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Tectonic, climatic and hydrothermal control on sedimentation and water chemistry of northern Lake Malawi (Nyasa), Tanzania

Philippe Branchu [a,1], Laurent Bergonzini [b,2], Damien Delvaux [c,*], Marc De Batist [d,3], Vladimir Golubev [e,4], Marc Benedetti [f,5], Jean Klerkx [g]

[a] *CEREGE, UMR 6635, Europôle Méditerranéen de l'Arbois, BP 80, 13545 Aix en Provence cedex 04, France*
[b] *UMR-CNRS 8148 IDES, Université Paris-Sud, Orsay, France*
[c] *Royal Museum for Central Africa, Department of Geology and Mineralogy, Leuvensesteenweg 13, B-3080, Tervuren, Belgium*
[d] *Renard Centre of Marine Geology, Universiteit Gent, Belgium*
[e] *Institute of the Earth's Crust, Irkutsk, Russia*
[f] *Laboratoire de Géochimie des eaux, UMR CNRS 7047, Université Denis Diderot, Paris, France*
[g] *International Bureau for Environmental Studies, Brussels, Belgium*

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Abstract

This paper presents a multi-disciplinary characterisation of processes that influence sedimentation and lake water chemistry in the northern part of the Lake Malawi (or Lake Nyasa), East Africa. This characterisation is based on geophysical (heat-flow), tectonic, hydrological, hydrochemical (major elements, stable isotopes) and sedimentological (seismic profiles, core mineralogy) studies of data acquired from 1990 to 1994 during the CASIMIR project (Comparative Analysis of Sedimentary Infill Mechanisms in Rifts).

Sub-surface activity is expressed through seismic and volcanic activity, as well as elevated heat-flow values, both beneath the lake and the surrounding area; hydrothermal activity is observed in the watershed however it was not clearly identified in the sub-lacustrine environment. Relatively high heat-flow values (80–90 mW/m^2) and the chemical composition of hydrothermal fluids in hot springs suggest the presence of a magmatic body at depth.

The influence of Quaternary tectonic activity on sedimentary dynamics and infilling is observed not only on land but also in the lake through high-resolution seismic profiles. The main feature is a general tilting of the Kyela Plain as shown by a shift in the river course. The Quaternary stacking pattern of seven sedimentary sequences identified on a grid of high-resolution seismic reflection profiles represents a complete long-term lake-level cycle, from a lake lowstand at about 320 m below the present level to the present-day lake highstand. The North-Kiwira and Songwe River delta systems, composed of a number of stacked lobes, were developed in response to the interplay between gradual lake-level rise, tectonic movement and sediment input. The river dynamics is also recorded in a short core by a mineralogical evolution probably due to a decrease of detrital inputs from the Songwe River in response to hydroclimatic changes. Such changes are very important as this northern part of the watershed is considered as a recharge zone for the entire lake. Sedimentological patterns (from shallow depth to about 240 m water depth) and hydrochemistry are both influenced by watershed characteristics (pedology, geology, vegetation, hydrology, climate, etc.) but also by lacustrine biological processes: diatom productivity in epilimnetic water and degradation or preservation in deeper waters.

* Corresponding author. Tel.: +32 2 7695426; fax: +32 2 7695432.
E-mail addresses: pons.branchu@wanadoo.fr (P. Branchu), lbergo@geol.u-psud.fr (L. Bergonzini), damien.delvaux@africamuseum.be (D. Delvaux), Marc.DeBatist@UGent.be (M. De Batist), golubev@earth.crust.irk.ru (V. Golubev), benedett@cicrp.jussieu.fr (M. Benedetti), jklerkx@ibes.be (J. Klerkx).
[1] Present address: Centre GEOTOP-UQAM-McGill - CP 8888, succursale Centre-Ville, Montréal, Qué., Canada H3C 3P8. Tel.: +1 514 495 4691; fax: +1 514 987 3635.
[2] Fax: +33 1 6915 4917.
[3] Fax: +32 9 264 4967.
[4] Fax: +39 52 462 900.
[5] Fax: +33 1 4427 8277.

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Physico-chemistry and isotopic data of epi- and metalimnetic waters document the importance of the various water sources but also of evaporation and mixing processes linked to the thermo-haline stratification. Even if hydrothernal discharges have not been observed in the lake, they contribute to the lake chemistry at least through riverine inputs (Kiwira River).

Keywords: East African Rift; Lake Malawi (Nyasa); Quaternary; Tectonics; Seismic profiles; Heat flow; Sediments; Water chemistry; Climate

1. Introduction

Lake Malawi or Nyasa (Fig. 1) is the second largest lake of the East African Rift by volume and the fifth largest in the world. As this water body contains 7% of the world's free surface fresh water, its study is extremely important for the proper management of freshwater resources. The creation and evolution of Lake Malawi, like others in the rift, was and still is closely linked with regional geological activity.

The purpose of the present paper is to evaluate the influence of endogenous and exogenous processes on the recent evolution of the Livingstone (or Karonga) Basin (northern basin of the lake) by combining different geological and limnological approaches. These included studies of active tectonic movements on land and those expressed by the lake bottom topography, high-resolution reflection seismic profiling to explore the sedimentary infill and the structural deformations affecting it, heat flow measurements, water chemistry and sediment mineralogy. These different approaches were performed within the framework of the CASIMIR project (Comparative Analysis of Sedimentary Infill Mechanisms In Rifts).

2. Materials and methods

All data presented here were collected during different field expeditions organised between 1990 and 1994 within the framework of the CASIMIR project. All lake operations were performed aboard the *Nyanja* vessel.

The tectonic context of the area was characterised using published geological informations (maps, catalogues and papers), fieldwork and the interpretation of Landsat TM images.

Thirteen seismic profiles (Fig. 1) were acquired in October 1992 using a Centipede-sparker-seismic source (frequency range: 150–1500 Hz, when operated at 300 J) and a single channel streamer (De Batist et al., 1996).

A total of 32 heat-flow measurements were performed in the northern part of the lake during the 1991, 1992 and 1993 fieldwork campaigns (Table 1) using a non-autonomous cable thermoprobe which measures the in situ temperature and thermal conductivity of the bottom sediments (Golubev and Klerkx, 1993).

Water and sediment samples for geochemical analysis were collected in the Livingstone Basin in October 1993 (Fig. 1). Three water columns (water depths from 200 to

