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THE SEDIMENTOLOGY OF THE
DIATOMITE BEARING LACUSTRINE DEPOSITS
OF ADAMI TULU AREA, ARSI, ETHIOPIA

A Thesis
Presented to
The School of Graduate Studies
Addis Ababa University

In Partial Fulfillment
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Master of Science in Geology

By
Ketema Amare
June, 1986



ADDIS ABABA UNIVERSITY
School of Graduate Studies

The Sedimentology of the Diatomite Bearing
Lacustrine Deposits of Adami Tulu Area

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Abstract

Sediments of Late Quaternary period are exposed in Adami Tulu area. They represent Deposition in a fault controlled basin in the northern part of the Main Ethiopian Rift Valley. They form thick successions of coarse and fine grained sediments, gravels, sands, silt and diatomites among which gravels and diatomites are volumetrically important. These sediments display sedimentary structures, such as bedding, laminations, cross-bedding, mudcracks, and load casts. Texturally, these sediments are poorly sorted, positively skewed, and characterized by mesokurtic-leptokurtic curves.

Compositional studies indicate pumice, glass shards, fragments of volcanic rocks, feldspars, and quartz to be the most important constituents of the rocks. Hornblende, pyroxene, magnetite and biotite are the important heavy mineral constituents. Obsidian, basalt and rhyolite dominate the lithic fraction. These composition of the sediments is indicative of a volcanic provenance.

The textural characteristics of the gravels and their distinct association with humic substances or gastropods and bivalve shells are indicative of fluvial and beach environments of deposition for the gravels, respectively. The structures of diatomites and associated silts are consistent with the deposition of these sediments in a lacustrine environment.

CONTENTS

	Page
Abstract	i
Contents	ii
Illustrations	iv
Figures	iv
Plates	vi
Tables	vii
Acknowledgment	viii
1. INTRODUCTION	1
1.1. Location and accessibility	1
1.2. Climate and vegetation	3
1.3. Objectives	3
1.4. Previous works	3
1.5. Methods and materials	4
2. GEOLOGY	6
2.1 General	6
2.2 Stratigraphy and Lithology	10
2.2.1 Lithology of the Lower Sequence ..	13
2.2.1.1 Sands	18
2.2.1.2 Silts	20
2.2.1.3 Diatomites	24
2.2.1.4 Ashes and Tuffs	26

	Page
2.2.2 Lithology of the Upper Sequence.....	30
2.2.2.1 Gravels	37
2.2.2.2 Sands	44
2.2.2.3 Silts	49
2.2.2.4 Diatomites	53
2.2.2.5 Ashes	58
2.2.3 Summary of lithologies	60
2.3 Textural studies	61
2.3.1 Textures of the Lower Sequence deposits	62
2.3.2 Textures of the Upper Sequence deposits	69
2.3.3 Summary of textural descriptions	81
3. Organic matter studies	84
4. Discussion of depositional environments	91
5. Provenance	102
6. Summary and Conclusion	104
7. Bibliography	106

List of Figures

	Page
1. Location of the study area	2
2. Schematic tectonic map of the Ethiopian Rift	
showing Wonji Fault Belt (WFB)	7
3. Station map	11
4. Geological map of the area	12
5. Descriptions of selected stratigraphic sections of the Lower Sequence	16
6. Correlation between sections of the Lower Sequence	17
7. Descriptions of selected stratigraphic sections of the Upper Sequence	31
8. Correlations of selected stratigraphic sections of the Upper Sequence	33
9. Cumulative curves of grain-size distributions for sand and ash samples of the Lower Sequence	63
10. Cumulative curves of grain-size distributions for silts and diatomites of Lower Sequence	66
11. Plot of standard deviation against median	67
12. Plot of sorting coefficient against median	67
13. Cumulative curves of grain-sizes distribution for the gravels of the Upper Sequence	70
14. Cumulative curves of grain-size distribution for the sands of the Upper Sequence	73
15. Cumulative curves of grain-size distributions for ash and silts of the Upper Sequence	75

	Page
16. Cumulative curves of grain-size distributions for diatomites of the Upper Sequence	78
17. A Scheme for the determination of organic matter	86
18. CM diagram of Adami Tulu Sediments	93
19. Plot of standard deviation against mean	94
20. CM diagram of Adami Tulu sediments	98

List of Plates

	Page
1. View of the Lower Sequence deposits	14
2. Hand specimen of silts of the Lower Sequence with small depressions at the bedding planes	21
3. Mud-cracks in the silts of the Lower Sequence	21
4. View of the Upper Sequence deposits	36
5. Cross-bedded gravel lenses in the diatomites at locality 17	40
6. Shells of gastropods and bivalve of the gravels of the Upper Sequence	41
7. Thin layers of organic matter in silts	50
8. Diatomites of the Upper Sequence (White)	54
9. Diatomites of the Upper Sequence (grayish white) ..	55

List of Tables

	Page
1. Description of lithology and grain size distribution of Lower Sequence	19
2. Compositional characteristics of the Lower Sequence deposits	23
3. Chemical analysis of diatomites of Lower Sequence	25
4. Description of grain size distribution of gravels (up.S.)	38
5. Description of grain size distributions of sands and Ashes (up.S.)	45
6. Description of grain size distributions of silts and Diatomites (up.S.)	52
7. Compositional characteristics of the Upper Sequence deposits	47
8. Chemical analysis of diatomites of Upper Sequence	57
9. Granulometric indices of Lower Sequence deposits	64
10. Granulometric indices of the Gravels (up.S.)	71
11. Granulometric indices of Sands and Ashes (up.S.)	74
12. Granulometric indices of diatomites and silts (up.S.)	76
13. Summary of textural characteristics	82
14. Results of organic matter analysis	88

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1. Introduction

1.1 Location and accessibility

The area covered by the present study is located about 170 Km to the south of Addis in the Galla Lakes region of the main Ethiopian Rift. It lies between lakes Zway and Langano due east of the town of Adami Tulu. To the north it is bordered by the southern shore of lake Zway and to the south by Aluto volcano, roughly covering an area of about 90 km² (Fig. 1).

It is accessible by the main Addis Ababa-Awassa highway. A dirt road between Adami Tulu and Chefe Jila (to the east of Adami Tulu) crosses the area. Two other dirt roads one which runs to the north branching from Adami Tulu - Chefe Jila road and the other to the south reaching to Langano can be used by four wheel drive to explore the area. Traverses could be taken from any of these roads by foot.

The main river that flows in this region is the Bulbula river. It starts from Lake Zway in the north and drains in to Lake Abyata in the south. Numerous dry seasonal streams that start from the volcanic hills flow south west feeding the Bulbula river during rainy seasons thereby cutting gorges through the soft lacustrine sediments and exposing thick sections of these sediments.

The topography is flat except in the central and south eastern parts where volcanic hills form elevated grounds. Exposures are found along the slopes or at the foot of the hills and along the dry valleys or streams.

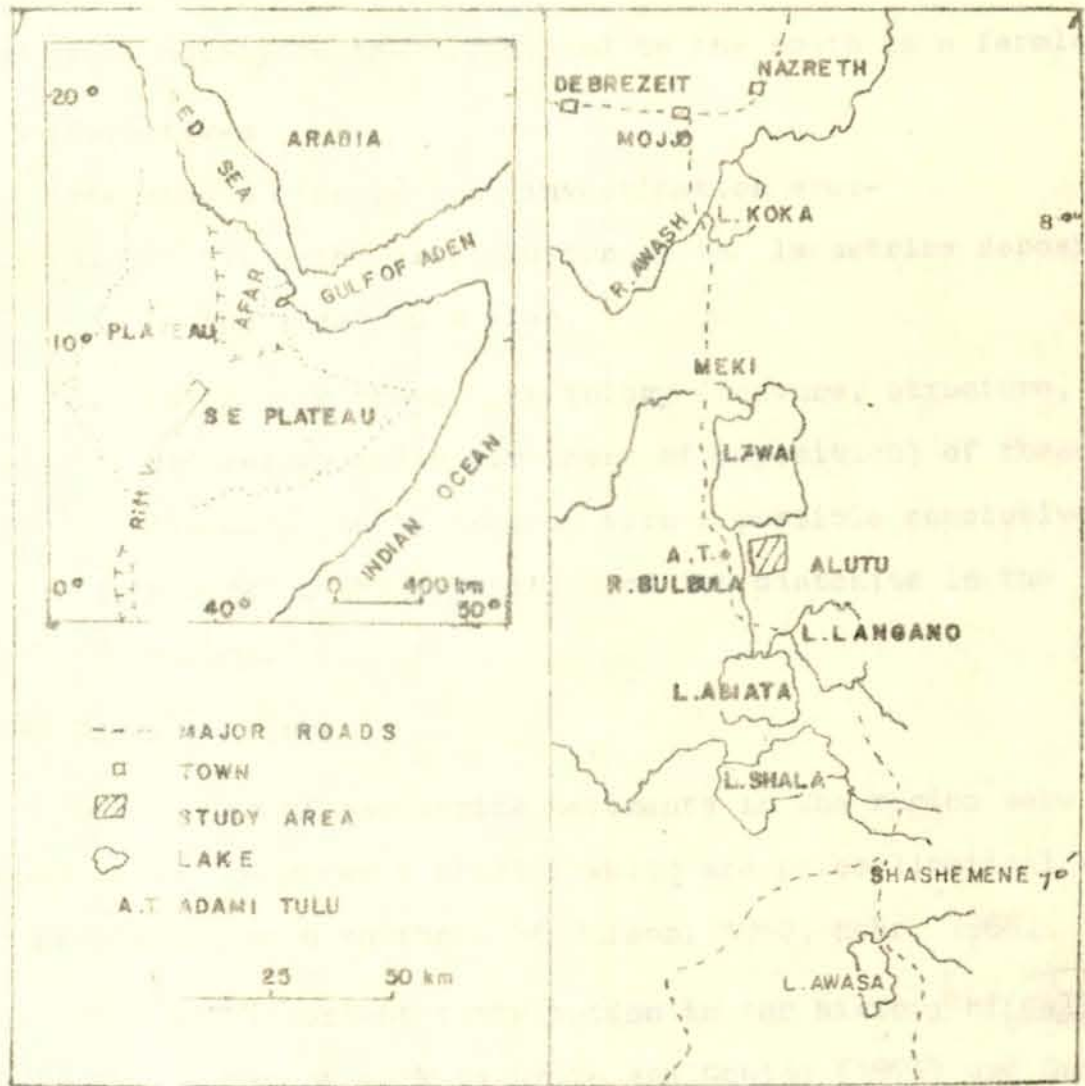


Fig 1 LOCATION OF THE STUDY AREA.

1.2 Climate and Vegetation

The climate is semiarid with a relatively short rainy season during July and August. The vegetation of the area consists mainly of low thornscrub and acacia trees. Part of the area, mainly to the north, and to the south is a farmland.

1.3 Objectives

The aims of the present investigation are:-

1. To study the distribution of the lacustrine deposits in the Adami Tulu area.
2. To examine the sedimentology (texture, structure, mineralogy and environment of deposition) of these deposits and to come up with a possible conclusive remark on the deposition of the diatomite in the region.

1.4 Previous Works

Occurrences of lacustrine sediments in the region were reported in the general studies which are paleoclimatical and or geological such as those of Nilson, 1940; Mohr, 1966.

The most important contribution in the history of Galla lakes is the recent work by Grove and Gouide (1971) and Gaze (1975) who also provided radiometric age dates from these sediments. The Ethiopian Institute of Geological Survey (EIGS) of the Ministry of Mines has conducted general geological investigations in the lakes district prior to 1970 and presently the UNDP for Geothermal research has mapped the region at the scale of 1:50,000. Recently the EIGS has been

studying the diatomite of the area mainly focusing on the determination of its quality based on physical properties and for few localities the estimation of reserves. No systematic study has been done in investigating the sedimentologic nature of these sediments prior to this study.

1.5 Methods and Materials

A topographic map of 1:50,000 scale was used as a base, with aerial photographs of the same scale as a supplementary. Traverses were taken along stream channels and also in profiles not uniformly spaced.

The following methods were generally employed in the study:-

1.5.1 Field logging

Fifteen exposed section along stream channels and dry gullies were described, sampled and measured using a field logging method of Bouma (1962). For each bed, thickness was measured and significant properties such as composition, grade, sedimentary structures and colour were recorded.

1.5.2 Granulometric analysis

Representative samples from each measured sections were air dried and then granulometric analysis was made following the methods described by Folk (1968). Grain size parameters are those of Folk (1968). Parameters such as mean grain-size, sorting, skewness, kurtosis and standard deviation have been determined graphically and the ϕ scale introduced by Krumbein (1934) has been used to simplify the arithmetic involved in computing these parameters.

1.5.3 Petrographic and Heavy Mineral Analysis

The difficulty of preparing thinsections of unconsolidated pumiceous sediments and pyroclastic deposits precluded extensive use of petrographic study. However, the fine fractions of these deposits were examined under the binocular microscope in order to have a clue in their composition.

Heavy mineral analysis was carried out using representative fine sand fractions following the procedure described by Carver (1975). The heavy minerals were separated from these fractions using bromoform (sp. gr. 2.85). Representative samples of both the light and heavy minerals were mounted in glass slide and then examined under the microscope. Counts were made of the individual heavy minerals to determine their percentage by number.

1.5.4 Other analysis

Semi-quantitative determination of organic matter content was done on 35 samples which were suspected for the presence of organic matter.

2. Geology

2.1 General

The main Ethiopian Rift valley is a huge graben which is occupied by volcano tectonic lakes. It is characterised by normal, step faults arranged in an enechelon style with a general NNE-SSW trend (Mohr, 1967). Its floor is marked by a persistent belt of intense, fresh faulting which has been termed by Mohr as Wonji Fault Belt (Fig. 2) which is supposed to be axial to the rift system. It extends from the northern shores of Lake Abaya northeast wards into the Afar Depression and is traceable for 1100 Kms along the Ethiopian Rift system. The belt is formed of short normal faults of small throw which is most frequently up to the west and is characterized by a line of Quaternary pantelleritic (silicic) volcanoes such as Aluto, Chabi, Shalla, Fantale, Rossetti Guda etc. which have extruded both lavas and ignimbrites (Mohr, 1960, 1967).

The Galle lakes section of the main Ethiopian Rift lies about 150 Kms due south of A.A. and contains four large lakes, as indicated on (Fig. 1). Lakes Langano and Zway lie against the eastern margin of the rift, whilst lakes Abaya and Shalla lie further west in the interior of the rift.

Lacustrine deposits containing shelly layers were first discovered along the Bulbla river by Neuman (1902) from which later Paci (1940) examined a collection of molluscs and noted a palaeartic affinities of the fauna.

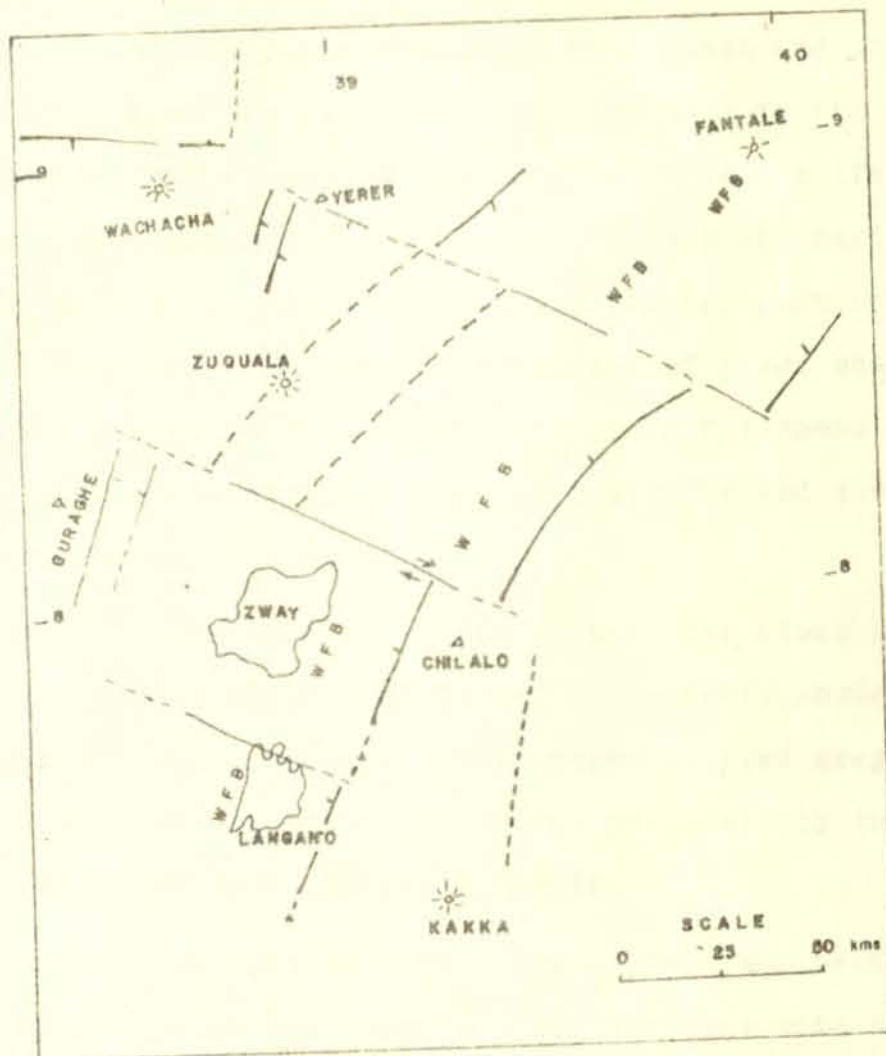


FIG. 2 SCHEMATIC TECTONIC MAP OF THE RIFT SHOWING THE WONJI FAULT BELT (WFB) AFTER P. A. MOHR (1967).

Mohr (1962,1966) also recognised two groups of rift floor sediments and suggested that in the late Tertiary the Galla lakes basin was continuous with the Awassa and Abaya basins to the south and with the Awash drainage to the north. In this protorift trough, fine grained water laid tuffs and pumice beds were deposited. According to Mohr the basin topography must have assumed almost its present form by the late Pleistocene and the subsequent period of large scale flooding identified by Nilson and him has been responsible for the almost undisturbed lacustrine sediments and shore lines surrounding the Galla lakes.

The older lacustrine sediments of the rift floor are relatively severely tilted and warped by tectonic processes. The younger sediments are generally unconsolidated grey gravels which are localised in their occurrence particularly to thick developments along Holocene beach levels.

The Adami Tulu area is within the Galla lakes basin mainly between the Zway-Langano basin. The diatomite bearing lacustrine sediments were laid down in a late Quaternary ancestral lake (Grove and Gouide, 1971; Geze, 1975). The Langano-Zway basin was developed and occupied by the ancestral Galla lake before volcanism commenced at Aluto volcanic center (UNDP, 1973). A thick sedimentary sequence was deposited in the basin. Where exposed, the sediments are dominantly fine grained tuffs, sandstones and pumice and rhyolitic gravels. Coarse pumice breccia are interbedded with them.

Old beach dunes occur as ridges on the west of Aluto and were formed during the shrinkage of the ancestral Galla lakes. These ridges which mark the Holocene lake levels are well preserved as gravel beach ridges near the shores of lakes Langano and Zway (UNDP, 1973).

The lacustrine sediments of the Galla lakes have been dated by Gouide and Grove (1971) in their study of pleistocene-Holocene history of the Galla lakes. They dated gastropod shells by C-14 method from different levels above lake shalla and obtained an age of 9220 ± 190 yrs B.P. and 5610 ± 100 yrs B.P. Another age dating which is more or less from the shell layers of the study region along the Bulbula river is determined by Geze (1975). He dated sediments below and above diatomaceous sediments near the Bulbula river and obtained 9360 ± 210 B.P. and 4960 ± 140 B.P. for the last lacustrine period. Based on these dates Geze suggested an age of 10,000 yrs for the beginning of the main lacustrine phase which came to a close around 5000 yrs ago.

It has been proved (by Grove and Gouide and by Mohr) that the basin of lakes Shala, Langano, Abyata and Zway formed a single lake. The analysis of diatom flora from these lakes helped much in revealing the continuous nature of these lakes during the Holocene. Observation of strandlines and parallel shore lines which are visible both on the field and on air photographs and satellite imageries (Grove and Gouide, 1975) were very helpful in drawing these conclusions.

2.2 Stratigraphy and Lithology

The fluviolacustrine deposits generally cover large part of the area and in most places are overlain by recent alluvial deposits especially at the foot of the hills. The central and south eastern part is dominated by volcanic hills and domes such as Belicha, Sida and Dodicha (Fig. 3). These volcanic hills are composed of rhyolitic products, obsidian flows and ignimbrites. The northern, central and southern part of the area are affected by faults whose trends vary from NE - SE (see map).

On the basis of the works of UNDP (1976), Knoth (1981) and this study, the stratigraphy of the region comprises the following:-

Alluvium	
porphyritic Obsidian	Holocene
Upper Lacustrine Sequence	
Pumiceous Pyroclastics	
Basalt Tuff	
Lower Lacustrine Sequence	Pleistocene
Basalt	

It follows from the stratigraphy that the lacustrine deposits of the region belong into two sequences. Lower Lacustrine and Upper Lacustrine. Lithologies of both sequences are largely dominated by volcanic material and range from coarse gravels to fine silts and ashes and are described below separately for both sequences.

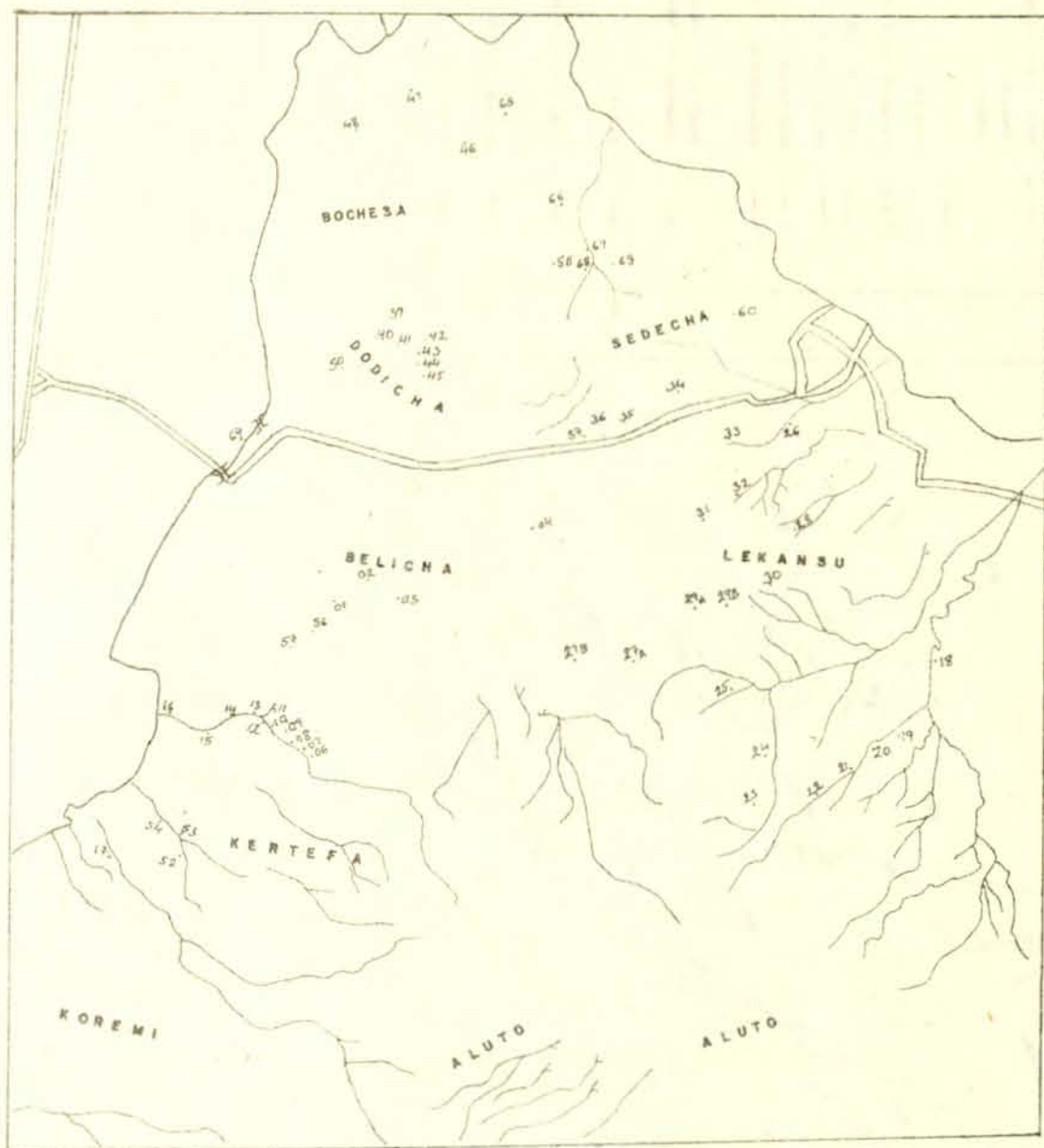


Fig. 3 STATION MAP.

