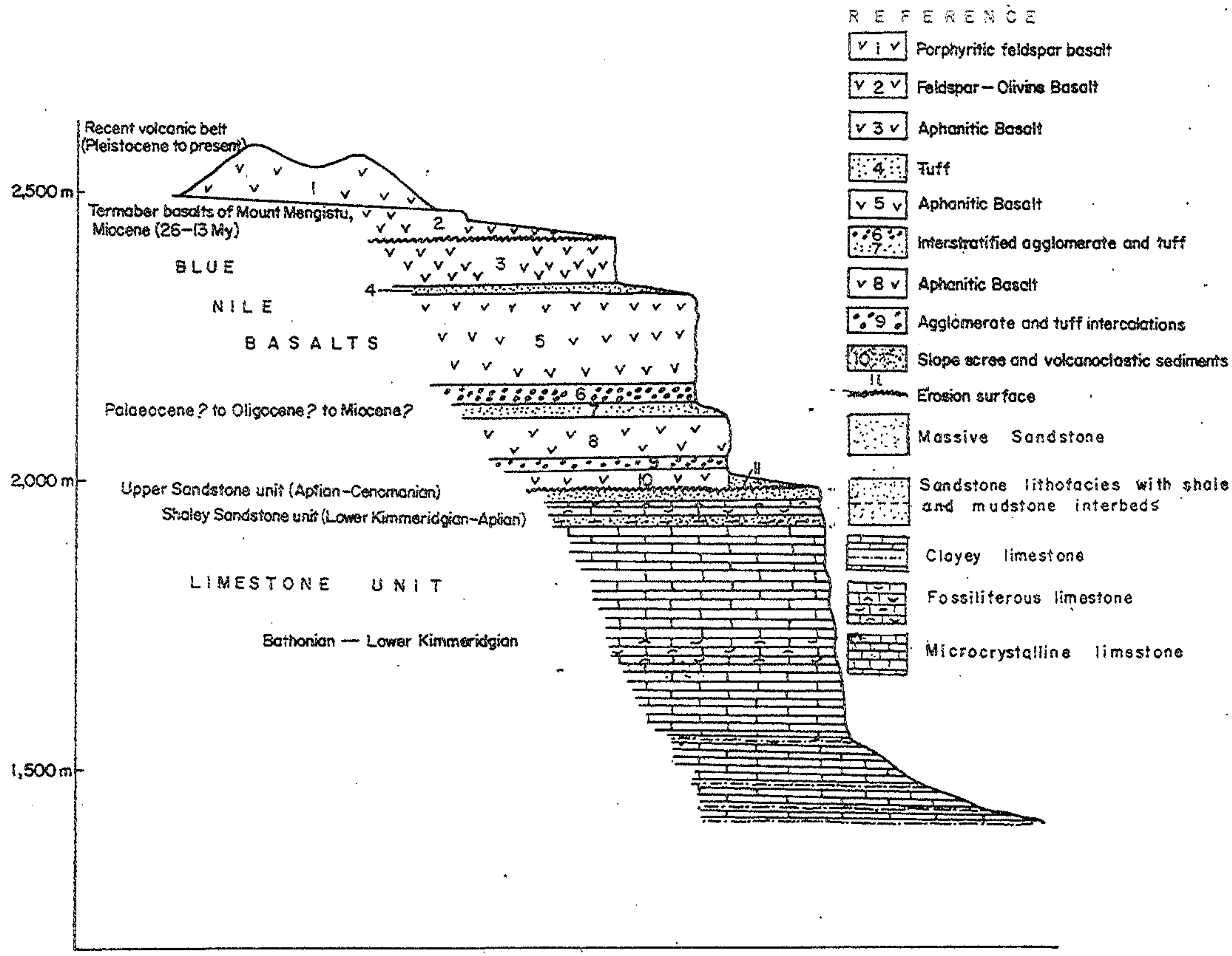
1.	Porphyritic feldspar basalt Unit	Pleistocene to Present
2.	Plagioclase-Olivine basalt Unit	Miocene
3.	Aphanitic basalt nit	Palaeocene? to Oligocene? to Miocene?
4.	Upper Sandstone Unit	Aptian-Cenomanian
5.	Shaly Sandstone Unit	Lower Kimmeridgian-Aptian
6.	Limestone Unit	Bathonian-L.Kimmeridgian

The stratigraphic sequence of a composite section, measured and described at sites conveniently available for complete geological information is shown in Fig. 3.

2.2 Lithology

2.2.1 Mesozoic rocks

A columnar section of the Mesozoic formations for what concerns lithology, structure and faunal distribution is summarized in Fig. 4.


Recent volcanic belt
(Pleistocene to present)
2,500 m
Termaber basalts of Mount Mengistu,
Miocene (26–13 My)
BLUE
NILE
BASALTS
Palaeocene ? to Oligocene ? to Miocene ?
2,000 m
Upper Sandstone unit (Aptian–Cenomanian)
Shaley Sandstone unit (Lower Kimmeridgian–Aptian)
LIMESTONE UNIT
Bathonian — Lower Kimmeridgian
1,500 m
REFERENCE
Porphyritic feldspar basalt
Feldspar – Olivine Basalt
Aphanitic Basalt
Tuff
Aphanitic Basalt
Interstratified agglomerate and tuff
Aphanitic Basalt
Agglomerate and tuff intercalations
Slope scree and volcanoclastic sediments
Erosion surface
Massive Sandstone
Sandstone lithofacies with shale and mudstone interbeds
Clayey limestone
Fossiliferous limestone
Microcrystalline limestone

2.2.1.1 Limestone unit

This lithostratigraphic unit represents the oldest rock unit with an approximate exposed thickness of 330 meters in the Suha river valley. The type section comprises of four Microfacies of carbonate rocks, from the bottom:

i. A yellow to white, fine crystalline limestone with alternating thin beds of grey to darkgrey calcareous shale and mudstone.

ii. A cliff forming yellowish brown, fossiliferous limestone with intercalations of clayey limestone and a few beds of Oolitic limestone.

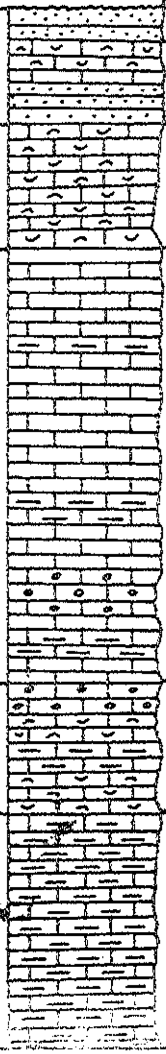
iii. A white grey to a yellowish brown, limonite stained, microcrystalline limestone interbedded with yellow mudstone and clayey limestone.

iv. A fossiliferous limestone (coquina) with yellowish brown clayey limestone interbeds,

The distinct features of the unit is its blanket shape and horizontal bedsets. The thickness of the beds is variable, ranging from 2 meters upto 5 meters in the microcrystalline

A COLUMNAR SECTION OF THE STUDIED SEDIMENTARY SEQUENCE OF SUHA RIVER VALLEY WITH SUMMARY OF THE CORRESPONDING LITHOLOGY, STRUCTURE AND

FAUNAL DISTRIBUTION



Age	Thickness	Lithology – Petrographic description	Structure	Fossil
L. Klmm. / Cenom.	60	Coarsegrained Sandstone (Quartzarenite)	Massive	
		Shelly limestone;(Biosparudite) Crystalline LST; fossil bearing micrite Fine grained SST with shale interbeds (sub- arkose)	Horizontal, thick bedded Horizontal, thick bedded, laminated	Gastropod (turrelid) Pelecypods and other fossils.
Bathonian — Lower Kimmeridgian	55	Shelly Limestone (Coquina);(Biosparudite)	Horizontal, thick bedded	Fragments of Brachiopods, (Rhynchonellidae, Terebratulidae), Pelecypods (Lammelibrachs) and other fossil casts.
	190	Microcrystalline LST with shale and calcareous shale interbeds and few beds of Oolitic LST; (Biomicrite, Fossil bearing Micrite, Oosparudite)	Horizontal, thick bedded, grooved solution planes and Stylolites	Algae, Bryozoa, shell and other fossil fragments
	60	Fossiliferous LST with Marl and Oolitic LST intercalations (Interaclast bearing Biosparite and Biopelsparite)	Horizontal, thick bedded	Rich in Foraminifera – (Milliolidae, Textularidae, Valvulinidae, and Opthalmidiidae)
	100 (?)	Clayey and Microcrystallie Limestone with alternating thin beds of light grey shale and mudstone; (Biomicrite and Dismicrite)	Horizontal, thick bedded	Fragments of Ostracod

Table 2. Petrographic Characteristics of the Carbonate Lithofacies of the Suha River Valley, these are from the bottom:

Sample No.	Allochen Grains (%)			Orthochemical Constitutents		Terrigenous Material (%)		Rock Clan
	Intraclast	Fossils	Oolites & Pellets	Microcrystalline Calcite Ooze	Sparry Calcite	Quartz	Feldspars	
T-1		5		85	10			Biomicrite
T-2				92	5	3		Dismicrite
T-3	15	30	5	15	35			Biosparite
T-4	7	35	10	10	35	2	1	Intraclast bearing Biosparite
T-5	10	15	30	5	40			Biopelsparite
T-6	20	25	10	10	35			Fossiliferous Intrasparudite
T-7		15		65	17	2		Biomicrite
T-8	7	5	50	15	20	2	1	Oosparudite
T-9	5	35	5	5	50			Intraclast bearing Biosparudite
T-10	5	25		10	60			Biosparudite
T-11		15		60	20	4	1	Biomicrudite
T-12	5	35		10	50			Biosparudite
T-13	5	10		80	10			Fossil bearning
T-14		15		80	5			Biomicrudite

limestone, and often crudely defined by layers rich in fossils. The nonfossiliferous carbonate facies display a grooved solution planes and less frequent stylolite structure.

The micro-section study of the unit is outlined in Table 2; and is set from bottom to the topmost.

This unit has yielded a rich fauna consisting of both larger and microfossils.

The identified megafossils mostly belong to Brachiopods, Pelecypods and Gastropods. Most common genera are, Rhynchonella, Terebratula, Ostrea, Turritella, Natica etc. Large number of microfossils can be seen in the thin sections. They are foraminifera, corals, Ostracodes, and algae, in order of abundance. Other organic debris is also present. It is possible to identify some foraminifera, samples T-3 and T-5, and this consist of Miliolids, Textularids, Valvulinids and Ophthalmidiids. The genera identified include: Pyrgo, Textularia, Valvulina and Kurnubia palistiniensis.

An attempt is made to interpret the environment of deposition of the different facies constituting the unit.

The lower section is characterized by the prominence of micritic the microfacies observations and Irwin's (1965) generalized model of the carbonate shelf sedimentation may be used for close approximations of the depositional conditions.

Regarding the age of the unit significant number of palaeontological research has been done which provides an age range of Bathonian to Lower Kimmeridgian. Moreover, in the present study, the presence of Kurnubia palastiniensis in the basal portion of the unit presumably indicates late Bathonian and Callovian age.

2.2.1.2 Shaly Sandstone Unit

The unit constitutes alternating lithofacies of sandstone, mudstone, shale and limestone, with apparent average thickness of 30 meters. This lithofacies succession has been established as the shaly sandstone informal rock unit of the Abbai sedimentary sequence by previous work.

The lower boundary of this unit and the underlying Limestone unit is marked by the conformable sandstone beds. The basal section consists of a few bedsets of sandstone lithofacies with mudstone and shale interbeds. The sandstone is dusky yellow to light gray coloured, clayey and not strongly cemented. It is horigontally bedded with well developed horizontal laminations; and has a tabular external configuration. The mudstone and shale are light grey coloured, very fine grained, friable, and are not so well exposed as are the more resistant sandstone lithofacies.

Petrographic characteristic of the sandstone follow:

Roundness: sub-angular - sub-rounded

Textural maturity: Mature

Mineralogical composition: Monocrystalline quartz-80%, Feldspars (Orthoclase, Microcline and Plagioclase) - 10%, Iron oxides (Haematite and Limonite) and clay minerals - 5%, Hornblende, Muscovite - 3%, Opaque minerals (Zircon etc.) - 1%, Rock fragment - 1%.

The detrital grains are closely packed with a clay and subordinate ferruginous cement, sutured contacts and a slight elongation parallel to the horizontal laminations. Accordingly, the rock is designated in the sub-arkose class.

The grain size distribution has been examined for various dispersion measures and these demonstrate that the rock is very fine grained, normal or near symmetrically skewed, moderately well sorted and leptokurtic in textural pattern.

The sandstone lithofacies passes upward into a carbonate lithofacies. It is dark grey coloured, horizontally bedded shelly limestone. The identified fauna are mainly Brachiopods and Pelecypods. Petrographic study of samples T-13 & T-14 are outlined in Table 2, show Biomicrudite and fossil-bearing micrite microfacies.

The interpretation of the environment of deposition of the sandstone has been attempted on the basis of textural characteristics and sedimentary structures. The textural pattern of this sediments is compared with the works of Friedman (1961, 1967) where distinction between dune, beach and river sand has been made from the textural characteristics. Accordingly, a river sand deposition of nearshore environment is inferred. The laminar structures seem to be the result of differing rates of supply of the sediments by floods. The occurrence of muscovite and a green variety of hornblende in the detrital mineral suite are characteristic of a nearby, high grade metamorphic source rock (PettiJohn, 1975). The conformable limestone could only occur if it were an epicontinental depositional environment, where a high input of terrigenous sediments can be maintained, while the rise of sea level results in carbonate deposition.

The unit is devoid of index fossils, therefore, the age can be inferred based on its stratigraphic relationship with the lower bounding limestone unit.

2.2.1.3 Upper Sandstone Unit

The shaly sandstone unit is often seen directly overlain by a nearly horizontal basalts, but at intervals an overlying cliff forming sandstone is intercalated. This rock has been represented as an informal unit in previous works pertaining to the lithostratigraphy of the Abbai sedimentary sequence. The apparent thickness ranges from 3 meters to 15 meters and tends to pinch out under the basalts. Therefore, it seems as a left over from a differential erosion.

The unit displays a massive external morphology and the rock is slightly consolidated. It has a dark red to yellowish brown colour, but the color appears the result of surfacial weathering of a white-grey coloured sandstone. The Micro-section study shows:

Roundness: Angular - sub-angular

Textural Maturity: Sub-marine

Mineralogical composition: Corroded monocrystalline, Quartz - 90%, Feldspars (Orthoclase, Microcline and Plagioclase - 3%, Haematite, Limonite and clay minerals - 5%, Opaque minerals - 1%, Rock fragment - 1%.

The overall microsection show that corroded quartz grains are the dominant detrital minerals scattered in a ferruginous and clay cement. The red coatings on the detrital minerals may point toward iron oxide cementation from surface water running downslope that also caused the discolouration of the original sandstone. Accordingly, the designated class of the rock is Quartz-arenite.

Grainsize analysis reveal that the rock is coarse grained, poorly sorted, fine skewed and mesokurtic type in textural pattern. Studies with regard to the textural characteristics in relation to the work of Friedman (1961, 1967) suggest a river sediment depositional environment.

2.2.2 Cenozoic Rocks

2.2.2.1 Aphanitic basalt (Blue Nile basalts)

Most of the Ethiopian plateau volcanics have been referred to as Traps, a general term coined to indicate fine grained layered volcanics representing the first volcanic activity on the pre-Tertiary surface. The present nomenclature of this formational unit, Blue Nile Basalts, is quoted from upgraded classification of the Cenozoic volcanic succession by Abbate et al (1979). The need for establishing a new volcanic unit is explained by the age record being older than that of other plateau Trap volcanics, and the thick and evident flows which can be traced all along the western side of the Blue Nile canyon as shown by Dainelli's (1970) photogeological map.