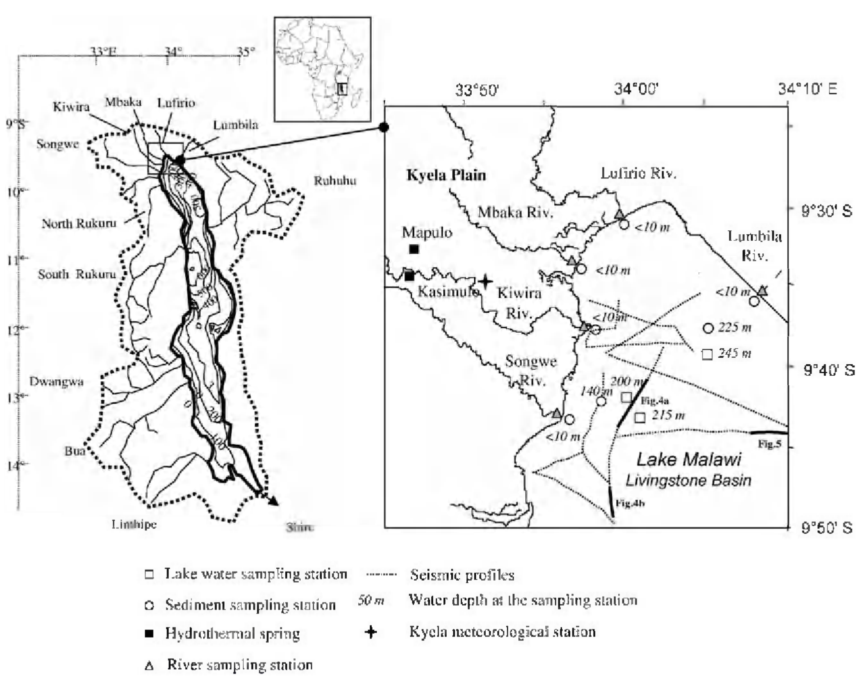

Fig. 1. Schematic bathymetric (from Johnson and Davis, 1989) and hydrographic map of Lake Malawi and locations of sediment/water sampling stations and seismic profiles in the Livingstone basin and its catchment. Inset box shows location of Lake Malawi in Africa.

Table 1
Heat flow through the bottom of Lake Malawi (Golubev and Klerkx, 1993; Golubev, personal communication)

Station	Longitude (East)	Latitude (South)	Q observed (mW/m^2)
1	34°03.00′	−9°39.00′	33
2	34°02.15′	−9°42.01′	24
3	34°01.98′	−9°41.82′	41
4	34°04.44′	−9°40.77′	15
5	34°07.23′	−9°37.09′	−7
6	34°05.64′	−9°41.63′	27
7	34°05.93′	−9°44.86′	37
8	34°06.05′	−9°46.99′	45
9	34°04.31′	−9°44.48′	24
10	34°07.60′	−9°37.49′	14
11	34°00.66′	−9°41.24′	50
12	34°00.98′	−9°41.05′	43
13	34°01.19′	−9°42.83′	72
14	34°05.9′	−9°39.04′	20
15	34°30.31′	−10°04.63′	21
16	34°00.98′	−9°40.44′	32
17	34°00.44′	−9°41.02	86
18	34°00.10′	−9°41.40′	87
19	34°00.31′	−9°41.77′	60
20	33°59.95′	−9°42.10′	83
21	33°59.62	−9°42.23′	79
22	33°59.11′	−9°42.00′	71
23	34°00.02′	−9°44.02′	80
24	34°00.55′	−9°43.26′	78
25	34°01.16′	−9°42.82′	87
26	34°01.90′	−9°42.28′	108
27	34°02.98′	−9°41.45′	45
28	34°03.82′	−9°40.08′	24
29	34°03.43′	−9°40.57′	41
30	34°02.24′	−9°46.28′	45
31	34°07.08′	−9°36.19′	15
32	34°07.28′	−9°36.00′	25

245 m) were sampled using 5 L PVC Hydro-Bios® bottles (Fig. 1). Five rivers (Lumbila, Lufirio, Mbaka, Kiwira and Songwe) and two hydrothermal springs (Mapulo and Kasimulo) were sampled on land (Fig. 1). Short cores were sampled in the river mouths (water depth <10 m) and at 140 and 225 m water depth using a Bowers & Connelly® multi-corer (Fig. 1). Electrical conductivity and temperature (°C) were measured in situ at each site using a sealogger CTD SBE 25 probe (Sea-Bird Electronics®) for lake waters and a hand-held pH-conductivity-thermometer for other waters. pH was measured in the laboratory (in France) for lake waters and in situ for other samples. Collected water samples were filtered (0.01 μm) and treated (sub-sampling and acidification) in the field and then stored in polypropylene bottles in the dark at 4 °C. Cations (Na, K, Ca, Mg) and anions (Cl, SO_4) were determined by capillary electrophoresis in acidified and unacidified subsamples, respectively. Si was determined by ICP-OES (Inductively Coupled Plasma – Optical Emission Spectrometry) and alkalinity was measured in the laboratory by potentiometric titration. Chemical analyses were performed at the CEREGE (Centre Européen de Recherche et d'Enseignement en Géosciences de l'Environnement) in France. For isotopic analysis untreated water samples were stored in amber glass bottles having a double closure. Samples were analysed for oxygen and deuterium isotopic ratios ($\delta^{18}O$ and $\delta^{2}H$) at the IDES Laboratory (Orsay, France) following the experimental protocols of Epstein and Mayeda (1953) and Coleman et al. (1982). Isotopic ratios are expressed in ‰ relative to SMOW (Standard Mean Ocean Water). Analytical uncertainties are ±0.2 and ±2, respectively for $\delta^{18}O$ and $\delta^{2}H$. X-ray diffraction was performed at the CEREGE on dried and sieved (80 μm) sediment samples and on dried filters used for river water processing (see above).

3. Geological, geographical, limnological and climatological setting

The Malawi Rift is the southernmost rift basin along the western branch of the East African Rift System (Figs. 1 and 2). It consists of several individual sub-basins which exhibit a typical asymmetric half-graben architecture (Reynolds and Rosendahl, 1984; Ebinger et al., 1984, 1987; Rosendahl, 1987), a common structure in many continental rifts (Bosworth, 1985). According to classical views, rifting kinematics have remained constant throughout the evolution of the Malawi Rift, with extension occurring either along a W/WSW–E/ENE (Ebinger et al., 1987, 1989; Morley, 1988; Morley et al., 1992) or a WNW/NW–ESE/SE (Tiercelin et al., 1988; Chorowicz, 1989; Wheeler and Karson, 1989) direction. An alternative view (Delvaux et al., 1992; Ring et al., 1992) proposes two successive phases of rift formation, with an early phase of normal faulting occurring during WSW–ENE extension followed by a phase dominated by strike-slip motion along a WNW/NW–ESE/SE direction. This evolution in tectonic control of the basin influenced its configuration and overall sedimentation pattern. During the first phase, half-grabens were formed and the general basin morphology of the Malawi Rift was created. In the second phase, NW–SE oriented sub-basins were formed due to transtension while transpression led to localised uplifts.

The main part of the Malawi Rift is occupied by Lake Malawi (or Lake Nyasa), which has a volume of 7790 km^3 (Vollmer et al., 2002), a N–S length of 500 km and a maximum depth of 700 m. The lake is divided into seven sub-basins corresponding to the half-graben architecture described above. The morphology of the Malawi Rift also influences the local climatic and hydrologic regimes, while the hydrology and hydrodynamics of the lake itself are, in turn, strongly influenced by the climate (Eccles, 1974). The climate is tropical with a "dry season" from May to October, characterised by dry cooler conditions and a fairly constant southerly wind, and a "wet season" during the rest of the year, characterised by wetter and warmer conditions. Lake surface water temperatures follow this seasonality with a maximum temperature (28 °C) at the end of February or the beginning of March and a minimum temperature (23 °C) in July and August when the water is refreshed by southerly winds. This period