FIG-4 GEOLOGICAL MAP OF THE
ADAMI TULU AREA.

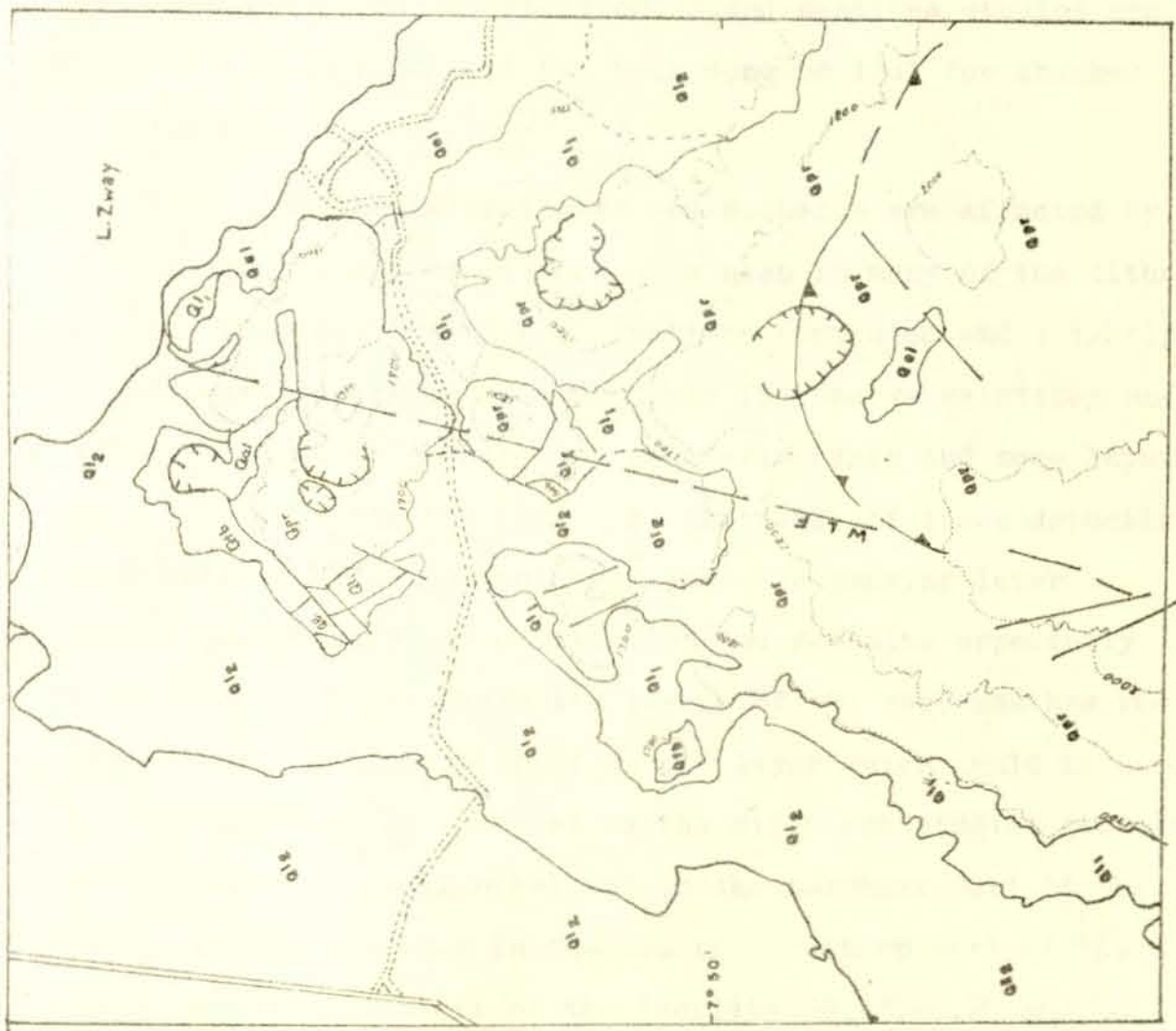
(Compiled from map of the U. N. Geothermal Project
with little modification)

SCALE 1:50,000



LEGEND

- Qa1 ALLUVIUM
- Ql2 UPPER LACUSTRINE DEPOSITS
- Ql4 LOWER LACUSTRINE DEPOSITS
- Qb5 BASALTS
- Op1 ISHIMIRITES, RHYOLITES & RHYOLITIC PUMICE
- GEOLOGICAL CONTACT DEFINITE
- - - GEOLOGICAL CONTACT INFERRED
- FAULT DEFINITE
- - - FAULT INFERRED
- ∇ CALDERA INFERRED
- CRATER
- ROAD
- TRUCK
- CONTOUR
- WLF WEST LANGANGAO FAULT



2.2.1 Lithology of Lower Sequence

The Lower Lacustrine deposits occur in the area where the different localities are uplifted by faults which are related mainly to the West Langano Fault. These are generally ridge forming localities such as Dodicha, Sedcha, between Kiki and Belicha and in the slopes of hills facing the Lekanshu plains (Fig. 3). None of them are seen to be found along recent valleys and are restricted mainly in the central and northern part of the study area. As a result of poor exposure the number of lithologies and sections studied are limited although attempt has been done to look for thicker sections.

The deposits belonging to the sequence are affected by faults and the effect of these are seen in many of the lithotypes. They are fractured, sometimes compacted and slightly welded although it is also possible to observe relatively unaffected deposits. These are generally ashes and some layers of diatomite. The structural relationship of these deposits is complicated due to faultings and accompanying later eruptions. Careful observation of the deposits especially associated with the diatomite layers of the sequence has revealed the identification of an ash layer which could be used as a marker bed for correlating the different studied sections mainly those in the central and in the northern part of the area. For occurrences in the central southern part of the area, the basaltic tuff of the locality 39,40,41,29 and 56 together with a 10 Cm sand layer which generally seems to lie always below the tuff layer that immediately comes above the diatomite of the sequence is used as a marker horizon.

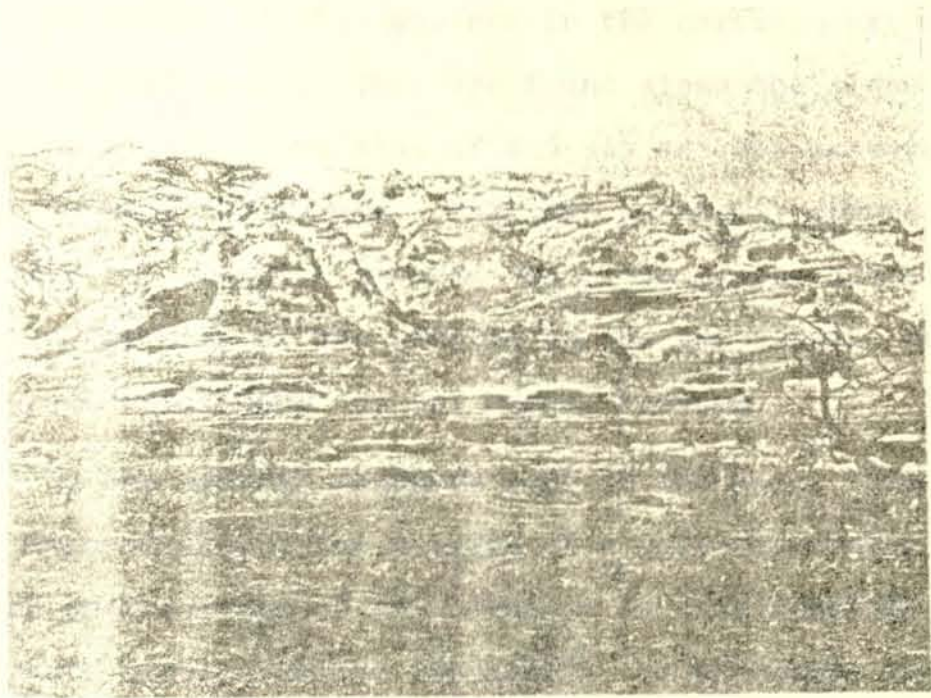


Plate 1 View of the Lower Sequence deposits

These two and stratigraphic observation in locality 41 and 56 were useful in constructing the stratigraphic relationship of the exposed parts of the sequence. Description and correlation of the different sections are presented in Figs 5 and 6 respectively.

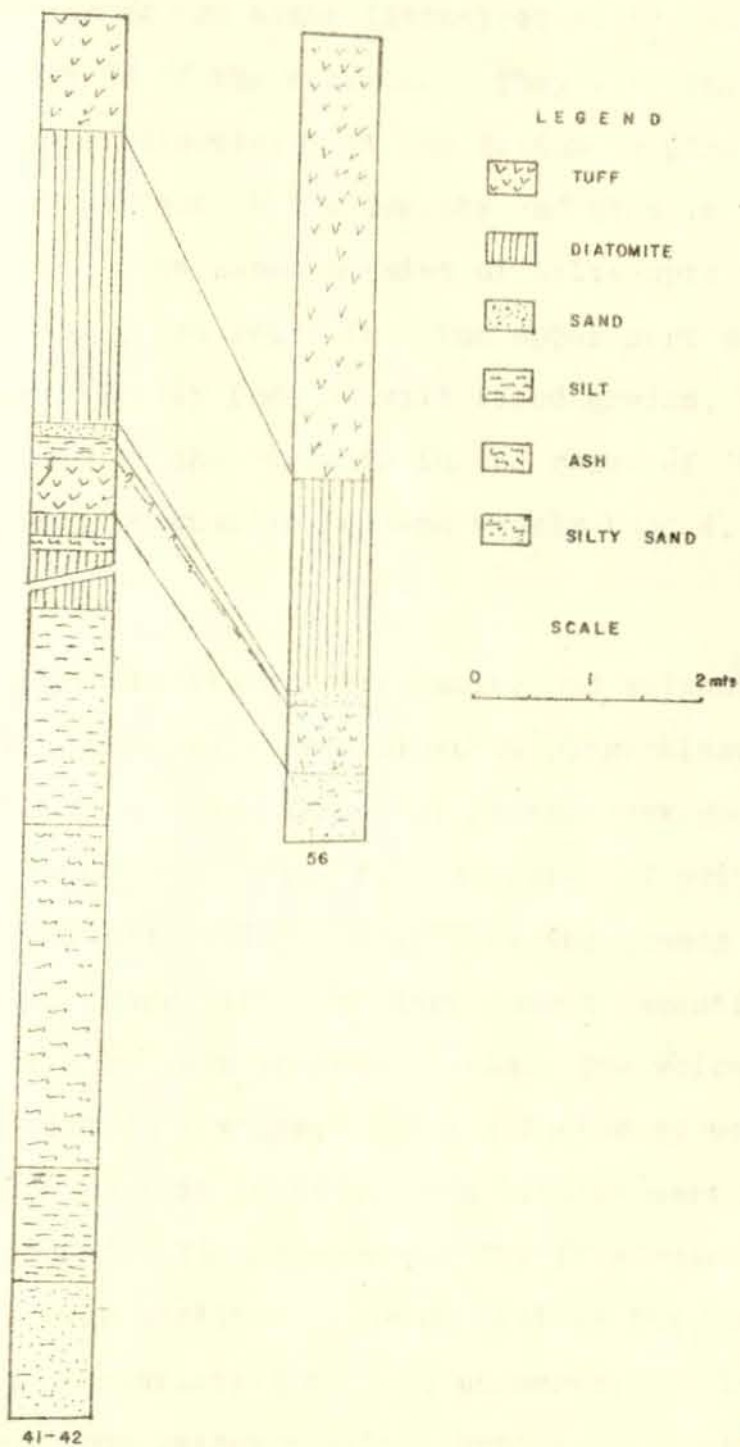
Exposures of the sequence in the northern extrem of the area is very small. They are found along the slope of Sedecho hill on a downthrown side of a fault and the measured thickness is only about 2mts. They are generally covered by pyroclastic breccia that covered the slope of the hills above them. The size of the cobbles in the pyroclastic breccia exceeds mostly 50cm and are nearly rounded.

In the central southern part of the area, these deposits are exposed around the margins of a volcanic crater. The measured thickness of the sequence in this locality is 7mts. They are highly faulted especially the diatomite is fractured into small blocks. The basaltic tuff covering them must have been erupted from the crater (Knoth, 1981).

The maximum thickness (more than 15mts), observed for the sequence is in the central part of the area. It is exposed along a large hill where at its foot represents probably the northern margin of the previous volcanic crater and the stratigraphy for the Lower Sequence is established here.

The Lower Sequence comprises of lithologies such as silt, ash, diatomite, sand, and ash and tuff of variable thickness. The lithologic description for these lithotypes is given below.

Fig. 6 CORRELATION BETWEEN SECTIONS OF THE LOWER SEQUENCE DEPOSITS.



2.2.1.1. Sands

These are among the minor lithotypes of the sequence and represent nearly 9% of the sequence. They vary in colour - from grayish white especially at the bottom to pinkish gray and exposed at the foot of the Dodicha and Sida in the central part of the area. The sands consist of silts upto 40% especially at the base, and sands from the upper part of the sequence is practically free of silt sized grains. The thickness of some beds in the sands is in the range of 10cm to 60cm. They are commonly unconsolidated and weakly bedded.

Composition

Most of the constituents are pumice and volcanic glass. Lithic clasts, feldspars - predominantly plagioclase feldspars quartz, chert with various shades of green, dark green, brownish yellow (which could be related to the degree of oxidation state of iron present as impurities) are the common components in most samples. Magnetites and hornblendes essentially form the heavy mineral portion in these sands. The volcanic glass is curved and flat in texture, little affected by weathering and occasionally contain bubbles. The lithics part consists of obsidian, andesite(?) and scoria. The plagioclase grains are seen with their distinct cleavage most of the time, although the other varieties are not uncommon. Carbonate concretions and iron oxides mostly limonite occur in some samples (42A)

TABLE 1: Description of Lithology and Grain Size Distributions of Lower Sequence

Sample No.	Lithology	Thickness	Colour	Mean Size ϕ	% Gravel	% Sand	% Silt	% Clay	Textural Nomenclature
04-C	Sand	0.5	Brownish grey	2.93	8.04	57.27	28.46	4.08	Gravelly silty med. sand
04-D	Sand	0.2	Grey	2.16	4.31	81.49	10.65	2.37	Slightly gravelly silty fine sand
42-A	Sand	0.6	Yellowish grey	4.73	-	58.08	27.15	14.81	Silty sand
04-F	Clayey silt	0.2	Grey	5.33	-	-	86.3	17.7	Silt
41-B	Silt	0.2	Yellowish white	7.03	-	-	70.76	29.24	Silt
42-E	Silt	1.8	Light yellow	6.03	-	-	84.35	15.65	Silt
58-C	Clayey silt	0.4	Yellow	6.33	-	-	70.84	29.16	Silt
04-B	Diatomite	2.9	Yellowish white	7.56	0.8	10.93	51.27	34.36	Slightly gravelly sandy mud
04-E	Diatomite	0.7	Yellowish white	7.16	-	-	75.36	24.64	Silt
40-A	Diatomite	2.75	Yellowish white	7.5	-	-	58.75	41.25	Mud
41-C	Diatomite	5.0	Pinkish yellow	6.26	-	-	79.48	20.52	Silt
41-E	Diatomite	0.5	Dark grey	7.13	-	-	71.3	28.7	Silt
58-B	Diatomite	11.0	Yellowish white	7.56	-	-	65.73	34.27	Mud
41-F	Ash	0.08	Dark grey	5.36	-	-	97.29	2.71	Fine ash
42-D	Ash	3	Light yellowish grey	2.53	12.19	49.02	33.06	2.36	Coarse ash
58-A ₀	Tuff	0.02	Dark grey	6.66	-	-	76.64	23.36	Fine ash

2.2.1.2 Silts

Silts in general are represented at the bottom and in the middle part of the sections for the sequence. They constitute roughly 19% of the stratigraphic sections of the Lower Sequence. The colour of the silts varies from grayish white to light gray, yellowish gray and light yellow throughout the whole sequence. In thickness individual beds range from 25cm to 1.6 mt. Lateral variation of these silts is not evident due to their occurrence in few localities.

These silts largely are fine to coarse silt. They are thinly bedded and laminated. The individual laminae in each bed varies between $\frac{1}{2}$ mm to 1mm in thickness and are relatively consolidated. Some inclusions of pumice clasts are observed along their bedding planes and the different beds are separated by very small irregular projections of the individual upper laminae which produced depressions in the lower or underlying laminae of same lithology (plate 2). This is especially in the grayish variety of the bottom sections.

The middle layer of silts which is more yellowish white than the lower layer is also bedded and relatively consolidated into siltstone. It is clayey limonitic, thinly bedded with mud cracks at its top (plate 3), and grades vertically into the overlying diatomite.

The silts at the top of the sequence is yellowish white in colour, thinly bedded and individual beds range from 2 to 3mm. Bedding alternates between yellow and yellowish white and light brownish colours. Discontinuous organic matter

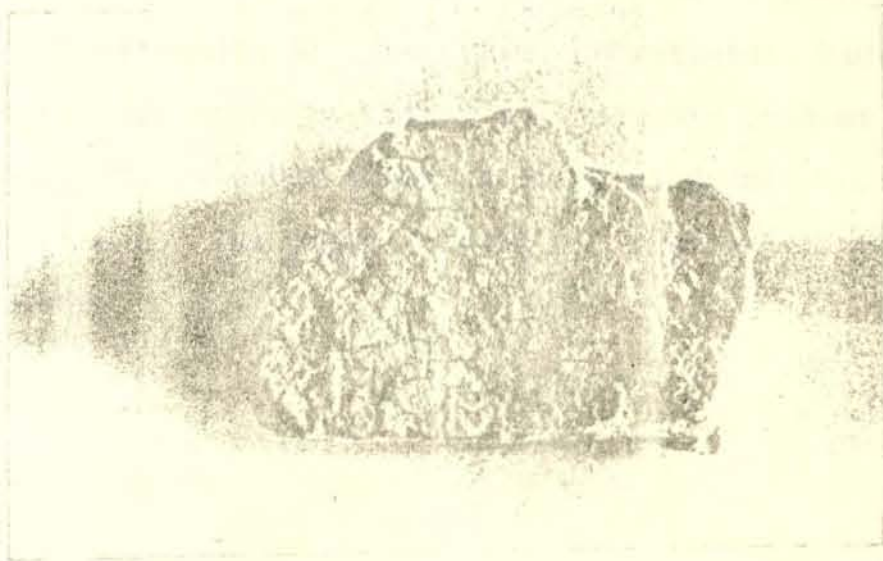
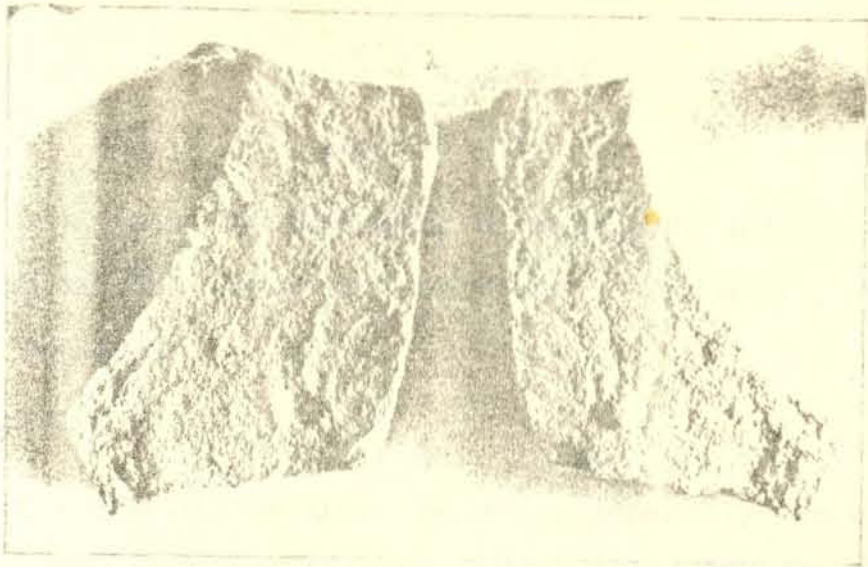


Plate 2 (top) Hand specimen of silts of Upper Sequence

with small depressions at the bedding planes.

Plate 3 (bottom) Mud cracks in the silts of the Upper Sequence.

lenses also mark the beginning of thin beds and are only observed in this layer and not found in the silts of the bottom section.

Composition

The silts of the Lower Sequence generally are clayey and the percentage of clay varies from 15-30%. Investigation under the binocular microscope showed that pumice, volcanic glass, plagioclase feldspars, lithics of obsidian, and basalt, limonite and quartz constitute the major mineralogical composition of most silts in that order. Hornblende, biotite and apatite (?) are among the minor constituents present as heavy minerals. The volcanic glass is flat, elongated and is relatively fresh. The pumice clasts are fibrous and tubular in structure.

TABLE 2: Compositional Characteristics of the Lower Sequence Deposits

Sample No.	Lithology	Pu	V.G.	K.F.	P.F.	Q	Rock Fragment				Heavy Minerals						
							Obs	Ba	Ry	Scor	F.Ox	Ch	Pxn	Mg	Hb	BI	HF
04-C	Sand	A	A	C	C	O	C	R	R	R	O	O	C	A	A	F	2.5
04-D	Sand	A	A	C	C	O	C	F	F	-	-	R	F	A	C	-	0.3
42-A	Sand	A	A	C	C	O	C	C	R	-	R	C	R	A	A	-	0.06
04-B	Diatomite	-	C	F	R	O	R	-	-	-	R	R	-	F	R	-	0.5
04-E	Diatomite	C	C	F	F	-	R	-	-	-	R	O	-	-	-	-	N.D.
40-A	Diatomite	C	C	F	R	O	R	-	-	-	R	R	-	-	-	-	N.D.
41-C	Diatomite	C	C	F	F	O	F	-	-	-	-	O	-	-	-	-	N.D.
41-E	Diatomite	C	C	F	F	O	F	-	-	-	-	O	-	-	-	-	N.D.
58-B	Diatomite	-	C	F	R	O	R	-	-	-	R	O	-	-	-	-	N.D.
04-F	Silt	A	A	R	C	C	C	F	-	-	F	F	-	R	A	C	N.D.
41-B	Silt	C	A	C	C	C	C	R	-	-	F	R	-	C	A	C	N.D.
42-E	Silt	C	A	C	R	F	C	R	-	-	O	-	-	-	A	C	N.D.
58-C	Silt	C	A	C	F	F	C	R	-	-	O	-	-	-	A	C	N.D.
41-F	Ash	A	A	R	C	-	C	R	-	O	O	O	C	A	R	-	N.D.
42-D	Ash	A	A	C	C	R	C	F	F	F	F	C	F	A	R	O	0.06
58-A	Tuff	A	A	F	C	-	F	O	-	R	R	C	C	C	R	-	N.D.
29-B	B.Tuff	-	F	-	A	-	-	C	-	-	-	-	-	-	-	-	N.D.

