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AGE OF LAKE MALAWI (NYASA) AND WATER LEVEL FLUCTUATIONS

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Abstract. - *Lake Malawi (Nyasa) is one of the few deep-water long-lived lakes that presently exist on earth. It lies in an uncompensated tectonic graben, controlled by differential vertical movements between the rift basin who subsides and the rift shoulders who are uplifted. Active tectonics is the major factor controlling the development and persistence of those deep lakes. For Lake Malawi (Nyasa), climatic influence is also important, due to the small dimensions of the hydrological catchment area and the subtropical climate with long dry seasons. The Malawi rift basin, hosting the lake, started to develop in the late Miocene (since 8.6 Ma), but deep water conditions were acquired only by 4.5 Ma. The lake then dried out almost completely at the beginning of the Pleistocene (from 1.6 to 1.0 Ma), as a consequence of stable tectonic conditions and dry climate. A new regression started at about 0.42 Ma until 0.25 Ma, which is well documented by high-resolution seismic stratigraphy. The tectonic lowering of the overflow sill, through subsidence of the rift floor, combined with erosional incision have lowered the water level by 40m since the late Pleistocene. Short-term, small amplitude lake-level fluctuations are documented by direct observations since 1915.*

Résumé. - *Le lac Malawi (Nyasa), dans la branche occidentale du rift est-africain, est l'un des rares lacs profonds ayant une très longue durée de vie. Il est localisé dans un graben tectonique non compensé, contrôlé par les mouvements différentiels des épaules, montantes, et du sol, subsident. La tectonique active est le facteur principal régissant le développement et la persistance de ce type de lac. L'influence climatique est aussi importante pour le lac Malawi, suite aux faibles dimensions de son bassin-versant et des conditions climatiques relativement sèches. Le bassin tectonique du lac Malawi a commencé à se développer au Miocène tardif (8,6 Ma). Le lac n'est cependant devenu profond, que vers 4,5 Ma. Il s'est asséché presque complètement au début du Pléistocène (1,6-1,0 Ma), pendant une période de stabilité tectonique sous un climat plus sec. Une nouvelle régression, documentée par la stratigraphie sismique de haute résolution, a eu lieu entre 0,42 et 0,25 Ma. Depuis la fin du Pléistocène, le niveau du lac s'est abaissé de près de 40 métres, suite à l'abaissement tectonique et à l'érosion de l'exutoire. L'observation directe, depuis 1915, montre l'existence de fluctuations de plus courte durée et d'amplitude réduite.*

Samenvatting. - *Het Malawimeer (Nyasa) is een van de weinige reeds lang bestaande diepwater meren op aarde. Het is gelegen in een niet-gecompenseerde graben, gecontroleerd door differentiële vertikale bewegingen tussen het inzakkende slenkbekken en de slenkschouders die opgeheven worden. Actieve tektoniek controleert als belangrijkste factor de ontwikkeling en het behoud van deze diepe meren. Voor het Malawimeer is de klimatologische invloed ook van belang ingevolge de kleine dimensie van het hydrologisch vergaarbekken en het subtropisch klimaat met zijn lange droge seizoenen. De ontwikkeling van het Malawislenkbekken begon in het Laat-Mioceen (8.6 Ma). De echte verdieping van het meer startte slechts rond 4.5 Ma. Het meer droogde bijna volledig uit bij het begin van het Pleistoceen (1.6 - 1.0 Ma) tijdens een periode van tektonische stabiliteit onder droog klimaat. Een nieuwe regressie, goed gedocumenteerd door hoge resolutie seismische stratigrafie, vond plaats tussen 0.42 en 0.25 Ma. Sinds het einde van het Pleistoceen is het meerniveau ongeveer 40 meter gedaald door tektonische subsidentie en uitvloei-erosie. Directe observatie sinds 1915 toont het bestaan aan van waterpeil fluctuaties met een korte periode en een kleine amplitude.*

1. INTRODUCTION

The age of formation of Lake Malawi, the fluctuation of water level and its eventual complete drying are essential questions regarding its biological evolution and degree of endemicity.

Lake Malawi (Nyasa) is, together with Lakes Tanganyika and Baikal (Siberia), one of the few deep-water long-lived lakes that presently exist on earth. The common characteristics of these lakes is that they lie in uncompensated tectonic grabens whose subsidence is faster than their filling by sediments. This requires specific and highly active tectonic movements that are typical for active continental rift systems: differential vertical movements between the rift basin who subsides and the rift shoulders who are uplifted. These movements are accommodated by faulting, which generated important seismic activity, controlled the location of hot springs, and probably also favoured the volcanic activity. Active tectonics is therefore the major factor controlling the development and persistence of those deep lakes. In consequence, they are relatively unstable on geological time-scale, because the intensity and the regime of tectonic activity fluctuate with time.

The small dimensions of the hydrological catchment area and the subtropical climate with long dry seasons result in a relative instability of the water level in Lake Malawi, very sensitive to climatic changes

2. GEOGRAPHY AND MORPHOLOGY

The East African rift system lies atop the East African plateau, and consists of two branches, the eastern one, running from the Gulf of Aden to the Kenya (Gregory) rift and the western one, from Lake Albert to the Indian Ocean,through the Tanganyika and Malawi (or Nyasa) rift valleys (Fig. 1). It developed mainly in the Proterozoic mobilebelts, between the Archean cratons. The Western Rift and Kenya Rift follow Proterozoic mobile belts and avoid the Central Tanganyika craton which acted as resistant block (for example, McConnell, 1972). The Western Rift is developed mainly along the Ubende mobile belt characterised by northwest-trending mylonites and shear-zones. The central part of the western branch has a general NW-SE orientation and is occupied by the Tanganyika, Rukwa and Malawi (Nyasa) rift valleys. In these rifts, the Cenozoic basins and major faults are partly superimposed on an older Permo-Triassic (Karoo) rift system (Dypvik *et al.*, 1990; Morley *et al.*, 1992).