Extensive outcrops of this unit unconformably overlie the shaly sandstone unit proper and in part the remnant of the upper sandstone unit forming the main lava plateau surface. The setting is nearly horizontal over the sediments which is indicative of their eruption over a subaerially eroded surface. The stratigraphic break is apparent in the yellowish brown coloured horizon which has been caused by deep weathering induced by the then prevailing climate. Other evidence could also be the presence of the fossiliferous limestone forming the topmost facies of the shaly sandstone unit with the characteristic release of silicified shells and casts, according to the report of Sanders & Friedman (1978) on interpretations of stratigraphic breaks. This suggests a

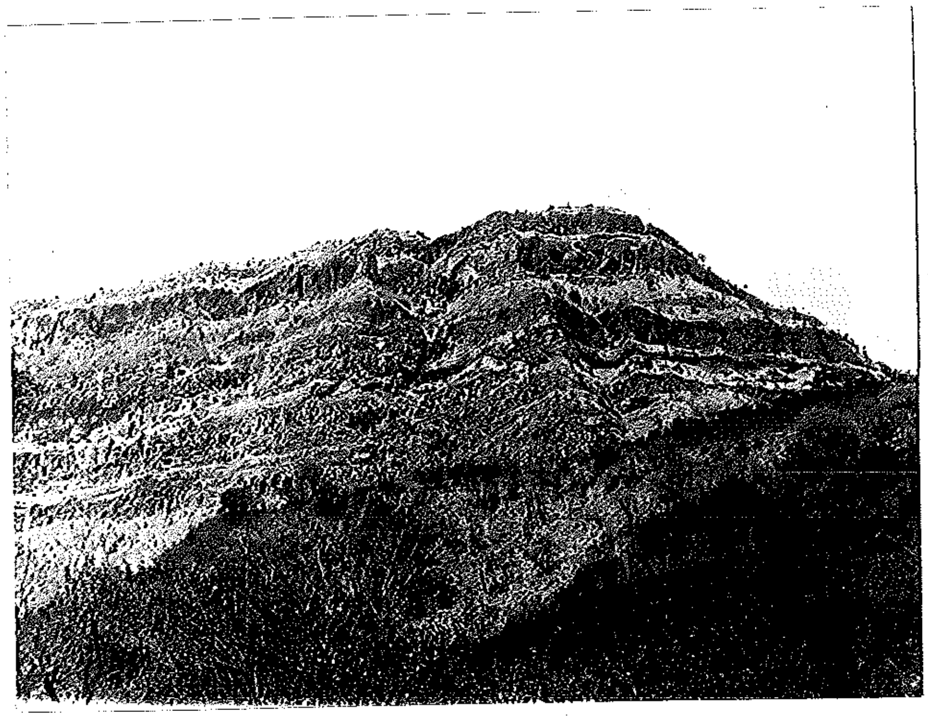


Plate 1. Horizontal setting of the Blue Nile fissural basalts.

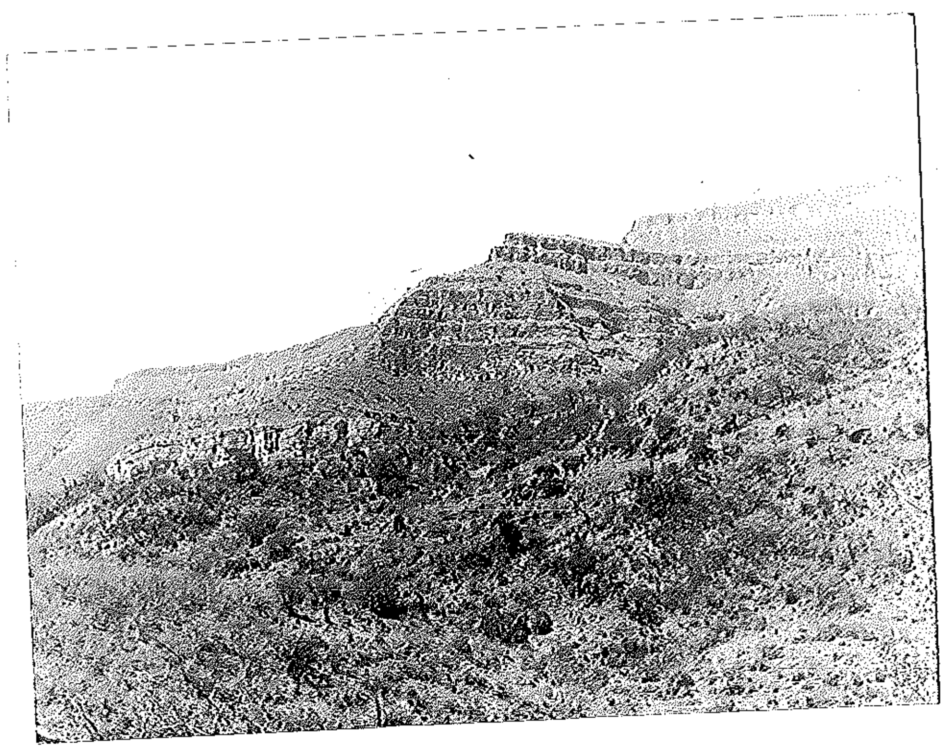


Plate 2. Disconformity of the Blue Nile basalts resting on the Mesozoic sediments.

considerable interval of time prior to the eruption of the lowermost basalt lava.

The unit consists of twelve (12) distinguishable basalt flows and is broken by at least three recognized horizons of tuff, agglomerates and volcanoclastic sediment interbeds. The thickness of individual flows cannot be given for it varies from one part to another. However, an overall approximation of the thickness of the unit as a whole can be given in the range of 400 to 450 meters. The precise upper and lower age limit is difficult to fix within close limits on the basis of the available radiometric, palaeontological and stratigraphic evidence. The validity of the radiometric age determined for the unit is questioned, for a total of thirteen datings have given a range from 69 m.y. to 23 m.y.B.P. by Grasty et al (1963), Megrue et al (1972), McDougall et al (1975) & Jones (1976). Beauchamp & Lemoigne (1975) suggested an upper Senonian to Eocene age from studies of palaeofloral datings of vegetal fossils in the Blue Nile basalt pyroclast interbeds at Fiche and Debra Libanos. Vegetal fossils of silicified tree trunks at the interface of the basalts and pyroclast beds has been observed in the study area, which insight correlation to the age determined by Beauchamp & Lemoigne. Though inconclusive, the works of Abbate et al (1979) on original radiometric data and a re-examination of the numerous published age determination may allow a lower age limit of 40 million years, B.P., Lower Oligocene age. There are no mappable lines of separation between the superimposed individual flows of the unit owing to the textural and compositional homogeneity. The pyroclast interbeds cannot be represented on the geological map with the scale provided.

The basalts have a typical dark brown to black colour, compact, fine grained and often show distinct hexagonal columnar jointing. The overall microscopic character is an aphanitic texture which may indicate a single period of rapid chilling and crystallization of the individual flows. A slight vertical variation is noted with an increase in modal abundance of pyroxenes.

The pyroclast horizons include fragments of volcanic origin: agglomerates, coarse and fine tuff. Petrographic studies reveal that the agglomerates have a basaltic mineralogy, plagioclase and pyroxenes with some disseminated glassy material. These beds are characterized by the presence of secondary minerals such as vesicle infillings of chlorite and secondary silica inclusions. These are the frequent alteration products of basaltic agglomerates and tuffs (Pettijohn, 1975). The foot of the cliff forming basalts is covered by secondary or reworked pyroclastic sediments.

Four micro-sections are studied, BT-13, BT-14, BT-15 and BT-12 and results are outlined in Table 6.

2.2.2.2 Plagioclase Olivine Basalts

This unit covers the western and central part of the area and extends to the summit of the (Plate 3) Mount Mangestu central type volcano. The central volcanoes have been defined by Mohr (1967) as the shield group. In the updated subdivision of Zannetin et al (1973) it is classified as the Termaber Basalts, after the Termaber pass near Debra Sina. Abbate et al (1979) reported that the

Plate 3. Series of lava flows with distinct break in slope, radiating from the summite of Mount Mangestu Volcano.

Mangestu volcano is the largest and best preserved central volcano in Ethiopia with an approximate diameter of 100 kms.

The presence of the thick zone of deeply weathered rock debris and often patchy for erosion will have removed much of the material on top of the Blue Nile basalts, may mark a surface of unconformity between the underlying basalt succession and the Termaber basalt series (Plate 4). This may coincide with the unconformities within the 'Trap Series' reported by Jepson and Athearn (1960) and Mohr (1966) recognized in western Gojjam and upper Abbai basin respectively.

There are no available radiometric age determined for the particular Mount Mangestu rock series. However, inferences can be made to the absolute age determination carried out by Zannetin et al (1974) on various Termaber basalts and these range in age from 26 m.y. to 13 m.y. B.P., early to late Miocene age.

2.2.2.3 Porphyritic Feldspar Basalt

These volcanics are abundant on the southern flank of the Mangestu volcano. They are porphyritic plagioclase feldspar basalts that merge into a zeolitised, amygdaloidal basalts. The eruption seems to have originated from fissures and aligned centres with a general orientation of NW. The rocks are correlated with volcanic rocks forming the axial ranges of the Ethiopian rift, and within the Afar depression, both in mineralogical composition and age (Kazmin, 1975). Abbate et al (1979) correlates this unit to the Lake Tana lava fields characterized and inferred on the basis of the good state of preservation of the volcanic cones, the freshness of the lava, and their superposition above Termaber basalts. Chemical analyses (Cummuci, 1950) of the Lake Tana basalts which are supposed to be of the same mineralogical composition and texture as the porphyritic feldspar basalt show a transition to alkaline character.

The micro-sections examined show euhedral plagioclase feldspars, and pyroxene phenocrysts. The feldspars have a polysynthetic albite twinning and slight zoning. Megascopically, zeolite

Table 3. Petrographic Characteristics of the Bichena Area Volcanic Rocks

Sample No. & Location	Texture	Phenocrysts	Groundmass	Rock Type
BT-12 From a terrace in the Suha river valley	Porphyritic with phenocrysts of plagioclase in groundmass consisting of fine grained plagioclase and pyroxenes & some glassy matrix	Plagioclase	Plagioclase, Pyroxenes rare volcanic glass, Fe-Ti Oxides	Basaltic agglomerate
BT-13 Lower cliff forming basalts, Suha river valley	Subaphyric Microcrystalline	———	Labradorite plag. $(An)_{64}$, coloured & augitic Cpx, & Fe-Ti oxides Alteration of pyroxenes to chlorite, sassuritization of plagioclase	Aphanitic basalt
BT-14 Middle section of the cliff forming basalts	Aphyric Microcrystalline	———	Plagioclase microlites, Augitic Cpx, volcanic glass with some altered to palagonite, and Fe-Ti oxides	Aphanitic basalt
BT-15 Topmost section of the basalt cliff	Subaphyric, subtrachytic Microcrystalline	Microphenocrysts of Olivine	Labradorite plag., Augitic Cpx, and Olivine Fe-Ti oxides	Aphanitic basalt

Table 3 cont'd........

Sample No. & Location	Texture	Phenocrysts	Groundmass	Rock Type
BT-16 Pediment near Yetmen	Glomeroporphyritic Microcrystalline	Clusters of iddingsitized serpentinized Olivine forming microphenocrysts, Plagioclase fledspar laths: sassuritized	Plagioclase microlites Augitic Cpx, Olivine and minor Fe-Ti oxides	Plagioclase Olivine basalt
BT-17 At the base of a volcanic centre near Bichena town	Slightly porphyritic, Vesicular-with frequent infillings of Zeolites, microcrystalline groundmass	Labradoritic plagioclase (An_{62})	Plagioclase microlites, augitic Cpx, and Fe-Ti oxides	Porphyritic feldspar basalt
BT-18 West of Bichena town	Porphyritic, Subdoleritic, Amygdaloidal, Microcrystalline groundmass	Large labradorite plagioclase laths (An_{60}), Augitic CPx, Olivine grains, chlorite as alteration product of pyroxenes	Plagioclase microlite, Augitic Cps, Opx, and abundant Fe-Ti oxides, pyroxenes alter to chlorite	Porphyritic feldspar basalt
BT-19 Bichena town	Porphyritic, Subdoleritic, Microcrystalline groundmass	Large Labradorite plagioclase,	Plagioclase microlites, Augitic Cpx, and Fe-Ti oxides	Porphyritic feldspar basalt

Note: Opx: - Orthopyroxene
Cpx: - Clinopyrcxene
An: - Anorthite
Fe-Ti:- Iron-Titanium

amygdales are recognized with an average long axis dimension of 4 mm. Tiny grains of clinopyroxenes are sometimes found included in the plagioclase laths indicating either a contemporaneous crystallization or a later cooling phase of a trapped liquid in the plagioclase framework. But, most pyrosenes have the tendency of an interstitial habit which evidence simultaneous crystallization. A Petrographic summary of three micro-section is given in Table 3.

2.3 Petrogenesis

The evolution of the Ethiopian plateau volcanics in relation to their Cainozoic tectonic environment has been discussed by Mohr (1963), Gouin (1963), Harris (1969), Zannetin et al (1974, 1976), LeBas (1979), Merla et al (1979), and Bailey (1979). The interpretations are still inconclusive and so a great deal remains yet to be done. The volcanic activity can be categorized in two major episodes. The Blue Nile basalt emplacement and the central type volcano eruption. All of the aforementioned workers related the episodes to the domal uplift of the Arabian-Ethiopian region.

The Blue Nile basalts are successions of nearly horizontal flows and each flow is represented by tens of meters thickness and over 40 kilometers observed lateral extent. Harris (1969) and Gass (1970) formulated a "Thermal expansion" model in which a clear insight to both the Afro-Arabian dome and the lava issuance can be obtained. The contempraneity of these events is explained as: the rising of Lithothermal plumes or penetrative convection through the upper mantle would cause partial melting in the upper mantle, and thereby making basaltic magma available; and an increase in volume manifested by vertical uplift. The field occurrences of the basalts and the possible explanation of the genesis leads one to conclude that these lavas have issued from the tensional system of fractures. Bailey (1979) states that the fissural eruption is important to the hypothesis that a partial melting of the upper mantle and deep crust account for floods of magma of constant composition over a large region. That is, no differentiation of the products of a central volcano which could possibly be ascribed to differentiation in a local, subjacent magma chamber. Hence, the Oligocene-Miocene boundary and an early Pliocene phases of uplift pastulated by Abul Haggag (1961) seems to be concomitant with these volcanism. Chemical analyses done by Zanetin et al (1976) decidedly mark an alkaline character. The presence of a purplish brown coloured and pleochroic clinopyroxene, i.e. Titanaugite, in samples BT-14 and BT-15, also suggests an alkaline nature of the basaltic magma (Bailey, 1979).

The building of the large central type volcanoes and smaller volcanic centres is related to the main phase of uplift and rifting and the later phases of uplift during and since Miocene. The above stated model attributes to the generation of magmas of the individual central volcanoes to part of a cycle of a regional melting where specialized products are emitted, representing local hotspots superimposed on a regional thermal pattern. The amygdales of the smaller volcanic centres demonstrate that the magma was relatively enriched in volatiles.

3. Geomorphology

3.1 General Statement

The study of landscape development is based on a complete knowledge of surface processes and forms. The evolution concerns the change of slope with time. However, no comprehensive data exist for the processes and forms of the past. The diverse environmental conditions and their variation through time limit the complete understanding of morphological evolution.

Rejuvenation of drainage through tectonic uplift during the late Oligocene to Miocene and the Plio-Pleistocene caused severe dissection in upland Ethiopia and the formation of very deep gorges. The Central Ethiopian plateau as a whole slopes generally to the west. It consists of highly dissected rolling ridges, flat grassland meadows, and meandering streams leading to rapids of various magnitudes on the vertical sides of canyons.