Note:

- | | | |
|-----------------------------|---|----------------------|
| Pu. - Pumice | Hb - Hornblende | A - Abundant |
| V.G.- Volcanic glass | BI - Biotite | C - Common |
| K.F.- Potassium feldspar | Obs - Obsidian | F - Few |
| P.F.- Plagio clase feldspar | Ba - Basalt | O - Occasional |
| Ch - Chert | Ry - Rhyolite | R - Rare |
| Q - Quartz | Sc - Scoria | N.D.- Not determined |
| F-Ox- Iron Oxide | HF - % of heavy minerals in very fine sand fraction | |
| Pxn - Pyroxene | | |

2.2.1.3 Diatomites

These lithotypes form 38% of the sequence. They commonly occur along the slopes of the recent volcanic domes such as Sida and Sedecha and in the margins of Belicha volcanic crater (Fig 4). They are mostly yellowish white in colour and largely are constituted of silt sized (51-78%) and clay sized (20-40%) materials. Texturally, they are classified as silt in most cases and as muddy in few cases (Folk, 1968). In most places they are covered by the tuffs of the sequence and are weakly bedded.

The thickness of individual beds of diatomites ranges between 80cm and 6mt and the maximum thickness is found in a block which has been uplifted by the West Langan Fault Fig 4. They are affected by faulting to a variable degree. Those in Sedecha, Belicha and Dodicha are more or less equally affected being intensively faulted, fractured into small blocks and are relatively compact.

Composition

These are extremely fine grained and coarser fractions are not available for observation under binocular. However from the coarser silt fractions, quartz, feldspars fine grained glass chert and fossil diatoms were identified to constitute most of the diatomites. The glass and feldspars are altered to chalky material to a certain extent. Unlike the diatomites of the Upper Sequence, they do not contain any shells of gastropods and pelocypods.

TABLE 6: Chemical Analysis of Diatomites of Lower Sequence (after Knoth, 1961)

Sample No.	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	MnO	TiO ₂	Loss on Ignition	H ₂ O at 110°C
13	85.5	3.9	2.4	0.3	0.3	1.9	1.5	0.1	0.1	4.1	5.9
14	85.8	4.2	2.3	0.6	0.2	2.8	1.3	0.1	0.2	4.6	5.7
15	91.3	1.9	1.2	0.1	0.1	1.3	0.4	0.1	0.1	3.7	6.7
16	88.8	3.0	1.5	0.1	0.2	1.4	0.6	0.1	n.d.	3.9	6.4
17	82.2	4.5	3.1	1.2	0.3	2.2	1.1	0.1	0.3	5.0	3.7
18	85.6	3.1	2.1	0.3	0.2	2.8	1.0	0.1	0.2	4.6	4.2
19	85.8	2.8	1.6	0.7	0.3	3.1	0.7	0.1	0.2	4.8	5.0
20	88.3	2.9	2.1	0.2	0.2	1.7	0.6	0.1	0.1	3.6	4.8
21	90.1	2.1	1.4	0.3	0.2	1.7	0.4	0.1	0.1	3.8	4.1
22	85.7	3.7	2.4	0.6	0.3	2.1	0.9	0.1	0.2	4.1	4.0
23	82.8	4.3	2.9	1.7	0.4	1.9	1.0	0.1	0.1	4.9	3.7
24	86.8	3.2	2.3	0.5	0.2	1.9	0.9	0.1	0.2	4.0	4.1
25	85.7	3.5	2.0	0.6	0.5	2.1	1.4	0.1	0.2	4.0	4.3
26	87.5	3.4	2.4	0.3	0.4	1.3	0.7	0.1	0.1	4.0	4.7
27	86.2	4.0	2.6	0.4	0.4	1.0	0.9	0.1	0.2	4.3	4.2
28	87.3	3.2	2.4	0.4	0.3	1.4	0.9	0.1	0.2	3.9	3.7
29	86.0	3.6	2.6	0.5	0.3	1.6	0.9	0.1	0.2	4.3	3.2
30	89.2	3.0	2.2	0.4	0.2	1.7	0.8	0.1	0.1	3.7	3.2
31	88.7	3.1	2.2	0.2	0.3	1.2	0.6	0.1	0.2	3.5	3.6
32	90.9	2.4	1.4	0.1	0.2	1.0	0.5	0.1	0.2	3.2	3.0
33	89.4	2.5	1.5	0.2	0.2	1.3	0.6	0.1	0.1	4.1	3.5
34	90.5	2.0	1.3	0.3	0.2	1.4	0.5	0.1	0.1	3.6	3.5
35	89.7	2.7	1.9	0.4	0.3	1.3	0.5	0.1	0.1	4.1	3.6
36	85.9	3.4	2.3	0.9	0.3	2.0	0.8	0.1	0.2	4.2	3.2
37	87.8	3.7	2.3	0.2	0.3	1.6	0.6	0.1	0.2	3.8	4.4
38	90.3	1.9	1.3	0.3	0.2	1.4	0.4	0.1	0.1	3.9	5.2
39	89.0	2.4	1.8	0.4	0.2	1.4	0.5	0.1	0.1	4.1	4.4
40	89.9	2.1	1.6	0.5	0.2	1.7	0.5	0.1	0.1	3.4	3.6

The result of chemical analysis of 28 samples after Knoth (1981) is given in table 3. These diatomites are characterized by higher SiO_2 percentages. The average of 28 samples is 87.5%. Average percentages of Fe_2O_3 and Al_2O_3 are 4.14 and 2.06 respectively.

2.2.1.4 Ashes and Tuffs

The ashes and tuffs of the Lower Sequence generally represent 30% of the stratigraphic column of the sequence. Two ashes and two tuffs have been identified in the sequence and the ashes are dominant over the tuffs (2:1 in proportion).

Ashes

The ashes are 3mts and 1/2mts thick and occur as intercallations between the silts and or silts and diatomites often causing impurity in both lithotypes. The colour of these ashes is different, the thicker being grayish white and the thinner dark olive gray. The dark olive gray colour is very distinctive, for the ash which made it possible to be used as a marker bed for correlating sections of the sequence.

The dark olive gary ash is identified in the central (Dodicha) and in the northern part of the area usually being interbedded in the diatomite of the sequence. Its contact both above and below is regular with the diatomite. It occurs persistently throughout the sections of the sequence. The maximum recorded thickness is 50cm but it is more often much thinner mostly being 15cm on the average. It is essentially loose fine ash, completely unconsolidated, and is apparently well sorted.

The second ash layer is the three meter thick grayish white ash which is interbedded within the silts at the bottom of the stratigraphic column for the sequence (Fig 5). It is represented in the sections of the central part (Dodicha) of the area.

It is weathered to yellowish material, semiconsolidated, dominantly composed of pumice having a maximum size of 8mm. It shows poor normal grading although the general distribution of the grains seems to be irregular.

Composition

The dark olive gray ash consists of fine pumice and obsidian chips, volcanic glass, few lithics and crystals. Pumice and colourless volcanic glass constitute the largest portion. The morphology of the glass shards vary from platy to slightly curved sickle-like, often the platy types being dominant over the latter.

The white grayish ash is composed of pumice grains, flat elongated, fibrous like and relatively fresh glass, feldspars, chert (with yellowish and brownish tint) and clasts of obsidian in the order of decreasing abundance. Plagioclase feldspars are dominant over sanidines. The pumice grains are of two types one is grayish white in colour, tubular and is the dominant type while the other is yellowish and a bit curved.

Tuff

Two main tuff horizons occur in the sequence usually resting on the diatomites. Stratigraphically, they are represented at the top part of the sequence. The first tuff horizon is light yellow in colour and regularly found in almost all sections of the Lower Sequence. This tuff is intensively faulted and at places highly fractured into small blocks.

The second tuff is the basaltic tuff which is greenish black in colour occurring in all the areas where the Lower Sequence is exposed, represents generally the top parts of the sections.

The thickness of the tuff is highly variable from locality to locality thickening markedly from topographic highs into topographically lower places within short distances. This is especially true in the central part at localities 39, 40, and 42 where its thickness decreases from 3 mts to 80cm within a distance of about 100mts. The maximum thickness measured at Belicha is 5mts.

This tuff is coarse grained rich in lithic clasts of variable sizes. The size of the lithic clasts varies from 2cm to 11cm. A general decrease in the size and abundance of the lithic clasts is observed from north to the south and east direction. It is generally massive in the central part and exhibits low angle cross-bedding locally. Continuous bedding of this deposit is observed in the north eastern part, and in the eastern part, the beds become thinner and are

by

dominated by fine grained texture of individual grains. In the northern part beds are thicker with the cross-stratification dipping downhill to the south west. The individual beds contain variable amounts of clasts of ignimbrite, basalt and obsidian and the latter two are dominant both in size and abundance.

The features shown by this tuff is mostly similar to that of base surge deposits - i.e. the small scale cross-bedding, variable thickness following the topography and the thin continuous beds especially in the north eastern part closely resembles that of base surge deposits (Fisher and Crowe, 1972) and hence this tuff is interpreted as a base surge deposit.

Composition

Observation under microscope showed marked differences in the composition of these tuffs. The light yellow tuff is largely constituted of pumice and volcanic glass. It is texturally distinctive, consisting of yellow and vesicular, or grey and non-vesicular pumice. Lithic clasts are sparse and feldspar phenocrysts are uncommon both as free crystals and in pumices. The volcanic glass includes bubble forms together with cusped shards. (Pirsson, 1915).

The basaltic tuff is a crystal tuff composed largely of fine to medium grained crystals of plagioclase and olivine. The olivine is iddingsitized and is subordinate to plagioclase (labradorite) crystals. Lithic fragments of basic volcanics with phenocrysts of plagioclases and olivine are present in small amount. The matrix consists of cryptocrystalline crystals of plagioclase and glass shards.

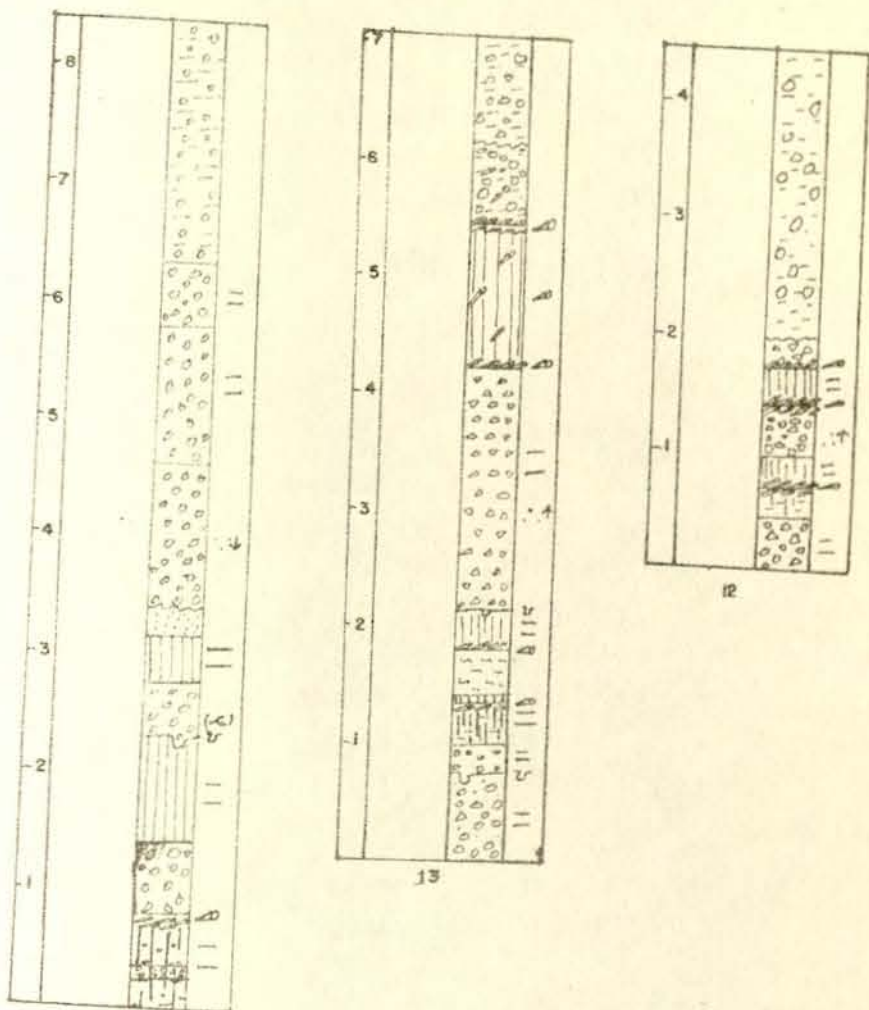
2.2.2. Lithology of Upper Sequence

The Upper Lacustrine deposits in general form 62% of the whole stratigraphic succession for the study area. They occur mainly in the western, southern, central and eastern corner of the study area. The thickness of the sequence varies from less than 4mts in the central part to about 16mts in Abelosa Wadi (Fig 2). Eventhough all lithotypes are not seen to be represented in single sections, the major lithotypes are represented in most of the studied sections.

The sequence is exposed mainly in dry valleys and along the seasonal streams feeding Bulbula river. This makes them easy for studing and hence many sections were studied from this sequence. Most studied sections are found in the southern and in the southwestern part and are poorly represented in the eastern part. The thicknesses of the sections are very small in this part of the area owing to the absence of rivers or streams that could cut or form gorges deep enough to expose the deposits. Figs. 7 and 8 represent the descriptions of selected sections and correlation of different sections respectively.


















Correlation between sections was relatively easy as compared to that of the Lower Sequence, since the deposits are unaffected by recent faulting. The correlation between the different sections was aided by (1) the occurence of shelly gravels that frequently come below the diatomite mainly in the upper part, (2) colour and character of pumice pebbles in ceratian gravels, (3) systematic observation of the

Fig. 7 DISRIPTION OF SELECTED STRATIGRAPHIC SECTIONS OF THE UPPER SEQUENCE.



06-07-09

L E G E N D

- | | | | | | |
|---|-----------|---|--------------------|---|----------------------|
|  | SILT |  | SANDY GRAVEL |  | GRADATION (reverse) |
|  | GRAVEL |  | DIATOMITOUS SILT |  | THICKLY BEDDED |
|  | SAND |  | SILTY GRAVEL |  | THINLY BEDDED |
|  | DIATOMITE |  | CROSS BEDDED |  | LAMINATED |
|  | ASH |  | LOAD CAST |  | GASTROPODS & BIVALVI |
| | |  | GRADATION (normal) |  | OSTRAKODS |

SCALE as in fig. 5

SECTION OF A BRITISH MARINE PLANTATION
OF THE YEAR 1850
PLAN

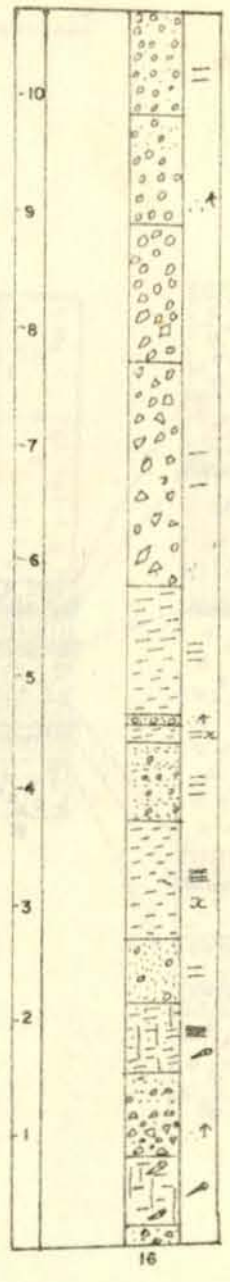
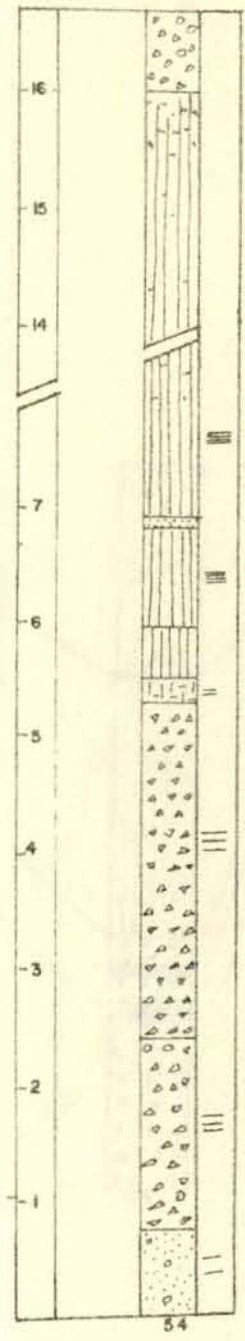
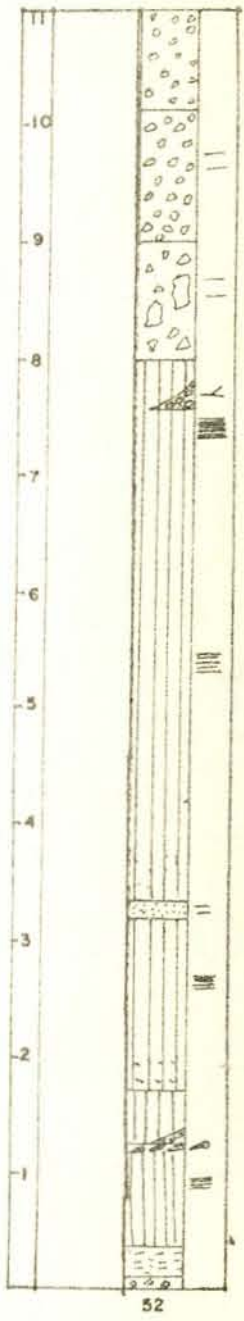


Fig. 2a. CORRELATION OF SELECTED STRATIGRAPHIC SECTIONS OF THE UPPER SEQUENCE.

SCALE

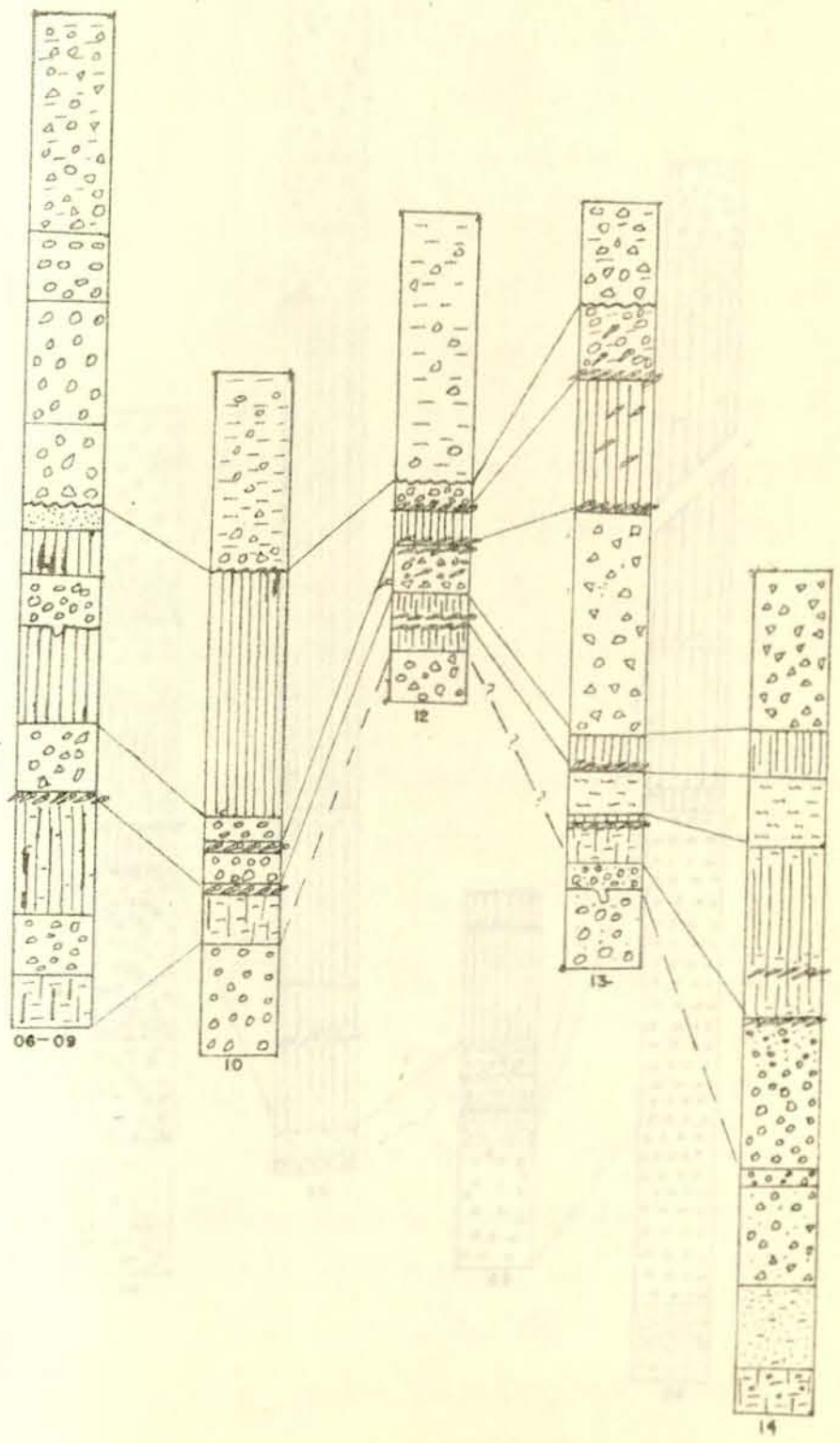
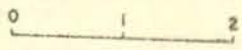
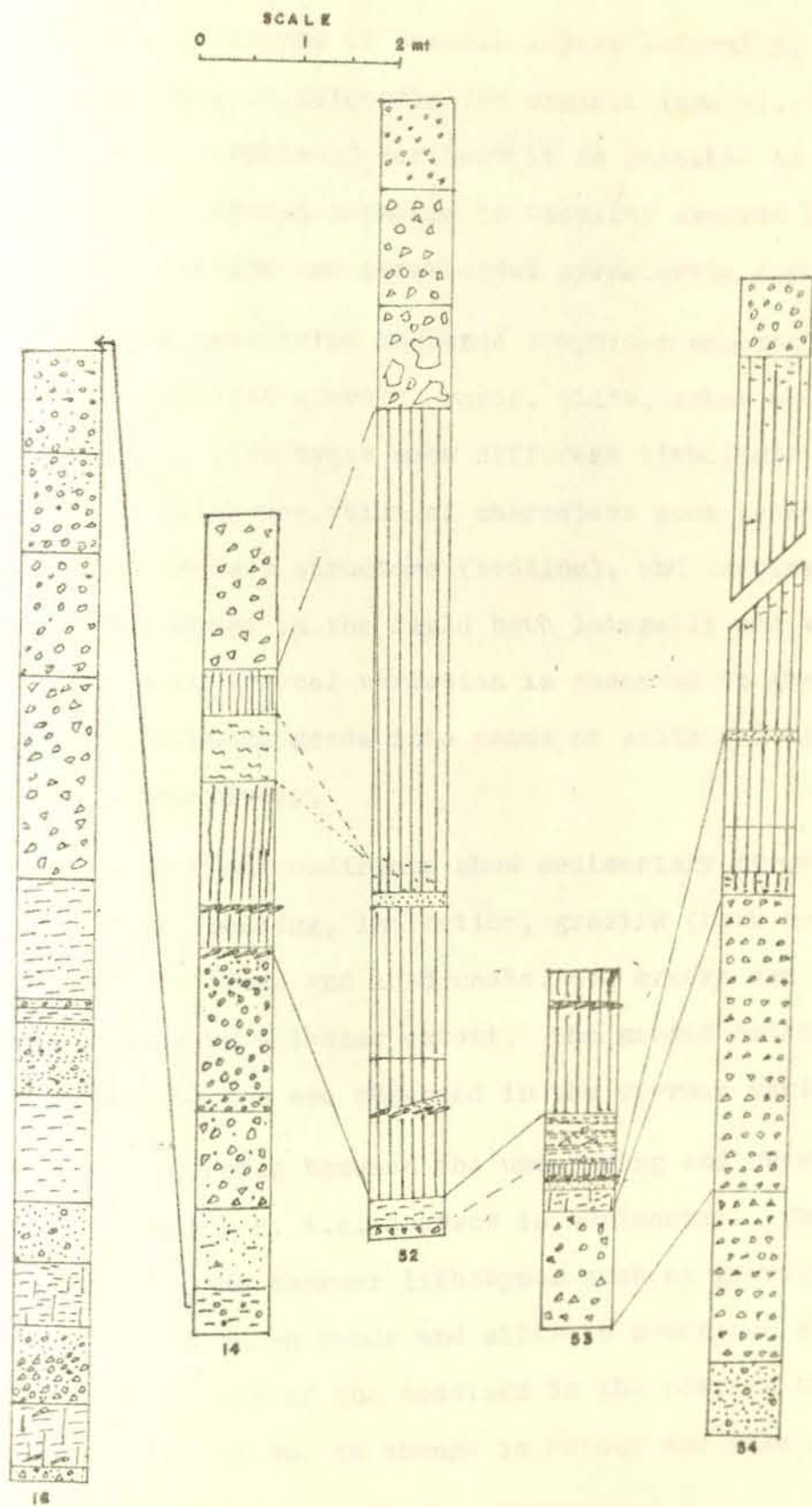


Fig. 2b CORRELATION OF SELECTED STRATIGRAPHIC SECTIONS OF THE UPPER SEQUENCE.



stratigraphic positions of certain layers laterally, and (4) the occurrence of paleosols (or organic layers). From the different correlated sections it is possible to conclude that the exposed sequence in totality exceeds 28 mts of flavio-lacustrine and interbedded pyroclastic deposits.