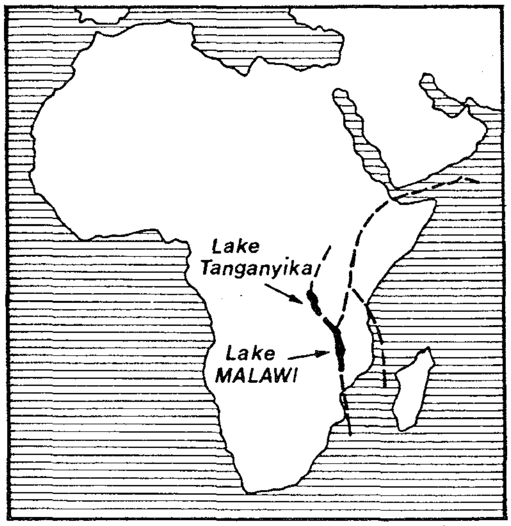


Fig. 1.- Location of the major branches of the East African Rift System, with the location of Lakes Tanganyika and Malawi.

The Malawi rift extends over 900 km from the Rungwe volcanic province in the north to the Urema graben in the south (Fig. 2). The rift sedimentary basin is about 750 km long and 75 km wide. Much of the rift valley floor is occupied by Lake Malawi, 570 km long and on average 60 km wide. The surface of the lake is 474 m above sea level and its floor descends to 225 m below the sea level. Maximum depth is close to 700 m and the flanks of the rift rise 400-2000 m above the surface of the lake. To the north, the Malawi rift is blocked by the development of the Rungwe volcanic provinces, with three major active volcanic centres, culminating at 2940 m (Harkin, 1960). To the south, the Malawi rift ends in Shire plain. The rift structures of Lake Malawi are assumed to be younger than mid-Miocene (Ebinger *et al.*, 1989).

3. AGE OF LAKE FORMATION

There is no direct measurement of the age of formation of Lake Malawi, and also there is no general agreement on its estimated age of forma-

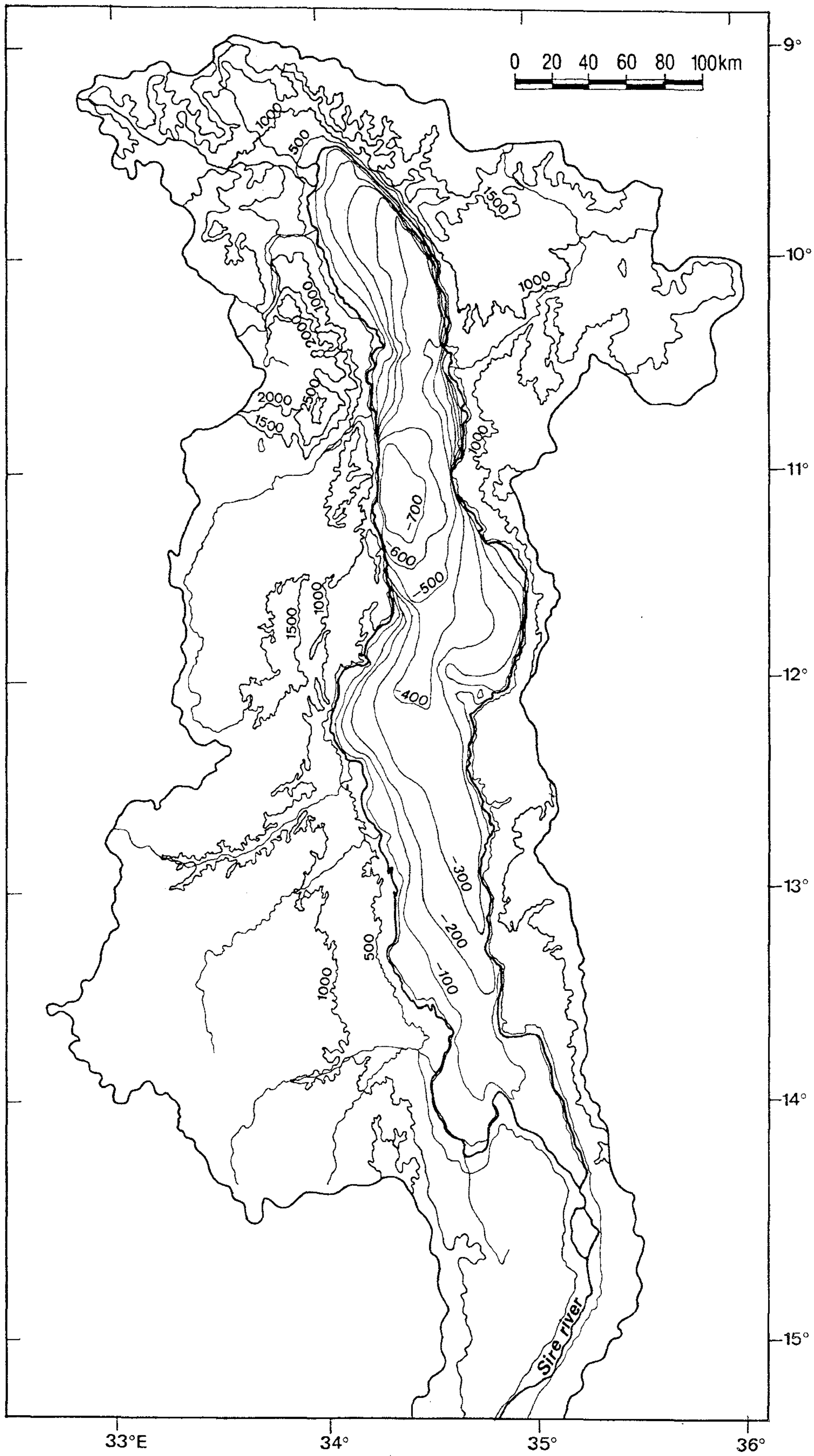


Fig. 2.- Hydrology, topography and bathymetry of the Lake Malawi catchment basin, compiled from Crossley, 1994). Contour lines : meters above sea level. Isobathes: meters below the mean lake water level (473m a.s.l.).