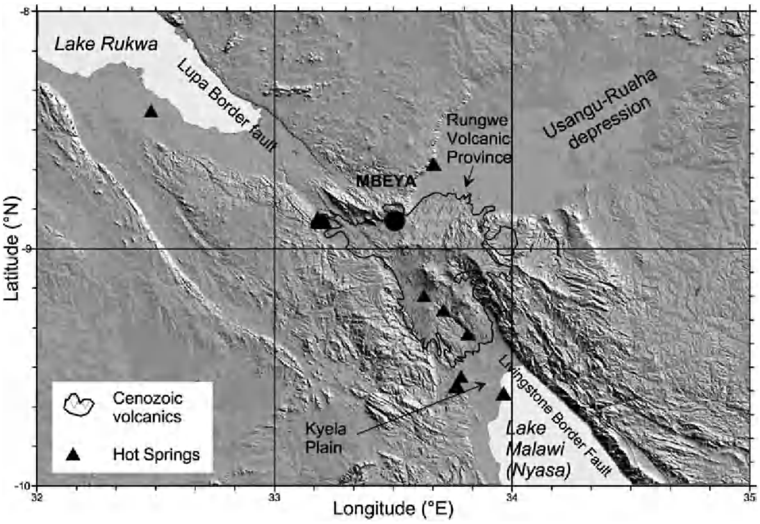

Fig. 2. The Mbeya triple junction and the Rungwe volcanic province between the Rukwa and Malawi rifts and the Usangu–Ruaha depression. The Rungwe volcanics lie at the intersection between the NE-trending basin of Livingstone at the NE extremity of the Malawi rift, the NE-trending Rukwa–Songwe basin at the SE extremity of the Rukwa rift and the NW-trending Usangu rift basin. This triple junction is seismically active, has many active hot springs and the last volcanic eruption happened about 200 years ago.

corresponds to the occurrence of upwelling and deep currents of cold water in the southern part of the lake (Eccles, 1974). The thermocline is located at 80–100 m and develops from September to March (Eccles, 1974). Lake Malawi is a meromictic lake and above the thermocline, in the epilimnion, the water column is well mixed (Eccles, 1974). Below 250–300 m, in the hypolimnion, oxygen is not detected in the lake water (Gonfiantini et al., 1979; Halfman, 1993). There is thus a partial mixing of the first 250 m of the water column (Vollmer et al., 2002).

The Livingstone (or Karonga) Basin, the northernmost sub-basin, is partly occupied by the Kyela Plain and shows a particularly well-expressed down-to-the-east half-graben asymmetry. The submerged portion of the basin is limited at its eastern side by the 2000 m high scarp of the Livingstone Border Fault (Fig. 2). It is deeper in this part (about 550 m water depth) and shoals to the southwest via a series of tilted fault blocks (Scholz et al., 1989; Specht and Rosendahl, 1989).

Meteorological stations at Kyela (Fig. 1), Musekera (9°20′ S – 33°41′ E) and Tukuyu (9°15′ S – 33°38′ E), in the northern part of the lake watershed, report a mean annual rainfall of 2500 mm year^{-1}, which is about twice that reported for the entire lake watershed (1350 mm year^{-1}) as well as from stations farther north (Mbeya: 1000 mm year^{-1}) and south (Karonga: 1200 mm year^{-1}). The up to 2700 m high mountains surrounding the northern shores of Lake Malawi are responsible for the high precipitation rates in this area.

River discharge in the Livingstone Basin is much higher than in the southern part of the lake (Bergonzini, 1998). Lake watershed (126 500 km^2, including the lake) is mainly located on its western coast (Fig. 1), which includes the watersheds of the Songwe, North and South Rukuru, Dwanga, Bua and Linthipe Rivers (Fig. 1). The eastern part of the basin is mainly drained by the Ruhuhu River (Fig. 1). In the northern part of the basin the Songwe, Kiwira, Mbaka, Lufirio and Lumbila Rivers (Fig. 1) drain the Poroto-Rungwe and Livingstone mountains; owing to heavy precipitation in this area these rivers have a very high annual discharge rate (Bergonzini, 1998).

4. Land and sub-lacustrine evidence of tectonic activity in the Livingstone Basin

The Kyela Plain is located at the northern extremity of Lake Malawi (Figs. 1 and 2). This part of the Malawi Rift basin is almost perfectly aligned with the south-eastern extremity of the Rukwa Rift valley, with which it forms a dominant NW–SE rift trend, and is structurally connected with the transversal NE–SW trending Usangu-Ruaha depression (Fig. 2). This configuration defines a rift–rift–rift triple junction, on the centre of which is developed the Rungwe volcanic province (Harkin, 1960; Ebinger et al., 1989). The area is known to be seismically active (Camelbeeck and Iranga, 1996), with volcanic eruptions occurring until early historical times and hot spring activity still found today.

Cenozoic rifting is believed to start at about 8 Ma ago (Late Miocene) in the Mbeya triple junction area via asymmetric normal faulting, block tilting and basin subsidence (Ebinger et al., 1989, 1993). Sedimentation occurred contemporaneously with the first two volcanic pulses of the Rungwe volcanic province, between 8.6 Ma and the Plio-Quaternary transition. Paleostress analysis of minor faults in relation to well-dated sediments and volcanics shows that the structural evolution of the rift basins and related sedimentation and volcanism occurred in a tectonic system dominated by normal faulting under a semi-radial extensional stress field (Delvaux et al., 1992; Ring et al., 1992).

The Late Pliocene to Early Pleistocene, a period of tectonic quiescence, is marked by a low lake level and intense weathering and erosion (Crossley, 1982; Ebinger et al., 1993). Neither sediments nor volcanics were deposited during this period, which corresponds to the development of an extensive morphological surface covered by lateritic soil (African two geomorphological surface of King, 1963). This exposure caused an erosional and structural unconformity, over which Quaternary lake beds were deposited (Crossley, 1982; Ebinger et al., 1993).

A new kinematic regime started during the Middle Pleistocene together with a new pulse of tectonic activity and renewed sedimentation (Delvaux et al., 1992). This second regime is still active today and corresponds to the Neotectonic period (Delvaux and Hanon, 1993). It is characterised by horizontal principal compression and extension axes, typical for a strike-slip regime, with a dominant N–S horizontal compression and an E–W principal extension. This regime induced dextral strike-slip reactivation of NW-trending rift faults. The volcanic activity continued during the Quaternary, with a series of eruptions in the Rungwe area occurring during the Holocene (Ebinger et al., 1989; Williams et al., 1993).

Two kinds of Quaternary vertical movements are evident in the Rukwa-North Malawi area: (i) block tilting in both the Kyela and Rukwa Plains (Delvaux and Hanon, 1993; Delvaux, 1995) and (ii) a regional domal uplift centred on the Rungwe–Ngozi volcanic area. These combined movements induced a SE and NE tilting of the Kyela Plain and caused an important mass transfer through erosion and sedimentation towards the Kyela Plain, at the foot of the Livingstone scarp.

Block faulting and active tilting in the Kyela Plain is shown from the examination of LANDSAT-TM imagery and fieldwork (Delvaux and Hanon, 1993). The NW-trending Mbaka fault traverses the central part of the plain. An abandoned section of the Mbaka River is located exactly on a well-defined lineament that could represent the track of the fault on the plain. The prolongation of this lineament into the lake is marked by an alignment of sub-lacustrine gas vent observed visually (at 4 m deep) near the mouth of the Kiwira River and by a small active fault scarp detected on seismic profiles (Versteeg et al., 1993; De Vos, 1994).