The Upper Lacustrine Sequence comprises unconsolidated to semi-consolidated gravels, sands, silts, ashes and diatomites. These lithotypes show different lithological characters. Quick variation of characters such as colour, texture, sedimentary structure (bedding), and sorting is frequently observed in the field both laterally and vertically. The main lateral variation is observed in gravels and diatomites which grade into sands or silts and diatomaceous ash respectively.

Generally these sediments show sedimentary structures such as massive bedding, lamination, grading (both normal and reverse) at large and load casts, mud cracks and cross-stratifications to a lesser extent. The graded bedding and cross-stratification are observed in the coarser varieties.

The relationship between the underlying and overlying sediments is regular, i.e. contact is horizontal. The contact between the coarser lithotypes such as gravels and sands and also between sands and silts is sometimes gradational. Infact most of the beddings in the coarser fractions are initiated due to change in colour and size of materials.

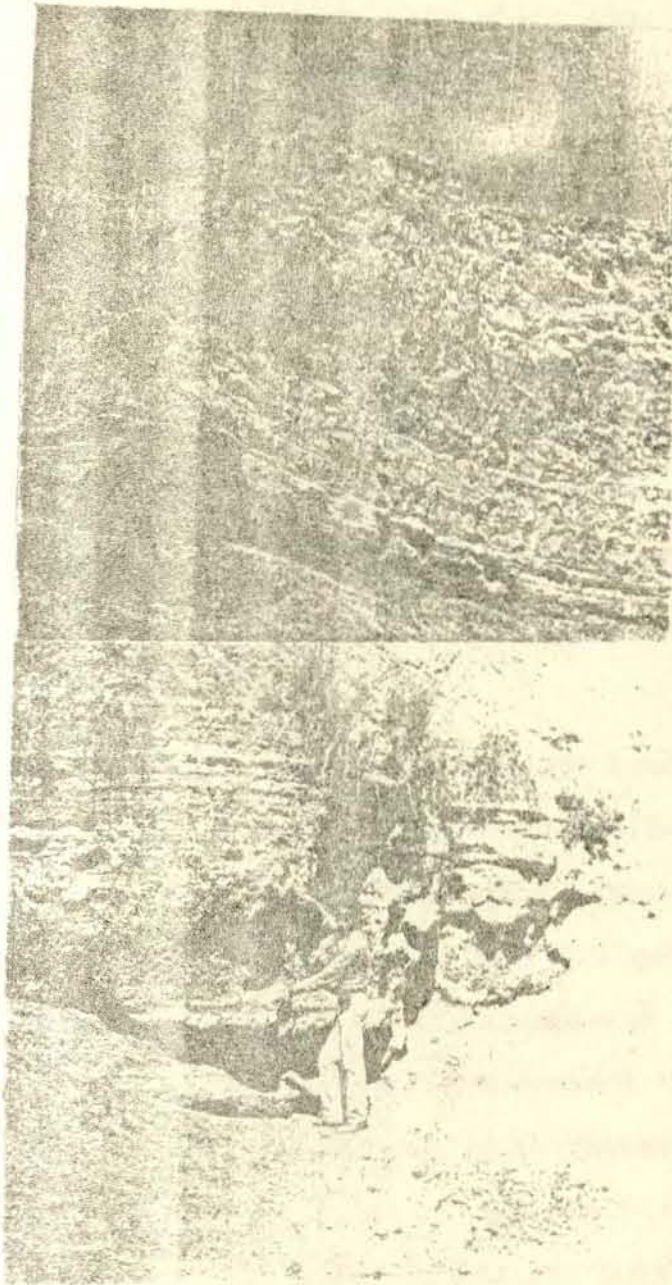


Plate 4 View of the Upper Sequence deposits at locality 16

Most of the sediments of sequence, similar to those of the Lower Sequence deposits are nonindurated to semi-indurated except in rare cases where some of gravels show relatively stronger consolidation.

2.2.2.1 Gravels

These lithotypes largely occupy the stratigraphic column of the Upper Sequence constituting mainly about 48% of it. They occur at almost all localities studied both as minor interbeds and as important layers below and above diatomites (Fig. 7). Although they occur in almost all sections of the studied area including the eastern part, the larger number of gravel layers dominantly occur in the south and southwestern part.

They vary in colour from the more common gray to brownish gray, yellowish, greenish yellow and yellowish brown. The thickness of these gravels is highly variable ranging from 6cm for the minor interbeds to 2mts for individual beds in outcrop. Lateral variation of thicknesses within beds is not regular. However, there is a general trend for individual gravel layers to increase in thickness to the southwest direction. They are in general unconsolidated to poorly consolidated and few gravel layers are relatively consolidated.

The gravels generally display horizontal bedding and are usually thick bedded. In most of the cases bedding seems to be initiated either by change in the colour or size of pumiceous materials. The contact of most gravel layers with other lithotypes, in particular with diatomites is

TABLE 4: Description of Grain Size Distributions of Gravels (Up.S.)

Sample No.	Lithology	Thickness	Colour	Mean Size ϕ	% Gravel	% Sand	% Silt	% Clay	Textural Nomenclature
03-C	Gravel	0.75	Yellowish grey	1.7	35.45	30.78	25.08	3.77	Silty gravel
03-D	Gravel	0.4	Gray	-1.5	86.92	5.04	6.86	0.34	Gravel
05-D	Gravel	2.0	Gray	1.66	32.53	39.91	24.16	-	Silty sandy gravel
15-B ₁	Gravel	0.3	Gray	-2	80.8	14.82	3.09	1.11	Gravel
15-B ₂	Gravel	0.45	Gray	0.23	36.36	44.6	14.7	-	Silty sandy gravel
15-C	Gravel	0.4	Greenish yellow	0.43	42.85	39.00	13.75	0.35	Dito
15-D	Gravel	0.5	Gray	-2.3	90.11	7.83	1.89	-	Gravel
16-A	Gravel	0.25	Gray	-1.06	57.86	37.94	3.04	0.15	Sandy gravel
16-C	Gravel	0.73	Gray	-0.3	55.47	41.63	1.68	-	Sandy gravel
16-I	Gravel	0.1	Yellowish gray	-0.13	30.04	58.84	9.71	-	Dito
17-A ₀₂	Gravel	0.06	Yellowish gray	1.9	43.21	12.75	37.37	2.41	Silty gravel
17-A ₀₄	Gravel	0.3	Yellowish gray	-0.23	67.97	4.78	21.51	1.08	Sandy gravel
17-B ₁	Gravel	2.0	Yellowish	-0.5	87.61	1.19	9.4	0.59	Gravel
17-B ₂	Gravel	1.75	Yellowish	-2.03	63.84	32.44	2.73	0.36	Sandy gravel
19-C	Gravel	2.5	Gray	-1.2	70.79	19.22	8.63	0.07	Silty sandy gravel
52-A ₁	Gravel	0.15	Light gray	0.86	51.07	16.57	29.83	0.24	Silty gravel
53-A ₁	Gravel	1.15	Gray	-1.53	65.96	29.54	3.58	0.10	Silty sandy gravel
54-B	Gravel	1.6	Yellowish Gray	-0.75	80.86	2.97	12.88	-	Gravel

distinct, but within the different gravels and sand beds it is most the time gradational. Poor gradation of size is common in most beds. Apart from horizontal bedding and gradation in size load casts are present locally in some gravels that immediately overly fine grained sediments. The relief of the load casts ranges from 5cm to 10cm.

The gravel in locality 17 (Plate 5) is different in characters both in composition, structure and texture than most beds of these lithotypes. It is characterized by large scale planar cross-bedding which dies out as lenses in the diatomites associated with it. Its colour is brownish yellow. Grains are extremely rounded, and the minimum size of pebbles here is fine granule, and sandy or silty matrix is either few or not present. It shows complete normal and inverse gradation of sizes regularly with in beds.

The gravels of the top section of the sequence, especially the interbeds in the diatomite are rich in shells of fresh water gastropods and bivalve at their top. The shells commonly form the upper 5-12cm of the gravel layers. The shelly gravels like the others are pumiceous with the grain sizes of the individual pebbles varying from 2mm to 2cm, often the proportion of the matrix being lower. They are sometimes inversely graded (locality 51). The pumice pebbles are subrounded to rounded in most layers. The shells are thin loosely attached to the pumice pebbles and are completely preserved. Their size is variable, but ellongated types seem to dominate in most horizons. Three species of gastropods



Plate 5 Cross - bedded gravel lenses at locality 17.

- 4 Syracusanites
- 4 Valenoides
- 4 Belonia
- 4 Corbicula

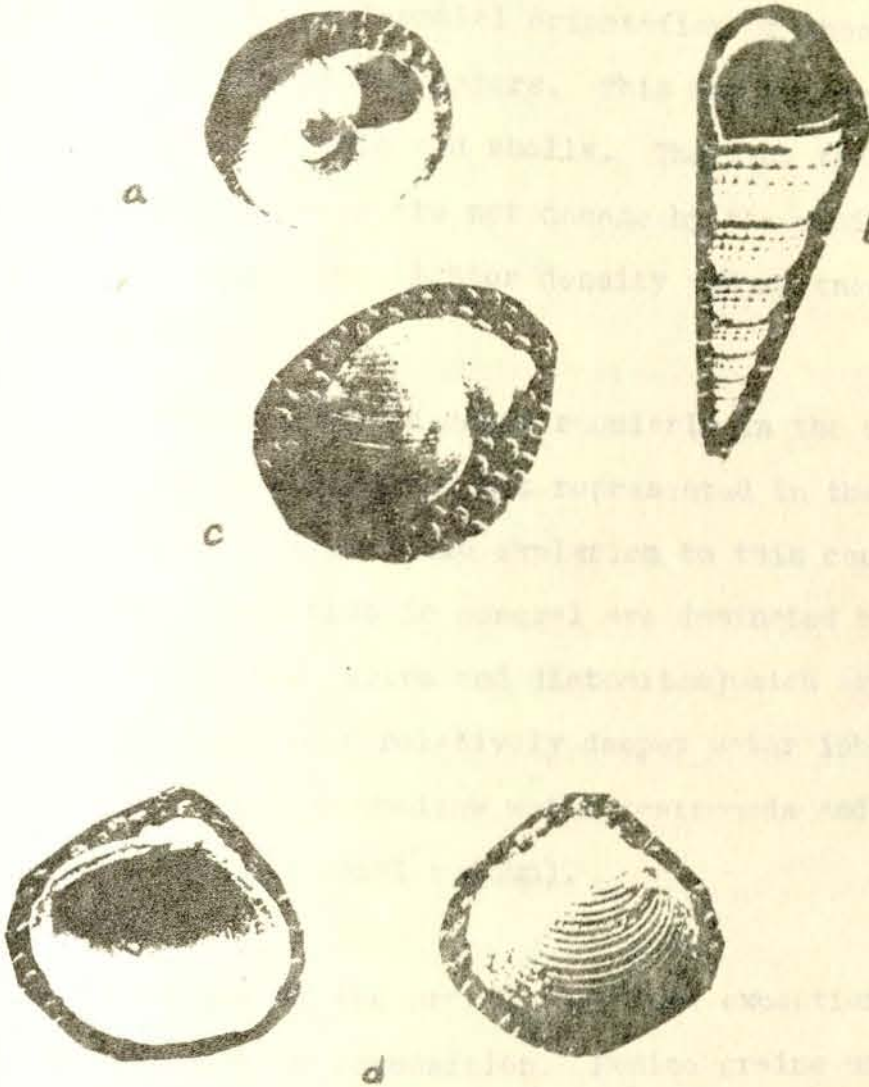


Plate 6 Shales of gastropods and bivalve

- Gastropods - a Gyranulus apertus
- b Melanoides tuberculata
- c Bulinus africanus
- Bivalve - d Corbicula consobrina

and one species of bivalve are identified (plate 6). The identified gastropods are Melanoides tuberculata, Gyranus apertus and Bulinus africanus and the bivalve is Conbicular consobrina. No preferential orientation of these shells is observed in the gravel layers. This may indicate the sudden deposition of gravels and shells. The fact that the gastropods and bivalves are not damaged by the pumice pebbles is attributed to the lighter density and softness of the pumice pebbles.

The shelly gravels occur regularly in the upper sections of the sequence and not represented in the southernmost sections. A possible explanation to this could be that these localities in general are dominated by finer grained sediments (silts and diatomites) which are thought to be deposited in a relatively deeper water inhospitable to these beach or very shallow water gastropods and bivalves (P. Russo, 1986, personal communication).

Composition

The majority of the gravels with one exception are more or less similar in composition. Pumice grains mostly form the largest portion, clasts of obsidian and basalt are the frequent lithic components in most of the gravels with variable proportion of size and shape. Scoria, ignimbrites and lithonized grains also occur as lithic fragments in few samples. The maximum size of lithics including the pumice clasts reaches up to 5cm. Glass shards, feldspars-sanidine and plagioclase, chert constitute the light mineral fraction of most gravels while biotite, magnetite, augite and horn-

blende in order of increasing importance largely present as heavy mineral fractions. Certain gravel layers contain few diatom tests and fragments of plants.

The gravel bed in locality 17 (17B,) shows different association of constituents from others. It consists of pumice, crystals and lithics. The lithic components include volcanic rocks such as obsidian, massive basalt, vesicular basalt and massive oxidized basalts, spilite materials (altered volcanic rocks of dacitic to andesitic composition). Chert, isolated crystals of quartz, biotite, tourmaline, hornblende and some lepidocrosites form the mineral proportion of this gravel. The complex composition and the high degree of roundness of the grains even in basalts imply a derivation from a mixed distant source.

2.2.2.2 Sands

Sands comprises 5% of the lithotypes of the stratigraphic column of the Upper Sequence. They are present in almost all sections of the sequence and occupy the bottom section of the column although few interbeds are present in the middle and upper parts of the column. They usually overlie or interbedded in the fine grained sediments such as silts or diatomites (see Fig. 7).

The sands vary in colour from whitish gray to gray and yellowish and are texturally classified as slightly gravelly medium sand, gravelly silty sand, and gravelly sand. The gravel fraction of the sands is mostly dominated by pumice grains and few lithics. The thickness of individual beds range from 5cm to a maximum of 55cm. Variation in thickness is impersistent both vertically and laterally. However, in some sand interbeds the thickness is regular. Generally the sands are poorly indurated and horizontally bedded.

The sand beds in the eastern part of the area (locality 19) are slightly different in character than other beds. They are light gray in colour, and apparently better sorted, both of them being fine sand with very little or no clay sized materials. They are relatively consolidated and coarser sand grains are locally concentrated as lenses within the beds. Traces of poorly represented small scale oscillatory ripples are present on the surface of these sand locally. These features-the cleanness of the sands (revealed in the absence of clay sized materials), the local concentration of

TABLE 5: Description of Grain Size Distributions of Sands and Ashes (Up.S.)

Sample No.	Lithology	Thick-ness	Colour	Mean Size ϕ	% Gravel	% Sand	% Silt	% Clay	Textural Nomenclature
03-E	Sand	1.4	Yellowish brown	3.11	17.53	56.54	20.71	0.75	Gravelly silty coarse sand
05-B	Sand	2.3	White gray	1.56	22.6	38.63	33.13	1.84	Gravelly silty sand
08-C	Sand	0.25	Yellowish	1.33	2.1	96.79	0.9	-	Slightly gravelly med. sand
14-B	Sand	0.8	Light brownish	-1.56	78.92	9.09	10.3	0.84	Silty sand
16-G	Sand	0.7	Grey	1.25	11.49	82.6	4.94	0.35	Gravelly coarse sand
16-E	Sand	0.55	White gray	-1.16	20.8	76.47	2.6	-	Gravelly coarse sand
19-A	Sand	0.5	Dark gray	2.93	-	78.6	20.53	-	Silty sand
19-B ₂	Sand	1.2	Gray	3.1	-	92.16	7.65	-	Sand
53-B ₂	Diatomaceous shelly sand	0.05	Gray	1.36	10.59	77.22	9.46	-	Gravelly silty med. sand
54-A	Sand	0.8	Yellowish	1.13	25.84	53-65	17.01	2.5	Gravelly silty sand
03-B	Ash	0.6	Gray	-0.03	52.17	40.42	6.53	0.47	Coarse ash
05-A	Ash	2.2	White gray	-0.03	56.81	17.83	22.93	0.16	Coarse ash
05-C	Ash	0.2	Gray	0.53	21.67	62.86	9.63	1.66	Coarse ash
18-A	Ash	4.3	Gray	5.3	-	-	98.84	1.16	Fine ash

coarser sand grains, and although poorly defined, the oscillatory ripples may indicate the action of waves during the deposition of the sands implying that they are formed in the beach part of the lake. The beach character of these sands is also shown in section 4.

Composition

The mineralogical composition of these sands does not show much difference between the individual samples. The important constituents include pumice, and lithic fragments. Glass and Crystals are second in importance. The clasts consist of basalt, scoria, rhyolite. Obsidian and Pumice.

The pumice grains are altered and sometimes limonitized and constitute the highest proportion. The common crystals are chert, quartz, sanidine and plagioclase with encrusted pyroxen (augite). Glass shards are abundant in the very fine fractions and are thin and fibrous like in shape. Hornblende, augite, biotite and magnetite are the frequent heavy mineral grains in all the sand samples. The sand interbeds in diatomities are diatomaceous.

TABLE 7: Compositional Characteristics of the Upper Sequence Deposits

Sample No.	Lithology	Pu	V.G.	K.F.	P.F.	Q.	Obs	Is	Ry	Sc	F.OX	Ch	Pxn	Mg	Hb	Bi	HF
03-C	Gravel	A	A	O	C	O	C	C	-	R	-	-	R	F	F	C	0.04
03-D	Gravel	A	A	C	C	R	C	-	-	-	-	O	O	A	C	F	0.16
05-D	Gravel	A	A	F	C	-	R	-	-	C	O	F	A	F	R	F	0.16
15-B ₁	Gravel	A	A	C	C	-	O	-	-	-	-	O	O	F	-	-	0.2
15-B ₂	Gravel	A	A	F	F	O	F	O	O	-	O	O	C	A	R	-	0.2
15-C	Gravel	A	A	F	F	O	O	O	-	-	O	O	C	A	O	-	0.2
15-D	Gravel	A	A	C	C	-	C	R	R	-	-	C	R	A	R	O	0.2
16-A	Gravel	A	A	F	C	O	F	-	R	-	-	F	F	F	A	-	0.6
16-C	Gravel	A	A	O	C	-	F	F	-	-	O	F	R	F	A	-	0.3
16-I	Gravel	A	C	O	F	R	C	-	-	O	-	-	C	F	A	-	0.1
17-A ₀₂	Gravel	A	C	C	C	O	F	O	O	-	O	O	O	F	A	-	0.1
17-A ₀₄	Gravel	A	C	C	C	O	F	O	O	-	O	O	O	F	A	-	0.1
17-B ₁	Gravel	A	A	F	F	O	C	C	O	R	-	F	A	O	C	F	0.3
17B ₂	Gravel	A	A	F	F	O	C	C	O	R	-	F	A	O	C	F	0.3
19-C	Gravel	A	A	F	F	O	F	-	O	-	O	F	R	O	F	O	0.06
52-A ₁	Gravel	A	C	C	C	-	C	R	-	C	C	C	A	C	R	R	0.06
53-A ₁	Gravel	A	A	F	F	R	O	-	R	-	-	-	R	O	A	-	0.2
54-B	Gravel	A	C	F	F	-	R	-	-	-	R	O	R	C	C	-	0.1
14-A	Silt	A	A	O	O	F	-	-	-	-	R	O	O	-	A	-	N.D.
16-H	Silt	C	A	C	C	C	C	R	-	-	O	-	C	C	-	-	N.D.
16-J	Silt	C	A	O	F	R	C	-	-	O	-	-	C	F	A	-	0.06
17-A ₀	Silt	C	A	F	C	R	F	-	-	-	O	-	C	R	F	-	N.D.
17-A ₀₁	Silt	C	A	C	C	O	F	R	-	R	-	O	R	F	A	-	0.2
17-A ₀₃	Silt	C	A	C	C	O	F	R	-	-	O	-	R	O	C	-	0.2
17-A ₁	Silt	A	C	C	C	O	C	-	-	R	-	-	A	R	R	-	N.D.
52-A ₂	Silt	A	A	O	F	-	O	F	R	C	F	C	A	F	R	-	0.3
03-E	Sand	A	C	R	F	R	C	O	-	-	-	O	R	A	F	-	0.26
05-B	Sand	A	A	O	F	F	R	-	-	-	-	-	F	R	R	-	0.1
08-C	Sand	A	A	R	R	O	O	R	O	O	-	C	A	O	R	O	0.76

Table 7 conted.

Sample No.	Lithology	Pu	V.G.	K.F.	P.F.	Q.	Obs	Ba	Ry	Sc	F-OX	Ch	Pxn	Mg	Hb	Bi	HF
14-B	Sand	A	A	F	F	O	F	-	-	-	-	F	R	F	A	-	0.5
16-E	Sand	A	A	F	F	R	O	-	-	R	-	O	-	A	C	-	0.15
16-G	Sand	A	A	C	O	O	C	-	R	-	R	O	A	C	R	-	0.7
19-A	Sand	A	A	F	C	R	-	-	-	-	-	O	-	R	O	O	0.06
19-B ₂	Sand	A	A	O	O	-	R	-	-	O	F	O	-	O	C	-	0.1
52-B ₂	Sand	A	A	C	C	R	-	-	-	-	-	-	-	O	A	-	0.23
54-A	Sand	A	A	F	C	-	F	-	-	O	-	F	C	O	A	-	0.1
63-A	Sand	A	C	F	F	R	F	O	F	R	O	O	C	F	F	-	0.26
63-G	Sand	C	C	F	F	-	O	O	R	-	-	-	F	F	C	R	1.06
07-A	Diatomite	F	F	O	O	-	-	-	-	-	-	R	-	-	-	-	N.D.
08-D	Diatomite	O	R	R	R	O	R	-	R	-	O	-	-	-	-	-	N.D.
20-A	Diatomite	R	O	-	-	-	-	-	-	-	-	-	-	-	-	-	N.D.
52-A	Diatomite	O	F	-	R	-	R	-	O	-	O	R	-	-	-	-	N.D.
52-B	Diatomite	R	F	R	-	R	-	-	-	-	-	-	-	-	-	-	N.D.
52-C	Diatomite	O	F	-	-	-	-	O	-	-	R	-	-	-	-	-	N.D.
52-D	Diatomite	C	C	-	R	-	O	-	-	-	O	-	-	-	-	-	N.D.
53-B ₃	Diatomite	F	F	-	-	-	R	-	-	-	-	O	-	-	-	-	N.D.
03-B	Ash	A	C	F	F	R	C	-	O	O	F	-	A	C	C	O	0.2
05-A	Ash	A	A	F	A	R	C	-	-	O	F	F	A	F	R	-	0.16
05-C	Ash	A	A	O	C	O	C	R	R	-	F	R	R	C	C	O	0.3
18-A	Ash	A	A	F	C	-	F	R	C	-	F	-	C	F	F	R	0.15

2.2.2.3 Silts

The silts of the Upper Sequence occupy 14% of the column, and are third in abundance next to gravels and diatomites. They are gray, grayish white, greenish gray and dark gray in colour. The thickness of these silts vary from 10cm to a maximum of 1.7mts. About 70% of the silts are dominantly medium silt sized and the rest 30% are either coarse silt or fine silt.

