

Bollettino

della

Società Paleontologica Italiana

Pubblicato sotto gli auspici
del Consiglio Nazionale delle Ricerche

Volume 43, n. 1-2, 2004

Proceeding of the
1st MEETING OF THE ITALIAN OSTRACODOLOGISTS
“IN MEMORY OF GIULIANO RUGGIERI”

Rimini, February 12-14, 2003

Editors:
Elsa Gliozzi
Antonio Russo

MUCCHI - MODENA

<i>Bollettino della Società Paleontologica Italiana</i>	43 (1-2), 2004	ISSN 0375-7633	235-266	2 pls.	Modena, Novembre 2004
---	----------------	----------------	---------	--------	-----------------------

Late Quaternary lacustrine ostracoda of the Ziway-Shala Basin (Ethiopia) as paleoenvironmental indicators

Balemwal ATNAFU

Department of Geology and Geophysics
Addis Ababa University
Addis Ababa, Ethiopia

Antonio RUSSO

Dipartimento del Museo di Paleobiologia
e dell'Orto Botanico
Università di Modena e Reggio Emilia, Italy

KEY WORDS – *Ostracoda, Lacustrine, Paleoenvironments, Late Quaternary, Ethiopia.*

ABSTRACT – *Ostracods from a number of Late Quaternary ¹⁴C dated outcrop sections and sediment samples from a core in Langano lake have been studied. Simple statistical characterization of valves, counted for each sample, allowed the recognition of different assemblages that have been interpreted as mainly controlled by salinity changes.*

Paleoecological evidence confirms salinity fluctuations, caused by climatic changes, which operated on water dilution, during the time interval considered. In addition, the results are in general agreement with previous results of lake-level changes, obtained using different research approaches.

RIASSUNTO – [Ostracodi lacustri del Quaternario superiore del Bacino dello Ziway-Shala (Etiopia) come indicatori paleoambientali] - Sono stati studiati gli ostracodi da diverse sezioni in affioramento e da un carotaggio nei pressi del Lago Langano (Etiopia). La datazione dei campioni è stata ottenuta per mezzo del ¹⁴C. La caratterizzazione delle associazioni è stata ottenuta per mezzo di una semplice statistica effettuata sul numero di valve trovate. Le diverse associazioni così riconosciute sono state interpretate come controllate principalmente da variazioni di salinità.

Le indicazioni paleoecologiche confermano dunque fluttuazioni di salinità, causate da cambiamenti climatici operanti principalmente per mezzo di diluizione delle acque, durante l'intervallo di tempo in esame. I risultati del presente studio sono in buon accordo con le precedenti stime dei cambiamenti di livello dei laghi, ottenute usando diversi metodi di ricerca.

INTRODUCTION

Lacustrine records are one of the main data sources in the reconstruction attempts of continental sequences, especially in the Quaternary.

Changes in lacustrine environment that result from changes in the evaporation-precipitation ratio – i.e. climate – include fluctuations in lake-level and salinity. Most sensitive in this respect are closed basin lakes, which lack surface outlets. Their tendency to fluctuate both in depth and areally is often clearly apparent from abandoned shorelines and/or abrupt changes of facies in sedimentary sections.

Ostracods are potential sources of information useful for the reconstruction of the past history of lakes.

The scope of the work is to evaluate if also the Ostracoda can contribute to reconstruct the history of the Ziway-Shala basin.

The present study is undertaken in a basin where climate-caused lake-level fluctuations are known to have occurred especially in the latest part of the Quaternary.

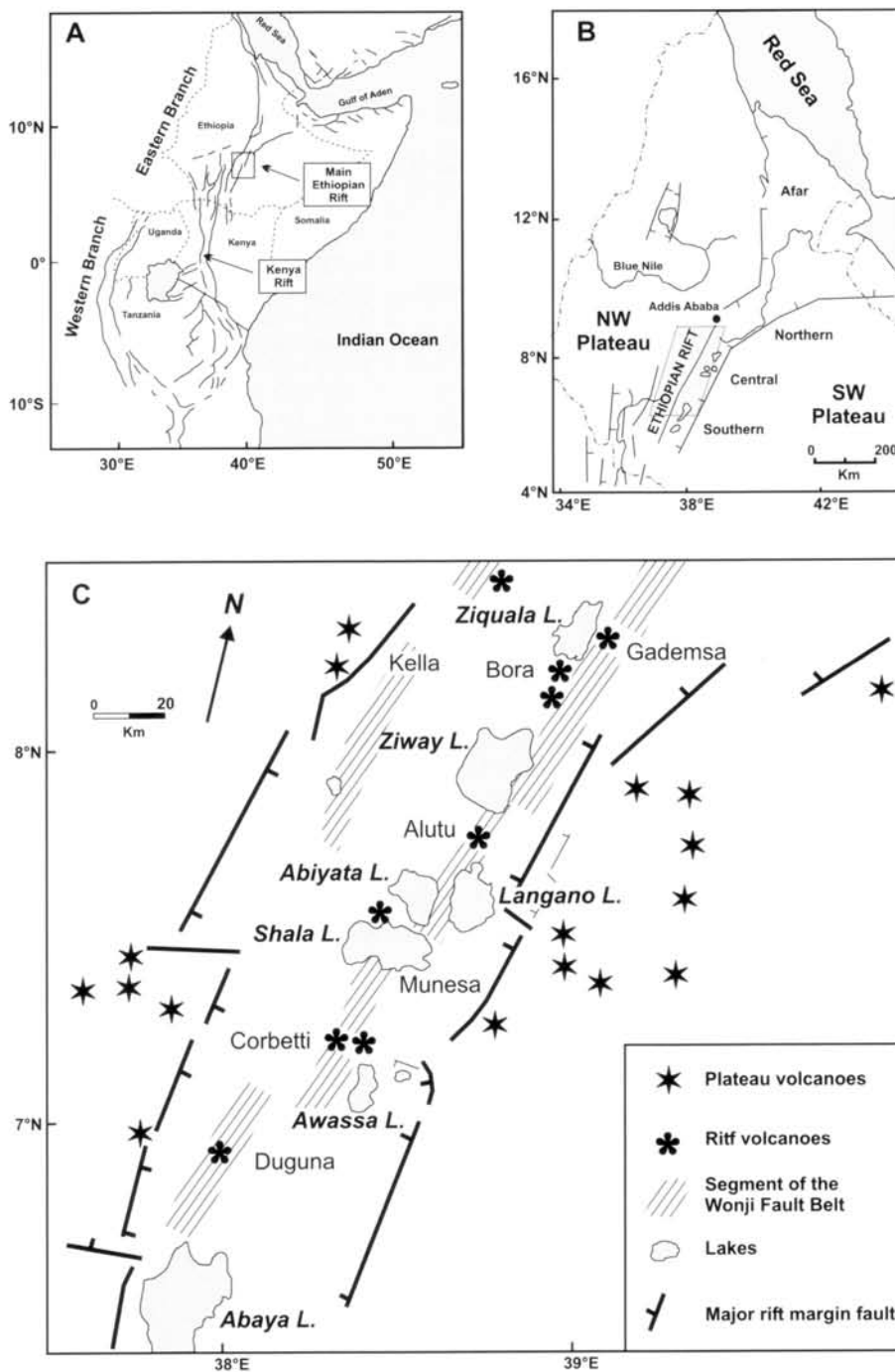
The change in ostracod assemblages with time (controlled by a chronologic framework of ¹⁴C datings especially in the Holocene) is evaluated in terms of environmental variability. The environmental variable mostly considered was the salinity level.

GEOLOGIC SETTING

The Main Ethiopian Rift (MER) is a symmetrical graben (lat. 5° - 9°N; long. 37°30' - 40°) bordered by the Ethiopian Plateau to the west and Somali Plateau to the east. Its development has been differently interpreted: pure tension (Di Paola, 1972; Woldegabriel *et al.*, 1990; Chorowitz *et al.*, 1994); transtension (Boccaletti *et al.*, 1992); oblique rifting (Bonini *et al.*, 1997). It is geographically divided into three sectors, namely: the southern, central and northern (Text-fig. 1). The study area i.e. the Ziway-Shala Basin is located within the central sector of the MER.

Following the development of the main escarpments, volcanic activity and structural deformation of the MER was confined to a zone of normal faulting, 5-15 km in width and arranged in *en échelon* fashion (Mohr, 1967; Di Paola, 1972; Woldegabriel *et al.*, 1990). This volcanotectonic axis is named the Wonji Fault Belt (WFB) (Mohr, 1960).

In the central sector of the MER, the WFB is right laterally offset into four *en échelon* rift-axis segments (Text-fig. 1c). From north to south these are the Gademsa-East Ziway, the Ziway-Shala, the Shala-Corbetti and the Duguna-Abaya segments (Mohr *et al.*, 1980; Woldegabriel *et al.*, 1990; Le Turdu *et al.*, 1999). Caldera topped shield volcanoes occur at each WFB offset. From north to south these are the Alutu Caldera,



Text-fig. 1 - A) Location of the Ethiopian Rift within the East African Rift System; B) Major physiographic features and the position of the central part of the Ethiopian Rift; C) The central part of the Ethiopian Rift and the segments of the Wonji Fault Belt (WFB) within it (modified from Woldegabriel *et al.*, 1990).

the O'a Caldera (presently occupied by Lake Shala) and the Corbetti Caldera (Mohr *et al.*, 1980). Woldegabriel *et al.* (1990) suggest that the Alutu and O'a (Shala) calderas formed contemporaneously before 0.24 Ma and after 0.27 Ma.

Voluminous parasitic silicic volcanism continued up to Holocene times from the Corbetti and Alutu Calderas (Di Paola, 1972) as shown by numbers of ash layers within the Late Pleistocene and Holocene deposits of the Bulbula plain and east of Lake

Abiyata (Street, 1979). Intermittent late Holocene activity of Alutu is demonstrated by obsidian flows and pumice breccias dated at about 2 ka (Gianelli & Teklemariam, 1993) and ash layers in the Macho area, west of the volcano, which were deposited shortly before 1.54 ka and shortly after 0.23 ka (Haynes & Haas, 1974).

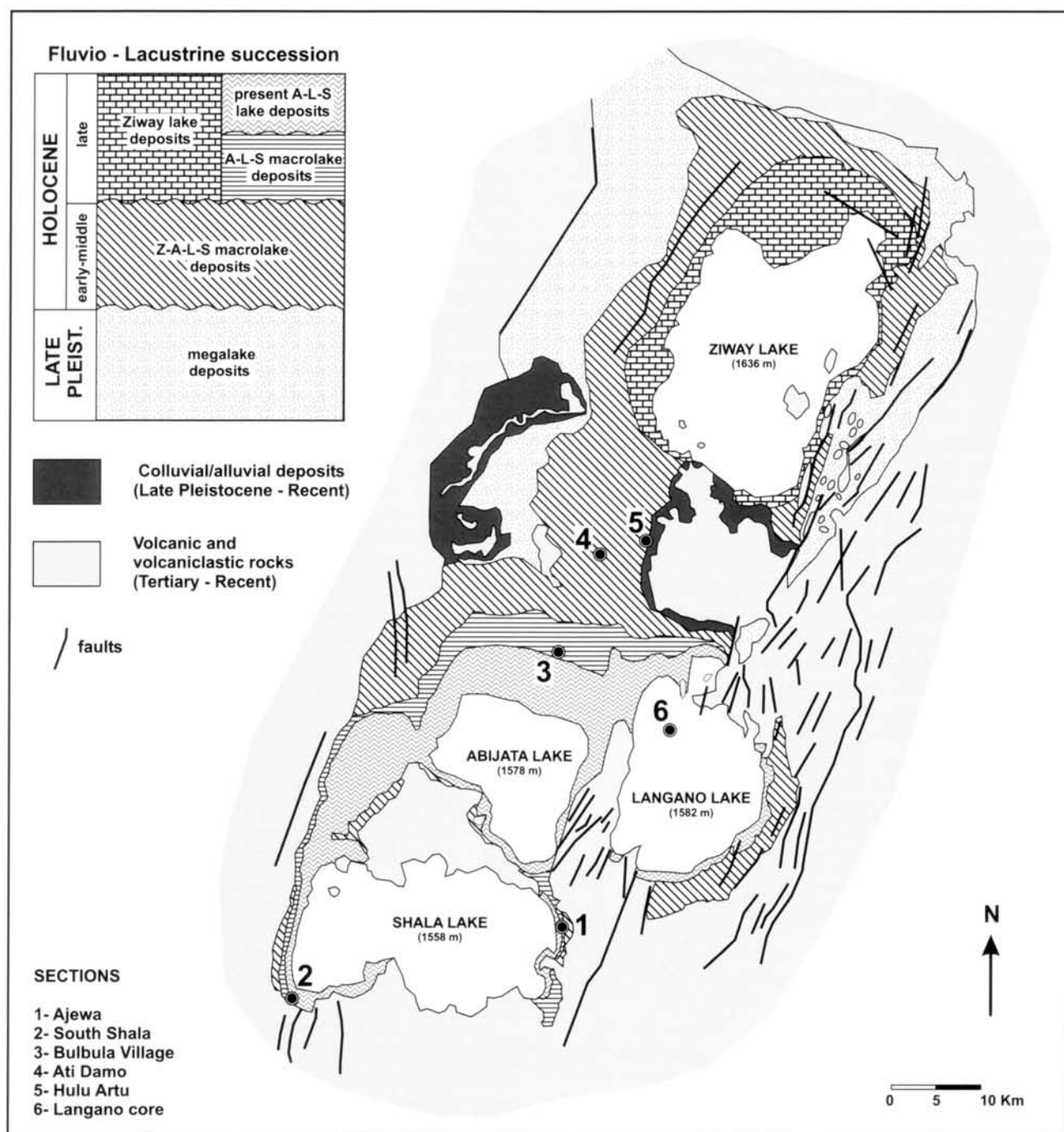
The fluvio-lacustrine sediments are of significant abundance and have been the subject of detailed studies (Street, 1979; Sagri, 1995; Alessio *et al.*, 1996; Le

Turdu *et al.*, 1999; Benvenuti *et al.*, 2002). Street (1979), Le Turdu *et al.* (1999) and Benvenuti *et al.* (2002) have undertaken an extensive stratigraphic and geomorphologic study of these sediments identifying a variety of lacustrine sediments (diatomites, clastic sediments, carbonate muds, marls).

The sediments are quite extensively distributed in

this part of the rift and have been recently mapped in the Ziway-Shala lacustrine basin by Sagri (1995), who has subdivided the fluvio-lacustrine succession into five Late Quaternary facies (Text-fig. 2), and by Benvenuti *et al.* (2002), who have established four major unconformity-bounded units (i.e. synthem).

The oldest sediments are Late Pleistocene lake de-



Text-fig. 2 - Schematic geological map of the Ziway-Shala Basin (after Sagri 1995, modified) also showing the location of the studied sections (n. 1-6).

posits (Megalake deposits of Synthem 1 and 2) which must have had a more extensive distribution than the succeeding phases in the Holocene, and outcrop on the east shore of Lake Shala, in the Bulbula River and Deka Wede gorges and on the slopes of the Gademotta Ridge (Benvenuti *et al.*, 2002). Macrolake deposits (Synthem 3), made up of lacustrine, fluvio-deltaic, colluvial, and volcanoclastic sediments, are Early-Middle Holocene in age, and represent the time when the present-day lakes were united. For the Late Holocene (Synthem 4) instead, different facies are identified around Ziway on the one hand and the more southern lakes on the other. The Late Holocene in the southern lakes has further been divided into an older facies where the three lakes would have been united and a younger one where deposits have been formed around the separated individual lakes until the present (Sagri, 1995; Benvenuti *et al.*, 2002).

With one or two exceptions, the Wonji Fault Belt does not appear to have displaced Late Quaternary sediments (Street, 1979). Although major displacements have occurred along the fault belt north-east of Langano since the Middle Pleistocene, the Holocene shorelines seem to be unaffected. The only areas where Late Quaternary sediments are demonstrably faulted are west of Ziway, north-east of Lake Shala, and east of Fiké (Street, 1979). Thus, according to this author (Street, 1979), some confidence can be placed in Late Quaternary lake-level fluctuations as a basis for water-balance calculations.

By correlating geomorphologic and chronologic data from the eastern coast of Lake Shala, Alessio *et al.* (1996) and Benvenuti *et al.* (2002) conclude that tectonic activities were important in the Late Quaternary. They therefore suggest that interpretations assuming a topographically stable rift floor during the interval considered should be taken with caution. Benvenuti *et al.* (2002) suggest that modifications of hydrological threshold, due to activity of structures parallel and transversal to the MER, established new lake boundaries between terminal Pleistocene and early Holocene, setting the maximum level of the Holocene lake system at about 1670 m. a.s.l.

In the present day, the four lakes (Ziway, Langano, Abiyata and Shala) form two disjunct hydrologic systems because there is no connection between Lake Abiyata and the southernmost Lake Shala, due to a faint topographic threshold. A lake level rise of only 13.8 m of Abiyata would unite these two systems - this occurred a number of times in the Late Quaternary history of the lakes (Street, 1979).

The remnant of the Gademotta Caldera, the Aluto Volcano, the O'a Caldera in which Lake Shala has formed, and the Corbetti Caldera are prominent physiographic features that stand out from the apparently flat rift floor of the basin. Streams and rivers have cut gullies and valleys, sometimes quite deep, enabling the exposure of Pleistocene and Holocene sediments.

The lakes are of tectonic or volcanotectonic origin

and the individual basins have their distinct characteristics.

The present-day Lake Shala is about 28 km long and 15 km wide with a maximum water depth of 266 m (Von Damm & Edmond, 1984). It is the most southern of the four lakes in the studied basin and lying at an altitude of 1558 m is also the lowest. The lake occupies not only the O'a Caldera which is oriented perpendicular to the WFB but also a tectonic depression immediately west of the Caldera belonging to the northern end of the Shala-Corbetti WFB segment (Mohr *et al.*, 1980). The general shape of the depression occupied by Lake Shala has been further modified by regional faulting (Tiercelin *et al.*, 1997; Le Turdu *et al.*, 1999).

Lake Abiyata occupies a very flat depression, about 18 km long, characterized to the east by a gently faulted margin corresponding to the eastern flank of the NNE-trending Katlo Horst (Tiercelin *et al.*, 1997; Le Turdu *et al.*, 1999) which separates Lake Abiyata from Lake Langano. To the north, a flat alluvial plain, opening toward the Bulbula Plain and the Lake Ziway Basin, is characterized by the preservation of beautiful abandoned shorelines created by lacustrine fluctuations in the basin. The southern and western margins of the basin, on the contrary, are essentially controlled by volcanic relieves.

Lake Langano is formed in a largely fault-bounded depression. It occupies an area of 230 km² (Grove *et al.*, 1975), being more extensive than the nearby small Lake Abiyata. The NNE fault trend controlling the morphotectonic structure of the Langano basin is directly related to the evolution of the Gademsa-East Ziway and Ziway-Shala WFB segments (Tiercelin *et al.*, 1997). The northern end of the Lake Langano basin abuts the southern flank of Mt. Alutu, which rises more than 600 m from the surrounding rift floor. This major silicic volcano lies on the rim of the much older and larger Gademotta caldera volcano (Laury & Albritton, 1975; Lloyd, 1977) and relates to the offset between the Gademsa-East Ziway and Ziway-Shala segments of the WFB (Mohr *et al.*, 1980).

Lake Ziway is the most northerly of the lakes in the studied basin and lies at an altitude of 1636 m, thus being also the highest. It is the most extensive of the lakes with a surface area of 434 km² (Grove *et al.*, 1975), and lies in a shallow downfaulted basin. Several islands of varying size rise above lake level. Lake level is maintained by a lava threshold just north of Adamitulu (Street, 1979).