The geological study discussed in the preceeding chapter and illustrated in Fig. 15 is essential in the attempt to reconstruct the morphological evolution of the area and the relations between different morphologic units. On the basis of morphologic analysis, the area is divided into several morphologic units (Fig. 16) Description of the individual morphological unit is given below:

(i) Deep Canyon

The unit is a denudational landform of deeply incised valleys with steep and rocky slopes. This dissected plateau has valley bottoms of mean altitude of about 1400 meters and a surface elevation of about 2400 meters. The major river valleys are oriented along a NNW-SSE line.

The basal section of the limestone unit is often reduced to the lowest valley surfaces, a result of limestone's soft nature. The upper part of the limestone unit, the shaly sandstone unit, and the Blue Nile basalts usually form high standing cliffs, where gravity plays a very important role in all the surface processes. The pyroclastic beds of the basalt succession form series of structural benches owing to their alternation with the resistant basalts; Plate 4. Slope recession in the lavas is governed by erosion of the underlying relatively less resistant sedimentary rocks, which result in rockfalls and slides in the lavas with their columnar structures. The slides form distinct scars in the upper part of the lava plateau and have contributed to the broadening of the tributary river valleys as these open to the main river.

(ii) Structural Plateau Surface

This is a broad stretch of almost level land underlain by a succession of fissural lavas. The unit boarders the deep canyon with sharp edges. It is of low relief, apparently determined by the horizontal attitude of the underlying flows. Drainage is scarce except for major meandering streams. The water courses have

Plate 4. Structural terraces of the deep canyon. Note that the river valley broadens with landslides.

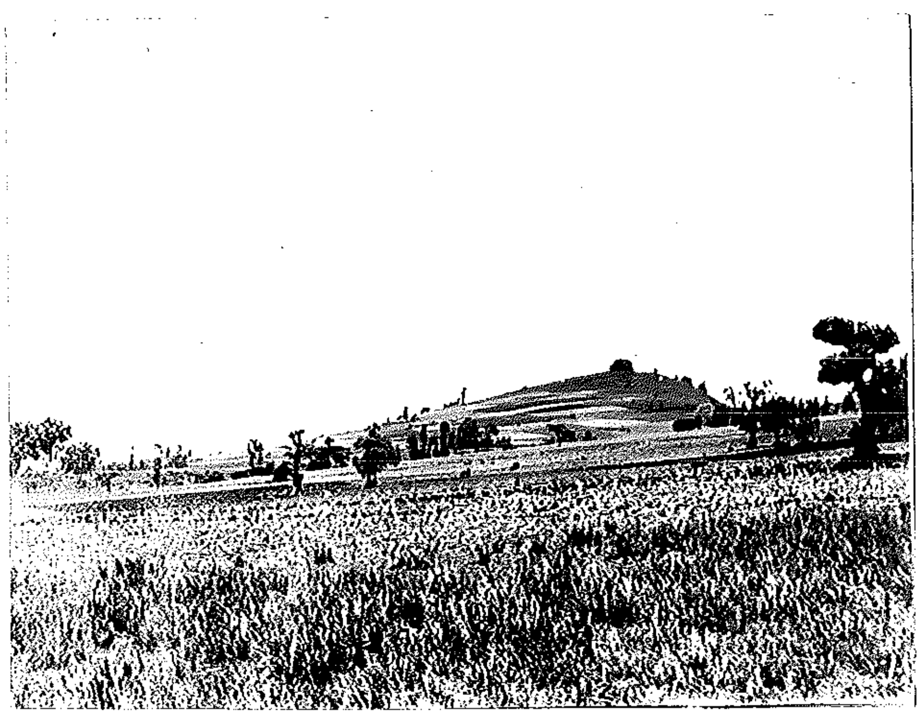


Plate 5. A convexo-concave slope development of an interfluve, remnant hill.

completed the phase of rapid downcutting and have smooth even gradients. The slope appears little affected by surface processes such as wash and mass movement, and there are no indications for the varied features of an alluvium. The slope is covered by deep soil, underlain by patches of deeply weathered basalts. The weathered profile, possibly represents a residual deposit. Hence, locally base levelled structural surface may be assumed, where the base level of erosion coincided with merely structural plains produced by stripping part of the horizontally set basalts.

(iii) Convexo-Concave Slope

This is a lava field on the southern flanks of Mount Mangestu. The unit is comprised of the Mount Mangestu volcanic series, the components of which are; an upper convex slope, a free face, structural terraces or benched hillsides, and a pediment that developed in homogeneous rock. The main morphodynamic process is surface wash.

The summite areas are flat with gentle peripheral slopes, and less frequently, steep peripheral slopes. A convex slope forms the hilltop together with a talus slope which often obliterates the free face. It is moderately dissected with interfluvial ridges and remanant hills. The free face is very thin when present, indicating a late stage of landscape development where active stream erosion has ceased. The pediment forms a basal concavity that extends to the flat plateau surface. It is a gently to steeply inclined erosion surface with an average slope angle of $5^{\circ} - 18^{\circ}$ that grades to a local erosional datum of the main plateau lava plain. The surface is moderately gullied and incision of channel bottoms is absent.

(iv) Composite Ridges

This morphologic unit is chiefly characterized by cone shaped hills with rounded tops and nearly vertical side slopes. It is built of interfingering volcanic centres and consequent composite ridges elongated in a NW direction. The lava issued from these centres forms the convex slope together with the underlying lava flows.

3.2 Morphologic Evolution

3.2.1 Pre "Trappean" Erosion Surface

The horizontally set Mesozoic sediments are overlain by the Blue Nile basalts. The sediment surface appears as a structural surface except for the poorly defined remnants of the upper sandstone unit, representing an erosional phase that left outliers that existed before the lavas were emplaced. The maximum known thickness of the upper sandstone unit in the Abbay basin is 94 meters (Getaneh, 1975) and no Mesozoic sediments younger than this unit are known in the basin. This fact could be a point of inference to reconstruct the entity of the degraded topographic elevation and the magnitude of erosion. This erosional surface has been considered as a peneplane in early works of Abbul Haggag (1961), Mohr (1972) and Merla (1979). However, in the original Davisian scheme of the cycle of erosion, a peneplane is defined as a nearly flat or broadly undulating surface, the ultimate stage of old age with an orderly sequence of landscape development of youth and maturity stages. In the case examined, the marine sedimentation left a structural surface without strong relief which does not allow for the occurrence of the early stages of the cycle of erosion.

The upper sandstone which ended the sedimentation cycle is almost everywhere still preserved. It seems that the land surface remained generally low for a long time after the sea had receded as has been postulated by Abbul Haggag (1961). Had the land undergone a considerable uplift at the time, it would have had a record on a much larger scale which would have affected significantly the geological sections so far observed. The lower age limit of the erosional phase could be Cenomanian, the age of the youngest sediment deposition of the upper sandstone unit. According to the five well defined erosion surfaces recognized in Southern Africa by King (1962), this erosion surface corresponds to the main "African" erosion surface, where erosion began at upper Cretaceous/early Tertiary subsequent to a relatively small degree of uplift. King's phase of uplift could correspond to the uplift which accounts for the emergence of the landmass from the Mesozoic sea.

Truncation of strata is essential before an erosion surface can be considered a peneplain. The scheme of development of the erosional surface is referred to as pediplanation by King and peneplanation by Merla et al (1979). The records of the truncated strata suggest that the development of the landscape have been changed before peneplanation could proceed uninterupted to a normal conclusion. Hence, for the attricute of the scheme of development could not be met, the writer hesitates to call it a peneplain and instead it is surface restricted to a sub-aerialy eroded structural surface.

3.2.2 Base Levelled Structural Surface

The second major morphologic episode is related to the extrusion of the fissural basalt succession. The petrogenetic features and age of the unit is discussed in the preceeding chapter (pp. 27). The lava sheet has adjusted to the prior surface with distinct horizontal contact (Plates 1 & 2), in which there are no indications of deep channels filled by the lava flows. The successive individual flows are often marked by strong weathering products and fairly evident paleosol, that suggest a significant time interval in between the individual flows. The absence of a deep dissection type denudation with "aggradation" of numerous lava sheets invokes a challenge in reconstructing the morphologic event. Indeed, the accumulation of lava piles must have raised the topographical surface, and supposedly involve lowering of the base level or strong downcutting along a river drainage network, i.e. assuming stability of the earth's surface the landmass will eventually be reduced to base level.

These observations lead to two possible explanations. Either no base level lowering is necessitated or particular palaeoclimatic conditions prevented the occurence of stream downcutting.

Case 1: Although there was a topographic rise even with the known lava "aggradation", i.e. Topographic rise of 450 meters thickness of the lava sheets, there is no evidence of base level variation. This could be attributed to a compensation by subsidence of the landmass in relation to the structural evolution of the rift systems which do not require base-level lowering. The rifting episode began just after the emplacement of the Blue Nile basalts; and is evidenced by the overlap of the tentative age range given for the upper age limit of the lavas and the onset of the rift systems as early Miocene. Though not proven, the rifting episode with subsidence of the adjacent landmass, could be responsible for the rise in base level to compensate for the disequilibrium condition, where the base level was restricted to the topmost surface of the lavas.

Case 2: The alternate explanation is that at the time, there were climatic conditions favouring the occurence of local base level. These may be fulfilled under a rainforest or arid climatic environment. There is no evidence of the latter, i.e. no eolinites. On the contrary, weathering features noted by the chemical alteration of basalts, together with the frequent vegetal fossils, such as the silicified tree trunks recognized in the field survey and reports of Beauchamp & Lemoigne (1975) at the interface of the succeeding lavas of the Central Ethiopian Plateau, suggest a rainforest palaeoclimate. The palaeoclimate, aided by the horizontal setting of the lavas forming the topographic surface, may have reduced the possibility of channel development and consequent linear erosion, therefore, provide a competing point of view for the absence of deep dissection.

The end of the fissural eruption is marked by a subaerial, deeply weathered structural surface indicating a considerable time lapse prior to the central type volcanic episode. However, the origin of this presently observed surface regarding the absence of alluzium lead to a case where a controversial scheme of evolution should be considered. This surface may be correlated to the erosional phase during and since Miocene subsequent to the middle Tertiary uplift, known as "coastal plain surface" or "Victoria Falls surface" of King (1962).

3.2.3 Origin of the Convexo-Concave Slopes

This event marks the development of a convexo concave slope profile. Field observations show that the interfluvial ridges are basalt promentories that radiate from the summite of Mount Mangestu, a central type volcano. The surfaces are gently rising smooth slopes of repeated outpourings of lava. This fact, however, does not secure the continuity of the flows issued from the volcano to cover the entire studied area. The surfaces of the ridges observed can of course be labelled as a structural surface for they represent the surface of a flow. Nevertheless, the evolution of the scarp, the nearly level, depression and the profile with a gentle inclination imposes three possible approaches.

1. Fault scarps: There are no traces of fault plane, no relative displacement of adjacent rock masses is recognized and the assumption is subject to rejection.
2. Scarps as flow boundaries: The ridges have a break in slope or are benched and so indicate that the lava "aggradation" is of more than one flow (Plate 6). Had the flat and gently inclined surface been a pre-existing structural surface, the series of flows would have assumed their path to lower surfaces with steep gradient, i.e. the law of fluid movement. However, these features are not observed, hence, the scarps are not flow boundaries.
3. The above rejected assumptions lead us to a conclusion that the products of Mount Mengestu volcano resting on a base-levelled structural surface represent an erosional slope profile.

Plate 6. A piedmont benchland; more than one flow radiate as a promentory from the central type volcano.

Hence, the newly emergent volcanic piles provided an initial slope for consequent stream downcut to the required base level (Fig. 5 & 6). The drainage pattern of streams upon the volcano is of necessity radial in pattern. The schematic representation of the slope development (Fig. 6), demonstrate cross-sections along the basalt portion of the volcanic landform. As the excavated valley reached the base level parallel retreat of the scarp and lateral planation exposed the pre-weathered profile of the base levelled structural surface. The basal erosion of the preweathered surface or residual deposit is maintained by transport mechanisms operating at a low gradient such as soil creep and sheet wash. As soon as the regolith on the planation surface attains an angle of stability, lateral planation ceases. These observations are the basis for deriving the presently recognized structural plateau surface. The lateral planation could be ascribed to a scheme of morphogenesis owning to contrasted resistance to erosion between the underlying weathered profile and the relatively fresh cap rock. The slope retreat produce strongly scarped faces on resistant rocks above. Such structures do not involve any departure from the general principlesof slope development. The writer does not wish to create the impression that all plateau surfaces marginal to high mountain areas are entirely planation surfaces determined by the attitude of the underlying rocks. But, consequent to the nonerodibility of the less resistant material or differential lowering of topographic surfaces on weak and hard rock, gives way to the development of a hillslope morphology.

The development could be correlated to the preconceived views of the hillslope cycle of King (1962). King's landscape cycle involves the formation of erosion surfaces by a process termed as Pediplanation which, incorporates a scarp retreat and the production of extensive plains by the growth and coalescence of pediments. In the standard hillslope of King, four elements are present: crest, scarp, debris slope, and pediment. The tentative age limit of the hillslope development is since Miocene, but it has no full development of the elements due probably to the climatic environments and lack of adequate relief.

The possible explanation of the present day profile could be further enlightened by the use of the qualitative process response model of Young (1972) to predict the development. The selected model is limited due to the fact that either two or more variables (e.g. climate, paleoclimate etc.) are unobserved and so the matching of the model to the observed landform remains speculative.

The assumptions on which the model is based are as follows:

1. Unimpeded basal removal, but no basal erosion.
2. Slope retreat subject to control by removal.
3. Removal of regolith entirely by surface transport.
4. Rate of surface transport proportional to Sine of slope gradient and to regolith thickness.
5. Regolith thickness proportional to total regolith weathered upslope of a given point, and inversely proportional to rate of down-slope transport at the point.