More than 60% of the silts are diatomaceous. The diatomaceous silts commonly occur in the middle and bottom of the section for the sequence. Whenever they are diatomaceous they often are associated with the coarser grained sediments and generally rest on sandy gravels.

The silts are poor to semi-consolidated in most of the sections and are thinly bedded. Lamination is the most common sedimentary structure displayed by them. The individual laminae vary from layers to layers and in some the laminations are less than 1mm. while in others they even reach upto 4mm. in thickness. In some of the silts organic matter layers, especially at their top are observed. The thickness of these layers is very very thin and in one sample (53B, plate 7) three layers, a $\frac{1}{2}$ mm thick and separated from the above two by $1\frac{1}{2}$ cm and two layers 1mm thick each and separated from each other by 1mm silt lamina are observed to occur persistently within the sample. However, from the results of the semiquantitative organic matter analysis given in section 3 most silts are found to contain very little amount of organic matter as compared to the gravels.

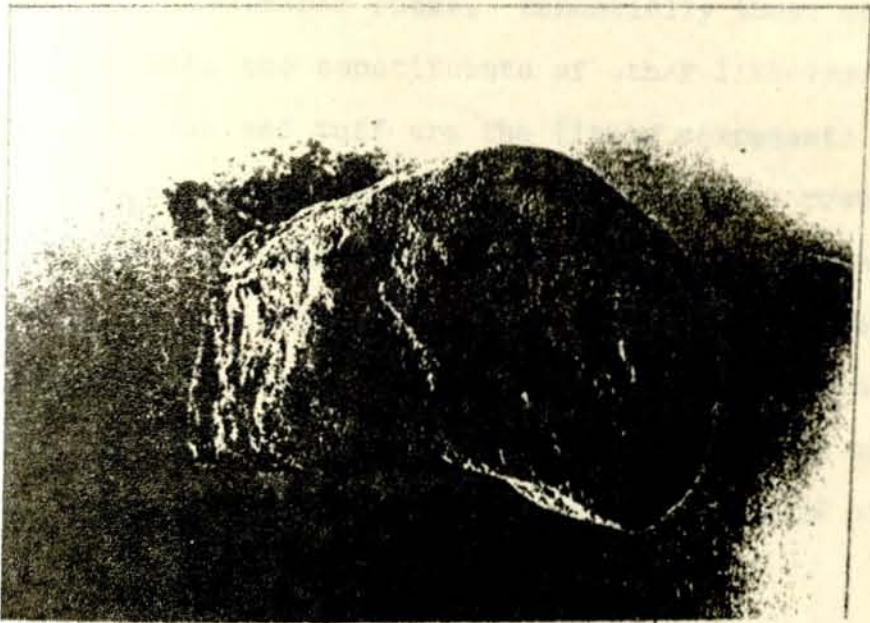


Plate.7. Thin layers of organic matter in silts.

Composition

Compositionally, the silts are formed of feldspars, glass shards, Cherts of Variable colour, quartz, pumice grains, and few lithics of volcanic rocks. Essentially these constituents are similar with the constituents of other lithotypes. Obsidian, scoria and tuff are the lithic components of the silts. Pumice grains are usually subrounded to rounded. The glass characteristically forms 70-80% of the components. Hornblende, tourmaline (?) and augite are the frequent heavy minerals in most silts and augite is the dominant type among them. Calcareous concretions, small amounts of iron oxides (limonite) and zeolites are present in some of the samples.

Some of the diatomaceous silts contain shells of gastropods and remains of plants. A remarkable feature of the silts of the bottom section (Fig. 8) is that they contain shells of ostracods. Especially, samples 16F, H and 52-A₂ are extremely rich in fresh water ostracod shell of the same type of species. The presence of few species of fresh water ostracods in oligotrophic association is suggestive of a very restricted and selective or closed environment of lagoonal type (F. Russo, Peronal Commun).

TABLE 6. Description of Grain Size Distributions of Silts and Diatomites (Up.S.)

Sample No.	Lithology	Thickness	Colour	Mean Size ϕ	Gravel	Sand	Silt	Clay	Textural Nomenclature
14-A	Silt	0.3	Yellowish white	3.58	-	49.31	49.85	0.65	Sandy silt
16-II	Silt	0.07	White	5.1	-	32.4	63.28	2.36	Sandy silt
16-J	Silt	1.18	Grayish white	4.53	30.04	58.81	9.71	-	Ditto
17-A ₀₀	Diatomaceous silt	0.2	Gray	5.46	-	2.3	89.67	3.93	Silt
17-A ₀₁	Diatomaceous silt	0.1	Gray	5.3	-	5.24	87.72	2.34	Silt
17-A ₀₃	Diatomaceous silt	0.12	Dark gray	4.83	12	5.95	72.85	4.95	Gravelly silt
17-A ₁	Diatomaceous silt	1.72	Grayish white	5.96	-	-	85.64	14.36	Silt
52-A ₂	Silt	0.25	Greenish gray	4.9	-	26.04	57.76	11.95	Sandy silt
53-B ₁	Diatomaceous silt	0.2	Yellowish	4.7	-	-	17.33	82.6	Silt
07-A	Diatomite	1.22	Yellowish white	6.43	-	-	83.45	16.55	Silt
08-D	Shelly diatomite	1.22	Ditto	6.76	-	-	74.69	25.31	Silt
20-A	Diatomite	0.5	White	6.86	-	-	65.92	34.08	Mud
52-A	Diatomite	0.85	Grayish white	6.13	-	-	88.63	11.37	Silt
52-B	Diatomite	0.5	Gray	6.46	-	-	84.36	15.64	Silt
52-C	Diatomite	1.5	Yellowish white	6.43	-	-	87.00	13.00	Silt
52-D	Diatomite	4.8	Yellowish white	5.38	-	-	81.55	18.45	Silt
53-B ₃	Diatomite	6.16	Grayish white	6.16	-	-	83.60	16.4	Silt

2.2.2.4 Diatomites

The diatomites of the Upper Sequence are one of the major lithotypes that occupy the largest section of the stratigraphic column of the sequence. They range in colour from light gray to yellowish white and chalky white. Sections of diatomites occur in the central and southwestern part. They are fine grained, poorly consolidated and extremely friable. The thickness of the individual diatomite layers varies from 50cm (locality 19) to over 10mts (locality 54). Thickest sections are found in the southwestern part of the area in the more deeper sections of the gullies feeding Bulbula river. The diatomites in the northeastern part of the area do not exceed 1mt and represent the upper portion of the sections. The simplest occurrence of these diatomites is shown in plates 8 and 9. Notice here the colour change of the diatomites in both localities.

Observation of these diatomites in the field have shown that with few exceptions they occur directly above the gravel layers. Two main diatomite layers or horizons are identified from their stratigraphic relationships. The top layer is represented in localities 07 and 09 and has a thickness of 2mts. The second layer is about 10mts thick and is exposed usually even in smaller sections both in the central and southern part of the area (localities 53 and 54). These two layers are not that much different in their lithologic details. However, the top layers contain atleast two gravel interbeds with shells of gastropods and bivalves.

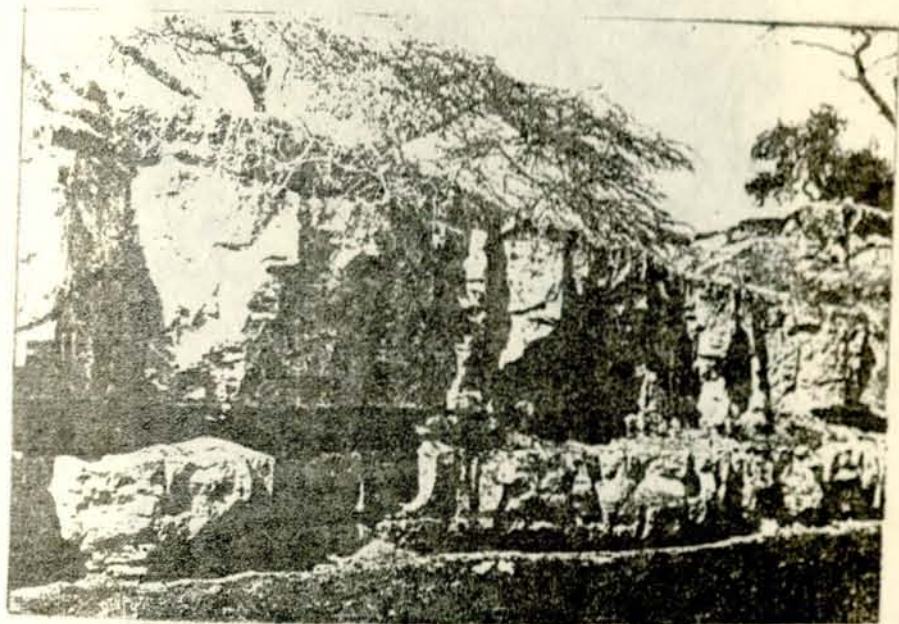


Plate 8 Diatomites of the Upper Sequence (white)

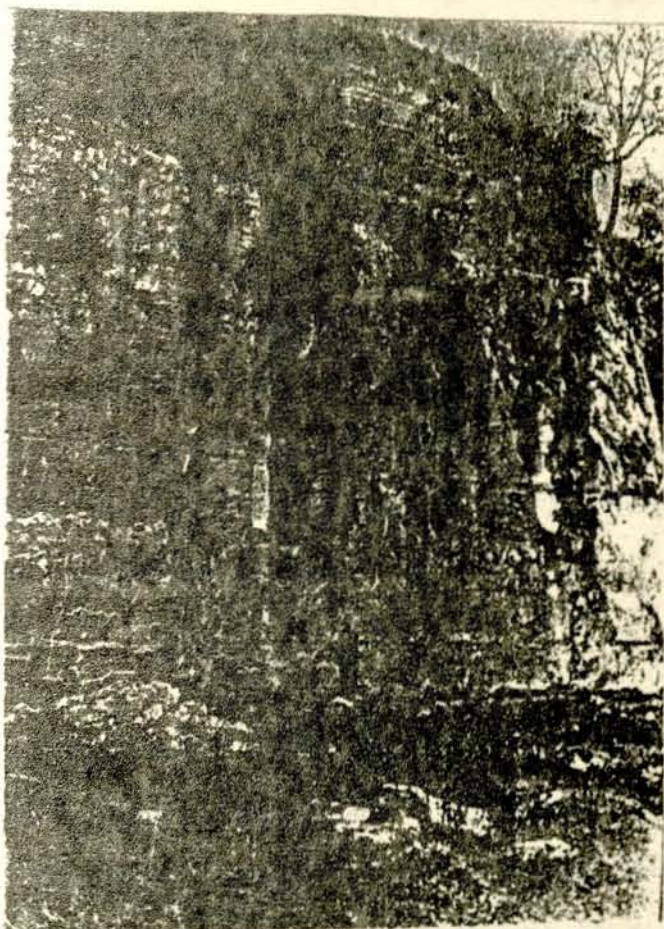


Plate 9 Diatomites of the Upper Sequence (grayish white)

The diatomites at the top of the section are massive and bedding is interrupted whenever gravel or ash are interbedded in between. The bottom sections of diatomites are thickly bedded and internally laminated. The lamination alternates between grayish white and yellowish white layers. The grayish laminae are probably caused by ash. The individual laminae vary between 1cm and 10cm. Although there is this variation in the thickness of the laminae, their thickness, however is regular being 4cm on the average. The bedding planes bounding the diatomites are sharp contacts regardless of what lies above and below them.

Unlike the diatomites of the Lower Sequence, these diatomites are unaffected by faulting and hence are loose and not fractured. Some of the diatomites contain occasionally organic matter and similar types of shells that occur in the gravel interbeds between them.

Composition

The composition of these diatomites are not different from the diatomites of the Lower Sequences. They are extremely rich in fossil diatoms. Other constituents commonly found in the other lithotypes are present to a smaller extent. These include pumice clasts, glass shards, silt sized lithic fragments, chert, few iron oxides and zeolites.

Chemical analysis of 12 samples (table 8) from these diatomites indicates a lower average SiO_2 percentage (83.4%). This value is low when compared to that of Lower Sequence (table 3) and is compensated by a comparative increase in

TABLE 2: Chemical Analysis of Diatomites of Upper Sequence (after Knoth, 1981)

Sample No.	SiO ₂	Al ₂ O ₃	Fe ₂ O ₂	CaO	MgO	Na ₂ O	K ₂ O	MnO	TiO ₂	Ignition	H ₂ O at 110°C
1	76.5	7.8	3.7	1.4	0.9	2.4	1.7	0.1	0.7	4.8	5.11
2	85.0	4.7	2.4	0.6	0.4	1.1	0.6	0.1	0.3	4.8	5.4
3	84.8	3.8	2.2	1.3	0.4	1.6	0.5	0.1	0.3	5.1	5.7
4	83.8	4.8	2.6	1.0	0.4	1.3	0.6	0.1	0.4	5.1	5.7
5	83.0	5.7	2.6	0.6	0.4	1.4	1.0	0.1	0.4	4.9	6.5
6	85.0	4.4	2.5	0.5	0.3	1.6	0.6	0.1	0.3	4.7	5.6
7	85.4	4.3	2.3	0.4	0.4	1.5	0.6	0.1	0.3	4.7	5.4
8	85.5	4.4	2.3	0.3	0.4	1.4	0.8	0.1	0.3	4.5	6.0
9	83.7	5.0	2.8	0.4	0.5	1.6	1.1	0.1	0.5	4.4	5.0
10	82.5	5.6	2.7	0.6	0.4	1.9	1.2	0.1	0.4	4.7	4.5
11	80.5	6.3	3.3	1.1	1.1	0.9	1.0	0.1	0.4	5.3	5.2
12	85.2	2.2	1.3	3.2	0.3	0.7	0.5	0.1	0.3	6.2	5.4

average values of Al_2O_3 (4.9%) and Fe_2O_3 (2.5%) which may be attributed to the increase of ash impurity in the diatomite of this sequence.

2.2.2.5 Ashes

The ash of the Upper Sequence generally are among the minor lithotypes in the stratigraphic sections. They occur in localities 13 and 52 most of them being in the southwestern part of the study area and in locality 51 in the central part. The thickness of these ashes varies from less than 10cm to a maximum of 70cm. Often they occur as thin interbeds in gravels and diatomites. The colour ranges from greenish gray to white gray.

Although they occupy only limited segment of the stratigraphic column of the sequence their abundance, however, is frequent. This is reflected in their frequent interbedding within the gravels or diatomites. In particular, in the diatomites, they often cause the greater degree of impurities and change its lithology to grade into diatomaceous ash or ashy diatomites. Although not seen by most ash layers, poor normal gradation and bedding is observed in some ashes (05C and 18A).

Most of the constituent materials are fine to coarse ash except in few cases which reach upto lapill size. In one sample (03-B) the size of pumice clasts even reaches upto 6cm. The green gray varieties consist of pumice clasts of variable size, obsidian chips and lithics of rhyolite, basalt (andesite ?) and scoria. The basalt size remains to be

smaller (1-1.5cm) than pumice grains. The marked property observed in these kind of ashes is that within the same type of lithic clasts, the size distribution seems to be similar. Most of the lithic fragments including the pumices also are angular.

Composition

The ash samples, when examined under the microscope are similar in mineralogy and texture. They are in general composed of chert, feldspars, glass and lithic fragments. The feldspars include both sanidine and plagioclase. Glass shards are mostly angular, flat, sickle-like and occasionally Y shaped particles. These are associated with crystals of sanidine and biotite in some of the ash layers. The lithic fragments come from basalt, rhyolite, obsidian and pumice in the order of their abundance in most ash samples. Most lithic fragments are limonitized.

The pumice fragments are white to gray tubular, vesiculated, thin and elongated most of the time. Sometimes glass with small scattered plagioclase, hornblende (pyroxene ?) are seen in association within few pumice grains. Among the heavy minerals present in these ashes, pyroxene (augite), magnetite, hornblende and biotite are dominant in decreasing order of importance.

2.2.3 Summary of Lithologies

The Lower Sequence and Upper Sequence were clearly identifiable in the field by their occurrence. Lower Sequence deposits are mainly exposed in uplifted blocks and are generally disturbed while the Upper Sequence deposits occur in the flat areas of the region without being affected tectonically.

The lithologic descriptions for both sequences showed that similarity exists in the gross characters of the lithotypes. Thickness of sediments increases westwards and north-eastwards. Sediments are generally friable and unconsolidated. Bedding is the most common sedimentary structure displayed by these sediments and seems to be initiated particularly in the coarse grained gravels by a slight change in colour and size of materials. This may suggest constant supply of sediments during the sedimentation period. Gravels belonging to the Lower Sequence were not identified. However, their occurrence in the sequence is suspected further to the south. Shells of gastropods, bivalves and ostracods are found in the sediments of the Upper Sequence. The absence of shells of gastropods in the Lower Sequence of the study area may be due to the lack of shallow water (beach) gravels.

The primary petrologic constituents of these sediments are predominantly pyroclastic materials which indicates that the supply of the sediments was from a volcanic center whose products are largely pumiceous materials. The major pebble and granule lithologies of the gravels are pumice, obsidian and basalt.

2.3 Textural Studies

The sediments of the Adami Tulu area studied varies from clay size to pebbles with a maximum diameter in excess of 30cm. Lateral and vertical changes in grain size are common and an accurate estimate of relative size abundance is not possible. However, some rationalization is achieved by grouping size classes into general lithotypes - gravels, sands, silts, diatomites and ashes.

Grain size distribution from the different lithotypes were determined by dry and wet sieving of the coarsest material and pipette analysis of silt and clay sized fractions. The results of the mechanical analysis are summarized by Figs 9 to 16. Where possible, the following parameters were calculated for each sample: median grain size (M), coarsest percentile (C), standard deviation, sorting coefficient, skewness and urtosis as in Folk (1968) (see tables 9 to 12).

Mean, median, sorting and standard deviation have been plotted against each other (Fig 11 and 12) after the manner of Miola and Weizer (1968). Values of coarsest percentile (C) have been plotted against median grain size (M), following the method of Passega (1957). These plots show the distribution of textural parameters in the deposits and are used for the interpretation of the environment of deposition in section 4.

2.3.1 Textures of the Lower Sequence deposits

Sands

The sands of the sequence are composed of on the average 4% gravels, 67% sands and 27% mud fractions. The median size ranges from 2.1 ϕ to 3.9 ϕ , the average being 2.9 ϕ and the average mean grain diameter (3.2 ϕ) for these sands is fine sand. This value is low for most sands because of the presence of significant, proportion of mud (table 1). The textural classification according to Folk (1968) for these sands are gravelly silty sand and silty sand.

In general the sediments are very poorly sorted and exhibit sorting coefficient values of the order (1.95 ϕ to 3.11 ϕ). The values of skewness for the samples analysed are positive ranging from 0.09 to 0.53 which indicates distribution from near symmetrical to strongly fine skewed.

Silts

The silts of the Lower Sequence generally comprise medium (46%) to coarse silt (33%) fractions with clay fractions in the range of 13 to 29%, average value being 21%.

From the granulometric indices of table 9 calculated from curves of Fig. 10, the median average is found to be 5.75 ϕ while the mean diameter is 6.86 ϕ (medium silt). Except one sample 42E which is moderately sorted, the majority of the samples are poorly sorted. Sample 42E is moderately sorted because of high percentage of medium silt fractions and relatively lower clay fractions. They have variable

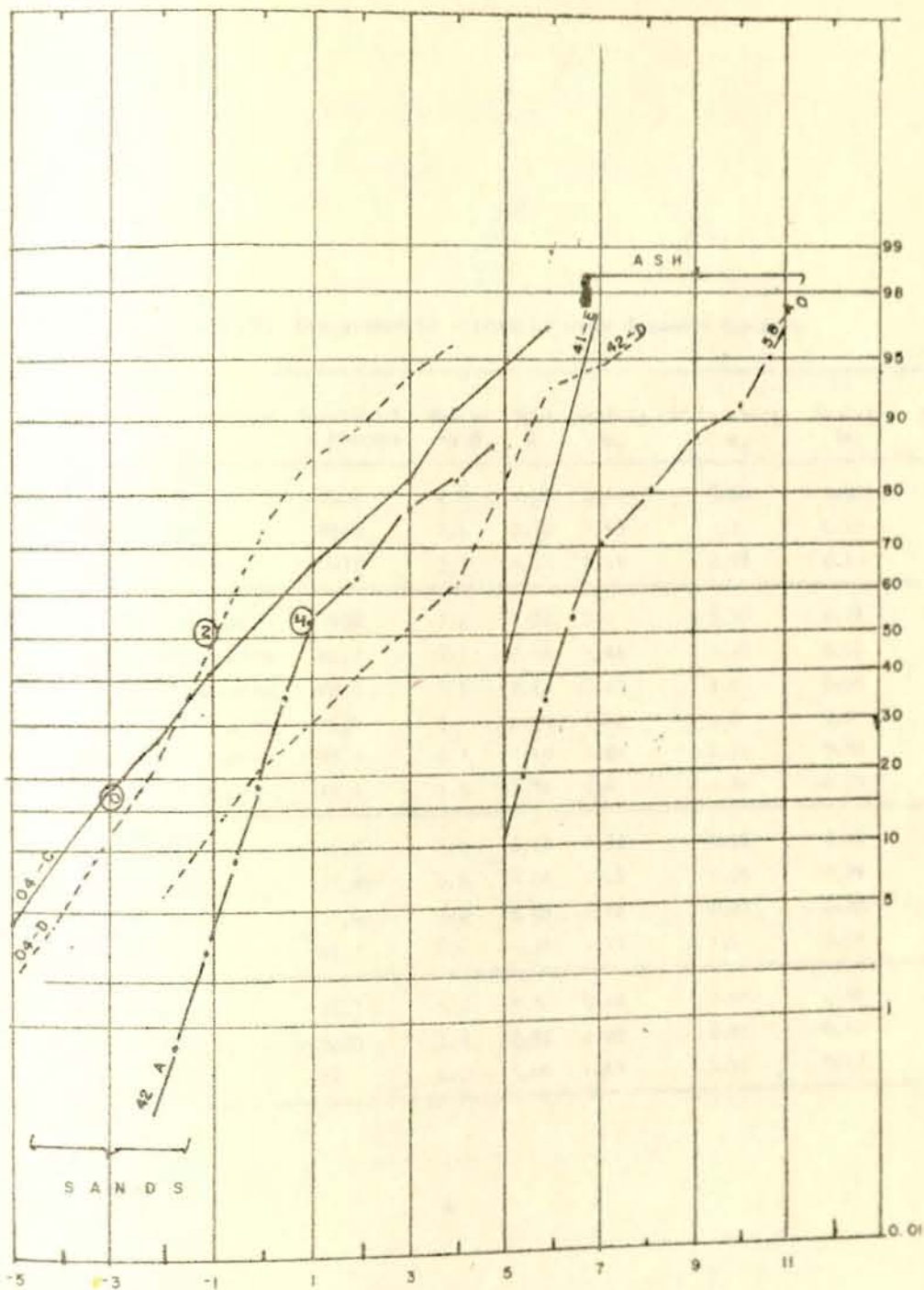


Fig. 9 CUMULATIVE CURVES OF GRAIN-SIZE DISTRIBUTIONS FOR SANDS & ASH SAMPLES OF LOWER SEQUENCE.