Around the north and west sides of the lake several lacustrine terraces are recognised. Laury & Albritton (1975) have distinguished five terraces in these sides of Lake Ziway. In the same area (NW of Ziway) an outflow channel to the Awash basin has been reported (Grove *et al.*, 1975) and has presumably acted as the means of outflow from the basin during phases of high lake-level.

PRESENT DAY LAKES IN THE AREA

The four separate lakes, nowadays occupying the Galla Lakes basin in present day, lie at altitudes between 1558 (Shala) and 1636 (Ziway) meters above sea level. The three northerly lakes (Ziway, Langano and Abiyata) are rather shallow while Shala is 266 m deep (Grove *et al.*, 1975). Separate from this basin but located in the vicinity is Lake Awassa, which lies south of Lake Shala.

Some basic limnological features of the lakes are given in Tab. 1.

The lakes are alkaline with pH ranging from 8.9 (Ziway) to 9.5 (Abiyata and Shala). Based on the classification of Beadle (1981), Ziway and Langano fall into the freshwater lakes group (K_{20} , 40-6000 $\mu\text{S}/\text{cm}$) whereas Abiyata and Shala are in the saline category (K_{20} > 6000 $\mu\text{S}/\text{cm}$). Alternatively, based on other schemes of classification (e.g. Gasse *et al.*, 1987; Societas Internationalis Limnologiae, 1959; Talling & Talling, 1965) only Lake Ziway has fresh waters while Langano and Awassa are oligohaline with Abiyata and Shala falling in the mesohaline waters group. This latter scheme will be retained as much as possible in this study.

A basic common feature of these and other East African lakes is the dominance of sodium and bicarbonate (and carbonate) ions with $\text{Na} > \text{K} > \text{Ca} > \text{Mg}$. Regards concentrations and ratios of the major ions in lake Ziway sodium makes up 50% of total cations. Abiyata and Shala are typical soda lakes with high concentrations of sodium, bicarbonate and chloride. Although much more diluted, Langano resembles the soda lakes as far as regards the major ionic ratios (Tudorancea *et al.*, 1989; Baumann *et al.*, 1975). The latter interpreted this similarity as evidence of a common underground saline water source.

Mean particle size ranges from coarse and medium sand in the shallows, to fine silt in deeper parts. Hard bottoms have also been encountered (in Langano and Shala). Organic contents of sediments with values between 21.4% (Ziway) and 1.25% (Langano, 6 m in depth) have been reported by Tudorancea *et al.* (1989). High organic content is associated with fine-grained sediments in deeper parts while low values are associated with coarse sediments in the shallow parts.

The thermal regime of the Ethiopian lakes has been described as indicating a polymictic thermal pattern, with complete or incomplete mixing at irregular intervals depending on lake depth and wind conditions (Baxter *et al.*, 1965; Tudorancea *et al.*, 1989).

All major benthic groups, except Bivalvia and Decapoda, are present in the Ethiopian Rift valley lakes (Tudorancea *et al.*, 1989), mainly the chironomids (19 species) followed by nematods (16 species) and ostracods (13 species). The ostracod associations have low species richness and they vary between lakes in species composition and abundance.

Lake Ziway is the most diluted of the rift lakes in Ethiopia. It is a shallow lake with a maximum depth varying between 7 m (Grove *et al.*, 1975; Tudorancea *et al.*, 1989) and 8.95 m (Von Damm & Edmond, 1984), depending on rainfall and season. The water level reflects the balance between rainfall and evaporation, and fluctuates throughout the year and from year to year (Makin *et al.*, 1975). The shoreline of Lake Ziway is fringed by vegetation to significant depths especially in the months of September and October.

Prevailing winds throughout the year in Lake Ziway prevent thermal stratification. The difference between the surface stratum (25 cm deep) and the bottom water temperature is usually less than 1.5°C (Tudorancea *et al.*, 1989).

Lakes	Altitude (masl) *	Surface area (sq.km) *	Maximum depth (m) *	pH **	Conductivity (K_{20} , $\mu\text{S}/\text{cm}$) ***	Salinity *** (g/l)	HCO_3^- ** (meq/l)
Ziway	1636	434	7.0	8.9	322	0.349	3.67
Langano	1582	230	46.2	9.0	1810	1.88	12.55
Abiyata	1580	205	14.2	9.5	15800	16.2	165.06
Shala	1558	409	266	9.5	19200	21.5	209.80
Awassa	1680	129	21.6	9.0	840	1.008	8.22
Abaya	1285	1162	13.1	8.7	623	0.771	7.31
Chamo	1233	551	12.7	9.2	1100	1.099	9.30

* morphometric data from Grove *et al.* (1975)

** pH and HCO_3^- from Tudorancea *et al.* (1989)

*** Conductivity and Salinity values from Wood & Talling (1988)

Tab. 1 - Basic limnological features of some lakes in the Ethiopian Rift.

The diversity of substrates found by the authors cited above was higher in Lake Ziway (and Awassa) compared to the other lakes with five types - coarse sand, medium sand, very fine sand, medium silt and fine silt.

Langano lies at an altitude of 1582 m and has an area of 230 km². It is quite deep with a maximum known depth of 46.2 m (Grove *et al.*, 1975), and it is oligohaline. Lake Langano, although much more diluted, resembles the soda lakes regarding major ionic ratios.

The waters of Langano are turbid due to the mud they receive from the surroundings.

Recent limnological studies on the lakes in the area (Tudorancea *et al.*, 1989) show that the temperature in the strata beyond 1 m depth is relatively uniform showing no deep thermocline. Hard bottom substrates have been reported in addition to coarse sand, coarse silt, and soft fine silt substrates.

Lake Abiyata is at about the same altitude as Lake Langano and has an area of 205 km² and a maximum depth of 14.2 m. It is a typical soda lake with high concentrations of sodium, bicarbonate and chloride.

In Abiyata, three types of soft substrate have been encountered by Tudorancea *et al.* (1989). These are very fine sand, medium silt and fine silt.

Lake Shala is the deepest lake in the Ethiopian Rift (with a maximum depth of 266 m). It has an area of 409 km² and its water is very clear.

Shala is a mesohaline lake. It is also a typical soda lake with high concentrations of sodium, bicarbonate and chloride.

Baumann *et al.* (1975) recorded a mean difference of 5°C between surface and bottom water temperature, and assumed a possible thermocline at a depth of 50-70 m. Tudorancea *et al.* (1989) found that the temperature beyond a depth of one meter was uniform, but did not measure the temperature beyond 15 m depth.

Three types of soft sediment substrates (very fine sand, sand and gravel, and fine silt) and hard bottoms at some stations were reported by Tudorancea *et al.* (1989).

RESEARCH ON FORMER LAKE LEVELS IN THE ZIWAY-SHALA BASIN

Neumann (1902) was the first to recognize the evidence for former higher lake levels in the Ziway-Shala lacustrine Basin. He discovered a 25-30 m thick section of shelly lacustrine deposits along the Bulbula river, which he attributed to 'a great Tertiary or Deluvial lake'. Bacci (1940) later examined a collection of molluscs from this exposure of 'the ancient bed of lake Ziway', and noted the "Palaeartic" affinities of the fauna.

Nilsson (1940) established that all four lakes had once been united to form a fresh water lake, whose

level was controlled by an overflow across the present watershed into the Awash basin. He recognized well developed horizontal beaches in several localities. The most important of these was a terrace about 40 m above Lake Ziway, which he correlated with his "Last Pluvial".

Mohr (1960, 1966) also recognized two groups of rift-floor sediments. He 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 proto-rift trough, fine-grained water-laid tuffs and pumice beds were deposited. According to him, this episode was followed by down-faulting of the rift, volcanism and transverse arching of the rift-floor, creating internal drainage basins.

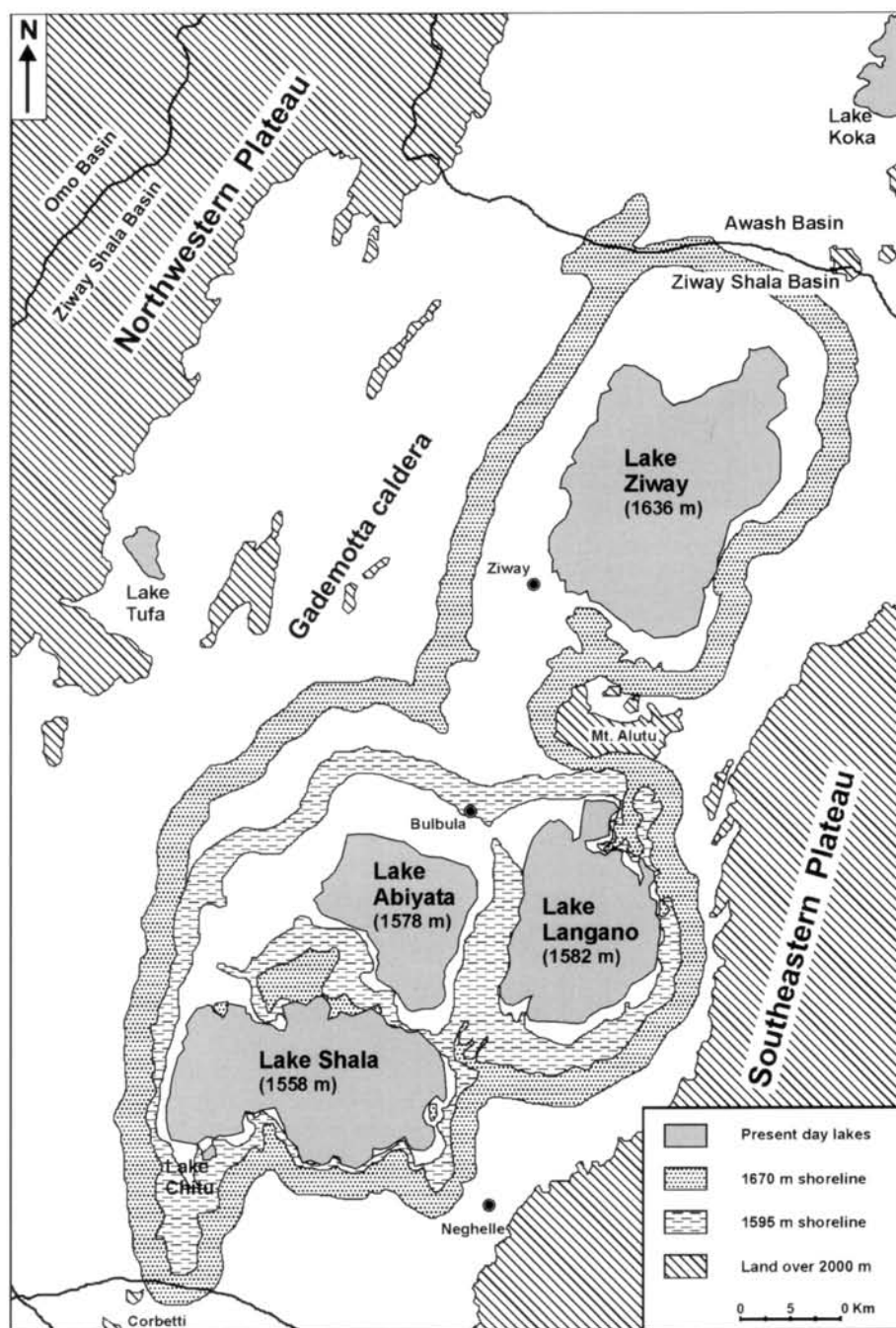
Grove & Goudie (1971) published radiocarbon dates of 9,220±190 BP and 5,610±100 BP on Mollusca from the beaches above Lake Shala. Grove *et al.* (1975) reconstructed the outlines of a Holocene united lake and named it "Pluvial Lake Galla". The same authors reported a date of 14,400±750 BP from a shelly limestone at 1626 m east of Lake Shala. Thus, they provided stratigraphic evidence for the presence of high lake levels during Late Pleistocene time.

A lake highstand during late Middle Pleistocene time was evidenced in the area west of Lake Ziway and the Gademotta Caldera area (Wendorf *et al.* 1975; Laury & Albritton, 1975). A K/Ar date of 0.181±0.006 Ma was obtained from sanidine in a unit which overlies the oldest Middle Stone Age site reported in the area (in a sequence of clastic slope deposits and lahatic mudstones). Another level interpreted as a result of a cut and fill cycle followed by a rise in lake level (Laury & Albritton, 1975) was found just below a tuff that gave an age of 0.149±0.013 Ma.

The work of Laury & Albritton (1975) also provided a map with a series of terraces indicating old lake levels. ¹⁴C dates provided for the area (Haynes & Haas, 1974) ranged from 4800 to 9330 BP. An additional date of 26,780±440 BP was derived from lacustrine sediments at the northern end of the Bulbula plain, confirming the existence of a large freshwater lake during the Late Pleistocene.

Street (1979) made a detailed study of the Late Quaternary history of the lakes in the Ziway-Shala basin. Her work involved the use of geomorphologic, and stratigraphic evidence to make inferences on paleoenvironments, and on the paleohydrology of the area. The results from this study together with other related works (Grove & Goudie, 1971; Grove *et al.*, 1975; Gasse & Street, 1978; Gillespie *et al.*, 1983) has allowed comparisons to be made between other lakes in Africa and hence, to assess the paleoclimatic importance of the records.

Gasse & Street (1978) and Street (1979) recognized that in the upper Late Pleistocene lake-level fluctuations can be interpreted in climatic terms. Four major highstands and six minor ones have occurred



Text-fig. 3 - Extent of Holocene Lakes in the Ziway-Shala Basin (after Gasse & Street 1978, modified).

since about 30,000 BP. These can be grouped into a complex Late Pleistocene lacustrine interval (ca 30,000 to ca 21,000 BP) and a complex Holocene lacustrine interval (ca. 11,500 to 4,800 BP); separated by a prolonged period of aridity. Since 4800 BP, lake levels have remained low and fluctuating, apart from a brief Late Holocene maximum after 2500 BP.

Gasse & Street (1978) have defined the extent reached by the Holocene lakes in the basin and the location of the paleo-overflow channel towards the

Awash basin which was utilised in cases when the lake reached the highest level (Text-fig. 3).

Gillespie *et al.* (1983) working in a section north east of Lake Shala (Ajewa Embayment) also identified repeated lake-level fluctuations and attributed them to repeated climatic fluctuations between humid and arid conditions.

In addition, Street (1979) concludes that the two most prominent shorelines in the Ziway-Shala Basin are situated at 1670 m and 1595-1600 m. The first

corresponds to the Early and Middle Holocene level and the second to a Late Holocene maximum which only united the three southern lakes (Langano, Abiyata, and Shala). The author (op. cit.) asserts that neither shows any significant tectonic or isostatic deformation.

Recently, however, Alessio *et al.* (1996) have made geomorphologic, stratigraphic and sedimentologic studies in fluvio-lacustrine deposits in the same basin and report deformational features within the lacustrine deposits. They conclude that the lacustrine fluctuations are results of an interplay of both climatic and geodynamic controls and caution correlations of dated levels of lacustrine deposits or surfaces with effective lacustrine stillstands.

RESEARCH ON LIVING OSTRACODS FROM ZIWAY-SHALA LAKES

Lowndes (1932) reported a number of Ostracod species in Lake Ziway. These are *Limnocythere michaelsoni*, *Gomphocythere angulata*, *Darwinula stvensoni*, *Oncocypris omercooperi*, *Parastenocypris curviumi*, *Aocypris platybasis*, *Stenocypris minutus*, *Stenocypris curviumi*, and *Stenocypris platybasis*.

Lindroth (1956) found seven ostracod species in the Lake Ziway, and one in Abyata (*Limnocythere michaelsoni*).

More recently, Tudorancea *et al.* (1989) and Martens & Tudorancea (1991) have made a more detailed ecological ostracod study in Lake Ziway. During their survey, they found six species in Lake Ziway: *Limnocythere thomasi thomasi*, *Gomphocythere angulata*, *Darwinula stvensoni*, *Potamocypris mastigophora*, *Hemicypris giesbrechtii* and *Candonopsis* sp.

These authors also noted that *Limnocythere thomasi thomasi* had been previously reported under different names. Lowndes (1932) and Cohen *et al.* (1983) reported it as *Limnocythere michaelsoni* while Carbonel *et al.* (1987) reported it as *Limnocythere africana*.

Martens & Tudorancea (1991) made a quantitative study from seven stations at various depths in the lake. The three most common species/sub-species were *Limnocythere thomasi thomasi*, *Gomphocythere angulata*, and *Darwinula stvensoni*.

Their results show that there were significant drops

in total numbers of specimens in all stations between August and October and in May-June, while there were two significant numerical peaks. The first one occurred in July. The second, larger one, occurred during the main dry season and lasted through the onset of the rainy season, with a maximum in March, after which a sharp decline followed. These population crashes remain as yet unexplained (Martens & Tudorancea, 1991).

The three common species had different habitat preferences (Martens & Tudorancea, 1991). *Darwinula stvensoni* avoids parts of the lake where temperatures rise high and both *G. angulata* and *L. t. thomasi* had a preference for sheltered habitats close to vegetation and/or for a specific grain size of the sediment (300-350 μ m).

The Ostracods in Lake Langano have not been subject to much detailed studies. Tudorancea *et al.* (1989) and Martens (1990b) have reported the presence of *Limnocythere thomasi langanoensis*, *Limnocythere borisi shalaensis*, *Darwinula stvensoni*, and *Hemicypris kliei*. Langano is the only lake in the Ethiopian lakes region where up to now more than one *Limnocythere* species are known to coexist.

Martens (1990b) has reported the presence of *Limnocythere borisi* and *Potamocypris mastigophora* in lake Abiyata based on material collected by Tudorancea *et al.* (1989). Lowndes (1932) has also reported *Limnocythere michaelsoni* in this lake. However, taking into account the remarks made on the reporting of the same species with a different name in Lake Ziway, it can be considered that this name probably refers to the species *Limnocythere borisi* of Martens (1990b).

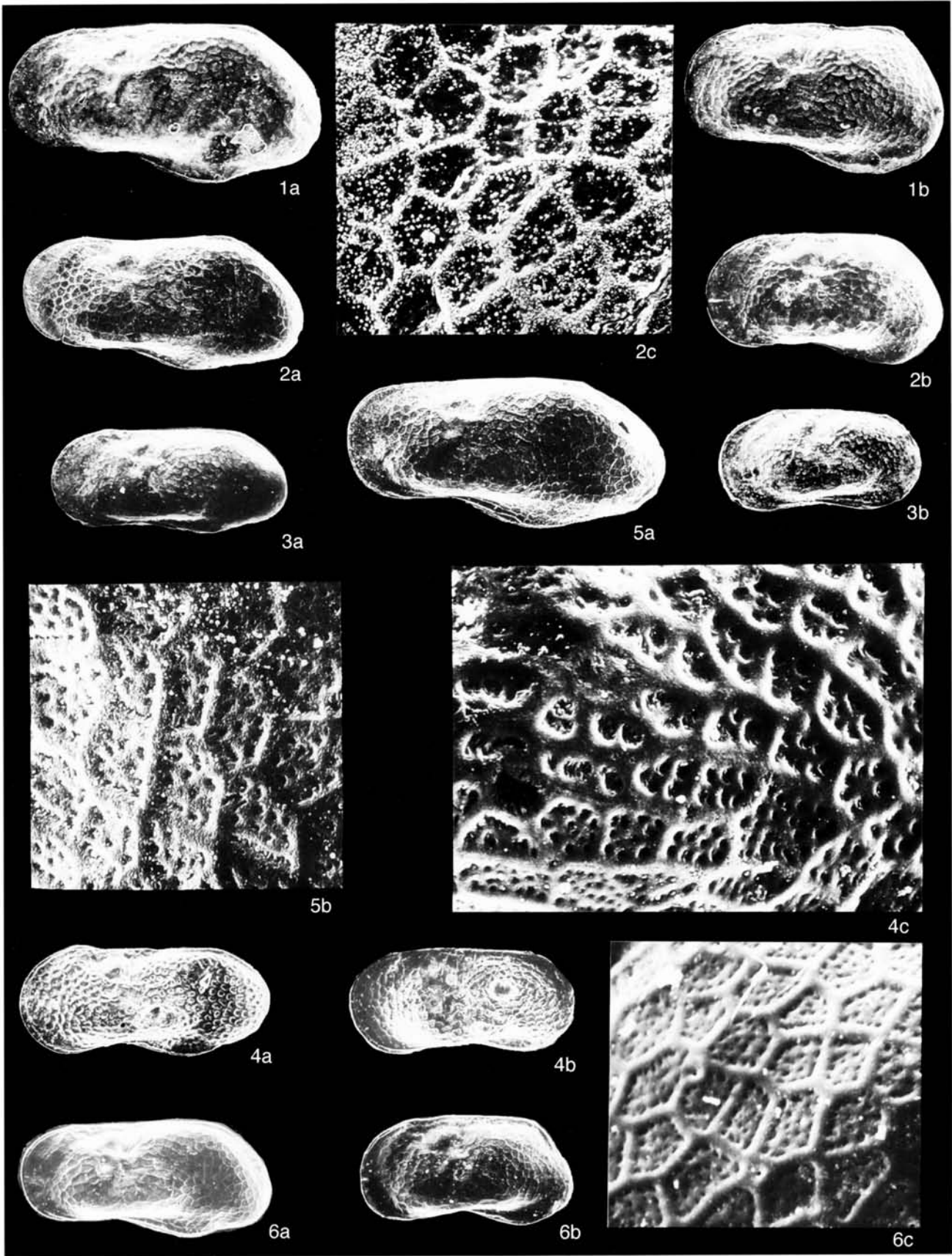
As for Lake Shala, the only Ostracods reported by Martens (1990b) are *Limnocythere borisi shalaensis*, *Gomphocythere angulata*, and *Darwinula stvensoni*. The *Limnocythere* species, however, highly dominates over the very low proportions of the other taxa (Tudorancea *et al.*, 1989).