A general tilting of the Kyela Plain is shown by a systematic north-eastward shift of the rivers, which flow into Lake Malawi. The best example is the migration of the active delta system of the Kiwira River (Fig. 3). On land, the southern branch of the Kiwira River delta system is inactive, but it is still clearly expressed. In the lake itself high-resolution seismic profiles demonstrate the successive north-eastward migration of three buried delta lobes (Figs. 3 and 4(a)) high in the sedimentary section (De Batist et al., 1996).

The soil moisture content, estimated from the vegetation index on LANDSAT-TM false colour composition gives an indication about the relative elevation of the plain. At the northern tip of Lake Malawi, a large wet area fringes the coastline and extends along the Lufirio River and its tributaries. It is also the lowest part of the Kyela Plain,

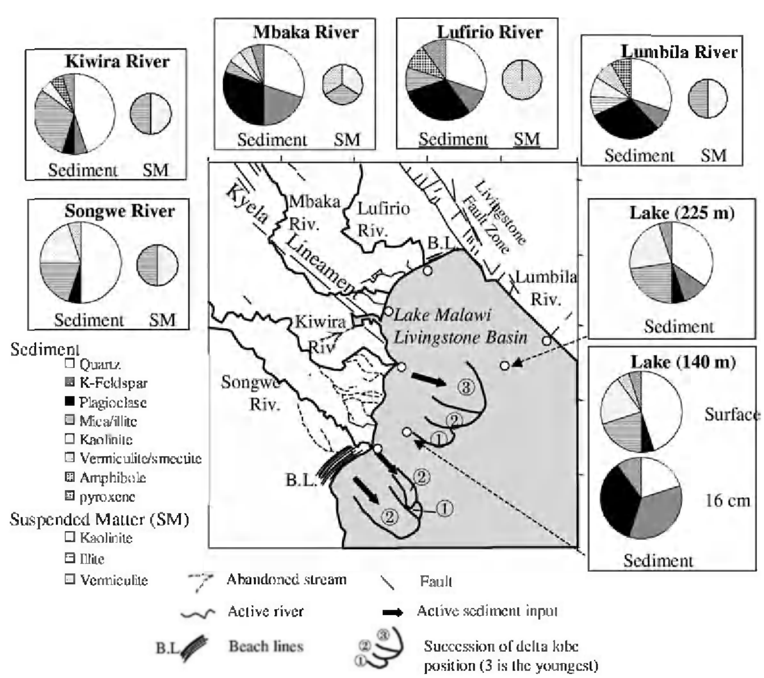

Fig. 3. Geomorphological and sedimentological evidences of the general tilting of the Kyela plain based on lateral shift of the river network towards the major Livingstone rift border fault (from Delvaux and Hanon, 1993). Migration of underwater delta lobes (based on the interpretation of high resolution seismic data of De Vos, 1994). Modern mineralogical assemblages of river/lake sediments and river suspended matter (SM).

and thus it can be considered to be the most subsided area. This wet area is bordered to the south by a dryer area, between the Lufirio and the Mbaka Rivers, which can be considered as having risen relative to the area occupied by the Lufirio River. The Kyela lineament abruptly separates this dry area from the wet plain of the Mbaka River. This observation combined with high-resolution reflection seismic information on the sub-lacustrine prolongation of this lineament, seems to indicate that the southern block of the Kyela lineament is downthrown with respect to the northern block, although no significant fault scarps were revealed during field investigations in the area. Farther south the wet area is restricted to elongated strips along the Kiwira and the Songwe Rivers, separated by very dry areas.

The uplifting of the southeastern side of the Kyela Plain is also indicated by the presence of fossil beaches on the southern side of the Songwe River as evidenced on air photos and satellite images (Fig. 3). They are progressively rising from the present-day lake level at 474 m, up to a little more than 480 m, as interpreted from the topographic map. In contrast, near Matema along the lake shore and at the junction between the Kyela plain and the Livingstone fault scarp (Fig. 3), only a single fossil beach line is observed along the coastline.

5. The sedimentary infill of Livingstone Basin

Based on the interpretation of multi-channel seismic profiles, Scholz et al. (1989) and Specht and Rosendahl (1989) defined three regional depositional sequences composing the sedimentary infill of the Livingstone Basin. The Nyasa/Baobab Sequence overlies the pre-rift bedrock and constitutes at least half of the basin fill. The overlying Mbamba Sequence is separated from the first sequence by a high-amplitude reflector, probably representing an abrupt change in lithology or a major erosional surface (the African two morphological surface of King, 1963) and forming the top of uplifted blocks on the shoaling western side of the basin. Both the Mbamba and Nyasa/Baobab Sequences were extensively eroded at the western margin during a lowstand of the lake-level, which was dated at about 78,000 years BP by Scholz and Finney (1994). The Songwe Sequence, deposited during and after this major lowstand, is the youngest sequence observed in Lake Malawi.

The new high-resolution reflection seismic data acquired in October 1992 (Fig. 1) provide a more detailed image of the stratigraphy and structural deformations of the north-western and north-central parts of the Livingstone Basin (De Batist et al., 1996). They allow the Mbamba and Songwe Sequences to be further subdivided into seven depositional sequences (S1–S5 for the Mbamba Sequence, S6 and S7 for the Songwe Sequence). These seven sequences contain a record of the complex history of lake-level fluctuations having different orders of magnitude and frequency, which can be interpreted from an analysis of the stratal patterns and seismic facies distribution. The most prominent lake-level change, illustrated in Fig. 5, seems to have occurred between the major lake lowstand in sequence S5 (about 320 m below the present level) and the highstand during deposition of sequence S6 (subsequently lake-level rose even further to its present-day level at the end of the sequence S7). Johnson et al. (2002) also reported records of a major lowstand (100–200 m lower than present) between 23,000 and 16,000 years ago during the Last Glacial Maximum.

Two buried delta systems, the North-Kiwira and Songwe river delta systems separated by the Karonga Fault Zone, can be identified within the S6 sequence along the western bank. The deltas are composed of a number of stacked lobes and characterised by complex packages of channel-fill deposits and of prograding and aggrading reflector sets, displaying the typical topset-foreset-bottomset facies (Fig. 4). The observed shifting of these lobes is interpreted to have developed in response to a delicate interplay of gradual lake-level rise, tectonic movement and sediment input. The southern Songwe delta system seems to have developed in response to lake-level rise and sediment input in a tectonically stable setting. The North-Kiwira delta system, on the other hand, shows a gradual shift towards the north-east, as mentioned above. The migration of these delta lobes is very likely allocyclic or tectonic in origin.

Within sequence S6 these delta lobes are overlain by migrating channel-fill (delta plain?) deposits, which themselves are cut by a sharp erosional surface, probably representing a storm- or wave-base surface (base of sequence S7, Fig. 4(a)). This surface corresponds to the base of the present-day river deltas. The backstepping of the depocentre within sequences S6 and S7 and the low amount of time-equivalent deposits in the deeper parts of the basin suggest a very rapid rise of the lake-level throughout the Songwe Sequence.