- CIRCLED NUMBERS INDICATE VALUES OF DIAMETERS.

TABLE 9: Granulometric Indices of Lower Sequence Deposits

Sample No.	Lithology	Coarsest % C Microns	Median Md ϕ	Mean ϕ	Sorting σ_1	St.Deviation σ_G	Skewness SK_1	Kurtosis K_G
04-C	Sand	5000	2.7	2.93	3.11	3.26	0.09	0.93
04-D	Sand	4500	2.1	2.16	1.95	1.7	0.42	1.42
42-A	Sand	375	3.9	4.73	2.18	2.25	0.53	1.21
04-B	Diatomite	1900	7.2	7.56	2.6	3.25	0.29	0.6
04-E	Diatomite	42.7	7.2	7.16	1.45	1.45	0.02	1.09
40-A	Diatomite	28.2	7.5	7.5	1.10	1.0	0.05	1.8
41-C	Diatomite	45.7	6	6.26	1.48	1.6	0.31	0.97
41-E	Diatomite	45.3	6.7	7.13	2.01	2.15	0.32	0.87
58-B	Diatomite	45.4	7.5	7.56	1.41	1.4	-0.03	1.07
04-F	Silt	48.0	4.9	5.33	1.33	0.85	0.39	3.51
41-B	Silt	37.45	6.8	7.03	1.25	1.05	0.29	1.63
42-E	Silt	37.45	5.8	6.03	1.12	0.85	0.53	3.14
58-C	Silt	43.7	5.6	6.33	1.77	1.8	0.65	1.48
41-F	Ash	43.7	5.2	5.36	0.64	0.65	0.40	0.95
42-D	Ash	5600	2.9	2.53	2.83	2.85	-0.12	0.90
58-A _c	Tuff	47	6.3	6.66	1.67	1.65	0.42	1.16

skewness (0.29 to 0.65) which varies from finely skewed to strongly finely skewed. The kurtosis value in table 9 indicates that the cumulative curves (Fig. 10) are leptokurtic, implying better sorting in the central position than the tails.

Diatomites

The diatomites of the the Lower Sequence comprise on the average 40% fine silt, 17% medium silt, 11% coarse silt and 31% clay sized fractions. This distribution of sizes shows that they are dominantly fine grained. The mean grain diameter for these sediments is well above 7ϕ (very fine silt). The average of 6 samples is 7.19ϕ . Although the abundant size in most samples is very fine silt, nearly all the analysed samples are poorly sorted as indicated by the value of their sorting coefficient (on the average 1.67ϕ).

The skewness value for these diatomites (average 0.16) indicates that 50% of the samples are near symmetrical while the rest 50% are finely skewed. Kurtosis values for the majority of the diatomites approaches normal kurtosis implying comparable sorting between the tails and central position of the cumulative curves (Fig. 10)

Ashes

Mechanical analysis of the ashes from the Lower Sequence showed that the ashes are generally composed of ash particles. From the three samples studied, 90% of the materials for two samples are smaller than 5ϕ ($1/32\text{mm}$) and for sample 42D 80% of the materials are in between 4mm and $1/32\text{mm}$. The median size lies between 2.9ϕ and 6.3ϕ . The textural parameters

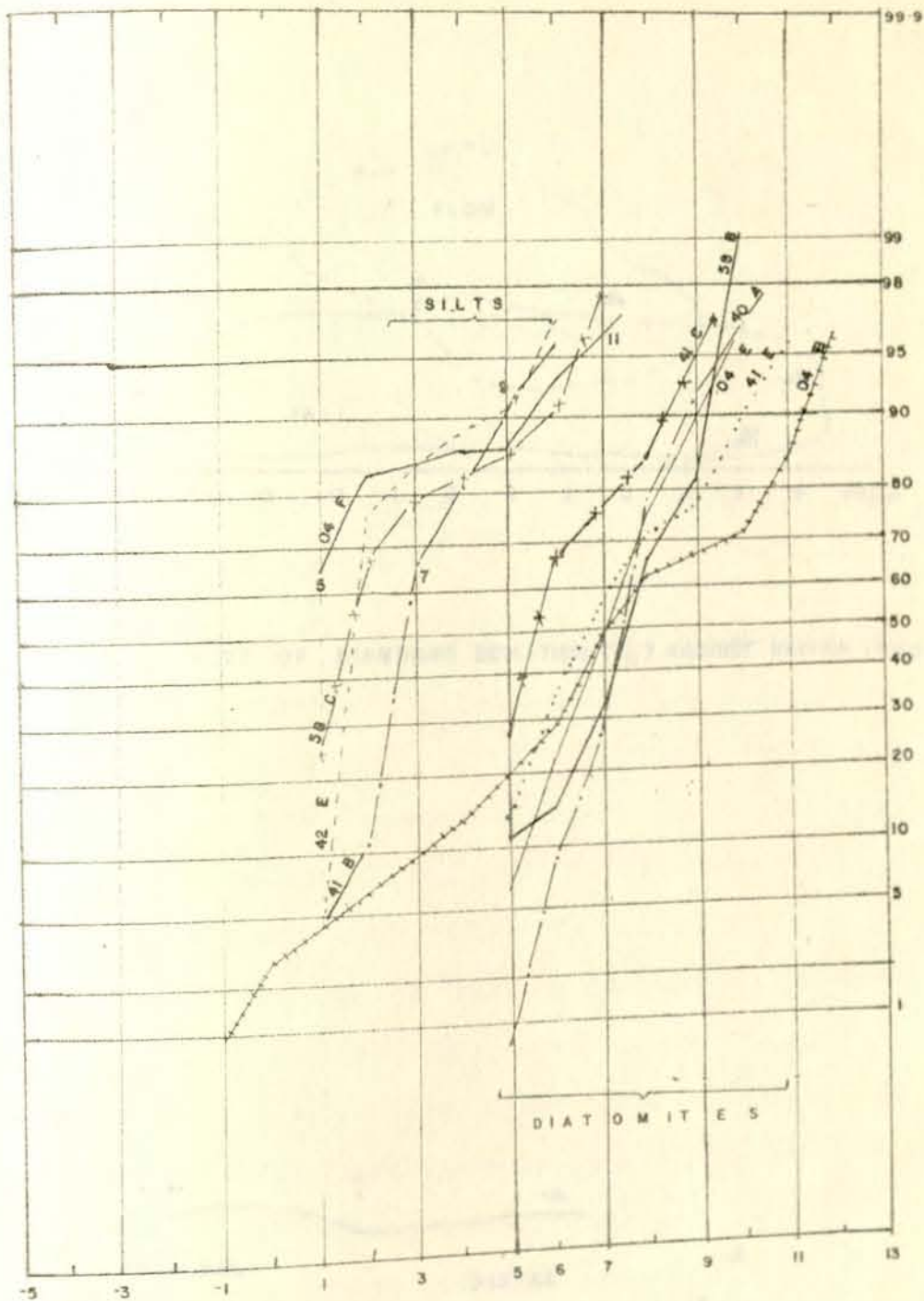


Fig. 10 CUMULATIVE CURVES OF GRAIN-SIZE DISTRIBUTIONS FOR SILTS AND DIATOMITES OF LOWER SEQUENCE.
— CIRCLED NUMBERS INDICATE VALUES OF DIAMETERS

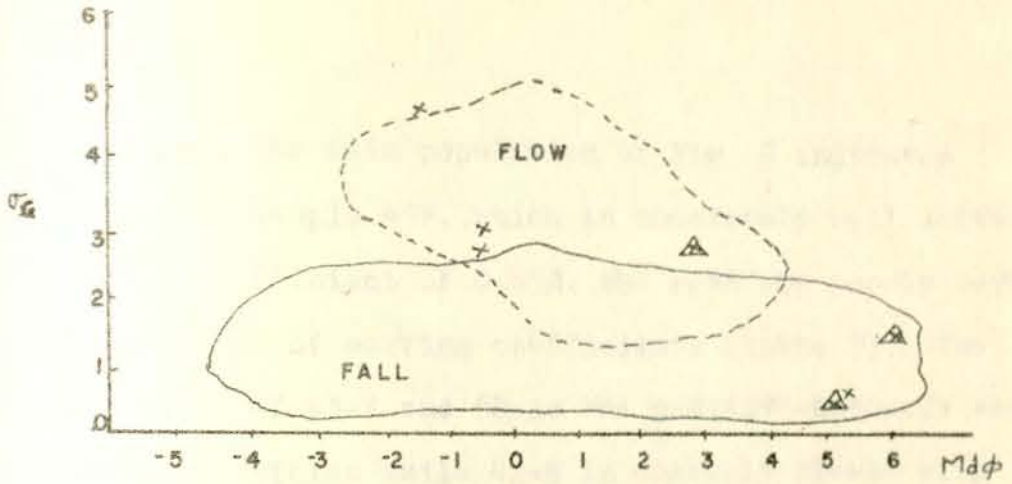


Fig. 11 PLOT OF STANDARD DEVIATION (σ_g) AGAINST MEDIAN ($Md\phi$)

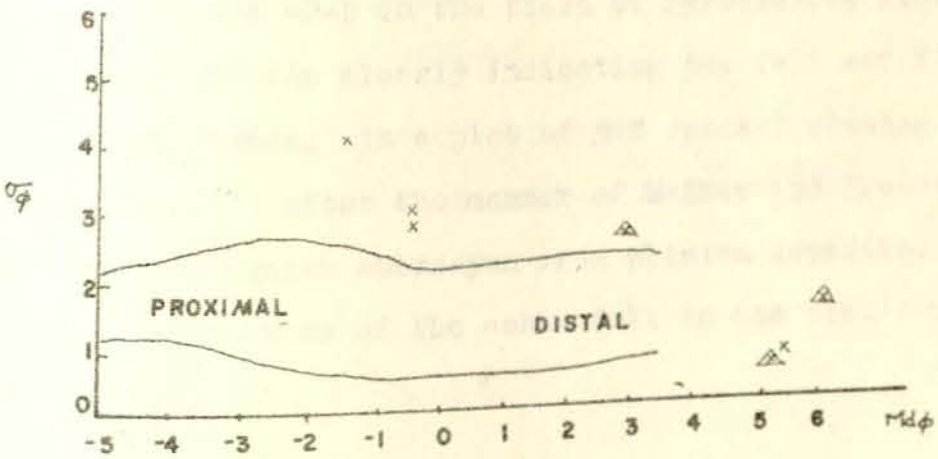


Fig. 12 PLOT OF SORTING COEFFICIENT (r_1) AGAINST MEDIAN ($Md\phi$)

calculated from the main population of Fig. 9 indicates that except one sample 41F, which is moderately well sorted with sorting coefficient of 0.650, the rest are poorly sorted with higher value of sorting coefficients (Table 9). The skewness values of 41-F and 58-Ao are positive-strongly skewed towards fine particles while 42-D is coarsely skewed with negative (-0.12) skewness value.

When the median diameter $Md\phi$ is plotted against standard deviation σ_s (Inman's parameter) for pyroclastic deposits, they generally plot in two fields, one characteristic of fall deposits, and the other of flows (Walker, 1971). Such a plot (Fig. 11) for the ashes of the Lower Sequence places the fine grained ashes 41-F and 58-Ao inside the fields of pyroclastic fall deposits and 42-D in the field of Pyroclastic flow deposits without overlap clearly indicating the fall and flow nature of the ashes. In a plot of $Md\phi$ against sorting coefficient (fig.11) after the manner of Walker and Croasdale (1972) to distinguish sutrseyan from plinian deposits, the grain size characters of the ashes fell in the fields of distal facies.

2.3.2 Textures of the Upper Sequence deposits

Gravels

The gravels of the sequence generally comprise particles of all sizes with highly variable amount. The gravel portion forms on the average 60%, sands 25%, and mud 15% of the constituent sizes. Although the average value of gravels seems to be lower because of the significant proportion of sand and or mud fractions in some samples, the gravels percentage, however, exceeds 80% in certain gravels. Such as 03-D, 15B, 17-B, and 54B (table 2). On the basis of the relative proportion of the constituents, the gravels are texturally classified as silty, sandy, silty sandy and gravel following the classification scheme of Folk (1968).

The high proportion of muds and sands in these sediments have reduced their average mean diameter to -0.48ϕ which is very coarse sand, however, in all the samples plotted at least 20% of the fraction are coarser than granule size (4mm).

The sorting characters of these sediments likewise are greatly influenced by the wide range of grain sizes. It lies in between 1.5ϕ to 4.15ϕ which is from poorly sorted to extremely poorly sorted (table 10). The skewness value for the gravels varies from 0 to 0.92, nearly all samples being strongly finely skewed.

The majority of gravels have angular to subangular grains. Certain gravels such as 17-B, 05-D and 17-Ao2 have grains displaying well rounded features.

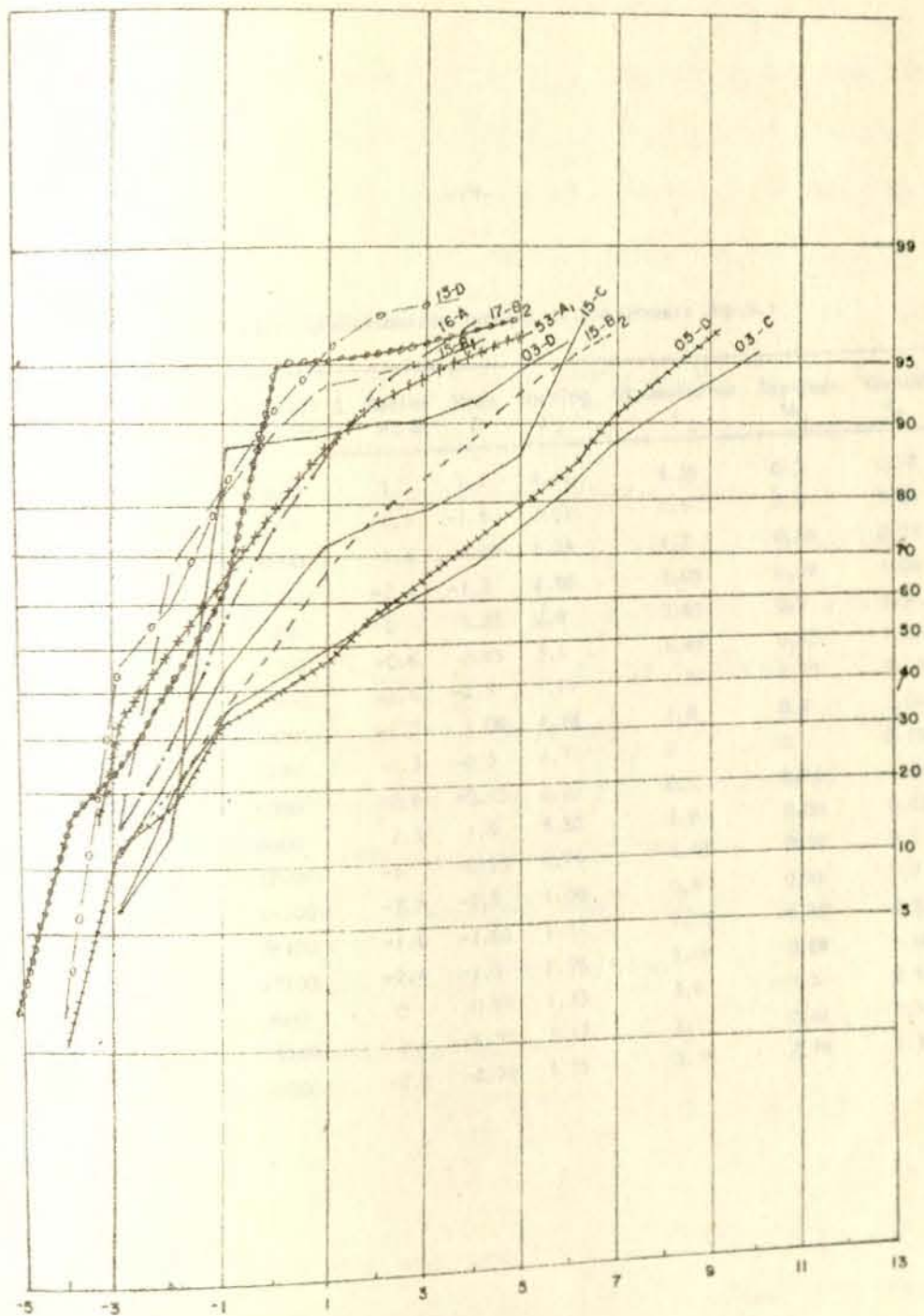


FIG. 15 CUMULATIVE CURVES OF GRAIN-SIZE DISTRIBUTIONS FOR GRAVELS OF THE UPPER SEQUENCE.

TABLE 10: Granulometric Indices of the Gravels (Up.S.)

Sample No.	Lithology	Coarsest % C (microns)	Median Md ϕ	Mean ϕ	Sorting σ_1	St.Deviation σ_G	Skewness Sk_1	Kurtosis K_G
03-C	Gravel	9600	1.	1.7	4.11	4.35	0.3	0.78
03-D	Gravel	11200	-1.5	-1.5	1.51	0.5	0.3	5.66
05-D	Gravel	16000	1.4	1.66	3.88	4.2	0.18	0.83
15-B ₁	Gravel	17100	-2.4	-1.2	2.96	3.05	0.69	1.08
15-B ₂	Gravel	11200	0	0.23	2.8	2.85	0.2	1.51
15-C	Gravel	11200	-0.6	0.43	3.1	3.45	0.43	1.03
15-D	Gravel	19200	-2.6	-2.3	1.29	1.35	0.40	0.94
16-A	Gravel	11200	-1.2	1.06	1.18	1.9	0.2	1.04
16-C	Gravel	8800	-0.3	-0.3	1.77	2	0	0.76
16-I	Gravel	6000	-0.6	-0.13	2.23	0.1	0.46	1.68
17-A ₀₂	Gravel	6000	2.3	1.9	3.52	3.8	0.00	0.63
17-A ₀₄	Gravel	12000	-3	-0.23	4.15	4.45	0.92	0.7
17-B ₁	Gravel	11200	-2.5	-2.5	1.68	0.5	0.41	7.7
17-B ₂	Gravel	38400	-1.6	-2.03	1.57	1.75	-0.33	0.81
19-C	Gravel	17100	-2.4	-1.2	2.96	3.05	0.69	1.08
52-A ₁	Gravel	9600	0	0.86	1.33	3.8	0.33	0.53
53-A ₁	Gravel	19200	-2	-1.53	2.17	2.1	0.42	2.72
54-B	Gravel	19200	-2.8	-0.76	3.25	3.75	0.78	1.91

Sands

These lithotypes consist of on the average 75% sand, 12% gravel, and 15% mud fractions. As shown in Fig. 14 of the size frequency distribution for these sands, more than 70% of the materials in most samples are below the coarse sand size as a result of which the mean and median values 1.28 ϕ and 1.17 ϕ respectively, are in the medium sand grade. Like all other sediments of the sequences, the polymodal nature of the size size distribution of these sands is seen by the breaks of the cumulative curves (Fig. 14). Sorting, except for two samples 08-C and 19B₂ (Table 11) which are moderately sorted, for most of the sands of the sequence is poor to very poorly sorted as it is indicated by the average value of 2.03 ϕ . The skeweness value is in the range of -0.16 to 0.78 which is from coarse skewed to strongly finely skewed. It can be inferred from their Kurtosis values that the sorting in the central position of the curves is better than in the tails of the curves.

The gravel fractions and most of the sands are angular to subangular.

Silts

The silts on the average consist of 67% silt, 17.4% sand and 5.8% clay sized particles. The size distribution of these sediments is shown in (Fig.15). The mean and median diameters are nearly similar for the analysed samples (5.15 ϕ and 5.2 ϕ respectively) which are in the medium silt range. These values are relatively lower when compared with those for the silts of the Lower Sequence due to the presence of sand fractions.

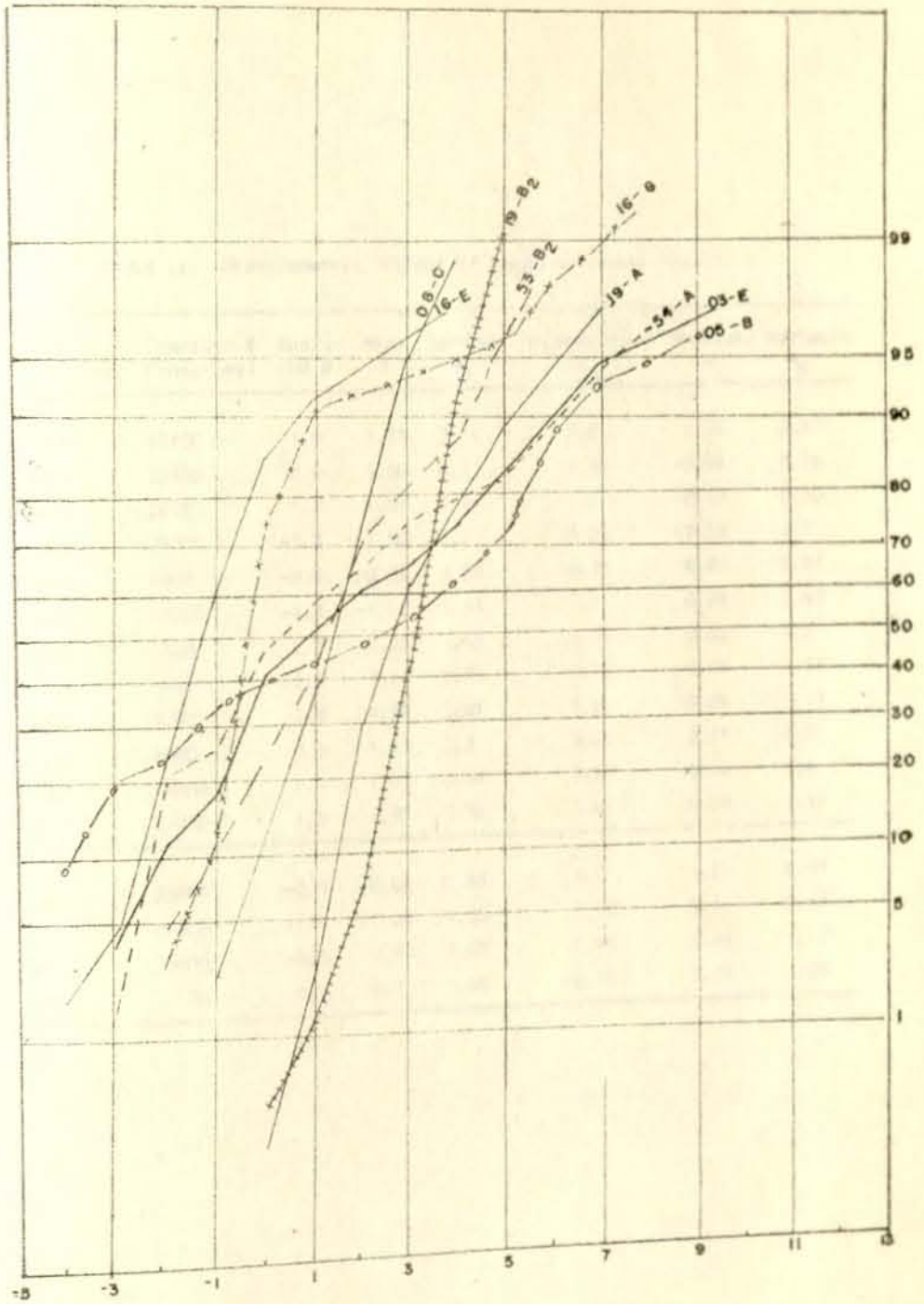


Fig. 14 CUMULATIVE CURVES OF GRAIN-SIZE DISTRIBUTIONS FOR THE SANDS OF THE UPPER SEQUENCE.