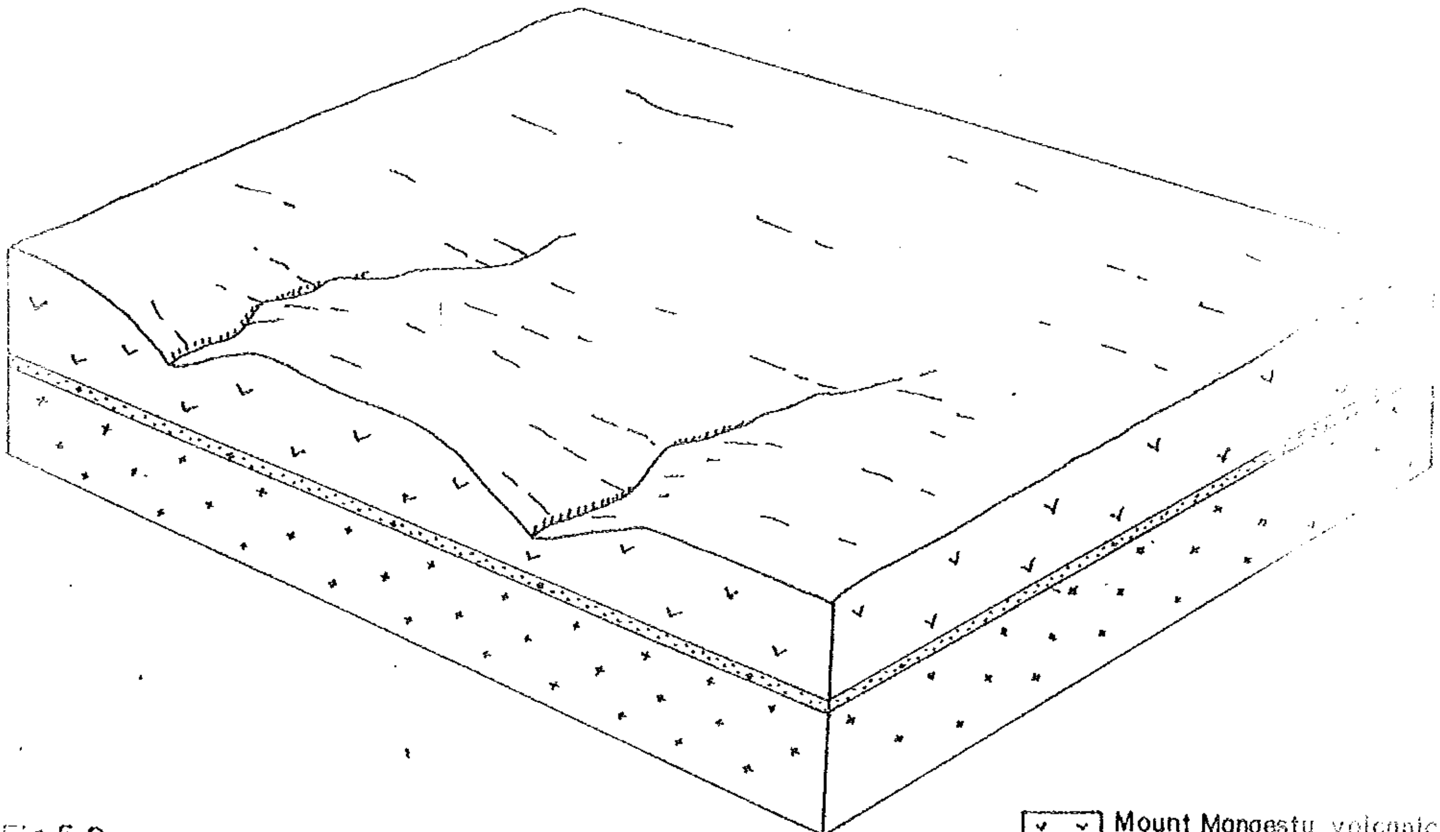
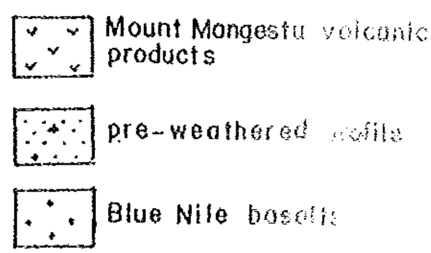


Fig. 5 Post Mount Mangestu volcano eruption; &

the beginning of stream dissection



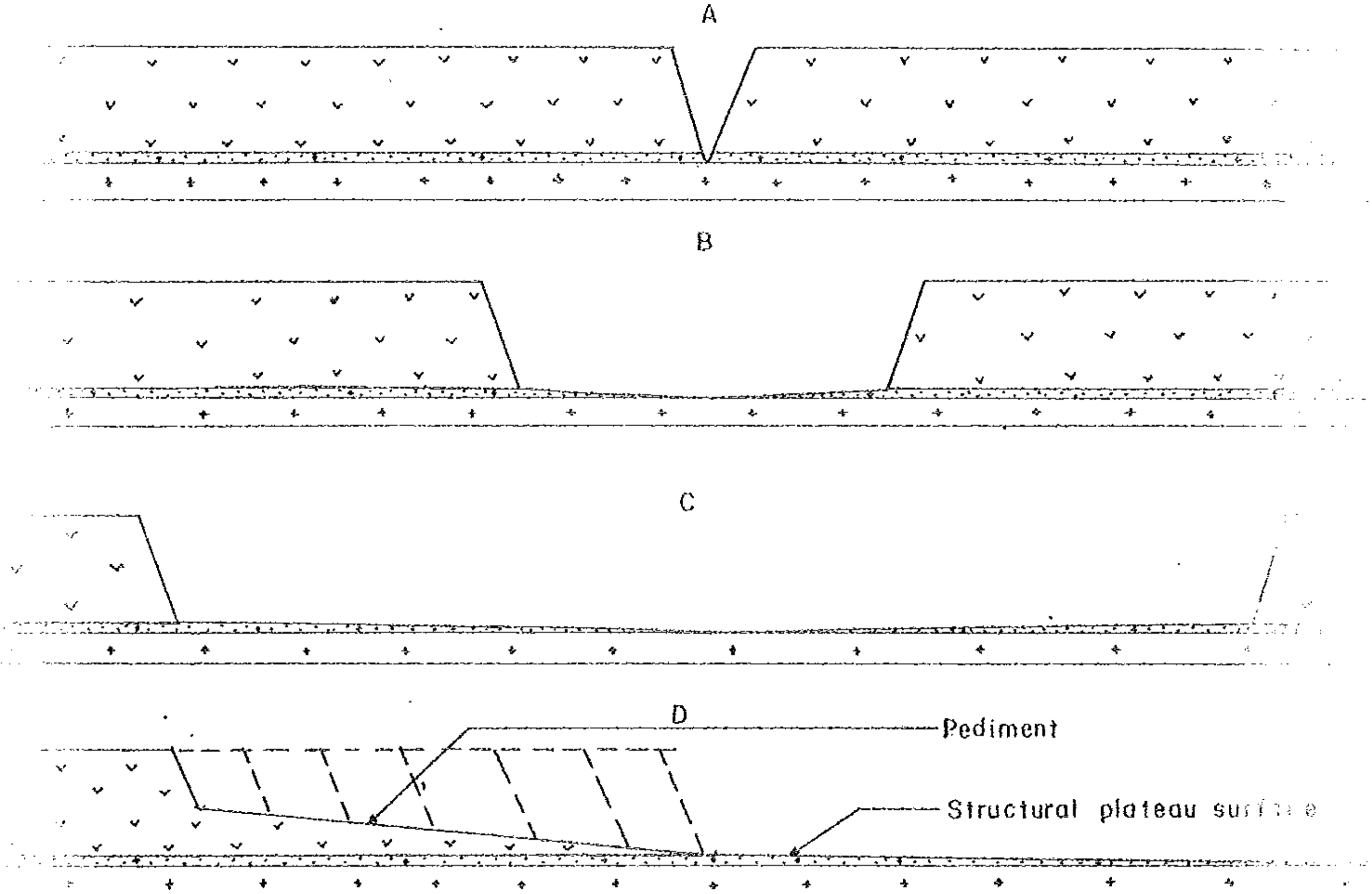


Fig. 6 Schematic representation of the convexo-concave slope development

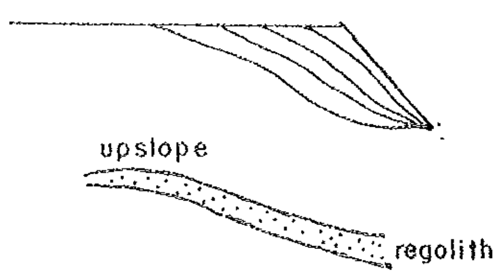
A, Base level lowered to the required level

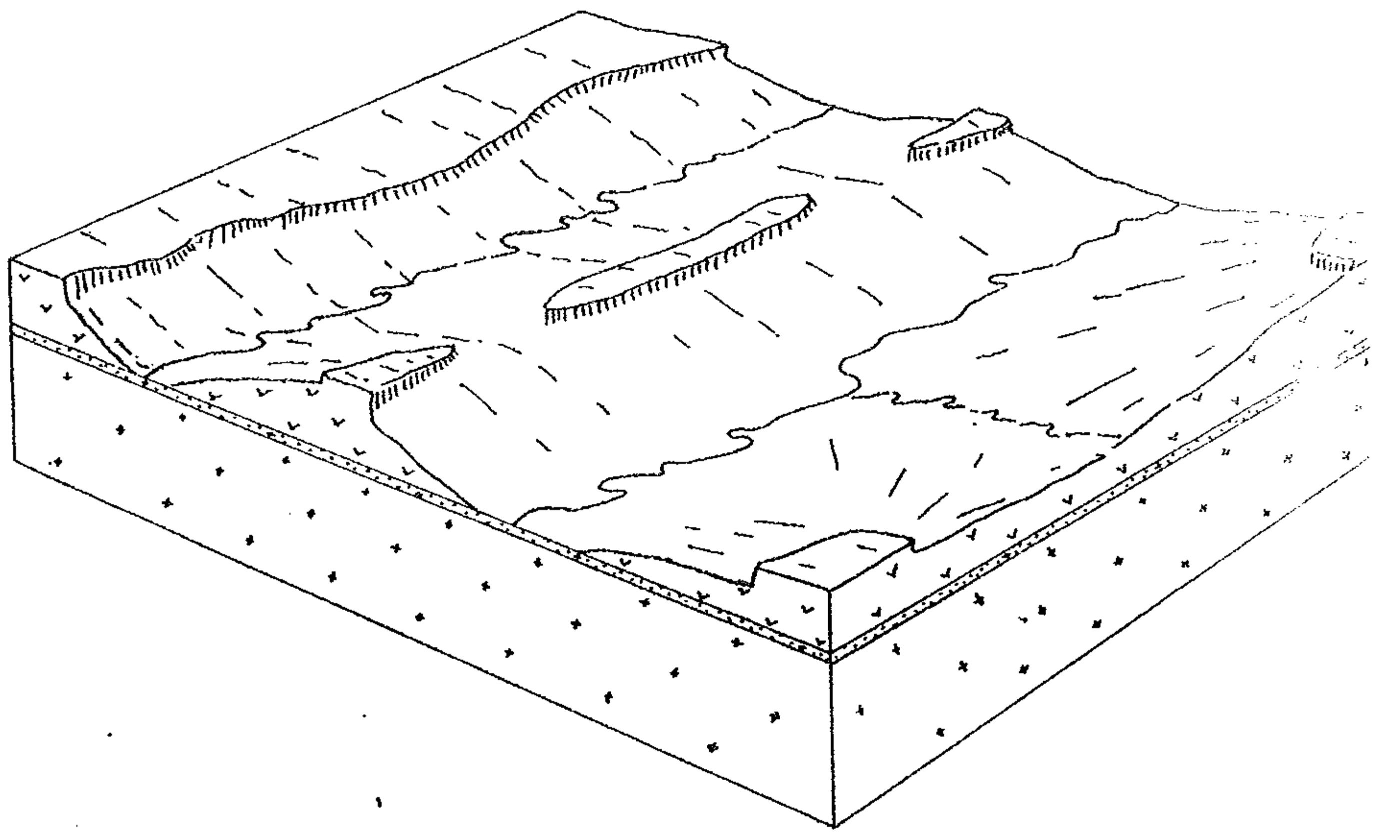
B, Basal erosion & lateral planation

C, Pre-weathered profile reached non-erodibility (an angle of stability)

D, The onset of pediplanation

Fig. 8 Process response model of slope evolution (After Young, A., 1972)





Fig· 7 Lateral planation & pedimentation

6. Rate of weathering (conversion of rock to regolith) proportional to Sine of slope gradient and inversely proportional to regolith thickness.

The process-response model of the convexo-concave slope evolution is shown in Figure 8.

The assumptions of the model suggest a soil creep process which is proportional to the sine of the slope gradient. The retreat of the whole of the rectilinear slope begins immediately giving rise to first the convex slope and then the concave slope profile. The model also represents an interaction between the regolith thickness and the slope profile with parameters of rates of weathering and transport process. The regolith thickness increases downslope gradually on the convexity and rapidly on the concavity.

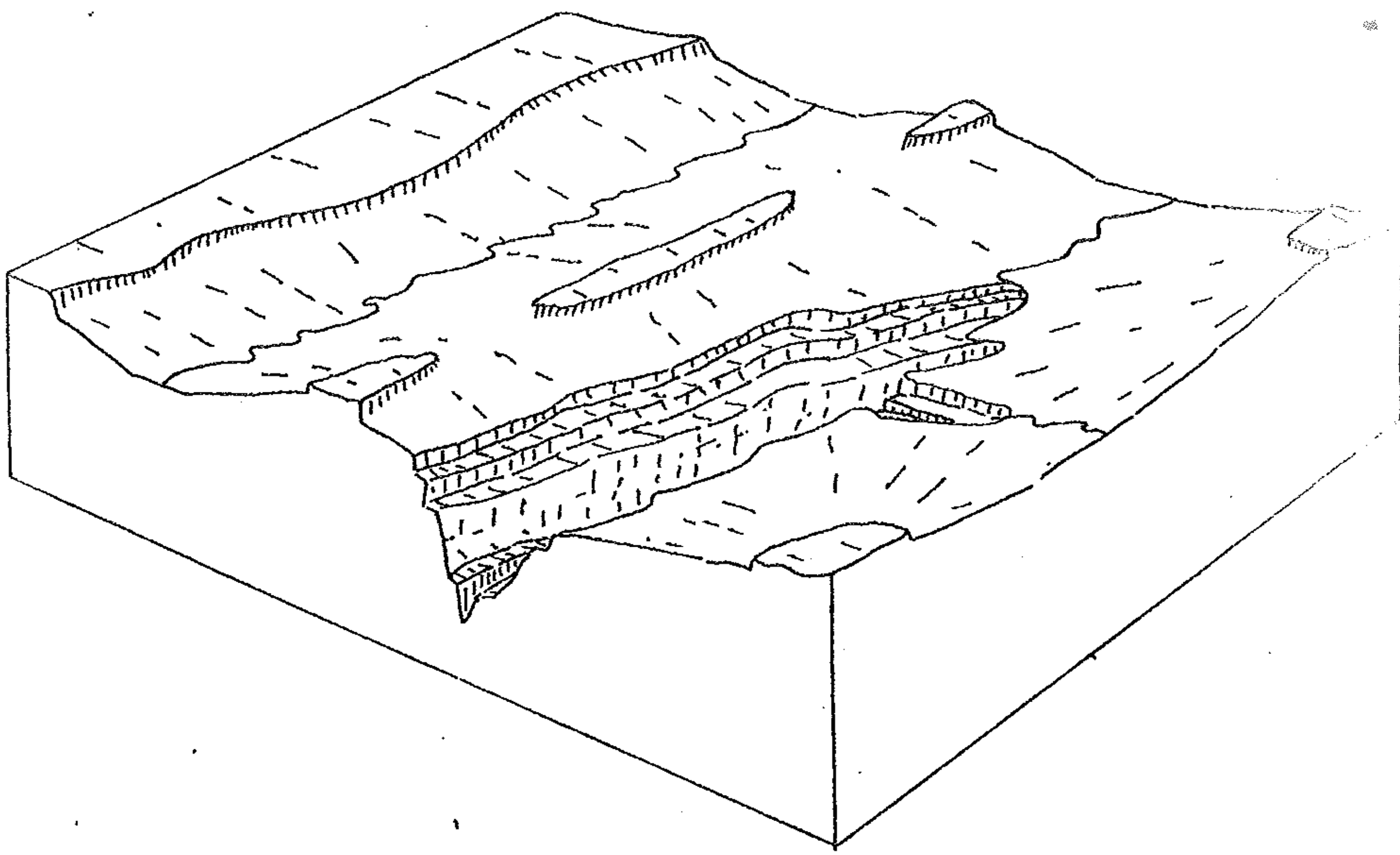
3.2.4 The Plio-Pleistocene Neotectonic Uplift and The Deep Canyon

The last phase of the morphologic event is the strong downcutting of the valleys of the Blue Nile canyon and its tributaries. The evolution could be the result of the rejuvenation of the domal uplifting of the Arabo-Ethiopian region.

Merla (1979) reported a tentative age of lower Pleistocene as the lower limit in the development of deep canyons of the Blue Nile and Tekazze. The conclusion reached is based on their young morphologic appearance and by analogy with other canyons. Butzer's (Williams & Faure, 1980) detailed analysis of the depositional record left by the Nile and its tributaries in upper Egypt shows that the influx of Ethiopian sediments into Egypt goes back to at least Middle Pleistocene times. He also suggested that the Blue Nile began to flood its lower valley very extensively during the terminal Pleistocene, for the climate of Ethiopia had become warmer and wetter at the time. This excavated surface also corresponds to the End-Pliocene to recent uplifts and erosion, coined as the "Congo" erosional surfaces of King (1962).

