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Effects of microbial activity on the hydrochemistry and sedimentology of Lake Logipi, Kenya

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Abstract

Lake Logipi is a saline soda and alkaline lake which marks the northern termination of the Suguta River drainage system. It also receives waters from streams, possible seepage from Lake Turkana, and hot springs. Present hydrochemistry and sedimentology is controlled by numerous factors including seasonal variations, composition of incoming waters, water depth and, above all, bacterial activity. Given the scarcity of Ca^{2+} and Mg^{2+} in the lake waters, bacterial activity seems to intensify the alkalinization of the waters which inhibits the deposition of organic matter and leads to the genesis of a poorly organic, zeolitic mud that reaches 1.5 m in tickness in the deepest part of the lake. This black layer may be overlaid with thin crusts of trona and halite which prograde over the basin from its southern bank when the lake is drying out and which are dissolved in the lake waters during the rainy season.

Introduction

Lake Logipi is the northernmost saline lake of the Kenyan Eastern Rift (Fig. 1). Within the limits of a former Pleistocene lake, it marks the northern termination of the Suguta River endorheic drainage system. This system is isolated from Lake Turkana by a transverse volcanic barrier (the Barrier) joining the southern Turkana and Nyiru breakaways or distensive faults (Fig. 2). The position of this barrier coincides with an 'accommodation zone', *i.e.* a zone where the terranes accomodate to the displacements of both faults (Bosworth, 1989; Lambiase & Bosworth, in press).

Lake Logipi is surrounded on the west, north and east sides by volcanic formations, mainly basalts, and superficial detrital covers. The alluvial plain of the Suguta River extends southward with delta fans along its eastern flank (Fig. 3).

The region may be considered as a semi-desert caused partly by foehn effects on the rift depression (the foehn is a dry and hot south wind blowing down from the Alps to the upper valley of the Rhône River). The rainfall is less than 300 mm per year (Gwynne, 1969) but is very irregularly distributed with generally two monsoon periods, spring and fall.

The present paper addresses some biogeodynamical aspects of the behavior of Lake Logipi by taking into account observations and studies made during the course of the Logipi Project, primarily during a few days of field work in November, 1988. This project was aimed at provid-

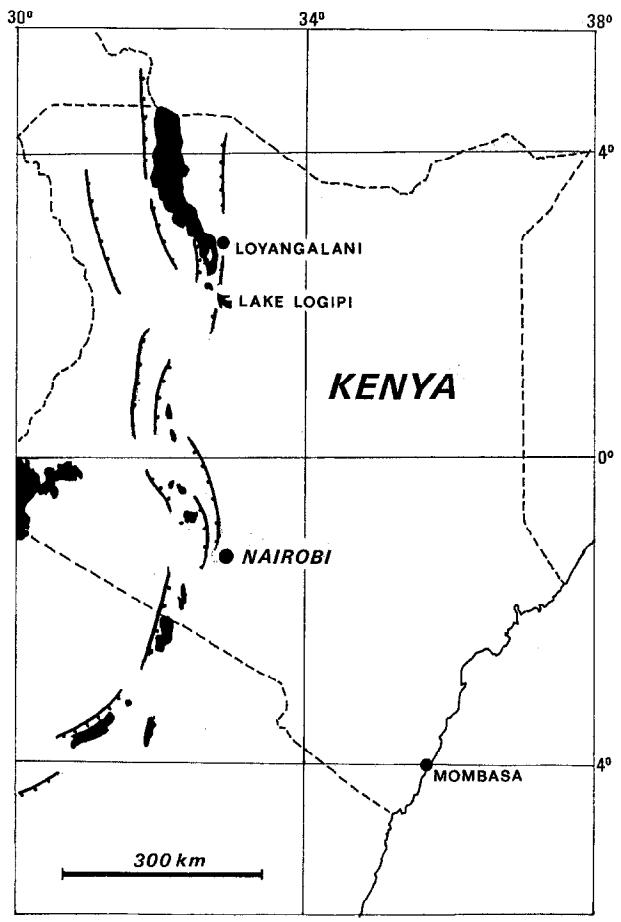


Fig. 1. Location of Lake Logipi.