Top sediments recovered at different depths at the bottom of the lake show three major patterns:

- shallow-depth sediments (<10 m) are heterogeneous detritic sands (or silty sands). Plant fragments, minerals, diatom debris and clay-oxide-organic matter amalgams are the main visible features on smear slides. Plant debris are abundant in the western rivers (Mbaka, Kiwira and Songwe) whereas Lumbila and Lufirio sediments are mainly mineral. Charcoals are present in Lumbila sediments in accordance with human practice in the watershed. Mineral assemblages are constituted by quartz, feldspars, amphiboles, pyroxenes and clay minerals (Fig. 3),
- 140 m water depth sediments are homogenous and more fine-grained. No minerals or vegetal fragments are visible in this silty mud. Smear slide observations reveal the high proportion of diatoms; minerals are rare and clay-oxide-organic matter amalgams are present. The

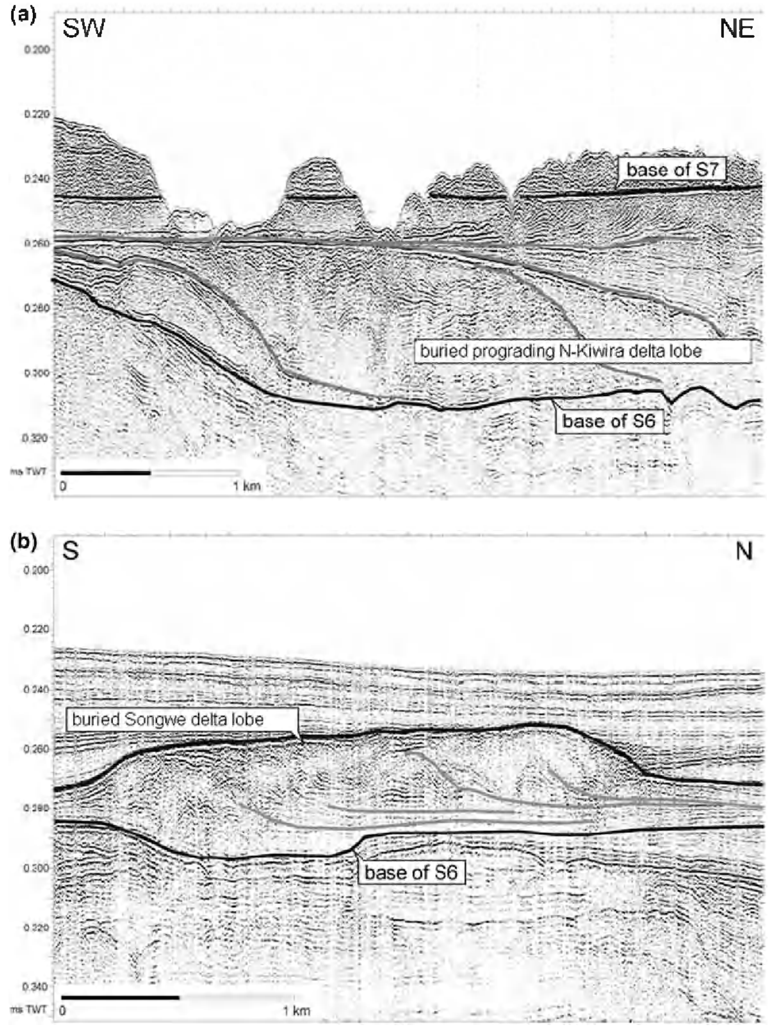

Fig. 4. Detail of seismic cross-section showing the evolution of the buried delta system of (a) the Kiwira River and (b) the Songwe River.

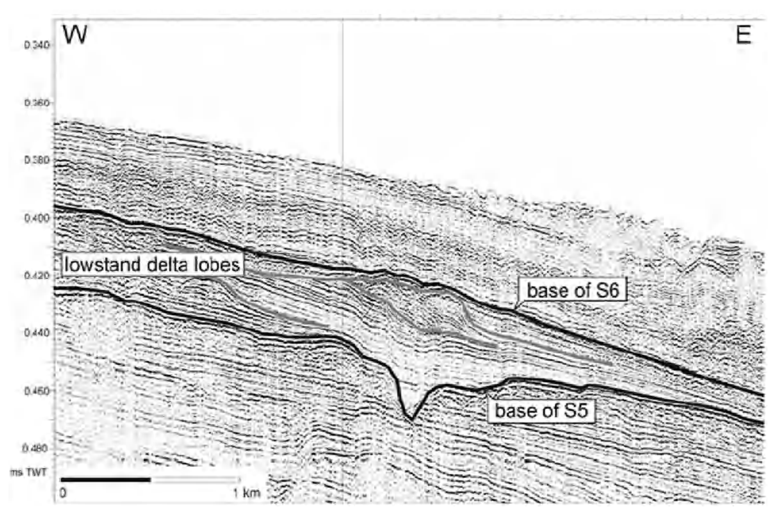

Fig. 5. Detail of seismic cross-section of a buried delta lobe indicating a lake-level lowstand of −320 m during deposition of sequence S5.

mineralogical assemblage is dominated by quartz and clay minerals, feldspars and pyroxenes being less abundant,

- deepest sampled sediments (225 m water depth) correspond also to a silty mud but characterised by a strong millimetric lamination with light and dark laminas.

Smear slides show the abundance of diatom and clay amalgams. The mineralogical assemblage is similar to the former one.

These features fit well shallow to deep sedimentological patterns defined previously (Johnson and Davis, 1989; Owen and Crossley, 1989; Johnson and Ng'ang'a, 1990; Pilskaln and Johnson, 1991). The lamination in the deepest core is a direct evidence of the seasonal signal. Diatomaceous (light) horizons are deposited during the dry windy season while the more terrigenous (mineral and organic) ones are deposited during the rainy season (Pilskaln and Johnson, 1991).

River sediment mineralogy is influenced by the geology of the watershed, the weathering processes and the hydrodynamism. White micas come mainly from the Kiwira and Songwe catchments (Precambrian micashists), plagioclases are present in all watersheds but the highest proportions occur in Lumbila sediments (Precambrian anorthosites), K-feldspars are mainly issued from Mbaka and Lufirio watersheds (trachytes and trachy-andesites). Black micas of the Mbaka River are probably issued from the trachytes and/or the phonolithes. X-ray diffraction performed on river suspended matter only exhibits clay mineral (Fig. 3). The kaolinite and illite minerals are present in the Songwe, Kiwira, Lumbila and Mbaka Rivers. Lufirio and Mbaka River suspended matters are characterised by occurrence of the vermiculite mineral. Kaolinite is a common mineral of weathering profiles under wet climate (Pedro, 1968). The illite mineral is mainly generated on granitic and metamorphic rocks that are present in Songwe, Kiwira and Lumbila catchments. Its occurrence in Mbaka River is probably associated to the presence of lacustrine sediments in the catchment. The vermiculite mineral characterises a low intensity weathering process that can occur in altitude on steep and instable slopes, conditions that are present in Mbaka and Lumbila watersheds where precipitation are important and where geology is dominated by the volcanic rocks.

Lake sediment mineralogy is then influenced by these different sources (geological + weathering) and depositional processes (vicinity of the river mouths and dynamic processes). Due to depositional dynamics, the proportion of clay minerals increases with the distance to the source.