tion. The proposed ages depend mainly on the definition of what is the age of lake formation, and the way of calculating it.

The maximum age for the lake formation is obviously the onset of rifting, since the Lake Malawi occurs in a rift basin. However, there were probably several episodes of rifting in the Malawi rift, as was clearly demonstrated for the Rukwa rift (Wescott *et al.,* 1991). An earlier period of rifting in the area of the present-day Malawi rift probably occurred in the late Paleozoic–Mesozoic, with the depositions of rocks of the Karoo series (Delvaux, 1991). This first rifting stage was followed by a long period of regional uplift, denudation and peneplanation, which resulted in the formation of the "Gondwana peneplain", in the late Jurassic times (King, 1963). The development of a second morphological surface with laterite crust is believed to have occurred in the mid–Miocene (African 1 surface of King, 1963). The latter is generally used as pre–rift reference surface for the estimation of the timing and intensity of vertical movements.

The age of the onset of Tertiary rifting is generally inferred from the age of the first rift–related volcano–clastic deposits, in absence of good stratigraphic ages for this period. The oldest radioisotopic ages obtained from lavas and tuffs in the Rungwe volcanic province, north of the lake depression, range from 5.45 to 8.60 Ma (Ebinger *et al.,* 1989; 1993a). A pebble of basalt in a fluviatile deposit overlying the basement gave an age of 6.27 Ma (Delvaux and Boven, unpublished data). From these data, it is generally concluded that rifting began some 8.6 Ma ago, as manifested by the deposition of lavas, tuffs, fluviatile sands and conglomerate (Betzler and Ring, submitted). It is therefore possible that a shallow lake already existed since that time.

Of interest for the development of endemic species of fauna and flora, is the age of formation of a permanent lake, deep enough to allow speciation and to avoid complete temporary drying. The occurrence of the fluvio–lacustrine lower Chiwondo beds containing fossils dated at 4–5 Ma and the youthful appearance of fault scarps bounding the rift are cited by Crossley and Crow (1980) and Crossley (1982) as evidence for an early Pliocene age of rift lake formation. An increased subsidence of the lake floor between 4.5 and 1.6 Ma is evidenced by Betzler and Ring (submitted), from the investigation of near shore lacustrine Plio/Pleistocene sediments along the northwestern coast of Lake Malawi. Based on this sedimentary record, the age of 4.5 Ma for the first deep lake formation is then proposed (Ring and Betzler, submitted).

4. RIFTING HISTORY

The history of Lake Malawi development is closely related to the history of rifting, driven by tectonic processes. We have already shown that the Malawi rift started its evolution in the late Miocene, at about 8.6 Ma ago. It then evolved in a succession of three tectonic stages.

The oldest Cenozoic deposits are Mio–Pliocene fluvial sands, phonolitic tuffs dated 8.6 Ma in Lake Malawi (Crossley and Crow, 1980; Ring and Betzler, in press) and fluvio–deltaic sands and lacustrine muds from the Rukwa basin (Wescott *et al.,* 1991). Increased subsidence in Pliocene times allowed the accumulation of water-deposited volcanoclastic sediments in the Rungwe volcanic area, separating the Malawi rift basin from the Rukwa depression. (Older Lake Beds in Tanzania and lower part of the Chiwondo Beds in Malawi). Sedimentation occurred contemporaneously with the first two volcanic pulses in the Rungwe volcanic province, between 8.6 and 1.7 Ma (Ebinger *et al.,* 1989; 1993a; Betzler and Ring, submitted). The structural evolution of these rift basins and the related sedimentation and volcanism occurred in a tectonic context dominated by normal faulting with a general extension at a high angle to the rift axis (Delvaux *et al.,* 1992; Ring *et al.,* 1992).

From the late Pliocene to the early Pleistocene, a period of tectonic rest under dry climatic conditions is marked by a low lake level, intense chemical weathering of surface rocks and erosion. Neither sediments nor volcanics were deposited during this period which corresponds to the development of the late Tertiary morphological surface, covered by lateritic soil (African 2 geomorphological surface of King, 1963). It caused an erosional and structural unconformity of Plio–Pleistocene age, over which Quaternary lake beds were deposited (Ebinger *et al.,* 1993a; Ring and Betzler, in press). The maximum duration of this erosional event related to the low lake level is estimated by Ebinger *et al.* (1993a) as 1.6–0.12 Ma. Using on–land data, it is possible to constrain the upper age to 0.57 Ma (Delvaux *et al.*, 1992), and even to 1.0 Ma (on the basis of unpublished new dating of lava flows). It is not known whether the Lake Malawi dried out completely during this period, or if it remained as a restricted shallow lake, possibly with a higher salinity.

During the middle Pleistocene, probably between 1 and 0.4 Ma, a new tectonic regime was established, together with a new pulse of volcanic activity and renewed sedimentation (Delvaux *et al.*, 1992). This second regime is characterised by dominantly strike–slip fault movements, related to a general N–S tectonic compression and E–W extension.