The lava sheets form three precipitous cliffs, each cliff exposing several separate flows. The intervening pyroclastic beds form broad structural terraces. These refer to a Morphogenetic threshold of slope retreat owing to differences in the rate of weathering and erosion of contrasted lithology.

Owing to the fact that it is younger than the widespread formations of Mount Mangestu volcanic products, the river system probably began during Miocene age and accelerated during Plio-Pleistocene times.



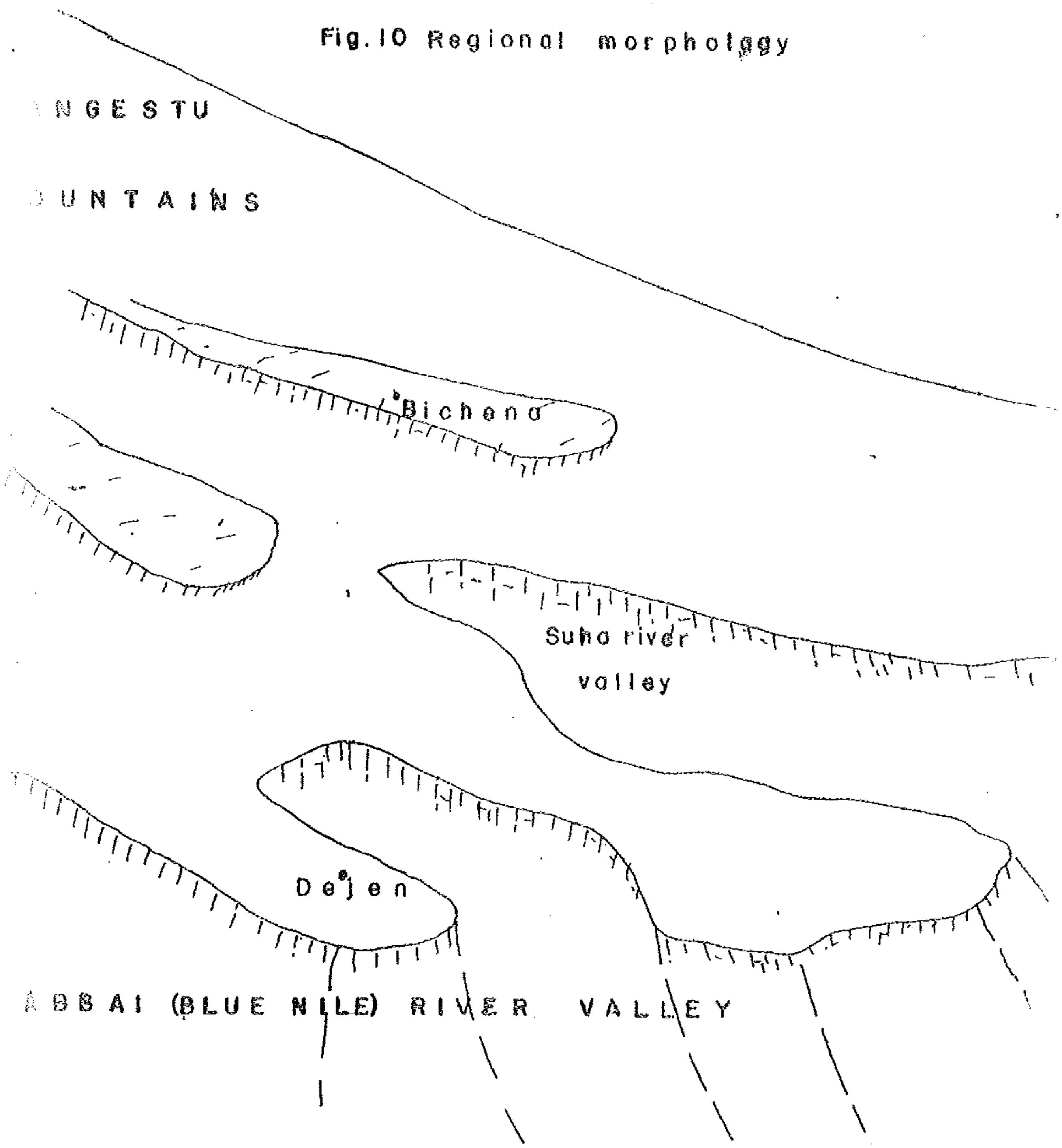
Fig·9 Development of deep canyon following the Plio-Pleistocene to Present uplift

3.3 Regional Morphogenesis

The central Ethiopian plateau region encompasses a major canyon and its tributaries, the sides of which are composed of series of cliffs; and numerous broad, gently sloping volcanoes. In the study area, these two major morphologic elements are recognized with tributary river valleys of the Blue Nile and the radiating mount Mangestu volcano products (Fig. 10). Satellite imagery mosaics at the scale of 1:2,000,000 depict a young regional landscape.

The overlaping basaltic lavas of mount Mangestu generally slopes from about 4 to 10 degrees extending, into the study area. As has been mentioned (page), the convexo-concave morphologic unit has developed on the flanks of this volcano, and is so subject to the influence of this young volcanic landform. Thus, the examined gently inclining planar landform (Pediment) could be labelled as a piedmont-pediplain for the partial structural control of the volcanic landform at a regional scale. The regional setting and spatial relationships of these surface forms may be fitted in a youth stage Morphologic elements of King (1962) where Mount Mengestu volcano represent a major convex slope and the river valleys, a developing free face.

Fig.10 Regional morpholggy



3.4 Hydrogeology

A general groundwater study of the area was done with water table level and rate of spring discharge measurements. On the bases of these measurements the influence of groundwater in the present study is evaluated.

On the convexo-concave morphologic unit, a shallow groundwater table is encountered at 2 to 8 meters in 12 handdug wells. The weathered profile of the basalts is the main aquifer. The high volume of precipitation and the acquired permeability of the weathered basalt account for the aquifer recharge.

Numerous water table level measurements on the structural plateau surface showed an average depth of 1 to 2 meters. The water table levels are represented in the solum. This observation together with the geologic and geomorphic history suggest the presence of a suspended water table. According to De Wiest (1966), buried weathered profiles are less permeable than the fresh parent rocks and so form important horizons for perched water table. The impermeability results from compaction and cementation of pores with secondary minerals. These impermeable zones impede the loss of water, forming sub-horizontal barriers to water movement and causing the water table to rise near the surface. Deep percolation of rainwater into the hillslope drainage channels direct water to the nearly level plain and together with the perched water and direct rainfall subject some part of the area to floods.

The Blue Nile basalt succession has a high transmissivity as a result of a columnar system of joints and fractures. Thus, groundwater drains freely to points of spring discharge at the basalt and pyroclast interface. The rate of spring discharge was measured at three sites and an average rate of 0.4 lit/sec was obtained. The presence of a deep groundwater aquifer can be postulated from the distribution of the springs in the river valley in general.

An attempt to represent the groundwater table configuration showed a general SE direction of groundwater movement.

4. Soils

4.1 General Statement

The consideration of soils inevitably leads to the question of the environmental controls affecting the manner in which a soil develops. These soil forming factors are: parent material, climate, age of land, living matter and topography (soil survey staff, 1967). Jenny (1941), considered soil properties as a function of these soil forming factors. This approach is useful for it is possible to take any soil forming factor and consider its variation against the background of the others; thus examining the effect of that particular one. Hence, in the current treatise, the final synthesis of the associated soils is made only on the basis of the preceeding discussions of the geology and morphology of the area.

Soils representative ofthe area were sampled and studied to determine the texture, structure, color, organic matter, total nitrogen, available phosphorous, exchangeable potassium, sodium, calcium and magnesium, and cation exchange capacity. On the basis of the analytical results, the soils can be said to have vastly different characteristics. For all sample sites, the least weathered materials were also examine.

The soils in the area show differences in physical appearance, of which color difference is the most conspicuous. The color ranges from a very dark gray or nearly black to various shades of reddish brown; and the soils are grouped by color as a preliminary step to treat the field and laboratory data.

A total of four soil mapping units are identified based on inventory of the studied soil properties; these are shown on the morpho-pedological map. (Fig. 16).

4.1.1 Vertisols

This soil unit occurs as the flat plateau surface. The vegetation cover consists of short to tall grasses. Some of these soils are under cultivation, but a sizable area approximately 100 square kilometers, is covered with grasses suited for supporting a good number of livestock. Teff and Noog are the major crops cultivated.

The laboratory data of three representative pedons are given in Table 4.

On the basis of determined physical and chemical properties, some general characteristics of these soils can be described as follows:

1. Brownish black to dark gray to black coloured and deep profile; and Gilgai microrelief.
2. Structural development is good with an angular blocky elements and clay texture; when wet the soils are plastic, sticky and structureless; crack when dry.

The analytical results for these soils seem to imply that they are old soils, the end product of a developmental sequence in which the B-horizons have become argillic or clayey with shrink and swell cycles and have eventually mixed with the A-horizon.

From the studies carried out, the soils qualify as Udic pellusterts subgroup of the vertisol order. (Soil Survey Staff, 1975).

4.1.2 Mullisols

This soil unit occurs in components of the hillslope morphologic unit, the convex slope and the pediment with basal concavity. A large portion i.e. 80 percent or more, of these soils is intensively cultivated. Crop growth is luxuriant. The physico-chemical analyses were done on samples from eleven test pits out of which the complete descriptions of four representative profiles is given in Table 5.

Based on the data provided, general diagnostic features are outlined below:

1. A dark medium brown to reddish brown subsurface color; horizon differentiation is rather indistinct and it has a paralithic contact.
2. Cracks do not develop on drying and the soil is easily tilled; friable; nonsticky when wet, and possess high porosity.

3. The structure is granular on the surface and sub-angular blocky in the subsurface, correlate with the increase in clay content at depth.
4. Organic matter content is moderately high, contributing significantly to the high value of cation exchange capacity which ranges from 35.4 to 57.0 meq/100 gm. soil.
5. Slight to moderate acidity.
6. Base saturation is generally 50 percent or more throughout the profile depth.

The distinct pedogenic processes recognized are decomposition, illuviation and melanization. The temperature and rainfall regimes have resulted in a rapid and fairly complete alteration of the highly weatherable primary silicates into clay minerals, accounting for the clay textural class of the soil. Following reports of early observations by Dawit Deguefu et al (1966) on physical and chemical properties of the reddish brown soils of Ethiopia, the predominating clay minerals are of the kaolinite group and some Montmorillonite. Extensive leaching occurs as a result of good surface and internal drainage. This made the soil more acid leading to the development of a cambic horizon. Decomposition of the abundant organic matter within the soil in the presence of calcium lead to the formation Mollic epipedon(Brady, 1978). Similarly, the proposed pedogenic processes and the observed soil properties allow the presence of Mollic epipedon and cambic horizon.

According to the classification and definitions of the soil survey staff (1975), the soils qualify and meet the requirements of the vertic argiaquolls of the mollisol order.

4.1.3 Alfisols

These are soils developed on the broad terraces at the interfaces of pyroclastic interbeds and the successive lava flows. The soils for the main part, i.e. 60 percent or more, are cultivated, the principal crops are sorghum and Teff. The surface color of the soil ranges from a very dark gray to dark brown. A total of four test pits were examined, of which the physico-chemical description of two representative profiles is given in Table 6 . A generalization of some relevant parameters is given below:

1. The soil profile is weakly developed with a lithic contact.
2. The soil is of fine to medium granular structure, when wet it is nonsticky, nonplastic, friable and is soft when dry.

3. The soil is dark gray to dark brown coloured. A possible explanation of its dark colour may be as Jackson (1964) points out, that amorphous minerals constituting volcanic ash that weather rapidly into an amorphous clay mineral (allophane) combine with humus to form a dark colored material and/or may be the result of the frequently encountered springs all along the terraces causing a reducing environment.
4. Clay accumulation at depths of 20 cm or more.
5. Base saturation is greater than 50 per cent in all subhorizons.
6. A high value of sodium in relation to the adjacent soils which may indicate the presence of sodium in the parent rock.

In light of the findings, the most reasonable description of the horizon sequence would be an ochric epipedon over an argillic horizon. Pedogenic processes that can be assumed for these soils are melanization and illuviation. These properties provide the limits of the Alfisol order in relation to all other known kinds of soil. Their presence in intertropical landscapes involve young geomorphic surfaces and concentration of sodium in the parent rock than those of adjacent soils (Buol, 1973). A lower level of tentative classification qualify these soils as Ochraqualfs sub-group (Soil Survey Staff, 1975).

4.1.4 Entisols

These are soils that characterize the actively eroding cliffs and steep unstable surfaces, the floor of the river valleys that receive new deposits of colluvium in large quantities, and the fresh volcanic centres. Such soils have little or no evidence of pedogenic horizons and are essentially loose material resting directly on hard rock close to the surface. The only pedogenic alteration recognizable is a small accumulation of organic matter in the upper 0-10 cm. A large portion of this unit is represented by rock outcrops. Steep slopes where erosion occurs rapidly as in the river valley, and hardness of the rock and an insufficient length of time for the distintegration of the rocks of the basaltic cones are the major factors that contributed to their existence.

Two soil profiles are examined and the data obtained are tabulated on Table 6. The results give a clue to the presence of an ochric epipedon. At high level of classification, these soils belong to the order of Entisols (Soil Survey Staff, 1975).

There is a sharp contrast between the vertisols and mollisols as can be observed from the tables. Outstanding differences are in the pH and organic matter content. The vertisols examined are moderately alkaline and the pH increases with depth. In mollisols, the entire profile is commonly acid, although in some cases the lower part of the profile may have a slightly higher pH than the surface. Most of the mollisols have a pH between 5.0 and 6.0. The mollisols are also usually lower in exchangeable calcium, magnesium and potassium than the vertisols. Thus, these profiles have been rather highly leached while of the vertisols show leaching effects only at the surface. The properties of the vertisols are those generally associated with a 2:1 expanding clay minerals, while those of the mollisols resemble more closely soils in which 1:1 type clay minerals predominate. The average cation exchange capacity of these two soil orders is comparable. This is in constrast to the expected exchange capacities of the soils given the inferences with regard to clay minerals present. The significantly higher organic matter content in the mollisols may have contributed appreciably to the cation exchange capacity of this soil.

It should be stated that laboratory data show that all the soils distributed in the area are deficient in available phosphorous. There is exchangeable potassium in the vertisol and mollisol where these soils are derived from no potassium bearing rocks, and no explanation can be given from the present survey.

Table 4. Descriptions of Pedons of the Vertisol O

Sample No.	Depth (cm)	Horizon	Texture: Sand %	Silt %	Clay %	Class	Color: Dry	Moist	pH	Organic Matter %	T N g
P_{14}	0-18	A_C	23.7	35.0	41.3	Clay	10YR 4/1	10YR 2/1	6.3	1.73	O
AP:1122	18-55	A_2	28.0	18.0	54.0	"	10YR 4/1	10YR 2/1	6.85	0.72	O
A:2410	55-92	B_{21g}	12.7	29.0	58.3	"	10YR 3/1	10YR 3/2	7.15	1.28	O
	92-135	B_{22}	13.7	9.0	77.3	"	10YR 3/1	10YR 3/2	7.4	2.55	O
	135-184	B_{23}	13.7	11.0	75.3	"	10YR 3/2	10YR 2/1	7.2	1.79	O
P_{10}	0-25		12.7	14.0	73.3	"	10YR 4/2	10YR 3/1	7.1	2.14	O
AP:2675	25-68		9.7	15.0	75.3	"	10YR 3/1	10YR 3/2	7.5	0.86	O
A:2415	68-112		18.7	20.0	71.3	"	10YR 3/1	10YR 3/2	7.05	0.17	O
	112-162		20.0	18.0	62.0	"	10YR 3/2	10YR 2/1	7.75	0.45	O
P_7	0-28		14.7	14.0	71.0	"	10YR 5/1	10YR 4/1	7.0	3	O
AP:2676	28-70		22.7	14.0	63.3	"	10YR 5/1	10YR 4/1	7.3	2	O
A:2410	70-110		8.7	8.0	83.3	"	10YR 5/1	10YR 4/1	7.4	1.14	O
	110-145		8.7	6.0	85.3	"	10YR 5/1	10YR 4/1	7.5	1.21	O.
	145-125		12.7	2.0	80.3	"	10YR 5/1	10YR 4/1	7.5	0.69	O.