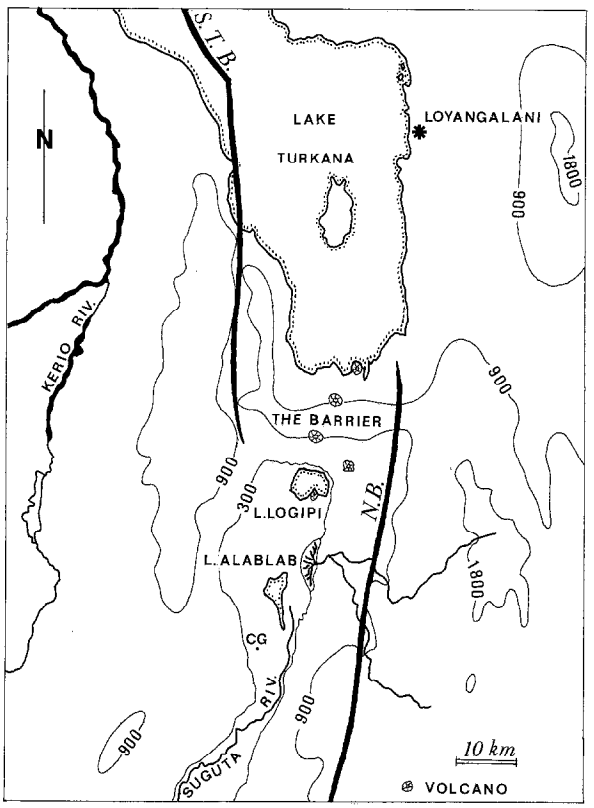


Fig. 2. Schematical map of South Turkana region (Modified after Lambiase and Bosworth, in press). S.T.B.: South Turkana breakaway; N. B.: Nyiru breakaway; CG: Crescent Geyser.

ing a modern model in order to improve understanding of the Kenyan fossil rift basins in which oil exploration had been undertaken. The preparation of the project included a short helicopter trip in November, 1985. A few samples of water and sediments were also collected in 1990 during a short additional expedition. The present paper is, therefore, not an exhaustive study, but aims at offering most of collected data and discussions on a highly inaccessible lacustrine system.

Hydrology

The water level of Lake Logipi depends upon water discharge and evaporation. The main water discharge comes from the Suguta River and other less important tributaries so that it varies widely as a function of rainfall in the river basin. The floods induce lacustrine transgressions when water invades the whole of the bottom of the rift and forms a single lake, inundating Lake Logipi and Lake Alablab, as in September 1975 (Fig. 4). During dry periods the water body progressively shrinks and may be reduced to small salt pans restricted to the deepest parts of both lakes. At its maximum extension we estimate the lake has a maximum depth of 3–5 m. The lake is also fed with freshwater by a few wadis (Pool) and by aquifers that emerge on the southern slope of the Barrier notably at Pelicans Bar (Fig. 5). These waters could come *via* a subterranean route from Lake Turkana although this has yet to be proven.

Lake Logipi is also fed by hot springs emerging on Central Island (Cathedral Rocks) and on the southern slope of the Barrier.