The change in mineralogical assemblage with depth in the 140 m water depth core (Fig. 3) suggests a temporal change in mineral sources. Due to the core location, the modern sediments are influenced by the Songwe and Kiwira material inputs. The relative increase of K-feldspar and mainly plagioclase proportions downward could be interpreted as a stop or a decrease of the sedimentary inputs by the Songwe River at this point. This evolution, not yet dated, could be linked to relatively drier climatic conditions with little impact on the farther north watersheds located in the rainy area of the Rungwe (see above). Such a decline in regional precipitation, associated with a drop of the lake-level was evidenced in Lake Malawi at the end of the Little Ice Age (Owen et al., 1990; Johnson et al., 2001; Nicholson and Yin, 2001). Thus the overall northward shift of the rivers of the Kyela Plain during the Quaternary (but not yet dated) is accompanied by hydrodynamic modifications of some rivers as the result of climatic changes.

6. Heat flow in Livingstone Basin

Von Herzen and Vacquier (1967) performed 20 heat-flow measurements in the bottom sediments of Lake Malawi, obtaining values from 8 to 120 mW/m^2 with an average of 45 mW/m^2. The high variability of the heat flow was assumed by these authors to be related to the effects of local high sedimentation rates and past changes in lake water temperature. Ebinger et al. (1987) calculated corrections for the sedimentation effect and defined the average heat flow through the bottom of Lake Malawi at 75.3 ± 35 mW/m^2, which is 1.5 times higher than the mean value for the African continent (49.8 mW/m^2, Sclater et al., 1980).

New heat-flow measurements were performed during the present study in the northern part of the lake between 1991 and 1993 (Golubev and Klerkx, 1993; Golubev, personal communication). The investigated area occupies 1/20 of the entire lake, but even in this small area the measured raw heat-flow values (32 measurements, Table 1) vary from −7 to 108 mW/m^2 (average: 47 mW/m^2). The negative value obviously is related to a landslide effect and was obtained near the north-eastern shore along the Livingstone border fault. The highest values were obtained in the foothill of the western underwater slope.

The measured heat-flow values were corrected using the nomograms of Hutchinson (1985), considering the thickness of the sediment layer given by Specht and Rosendahl (1989). After corrections the variations of the heat-flow values appear to be smaller. The values do not exceed 30 mW/m^2 near the north-eastern border, then increase to 50–60 mW/m^2 along the lake axis and reach values of up to 80–90 mW/m^2 in the western part of the lake.

Several possible mechanisms may explain the three-fold increase of the heat flow along a NE–SW profile across Livingstone Basin:

- the increase reflects the actual trend of the deep heat flow through the basement as caused by a local heat-flow source. For example, the presence of a "fresh" mantle diapir was suggested by Ebinger et al. (1987) on the basis of multi-channel reflection seismic profiles;
- the increase may be related to seasonal and longer-term variations of bottom water temperatures. In this regard it should be noted that high values were obtained in the sites where the water depth was less than 200 m, where such effects can be important;

- local heat flow increases may be related to hydrothermal discharge on the lake floor. Although the presence of hydrothermal activity could not be ascertained, gas emanations at the lake floor have been observed locally (see part 4);
- the blanketing effect of sediments which has a greater thickness towards the Livingstone border fault.

7. Geochemical characteristics of Livingstone Basin

7.1. Hydrothermal activity

Two hydrothermal springs were observed and sampled on land during the present work (Delvaux and Hanon, 1993; Branchu, 2001) extending previous characterisations of this area (part of the volcanic Rungwe Massif located in Lake Malawi catchment) by other authors (James, 1959; Kirkpatrick, 1969; Pisarskii et al., 1998; Hochstein et al., 2000). The Mapulo spring is located in a swampy area covered by calcareous crusts. In this hydrothermal field both hot and cold (not sampled) springs occur with gaz emission. The Kasimulo spring is located between the Songwe and Kiwira Rivers and is restricted to one spring with lower discharge rate than in Mapulo and with no visible gaz emission. The chemical and isotopic composition and the temperature of the samples are presented in Table 2. Both springs have neutral pH. The majority of the North Malawi hydrothermal springs are characterised by temperatures ranging from 50 to 80 °C (Table 3) but some cold vents are present. Fluids have high Na (>34 mmol/l), and HCO_3 (>1400 mmol/l) contents (Table 3). In a triangular Cl–SO_4–HCO_3 diagram (Giggenbach, 1991) all the springs plot in the carbonate corner. Based on their chemical composition two groups are defined: the northern (upper Songwe valley) and the southern groups with higher Na, sulfate and carbonate and a lower K content. In each group Na/K mass ratio is constant suggesting an homogenous fluid at depth. Springs plotted in a triangular Na–K–Mg diagram (Giggenbach, 1991) are immature (no chemical equilibrium) and partially equilibrated for the southern and the northern groups, respectively. These positions do not allow to compute a reservoir temperature by cationic geothermometers. However temperatures of 220 and 250 °C, for the southern and the northern groups, respectively, are estimated from the spring alignment for each group. The isotopic composition of the two sampled springs are located on the regional meteoric line (Bergonzini, 1999) and below the mean composition ($\delta D = -21‰$; $\delta 18O = -4.1‰$) of the three AIEA/WMO stations enclosing the region (Rozanski et al., 1996; Bergonzini et al., 2001). Furthermore their compositions are similar to those of the Kiwira River. The same origin is attributed to the two groups of spring and in the Songwe group Ca, Mg, Li, Rb and Sr come from a magma chamber at depth linked to the Rungwe Massif (Pisarskii et al., 1998). From their isotopic and chemical compositions these springs can be associated with high-temperature systems, probably of volcanic origin, but highly diluted by meteoric water. This hydrothermal context is then pretty similar to the nearby Lake Tanganyika where Na–HCO_3 rich sub-aquatic manifestations are associated to the presence of a degassing magmatic body at depth (Pflumio et al., 1994).

Table 2
Physical–chemical characterisation of the lake water column, rivers and hydrothermal springs sampled in the northern part of Lake Malawi (Tanzania)

	δD (‰ vs. SMOW)	$\delta^{18}O$ (‰ vs. SMOW)	T (°C)	pH	K (mmol/l)	Ca	Na	Mg	Cl	SO_4	Si	Alkalinity (meq/l)	Relative density[a]
Lake													
Epilimnion 0–75 m (13[b])	+11	+2.0	24.9	8.47[d]	0.16	0.47	0.89	0.30	0.12	0.01	0.017	2.37	1
Metalimnion 100–240 m (11[c])	+12	+2.0	23.4	8.04[d]	0.17	0.48	0.9	0.30	0.11	0.004	0.091	2.42	–
Rivers													
Songwe	−24	−3.8	30.0	8.14	0.15	0.32	0.5	0.21	<0.01	0.07	0.36	1.27	0.998
Kiwira	−26	−4.7	27.2	8.38	0.35	0.18	2.66	0.20	1.04	n.d.	4.25	2.29	0.999
Mbaka	−18	−3.9	27.0	7.46	0.18	0.24	0.87	0.18	0.02	n.d.	0.54	1.75	0.999
Lufirio	−14	−3.1	27.7	6.86	0.11	0.49	0.68	0.23	n.d.	n.d.	0.30	2.12	0.999
Lumbila	−31	−5.4	19.5	8.17	0.06	0.22	0.21	0.1	n.d.	n.d.	0.30	0.82	1.001
Thermal spring													
Mapulo	−26	−5	50	7.1	1.75	0.95	53.21	0.91	7.12	3.12	1.78	50[e]	–
Kasimulo	−25	−4.8	63	7.4	1.89	1.13	58.23	0.93	6.27	3.89	1.52	45[e]	–

n.d. = not detected.
– = not calculated.
[a] Relative density: (computed density)/(computed density of lake surface waters). Density is computed from salinity and temperature (Millero and Poisson, 1981). Lake and river salinities are computed from their chemical composition. Density linked to suspended matter is not considered.
[b] (13) is the number of samples used to calculate metalimnetic average values except for isotopes (7) and alkalinity (3).
[c] (11) is the number of samples used to calculate epilimnetic average values except for isotopes (5) and alkalinity (4).
[d] Measured at the laboratory in France.
[e] Values calculated (as HCO_3) from the difference of meq cations minus meq anions.