In the late middle Pleistocene, a domal uplift of the region comprised between Lakes Malawi and Rukwa started, centred on the Rungwe – Ngozi area. This caused the regression of Lakes Rukwa and Malawi away from the Rungwe area and the dissection of the Songwe plain by the Songwe river and its tributaries. The stepwise character of the uplift is shown by the profiles of the valleys cross–cutting the Songwe plain. This domal uplift is probably related to the renewed magmatic activity in the Rungwe volcanic province, since middle Pleistocene.

The domal uplift caused the renewed erosion of the volcanic deposits from the Rungwe area, and their redeposition at the margins of the uplifted Rungwe–Songwe area in the lower parts of Rukwa, North–Malawi and Usangu basins. The resulting sediments are the Chitimwe alluvial fan deposits in Malawi and the Younger Lake Beds in Tanzania (Quaternary alluvia). The lower part of the Chitimwe alluvial deposits is dated at 20 Ka (Stokes, in Betzler and Ring, submitted) and a calcitic episode is dated at 10 to 6 Ka (Finney and Johnson, 1991).

An intense explosive volcanic phase occurred in the late Pleistocene, along a NW–SE alignment, and is expressed by abundant explosive craters of the Ngozi and Rungwe volcanoes, and along the Mbaka fault zone. An explosive crater along the Mbaka fault zone is dated at 0.12 Ma, by Ebinger *et al.* (1989). A major explosive eruption of the Rungwe volcano is dated at 11 Ka and covered the whole area with up to one meter of volcanic ashes (Livingstone, 1965). The youngest eruption in the area occurred in the Kiejo volcano, 150-200 years ago (Harkin, 1960). Williams *et al.* (1993) reveal the presence of discrete ash horizons in Holocene sediments from northern

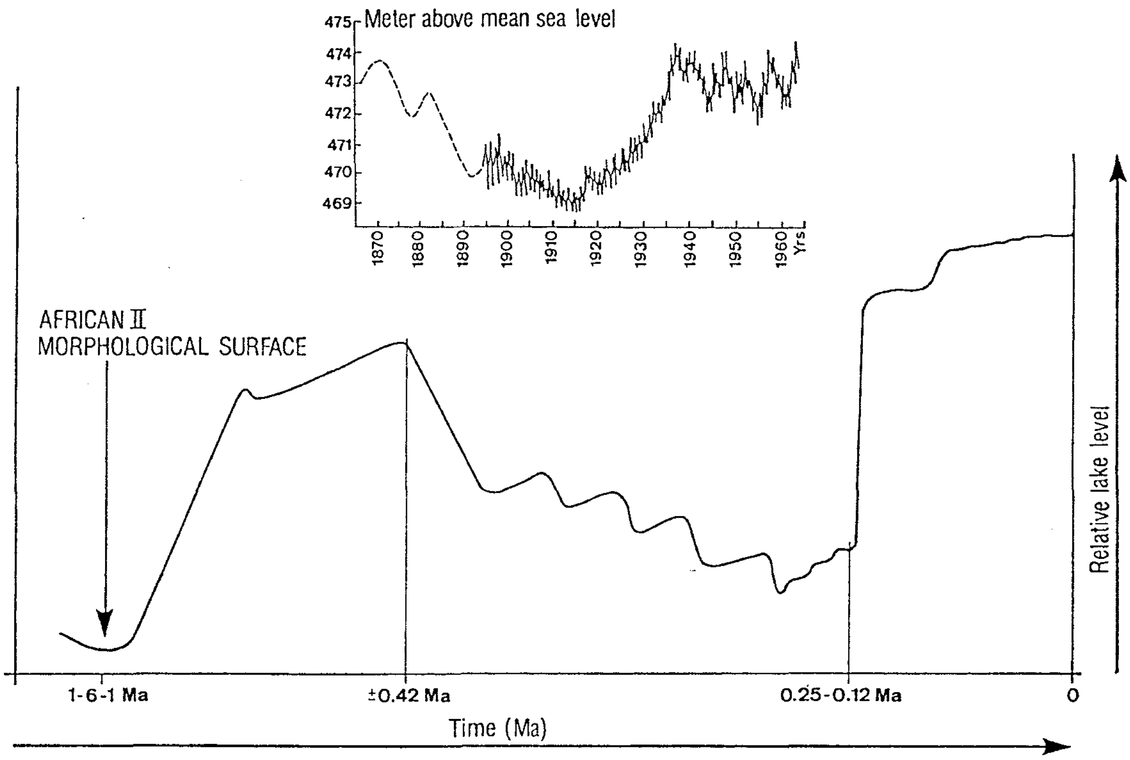


Fig. 3. - Long–term lake level fluctuations from De Vos (1994) and short–term fluctuations, redrawn from Johnson and Ng'ang'a (1990).

Lake Malawi, providing evidences of at least six eruptive episodes in the Rungwe volcanic field, between 9,000 and 300 BP.

The recent tectonic activity of the Mbeya area is characterised by historical eruptions, hot spring activity, active faulting, high seismicity, vertical movements and the continuation of sedimentation in the rift depressions. Vertical movements are expressed by the continuation of the regional domal uplift centred on the Rungwe - Ngozi volcanic area, causing mass transfer through erosion and sedimentation. In addition to the domal uplift, a general tilting of the Kyela plain, with progressive deepening of the northwestern side, is evidenced by Delvaux and Hanon (1993). The analysis of a LANDSAT satellite image of the Kyela plain reveals that the course of the major rivers, flowing from the Rungwe volcanic massif to the lake, are systematically shifted in a western direction (Fig. 4). On the southeastern side of the plain, the rivers are incised in the alluvial plain, with wet areas restricted to the river valleys, while the uplifted terraces are more dry. In addition, along the coast, fossil beaches exist 10-20 m above the present water level. In contrast, the northwestern side of the plain is depressed against the Livingstone fault scarp, the rivers merge into a large swamp and the beach lines are restricted to the present lake shore.