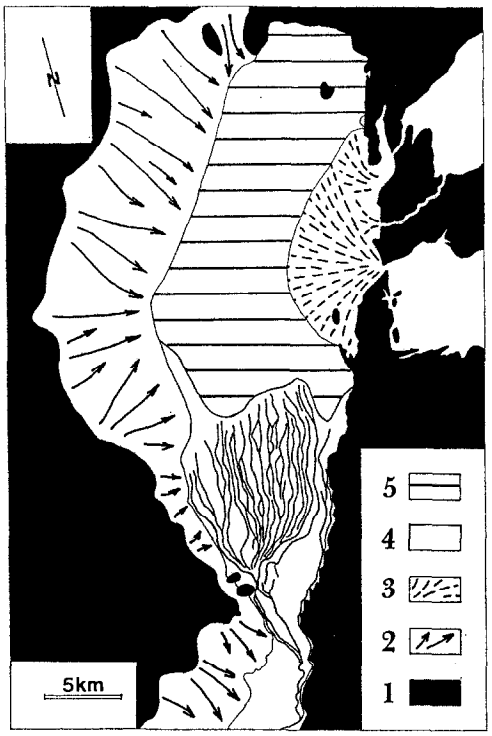


Fig. 3. Geological sketch map of Lake Logipi region. 1. Basalts; 2. Detritical coverspreadings; 3. Delta fans; 4. River alluvium; 5. Lacustrine deposits.

At the end of the dry periods, Lake Logipi and Lake Alablab remain partly flooded because of these inflows and represent windows in the water table of the alluvial plain. When Lake Logipi reaches its minimum level, three ponds remain. A large one is situated along the northern shore and two tiny ones, north and south of Central Island, correspond to hot springs discharges (Fig. 4, February 1987).

Hydrochemistry

Materials and methods

The October 1988 expedition took place during an intermediate stage of the lake, similar to the March 1975 situation. On October 20, 21, 22 and 26 several variables were measured directly in the field: pH and Eh (with a pHmeter CG 837 F Schott Gerate), dissolved oxygen content (with a DOmeter HI 8543 Bioblock) at 11 stations, and salinity at 59 stations (Table 1; Fig. 5). Salinity was measured by means of a refractometer calibrated with pure NaCl solutions ($g\,l^{-1}$). This is, of course, a very approximate method, especially since the various dissolved salts do not necessarily have the same effect as NaCl on the refractive index of water. Dissolved organic compounds may furthermore be present in the water. It is, nevertheless, a very easy method which gives rapid information in the field.

Lake water samples were collected in the morning (October 20, 21, 22 and 26) at 12 stations and analyzed in the evening in a field laboratory carried from France and arranged in a room of the Oasis Lodge in Loyangalani. Analyses were performed using spectrophotometric methods for SO_4^{2-} (Rodier, 1984), NH_4^+ (Solorzano, 1969), NO_2^- (Rodier, 1984); we had no mean to measure the NO_3^- concentrations) and total alkalinity by acidification (Rodier, 1984, modified after Castanier, 1987). Alkalinity is due to carbonate, bicarbonate, borate and hydroxyl ion concentrations. Hydroxyl concentration is negligible even at pH 9.5. Borate concentrations in the lake and surrounding water sources have not been measured but they are probably low so that alkalinity is essentially due to carbonate and bicarbonate ions concentrations. Data are given Table 1.

A brine sample (LL) was also collected in February 1990 when the lake was near its lowest level. Analyses were made back in the laboratory two months later for major ions (Na^+ and K^+ by flame emission spectrometry, Ca^{2+} and Mg^{2+} by flame atomic absorption spectrometry, Cl^- by titrimetry (Rodier, 1984), SO_4^{2-} by turbidimetry (Rodier, 1984), silica and phosphate by colorimetry (Rodier, 1984), and trace metals by electrothermal atomic absorption spectrometry. As the sample was stored in a refrigerator and there were no deposit in the bottle we assume the obtained values are representative for the above components. Ammonium and nitrate (after reduction to nitrite) were also analysed but they might have varied during storage and the results are possibly questionable (Table 2).