CEC - Cation exchange capacity

AP - Index no. of airphoto

A - Altitude in meters

e 5. Descriptions of Pedons of the Mollisol Order

Class	Color		pH	Organic Matter %	Total Nitrogen %	C/N	Avail p (ppm)	Milliequivalent per 100 gms Soil					
	Dry	Moist						Ca	Mg	K	Na	Total Bases	CEC
Clay	10YR 3/4	10YR 2/3	5.50	3.04	0.140	21.7	Nil	14	19	1.9	0.44	25.34	39.2
"	7.5YR 3/4	7.5YR 3/3	5.20	1.38	0.084	16.4	"	14	13	0.6	0.87	28.47	33.0
"	5YR 3/4	5YR 2/4	5.60	1.38	0.084	16.4	"	25	7	0.6	0.44	33.04	41.2
"	7.5YR 4/6	7.5YR 3/4	5.60	0.62	0.042	23.8	0.9	32	2	0.6	0.87	35.47	37.0
"	10YR 3/2	10YR 2/2	5.80	3.52	0.182	19.3	Nil	30	5	0.6	-	35.6	41.0
"	10YR 2/3	10YR 2/2	5.85	3.04	0.154	19.7	"	31	1	1.3	0.44	33.74	43.6
"	10YR 3/2	10YR 2/2	6.00	2.14	0.112	19.10	0.9	31	1	0.6	0.87	33.74	40.6
andy Clay loam	10YR 4/3	10YR 3/3	5.85	0.79	0.070	11.30	Nil	-	-	1.9	1.31	3.21	49.6
Clay	7.5YR 4/6	7.5YR 2/3	5.85	4.49	0.238	18.87	1.8	18	2	3.8	0.87	24.67	57.0
"	7.5YR 4/4	7.5YR 2/3	6.1	2.93	0.126	23.3	Nil	25	5	2.6	0.87	33.47	46.0
"	7.5YR 3/4	7.5YR 3/3	6.35	1.9	0.112	16.96	"	-	-	2.6	0.87	3.47	37.8
"	5YR 3/4	5YR 2/2	5.7	0.9	0.056	16.1	"	20	15	0.6	0.44	36.04	38.8
"	10YR 4/2	10YR 3/1	6.6	3.83	0.21	18.2	"	-	-	1.3	0.87	22.17	46.6
"	10YR 2/2	10YR 3/1	5.7	2.93	0.154	19	"	-	-	0.3	1.31	1.61	43.2
"	10YR 3/2	10YR 3/1	6.1	2.14	0.112	17.2	"	32	9	0.3	1.31	41.61	42.6
"	10YR 3/1	10YR 2/1	7.25	1.93	0.070	17.28		35	7	0.3	0.87	43.17	50.6

A - Altitude in meters

scriptions of Pedons of the Alfisol & Entisol Orders

Class	Color: Dry	Color: Moist	pH	Organic Matter %	Total Nitrogen %	C/N	Avail p (ppm)	Ca	Mg	K	Na	Total Bases	CEC
Clay loam	10YR 3/4	10YR 2/3	5.80	0.76	0.070	10.86	1.8	24	6	1.9	1.74	33.64	38.6
Clay	10YR 2/3	10YR 2/2	6.45	1.59	0.098	16.2	Nil	30	12	1.9	1.31	45.21	41.2
Clay loam	7.5YR 3/3	7.5YR 2/3	6.35	0.83	0.070	11.86	"	15	8	1.3	0.87	25.17	39.4
Clay	10YR 4/2	10YR 3/2	6.05	0.66	0.028	23.5	"	20	5	1.3	0.87	27.17	34.2
"	10YR 4/4	10YR 3/4	7.00	0.83	0.070	11.8	4.4	20	6	1.3	1.31	28.61	36.6
"	10YR 3/3	10YR 3/3	7.10	0.17	0.014	12.1	1.7	30	4	0.3	1.31	35.61	35.6
"	7.5YR 4/2	7.5YR 3/2	7.45	0.35	0.028	12.5	Nil	35	10	1.3	1.31	47.61	35.6
Clay	10YR 3/4	10YR 2/2	5.55	8.83	0.56	15.77	12.6	22	9	3.8	0.87	36.67	33.6
"	10YR 4/4	10YR 2/3	5.95	1.04	0.084	12.4	0.9	31	8	3.8	0.87	43.67	32.0
"	7.5YR 4/3	7.4YR 3/2	4.95	2.55	0.126	20.2	13.5	25	3	0.3	2.18	30.48	35.6

(Ca, Mg, K, Na, Total Bases, CEC: Milliequivalent per 100 gms. Soil)

5. Discussion and Results

5.1 General Statement

The objective of the study is to consider the interrelations of the weathering of bedrock into regolith, the transport of regolith across and away from slopes, the consequent retreat of the ground surface and the soils so formed. The effect of the composition of soil parent materials and topographic settings on pedogenic processes has long been recognized. The fact that the other soil forming factors have varying effects, determination of the influence of all genetic factors remains a difficult task. Thus, some approximations must be made to narrow the gaps.

The data conveniently available to draw the relationships may be summarized as follows:

5.1.1 Soils as a continuam in geologic history

The soils on the structural plateau surface morphologic unit, the vertisols, are formed on pre-weathered Blue Nile basalts. The weathered surface is the result of sub-aerial weathering of the upper fissural lava in which the base level of erosion was reached before the basalt was all removed. This is evident in the existence of patches of rotted rock that reach the present surface with very little modification. The first cycle of weathering took place during and after Miocene, following reports on the tentatively established age of the rocks and the erosional surfaces of King (1962). Further weathering and pedological change is taking place in the present cycle.

This is supported by evidence from geomorphology and soil mineralogy. The significant feature of the morphology is that lateral planation has exposed a pre-weathered surface to the present cycle of pedogenesis. The relative wetness of the soil profile has resulted from a suspended water table held by the pre-weathered surface buried by later volcanic products. The mineralogic implication could be a high clay content and more particularly the prominence of the inferred 2:1 expanding clay mineral group which indicate a fairly extensive period of weathering of basalts (Buol, 1973). Therefore, the occurrence of the recognized soil type demonstrate the significant role of topography, soil parent material and time in the modification of soil materials.

5.1.2 Soil properties in relation to parent material

5.1.2.1 Composition of parent material

The composition of soil parent material has played an important role in determining or modifying certain types of profiles formed. Field observations show the continuation of in situ rock weathering during soil formation. The soils are intensely weathered and have 80 percent or slightly higher clay fraction. The minerals present in the soil usually have been derived from the parent material by weathering. In all the soils examined, the original weatherable minerals such as feldspar and pyroxenes are virtually absent so that only stable minerals that have been formed by alteration or synthesis of original minerals remain. Hence, an attempt must be made to qualitatively reconstruct the mineral portion of the soil from the minerals constituting the parent rock.

Background:

1. A Soda-calcium feldspar (Labradorite) may alter to clay minerals and to calcium and sodium bicarbonate giving calcium and sodium ions; through the processes of hydration, carbonation and solution.

$$\underset{\text{(Labradorite)}}{CaAl_2Si_2O_8 \cdot 2NaAlSi_3O_8} + \underset{\text{Carbonic acid}}{4H_2CO_3} + \underset{\text{Water}}{2(nH_2O)} \longrightarrow$$

$$\underset{\text{(Montmorillonite)}}{2Al_2(OH)Si_4O \cdot nH_2O} + Ca(HCO_3)_2 + 2NaHCO_3$$

2. The pyroxene minerals and other ferro-magnesian minerals alter forming clay minerals, residual iron oxides, silica and salts that are either removed from

the soil by solution or redeposited as a cement in the pores of the soil.

$nCaMgFeAl_2Si_3O_{12} + O + nH_2O \longrightarrow Fe_2O_3 \cdot 3H_2O +$

Augite

$Al_2(OH)_4Si_2O_5 + Al_2O_3 \cdot 3H_2O + Ca^{+2} + Mg^{+2} + SiO_2$

Kaolinite Gibbsite

3. Magnetite oxidizes to hematite

$2Fe_3O_4 + O \longrightarrow 3Fe_2O_3$

4. The soil clay minerals of basaltic parent rocks tend to be kaolinite and halloysite if the soil is well drained, but montmorillonitic if the soil is poorly drained (Buol, 1973).

Vertisols versus parent material:

The investigated vertisols have developed on aphanitic basalts of the structural plateau surface. The mineral analysis of the soils show that the preexisting primary minerals are virtually absent from the soil profile. The identified secondary minerals are; inorganic carbonate, quartz, iron-manganese concretions and pyrite; also soil materials as glass shards and rock fragments. These soil materials are considered as products of weathering and pedogenic processes.

The occurrence of inorganic carbonates can be explained if due weight is given to the exchangeable calcium and magnesium ions set free by weathering of the parent rock. An important calcium bearing primary mineral is Plagioclase feldspar (Labradorite); and Magnesium minerals are augite and the less frequent olivine. The Ca^{+2} and Mg^{+2} released by weathering is leached and/or brought up by capillary rise from the perched water table, combined with HCO_3^- and reprecipitated in a closed system, involving a carbonate-bicarbonate equilibria (Krauskopf, 1967).

The presence of these carbonates has been found a major influence on soil texture, pH, argillic alteration and cation exchange capacity. The carbonates have uneven distribution and strongly enrich the lower horizons. Such a distribution tends to retard and inhibit the decomposition of non-calcareous parent materials (Grim, 1953, and Ghrlich et al., 1955). This fact is in accord with the observed abrupt decrease with depth in the amounts of clay fraction despite the effect of the two cycles of pedogenesis. The carbonates also create constant pressure to saturate the exchange complex with calcium and magnesium but significant number of ions dissociate from the cation exchange surfaces and on dissociation the exchangeable bases cause hydrolysis of the carbonates

(Brewer, 1976). This provides hydroxides, strongly alkaline, as compared to the production of H^+ from the weak carbonic acid and ultimately cause the observed alkaline pH.

The impeded drainage condition of the structural plateau surface holds the first released products of weathering such as hydrous oxides within the soil thus increasing the opportunity for development of complex-layer lattice silicates due to retention of a larger variety of constituents required for their formation. Apart from that, the alkaline moisture leads to the formation of an expanding clay mineral, the montmorillonite group with an added tendency to block the formation of kaolinite clay (Grim, 1953). In view of the above discussed conditions, together with the high adsorption capacity of cations and a high concentration of exchangeable bases in comparison to the adjacent soils, the conclusion is that expanding clay minerals dominate the clay fraction of these soils. There is no significant fixation of calcium and magnesium ions into unavailable forms, therefore, the amount available is directly related to the total exchangeable bases. Compared to calcium, magnesium is less strongly adsorbed to cation exchange sites (Foth, 1978), and much less exchangeable magnesium exists.

Quartz is the common mineral in these soils. It has been derived from primary mineral, augite, which has been redeposited through the pedogenic process of silicification. The abundance seems to be the result of an extended period of weathering, despite its development from a parent rock with no free quartz. The non-crystalline residues are also formed in the soil during the weathering of the pyroxenes. Flooding or water logging in these soils creates reducing conditions where sulfate ions in soil water and ferrous iron (magnetite), accessory constituent of the parent material, react to produce pyrite or iron sulfide.

Mollisols versus parent material:

The mollisols have developed from intensely weathered porphyritic feldspar basalts forming the hillslope. The identified minerals of the insoluble residue of these soils are; augite, quartz, magnetite, ilmenite, rutile, leucoxene, haematite and limonite; and glass particles and rock fragments. The origin of these soil materials and their variation from soil minerals of the vertisols which have been derived from similar primary minerals are largely controlled by their free drainage condition. This has effected a high rate of leaching where chemical migration and eluviation of soluble materials from the solum takes place. Hence, soil profiles with podzol characteristics have developed. The hydrolysis and oxidation of pyroxenes and magnetite gives the non-crystalline haematite and limonite, which impart the persistent reddish brown colour of these soils.

Alfisols versus Parent Material:

The soil material found in the sand and silt fraction of these soils are; volcanic glass, palagonite, quartz, haematite and limonite as coatings on rock fragments and a mineral aggregate with a greenish gray colour and soapy feel. The secondary quartz is generated by divitrification of the glass residue. According to Blatt (1972), the alteration of glass is considered as a hydrolysis reaction and is summarized as:

$$\text{Glass} + H_2O \longrightarrow \text{Smectite} + \text{Zeolite} + \text{Silica} + \text{Metal ions in solution}$$

This reaction together with the diagnostic features discussed may match the unidentified mineral with the smectite group clay minerals. Palagonite is also derived from hydration of volcanic glass in pyroclastic deposits (Kerr, 1959).

5.1.2.2 Texture of parent material

The investigations show that the vertisol and mollisol have developed clay textured soils from basaltic rocks. Since the minerals constituting basalts weather more easily than the rest of the rock forming minerals, it produces soils mainly composed of clay sized particles.

5.1.3 Slope-soil property relationships

General areal interactions of the morphologic units particularly of the convexo-concave slope are manifested by variations in depth of the solum, organic matter content, pH and base saturation. These properties tend to correlate with the slope steepness. An increase in slope gradient is recognized with thinning of the solum, less organic matter content and less alkalinity and base content. The trends have resulted from surface erosion of elevated areas, and the high volume of percolating water over areas with low gradient. There are no apparent colluvial deposits. As has been disucssed in the preceeding chapter, the soils seem to have a sedentary development. This may allow the hypothesis that the slopes graded to the present outline before pedogenesis. Hence, the rate of soil development in part can be attributed to the degree of loss of water by runoff on the slopes, where increase in steepness reduces the amount of percolating water which accounts for slow weathering that results in a thinner solum. In addition, clay formation differences downslope can be explained by the weathering of the underlying rock in situ due to the ability to receive more moisture than those in upslope positions. Accumulation of organic matter on gentle slopes is promoted by a low energy runoff conditions. The good internal drainage of the soils contribute to a considerable leaching of bases and make the soil more acid over the slopes with steep gradient. The variation in the base content characterized by mineralogically uniform parent rock indicates the importance of other factors on soil chemical properties.