Table 3
Chemical composition of hydrothermal springs in the part of the Rungwe volcanic massif located in Lake Malawi catchment

	Ref.	T (°C)	pH	Ca	Mg	Na	K	Cl	SO_4	Si	HCO_3
				(mmol/l)							
Southern springs											
Kasimulo	1	50	7.1	1.13	0.93	58.20	1.89	6.27	3.9	1.52	51.1
Mapulo	1	60	7.4	0.95	0.91	53.20	1.75	7.12	3.12	1.78	47.9
Kasimulo	2	58	7	1.57	0.78	57.85	1.89	6.21	2.71	2.50	49.33
Kilambo	2	58	7	1.35	1.40	53.94	1.53	11.28	2.65	2.51	42.61
Mampulo[a]	3	63	7.2	0.90	0.74	39.58	n.d.	3.81	2.39	2.08	23.35
Northern springs											
Songwe 1	4	65	7.9	0.50	0.60	38.01	2.78	6.40	1.72	0.79	31.40
Songwe 2	4	75	8.2	0.60	0.60	36.79	2.78	6.30	1.71	1.04	30.90
Songwe 3	4	18	7.8	0.50	0.80	37.20	2.89	5.60	1.70	0.83	32.01
Songwe	2	73	6.9	1.22	0.78	34.36	2.61	5.22	1.67	1.41	32.61
Rambo	5	66	8.4	0.62	0.24	36.32	2.92	6.29	1.7	1.5	31.5

n.d.: not determined.
Ref.: 1, This work; 2, Makundi and Kifua (1985) in Hochstein et al. (2000); 3, Harkin (1960) in Hochstein et al. (2000); 4, Pisarskii et al. (1998); 5, James (1959).
[a] Doubtful composition: cationic excess.

7.2. Water chemistry and isotopic composition

The lake water chemistry is controlled by the nature of the different inputs (hydrothermal, rivers, atmospheric), by lake surface evaporation, by biogeochemical processes in the water column (productivity/degradation, precipitation/dissolution) and by mixing/exchange processes between the different lake compartments (epi-, meta- and hypolimnion).

The chemical composition of the different inputs and the mean chemical composition of the lake water (both epilimnion and metalimnion) are presented in Table 2. The presence and concentration of major elements in the different water samples are controlled by "mixing" of the various end-member sources. An example of this "mixing" is given in Fig. 6, where Ca/Cl versus Na/Cl is plotted for the different samples; normalisation to chloride content is performed in order to remove the effect of evaporation. Three kinds of waters can be distinguished in Fig. 6, even if data were acquired during different years and different seasons. One type is represented by Songwe, Lumbila and Lufirio River waters having Ca/Cl and Na/Cl (as well as alkalinity/Cl and Mg/Cl) values which are higher than lake water values due to the presence of basic bedrocks in the watershed. A second type is represented by rain and diluted river waters (Mbaka, Linthipe, Bua, Dwangwa, South Rukuru) with low Ca/Cl and Na/Cl ratios. The third type, illustrated by the Kiwira River, characterises the influence of hydrothermal activity. According to chemical and isotopic compositions, the Kiwira river waters may result from the mixing of rain water and hydrothermal waters from springs that are located within the river's watershed and have discharge rates of a few m^3/s (James, 1959).

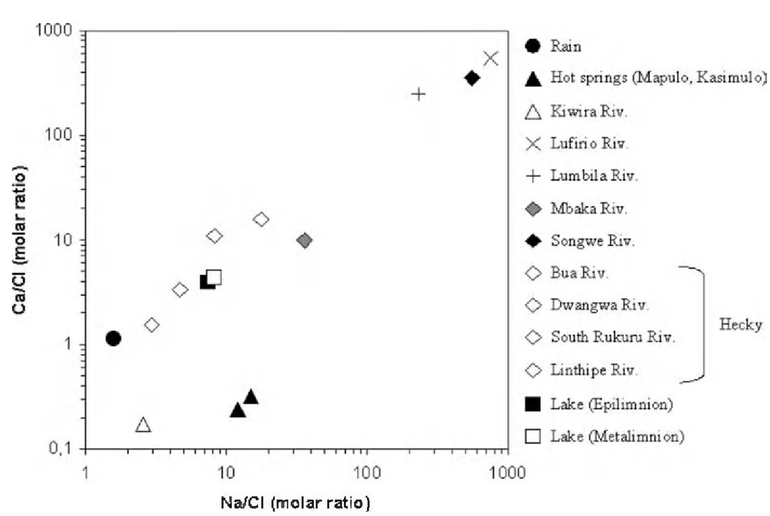

Fig. 6. Chemical composition (Ca/Cl vs. Na/Cl molar ratio plotted on a logarithmic scale) of various water types present in Lake Malawi watershed. Data for precipitations are from Bootsma et al. (1996). Data for rivers outside of our studied area noted "Hecky" in the legend are from the data set used by Hecky and Bugenyi (1992). Data plots of Lufirio and Lumbila Rivers are relative as Cl was not detected during analysis. Data plot of Songwe River is approximate as Cl is detected just below the quantification limit. For the three rivers Cl concentration in the figure is fixed at 0.01 mmol/l.

This result underlines the hydrochemical importance of the Songwe and Kiwira Rivers. These major tributaries contribute to about 4% and 5%, respectively, of the annual river input to the lake and are characterised by high specific flow values in their drainage basin relative to the entire lake watershed (Bergonzini, 1998, 1999). The location of the lake waters in this figure is thus explained by mixing between several end members, including inputs from hydrothermal activity (Kiwira River), basic bedrock alteration (Songwe River) and rain diluted river waters. Hydrothermal influence can thus be observed in river inputs, but in contrast to Lake Tanganyika hydrothermal activity has not yet been directly observed in Lake Malawi. However, Müller and Förstner (1973) report an increase of temperature in deep water temperatures that could be due to important hydrothermal discharges associated with the precipitation of nontronite, limonite and vivianite in deep water sediments from SiO_2-rich geothermal fluids. This increase in deep water temperature is still observed today with a rate of 0.009 °C/year recorded between 1939 and 1997 (Fig. 7). Nevertheless, this warming is comparable with the one described in Lake Tanganyika (0.005 °C/year between 1938 and 2003) that has been associated with climatic changes (O'reilly et al., 2003). As such the idea of hydrothermal discharges on the lake floor, also suspected through heat-flow measurements, are not supported by this comparison, nor is it supported by lake water measurements (CTD casts) or chemical measurements performed during the CASIMIR project.