The ostracod species reported (Kibret & Harrison, 1989; Martens, 1990b) from the Awassa lake are: *Limnocythere borisi awassaensis*, *Gomphocythere angulata*, *Darwinula stvensoni*, *Potamocypris mastigophora*, and *Parastenocypris acocyproides*.

In addition to this, evolutionary aspects of African

EXPLANATION OF PLATE 1

- Figs 1a-b - *Limnocythere borisi borisi* Martens, 1990. a) Left valve, normal view, male, x 85; b) Left valve, normal view, female, x 85.
 Figs 2a-c - *Limnocythere borisi shalensis* Martens, 1990. a) Left valve, normal view, male, x 85; b) Left valve, normal view, female, x 85; c) Left valve, ornamentation, male, x 680.
 Figs 3a-b - *Limnocythere borisi awassaensis* Martens, 1990. a) Left valve, normal view, male, x 85; b) Left valve, normal view, female, x 85.
 Figs 4a-c - *Limnocythere thomasi thomasi* Martens, 1990. a) Left valve, normal view, male, x 85; b) Left valve, normal view, female, x 85; c) Left valve, ornamentation, female, x 680.
 Figs 5a-b - *Limnocythere minor* Lindroth, 1953. a) Left valve, normal view, male, x 85; b) Left valve, ornamentation, male, x 680.
 Figs 6a-c - *Limnocythere* aff. *tudoranceai* Martens, 1990. a) Left valve, normal view, male, x 85; b) Left valve, normal view, female, x 85; c) Left valve, ornamentation, x 710.



Limnocythere s.s. have been discussed (Martens, 1990a, b, 1994) with particular attention to the distribution of the different species.

RESEARCH ON FOSSIL OSTRACODS FROM THE EAST AFRICAN RIFT

The study of fossil ostracods for different aspects of paleoenvironmental interpretations in East Africa dates back to the works of Carbonel & Peypouquet (1979) and Peypouquet *et al.* (1979). These researchers attempted ostracod-based paleochemical interpretations of the Omo-basin (Southern Ethiopia) for the Pliocene-Pleistocene. Work continued to be published by the French group on ostracods from eastern Africa. Peypouquet *et al.* (1983) published on ostracods from the Hadar Formation in the Afar depression of north-eastern Ethiopia and made use of the ostracod micro-fauna in understanding the evolution of the paleohydrological environments in the region.

Carbonel *et al.* (1983, 1987) studied a 30,000 year record from the Baringo-Bogoria half-Graben of the Gregory Rift in Kenya. Ostracod ornamentation changes, reticulation and nodding in particular, were used in making paleoenvironmental interpretations for the record studied. The "agradation-degradation" phenomenon defined by Peypouquet *et al.* (1980) has been continuously applied in these types of interpretations.

Moreover, Carbonel & Peypouquet (1983) outlined a methodology for using ostracods as indicators of ionic concentrations and dynamic variations in lacustrine environments. Here again, in addition to the principle of indicator groups, the relative abundance of reticulated forms and nodding occupy a major part of the outline, demonstrated by taking Lake Bogoria as an example.

More recently, studies based on similar principles that concentrate on morphological variability of valves are also being made in South American lakes (Mourguiart *et al.*, 1986; Mourguiart, 1987; Carbonel *et al.*, 1990).

Late Quaternary continental ostracods of the East African Rift Valley lakes have been studied by Cohen (1982) to assess the paleoecological uses of this group. His extensive study involved the collection of data regarding the ecological tolerance of many ostracod species and genera, particularly to hydrochemical parameters. These data, together with previously reported occurrences, were then used for purposes of paleoecological interpretations. Based on data from this study Cohen *et al.* (1983) published their work on paleochemical interpretations based on eastern and southern African ostracods. In that work a fossil-typological approach was utilised, where a series of fossil assemblages was used to indicate a particular overlapping range of ecological tolerances to a given ionic parameter. Thus, they defined four ostracod range

assemblages, based upon increasing alkalinity and salinity. These are:

Range I, the *Stenocypris* assemblage ($K_{20} < 500 \mu\text{mho}$)

Range II, the *Mecynocypris* assemblage ($K_{20} = 500-1500 \mu\text{mho}$)

Range III, the *Gomphocythere* assemblage ($K_{20} = 1500-4000 \mu\text{mho}$)

Range IV, the *Limnocythere* assemblage ($K_{20} > 4000 \mu\text{mho}$)

The application of the ostracod-typology to the fossil record in a core from lake Nakuru, suggested a fluctuation of alkaline and fresh water conditions in the lake during the Late Quaternary.

An independent interpretation based on diatoms showed agreement in most cases.

A similar approach was applied to Late Quaternary ostracod fossils from a radiocarbon-dated core from Lake Elementia, a small rift-valley lake of central Kenya by Cohen & Nielson (1986).

More recently, Martens (1990a, b, 1993) studied the recent ostracod fauna of the Ethiopian Rift Valley Lakes (mainly the lakes of the Ziway-Shala and Awassa basins). The *Limnocythere* genus was the most widespread and therefore most of our attention focused on this group. However, for Lake Ziway a detailed ecological study including *Gomphocythere angulata* and *Darwinula stvensoni* as distinct from the *Limnocythere* (sub)species was made (Martens, 1993).

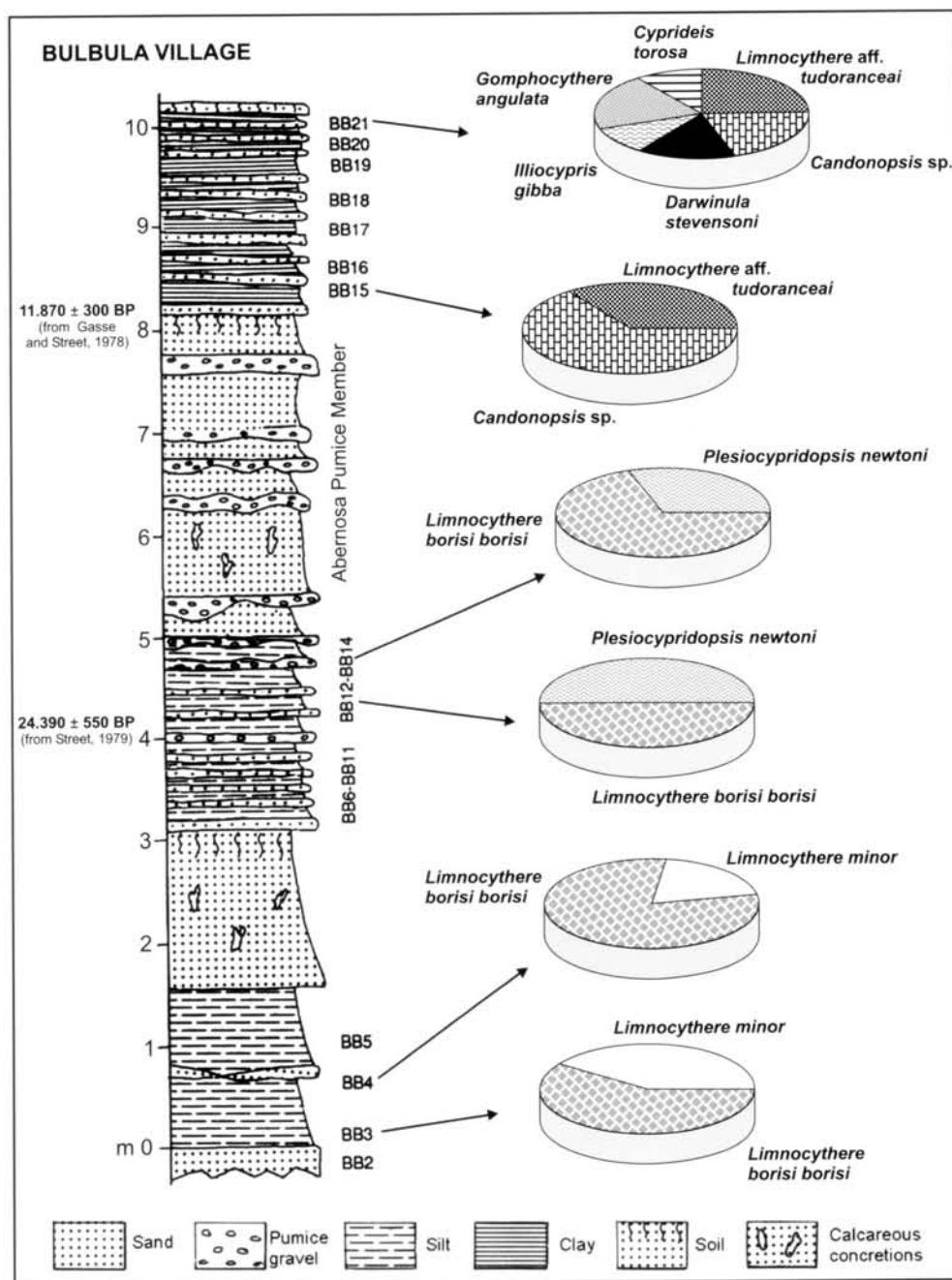
Martens (1990b) discusses also the hitherto unresolved problem of speciation timing of the *Limnocythere* (sub)species living in the present Lakes Ziway, Langano, Abiyata, Shala, and Awassa. Although he put forward a hypothesis correlating the origin of the species with the regression of the four Galla Lakes (4000-5000 BP) he has also pointed out the arguments for and against his hypothesis.

Finally, more recently Park *et al.* (2003) published a basic work to describe the use of non-marine ostracodes as proxy indicators for the biotic response to climate as well as anthropogenic changes in lakes.

LATE QUATERNARY SEDIMENTS

Recent works (Sagri, 1995; Alessio *et al.*, 1996) of the Ziway-Shala Basin sediments have provided a schematic geologic map of the area showing the main sedimentary units of the Late Quaternary continental succession (Text-fig. 2). In this map, the different sedimentary units are differentiated according both to their age and geographic distribution and to the facies changes that they show in the field. A major subdivision is made between the Late Pleistocene Megalake deposits and the mainly Early-Middle Holocene macrolake deposits. Furthermore, the Late Holocene facies around lake Ziway are differentiated from the contemporary facies produced by the Abiyata-Langano-Shala macrolake deposits.

Brief descriptions of measured section of the Bul-



Text-fig. 4 - Ostracod distribution in the Bulbula village section.

bula (Text-figs 4-5) and Ajewa (Text-figs 7-17) formations and one drilled core from Lake Langanu will be provided in the following part.

THE BULBULA VILLAGE SECTION (TEXT-FIG. 2, NO. 3)

Twenty samples (labelled BB2-BB21) have been collected from the base to the top of the Bulbula Village Section. The thickness (more than 10 m), lithology, and distribution of the ostracofauna is shown in Text-fig. 4.

Three main phases of lacustrine deposition are distinguished from the ostracofaunal distribution.

The oldest phase is represented by samples BB2-BB4, and the ostracod assemblage is exclusively made up of the genus *Limnocythere*. Of the species present, *L. borisi borisi* and *L. minor* are recognizable.

This assemblage is suggestive of elevated salinities and alkalinities (mesohaline waters, > 30 meq/l alkalinity). Such an inference is not a mere result of previous assertions that a *Limnocythere* assemblage is indicative of such waters (Cohen *et al.*, 1983). It acquires

strength from the fact that *L. borisi borisi* is encountered in significant amounts in these sediments (about 60% in BB3 sample and 80% in BB4 sample), while *L. minor* is present with 40% in BB3 sample and with 20% in BB4. This species is presently living in the mesohaline and alkaline waters of Lake Abiyata (Martens, 1990).

The second phase (BB6-BB14), ^{14}C dating around 24,000 BP (sample BB12), consists of *Plesiocypridopsis newtoni* (50% in the sample BB12 and 30% in sample BB14) in addition to species of *Limnocythere borisi borisi* (50% in the sample BB12 and 70% in the sample BB14). Within this phase, a general trend of vertical decrease in proportion of *P. newtoni* is observed, especially in the upper half of the sediment interval representing this phase.

The presence of *Plesiocypridopsis newtoni* in considerable amounts is indicative of the agitated and unsheltered nature of the lake environment. In terms of salinity, although conclusive data are lacking, lower salinities and alkalinities than the previous phase are inferred. In most cases, oligohaline waters would have been represented.

The third phase (BB15-BB21) is Early Holocene in age and is represented by an assemblage of diversified ostracofauna at the top of the section, above the pumice deposits known as Abernosa Pumices Member. In Deke Wede valley, it terminates with paleosoil ^{14}C dating 11,870 $\pm$ 300 BP (Gasse & Street, 1978). Species present (BB18-BB21) are *Darwinula stevensoni*, *Cyprideis torosa*, *Gomphocythere angulata*, *Limnocythere* aff. *tudoranceai*, *Candonopsis* sp. and *Ilyocypris gibba*. The lowermost beds of this phase (BB15-BB16) consist of mainly *Limnocythere* aff. *tudoranceai* and *Candonopsis* sp. Above these (BB17-BB21) the diversity increases with the other mentioned species being encountered.

The assemblage is of a low salinity lake environment, with essentially calm (sheltered) waters. The noded *C. torosa* and the significant presence of *D. stevensoni* support this interpretation, in addition to the high relative diversity of the assemblage. The importance of the lake margin vegetation zone is marked by the presence of *Candonopsis* sp.

THE ATI DAMO SECTION (KURKURA AREA) (TEXT-FIG. 2, NO. 4)

A more than 25 m thickness of exposed section along the Bulbula River occurs about 3 km NE of Bulbula village. The exposure is located where a number of cattle tracks meet nearby the Bulbula River. The river is at an elevation of 1590 m a.s.l. at this locality. The thickness, lithology and distribution of the ostracofauna is shown in Text-fig 5.

As concerning the dating of this section, a Late Pleistocene age can probably be inferred indirectly from the field relationship, in that the position of the described sediments is below a thick and somewhat re-

worked pumice unit, correlable to the "Abernosa Pumice Member" (Street, 1979). This age is confirmed also by a ^{14}C date of 11,870 $\pm$ 300 BP on paleosoil at the top of the pumice beds in the Deke Wede Valley (Gasse & Street, 1978).

Twenty-nine samples (AD1-AD29) have been collected from the Ati Damo Section. Two diatomite intervals, corresponding to samples AD12-AD14 and AD21-AD23 respectively, have been resulted barren in ostracods.

A remarkable dominance of *Limnocythere* species is observed from ostracofaunal analysis. Despite the generally monotonous succession of *Limnocythere* dominated assemblages, however, certain subdivisions of the section with significant environmental implications can be made.

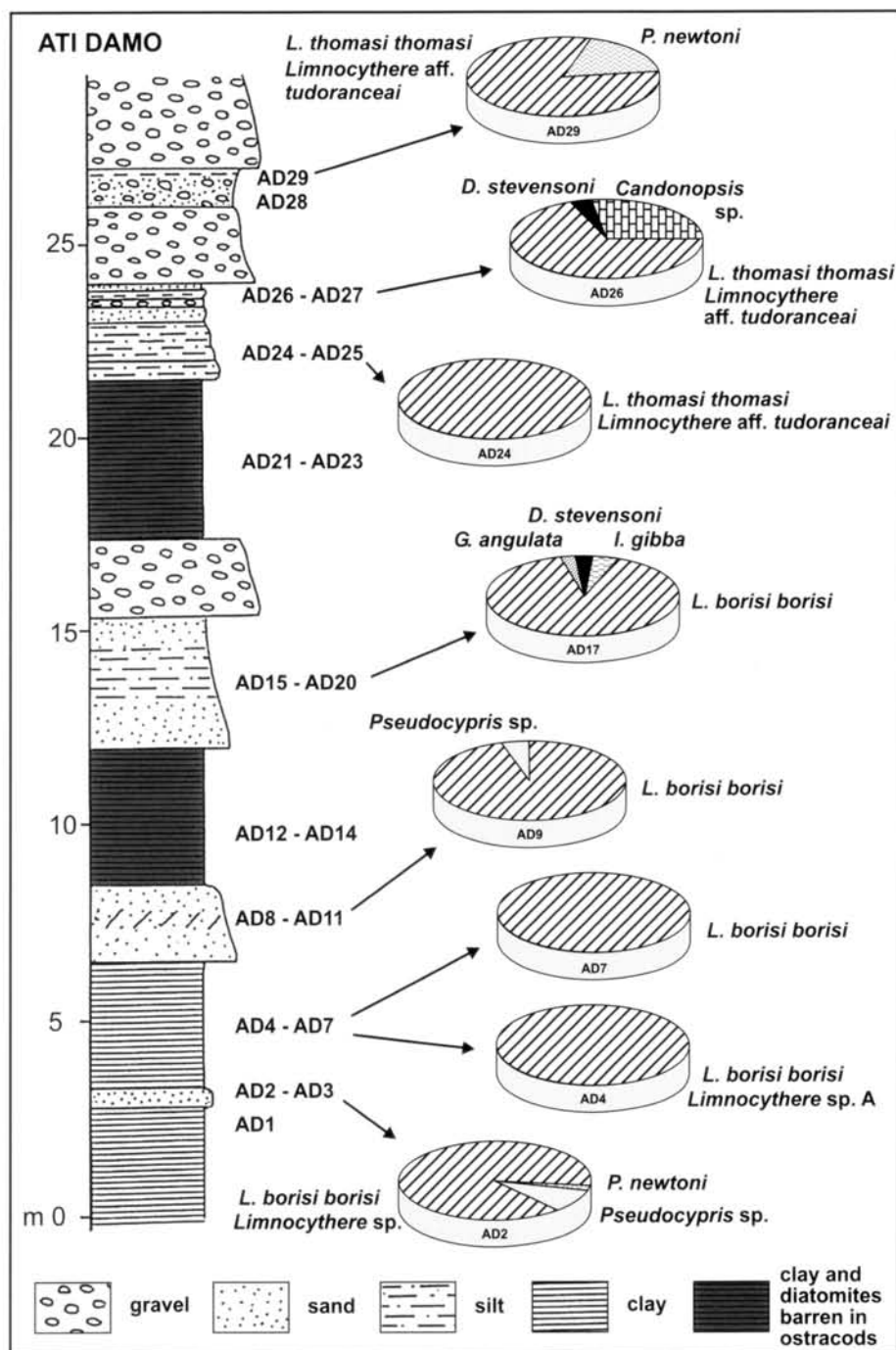
The base of the section (AD1-AD3) consists of *Pseudocypris* sp. and *Plesiocypridopsis newtoni* in addition to the dominating *Limnocythere borisi borisi*. The lowermost sample AD1 differs from the others in that it is not as rich in ostracods as the overlying two samples.