TABLE II: Granulometric indices of Sands and Ashes (Up.S)

Sample No.	Lithology	Coarsest % C(microns)	Median Md ϕ	Mean $\bar{\phi}$	Sorting σ_1	St.Deviation σ_G	Skewness Sk ₁	Kurtosis K _G
03-E	Sand	10400	1.0	1.53	3.11	3.2	0.24	0.87
05-B	Sand	22400	2.4	1.56	4.2	4.55	-0.16	0.74
08-C	Sand	2400	1.4	1.33	0.91	1.1	0.12	0.70
14-B	Sand	25000	-3.2	-1.56	3.17	3.25	-0.33	1.7
16-G	Sand	4800	-0.4	-0.23	1.25	0.75	0.45	2.97
16-E	Sand	19200	-1.3	-1.16	1.33	1.1	0.28	1.63
19-A	Sand	700	2.7	2.93	1.43	1.35	0.32	1.2
19-B ₂	Sand	600	3.2	3.1	0.75	0.75	-0.16	1.13
53-B ₂	Sand	5200	1.3	1.36	2.01	2.0	0.04	1.19
54-A	Sand	8800	0.3	1.13	3.3	3.65	0.37	1.0
63-B	Sand	12000	1.3	1.65	3.54	3.57	0.19	1.4
63-G	Sand	11000	1.0	1.73	3.56	3.6	0.29	1.11
03-B	Ash	20800	-0.5	-0.03	2.83	3.0	0.21	0.85
05-A	Ash	23400	-1.6	-0.03	4.05	4.75	0.51	0.62
05-C	Ash	20800	-0.5	0.53	3.03	2.85	0.44	1.17
18-A	Ash	50	5.3	5.3	0.68	0.55	0.28	1.38

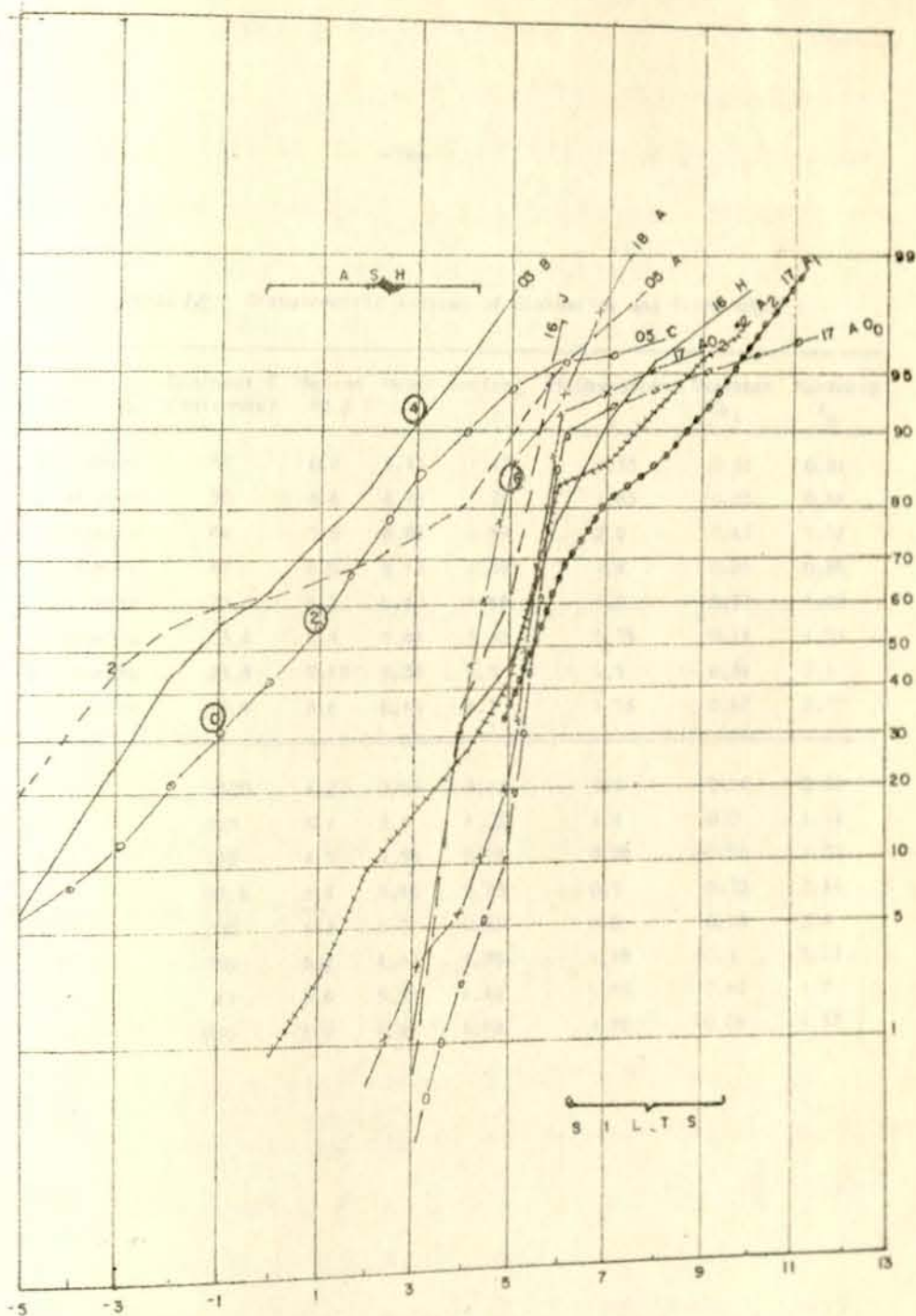


Fig. 85 CUMULATIVE CURVES OF GRAIN-SIZE DISTRIBUTIONS FOR ASH B SILTS OF THE UPPER SEQUENCE.
— CIRCLED NUMBERS INDICATE VALUES OF DIAMETERS.

TABLE 12: Granulometric Indices of Diatomites and Silts (Up.S.)

Sample No.	Lithology	Coarsest % C (Microns)	Median Md ϕ	Mean ϕ	Sorting I	St.Deviation G	Skewness Sk _I	Kurtosis K _G
07-A	Diatomite	47	6.2	6.43	1.47	1.55	0.33	0.81
08-D	Diatomite	50	6.6	6.76	1.79	1.85	0.23	0.86
20-A	Diatomite	44	5.8	6.86	1.99	2.2	0.43	1.72
52-A	Diatomite	47	6.0	6.13	1.39	1.4	0.26	0.89
52-B	Diatomite	23.4	6.2	6.46	1.44	1.4	0.37	1.05
52-C	Diatomite	23.4	6.4	6.43	1.40	1.35	0.18	1.03
52-D	Diatomite	23.4	5.15	5.38	1.5	1.5	0.34	1.1
53-B ₃	Diatomite	23.4	5.6	6.16	1.7	1.55	0.62	2.77
14-A	Silt	1600	4.2	3.92	3.13	3.5	-0.14	0.63
16-H	Silt	125	5.1	5.1	1.55	1.4	0.0	1.14
16-J	Silt	125	4.5	4.53	0.94	0.85	-0.08	1.07
17-A ₀₀	Silt	87.5	5.4	5.46	0.95	0.5	0.38	3.14
17-A ₀₁	Silt	200	5.3	5.3	0.92	0.6	0.13	2.4
17-A ₀₃	Silt	750	5.2	4.83	1.75	1.15	-0.3	3.17
17-A ₁	Silt	47	5.4	5.96	1.48	1.45	0.63	1.2
52-A ₂	Silt	950	5.2	4.9	1.98	1.75	-0.09	1.57

The values of average sorting coefficients exhibited by the analysed silt samples are of the order 0.92 ϕ to 1.98 ϕ which indicates moderate to poor sorting. The skewness is also variable between -0.09 and 0.63 which is in the range of near symmetrical to strongly finely skewed. However majority of them show near symmetrical distribution. Like the silts of the Lower Sequence, they have leptokurtic cumulative curves which according to Folk (1968) implies better sorting of the central portion than the tails.

Diatomites

The diatomites of the Upper Sequence are fine-grained and are essentially composed of silt and clay sized particles. The studied samples are especially marked by a predominance of silts averaging 81%. The rest is made up of clay and sand fractions, of which the former is dominant over the latter. This fine grained nature of the diatomites is reflected in their median and mean diameters (tables 12), the average of which is fine silt 6.11 ϕ and 6.46 ϕ respectively. However, when compared with the diatomites of the Lower Sequence, the diatomites of the Upper Sequence are characterized by relatively lower ϕ values of median, and mean diameter, sorting coefficient, and standard deviation (table 12), being relatively coarser, with a tendency to be moderately sorted. Although they are dominantly constituted by silt sized fractions, they are poorly sorted as it is indicated by their sorting coefficient values (on the average 1.59 ϕ). Skewness values for these lithotypes are relatively higher than those of the Lower Sequence. The range is from 0.18 to 0.62

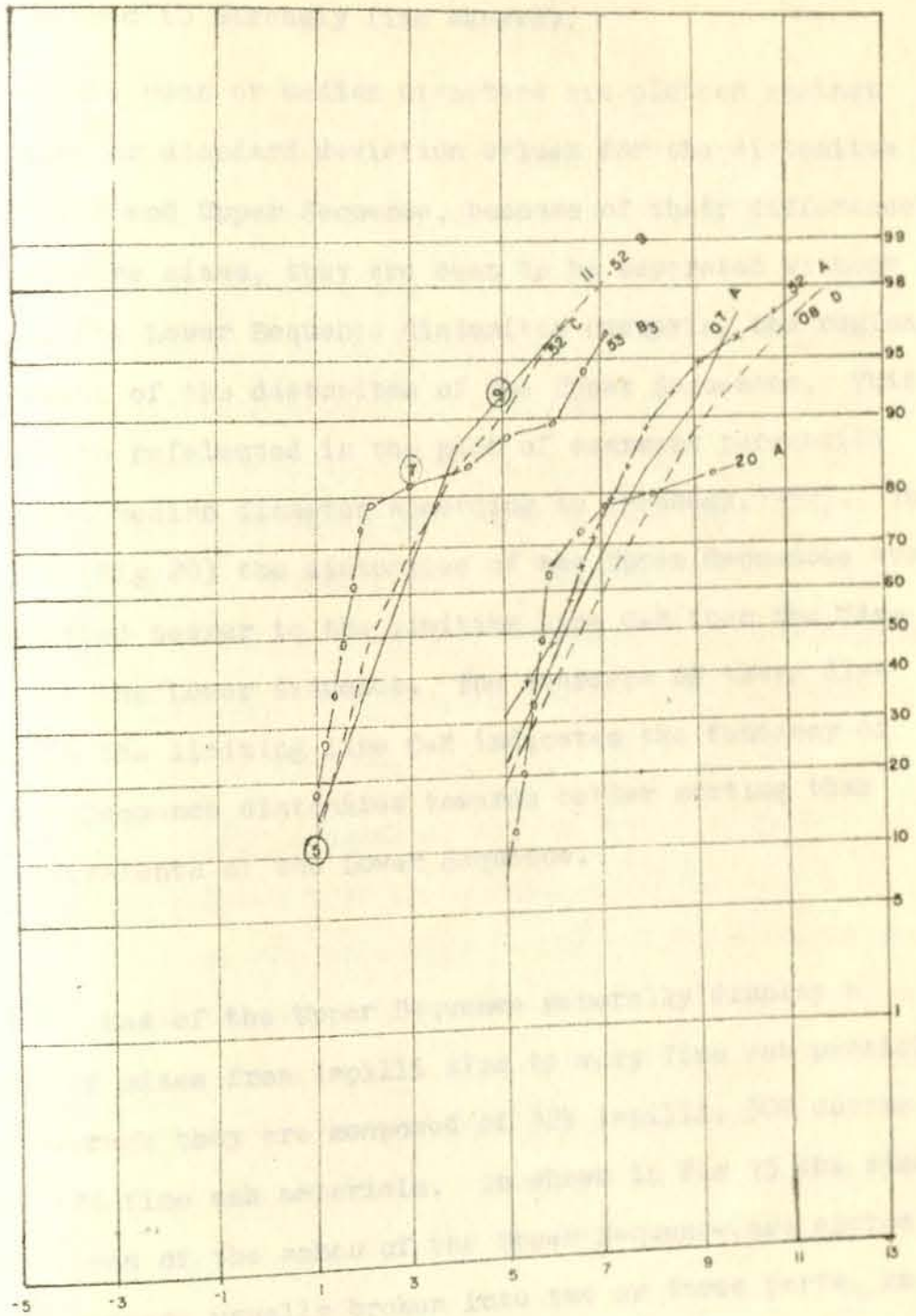


Fig. 16 CUMULATIVE CURVES OF GRAIN-SIZE DISTRIBUTIONS FOR DIATOMITES OF THE UPPER SEQUENCE.

— CIRCLED NUMBERS INDICATE VALUES OF DIAMETERS.

(finely skewed to strongly fine skewed).

When the mean or median diameters are plotted against the sorting or standard deviation values for the diatomites of the Lower and Upper Sequence, because of their differences in the average sizes, they are seen to be separated without overlaps, the Lower Sequence diatomites occupying the region to the right of the diatomites of the Upper Sequences. This fact is also reflected in the plot of coarsest percentile 'C' against median diameter according to (Passega, 1957). In this plot (Fig 20) the diatomites of the Upper Sequences are concentrated nearer to the limiting line $C=M$ than the diatomites of the Lower Sequence. The nearness of these diatomites to the limiting line $C=M$ indicates the tendency of the Upper Sequence diatomites towards better sorting than their equivalents of the Lower Sequence.

Ashes

The ashes of the Upper Sequence generally display a spectrum of sizes from lapilli size to very fine ash particles. On the average they are composed of 32% lapilli, 30% coarse ash and 37% fine ash materials. As shown in Fig 15 the size distributions of the ashes of the Upper Sequence are approximated by curves, usually broken into two or three parts, on probability paper. This means that they have polymodal distributions, (Yamazaki, et al, 1973) each of which is a log-normal distribution. In all the samples plotted more than 80% of the materials are smaller than -2ϕ (4mm). Both the median and mean sizes except for 18A have lower ϕ values

(table 11), with the average of -0.86ϕ and 0.15ϕ respectively. The mean and median values for sample 18A are higher.

The sorting characters of these ashes are very poorly sorted with variable sorting coefficient value 2.83ϕ to 4.05ϕ . The skewness values for all the ashes are positive and varies from finely skewed to strongly finely skewed, the average skewness value is 0.36 . The ash sample 18A is distinct in its textural characteristics from the three ash samples. It is characterized by higher mean and median values, and lower value of sorting coefficients (0.68ϕ) which is moderately well sorted.

Walker's (1971) diagram of $Md\phi$ against $\sigma\phi$ (Fig. 11) separates these ashes into pyroclastic flow and fall deposits. Ashes 05A, 05C and 03B plot well in the fields of flows while 18A falls in the fields of fall deposits. When the sorting coefficient is plotted against $Md\phi$ (Fig. 12) after Walker (1972), only the fine ash (18A) displays features of the distal facies, while the other 3 samples lie in the region between the proximal and distal but more nearer to the proximal facies. This may suggest that they probably represent the marginal part of the proximal facies.

Summary of textural descriptions

The granulometric study of the Admi Tulu sediments show a wide variation in the textural parameters. Average sediment size ranges from very coarse sand to very fine silt. It will be noted from table 13 that the sediments of the Upper Sequence are relatively coarser than their corresponding equivalents of the Lower Sequence. This may suggest that when the Upper Sequence sediments were deposited, there probably was a continuous and rapid supply of materials to the basin with little or no reworking.

The standard deviation values are highly variable because of wide variation of sizes in most lithotypes. Nearly all the deposits are positively skewed and are in general poorly sorted. The positive skewness and poor sorting may reflect the lack of winnowing current action. Lower Sequence sediments are largely mesokurtic while sediments of Upper Sequence are largely leptokurtic (table 13).

The polymodality of these sediments particularly of the coarser sediments i.e. sands and gravels is shown by breaks in the cumulative curves (Fig. 9, 13 and 14). However, this may not necessarily imply that parts of the sediments achieved their sorting elsewhere in a high-energy environment, and that they were transported essentially with their size characteristics unmodified into another environment as Folk and Ward (1957) suggested for Brazos River bar sediments. But rather it could be due to the nearness of the source. The subangular

TABLE 13: Summary of Textural Characteristics

	Textural Parameters	Gravel No. of Samples	Sand	Silt	Diatomite	Ash
Lower Seq.	Sorting	-	1 VPS 2 PS	3 PS 1 MS	1 VPS 4 PS 1 MS	1 VPS 1 PS 1 MS
	Skewness	-	SFS	SFS	SF-NS	CS-SFS
	S. Dev.	-	1.7-3.26	0.85-1.8	1-3.25	0.65-2.85
	Kurtosis	-	MK	LK	MK-PK	LK-MK-PK
	Mean ϕ	-	3.2	6.86	7.0	4.85
Upper Seq.	Sorting	9 VPS 9 PS	3 VPS 4 PS 2MS	3 PS 3 MS	PS	VPS
	Skewness	SFS	CS-SFS	NS-SFS	SFS	SFS
	S.Dev	0.5-4.45	0.75-4.55	0.5-1.75	1.35-2.2	0.95-4.95
	Kurtosis	7LK 4MK 7PK	5LK 1MK 3PK	5LK 1MK	3PK 2MK 2LK	2LK 2PK
	Mean ϕ	-0.48	1.28	5.15	6.46	0.15

Note:

VPS - very poorly sorted
 PS - poorly sorted
 MS - moderately sorted
 SFS - strongly finely skewed
 FS - finely skewed

NS - near symmetrical
 CS - coarse skewed
 LK - leptokurtic
 MK - mesokurtic
 PK - platykurtic

nature of the pumice pebbles and the homogeneity in composition of these sediments are in favor of short transport and nearness to the source. If the sediments are near the source of the sand, they are characteristically leptokurtic and positively skewed (Folk and Ward, 1957). The sands of both sequences are in general leptokurtic and positively skewed (table 13) in agreement with this statement. These considerations may suggest that sorting was primary and polymodality resulted only due to the variation of the sizes of initial source materials.

3. Organic Matter Studies

Because of the abundant population around their shores, phytoplankton in their near surface waters, some of the organic matter derived from decaying of plant and animal organisms become incorporated into lake sediments.

The organic matter incorporated in lake sediments according to Eglinton (1969) mainly consists of carbohydrates, lignin, glyceroides of fatty acids and waxes, and resins. These, latter as a result of microbial activity and physico-chemical processes occurring in sediments are degraded and fossilized to H_2O and CO_2 but the most stable compounds are preserved as complex derivatives such as humic substances (mainly allochthonous) and bitumoids (autochthonous).

Terrestrial organisms mainly plants give rise to humic substance. Aquatic organisms (phytoplankton and zooplankton) give rise to bitumoids. The humic substances may withstand oxidizing environment while the bitumoids may be preserved only in reducing environment. Hence the presence of humic substances in sediments in general indicate an oxidizing environment, areas of mass input of allochthonous material, and/or paleosol horizons. In reducing environment the autochthonous material will be preserved as bitumoids (Warner, 1970).

The quantity and type of allochthonous (humics) and autochthonous (bitumoids) of the incorporated organic matter in sediments characterize the environmental passways of detritus into areas of sedimentation and paleosol horizons.

The presence of organic matter in the sediments of Adami Tulu was suspected from the observation of dark brown coatings on some pumice gravels and the presence was tested in the field by using 5% sodium hydroxide which usually turns yellowishbrown or brownish by the dissolved organic matter. Preliminary field test convinced the existence of humic substances in these lacustrine deposits and the analysis continued in the laboratory.

Methods of Study

The procedure followed for the organic matter analysis was the well known methods described by Florovskaya V.N. (1975) and Eglinton (1969).

After preliminary fieldtest showed the existence of humic substances, 33 samples suspected for their content of organic matter were selected for laboratory analysis. The procedure followed for the analysis gives semi-quantitative results and the scheme is outlined in Fig. 17. For each sample 4gms of the 1/4mm sieve fraction was treated by 5% NaOH and was allowed for 24 hours. Extracts were used to prepare preliminary etalon collection with fixed (known) concentration of humic substances. The amount of humus was determined by colorimetric method. The error in the determination could be high from individual to individual and the results are therefore only semi-quantitative.

Bitumoids were also determined by treating the same samples with chloroform and benzine. The amount was determined semi-quantitatively by weighing the filter paper extracts and converting this to 100%.

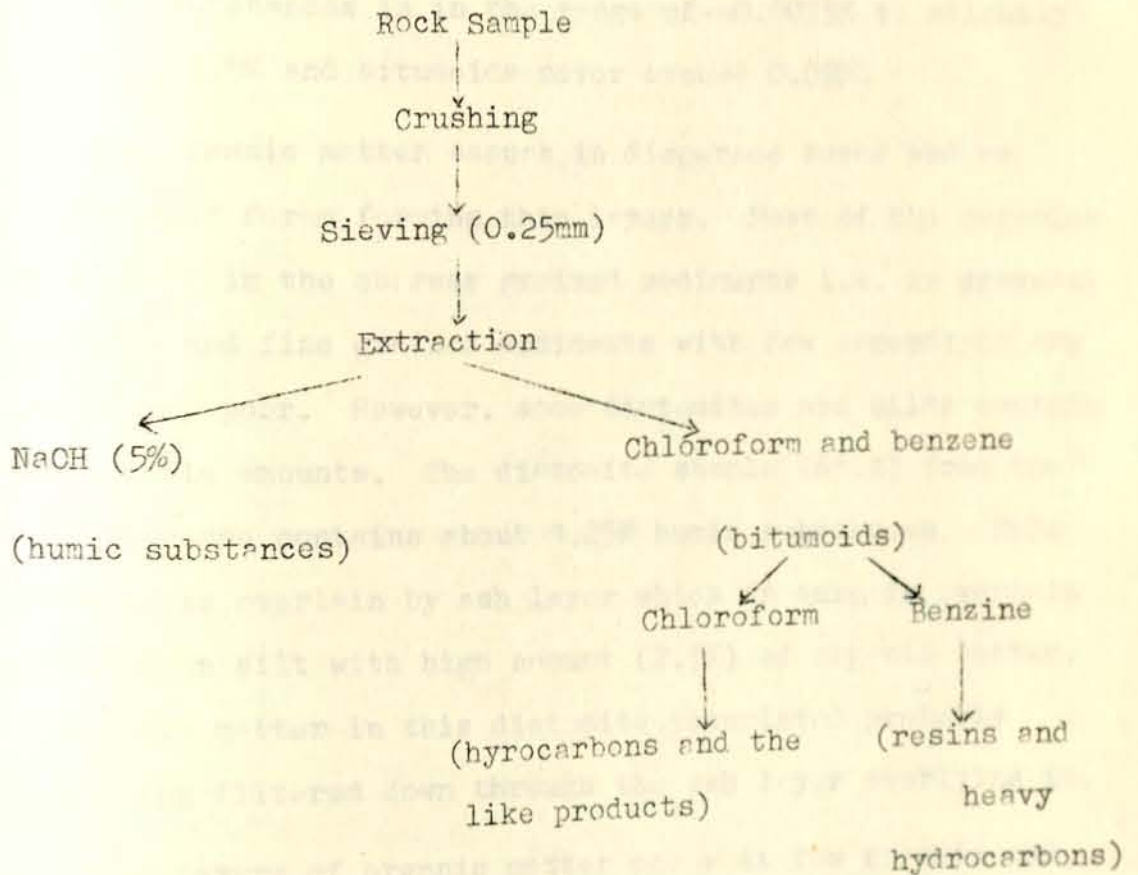


Fig. 17 A scheme for the determination of organic matter

Results and Discussion

The result of the organic matter analysis of the 33 samples is summarized in table 14. In many of the analysed samples presence of organic matter was detected and most of the organic matter belong to humic substances. The amount of humic substances is in the range of $<0.0025\%$ to slightly more than 2.5% and bitumoids never exceed 0.09% .