An active fault, locally associated with hydrothermal activity and gas emissions (CO_2, CH_4), displaces the Younger Lake Beds in the Kyela plain. This fault seems to continue in the lake itself, as shown by the presence of underwater gas emissions near Itungi harbour, and as also suggested by high resolution siesmic profiles (Versteeg *et al.,* 1993).

5. LONG-LIVED LAKE LEVEL FLUCTUATIONS

The results of recent multichannel seismic surveys reveal the presence of low stands in Lake Malawi, indicating that since the beginning of lake formation, important lake level fluctuations occurred, with apparent fluctuations of 250–400 m (Scholz and Rosendahl, 1988; Johnson and Davis, 1989; De Vos, 1994). Because similar variations were recognised also in Lake Tanganyika, at least part of these fluctuations can be explained by climatic changes. However, in such an active rift basin, the processes of extensional faulting, basin subsidence, rift flank uplift and volcanism can also induce regional vertical movements and tectonic tilting, that can redistribute water masses and sediments. High-angle sedimentary discordances, 250 to 500 m below the current lake level in Lake Malawi suggest that a low lake stand probably lasted several tens of thousands of years. The Lake Malawi was restricted to a single paleolake, in the northern half of the depression, where the present water depth reaches more than 700 meters. The Lake Tanganyika had three separate paleolakes, because of its basement topography. Scholz and Rozendahl (1988) suggest that these different paleogeographies may be responsible for part of the differences in the endemic fish populations between these two lakes. The age of this unconformity was preliminary estimated by Scholz and Rosendahl (1988) as older than 25,000 years ago. Finney and Johnson (1991) suggest that the period of low water level occurred between 6,000 and 10,000 years, while Scholz and Finney (1994) estimated it between 28,000 and 40,000 years, with an amplitude of about 250 m. However, these age estimations are questionable.

A recent detailed investigation of sedimentation processes in the Livingstone basin, at the northern extremity of the lake, by high resolution seismic profiles brings new and more precise data on lake regression and transgression (De Vos, 1994). Correlations with on-land geological evolution in the Rungwe area (Delvaux and Hanon, 1993) also allow to precise the dating of this regressive phase. De Vos concluded that a stepwise progressive regression of the lake level started at about 0.42 Ma, until 0.25 Ma. It is followed by a rapid transgression between 0.25 and 0.12 Ma (Fig. 3).

It results that Lake Malawi had two important regression phases with low lake level and erosion of lake sediments. The first regression corresponds to the unconformity between late Pliocene and early Pleistocene sediments (1.6–1.0 Ma), and was probably caused by tectonic quietness under dry climate. The following transgression corresponds to a marked change in tectonic regime and intensification of fault activity. After a high stand of the lake level, a stepwise progressive regression led to a new major erosion surface and sediment unconformity. The latter is best

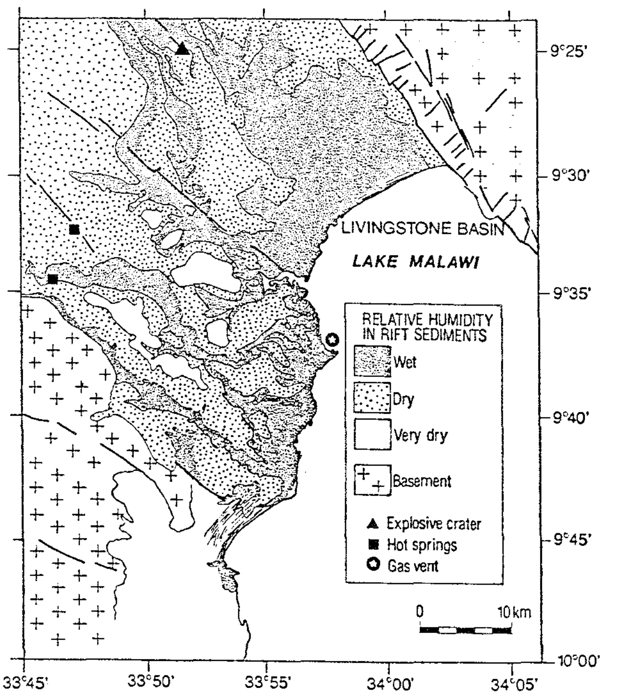


Fig. 4

Fig. 4. - Interpretation of a Landsat TM false-colour composition of the Kyela plain at the northern extremity of Lake Malawi, taken during the dry season. The soil relative moisture is estimated from the vegetation type. The wet area corresponds to dense tropical vegetation with green leaves. The dry areas correspond to cultivated fields. Note the presence of uplifted fossil beach lines along the coast at the southern side of the plain (in Malawi) and active beach lines along the northwestern coast (reprinted from Delvaux and Hanon, 1993).

Fig. 5.- Old river terrace along the Lupingu river, Lupingu (northwestern coast).

Fig. 6.- V-shaped profile of the lower part of the Ukenju river valley, evidencing renewed erosion due to the lowering of the lake base level.

Fig. 7.- Trace of higher water level on an isolated rock, up to about 1 m above the lake level at the end of the dry season, near Ukenju (November 1992).

Fig. 8.- Trunks of dead trees emerging from the lake, near Manda (October 1993).