The agitated nature of the environment is indicated by the presence of *Plesiocypridopsis newtoni*. This species indicates probable fresh or slightly brackish water environments. The characteristic element of the zone is *Pseudocypris* sp. Although sure results have not yet been provided, Cohen *et al.* (1983) have pointed out the need for further studies on this genus as a potential for low salinity and alkalinity conditions.

In the following part of the section (AD4-AD11) *Limnocythere* species are the almost exclusive components of the assemblage. *Limnocythere borisi borisi* is identified while it is not at present clear whether the other forms are morphological varieties of described *Limnocythere* species or probable new ones. One form (*Limnocythere* sp. A) has a significantly different outline, and has been described under open nomenclature. One sample that seems slightly out of the norm of the ecozone is sample AD9, and it consists of small amounts of *Pseudocypris* sp. in addition to the still dominant *Limnocythere borisi borisi*.

An environmental assessment based on the present ecological knowledge, suggests a mesohaline and alkaline lake environment for this interval of lake sediments. This can be inferred from the fact that *Limnocythere* species are the sole components of the assemblage and that *L. borisi borisi* at present lives in relatively saline and alkaline Lake Abiyata of the Ziway-Shala basin.

The interval of section between 12 m and 15 m represents another ecozone. The samples are far from uniform with alternations between samples which are very rich (>1000 valves/gram) in ostracod valves (AD16, AD18 and AD20) and others poor (<50 valves/gram) to moderate (few hundred valves/gram) in valve abundance (AD15, AD17, and AD19). The samples rich in ostracods are composed exclusively of *Limnocythere* spp., like the previous ecozone. In the



Text-fig. 5 - Representative ostracod assemblages from the Ati Damo section (Kurkura area).

other samples, additional species found are *Gomphocythere angulata*, *Darwinula stevensoni*, and *Ilyocypris gibba*.

A fluctuating lake environment with corresponding fluctuations in salinity and alkalinity is inferred for this interval.

Following this, until about 22 m, the diatomite samples (AD21-AD23) are barren in ostracods. The other assemblages above are non-uniform with three

different levels found to contain ostracods (AD24, AD26, and AD29) giving diverse assemblages which also differ from the previously described assemblages.

AD24 is moderately rich in ostracods and consists of *Limnocythere thomasi thomasi* and *L. aff. tudoranceai* only. AD26 is again moderately rich but is composed of *Limnocythere thomasi thomasi* and *L. aff. tudoranceai*, *Candonopsis* sp. and *Darwinula stevensoni*.

Finally, AD29 from the topmost lacustrine beds is

rich in ostracods and consists of mainly *Limnocythere thomasi thomasi* and *L. aff. tudoranceai* species (including *Limnocythere* sp. B) and a significant amount of *Plesiocypridopsis newtoni*.

All three samples represent the lowering of the lake level after the phase of deep lake deposition represented by the diatomites barren in ostracods. A *Candonopsis* sp. is reported (Martens, 1990b; Martens & Tudorancea, 1991) from Lake Ziway as occupying the vegetated zone at the lake margin. According to Carbonel *et al.* (1987), the presence of a species of *Candonopsis* is related to the existence of a vegetation zone around the lake. Salinity probably fluctuated in the low-moderate salinity and alkalinity area. The presence of *Plesiocypridopsis newtoni* witnesses a change of energy in the physical environment in the latest stages (i.e. the topmost beds). This species is indicative of agitated waters and points to the change from vegetated calm waters (in AD26) to the agitated shallow lake waters (AD29) in a later stage of the general lowering of lake level that followed the deep water diatomites barren in ostracods in the Ati Damo Section.

The Kurkura area is known for its thick diatomitic deposits. In addition to the area studied in this work, more to the north west at about 6 km from the Bulbula village, a diatomitic section more than 50 m thick has been described (Street, 1979).

The Ati Damo section, although not as thick as the previously mentioned section, clearly shows two important phases of lacustrine deposition in the Late Pleistocene. A 2 m sandy and gravelly fluvial unit represents the complete regression between the two phases. The two lacustrine phases are named Phase I (from AD1 to AD20) and Phase II (from AD21 to AD29) in order to simplify our discussion of environmental conditions in the Ati Damo section.

The stage before the initiation of Lacustrine Phase I is represented by the palustrine sediments and the overlying thin sand beds at the bottom of the section. The ostracod assemblages in this interval are also distinct, in that they contain *Pseudocypris* sp., and *Plesiocypridopsis newtoni* in addition to *Limnocythere*, which is common throughout the section.

With the start of the open lake conditions of phase I, marked by the diatom rich, clayey sediments, the ostracod assemblage also gives way to a rich assemblage of *Limnocythere* spp. Although the ecological preferences of most of the *Limnocythere* forms encountered are at present unknown, due to the presence of *L. borisi borisi* an alkaline and saline environment is suggested for the lacustrine conditions that produced the sediments in this ecozone. As evidenced by the sand rich interval in between, a shallowing of the lake occurred, but without any evident change in assemblage and thus by inference without any significant salinity change.

In the studied section, the end of the lacustrine Phase I is marked first by a fluctuating regression. An alternation of the ostracod assemblages is evident with

euryhaline species such as *Ilyocypris gibba* being encountered. Complete regression is marked by the previously mentioned fluvial unit consisting of reworked volcaniclastic material.

The abrupt appearance of the diatomites above the fluvial unit marks the second open lake water phase of the Ati Damo section. Despite the lack of ostracods, some information can be given for environmental conditions characterizing this phase from diatom studies made on the same (or very similar) section in Kurkura area by Gasse (Gasse & Street, 1978; Street, 1979). According to her data, this highstand made up of non-calcareous diatomites, represents a deep lake with tropical flora.

The final regression of the lake after phase II also proceeded in a fluctuating manner, in that beds containing ostracods alternated with more abundant levels where ostracods were lacking. This indicates that the lake receded and returned a number of times before finally giving way to the extensive pumice beds that top the section.

The *Limnocythere* species of Phase I (i.e. *L. borisi borisi*) generally have a smooth or light reticulate carapace, while the *Limnocythere* species of Phase II (i.e. *L. thomasi thomasi* and *L. aff. tudoranceai*) have heavy reticulate carapaces. Besides being related to salinity (and therefore to climate), this change of *Limnocythere* species (smooth or light reticulation versus heavy reticulation) could also be related to geochemical variations at the water-sediment interface modifying the carbonate equilibria caused by volcanic activity, which was very intense during the latest Pleistocene (Benvenuti *et al.*, 2002).

THE AJEWA FORMATION AND THE AJEWA EMBAYMENT (TEXT-FIG. 2, NO. 1)

The gully exposures in the Ajewa Embayment, on the north-east coast of Lake Shala, have been subject to a number of geomorphologic, stratigraphic and sedimentologic studies starting from the 1970's (Grove *et al.*, 1975; Street, 1979; Gillespie *et al.*, 1983) and still attract the attention of Quaternary researchers (Alessio *et al.*, 1996; Sagri, 1995, 1996, 1997). This interest is mainly due to the fact that a number of datable stratigraphic sections are preserved at different elevations along the inner wall of the O'a caldera that hosts the present day Lake Shala. The deformation, resulting from volcanic and tectonic events that have characterized the recent evolution of the caldera hosting lake Shala, has produced minor depositional basins within the Ajewa embayment (Alessio *et al.*, 1996).

Lateral stratigraphic relationships among the fluvio-lacustrine deposits of the separate sections exposed are quite complex (Street, 1979). However, thanks to the considerable number of ^{14}C dates available from the previously mentioned works in the area, quite a detailed picture of lake level fluctuations, especially in the Holocene, can be outlined.

After a detailed geological survey, Alessio *et al.* (1996) recognized a number of stratigraphic units in the Late Quaternary fluvio-lacustrine succession exposed in the area of Ajewa (Text-fig. 6). Each unit registers one or more phases of lake-level fluctuations evidenced by the sedimentary bodies formed in the depositional systems. They vary from fluvio-deltaic (sands and gravels with plane cross-bedding), to marginal lacustrine deposits (beach sands, palustrine organic muds) and deep lacustrine facies (muds, diatomites, and minor resedimented sands). Erosive surfaces and surfaces of lacustrine transgression signal regressive and transgressive events respectively.

The present study regards the ostracofauna from this embayment, which were mainly from the dated sections of Alessio *et al.* (1996), starting from the oldest to the youngest in age. Text-fig. 6 shows the location of the studied sections (Text-figs 7-13)

Some late Pleistocene deposits are lithologically dominated by diatomites barren in ostracods.

Section Ajewa 8

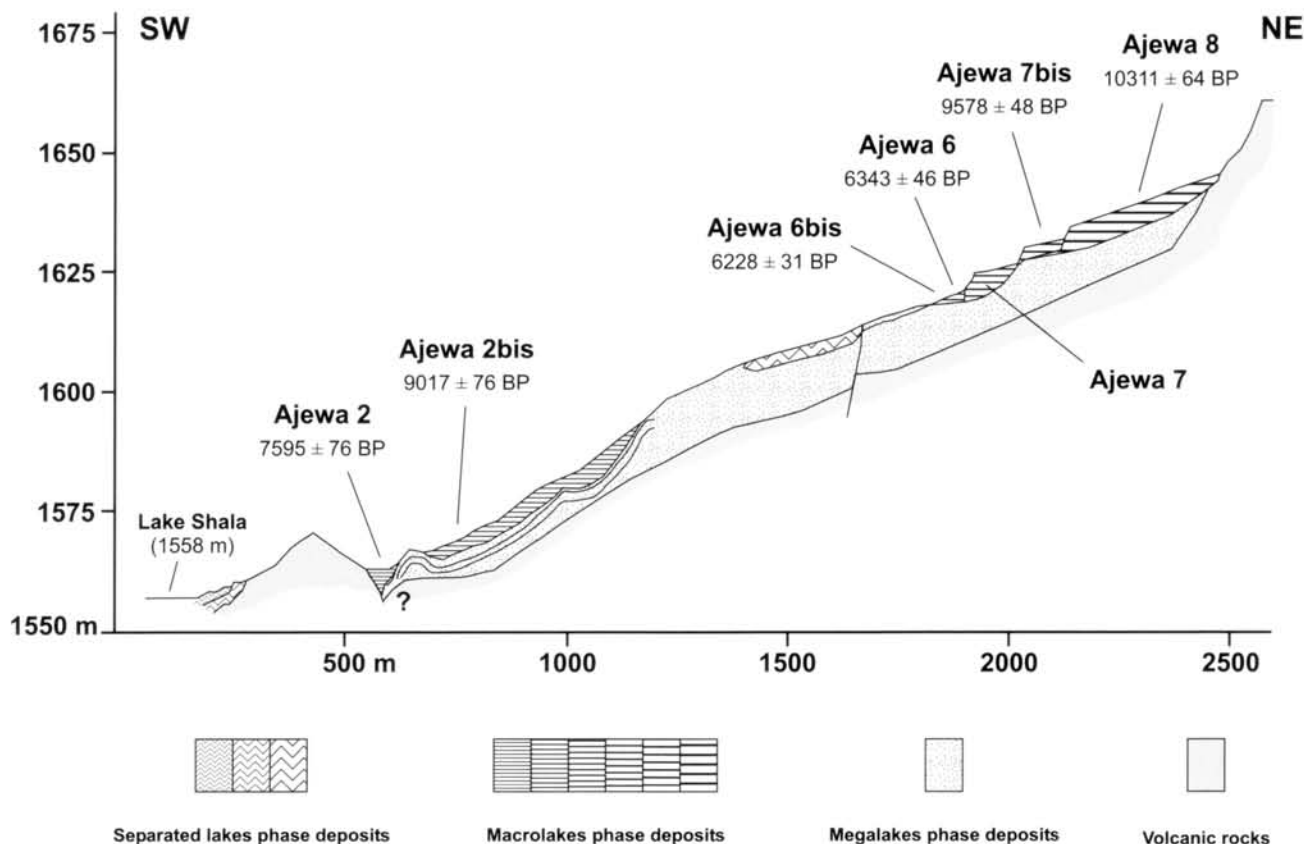
This section presents one of the most upstream

parts of the Ajewa gully. The section was measured at an elevation of around 1640 m a.s.l., although, as can be seen in the schematic geologic section of the gully (Text-fig. 6) the unit continues up to an elevation of 1650 m. The stratigraphic section (Text-fig. 7) is relatively thick (more than 6 m). A thin sand layer (Ajewa 8.2) has provided a ^{14}C age of $10,311 \pm 64$ BP.

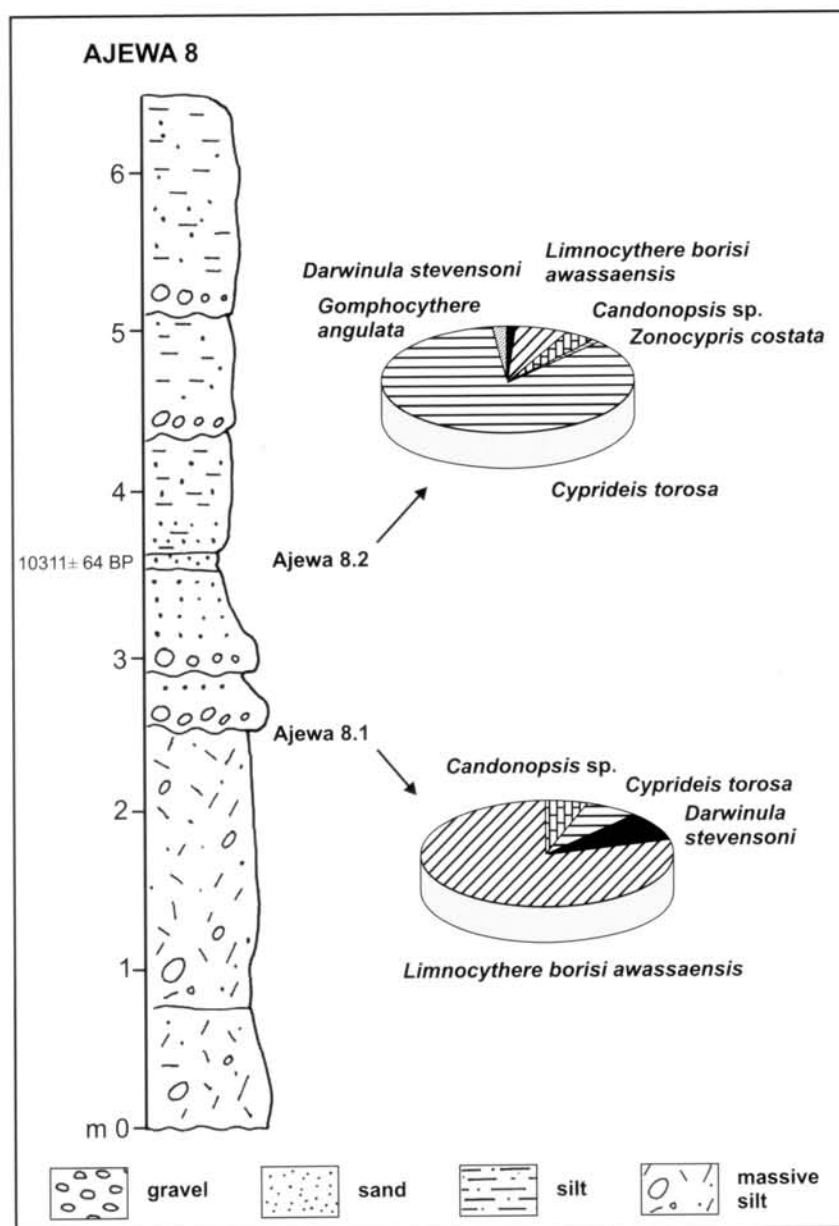
The sands containing the mollusc shells (Ajewa 8.2) are dominated by noded *Cyprideis torosa* (85%). The other component taxa are small numbers of *Limnocythere borisi awassaensis*, *G. angulata* and very small numbers of *Candonopsis* sp., *D. stevensoni*, and *Zonocypris costata*. The latter three together, account for less than 3% of the total encountered valves.

The noded *C. torosa* assemblage in the Ajewa 8.2 sands, as has been previously mentioned for similar assemblages is indicative of oligohaline lake waters. These are, therefore, the inferred hydrochemical conditions of the lake environment before 10.3 ka.

The silts in the lower parts of the section (Ajewa 8.1) are dominated by *Limnocythere borisi awassaensis* (79%). Other component species of this assemblage are *G. angulata*, *C. torosa* and *Candonopsis* sp. The assemblage from the dated sand level as seen from the



Text-fig. 6 - Schematic geological section of the Ajewa Gully (modified from Alessio *et al.*, 1996), showing the different C^{14} dating sections studied in the present work.



Text-fig. 7 - Section Ajewa 8 with representative pie charts of ostracod assemblages.

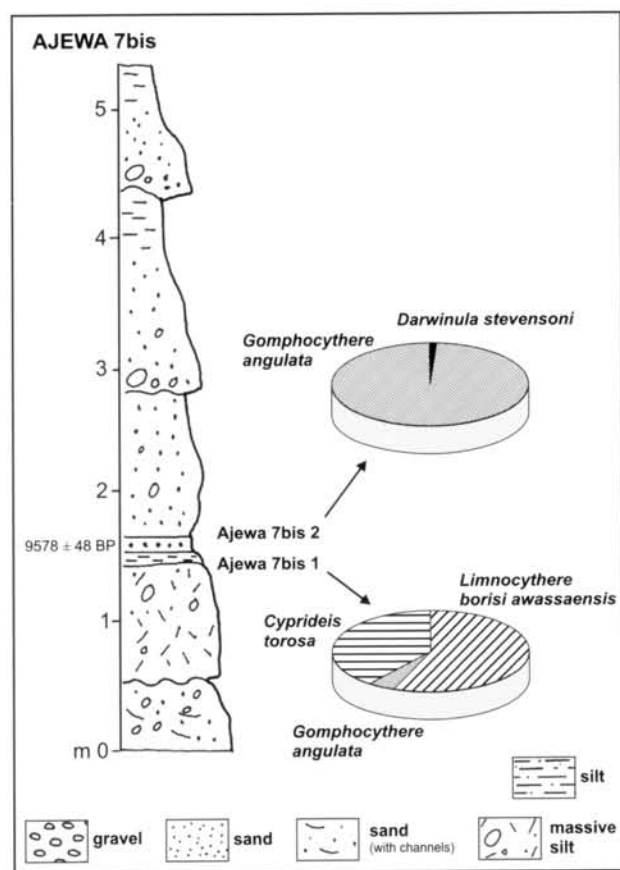
descriptions above is quite different from this older sample (Ajewa 8.1). In this case the assemblage is a *Limnocythere* dominated assemblage, but the species

present was surprisingly found to be *L. b. awassaensis* which is at present found living in the oligohaline lake Awassa. Thus, although we are dealing with an

EXPLANATION OF PLATE 2

- Figs 1a-b - *Gomphocythere angulata* Lowndes, 1932. a) Right valve, normal view, female, x 85; b) Left valve, normal view, female, x 85.
 Figs 2a-b - *Candonopsis* sp. a) Left valve, normal view, x 85; b) Right valve, normal view, x 85.
 Figs 3a-b - *Zonocypris costata* (Navra, 1897). a) Right valve, normal view, x 85; b) Left valve, normal view, x 85.
 Figs 4a-b - *Heterocypris* sp. a) Right valve, normal view, x 85; b) Left valve, normal view, x 85.
 Figs 5a-b - *Plesiocypridopsis newtoni* (Brady & Robertson, 1870). a) Right valve, normal view, x 85; b) Left valve, normal view, x 85.
 Figs 6a-b - *Cyprideis torosa* (Jones, 1850). a) Left valve, normal view, male x 85; b) Right valve, normal view, x 85.
 Fig. 7 - *Darwinula stevensoni* (Brady & Robertson, 1870). Left valve, normal view, x 85.
 Fig. 8 - *Ilyocypris gibba* (Ramdohr, 1808). Left valve, normal view, x 85.