The organic matter occurs in dispersed forms and as concentrated forms forming thin layers. Most of the organics are present in the coarser grained sediments i.e. in gravels. The ashes and fine grained sediments with few exceptions are practically poor. However, some diatomites and silts contain recognisable amounts. The diatomite sample (41.E) from the Lower Sequence contains about 1.25% humic substances. This diatomite is overlain by ash layer which in turn is overlain by the brown silt with high amount (2.5%) of organic matter. The organic matter in this diatomite accumulated probably after being filtered down through the ash layer overlying it.

Thin layers of organic matter occur in few gravels and in some silts of the Upper Sequence. In silt sample 53B₁ (plate 7) in particular, as described in section 2.2.2.3, three layers of organic matter are present. Although the individual concentrations are high, the overall average content of organics in the sample is not very high and is about 0.06% . This figure is for the humic substances and bitumoids are not detected. The presence of humics and absence of bitumoids led to the assumption that the organic matter in

TABLE 14: Results of Organic Matter Analysis

Sample No.	Lithology	Humic Substances	Bitumoids % (Chloroformic Ext.)	Humic / Bitumoid
04-D	Sand	0.0025	0.00075	1:3
42-A	Sand	<0.0025	No	humics only
04-B	Diatomite	No	-	-
04-E	Diatomite	No	No	100:1
58-B	Diatomite	<0.0125	0.00025	~ 5:1
04-F	Silt	0.0025	No	humics only
41-B	Silt	2.5	No	humics only
42-E	Silt	No	0.012	Bitumoids only
58-C	Silt	<0.0025	0.012	~ 1:5
42-D	Ash	<0.0025	0.0075	1:3
58-A ₀	Tuff	0.090	0.012	Bitumoids only
05-D	Gravel	0.0025	<0.0025	1:1
07-B	Gravel	0.12	-	-
08-A	Shelly gravel	0.9	0.09	10:1
14-B ₁	Gravel	0.12	0.025	48:1
15-B ₁	Gravel	<0.0025	0.08	1:32
15-B ₂	Gravel	<0.0025	-	humics only
16-1	Diatomaceous gravel	0.0025	-	humics only
17-B ₂	Gravel	<0.0025	No	humics only
19-B ₁	Gravel	0.0035	-	humics only
53-A	Gravel	0.0025	No	humics only
08-C	Sand	0.0035	-	humics only
05-A	Ash	0.035	0.035	1:1
18-A	Ash	<0.0025	-	humics only
08-D	Diatomite	0.12	0.0035	34:1
15-A	Silt	0.0025	-	humics only
16-D	Diatomaceous silt	<0.0025	-	humics only
16-F	Silt	<0.0025	-	humics only
17-A ₀₃	Diatomaceous silt	<0.0025	-	humics only
53-B ₁	Diatomaceous silt	0.06	No	humics only

this silts is of allochthonous origin supplied to the lake by a small low energy river during the deposition of the silts. If so, then the three layers may indicate three successive periods of organic matter input of variable time as evidenced by the gap between the layers.

Based on their solubility in alkalies, acids and alcohol (Stevenson and Butler, 1969) divided humic substances into humin (insoluble in none of the reagents), fulvic acids (soluble in alkali and acids) and humatomelanic acid (soluble in alkali and alcohol). Testing the extracts with HCL and alcohol ($C_2H_5O_4$) have shown the presence of fulvic and humatomelanic acids which indicates the heterogeneous character of humics relative to the initial source material.

Although the average amount of humic substances is little, zones of relatively higher concentration were observed from the analysis in both sequences. The first one is in the upper part of the Upper Lacustrine gravels (samples 08A, 08D and 14B), and the other is in the brown silt at the bottom of the column of the Lower Sequence (sample 41E) where the higher concentration of humics is detected (table 14).

Bitumoids are present comparatively in small amount and rarely reaches 0.09%. They are not detected in all lithologic varieties and appreciable amounts are spotted in the very fine grained sediments such as silts and diatomites.

From this preliminary study, although the determinations are not far from error and the results are more of qualitative nature than quantitative, the following generalizations could be made.

1. The organic matter is present in the sediments of the region with variable amounts.

2. The predominance of humic substances in most sediments is an evidence of the allochthonous character of the organic matter and indicates the existence of oxidizing conditions in the basin of deposition (Werner, 1970).

3. The presence of concentrated forms of organic matter as thin layers may indicate periodicity in the formation and accumulation of the organic matters.

4. Discussion of Depositional Environments

The mechanisms and energy of grain transport and the environment in which the sediments were formed were analysed with the use of Moiola-Weiser (1968) and Passega (1957) diagrams and with the method of sedimentation environment interpretation based on the distribution of grain populations (Figs 9 to 16) with Visher's method (1969).

The texture of sediments reflects the process of deposition of the sediments. 'C', the maximum grain size and 'M' the median are characteristics of depositional agent. The C-M patterns are generally sharply defined and vary considerably with the type of depositional agent (Passega, 1957).

Lithologies of the Adami Tulu sediments are dominated by volcanic material essentially pumiceous. The most important lithologies are gravels, sands, silts and diatomites and the gross character of the deposits changes little within individual lithologic groups for both sequences. For this reason discussion of depositional environment is given for the lithologic groups in general.

Gravels

The plot of median ($Md\phi$) against coarsest percentile (C) (Fig 18) after Passega (1957) shows that most gravels follow a pattern similar to that shown by river sediments. Almost all samples are concentrated in that part of the pattern in which the transport of these coarser materials is by rolling suspension. The mean and standard deviation dependence (Fig. 19) of Moiola-Weiser (1968) of the analysed samples also gives projection points which are mostly concentrated in the section of river sediments except for samples 15B₁, 17B₁ and 16-I which fell in the beach section.

The fact that the majority of the gravels are relatively richer in pumice substances derived from terrestrial vegetation could also be additional evidence for their fluvial character. The gravels which mostly occur as interbeds within the diatomites or diatomaceous silts are, however, interpreted to be probably of shallow water lacustrine as they are rich in shallow fresh water shells of gastropods and bivalves. The accumulation of these shells in mass in relatively thin layers of gravels suggests that there must have been mass death. Based on the assumption that the pumice gravels have been supplied to the lake by rivers after they have been erupted from the concurrent volcanic activity, a change in the physico-chemical balance of the lake water could be inferred. Such a change could probably cause the sudden death and rapid consequent deposition of these organisms along with the gravels.

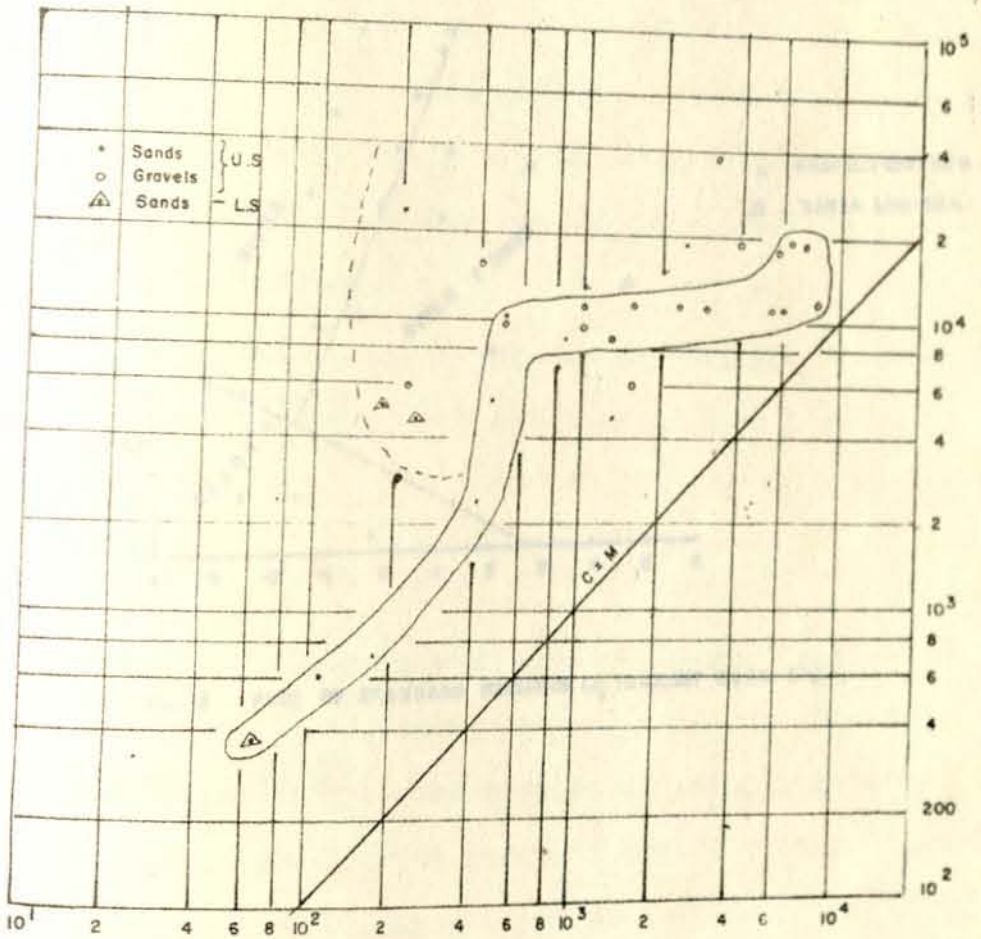


Fig. 18 CM DIAGRAM OF ADAMI TULLU SEDIMENTS

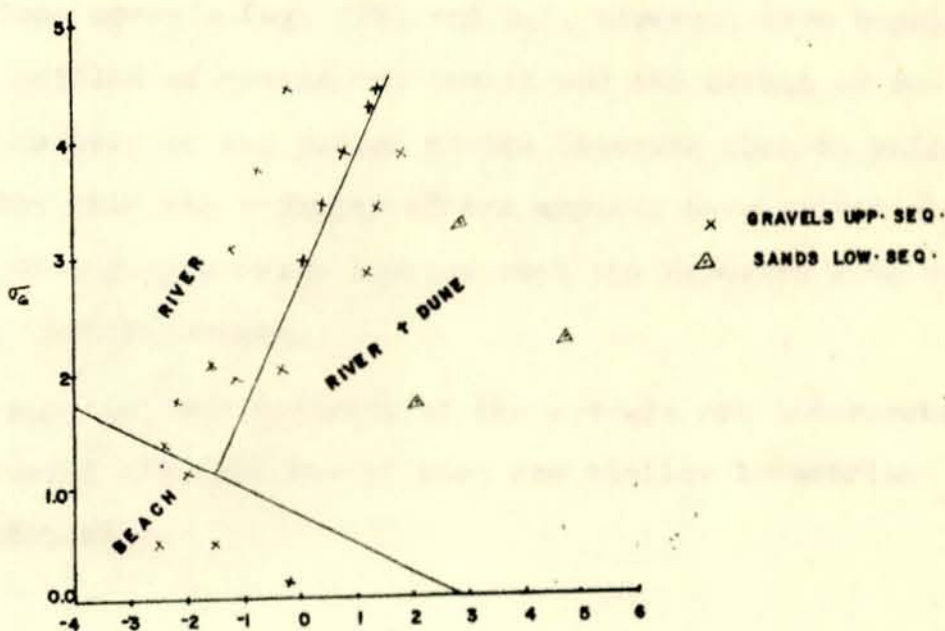


Fig. 19 PLOT OF STANDARD DEVIATION (σ_g) AGAINST MEAN (M_g).

The materials of the gravels like other lithotypes in the region are largely dominated by pumice. The poor rounding of most of the pumice pebbles of these gravels inspite of their soft and friable nature, suggests that most of the materials have not been transported for longer distances. Some gravels (eg. 17B₁ and B₂), however, have highly rounded pebbles of pumice and basalt and the effect of reworking is seen in the pumice grains altering them to yellow. Except for this the majority of the gravels have relatively fresh pumice grains which implies that the deposits have not suffered much reworking.

In summary, the majority of the gravels are interpreted to be fluvial although few of them are shallow lacustrine (beach) deposits.

Sands

The sands of the study area showed distinct pattern on a C-M diagram of Passega (1957). The plot on Fig. 18 shows that the majority of the sand samples followed a pattern shown by most recent fluvial deposits. This pattern suggests that the mechanism of transport for most sands to be by suspension, the part of the pattern representing the graded suspension being longer than the part of the pattern representing sediments whose particles moved in rolling suspension. Coarser particles up to 800 microns were able to be transported in suspension by the depositing river. The analysis of the shapes of curves with Visher's method (1969) based on the

grain population of Fig. 14 indicated that most of the curves are more or less similar to those of fluvial deposits.

The use of such diagrams leads to a conclusion that most of the sands are probably fluvial and that they are possibly deposited during the periods in which the level of the lake was lowered. Lake level fluctuations have been reported in the region (Nilson, 1940; Mohr, 1966; UNDP, 1973; Geze, 1975). During these periods deposition along the beaches of the lake could be probable. Certain sand layers are observed to be overlain or underlain by diatomaceous sediments. As is expected such fine grained sediments are formed in quiet water. Obviously main diatomite horizons are observed to be underlain by fine gravel or gravelly sand and in some places (locality 53) the deposition of diatomites is marked by the deposition of sands and gravelly silt interbeds after which then the increase in the lake level was inferred by the deposition of the diatomites. The sands and gravels that overly and underly these fine grained sediments could therefore be formed in the shallower (beach) part of the lake during such fluctuations. This could be a possible explanation for some sands to plot within the extended field of beach sediments after Passega (Fig. 18). This same view was suggested also for some gravels earlier.

Silts and Diatomites

The silts and diatomites are thought to have settled from suspensions in the lake. The sediments contain abundant and well preserved planktonic fossil diatoms. These fine grained sediments are interpreted to be lacustrine because of the absence of current produced structures and the presence of laminations.

The diatomites in general display two types of structure-massive bedding and lamination. Those with massive bedding may be interpreted to have resulted from extremely slow sedimentation and those with laminations might have been formed by rapid sedimentation or fluctuations of the supply of suspended sediment (Collinson and Thompson, 1982).

In the plot of 'C' against 'M' (Fig. 20), these sediments fell in the field of quiet water deposits which is a character of lakes and lagoons. The significant feature of these sediments in this diagram is that the silts of the Lower Sequence and the diatomites of the Upper Sequence are nearer to the limiting line C=M. As this area is the area of better sorting (Passega 1957), comparatively the diatomites of the Upper Sequence and silts of the Lower Sequence are moderately sorted than diatomites of Lower and silts of Upper Sequence respectively.

The frequent occurrence of the diatomites immediately on the gravels requires some explanation. Deposition of diatomites requires quiet water basin free of current activity and most of the gravels are thought to be fluvial.

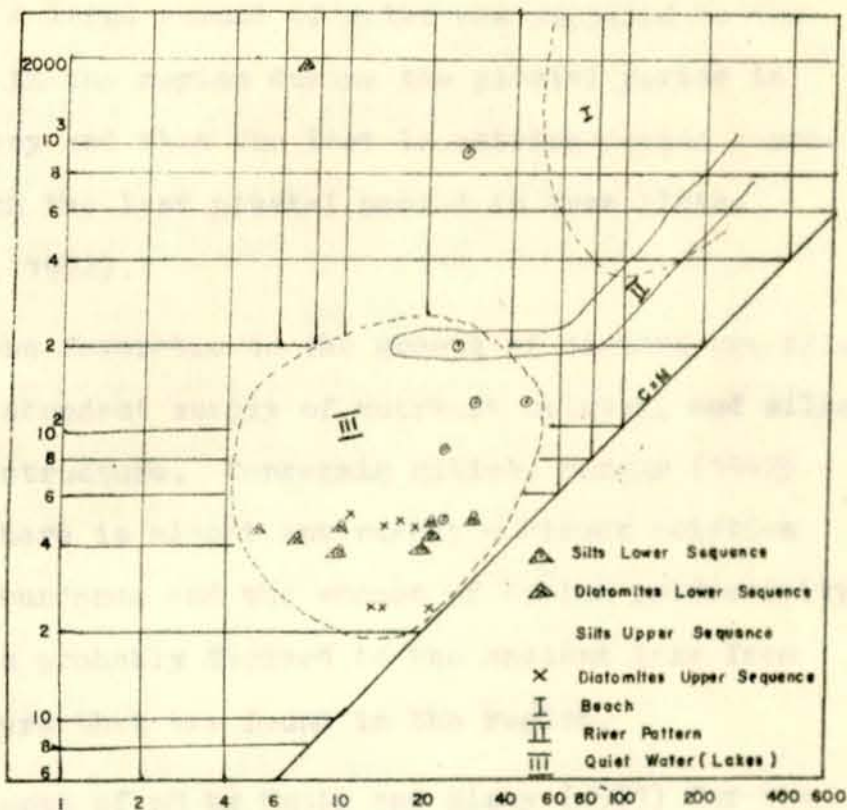


Fig. 20 CM DIAGRAM OF ADAMI TULU SEDIMENTS

There could be two possibilities for the diatomites to be deposited directly on these gravels

- 1) Either the basin was continuously subsiding or
- 2) There was an increase in the level of the lake.

From the limited data inference of subsidence of the basin would be unlikely. However, increase of the lake level appears to offer the best explanation. It was established earlier that a large amount of water was supplied to the ancient lake in the region during the pluvial period in Late Quaternary and that the last lacustrine period correlate well with the last pluvial period in East Africa (Butzer et al, 1972).

Conditions favorable to the growth of diatoms are illumination, an abundant supply of nutrient solutes, and silica for skeletal structure. Concerning silica, Conger (1942) stated that there is almost invariably a direct relation between its abundance and the amount of diatom productivity. The silica was probably derived to the ancient lake from volcanic centers that are found in the region.

Measurements of pH by Knoth and Sisay (1981) for the diatomites mainly in the Upper Sequence, are on the average 8.8 indicating a slightly alkaline nature of the lake waters during the deposition of diatoms. According to Conger (1942), diatoms appear definitely favored in general by an approximately neutral or slightly alkaline pH, and strong acidity suppresses the diatom flora. He also stated that diatom growth is favored by relatively low temperatures because inhibited bacterial activity reduces the acidity

resulting from decomposition processes and because lower temperatures are generally recognised as optimal to diatom metabolism.

Inference therefore may be made on the temperature and pH of the water of the ancient lake. It appears that the diatomite of the area originated by the settling of the siliceous frustules in a lake having a relatively lower temperature and slightly alkaline pH.

The ash intercollations which often causes the impurity of the diatomites imply concurrent volcanic activity along with the depositions of the diatomites.

Observation of variation in the thickness of the diatomites and diatomaceous sediments gives clue in the nature of the basin of deposition. As described earlier in the lithological section thickness of these sediments increase on the opposite sides of the uplifted blocks and volcanic hills. The thicknesses were seen to increase to the west and southwest. They also increase in thickness north-eastwards away from the foot of the northeastern end of Alutu towards the Zway lake. This observation indicates that the diatomaceous sediments particularly of the Upper Sequence probably deposited in a basin which was widening to the east and southwest.

Volcanism at Alutu was probably contained within the Pleistocene and Holocene. Early eruptions were thought to have been sublacustrine, and lava injection probably domed

the sediments locally (UNDP, 1973). The deposition of the diatomites of the Lower Sequence perhaps could be related with the early phases (?) of the eruption of Alutu.

Radiocarbon age datings of the shells from the base and top of diatomites belonging to the Upper Sequence indicates that the diatomite was deposited in 4400 years between 9360 ± 210 BP and 4960 ± 140 BP. (Geze, 1975). Around 10,000 to 11,000 yrs. BP. the four, Galla lakes (Zway, Langano, Abiyata and Shala) were still or were again united as a single lake standing at a height of about 35 to 45 mts above the present level of Lake Zway (Laury and Albrilton, 1975). This was the period at which deposition of the diatomites of the Upper Sequence began to take place. This supports the previous statement regarding the nature of the basin. Since the level of the lake was only few mts above the present level of Lake Zway (1636mt) and the height of the Aluto Volcano (336 mt above the surrounding plain) being considerably high, the supposition of the east and southwest deepening of the lake away from this volcano is likely.

Provenance

The lithology of Adami Tulu sediments is largely or ~~exclusively dominated by pumiceous sediments.~~ The dominance of these pumiceous sediments indicates that there was intense rhyolitic volcanism during the late period of sedimentation (UNDP, 1973). ~~The eruption of basalts from north-north-east faults east of Alutu is reported by the same authors.~~

Dipaola (1970) reported the existence of rhyolitic dome 2 Km west of Adami Tulu and ~~phreatic explosion craters~~ north east of Lake Zway. Gibson and Dakin (1971) described the Alutu volcanic center to be ~~panelleritic.~~ According to them, the geology of Alutu is dominated by a group of porphyritic pitchstone flows and domes. Pumice and voluminous ash flow tuffs particularly occupy the area south of Lake Langano. The activity of Alutu volcano is believed to have began in the Pleistocene and continued in the Holocene (Dakin, 1971; UNDP, 1973).

Field and microscopic observation of the composition of these sediments have shown the sediments of the area to contain largely of pumice, and lithic fragments of obsidian, rhyolite and basalt. The less degree of rounding or the angularity and freshness of the soft pumice grains in the sands and gravels indicate transportation for short distance. The leptokurtic and positively skewed nature of the sands may also indicate the nearness of the source. The proximity of the area to the volcanic centers, freshness of the soft

Conclusion -103-

pumice grains, the dominance of glassy materials in both coarse and fine grained sediments and the lithologic and age relationship of the Adami Tulu sediments with the available data suggest that the source of the sediments to be from a volcanic province to the south east of the area from Aluto and its contributory volcanoes.

The Adami Tulu sediments show horizontal bedding, massive bedding, block bedding and load casting. The fine grained sandstone is either massive, thinly bedded or laminated.

The volcanically important constituents of the Adami Tulu are pumice, glassy sands, volcanic rock fragments, feldspars and quartz. Generally they are characterized by high silica to total volcanic silica percentage ratios. The lighter heavy minerals are pyroxene, amphibole, olivine and biotite. The major pebbles and gravel fragments of the gravels are pumice, cherted and basalt. These characteristic features indicate derivation of these sediments from a volcanic source.

The sediments contain organic matter in concentrated form. The relatively higher concentrations of organic matter at the bottom of the lower part of the Adami Tulu may be due to the presence of lignified plant material.

Summary and Conclusion

The Adami Tulu sediments which range in age from the Pleistocene to Holocene consists of gravels, sands, silts, diatomites and intercallation of ash and tuffs. The deposits in general are unconsolidated and poorly sorted with wide variations of textural parameters. Sediment size ranges from fine silt to coarse gravel with occasional gradation. Coarse grained sediments show horizontal bedding, massive bedding, crossbedding and load casting. The fine grained sediments are either massive, thinly bedded or laminated.

The volumetrically important constituents of the deposits are pumice, glass shards, volcanic rock fragments, feldspars and quartz. Generally they are characterized by high pumice to total volcanic lithic fragments ratios. The important heavy minerals are pyroxene, hornblende, magnetite and biotite. The major pebble and granule lithologies of the gravels are pumice, obsidian and basalt. These compositional features indicate derivation of these sediments from a volcanic source.

The sediments contain organic matter in concentrated and dispersed form. The relatively higher concentration of organic matter at the bottom of the Lower and top of the Upper Sequence may be indicative of two periods of increased supply of organic matter.

The sediments are identified to be fluvio-lacustrine. The majority of the gravels and sands are interpreted as fluvial deposits. The gravels rich in shells of gastropods and bivalves and associated sands are identified to be shallow water beach sediments. The lacustrine deposits are recognised as diatomites and silts. Interstratified ash and tuff are either flow or fall deposits.

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D E C L A R A T I O N

I, the undersigned, declare that this thesis is my work and that all sources of material used for the thesis have been dully acknowledged.

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Place and date of submission School of Graduate
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