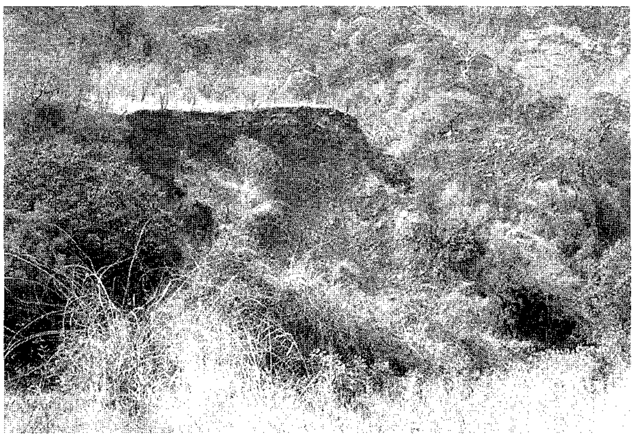


Fig. 5

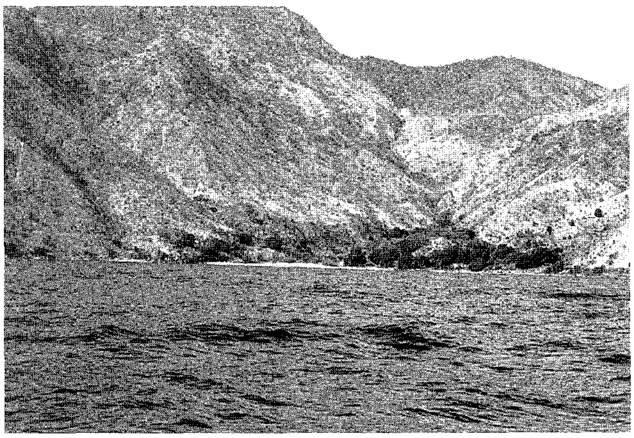
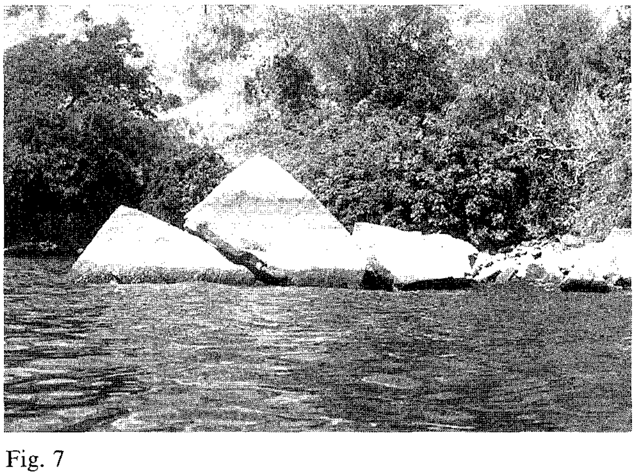


Fig. 6



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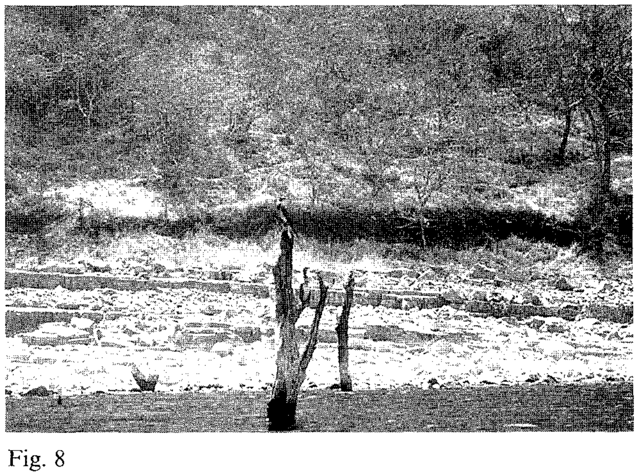

Fig. 8

estimated between 0.42 and 0.25–0.11 Ma, and may have been induced by a major climatic change. A rapid transgression followed, and the high stand water level was progressively restored, with minor short-term fluctuations.

6. SHORT-LIVED LAKE LEVEL FLUCTUATIONS

In the course of its history, the water level in Lake Malawi fluctuated as much as 250–400 m, as a consequence of climatic changes, tectonic subsidence and erosion of the outlet. Lake Malawi has to be considered as a dynamic system, being enclosed in an active rift setting. The tectonic depression is formed by the conjunction of rift floor subsidence and rift shoulder uplift. Most part of the Malawi basin is flooded, the tectonic depression is uncompensated (not completely filled by sediments) and the water is thermally stratified. In the course of its evolution, a series of major rivers have been captured by the Malawi drainage system, so that the catchment area is more than the double of the lake area (Fig. 2). In the present climatic conditions, this enables the lake to be slightly overflooded by fresh water, and the water level is generally controlled by the altitude of the outlet, via the Zira river. The balance between the catchment area and the climatic conditions is important in determining whether the rift basin is filled to an overflow level by fresh water (e.g. Lakes Malawi and Tanganyika), or is partly occupied by an enclosed, more saline lake (e.g. Lakes Rukwa and saline lakes of the Rukwa rift).

The location of the outlet has also its importance on the long-term stability of the maximum water level. The outlet of Lake Malawi is located at its southern extremity, in the valley floor, while the one of Lake Tanganyika is located on its western side, cutting the rift shoulder. It is well known that in rift depressions, long-term tectonic movements tend to lower the rift floor and rise the rift shoulders. For Lake Malawi, the lowering of the overflow sill, through subsidence of the rift floor since the late Pleistocene is estimated to some 30 m. In addition, erosional incision of the overflow sill has lowered the lake level by a further 7 m (Crossley and Davison-Hirschmann, 1982). This lowering of the base level caused the incision of all inflowing rivers into their alluvial deposits, and left perched lacustrine terraces around the entire lake (e.g. terraces at Lupingu and Ukenju, Figs. 5, 6).