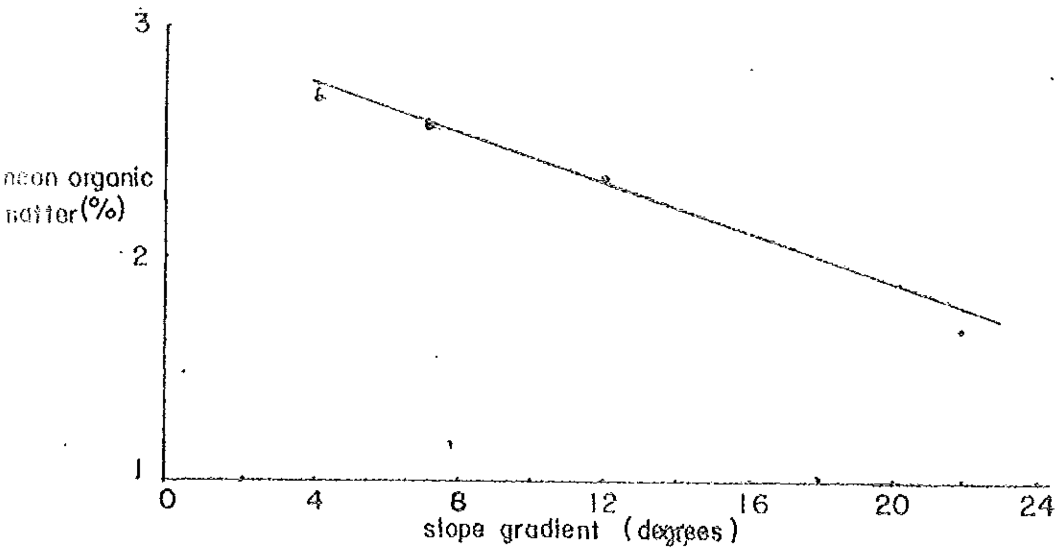
Slope also causes changes in surface soil color. Color is considered as a useful index of the degree and depth of rock weathering, and drainage conditions which are related to soil aeration (Lutz & Chandler, 1949). The distribution is caternary, where reddish brown and darkbrown soils have developed on drainage divides and concave slopes with gentle gradient, and reddish soils over intervening slopes with steep gradient.

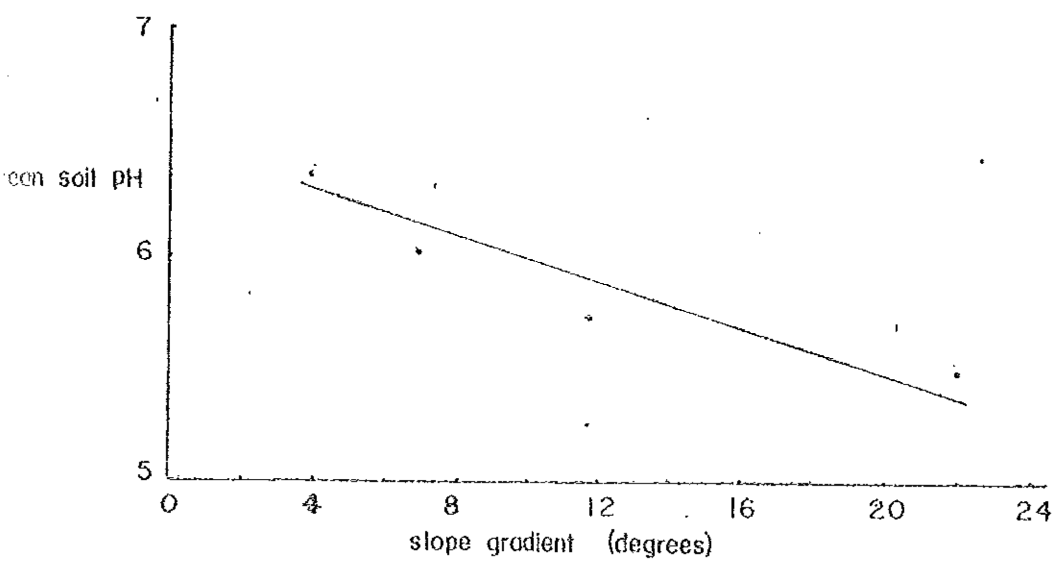
The relationships between slope gradient and the values of four soil properties from four soil profiles across a transect from the convexo-concave slopes morphologic unit are tabulated in Table 7, and illustrated in Fig. 11-14.

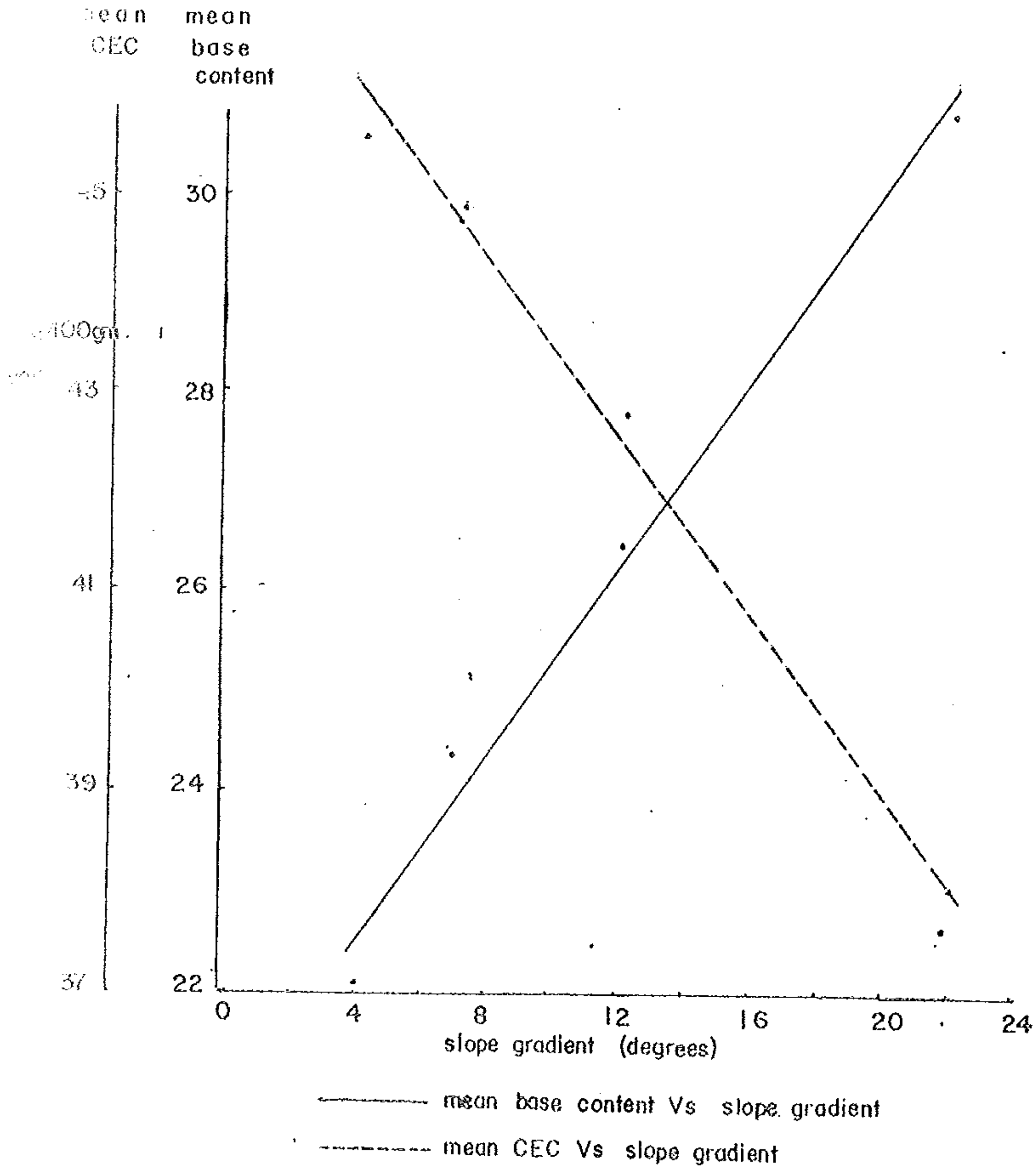
Table 7. The Slope Gradient, Altitude and the Statistical Mean of Four Soil Properties of Pedons of the Mollisol Order.

Pedon No.	P_{12}	P_8	P_6	P_4
Slope gradient	4^{o}	7^{o}	12^{o}	22^{o}
Altitude	2420	2445	2470	2510
Mean Organic Matter	2.70	2.56	2.37	1.615
" pH	6.41	6.05	5.7	5.5
" Base content	22.14	24.41	26.51	30.57
" CEC	45.75	44.9	43.7	37.6

Fig. II-14 Relationship between slope gradient & some soil properties across a transect from Bichena convex slope to the basal concavity







mean CEC
mean base content
45
43
41
39
37
30
28
26
24
22
0
4
8
12
16
20
24
slope gradient (degrees)
mean base content Vs slope gradient
mean CEC Vs slope gradient

The relationship between these soil properties and the slope gradient can be tested to see if the points form some definite pattern. From the scatter diagram, it is reasonable to assume a linear relationship of the soil properties (y) on the slope gradient (x). The straight line formed can be described by an equation of the general form; $y = a + bx$, where x is the independent variable and y is the dependent variable; and a & b are numerical constants which designate the y - intercept and the slope of the straight line respectively. The value of the slope, b, is significant apart from making an error of one in ten. The estimated equations for the particular relationship are found to be;

1. Mean organic matter Vs slope gradient;

$$y = 3-0.06x$$

2. Mean soil pH Vs slope gradient;

$$y = 6.5-0.05x$$

3. Mean base content Vs slope gradient;

$$y = 20.85 + 0.45x$$

4. Mean cation exchange capacity Vs slope gradient;

$$y = 48.16-0.46x$$

The regression lines depict a negative, linear relationship between that of 1, 2 & 4; and a positive linear relationship between the variables of 3. Hence, the estimated values of the organic matter, pH and cation exchange capacity decrease with an increase in slope gradient; and an increase in the values of the total exchangeable bases occurs with an increase in slope gradient. Cation exchange capacity and the total exchangeable bases show antipathetic variation and no substantial explanation can be given from the present survey. The coefficient of determination, which measures the per cent to which the change in the values of the soil properties corelates with the change in the values of theslope gradient, demonstrate the existence of strong relationship. The computed values are:

1. 96.4 per cent of the variation in the mean organic matter can be explained in terms of the slope gradient.
2. 77.5 per cent of the variation in the mean soil pH can be explained in terms of the slope gradient.
3. 97.9 per cent of the variation in the mean base content can be explained in terms of the slope gradient.
4. 94 per cent of the variation in the cation exchange capacity can be explained in terms of the slope gradient.

Hence, the soil characteristics of the Mollisol order are significantly influenced by the geomorphology.

5.1.4 Soils of the Morphogenetic Threshold Slopes

The Alfisol order distributed on the pyroclastic beds of the Blue Nile basalts succession have their origin to differences in response to land sculpturing agents. Since two different lithologies offer different resistance to erosion, the equilibrium slope changes respectively. The angle of stability of these rocks are different and so results in morphogenetic threshold slopes. The evolving structural terrace allowed the development of the soils which require geomorphic surfaces so young as to limit soil development. Besides, the morphologic setting permits the discharge of superimposed threshold springs that provide an aquic soil moisture regime.

An attempt has been made to match the possible relationship of the geology, morphology and soil distribution and is summarized in Table 8.

Possible Relationship between the Geology, Morphology and Associated Soils

	Soils	Possible Relationships
ral sur- urface l plana- ne; er table ers rocess: l creep;	Vertisol - Depth: 162-184 cms. - Clay content: 41.3-85.3% - Textural class: Clay - Organic matter: 0.45-2.55% - Cation exchange capacity: 34.6-53.8 (meq/100 gm soil) - Total bases: 28.04-71.34 meq/100 gm - Important pedogenic processes: Illuviation, Enrichment, Calcification, Haploidization through pedoturbation, & gleization - Soil materials of the insoluble residue: Inorganic carbonate, quartz, Iron - Manganese concretions, Pyrite, & glass residue - Diagnostic horizons: absence of argillic, natric, spodic & Oxic horizons.	- Soils as a continuum in Geologic history; i.e. Influence of the Morphologic evolution which allows two cycles of weathering and pedogenesis. - Effects of the mineralogic composition of the parent rock, and its alteration as controlled by micro-environments such as a reducing moisture regime.

	Soils	Possible Relationships
ain cess: wash, lying	Mollisol - Depth: 90-125 cms. - Clay content: 29.3-76.3 % - Textural class: clay to sandy loam - Organic matter: 0.79-4.49% - Cation exchange capacity: 33-57 meq/ 100 gm - Total exchangeable bases: 3.21-43.17 meq/100 gm - Important pedogenic processes: Decomposition, illuviation, leaching (depletion), podzolization (silication) melanization & surficial erosion. - Soil materials of the insolube residue: quartz, haematite, limonite, leucoxene, magnetite, ilmenite, rutile & glass residue - Diagnostic horizon: mollicepipedon & cambic horizon.	-The composition of the soil parent material left insignificant imprint, where the soil behaviour is largely controlled by the geomorphic surface.

Table 8 Cont'd........

Geology	Geomorphology	Soils	Possible Relationships
Basaltic agglomerate & Tuff - Pyroclastic inter-beds of the Blue Nile basalts. - Age: Lower Oligioc-ene - Miocene (40 m.y. - 25 m.y.) - Mineralogy: Plagio-clase feldspar series, pyroxene scattered in a glassy groundmass.	Morphogenetic threshold slope of the deep canyon - Excavated surface that corresponds to the Plio-Pleistocene to recent uplift & erosion; 7 m.y. - Morphodynamic process: surface wash processes such as sheet wash, and rill wash.	Alfisols - Depth: 55-75 cms. - Clay content: 35-3-71.3% - Textural class: clay to clay loam - Organic matter: 0.17-1.59% - Cation exchange capacity: 35.6-41.2 meq/100 gm - Total bases: 25.17-47.16 meq/100 gm - Important pedogenic processes: Illuviation & melanization - Soil materials of the insoluble residue: volcanic glass, palag-onite, quartz, haematite, and limonite - Diagnostic horizons: Ochric epipedon and argillic horizon.	The effect of morphologic evolut-ion that has exposed structural terraces i.e. Morphogenetic thre-hold slopes, young geomorphic su-faces with rough chronology of late pleistocene age giving way to modern soils.

Table 8 Cont'd......

Geology	Geomorphology	Soils
a) Porphyritic feldspar - Fresh volcanic centres -Age: Pleistocene to recent, 2 m.y. - Mineralogy: Plagioclase feldspar series, augite, orthopyroxenes, soda amphiboles (kataphorite), magnetite and ilmenite	Composite ridges - Cone shaped hills with rounded tops and nearly vertical side slopes - Morphodynamic process: Rapid mass movement such as debris avalanche & rock slide.	Entisols - Depth: 16 - Clay conte - Textural c - Cation exc 100 gm - Total base - Important Surficial - Soil mater residue: a coated wit pyroxenes, - No diagnos
b) Limestone, sandstone & basalt Cliffs		

6. CONCLUSION

A brief description of the lithology, morphology and soils represented in the area is presented.

The tributary river valleys of the Abbai river provide magnificient sections of part of the Mesozoic sedimentary formations and Tertiary volcanics. The outcropping formational units are Limestone, Shaly Sandstone and Upper Sandstone units of the Mesozoic sequence disconformably overlain by horizontal, thick basalt flows separated by levels of pyroclastics of the Blue Nile basalts, followed by the basaltic lavas of Mount Mangestu and basalts from young volcanic centres. The relations among these formational units are examined on the basis of their lithostratigraphic character and through the analysis of the morphology.

The prominent morphological features are the pre-Blue Nile basalt erosion surface, the lateral planation and pedimentation that exposed the pre-weathered profile of the structural plateau surface, and the neo-tectonic uplift that resulted in the development of the deep canyon. Four soil orders are recognized and these are; Vertisol, Mollisol, Alfisol & Entisol.

The fundamental aim of the study was to determine whether or not the soils development and distribution is associated with the geology and morphological evolution, or in terms of soil forming factors, parent material, topography and time. Soil is dynamic and undergoes a process of evolution, a gradual change as a function of time with variations in the physico-chemical and biological environment

(Birkeland, 1974). The study has revealed that soil parent materials with similar mineralogy and texture can give way to soil varieties, and different soils are recognized when the nature of geomorphic surfaces are changed.

The development of vertisols from aphanitic basalts has been attributed, to two cycles of weathering and pedological change a record discovered in the attempt made to reconstruct the evolution of the base-levelled structural plateau surface. The perched ground water table of this surface imparts hydromorphic features, poor drainage conditions, and alkalinity. The alkalinity is also caused by the high content of exchangeable calcium and magnesium ions which correspond to the chemistry of the minerals constituting the parent rock.