Text-fig. 8 - Section Ajewa 7bis with representative pie charts of ostracod assemblages.

assemblage dominated by *Limnocythere* in this case the particular species of this genus present together with the other more diluted water species leads us to infer an environment of an oligohaline nature.

Section Ajewa 7bis

This section is exposed at about 1630 m (Text-fig. 6); its thickness is less than 5 m (Text-fig. 8) and a fossiliferous sand unit has provided a ^{14}C age of 9578 ± 48 BP.

The two samples taken from the lacustrine levels were both rich in ostracod valves although the assemblage in the two cases was a bit different. The laminated clayey silts (Ajewa 7bis1) have *Limnocythere borisi awassaensis* (56%) and *Cyprideis torosa* (39%) as their two most important components. However, *G. angulata* and a very small proportion of *Candonopsis* sp. are also present. The *C. torosa* valves encountered are all of the noded variety.

The presence of significant numbers of noded *Cyprideis torosa* in this assemblage is indicative of an oligohaline lake environment.

The shell containing sand beds (Ajewa 7bis2) from

which the date 9578 ± 48 BP was derived, contains an assemblage almost entirely consisting of noded *Cyprideis torosa* (99%). The remaining portion is made up of *G. angulata* and *D. stevensoni*.

Again, this assemblage confirms the idea that the lake waters were of an oligohaline nature with the noded *C. torosa* being the dominating indicative element of the assemblage.

Section Ajewa 2bis

The section is about 6 m in thickness (Text-fig. 9), and lies at an elevation of 1570 m (Text-fig. 6). A thin peaty clay bed (10 cm) has given an age of 9017 ± 145 BP.

In this section, the massive silts at the base (Ajewa 2bis1) below the peat layer and the peat layer itself (Ajewa 2bis2) are barren in ostracods.

On the contrary, the silt unit above the peaty layer, represented by samples Ajewa 2bis3 and Ajewa 2bis4, is very rich in ostracods. The former sample is almost totally composed of *Limnocythere borisi awassaensis* valves with a very scarce 1% of *Cyprideis torosa*. Ajewa 2bis4 is also characterized by the predominance of *Limnocythere*. However, in this case the presence of *Candonopsis* sp. is significant (13%).

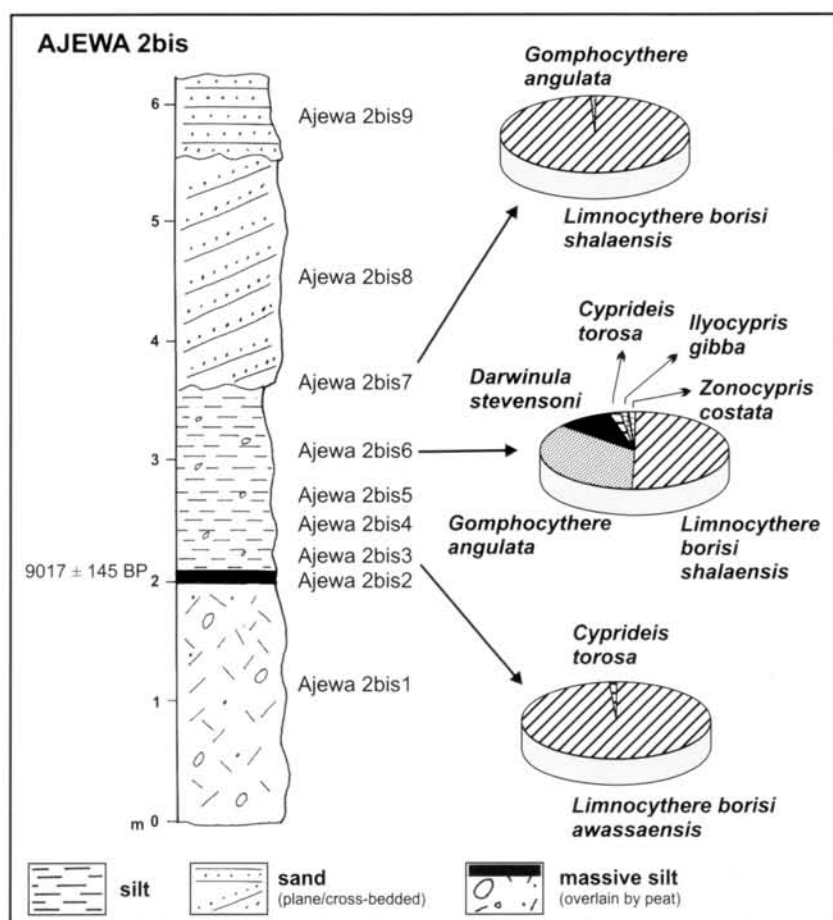
The overlying silty clays are ostracod poor in the lower part. Sample Ajewa 2bis5 from this part contained a small number of valves of *D. stevensoni* and *G. angulata*, and an even smaller amount of *Limnocythere* and *Candonopsis* sp. The upper parts of the same silty clays (Ajewa 2bis6) instead have a very high concentration of ostracods. In addition to the large number of valves present in the sample, the species diversity was also relatively high. The dominant taxon is *Limnocythere borisi shalaensis*. Its dominance, however, is not as significant as other common *Limnocythere* assemblages - it accounts for 51% of the ostracofauna in this case. Other species of the assemblage are *Gomphocythere angulata* (36%), *Darwinula stevensoni* (8%), noded *Cyprideis torosa* (3%), *Candonopsis* sp. (2%) and *Zonocypris costata* (<1%).

The overlying sands are on the whole poor in ostracods (Ajewa 2bis8 and Ajewa 2bis9) except for the lowermost sands of the unit overlying the silts of the previous unit (Ajewa 2bis7) which contain an abundant valve concentration with >99% *Limnocythere borisi shalaensis* and <1% *Gomphocythere angulata*.

The notable dominance of *Limnocythere* in the majority of the samples indicates the saline and alkaline conditions of the lake water during this period. The only sample (Ajewa 2bis6) where a more or less diversified fauna was noted would indicate slight dilution, which however did not involve a drastic and long-lived shift towards low salinity waters.

Section Ajewa 7

The section is about 7 m thick (Text-fig. 10) and



Text-fig. 9 - Section Ajewa 2bis with representative pie charts of ostracod assemblages.

lies at an elevation of about 1620 m (Text-fig. 6). Some ^{14}C dates are available for this section, but these are based on the stratigraphic and sedimentologic studies by Sagri (1995) and Alessio *et al.* (1996).

According to one of the hypotheses put forward by Alessio *et al.* (1996), a lake-level drop due to climatic reasons is recorded around 9 ka. This hypothesis is also supported by the results of the present study in that the ostracod assemblages from the section dated by Alessio *et al.* (1996) are indicative of mesohaline waters. These authors also affirm that the succeeding rise of lake-level would have occurred around 8,000 yrs BP. It is highly likely that the upper part of Section Ajewa 7 represents this rise (Marco Benvenuti, pers. comm.).

At least three assemblages can be distinguished within this measured section. The first four samples from the base (Ajewa 7.1 - Ajewa 7.4) are all rich in ostracods and consist of *Limnocythere borisi borisi* and *Plesiocypridopsis newtoni*. In all four cases *Limnocythere borisi borisi* dominates with *P. newtoni* forming proportions that range from 8% (Ajewa 7.4) to 31% (Ajewa 7.1).

The physical environment indicated by this assemblage is a high energy agitated waters.

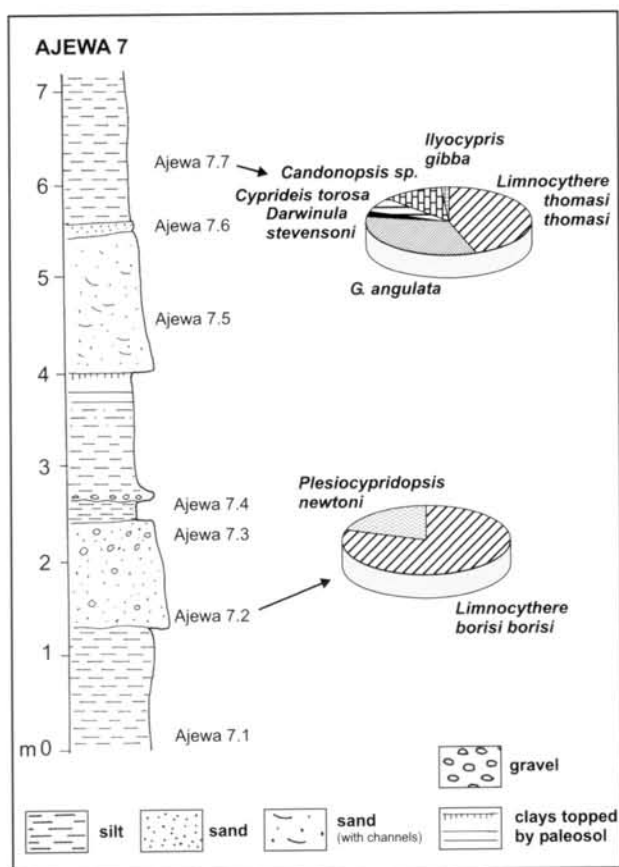
Ajewa 7.5 comes from the base of the fluvial sand

unit that overlies the paleosol which formed over the clayey silts with scattered pumice clasts. The sample is poor (<50 valves/gram) in ostracods and the limited valves encountered were all of *Limnocythere borisi awassaensis*.

From the medium to fine sands containing molluscs, a sample (Ajewa 7.6) gave an assemblage rich in *Cyprideis torosa* (61%) and *Gomphocythere angulata* (27%). In addition to these, *Darwinula stevensoni* (7%) occurred in higher proportions as compared to *Limnocythere*, *Candonopsis* sp. and *Ilyocypris gibba* which together account only for 5% of the sample. The *Cyprideis torosa* encountered were of the noded variety.

The environmental significance attached to the noded nature of *Cyprideis* has been previously discussed. Here again this assemblage gives indications on the oligohaline nature of the lake during the deposition of the sediments under consideration.

The sample from the greyish silts that form the uppermost unit of this section (Ajewa 7.7) in turn gave a diverse assemblage. *Limnocythere thomasi thomasi* (44%), *Gomphocythere angulata* (30%), *Cyprideis torosa* (10%) and *Candonopsis* sp. (10%) represent the main components of this assemblage. In addition to these *D. stevensoni* (3%) and *Ilyocypris gibba* (3%)



Text-fig. 10 - Section Ajewa 7 with representative pie charts of ostracod assemblages.

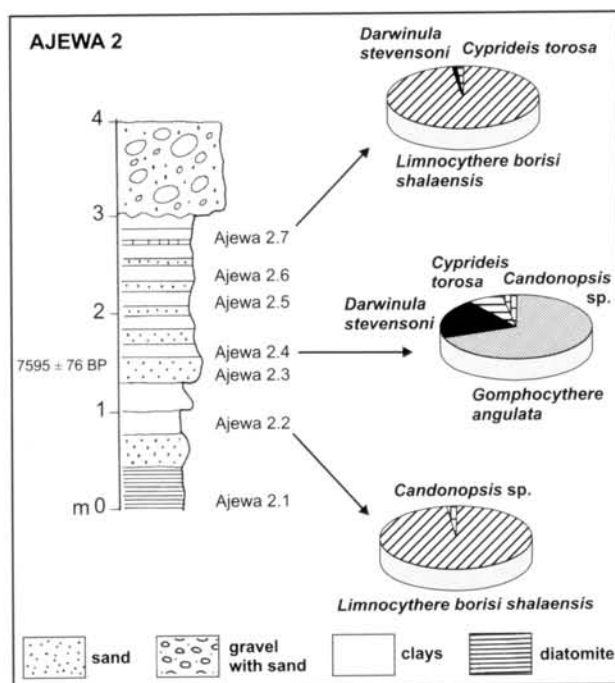
form subordinate components. As in Ajewa 7.6, this sample is diversified but the relative importance of the component taxa in the assemblage varies. Lake waters of fresh salinities are suggested for this assemblage.

Section Ajewa 2

Ajewa 2 is a 4 m thick stratigraphic section (Text-fig. 11) located at an elevation of 1565 m (Text-fig. 6). A 15 cm thick gravelly sands bed, rich in shells (gastropods and lamellibranchs) and pumice pebbles, has given a ^{14}C dating age of 7595 ± 76 BP (sample Ajewa 2.3).

Of the seven samples collected in the field from section Ajewa 2 for ostracod analysis, three samples (Ajewa 2.2; Ajewa 2.4; Ajewa 2.7) have proved to be very rich in ostracofauna (more than 1000 valves/gram sediment) while the others were moderately rich (few hundred valves/gram of sediment washed) to poor (less than 50 valves/gram).

The laminated diatomites at bottom of the section (Ajewa 2.1) are very poor in ostracods, while the overlying silt (Ajewa 2.2) are ostracod rich with a dominant *Limnocythere borisi shalaensis* microfauna and a



Text-fig. 11 - Section Ajewa 2 with representative pie charts of ostracod assemblages.

subordinate proportion of *Candonopsis* sp. In Ajewa 2.4 there is a rich ostracofauna with *Gomphocythere angulata* (70%) dominating over *Darwinula stevensoni* (20%), *Cyprideis torosa* (12%) and *Candonopsis* sp. (2.5%). Ajewa 2.3 instead is poor in ostracods and the few valves encountered were of *Cyprideis torosa* and subordinately of *Gomphocythere angulata*.

Above the previous two samples, represented by the gravelly sands and fossiliferous sands, a finer (diatomaceous clays) unit has proven to be barren in ostracods (Ajewa 2.5-2.6).

Ajewa 2.7 is a clayey silt sample from the topmost parts of the lacustrine sediments in this section. The assemblage from this sample here again is dominated by *Limnocythere*, with valves of *C. torosa*, *G. angulata*, and *D. stevensoni* occurring only in proportionally insignificant amounts (in unison <2% of the ostracofauna). The basal part of this same unit composed of fine sediments sometimes contains levels poor in ostracods (Ajewa 2.6). Even in this case, however, there is a clear dominance of *Limnocythere borisi shalaensis*, as no other ostracod species is present in the sample.

As can be observed from the descriptions of the ostracod assemblages above, a saline and alkaline lake environment (mesohaline) characterized the depositional environment (*Limnocythere* assemblage). In cases where other species are found their insignificant proportions are demonstrated by the pie diagrams in Text-fig 11. It is worth mentioning here that *Darwinula stevensoni*, which is quite abundant in fresh

water lake environments, has recently been reported as found living in Lake Shala which is a saline and alkaline lake where the ostracofauna is highly dominated by *L. borisi shalaensis* (Tudorancea *et al.*, 1989; Martens, 1990).

A significant shift of assemblage is noted in the lower middle part of the section with coarse sediments (Ajewa 2.4). *Gomphocythere angulata* dominates with *Darwinula stevensoni* and *Candonopsis* sp. being quite significant. In terms of salinity this assemblage suggests a shift towards waters of moderate-low salinity. The fact that this shift in assemblage is associated also with an abrupt change of grain size, leads to the idea that a significant depositional event such as a high energy inflow of water (storm) could have been involved. A significant inflow of fresh water from the surroundings would have caused a dilution, at least temporarily, of the generally saline lake during that time.

Section Ajewa 6

Section Ajewa 6 is a bit less than 4 m thick (Text-fig. 12), and lies at an elevation of about 1610 m (Text-fig. 6). It is predominantly made up of fine sediments. A radiocarbon age of 6343 ± 46 BP, has been obtained from a thin sand layer (10 cm) containing mollusc shells. More silt was deposited over this sand layer.

The massive clayey silts in the lower parts of the section (Ajewa 6.1) are very rich in ostracods. The

assemblage is a monogeneric assemblage of *Limnocythere*, with transparent valves of females dominating (*Limnocythere borisi shalaensis*).

Quite saline (mesohaline) and alkaline waters are indicated by such an assemblage, in that it is only composed of *Limnocythere* and that other species common in more diluted waters in the area are absent.

Ajewa 6.2, from the dated sand level further up in the section, is also ostracod-rich but presents a completely different assemblage compared with the underlying massive clayey silts. To start with we are now dealing with a diversified assemblage and not a monogeneric one unlike the case of Ajewa 6.1. The dominant component is *Cyprideis torosa* (79%). In order of decreasing abundance then come *Gomphocythere angulata*, *Darwinula stevensoni* and *Limnocythere* sp. (juveniles), *Ilyocypris gibba* and *Candonopsis* sp. together only form 1% of the total assemblage. Juvenile instars and full carapaces are present although not in large numbers. *C. torosa* valve surfaces showed brown colorations.

As opposed to the previous one, this assemblage indicates diluted waters (oligohaline waters) in that the assemblage is highly diversified, more fresh water species are encountered, and all *Cyprideis torosa* valves are noded.

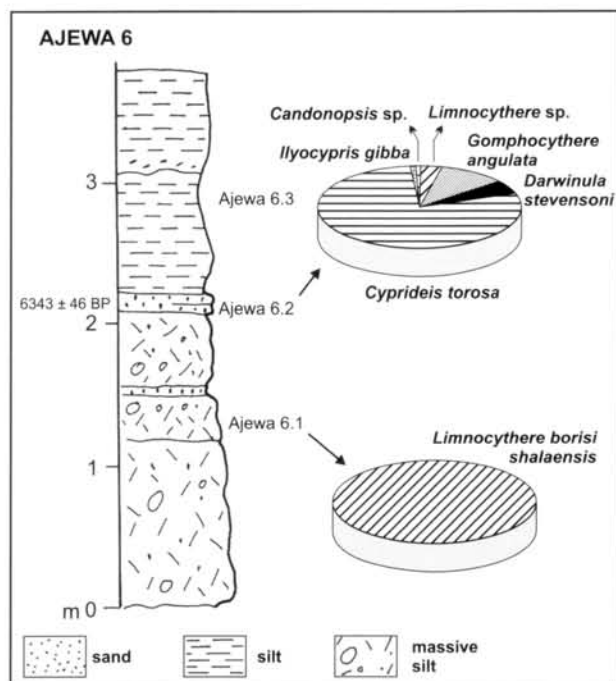
A sample from silts in the uppermost parts of the section (Ajewa 6.3) provided only a small number of ostracod valves. The dominant species was again *Cyprideis torosa* (77%). *G. angulata*, *Limnocythere* sp. and *D. stevensoni* were also present. Here again the *C. torosa* valves encountered were all of the noded variety again indicating the oligohaline nature of the lake waters during this time.