The isotopic composition of the river waters ($-5.5‰ < \delta^{18}O < -3‰$ and $-31‰ < \delta^2H < -15‰$) lies on the local precipitation line (Rozanski et al., 1996; Bergonzini et al., 2001) and does not show an evaporative signature (Bergonzini, 1999), although the Songwe River may have experienced some enrichment by evaporation. The mean isotopic composition of the lake water is +2‰ for $\delta^{18}O$ and +12‰ δ^2H. This isotopic enrichment, relative to the local precipitation line, is due to intense evaporation at the lake's surface. The chemical and isotopic compositions are relatively similar to those observed 17 years before (Gonfiantini et al., 1979), although the epilimnion sampled in 1993 is more enriched in ^{18}O ($\delta^{18}O = +2.0‰$ at the end of the dry season) than that analysed by Gonfiantini et al. (1979) in 1976 ($\delta^{18}O = +1.7‰$) at the end of the rainy season). This difference is attributed to evaporation on the lake surface during the dry season. The oxygen composition of the metalimnion ($\delta^{18}O = +2.0‰$) also appears to be slightly enriched relative to Gonfiantini et al. (1979) values ($\delta^{18}O = +1.9‰$). Water isotopic composition profiles (Bergonzini, 1999) are spatially homogeneous and characterised by a depleted layer (values ($\delta^{18}O = +1.9‰$ and $\delta D = +10‰$) above the thermocline (between 50 and 100 m). This depleted isotopic layer corresponds on the CTD casts to a level of diluted waters characterised by temperature gradients in the epilimnion. The deepest gradient corresponds to the thermocline. The origin of this "diluted" water may be linked to precipitation or to river discharge. Lake and river water salinity has been computed from their chemical compositions. All rivers are characterised by a low salinity (relative to that of the lake) except for the Kiwira River, which is influenced by hydrothermal activity. Density values, calculated using temperature and salinity data (Millero and Poisson, 1981), are compared to epilimnetic water density (Table 2). Only Lumbila River waters have density values which are higher than those of the surface lake waters. It can thus be assumed that the Lumbila waters penetrate down to the thermocline where they are stopped. This assumption is supported by the isotopic composition of the Lumbila waters, as these are the most depleted of the sampled rivers. Cold Lumbila waters come directly from the Livingstone Mountains, with headwaters at a maximum of 2000 m above lake-level. In contrast to the Lumbila waters, the waters of the other rivers are retained on the surface of the lake due to their lower densities. Halfman and Schloz (1993) have characterised a similar structure at the mouth of the Ruhuhu River (eastern coast of Lake Malawi) during the wet season. They interpret this structure as being the penetration of cold river water into the lake. Due to the seasonal evolution of Lake Malawi thermo-haline stratification, such river sinking processes should be considered as contributing to lake mixing.

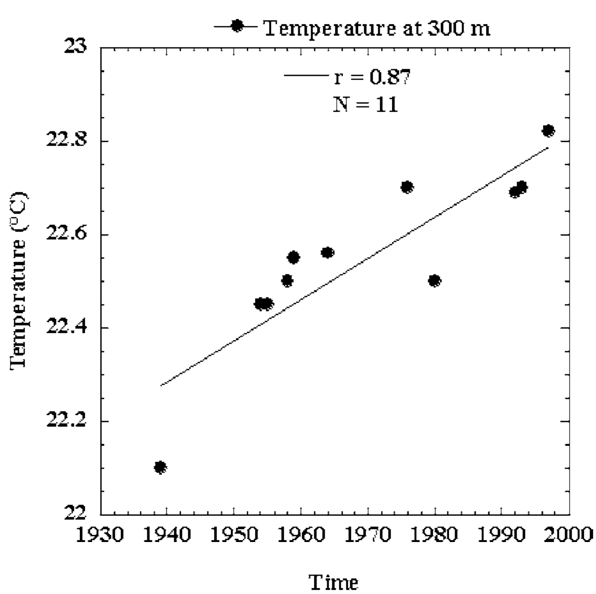

Fig. 7. Temporal evolution, between 1939 and 1997, of lake Malawi deep water (300 m) temperature. Data are from Beauchamp (1953), Jackson et al. (1963), Eccles (1974), Iles (1960) (in Eccles, 1974), Gonfiantini et al. (1979), Degnbol and Mapila (1982) (in Crul, 1997), Halfman (1993), Vollmer et al. (2002) and this study.

7.3. Hydrological and isotopic mass balance for Livingstone Basin

The contribution of river input to the total hydrological mass balance was calculated using various river discharge rates (Tanzanian Ministry of Water, unpublished data; Bergonzini, 1998). Although the northern watershed area represents only 8% of the total lake watershed, the river inputs from this area account for almost 8 km^3/year and represent about 20% of total runoff into the lake.

The annual hydrological budget for the northern part of the Livingstone basin shows that river water input represents 82% of the total input (precipitation + runoff). This zone covering 690 km^2, represents about 9% of the lake's surface and has a mean depth of 203 m. This area has no real hydrological existence but has been used in order to compute the role of the corresponding watershed. This annual budget, calculated under the assumption of steady state conditions (precipitation + runoff = evaporation + "outflow"), highlights a net north-to-south water flux and indicates that this region is one of the main water recharge areas for the entire lake. A water residence time of 18 years has been calculated for this zone. Moreover, a crude isotopic budget for the northern part of the lake shows that the composition of the northern area results from a north–south water exchange of several km^3/year and that this area is an important zone of mixing with regards to hydrodynamics of the entire lake.

8. Summary

A multi-disciplinary characterisation of the northern part of Lake Malawi has been performed on both land and in the lake during several fieldtrips related to the CASIMIR project. This study illustrates the geological and hydro-sedimentological dynamics of the system.

Relatively high heat-flow measurements (80–90 mW/m^2) in the area can be interpreted as being due to the presence of a "fresh" mantle diapir, long-term variations of bottom water temperature, or sub-lacustrine hydrothermal discharges. Chemical characterisation of hydrothermal springs on land can also be explained by the presence of a degassing magmatic body in depth. Physical–chemical characteristics of the lake water, including deep-water heating, which is probably linked to climate change, do not support the assumption of large sub-lacustrine hydrothermal discharges. Major element and isotope hydrochemistry of the lake and river waters is explained by the control of rainwater and watershed geology, by on-land hydrothermal activity, by evaporation from the lake and by biogeochemical processes in the water column.

The seismic profiles show the presence of seven depositional sequences making up the upper part of the basin fill of Livingstone Basin. These seven sequences define a complete long-term lake-level cycle, from a lake lowstand at about 320 m below the present level to the present-day lake highstand. Higher-frequency lake-level oscillations controlled the succession of sedimentary facies within each of the sequences. Two buried delta systems, the North-Kiwira and Songwe River delta systems are composed of a number of stacked lobes. The Songwe delta system developed in response to the interplay between gradual lake-level rise, tectonic movement and sediment input, while the north-eastward migration of the North-Kiwira system is likely to be allocyclic or tectonic in origin. These dynamics are illustrated, on a shorter time-scale, by mineralogical changes observed down a core, suggesting a recent change in mineral sources linked to a decrease of detritic inputs by the western Songwe.

This multi-disciplinary approach has led to a precise characterisation of a poorly known area of the Lake Malawi watershed. This area is a main recharge zone for the entire lake, is characterised by an unique geological setting (active volcanism, hydrothermal activity) and is affected by tectonic block tilting.

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