The Mollisols have developed from soil parent materials with similar mineralogy as that of the vertisols. The variation is partly caused by the differences in the time lapse of the evolving geomorphic surface and their manner of evolution, resulting in these surfaces belonging to different morphologic units. Soil properties of the mollisols vary laterally as explained in part by the steepness of the slope.

The soils developed on the morphogenetic threshold slopes, Alfisols, owe their origin to the evolution of young geomorphic surfaces of the deep canyon tentatively designated as late-Pleistocene, subsequent to the Plio-Pleistocene to recent neo-tectonic uplift. Entisols occur on the outstanding cliffs of Limestone, Sandstone, and basalt of the deep canyon, and fresh volcanic centres of Pleistocene to present age. These form geomorphic surface so young as to limit soil development.

The area appears to be a very prosperous and productive agricultural area especially on the Mollisols that occupy the elevated areas adjacent to the bottom plateau surface. These soils, although clayey in texture, are permeable and friable. The studied profiles show the soil to be a good rooting media and to have sufficient nutrient supply and are utilized for a wide variety of crops. The wetness of the vertisols in the more nearly level plains have limited crop production. These soils are best used for pasture. Many herds of cattle are being grazed on the portion of the uncultivated soils. The soils of the river valleys are generally erosive, and conservation practices need emphasis.

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Appendix I

Soil Analytical Methods

Texture

The Bouyoucos's hydrometer method is used. 50 grams of soil is wetted with distilled water; the organic matter is destroyed with H_2O_2. Sodium hexameta phosphate ("Calgon") and distilled water are added and the suspension is stirred for 5 to 10 minutes to get complete dispersion. The dispersed soil is transferred to a 1000 ml cylinder, filled with distilled water, and shaken before the first hydrometer reading. Hydrometer readings at 40 sec, 1 hr., and 2 hr., intervals is taken. These three readings furnish the data for the following three classes of material: sand (0.05 mm. diameter), silt (0.05 to 0.005 mm) and clay (0.005 mm). These limits do not agree with the wentworth grade limits.

Colour

The munsell soil colour chart and the revised standard soil color chart by M. Oyama and H. Takehara are used jointly. The former gives better description, of dark gray soils, while the latter is good for tropical red soils.

pH

An electrometric method employing a glass electrode and a calomel, reference electrode, is used to determine soil pH. A 1:1, soil-water suspension is stirred several times for more than one hour. The suspension is left overnight for equilibration.

The measurement is done with two buffer solutions of pH 4.2 and 9.2 to standardize the pH meter, every time the reading is made.

Organic matter

Walkley black's method is used, in which one gram soil is di digested with a mixture of chromic and sulphuric acids, making use of the heat of dilution of sulphuric acid. Excess dichromate is titrated with 0.5N ferrous sulphate solution to a brightgreen end point using barium - di phenylamine sulfonate as the redox indicator.

Total Nitrogen

One gram of soil that has passed a 70 mesh-sieve, is digested with concentrated sulphuric acid to fix nitrogen as ammonium sulphate using a catalyst mixture of potassium sulphate, copper sulphate, and selenium powder. Sodium hydroxide (10N) is then added to liberate ammonia which is distilled into 0.2N H_2SO_4. A semi-micro-kjeldahl apparatus is used for distillation. Excess 0.2N H_2SO_4 is back titrated with 0.1N NaOH using methyl red as the indicator.

Available Phosphorous

Olsen's or sodium-bicarbonate method is used. This method utilizes 0.5N sodium bicarbonate buffered at pH 8.5, as the extracting solution. Chlorostannous reduced ammonium-molybdate in concentrated H_2SO_4 with blue colour is used to estimate the amount of available phosphorous.

Available Potassium

Peech's method is used which employs cobalt nitrites precipitation method based on Morgan's extracting solution. It is a visual turbidimetric method determined by a colorimeter.

Exchangeable Calcium and Exchangeable Magnesium

Exchangeable clacium and magnesium are leached from the soil by neutral normal ammonium acetate. On the extract so obtained exchangeable clacium and magnesium are first determined by the versenate method using eriochrome black-T as the indicator. Then, exchangeable clacium alone is determined by versenate method, using HSN indicator. Exchangeable magnesium is obtained from a difference of the total calcium and magnesium extracted and that of the re-extracted clacium.

Sodium

Sodium is determined by flame photometer using neutral normal ammonium acetate extract.

Cation Exchange Capacity (CEC)

Soil thoroughly leached with neutral normal ammonium acetate to remove cations is washed to clean off its excess acetate with 95% ethylalcohol. The remaining ammonium ion that occupies the exchange positions is vacated with 10% NaCl, and is then determined by Kjeldahl's method. The ammonium liberated is distilled into 0.2N H_2SO_4 and excess 0.2N H_2SO_4 is backtitrated with 0.1 N NaOH using methyl red as the indicator.

References

Abbul Haggag, 1960, A contribution to the Physiography of northern Ethiopia: University of London, Athlone press, 153p.

Abbate, E., Azzaroli, A., Zannetin, B., & Justin Visentin E., 1968, A geologic &petrographic mission of the C.N.R. to Ethiopia: Preliminary results: Boll. Soc. Ital., 87, pp.1-20

Bailey, D.K.,1979, Melting in the deep crust in H. Srensen: The Alkaline rocks, John Wiley & Sons, 622p.

Beauchamp, J., & Lemoigne, Y., 1975, Paleofloral dating of volcanics on the Ethiopian plateau, Bull. Geophysics Observatory, Addis Abeba, 15, pp. 125-131

―――――――,1977, La Serie Sedimentaire en Ethiopie Centrale et Orientale: These de Doctorat, Univ. Claude Bernand, Lyon, 419p

Birkeland, P.W., 1974, Pedology, Weathering and Geomorphological research, Oxford University press, London, 285p.

Blatt, H.c Middleton, G., Murray, R., 1972, Origin of Sedimentary rocks, Prentice-Hall inc., New Jersey, 634p.

Brady, N.C. 1974, The Nature & properties of soils. Macmillan, London.

Bridges, E.M. 1978, World Soils, Cambridge University press, Malta, 128p.

Buol, S.W. Hole, F.D., McCracken, 1973, Soil genesis & Classification, The Iowa State Univ. press, Ames, U.S.A.,360p.

Carmichael, I.S.E., Turner, F.J., Verhoogen, J., 1974, Igneous Petrology, McGraw Hill book company, New York, 739p.

Commuci, P., 1950, Le Vulcaniti del Lago Tana (Africa Orientale) in Merla etal (1979): A geological Map of Ethiopie& Somalia - Comment with a map of major landforms, Firenze

Dainelli, P., 1970, Photogeology of the Debre Markos - Blue Nile area, Southern Gojjam, Ethiopia, Mem. della Soc. Geol. Ital., 9, pp.779-791

Daniel Gamechu, 1977, Aspects of Climate and Water budget in Ethiopia: A technical monograph published by AAU press

Dasit Deguefu, & Reed, H.L., Clay mineral types in blackland and reddish brown soils of Ethiopia (Unpublished)

————;Murphy, H.F.,& Reed, H.L., 1966, Physical & Chemical properties of some reddish brown, darkbrown and brown-soils of Ethiopia

&

Cation exchange & base Saturation of blackland soils of Ethiopia; Oklahoma State University, Stillwater (Unpublished)

DeWiest, R.J.M., Davis , S.N.,1976, Hydrogeology, John Willey & Sons, 463p

FAO - UN, 1977, Guidelines for soil profile description, Rome

Folk, R.L., 1968, Petrology of Sedimentary rocks, The Univ. of Texas, Hemphill's, 172p.

Foth, H.D., 1978, Fundamentals of soil science, Sixth edition, John Wiley & Sons, New York, 436p

Friedman, G.M., 1961, Distinction between dune, beach and river sands from the textural characteristics, Jour. Sed. Petrology, V.31 pp. 514-529

———— , 1967, Dynamic processes & Statistical parameters Compared for size frequency distribution of beach & river sands, Jour. Sed. Petrol., V 37, pp 327 - 354

———— , & Sanders, J.E., 1978, Principles of Sedimentology, John Wiley & Sons, New York, 792p.

Gass, I.G., 1970, The evolution of volcanism in ghe function area of the Red Sea, Gulf of Aden and Ethiopian rifts, Phil. Trans. Roy. Soc. London, Ser. A, 267, pp.369-381

Gass, I.G., 1975, Magmatic & Tectonic processes in the development of the Afro-Arabian dome, in A. Pilger & A. Rosler eds: Afar depression of Ethiopia, Schweizerbart, Stuttgart, pp. 10-18

Getaneh Assefa, 1975, The Stratigraphy and Sedimentology of the upper Blue Nile basin, Thesis for the PhD, Univ. of Minnesofa, 304 p.

Ghrlich, W.A., Rice, H.M., Ellis, J.H., 1955, Influence of the composition of parent materials on soil formation in Manitoba., Can.J.Agr.Sci.35.pp. 407-21

Gouin,P.,& Mohr, P.A.,1964, Gravity traverses in Ethiopia (interim report) Bull. Geophys.Obs., Addis Abeba,7, pp.185-239

Grasty, R., Miller, J.A.,& Mohr, P.A., 1963, Preliminary results of K-Ar age determination on some Ethiopian Trap Series basalts. Bull. Geophys. Obs., Addis Abeba,6, pp. 97-101

Grim, R.E., 1953, Clay Mineralogy, McGraw-Hill book Comp., Inc., New York, 384p.

Harris, P.G., 1969, Basalt type and Arrican rift valley tectonism, Tectonophysics, 8, pp. 427-436

Hunt, C.B., 1972, Geology of Soils, Freeman W.H.,& Comp., San Francisco, 344p.

Ingerson, E. 1963, Order Foraminifera, in J.W.Neale, ed., Principles of zoological Micropalaeontology, Pergamon

Irwin, M.L., 1965, General theory of epeiric clear water Sedimentation, in R.C.Selley; Ancient Sedimentary environments, 1969, Chapman and Hall Ltd., London, 237p.

Jackson, M.L., 1964, Chemical Composition of the Soil, in F.S. Bear, ed., Chemistry of the Soil, Rainhold publ. Corp., New York, 515p.

Jenny, H., 1941, Factors of Soil formation, McGraw - Hill,New York

Jepson, P.H., & Athearn, M.J., 1961, Geological plan and section - left bank of Blue Nile Canyon near crossing of Addis Abeba - Debre Markos road, in, Land & water resources of of the Blue Nile Basin- Ethiopia, U.S.Dept. State/Water resources, Addis Abeba (Unpublished)

Jones, P.W.,& Rex, D.C., 1974, New dates from the Ethiopian plateau volcanics, Nature, 252, pp. 218-219

——————, 1976, Age of the lower flood basalts of the Ethiopian plateau.

Kang, B.T., 1978, The fertility of tropical soils, Lecture notes training course on fertilizer use in the tropics, Nairobi (Unpublished)

Kazmin, V., 1975b, Explanation of the geological map of Ethiopia: Geol. Survey Ethiopia, Bull.,1, pp. 1-15

——————; , Stratigraphy & Correlation of Tertiary Volcanic rocks in Ethiopia

Kerr, P.F., 1959, Optical Mineralogy, 3rd edition, Mc Graw-Hill Book Company New York, 442p.

King, L.C., 1962, The Morphology of the earth, Oliver and Boyd, Edinburgh

Krauskopf, K., 1967, Introduction to Geochemistry, McGraw-Hill Book Company, New York, 721 p.

Le Bas, M.J., & Mohr, P.A., 1970, Tholeiite from the Simien alkali basalt centre, Geol.Mag., V. 107, Printed in Great Britain, pp. 529.

Le Houeron, H.N., Corra, M., Haywood, M., 1980, Report on a mission to the Gojjam Province, ILCA, 18 p. (unpublished).

Lutz, H.J., & Chandler, R.F., 1949, Forest Soils, John Wiley & Sons, Inc., New York, pp. 263-267.

MeDougall, I., Morton, W.H., & Williams, M.A.D., 1975, Age and rates of denudation of Trap Series basalts at the Blue Nile gorge, Ethiopia, Nature, 254, pp. 207-208.

Megrue, G.H., Norton, E., & Strangway, D.W., 1972, Tectonic History of the Ethiopian rift as deduced by K-Ar ages and paleomagnetic measurements of basaltic dykes, Jour. Geophys. Res., 77, pp. 5744-5754.

Merla, G., Abbate, E., Azzaroli, A., Bruni, P., Cannti, P., Fazzuoli, M., Sagri, M., Tacconi, P., 1979, A geological map of Ethiopia & Somalia, C.N.R. Firenze.

Milner, H.B., 1940, Sedimentary petrography, 3rd ed.; London, 666 p.

Mohr, P.A., (1962): The geology of Ethiopia Univ. Coll. of Addis Ababa, (reprinted in 1971)(AAU Press), Addis Ababa, 268 p.

__________, 1967a, Review of the geology of the Simien Mountains, Bull.Geophys.Obs., Addis Ababa, 10, pp. 79-93.

__________, 1967b, Reclassification of the Ethiopian Cainozic Volcanic succession, Reprinted from Nature, Vol. 208, No. 5006, pp. 177-178.

__________, 1968, The Cainozoic Volcanic succession in Ethiopia., Bull.Volc., 32, 5-14 p.

__________, 1971b, Ethiopian rift and plateau: Some volcanic petro-chemical differences, Journal of Geophysical research, Vol. 76, No. 8.

Murphy, H.F., 1959, A report on the fertility status of some soils of Ethiopia, Exp.St.Bull. No. 1, Imp.Eth.College of Agriculture and Mechanical Arts, Alemaya.

PettiJohn, F.J., 1975, Sedimentary rocks: third edition, Harper & Row publishers, 628 p.

Soil Survey Staff, 1967: Supplement to soil classification a comprehensive system: 7th approximation, U.S. Dept. Agr., U.S.Govt. Printing Office, Washington.

Soil Taxonomy, 1975: A basic system of soil classification for making and interpreting soil surveys: Soil Survey Staff, Soil Conservation Service, U.S. Dept. Agr. Agr. Handbook no. 436, U.S.Govt. Printing Office, Washington, 754 p.

Williams, M.A.J., & Faure H., eds., 1968, The Sahara and the Nile: Quaternary environments and prehistoric occupation in northern Africa, A.A. Balkama publishers, Rotterdam, 607 p.

Young, A., 1972, Slopes: ed., by K.M. Clayton, Oliver and Boyd, Edinburgh, 288 p.

United States Dept. of the Interior, Bureau of reclamation, 1964, Land and Water Resources of the Blue Nile basin, Ethiopia, Appendix IV - Land Classification, 112 p.

Zannetine, B., Justin Visentin, E., 1974, The volcanic succession in Central Ethiopia, Mem.Ist.Geol.Min.Univ. Padova, 31, 20 p.

Zannetine, B., Gregnanin, A., Justin Visentin, E., Morbidelli, L., Piccirillo, E.M., 1974, Geological & Petrological researches on the volcanics of central Ethiopia: C.N.R., Centr.Stud. Geol. Petrologia Formazione Cristalline, Padova, 6 p.

Zannetine, B., Gregnanin, A., Justin Visentin, E., Mezzacasa, G., & Piccirillo, E.M., 1974a, Petrochemistry of the volcanic series of the central eastern Ethiopian plateau and relationships between tectonics and magmatology, Mem.Ist.Geol.Min.Univ. Padova, 31, 1-35.

———, 1976, New Chemical analyses of the Tertiary volcanics from the central eastern Ethiopian plateau, C.N.R., Centro.Studio. Geol. Petrologia Formazione cristalline, Padova, 43 p.