Section Ajewa 6bis

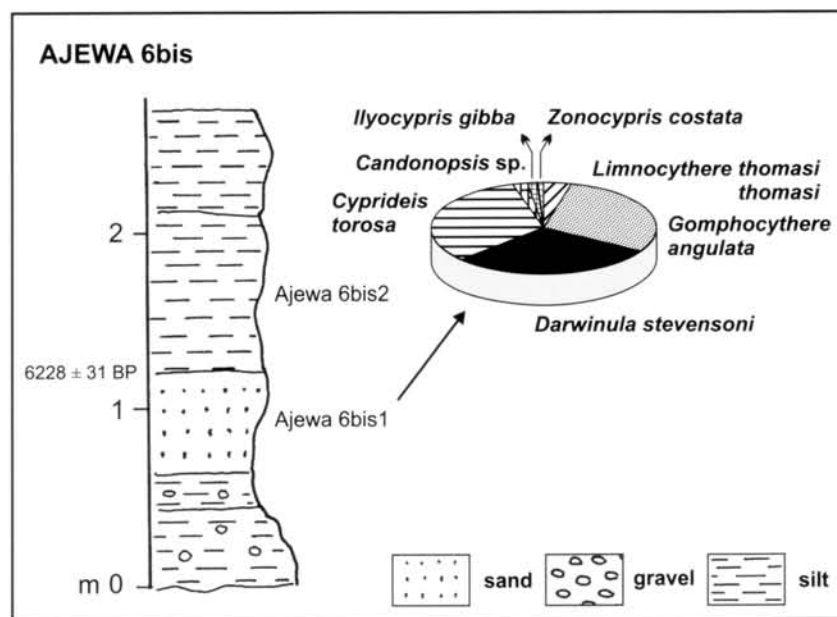
Ajewa 6bis is about 2.5m thick (Text-fig. 13), and lies at an elevation of about 1605 m (Text-fig. 6). The base presents an uncompletely exposed 30 cm layer of silt with scattered pebbles. These are overlain by sands about 80 cm thick. The top parts of these sands contain gastropod shells. ^{14}C dating on these shells has provided an age of 6228 ± 31 BP. On top of this dated sands, 150 cm of clayey silts were sedimented.

A fault that has cut through Ajewa 6bis sediments indicates that they were deformed after the regression of the lake which had led to the accumulation of the lacustrine sediments in the Ajewa 6bis section.

The sample from the dated sand beds (Ajewa 6bis1) showed a very high species diversity with *Cyprideis torosa*, *Darwinula stevensoni* and *Gomphocythere angulata* occupying a large share of the total. *Limnocythere*, *Candonopsis* sp., *Ilyocypris gibba* and *Zonocypris costata* occur in much lower proportions. The only slight occurrence of *Limnocythere* is notable. Furthermore, of the few adult valves identifiable the presence of *L. thomasi thomasi* has been established. Brownish colorings on *C. torosa* valves is frequently observed.



Text-fig. 12 - Section Ajewa 6 with representative pie charts of ostracod assemblages.



Text-fig. 13 - Section Ajewa 6bis with representative pie chart of ostracod assemblages.

Shallow lake waters of a much diluted nature (fresh waters) are inferred from this assemblage.

The overlying clayey silts (Ajewa 6bis2) present a significantly different assemblage both in the species present and the relative proportions of the present taxa. *Limnocythere borisi borisi* is the dominant element (71%) while *Gomphocythere angulata* (14%) and *Candonopsis* sp. (10%) also account for significant percentages. In addition to these, *Cyprideis torosa* and *Ilyocypris gibba* together form a small part (5%) of the assemblage. A point to make here is that in addition to adult valves, instars were present in great abundance in the sample.

The difference between this assemblage and the previous one is evident. An increase in salinity is certainly involved but the shift was not significant enough to result in a truly mesohaline lake. Thus, an oligohaline salinity level is inferred again for this assemblage with the absolute concentration values being more close to the upper limits of the oligohaline interval and the lower limits of mesohaline salinities (oligohaline alpha). The presence of noded *C. torosa*, although in very low proportions, favours the inference of an oligohaline environment.

THE SOUTH SHALA SECTION (TEXT-FIG. 2, NO. 2)

The section investigated for the ostracoda studies consists of a more than 3 m succession of shoreface and marginal lacustrine sediments (Text-fig. 14).

No chronologic calibration is available for this succession. But a generic post 2,000 BP age is proposed by Sagri (1995) for the presently investigated section and the related sediments in the north eastern coast of the lake.

Samples Sh-B, Sh-C and Sh-O were either poor or barren in ostracods. In the latter two cases the sediments were rich in organic matter and were represented by fine, more basinal sediments. Perhaps a sediment control can be inferred in that ostracods are seen to prefer fine to medium sand sediments (Tudorancea *et al.*, 1989).

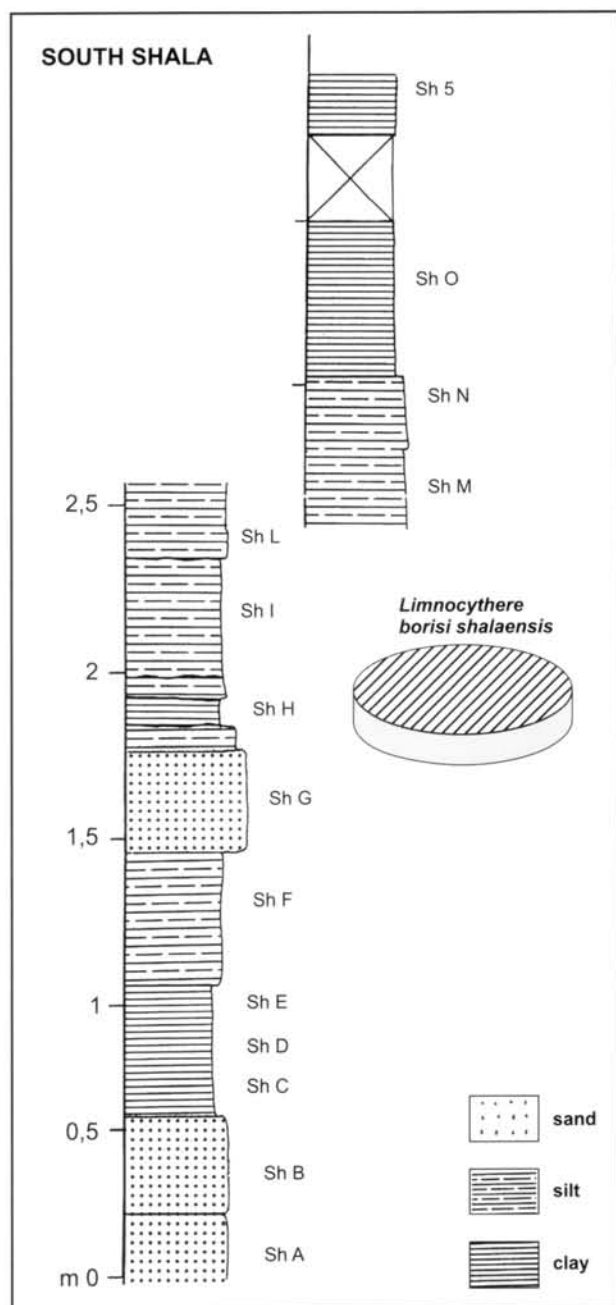
In the samples where ostracods were found the species identified are *Limnocythere borisi shalaensis*, *Gomphocythere angulata*, and *Cyprideis torosa* (noded variety).

The latter species was found as reworked carapaces and valves in samples Sh-A, Sh-B, Sh-H, Sh-M, and Sh-N. Taking into consideration its occurrence in very small numbers in the samples where it was recorded and the reworked nature of the valves, it is logical to assume that they are constituents derived from the sediments of the previous lake phases in which occasionally consisted appreciable proportions of noded *C. torosa* in their assemblages as is described in the part on the stratigraphic sections from the Ajewa embayment.

Thus, essentially we are dealing with a *L. borisi shalaensis* assemblage, which is the *Limnocythere* species presently living in Lake Shala (Martens, 1990). Sh-F, Sh-G, and Sh-M are the samples richest in ostracods.

In sample Sh-F, which is very rich in ostracods, in addition to the very abundant *Limnocythere*, very few (<1%) *Gomphocythere angulata* valves were also present. The presence of this species gives additional evidence of the proximity of the assemblage to the present day ostracofauna living in the lake.

Environmental conditions were more or less the same as today i.e. mesohaline and alkaline, without



Text-fig. 14 - The South Shala section and its representative ostracod assemblage.

significant changes in water chemistry despite the small scale, high frequency fluctuations of lake-level.

Sh-5 is a sample taken from the beach, about 20 m laterally from the lake waters. It thus represents the youngest subrecent sediments and the corresponding subfossil ostracods. Here again, only *Limnocythere borisi shalaensis* valves were encountered – a further indication of the general uniformity of the salinity conditions in Lake Shala in the considered interval of the south Shala section.

This phase of fluctuations represents the last stages in the evolution of the lakes in the Ziway-Shala Basin, in which the lakes, as in present day conditions, were separated from each other (latest Holocene separated lakes phase of Sagri, 1995).

THE HULU ARTU SECTION (TEXT-FIG. 2, NO. 5)

The Hulu Artu section, which represents the most northern one, consists of about 4 m thick of condensed lacustrine beds, with significant proportions of non-lacustrine coarse sediments (Text-fig. 15). The importance of the section lies in the fact that shell beds rich in molluscs are present in the section allowing these levels to be ^{14}C dated.

The section is located not very far from the foot of the Alutu volcano in a small river gully in the Hulu Artu area, at 1660 m a.s.l. In terms of general location, it is located south of the Deke Wede valley, from which sections have been studied by Street (1979).

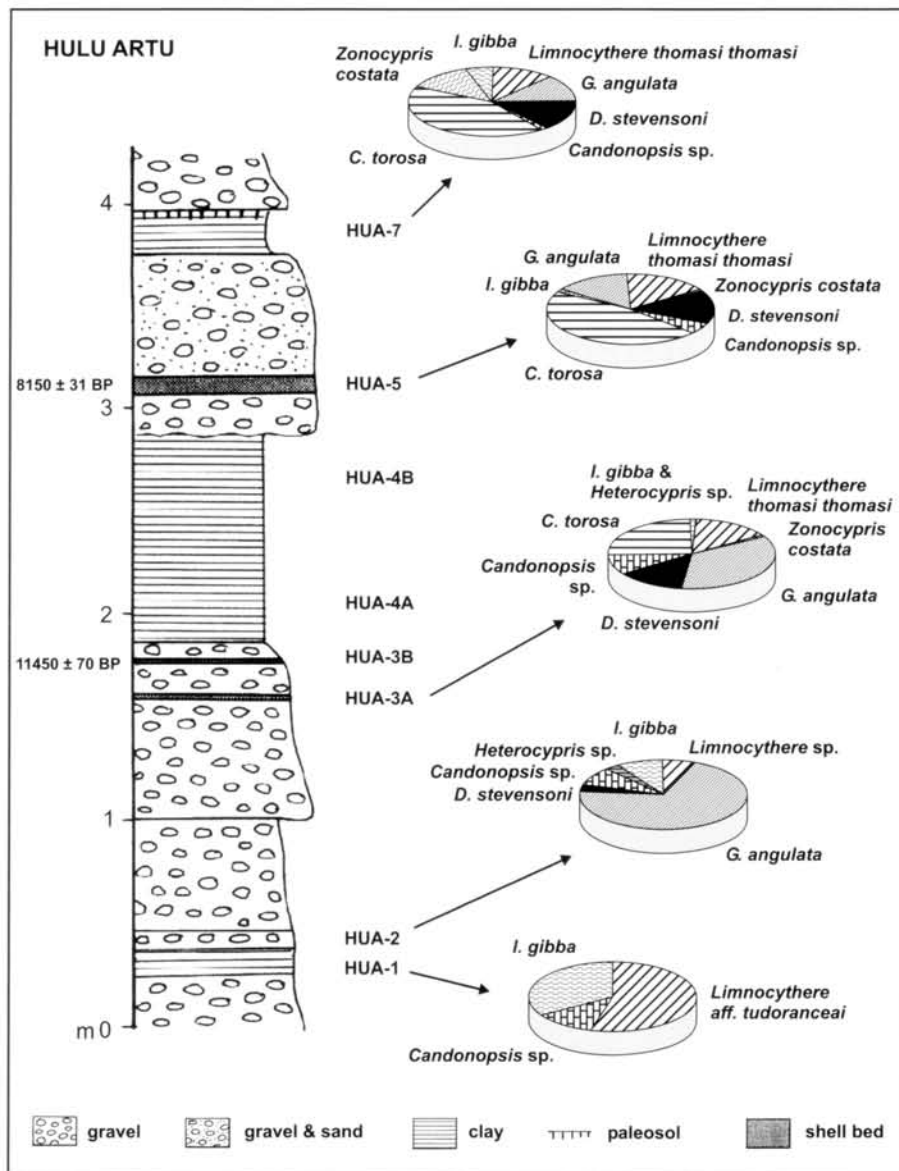
Two radiocarbon datings from the levels of HUA-3a and HUA-5, have provided measured ^{14}C ages of $11,110 \pm 70$ BP and $7,870 \pm 100$ BP, respectively (conventional ages of $11,450 \pm 70$ BP and $8,150 \pm 100$ BP are given).

Samples from five horizons contain ostracods, four of which have rich (>1000 valves/gram) concentrations. Starting from the base sample HUA-1 presents a quite different assemblage as compared to the others to be described later. Three taxa were identified of which *Limnocythere* sp. (55%) and *Ilyocypris gibba* (34%) dominate over *Candonopsis* sp. (11%).

An environment of moderate-high salinity with a nearby vegetation zone is suggested for these sediments given that the species of *Limnocythere* (*L. aff. tudoranceai*) found were not of a limited salinity range. Some species of *Ilyocypris* according to Carbonel *et al.* (1988) are oligohalophile. A *Candonopsis* species similar to the ones identified in these samples have been used by Carbonel *et al.* (1987) as indicators of the development of littoral plants.

HUA-2 is poor (<50 valves/gram) in valve abundance, but in terms of diversity a remarkable diversity was observed. The relative high numbers counted were of *Gomphocythere angulata* (71%) with *Candonopsis* sp. and *Ilyocypris gibba* with slightly higher numbers than *Limnocythere* sp. *Darwinula stevensoni* and other unidentified broken fragments make up the remaining part.

The remaining three samples have a similarly diversified ostracofauna, with only certain differences in relative proportions. The microfaunal components are *Cyprideis torosa*, *Gomphocythere angulata*, *Limnocythere thomasi thomasi*, *Darwinula stevensoni*, *Candonopsis* sp., *Ilyocypris gibba*, *Zonocypris costata*, and *Heterocypris* sp. Important morphologic features were noted especially in the most common species. All *Cyprideis torosa* were the noded varieties (commonly with three nodes) and this will have its significance in the environmental



Text-fig. 15 - The Hulu Artu section and pie diagrams of the ostracod assemblages.

interpretation as will be seen later. The *Limnocythere thomasi thomasi* valves were almost all reticulated and in most cases also with tubercles (usually two tubercles). *Ilyocypris gibba* valves were also almost invariably noded (usually four pointed nodes).

In HUA-3a, *Gomphocythere angulata* has the greatest proportion (37%) followed by *Cyprideis torosa* (25%), *Limnocythere thomasi thomasi* (16%), *Darwinula stvensoni* (13%) and *Candonopsis* sp. (9%). The other species are present in only very small numbers.

Sample HUA-5 is instead dominated by *Cyprideis torosa* (47%), followed in abundance by *Limnocythere thomasi thomasi* (16%), *Darwinula stvensoni* (15%), *Gomphocythere angulata* (15%) and *Candonopsis* sp. (5%). As in the previous sample, the other species are present only in very small numbers.

Also in HUA-7, *Cyprideis torosa* is the dominant species (42%). In this sample, however, it is followed in abundance by *Darwinula stvensoni* (15%) and then by *Gomphocythere angulata* (13%), *Ilyocypris gibba* (12%), *Limnocythere thomasi thomasi* (12%), and *Zonocypris costata* (5%). *Candonopsis* sp. is present in very small amounts (<1%).

Given the similarity of the assemblages in these three phases, the environmental implications of the microfauna can be considered together. The noded *C. torosa* valves help to define the low water salinity conditions in that according to a number of works (Sandberg, 1964; Vesper 1972a, b; Kilenyi, 1972), nodose specimens of *Cyprideis* are only found in the oligohaline environment. In the light of these results, Carbonel *et al.* (1988) have further suggested that

nodosity is a double marker to indicate salinity (never above 5-6‰) and abundant organic matter and silica.

L. thomasi thomasi is a subspecies living presently only in Lake Ziway, a fresh water lake of very low salinity. Its invariable presence in the three samples thus suggests low salinity waters.

Darwinula stevensoni is found in all three samples in significant amounts, although it is not numerically dominant over a number of other species. Its significant presence is also indicative of the low salinity environment.

Species of *Candonopsis* and *Heterocypris* are reported from present day lakes as being common in the marginal lake environments where vegetation abounds (cf. Martens & Tudorancea, 1991). *Gomphocythere angulata* has also been reported in large numbers from present lakes in the basin with a fresh water nature i.e. Lakes Ziway and Langano (Martens, 1990; Martens & Tudorancea, 1991).

In addition to the fact that certain individual species are indicative of the fresh water nature of the lake waters that are reflected by these three phases of deposition, the general assemblage is also instructive towards this end: a diversified assemblage is generally indicative of low salinity stable environments. With an increase in salinity due to evaporation, the diversity tends to diminish.

The altitude of the section marks the level reached by the lake during its major extensions or highstands. The first phase of fine sediment deposition could have marked the presence of a small pool or swamp, in that unlike the other phases in the section, it presents an ostracod assemblage (HUA-1) not characteristic of periods of lake extension i.e. freshening. Surrounding vegetation would have been present and the salinity could have fluctuated as indicated by the euryhaline *Ilyocypris gibba*.

At around 11,110 BP, the lake reached this level as shown by the lake-margin deposits (HUA-3). The lake was most probably fresh or at most oligohaline and was calm and sheltered with significant amounts of *Darwinula stevensoni* inhabiting the lake margin. The associated swampy nature or at least the presence of nearby vegetation, as in the present case of Lake Ziway, is suggested by the presence of *Candonopsis* sp. and *Heterocypris* sp.

Of the following phase of lacustrine deposition (HUA-4a; HUA-4b) not much can be said because it is barren in ostracods. Compared with the lake-margin deposits that are found above and below, it is represented by finer sediments indicating deeper lake sediments. The lake margin would have been higher during this time.

At around 7,870 BP, lake-margin conditions reappeared (HUA-5). Conditions were more or less similar to those of the previous shallow water phase at around 11 ka. After the lake had passed this limit of extension with the deposition of finer sediments, a

drop in level had occurred restoring the conditions of a freshwater lake margin.

The final phase recorded in the Hulu Artu section had characteristics similar to the previous phases, as the lake was freshwater – lower limits of oligohaline waters. Differences occur in that nearby surrounding vegetation was highly reduced (diminishing amounts of *Candonopsis* sp.) and the sediments are fine implying that we are not dealing with a true margin environment as in the previous cases. The diminishing importance of margin vegetation also agrees with the deeper conditions of the lake.

THE LAKE LANGANO CORE (TEXT-FIG. 2, NO. 6)

A 14.7 m core (LL-III) at a water depth of 15 m was made at the northern part of Lake Langano. An Upper Pleistocene-Holocene age has been established for the core based on preliminary radiocarbon chronology (Tiercelin *et al.*, 1997).

The interval between 14.7 m and 9 m is characterized by sedimentation of heterogeneous lithologies ranging from coarse sands and indurated gravel layers to fine homogeneous mud in irregular alternation. Locally, the finer sediments are ostracod-rich.

In this interval the ostracods, when present, are represented by *Limnocythere* with species of other genera very limited indeed.