Lake Rukwa is in close equilibrium between the rainfall inflow and the annual evaporation losses from the lake surface. Consequently, the water level is very sensitive to climatic variations. Seasonal water level fluctuations are represented by a mean 1100 mm fall during the dry season (Fig. 7). Fluctuations of a few meters occur over short periods (10 years), while longer-period fluctuations are of 7 meters or more (Fig. 4). Changes to a more humid climate will not have a great impact on the lake level rise, because of the limiting effect of the overflow. On the other hand, a change to a dryer climate will result in interruption of the outflowing and in substantial lowering of the lake level. Because of the generally steep bathymetric gradients, the change in lake surface area required to equilibrate the evaporation in dryer climatic conditions can only be achieved by a large fall in lake level.

Based on archaeological and radiocarbon dating, Owen *et al.* (1990) evidence recent lake level fluctuations in the last two thousand years. Former higher levels, close to the present one occurred at the beginning of the first millennium A.D., around the 10th century, during the 15th century and in the present century, with a peak in 1981. Low periods are suggested in the 6th and 13th centuries, and from 1400 to 1850 A.D., with a important drop of 108–150 m. At present, the basin is flooded to overflow level, but in 1915, the lake level was several meters lower than the present one and no outflow occurred (Crossley, 1984). Three beach ridges, related to high lake levels were recognised. A submerged beach line, at least 7 m below the 1915 low level has been found at several places. Dead trunks of old trees under the water, near Manda also reflect recent lowering of the lake level (Fig. 8). After the modern flood peak in 1981, the lake level is slightly but continuously dropping. Since the beginning of our field investigation in the region of Lake Malawi, in 1989, the lake level dropped of about 1–2 meters. This causes some problems for boat circulation in the Itungi harbour, at the northern extremity of the lake.

7. ASPECTS OF DEEP WATER HABITATS

The conjunction of lake bathymetry and tropical climatic conditions produces thermal stratification of the lake, with the oxic epilimnion down to 250m depth and anoxic hypolimnion, deeper (Crossley, 1984). Eccles (1974) reports that below 250m, the lake is homothermal at about 22.5 °C and is anoxic. The temperature of the upper 60 m reaches 27 °C during the wet season, and decreases during the dry season, due to rapid evaporative cooling. Exceptionally in 1937, the temperature of the epilimnion approached the 22.5 °C of the hypolimnion value, causing local partial water mixing and mass fish mortality off Nkhata Bay.

The temperature difference between the epilimnion and hypolimnion prevents water mixing, but the small difference is a factor of instability of the water colomn. In addition, during the last 33 years, the temperature of the deep water increased by 0.02 °C annually (Mueller and Forstner, 1973). Morever, the discharge of geothermal solutions and gases (CO_2 and CH_4) and the presence of gas accumulation under a small cover of sediments (a few meters), that was revealed by high resolution seismic profiling, are additional factors that may cause the overturning of the water column, releasing poisonous gases and causing the upwelling of the methane-charged bottom water of the anoxic lake (Ebinger *et al.*, 1993b).

Iron-rich sediments are accumulating on the shallower parts of the lake floor, above the depth of 250 m (Muller and Forstner, 1973). The latter suggest that the iron precipitates when the iron and silica-rich solutions that rise trough the lake sediments come into contact with the oxic epilimnion waters.

8. CONCLUSIONS

Lake Malawi is a relatively unstable deep water lacustrine system, controlled dominantly by tectonic and climatic factors. Its age of formation is still controversial, but it seems reasonable to consider the following stages. The Malawi rift started to develop since 8.6 Ma, but deep water conditions were acquired only by 4.5 Ma. A major erosional unconformity at the beginning of the Pleistocene (from 1.6 to 1.0 Ma) marks a long period of tectonic stability and dry climatic conditions, during which the lake dried out almost completely. The short-term fluctuations did not affect substantially the lacustrine habitats. The stability of the water column is relatively weak, due to the small difference in temperature between the oxic epilimnion and the anoxic hypolimnion.

REFERENCES

Betzler, C. and Ring, U. - Nearshore lacustrine sedimentary record of an active rift: the Plio/Pleistocene deposits of Lake Malawi (East African Rift). Submitted to Sedimentology.

Crossley, R. and Crow, M.J. (1980) - The Malawi rift. - *In:* Geodynamic Evolution of the Afro-Arabian rift system, Accademia Nazionale dei Lincei, 47, 77-87, Rome.

Crossley, R. (1982) - Late Cenozoic stratigraphy of the Karonga area in the Malawi rift. - *Palaeoecol. Afr.*, **15,** 139-144.

Crossley, R. (1984) - Controls of sedimentation in the Malawi rift valley, Central Africa. - *Sedimentary Geology,* **40,** 33-50.

Crossley, R. and Davison-Hirschmann, S. (1982) - High levels of Lake Malawi during the late Quaternary. - *In:* J.A. Coetsee and E.M. Van Zinderen-Bakker Sr. (Eds.), Paleoecology of Africa, 15. Balkema, Rotterdam, pp.109-115.

Delvaux D. and Hanon, M. (1993) - Neotectonics of the Mbeya area, SW Tanzania. - *Mus. roy. Afr. centr. Tervuren (Belg.), Dept. Géol. Min., Rapp. ann., 1991-1992,* 87-97.