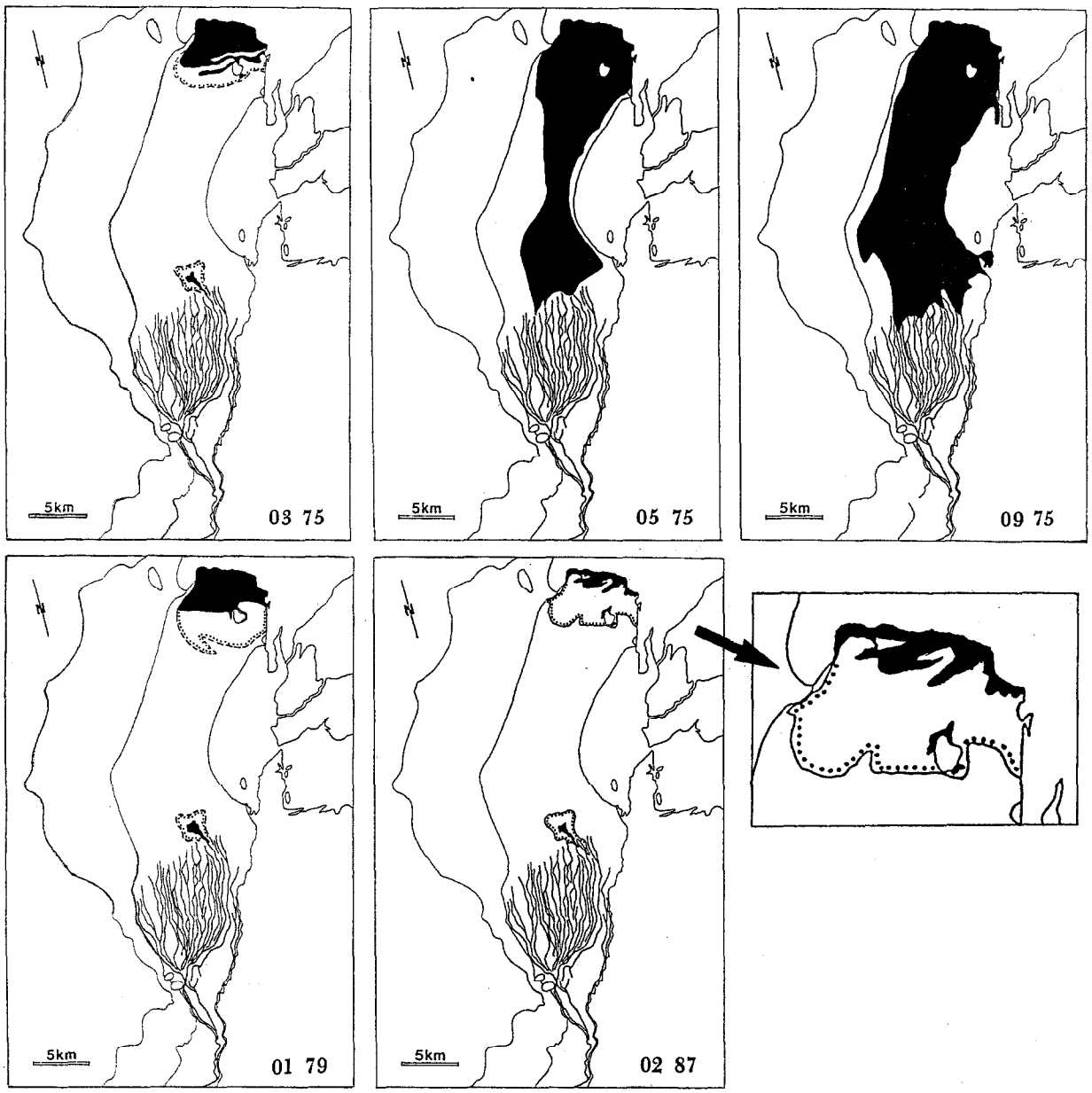


Fig. 4. Several stages of the extension of Lake Logipi, 1975–1987. Dotted line indicates the southern margin of salt crusts.

Several inflows were sampled in October 1988 (Fig. 5). These were: inlet of a small stream east of the lake and pool a few hundred meters upstream (PL 1, PL 2); interstitial water in oxygenated and reduced sediment, respectively, at Pelicans Bar (PB 1, PB 2); waters sampled directly in the vent of the hot spring (70 °C) in the southern part of Central Island, in the effluent channel and in the inundated sand downstream (SV 1, SV 2, SV 3); and water from the vent of the hot spring (54 °C) in the northern part of Central Island and interstitial water in the inundated sand downstream (NV 1, NV 2). They were analysed in the field laboratory following the same methods as mentioned above. Data are given Table 3.