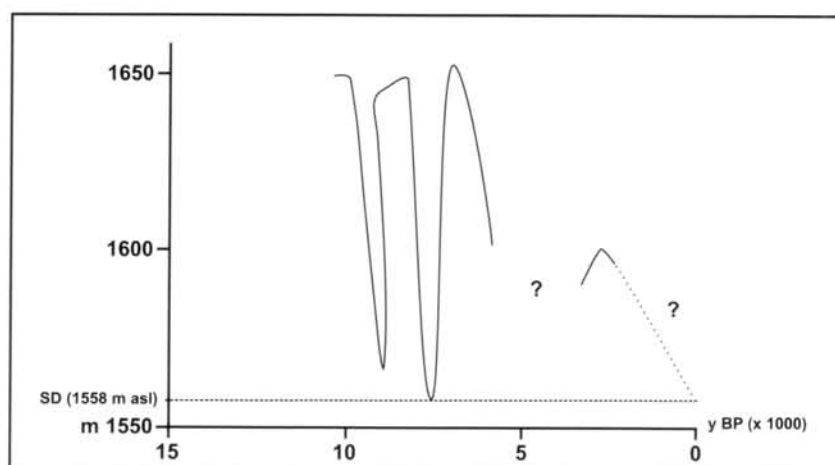
From 9 m to the top, silty to sandy mud lithologies dominate with fine and coarse pyroclastic intercalations. The muds are often diatom and/or ostracod-rich.

As in the exposed sections previously described, the dominant ostracods are species of the genus *Limnocythere*. In addition to these, valves of *Darwinula stevensoni*, and *Gomphocythere angulata* are often encountered. Between 5.50 and 2.30 m (c. 7-6 ka), *L. aff. tudoranceai* and *L. thomasi thomasi* are the representatives of the genus *Limnocythere*. Together with *D. stevensoni* and *G. angulata* these indicate low salinity waters (Atnafu, 1998; Le Turdu *et al.*, 1999).

In LL-III the uppermost parts of the core were lost. However, LL-II, provides information regarding the upper few centimeters of the basin sediments. The two core samples taken at 4.5 and 13 cm depth from the water sediment interface were rich in ostracods. *Limnocythere thomasi thomasi* and *L. aff. tudoranceai* were present also in these samples in addition to *Darwinula stevensoni*. This association suggests that salinities were even lower than today or in the very recent past.

SALINITY VERSUS LAKE-LEVEL FLUCTUATIONS IN THE BASIN

The results obtained from ostracofaunal assemblages and related ¹⁴C datings from the studied stratigraphic sections provide us with a means of examining the relationship between the fluctuation in lake-levels with



Text-fig. 16 - Fluctuations of Lake Shala starting from the Early Holocene as interpreted from the succession of the Ajewa Embayment (after Alessio *et al.*, 1996).

the fluctuations in salinity. On the basis of this relationship we can have a better understanding of the history of the individual lakes in particular and of the basin in general, especially in terms of climatic changes.

Attempts to correlate variations in lake level and variations in salinity are warranted in cases where lake-level fluctuations have climatic causes. This is especially true when we are dealing with closed basin lakes in sub-humid to semi-arid regions, such as the Ziway-Shala basin in the Late Quaternary. The change in moisture balance (i.e. balance between precipitation and evaporation) of a closed basin has an effect on the volume of the water (variations of the lake-level) and is also evaporatively coupled to water chemistry (variations in salinity included). The relationship between the moisture balance and the lake water chemistry is quite complex, being related also to the solute evolution (Eugster & Hardie, 1978; Eugster & Jones, 1979). However, for our present purposes it is clear that evaporation from a waterbody increases its salinity.

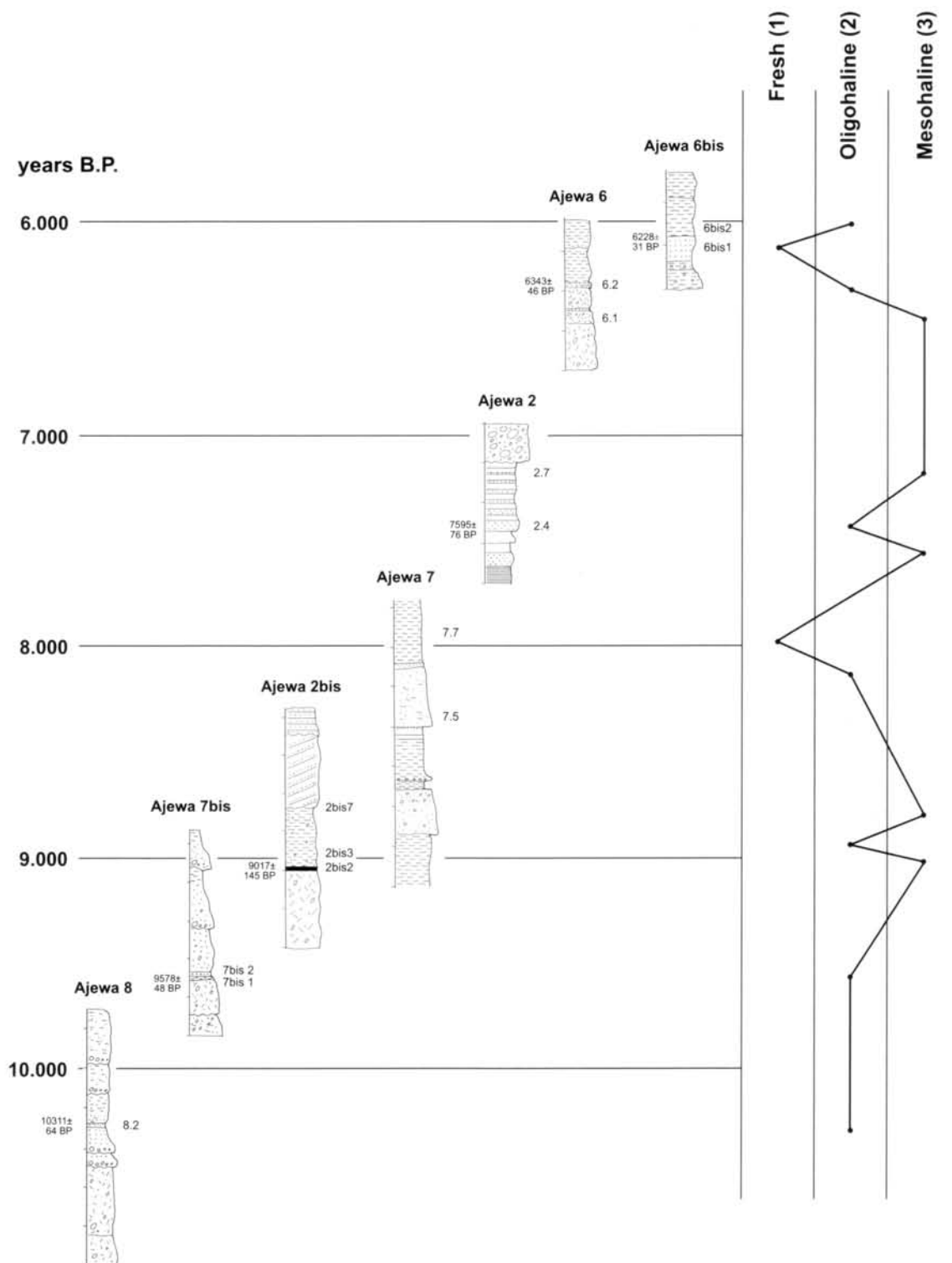
To give an oversimplified outline of what effects would be expected with variations in the water balance of a closed basin the following consideration will do. When precipitation is greater than evaporation in a wet climate, the lake level will rise due to the increased amount of water available; the water, however, will also be more diluted due to such an input and, thus, will result in a lake of lower salinity. When evaporation is greater than the precipitation, on the other hand, the opposite effect will occur as the lake level will drop, with a corresponding increase in the concentration of salts, which will mean a more saline lake.

Curves of fluctuations of lake-level in the Ziway-Shala Basin (Gillespie *et al.*, 1983) and for the Lake Shala Area (Alessio *et al.*, 1996) are presented in Text-fig. 16. This curve, together with the discussion to follow will allow comparisons to be made between the salinity variations derived from the present ostracofaunal studies and the previous lake-level fluctuations derived mainly from stratigraphic studies.

The studied sections and their ostracod fauna have helped to outline the following environmental history of the basin.

The Late Pleistocene ostracofaunal assemblages recorded in the study can be associated to at least two important phases of lacustrine deposition as is marked in the Bulbula Village Section. The second and later phase has been dated as being around 24 ka. The ostracod assemblages have recorded a clear difference in the salinity level of the two phases: the earlier one being much more saline than the second phase which was a lake of fresh to slightly brackish water nature (fresh-oligohaline). The two phases of deeper water lake deposits in the Ati Damo section are also provisionally considered as being of Late Pleistocene age although in the absence of dated levels doubts do remain (M. Benvenuti, pers. comm.). In the Ajewa embayment, samples from the Megalake phase deposits of Sagri (1995) have resulted, like the Bulbula section, in two types of ostracofaunal assemblages suggestive of two phases of deposition differing in salinity. Although it is worth mentioning the marked similarity between these assemblages and those of the Upper Pleistocene of the Bulbula section, it will be premature to assert that we are dealing with the same phases given that the data available for facies correlations are limited.

Around 11.5 ka a high lake-level is recorded especially from the Hulu Artu Section which represents the most north-easterly located section in this study, lying at about 1660 m a.s.l. The lake was a fresh water lake as seen from the characteristic diverse assemblage and the presence of *L. thomasi thomasi*. The fauna also indicates the lake-margin nature of the environment and its proximity to a swampland with vegetation. In the Ajewa section, the continuation (with a slight regression) of this phase is marked by younger sediments (c. 10.3 ka) and less diluted waters (Ajewa 8) that had reached oligohaline salinity levels. Even in this case, however, the level of the lake was higher than 1640 m.



Text-fig. 17 - Salinity variation in the sections of the Ajewa Embayment as inferred from ostracod assemblages.

1. (Assemblage indicative of fresh waters): Diversified assemblage containing most of the following species: *Limnocythere thomasi thomasi*, *Limnocythere* aff. *tudoranceai*, *Darwinula stevensoni*, *Gomphocythere angulata*, noded *Cyprideis torosa*, *Ilyocypris gibba*, *Zonocypris costata*, *Candonopsis* sp., and *Heterocypris* sp.
2. (Assemblages indicative of oligohaline waters): a) dominated by noded *Cyprideis torosa*, or b) with *Limnocythere* and/or *Gomphocythere angulata* dominant, with few associated other species in subordinate amounts.
3. (Assemblage indicative of mesohaline lake waters: highly dominated by one or two *Limnocythere* species (*Limnocythere thomasi* excluded) with the presence of other species very limited indeed.

The previously discussed phase of a low-salinity lake has also been recorded previously in the Ziway-Shala Basin by geomorphologic and stratigraphic means (Gasse & Street, 1978; Street, 1979; Gillespie *et al.*, 1983; Benvenuti *et al.*, 2002). It has been named the Ziway-Shala IV phase (Street, 1979) and represents the very latest Pleistocene high-lake level phase recorded in the basin. The lake-level drop and increase in salinity that follow are, therefore, reflections of the start of the intervening arid period identified by the previous works.

In the Ajewa 7bis section, the next phase recorded is represented by the 9,578 BP date, and the ostracofaunal assemblages again indicate an oligohaline lake. These are at present considered as the start of the next wet phase in the region i.e. Ziway-Shala V of Street (1979).

The next important interval identified in the present study, involves a low-lake level around 9 ka, where relatively saline (mesohaline) lake waters are indicated by the ostracofauna. The section is characterized by palustrine peaty sediments dated around 9,017 BP in the Ajewa 2bis section. The measured section is located at a low elevation (1570 m) not very much higher than the present level of Lake Shala, and thus the increased salinity can be attributed to a lake-level drop during this time.

The chronology of lake-level fluctuations in this area, as reported by Street (1979) and Gillespie *et al.* (1983) does not recognize a low lake-level around 9,000 BP. Alessio *et al.* (1996) and Benvenuti *et al.* (2002) from the association of sedimentary facies in the section assert that the palustrine deposits around 9 ka that lie over colluvial and alluvial deposits in that sedimentary unit represent the significant initial submersion of the area. To explain this evidence they have put forward two hypotheses:

In the first hypothesis, a previously unreported lacustrine regression due to climate would have occurred. The alternative hypothesis considers a localized uplift of the Ajewa area with corresponding gravitational plastic deformation of the old beds that underlie the Ajewa bis sediments, and the formation of the sub-basin that would later host the former. In this context, the lake level which was probably rising due to climatic causes, is subjected to a relative lowering. With the stasis of the deformational event the lake level will continue to rise thus forming the transgressive relationships reported earlier.

Since, as previously mentioned, the ostracofaunal assemblage largely indicates relatively saline lake waters during that time, a lake-level drop due to climate is suggested by the results of this study. A lake-level drop due to tectonic reasons would not have caused an increase in salinity in an otherwise wet climate where the water balance is in favour of precipitation and not evaporation. Within the Ajewa 2bis section, certain levels have shown assemblages indicative of fresher waters. These are interpreted as being related

to local hydrologic events such as storms causing dilution of the lake waters in a generally mesohaline lake.

At around 8.1 ka, a high lake-level is recorded from the Hulu Artu section. A characteristic freshwater assemblage is associated with these sediments, accentuating further the correspondence between a lake-level rise and a dilution of the lake waters in this area as is expected for climatically caused fluctuations. The ostracod assemblage again points towards marginal lake conditions with the proximity of swamp vegetation. Although no precise dating is available at present relative to Ajewa 7.6 and Ajewa 7.7, the interval around 8 ka is estimated for the upper portion of section Ajewa 7 by consideration of the succession of events documented from the Ajewa embayment by previous works (Street, 1979; Gillespie *et al.* 1983) and the recent assumptions of Alessio *et al.* (1996).

Fresh water lake conditions are hereby considered part of the ultimate stages of the Ziway-Shala V phase (Street, 1979; Gillespie *et al.*, 1983).

Shortly after this phase, the Ajewa 2 section (7.6 ka) marks a fall of lake level associated with an ostracod assemblage indicative of generally mesohaline waters (*Limnocythere* assemblage). Except for a small break, where moderately diluted waters are indicated (Ajewa 2.3), mesohaline lake water conditions did continue for a relatively considerable amount of time, as seen from the thickness of lacustrine sediments in the Ajewa 2 section. Within a general background of a mesohaline water lake environment, thus, a short interval of freshening can be envisaged. This period of low lake-levels is the Shala V/VI dry phase noted in Gillespie *et al.* (1983).

The results from the ostracofaunal analysis in the Ajewa embayment show that the lake did not attain the next truly fresh state until after 6.3 ka. The basal sample of section Ajewa 6 (Ajewa 6.1) is characterized by an assemblage of mesohaline waters leading to the assumption that the conditions in Ajewa 2 continued even up to the time of the first stages of lake-level rise shown by Ajewa 6. However, the remaining sediments of the latter and samples from Ajewa 6bis provide evidence from ostracods that more diluted concentrations were reached shortly after. ^{14}C ages of 6343 ± 46 BP and 6228 ± 31 BP mark the chronologic position of this phase especially in the Ajewa embayment.

This phase is the Ziway-Shala VI of Street (1979) and Gillespie *et al.* (1983). In the Hulu Artu Section, a fresh water indicative ostracod assemblage is found from the HUA-7 level. The level has not been dated but at this point it can be said with certain confidence that it represents Phase VI of the high lake-levels identified in the Ziway-Shala basin. In the Langan core a fresh water lake interval is recorded between roughly 7–6 ka and surely represents this same phase. Although we do not have evidence from the studied sections regarding duration of this particular wet phase, the Ziway-Shala VI phase is reported to have occurred between 7 and 4 ka (Street, 1979).

The Late Holocene in the basin is generally marked by low lake-levels that continued to the present day (Street, 1979; Gillespie *et al.*, 1983; Alessio *et al.*, 1996; Benvenuti *et al.*, 2002). Within the time interval following 4 ka, the above-mentioned works have reported a moderate rise in lake level that would have joined the three southern lakes at around 2,500 BP. At present, not much can be said regarding this phase because no ostracod containing sections have been studied in enough detail. The only sample (C-1) taken from the vicinity of the section of Alessio *et al.* (1996) had a poor ostracofaunal assemblage that was *Limnocythere* dominated and with few *Gomphocythere angulata*. If we are to extract information from a single sample, an indication would be that even with the rise, the lake did not attain oligohaline salinities.

The ultimate stages of lake evolution in the basin proceeded as the separated lakes phase of the latest Holocene (Sagri, 1995) represented by the separate deposits around Shala, Abiyata, and Langano. In the South Shala section the post 2 ka (Sagri, 1995) history of Lake Shala shows that lake-water salinities remained essentially the same as in the present day lake with *Limnocythere borisi* being the principal ostracod species, despite the fact that small-scale fluctuations of lake-level had occurred (Benvenuti *et al.*, 1995). A comparable lake succession of about 5 m thickness cored in Lake Abiyata and not older than 1,720 BP (Bonnefille *et al.*, 1986) represents the basinal facies in Lake Abiyata during that time. For lake Langano, the samples from the upper few centimeters of the studied core give indications that more fresh waters had existed in the recent past. The presence of *Limnocythere thomasi thomasi* and *Darwinula stevensoni* are important indicative elements of the assemblage.

Ostracod valve trace element analysis results from the Ziway-Shala basin show that valve Sr/Ca and valve Ba/Ca can be utilised as reliable markers of variations in the salinity of lake waters. These results are in general agreement with fluctuations interpreted from the ostracod assemblages (Atnafu, 1998).

CONCLUSIONS

The utility of Late Quaternary ostracofauna in reconstructing the variations in the salinity of lake environments has been confirmed from the present study of ostracod assemblages in the Ziway-Shala Basin. The results from this study should encourage the use of this fossil group in the study of other lake records especially within the Ethiopian Rift.

Starting from the ostracod assemblages data of the present day lakes of the Ziway-Shala basin, salinity classes and ostracod assemblages for late Pleistocene and Holocene have been established (Text-fig. 17). The salinity levels have been divided into fresh, oligohaline and mesohaline, while the characteristic ostracod assemblages for such inferences are summarised as follows:

1. (Assemblage indicative of fresh waters) - Diversified assemblage containing most of the following species: *Limnocythere thomasi thomasi*, *Limnocythere* aff. *tudoranceai*, *Darwinula stevensoni*, *Gomphocythere angulata*, noded *Cyprideis torosa*, *Ilyocypris gibba*, *Zonocypris costata*, *Candonopsis* sp., and *Heterocypris* sp.

2. (Assemblages indicative of oligohaline waters) - a) dominated by noded *Cyprideis torosa*, or b) with *Limnocythere* and/or *Gomphocythere angulata* dominant, with few associated other species in subordinate amounts.

3. (Assemblage indicative of mesohaline lake waters) - highly dominated by one or two *Limnocythere* species (*Limnocythere thomasi* excluded) with the presence of other species very limited indeed.

The use of *Limnocythere* as a hydrochemical indicator group of elevated salinities and alkalinities outlined by Cohen *et al.* (1983) can be utilised, as has been applied in this work, in a slightly modified form. The modifications involve the consideration of the particular *Limnocythere* species present and their quantitative proportions with the associated fauna. As a genus, however, it cannot be considered typical of saline waters since some (sub)species such as *Limnocythere thomasi* are found exclusively in fresh-oligohaline waters while others, common in mesohaline waters, can also survive in reduced salinities. For example, the present study has shown the utility of *Limnocythere thomasi thomasi* as an indicator of very diluted waters comparable to salinities of present day Lake Ziway.

The presence of nodes on the valves of *Cyprideis torosa* as an effect of reduced salinities in the lake environment has been confirmed and successfully used in semi-quantitative terms to recognise oligohaline waters in particular, although its presence in more reduced proportions is not excluded from waters especially of lower salinities, i.e. fresh waters.

The environmental interpretation in this study has mostly concentrated on salinity variations and to some extent on water turbidity. The study, based mainly on autoecological information of ostracod assemblages of present day rift lakes, has evidenced the salinity fluctuations during the latest Pleistocene and Holocene time.

Generally ostracod assemblages indicating lower salinity (i.e., fresh water) correspond to periods of high humidity, whilst ostracod assemblages typical of high salinity (i.e., mesohaline water) correspond to dry periods, also with lake-level fluctuations, as tested by Alin & Cohen (2003) for the late Holocene of Lake Tanganyika.