Delvaux, D., Levi, K., Kajara, R. and Sarota, J. (1992) -Cenozoic paleostress and kinematic evolution of the Rukwa - North Malawi rift valley (East African rift system). - *Bull. Centres Rech. Explor.-Prod. Elf Aquitaine,* **16,** 383-406.

Delvaux, D. (1991) - The Karroo to Recent rifting in the western branch of the East-African rift system: A bibliographical synthesis. - *Mus. roy. Afr. centr., Tervuren (Belg.), Dépt. Géol. Min., Rapp. ann. 1989-1990,* 63-83.

De Vos, A. (1994) - Pliocene en Kwartaire evolutie van het Livingstone bekken (Malawi rift, Tanzanie) afgeleid uit hoge-resolutie reflectieseismische profielen. - *Licenciaat thesis, Universiteit Gent (Belgium),* 91 p.

Dypvik, H., Nestby, H., Rudent, F., Aagaard, P., Johansson, T., Msindai, J. and Massay, C. (1990) - Upper Paleozoic and Mesozoic sedimentation in the Rukwa-Tukuyu Region, Tanzania. - *J. Afr. Earth Sci.,* **11,** 437-456.

Ebinger, C.J., Deino, A.L., Drake, R.E. and Thesa, A.L. (1989) - Chronology of vulcanism and rift basin propagation : Rungwe volcanic provinces, East Africa. - *J. Geophys. Res.,* **94,** 15783-15803.

Ebinger, C.J., Deino, A.L., Tesha, A.L., Becker, T. and Ring, U. (1993a) - Tectonic control of rift basin morphology: Evolution of the northern Malawi (Nyasa) rift. - *J. Geophys. Res,* **98 (B10),** 17821-17836.

Ebinger, C., Klerkx, J., Delvaux, D. and Wust, A. (1993b) -Evaluation of natural hazards in the northern part of the Malawi rift (Tanzania). - *Mus. roy. Afr. centr., Tervuren (Belg.), Dépt. Géol. Min., Rapp. ann. 1991-1992,* 83-86.

Eccles, D. (1974) - An outline of the physical limnology of Lake Malawi (Lake Nyasa). - *Limnol. Oceanogr.,* **19,** 730–742.

Finney, B.P. and Johnson, T.C. (1991) - Sedimentation in Lake Malawi (East Africa) during the past 10.000 years: a continuous paleoclimatic record from the southern tropics. -*Palaeogeogr. Palaeoclimatol. Palaeoecol.,* **85,** 351-366.

Harkin, D.A. (1960) - The Rungwe volcanics at the northern end of Lake Nyasa.- *Mem. Geol. Surv. Tanganyika,* **11,** 172 p.

Johnson, T.C. and Davis, T.W. (1989) - High resolution profiles from Lake Malawi, Africa. - *J. Afr. Earth. Sci.,* **8,** 383-392.

Johnson, T.C. and Ng'ang'a, P. (1990) - Reflections on a rift lake. - *In:* Lacustrine basin exploration - Case studies and modern analogs. (Katz, B.J., Ed.). Am. Ass. Petr. Geol., Mem., 50. 113-135.

King, L.C. (1963) - South African Scenery. *Oliver and Boyd* (Eds.) Edinburgh, 699 p.

Mc Connell, R.B. (1972) - Geological development of the rift system of eastern Africa. - *Bull. Geol Soc. Am.,* **83,** 2549-2572.

Morley, C.K., Cunningham, S.M., Harper, R.M. and Wescott, W.A. (1992) - Geology and geophysics of the Rukwa rift, East Africa. - *Tectonics,* **11,** 68–81.

Muller, G. and Forstner, U. (1973) - Recent iron ore formation in Lake Malawi, Africa. - *Mineralium Deposita,* **8,** 278–290.

Owen, R.B., Crossley, R., Johnson, T.C., Davison-Hirschmann, S., Tweddle, D. and Engstrom, D.E. (1990) - Major low levels of Lake Malawi and implications for evolution rates in cichlid fishes. - *Proceedings Royal Soc. London,* **B240,** 519–553.

Ring, U. and Betzler, C. - Architecture, Tectonics and Sedimentation of the Malawi Rift (East Africa). Zeitschrift Deutsche Geologische Gesellschaft (in press).

Ring, U., Betzler, C. and Delvaux, D. (1992) - Normal vs. strike-slip faulting during rift development in East Africa: the Malawi rift. - *Geology,* **20,** 1015–1018.

Scholz, C.A. and Finney, B.P. (1994) - Late Quaternary sequence stratigraphy of Lake Malawi (Nyasa), Africa. - *Sedimentology,* **41,** 163–179.

Scholz, C.A. and Rozendahl, B.R. (1988) - Low lake stands in Lakes Malawi and Tanganyika, East Africa, delineated from multifold seismic data. - *Science,* **240,** 1645–1648.

Versteeg, W., Van Heuverswyn, A., Fernandez-Alonso, M., Van Rensbergen, P., Back, S. and Klerkx, J. (1993) - Tectonics and sedimentation of the northern part of the Livingstone Basin, Lake Nyasa (Tanzania). - *Abstract supplement 1 to TERRA nova,* **5,** p. 736.

Wescott, W.A., Krebs, W.K., Engelhardt, D.W. and Cunningham, S.M. (1991) - New biostratigraphic age dates from the Lake Rukwa rift basin in Western Tanzania. - *Am. Ass. Petr. Geol. Bull.,* **75(7),** 1255–1263.

Williams, T.M., Henney, P.J. and Owen, R.B. (1993) - Recent eruptive episodes of the Rungwe volcanic field (Tanzania) recorded in lacustrine sediments of the Northern Malawi rift. - *J. Afr. Earth Sci.,* **17,** 33–39.