Two more samples were collected in February

Table 1. Hydrochemical data on Lake Logipi waters, October 1988. For location of stations see Fig. 5.

Station no.	Salinity ($g\,l^{-1}$)	Eh mV	DO ppm	SO_4^{2-} ($G\,l^{-1}$)	NH_4^+ ($mg\,l^{-1}$)	NO_2^- ($\mu g\,l^{-1}$)	Alkalinity ($g\,l^{-1}$ HCO_3^-)	pH
0				0.900	1.718	22.3	2.722	9.54
1	12	+89	12.8	0.938	2.440	30.3	2.573	9.53
2	5	+87	12.0				2.486	9.53
3	10	+86	11.6				2.560	9.55
4	2	+86	13.1	0.750	2.637	43.7	2.593	9.54
6	13	+90	8.9				2.269	9.52
8	10						2.595	9.52
9	12	+87	7.7				2.542	9.61
18	10	+86	7.5	0.900	2.232	85.0	2.625	9.53
25	5			0.788	1.400	78.3	2.734	9.54
29	15	+87	7.2	0.375	1.390	71.9	2.584	9.55
43	17			0.412	2.341	118.3	2.678	9.56

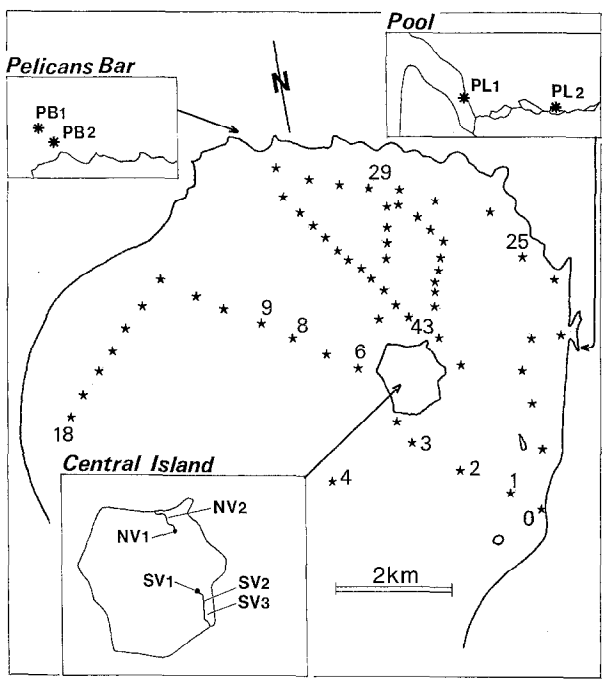


Fig. 5. Location of hydrochemical measurements and sampling stations, October, 1988. Stars: lake waters; dots and asterisks: surrounding inflows.

1990. The first one was collected in the Crescent Geyser (CG), SW of Lake Alablab (Fig. 2), and the second one was collected in the pond receiving the water from the hot spring in the southern part of Central Island (SV). They were analysed in the same ways as sample LL (Table 2).

Table 2. Hydrochemical data of samples collected in February 1990. Results are expressed in $mg\,l^{-1}$, n.a.: not analysed.

Variable	Lake Logipi brine (LL)	Central Island Pond (SV)	Crescent Geyser (CG)
pH	10.5	9.5	9.5
Ca^{+2}	0.63	0.14	0.02
Mg^{2+}	0.09	0.09	0.03
Na^+	17500	2650	4650
K^+	382	188	194
Cl^-	n.a.	5.0	n.a.
SO_4^{2-}	1600	50	1150
HCO_3^-	n.a.	n.a.	n.a.
SiO_2	83.8	140.5	86.7
Al	12.5	23.0	25.5
Fe	4.4	1.4	0.6
Mn	0.06	0.02	<0.02
Zn	0.36	0.20	0.14
Pb	<0.01	<0.01	<0.01
Cu	<0.01	<0.01	<0.01
NO_3^-	1.45	1.70	0.70
NH_4^-	0.06	n.a.	0.04
PO_4^-	0.25	51.7	0.25