Our data, integrated with previous ones (summarized by Benvenuti *et al.*, 2002), confirm the picture of environmental changes, which are mainly driven by changes in climate, even if Late Quaternary tectonism and volcanism in the MER modulated such a climatic control (Benvenuti *et al.*, 2002).

ACKNOWLEDGEMENTS

Many thanks to colleagues of the Dept. of Geology and Geophysics of Addis Ababa University, and in particular Prof. Assefa Getaneh, for their invaluable help.

Thanks to Dr. Koen Martens, Brussels, for the very useful discussions with regards ostracods from Ethiopia, Professors P. Carbonel and J.P. Peyrouquet (both from the University of Bordeaux) have provided us with many references and were important in the exchange of ideas. We appreciate for their fruitful help. The group of Prof. Mario Sagri and Dr. Marco Benvenuti (Florence) has been of great help: in the field through exchange of ideas and in providing ^{14}C dating for the sections from the Ajewa Embayment. Prof. Jean Jacques Tiercelin is thanked for having allowed one of the Authors (B.A.) to study his core samples from Langanu.

REFERENCES

- ALESSIO, M., ALLEGRI, L., BELLUOMINI, G., BENVENUTI, M., CERASOLI, M., IMPROTA, S., MANFRA, L., SAGRI, M. & VENTRA, D., 1996, Le oscillazioni tardo-Quaternarie del Lago Shala (Rift Etiopico): Analisi dell'evoluzione ambientale dall'integrazione di evidenze morfologiche, sedimentarie e cronologiche: Il Quaternario, Italian Journal of Quaternary Sciences, 9 (1): 387-392.
- ALIN, R.S. & COHEN, A., 2003, Lake-level history of Lake Tanganyika, East Africa, for the past 2500 years based on ostracode-inferred water-depth reconstruction: *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, 199 (1-2): 31-49.
- ATNAFU, B., 1998, The Late Quaternary Lacustrine Sediments of the Ziway-Shala Basin (Ethiopia): Palaeoenvironmental Interpretation based on the Ostracofauna: Ph.D. Thesis (X Cycle), Modena.
- BACCI, G., 1940, Molluschi fossili dell'antico fondo del Lago Zwai: *Ann. Mus. Stor. nat. Genova*, 60: 454-458.
- BAUMANN, A., FORSTNER, U. & RHODE, R., 1975, Lake Shala: water chemistry, mineralogy and geochemistry of sediments in an Ethiopian Rift lake: *Geol. Rundschau*, 64: 593-609.
- BAXTER, R.M., PROSSER, M.V., TALLING, J.F. & WOOD, R.B., 1965, Stratification in tropical African lakes at moderate altitudes (1500 to 2000 m): *Limnol. Oceanogr.*, 10: 511-520.
- BEADLE, L.C., 1981, The inland waters of tropical Africa. Second Edition. 365 pp., Longman, London.
- BENVENUTI, M., CARNICELLI, S., BELLUOMINI, G., DAINELLI, N., DI GRAZIA, S., FERRARI, G.A., IASIO, C., SAGRI, M., VENTRA, D., ATNAFU, B. & KEBEDE, S., 2002, The Ziway-Shala lake basin (main Ethiopian Rift, Ethiopia): a revision of basin evolution with special reference to the Late Quaternary: *Journ. of Afric. Earth Sc.*, 35 (2): 247-269.
- , SAGRI, M., & VENTRA, D., 1995, Climatic change and sequence stratigraphy in the Quaternary lacustrine deposits of the Main Ethiopian Rift: First Int. Limno-Geol. Congr., Abstract volume: 10.
- BOCCALETTI, M., GETANEH, A. & TORTORICI, L., 1992, The Main Ethiopian Rift: an example of oblique rifting: *Annales Tectonicae*, 6: 20-25.
- BONINI, M., SOURLOT, T., BOCCALETTI, M. & BRUN, J.P., 1997, Successive orthogonal and oblique extension episodes in a rift zone: laboratory experiments with application to the Ethiopian Rift: *Tectonics*, 16: 347-362.
- BONNEFILLE, R., ROBERT, C., DELIBRIAS, G., ELENGA, C., HERBIN, J.P., LEZINE, A.M., PERINET, G. & TIERCELIN, J.J., 1986, Palaeoenvironment of Lake Abiyata, Ethiopia, during the past 2000 years. In Frostick, L.E. et al. (eds) *Sedimentation in the African Rifts*: *Geol. Soc. Spec. Publ.*, 25: 253-265.
- CARBONEL, P., COLIN, J.P., DANIELOPOL, D.L., LOFFLER, H. & NEUSTRUEVA, I., 1988, Paleocology of limnic ostracodes: a review of some major topics: *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, 62: 413-461.
- , GROSODIER, E. & PEYPOUQUET, J.P., 1987, Les ostracodes et l'évolution des milieux en termes hydrologiques. In Tiercelin, J.J. et al. (28 authors), *The Baringo-Bogoria half-graben, Gregory Rift, Kenya, 30,000 years of hydrological and sedimentary history*: *Bull. Centres Rech. Explor.-Prod. Elf-Aquitaine*, 11 (2): 394-411.
- , — & TIERCELIN, J.J., 1983, Les ostracodes, témoins de l'évolution hydrologique d'un lac de rift: exemple du lac Bogoria, Rift Gregory, Kenya: *Bull. Centres Rech. Explor.-Prod. Elf-Aquitaine*, 7 (1): 301-313.
- , MOURGUIART, PH. & PEYPOUQUET, J.P., 1990, The external mechanism responsible for morphological variability in Recent Ostracoda: seasonality and biotope situation: an example from Lake Titicaca. In Whatley, R. & Maybury, C. (eds), *Ostracoda and Global Events: Proceedings of the 10th International symposium on Ostracoda*, Chapman & Hall: 331-340.
- & PEYPOUQUET, J.P., 1979, Les ostracodes des séries du Bassin de l'Omo: *Bull. Inst. Géol. Bassin d'Aquitaine*, 25: 167-199.
- CHALIC, F. & GASSE, F., 2002, Late Glacial- Holocene diatom record of water chemistry and lake level change from the tropical East African Rift Lake Abiyata (Ethiopia): *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, 187 (3-4): 259-283.
- CHOROWITZ, J., COLLET, B., BONAVIA, F.F. & KORME, T., 1994, Northwest to north-northwest extension direction in the Ethiopian Rift deduced from the orientation of extension structures and fault slip analysis: *Geol. Soc. America Bull.*, 105: 1560-1570.
- COHEN, A.S., 1982, Ecological and paleoecological aspects of the Rift Valley Lakes of East Africa. Ph.D. Dissertation. Department of Geology, University of California at Davis, 314 pp.
- , DUSSINGER, R. & RICHARDSON, J., 1983, Lacustrine paleochemical interpretations based on eastern and southern African ostracodes: *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, 43: 129-151.
- & NIELSON, C., 1986, Ostracodes as indicators of paleohydrochemistry in lakes: A Late Quaternary example from Lake Elementeita, Kenya: *Palaos*, 1: 601-609.
- DI PAOLA, G.M., 1972, The Ethiopian Rift Valley (between 7°00' and 8°40' lat. North): *Bull. Vulcan.*, 36: 517-560.
- EUGSTER, H.P. & HARDIE, L.A., 1978, Saline lakes. In Lerman (ed.), *Lakes: Chemistry, Geology, Physics*. Springer Verlag, New York: 237-293.
- & JONES, B.F., 1979, Behaviour of major solutes during closed basin brine evolution: *Am. Journal of Science*, 279: 609-631.
- GASSE, F., FONTES, J.C., PLAZIAT, J.C., CARBONEL, P., KACZMARSKA, I., DE DECKKER, P., SOULIÉ-MARSCHE, I., CALLOT, Y. & DUPEUBLE, P.A., 1987, Biological remains, geochemistry and stable isotopes for the reconstruction of environmental and hydrological changes in the Holocene lakes from North Sahara: *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, 60: 1-46.
- & STREET, F.A., 1978, Late Quaternary lake-level fluctuations and environments of the Northern Rift Valley and Afar region (Ethiopia and Djibouti): *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, 24: 279-325.
- GEZE, F., 1975, New dates on ancient Galla lake levels (Ethiopian Rift Valley): *Bull. Geophys. Obs., Addis Ababa*, 15: 119-124.
- GIANELLI, G. & TEKLEMARIAM, M., 1993, Water-Rock interaction processes in the Alutu-Langanu geothermal field (Ethiopia): *J. Volcan. Geotherm. Res.*, 56: 429-445.
- GILLESPIE, R., STREET-PERROT, A.F. & SWITSUR, R., 1983, Post-glacial arid episodes in Ethiopia have implications for climate prediction: *Nature*, 306: 680-683.
- GROVE, A.T. & GOUDIE, A.S., 1971, Late Quaternary lake levels in the Rift Valley of Southern Ethiopia and elsewhere in Tropical Africa: *Nature*, 234: 403-405.

- , STREET, F.A. & GOUDIE, A.S., 1975, Former lake levels and climatic change in the rift valley of southern Ethiopia: *Geog. Journ.*, 141: 177-202.
- HAYNES, V. & HAAS, H., 1974, Southern Methodist University radiocarbon date list I: *Radiocarbon*, 16: 368-380.
- KIBRET, T. & HARRISON, A.D., 1989, The benthic and weed-bed faunas of Lake Awassa (Rift Valley, Ethiopia): *Hydrobiologia*, 174: 1-15.
- KILENYI, T.I., 1972, Transient and balanced genetic polymorphism as an explanation of variable nodding in the ostracode *Cyprideis torosa*: *Micropaleontology*, 18 (1): 47-63.
- LAURY, R.L. & ALBRITTON, C.C.JR, 1975, Geology of middle stone age archaeological sites in the main Ethiopian Rift Valley: *Geol. Soc. Am. Bull.*, 86: 999-1011.
- LE TURDU, C., TIERCELIN, J.J., GIBERT, E., TRAVI, Y., LEZZAR, K., RICHARD, J.P., MASSAULT, M., GASSE, F., BONNEFILLE, R., DECOBERT, M., GENSOUS, B., JEUDY, V., TAMRAT, E., MOHAMMED, M.U., MARTENS, K., ATNAFU, B., CHERNET, T., WILLIAMSON, D., TAIEB, M., 1999, The Ziway-Shala basin system, Main Ethiopian Rift: Influence of volcanism, tectonics, and climatic forcing on basin formation and sedimentation: *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, 150: 135-177.
- LINDROTH, S., 1956, Taxonomic and zoogeographical studies on the ostracod fauna in the inland waters of East Africa: *Zool. Bidrag from Uppsala*, 30: 41-156.
- LLOYD, E.F., 1977, Geological factors influencing geothermal exploration in the Langan region, Ethiopia. Unpublished MS, 73 pp.
- LOWNDES, A.G., 1932, Report on the Ostracoda: Mr. Omer-Cooper's investigation of the Abyssinian fresh waters: *Proc. Zool. Soc. London*, 3: 677-708.
- MAKIN, M.J., KINGHAM, T.J., WADDAMS, A.E., BIRCHALL, C.J. & TEFERRA, T., 1975, Development prospects in the southern Rift Valley, Ethiopia: Land Resources study 21, Land Resources Division, U.K. Ministry of Overseas Development, Tolworth, England, 270 pp.
- MARTENS, K., 1984, Annotated checklist of non-marine ostracods (Ostracoda, Crustacea) from African inland waters: *Zool. Bijdr., K. Mus. mid. Afr., Terv.*, 20: 1-51.
- , 1988, Seven new species and two new subspecies of *Sclerocypris* Sars, 1924 from Africa, with new records of some other Megalocypridini (Crustacea, Ostracoda): *Hydrobiologia*, 162 (3): 243-273.
- , 1990a, Revision of African *Limnocythere* s.s. BRADY, 1867 (Crustacea, Ostracoda) with special reference to the Eastern Rift Valley Lakes: morphology, taxonomy, evolution and (paleo)ecology: *Arch. Hydrobiol., suppl.* 83 (4): 453-524.
- , 1990b, Speciation and evolution of the genus *Limnocythere* Brady, 1867 s.s. in the East African Galla and Awassa basins: *Cour. Forschungs inst. Senckenb.*, 123: 87-95.
- , 1993, On the taxonomy and zoogeography of the Genus *Gomphocythere* Sars, 1924 (Crustacea, Ostracoda), with a description of a new species from the Nahal Dan (Israel): *Belg. J. Zool.*, 123 (1): 39-54.
- , 1994, Ostracod speciation in ancient lakes: a review. In Martens, K., Goddeeris, B. & Coulter, G. (eds), *Speciation in Ancient Lakes*: *Arch. Hydrobiol. Beih. Ergebn. Limnol.*, 44: 75-96.
- & TUDORANCEA, C., 1991, Seasonality and spatial distribution of the ostracods of Lake Zwai, Ethiopia (Crustacea, Ostracoda): *Freshwater Biology*, 25: 233-241.
- MOHR, P., 1960, Report on a geological excursion through Southern Ethiopia: *Bull. Geophys. Obs. Addis Ababa*, 2: 9-20.
- , 1966, Geological report on the Lake Langan and adjacent plateau regions: *Bull. Geophys. Obs. Addis Ababa*, 9: 59-75.
- , 1967, The Ethiopian Rift System: *Bull. Geophys. Obs. Addis Ababa*, 11: 1-65.
- , MITCHELL, J.G. & REYNOLDS, R.G.H., 1980, Quaternary volcanism and faulting at O'a caldera, Central Ethiopian Rift: *Bulletin Volcanologique*, 43: 173-189.
- MOURGUART, PH., 1987, Les ostracodes lacustres de l'Altiplano bolivien. Le polymorphisme, son intérêt dans les reconstitutions paléohydrologiques et paléoclimatiques de l'Holocène: Thèse 3^{ème} cycle, Bordeaux I, 2191, 263pp.
- , CARBONEL, P., PEYPOUQUET, J.P., WIRRMANN, D. & VARGAS, C., 1986, Late Quaternary palaeohydrology of Lake Huinamarca (Bolivia): scenarios based on ostracod fauna: *Hydrobiologia*, 143: 191-197.
- NEUMANN, O., 1902, From the Somali coast through southern Ethiopia to the Sudan: *Geogr. J.*, 20: 373-401.
- NILSSON, E., 1940, Ancient changes of climate in British East Africa and Abyssinia: a study on ancient lakes and glaciers: *Stockholm Geogr. Annl.*, 22: 1-79.
- PARK, L.E., COHEN, A., MARTENS, K. & BRALEK, R., 2003, The impact of taphonomic processes on interpreting paleoecologic changes in large lake ecosystems: ostracodes in Lakes Tanganyika and Malawi: *Journ. of Paleolimn.*, 30: 127-138.
- PEYPOUQUET, J.P., CARBONEL, P. & HEINZELIN, J.D., 1979, Les ostracodes indicateurs de l'évolution des environnements lacustres de la fin du Cénozoïque dans la branche orientale du Rift africain: *Bull. Inst. Géol. Bassin d'Aquitaine*, 25: 201-219.
- , —, TAIEB, M., TIERCELIN, J.J. & PERINET, G., 1983, Ostracoda and evolution process of paleohydrologic environments in the Hadar Formation (The Afar Depression, Ethiopia). In Maddocks, R.F. (ed.), *Applications of Ostracoda: Eighth Int. Symp. on Ostracoda*, Houston: 277-285.
- , DUCASSE, O., GAYET, J. & PRATVIEL, L., 1980, Agradation et dégradation des tests d'ostracodes. Intérêt pour la connaissance de l'évolution paleohydrologique des domaines margino-littoraux. Cristallisation, déformation, dissolution des carbonates: Réunion spéciale, Bordeaux III: 357-369.
- ROSSETTI, G. & MARTENS, K., 1996, Redescription and morphological variability of *Darwinula stevensoni* (Brady & Robertson, 1870) (Crustacea, Ostracoda): *Bull. Ist. Roy. Sc. Belg., Biol.*, 66: 73-92.
- SAGRI, M., 1995, Land resources inventory, environmental changes analysis and their applications to agriculture in the Abaya lake region (Ethiopia): Report n° 4, Annual report, Florence.
- , 1996, Land resources inventory, environmental changes analysis and their applications to agriculture in the Abaya lake region (Ethiopia): Report n° 6, Half year report, Florence.
- , 1997, Land resources inventory, environmental changes analysis and their applications to agriculture in the lakes region (Ethiopia): Report n° 7, Half year report, Florence.
- SANDBERG, P.A., 1964, The ostracod genus *Cyprideis* in the Americas: *Stockholm Univ., Contr. Geol.* 12: 1-78.
- SOCIETAS INTERNATIONALIS LIMNOLOGIAE, 1959, Symposium sur la classification des eaux saumâtres, Venice. *Arch. Oceanol. Limnol., suppl.*, 250pp.
- STREET, F.A., 1979, Late Quaternary lakes in the Ziway-Shala basin, southern Ethiopia. Ph.D. dissertation, Cambridge, 457pp.
- & GROVE, A.T., 1976, Environmental and climatic implications of late Quaternary lake-level fluctuations in Africa: *Nature*, 261: 385-390.
- TALLING, J.F. & TALLING, I.B., 1965, The chemical composition of African lake waters: *Int. Revue ges. Hydrobiol.*, 50 (3): 421-463.
- TIERCELIN, J.J., LE TURDU, C. & GASSE, F., 1997, Paleoclimates (Abiyata, Shala and Langan lakes) - Excursion guide book. International Symposium: Flood basalts, Rifting and Paleoclimates in the Ethiopian Rift and Afar Depression, Feb 5-7, Addis Ababa, 36pp.
- TUDORANCEA, C., BAXTER, R.M. & FERNANDO, C.H., 1989, A

- comparative limnological study of zoobenthic associations in lakes of the Ethiopian Rift Valley: Arch. Hydrobiol., Suppl. 83: 121-174.
- VAN HARTEN, D., 1996, *Cyprideis torosa* (Ostracoda) revisited: Of salinity, nodes and shell size: Proceedings of 2nd European Ostracodologists Meeting, Glasgow 1993, British Micropaleontological Society, London: 191-194.
- VESPER, B., 1972a, Zur Morphologie und Ökologie von *Cyprideis torosa* (Jones, 1850) (Crustacea, Ostracoda, Cytheridae) unter besonderer Berücksichtigung seiner Biometrie: Mitt. Hamb. Zool. Mus. Inst., 68: 21-77.
- , 1972b, Zur problem der Buckelbildung bei *Cyprideis torosa* (Jones, 1850) (Crustacea, Ostracoda, Cytheridae): Mitt. Hamb. Zool. Mus. Inst., 68: 79-94.
- VON DAMM, D. & EDMOND, A., 1984, Reverse weathering in closed-basin lakes of the Ethiopian Rift Valley: Am. J. Sci., 284: 835-862.
- WENDORF, F., LAURY, R.L., ALBRITTON, C.C., SCHILD, R., HAYNES, C.V., DAMON, P.E., SHAFIQUILLAH, M. & SCARBOUROGH, B., 1975, Dates for the Middle Stone Age of East Africa: Science, 187: 740-742.
- WOLDEGABRIEL, G., ARONSON, J.L. & WALTER, R.C., 1990, Geology, geochronology, and rift basin development in the central sector of the Main Ethiopia Rift: Geol. Soc. Am. Bull., 102: 439-458.

(manuscript received November 28, 2003
accepted April 5, 2004)

Balemwal ATNAFU

Department of Geology and Geophysics
Addis Ababa University
Addis Ababa, Ethiopia

Antonio RUSSO

Dipartimento del Museo di Paleobiologia e dell'Orto Botanico
Università di Modena e Reggio Emilia
Via Università 4, I-41100 Modena, Italy
e-mail: russo@unimo.it