Results and discussion

The isohaline map of lake waters indicates probable clockwise water movements as fresh water inputs mainly come from the south of the basin and from the northern bank of the lake (Fig. 6). The central position of the most concentrated

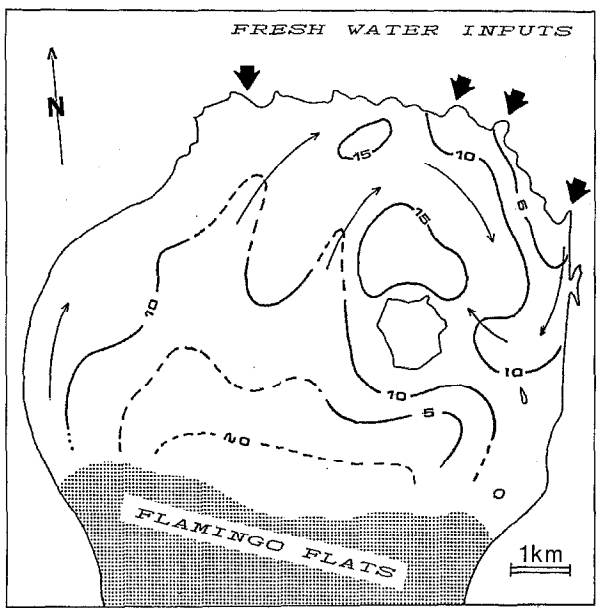


Fig. 6. Salinity map of Lake Logipi surficial waters, October, 1988, Salinity expressed as optical equivalent of g l^{-1} NaCl.

waters must be interpreted partly in terms of the recycling of brines and evaporitic salts deposited in the central part of the basin at the end of previous dry period.

Measured pH and Eh values were rather constant all over the basin (respectively around 9.6 and + 90 mV). The dissolved oxygen content in surface waters varied from 11–12 ppm south of Central Island to 6–7 ppm in the central part of the lake. Values rapidly decreased with depth especially in the central part of the basin where nearly anoxic conditions were reached around 1.5 m below the surface.

Table 3. Hydrochemical data of surrounding inflows, October 1988. For location of stations see text and Fig. 5.

Station	SO_4^{2-} ($g l^{-1}$)	NH_4^+ ($\mu g l^{-1}$)	NO_2^- ($\mu g l^{-1}$)	Alkalinity ($g l^{-1}$ HCO_3^-)	pH
PL 1	0.825	1.335	18.7	2.585	9.51
PL 2	1.312	0.208	0.0	4.519	9.52
PB 1	3.337	1.696	62.3	4.084	9.39
PB 2	1.425	2.605	87.5	3.953	9.34
SV 1	2.475	18.186	17.7	6.972	9.44
SV 2	2.437	17.879	4.0	7.043	9.45
SV 3	2.700	31.405	27.8	7.430	9.40
NV 1	1.313	0.000	2.8	1.067	9.40
NV 2	0.750	7.254	175.5	2.104	9.40

The lake waters total alkalinity due to carbonate and bicarbonate ions is very high which corresponds to the high pH. Sulfate concentration decreases towards the saltier central part of the basin whereas nitrite concentration increases. This might be related to higher bacterial reducing activities in the deepest part of the basin. Besides, the constant and high ammonium concentrations together with the high nitrite and, presumably, nitrate (Table 2) concentrations in the surface water reflect the efficiency of the bacterial nitrogen cycle and the accumulation of soluble nitrogen compounds in the lake.

The brine collected in 1990 is very poor in Ca^{2+} and Mg^{2+} which is rather surprising in such a mafic geological environment (Table 2). This will be discussed later. On the other hand the high Fe, Mn and Zn concentrations logically result from this environment. Lastly, the high pH accounts for the high Al and silica content of the lake brine.

The inflow waters, especially the hot springs, are generally richer in sulfate ions, in nitrogen compounds and in carbonate and bicarbonate ions than the lake water itself. It is possible that some of the inputs from hot springs comprises recycled, infiltrated brines. More generally, all water sources seem to reflect a common hydrochemical background reflecting the regional geological and bio-climatic conditions.

Lake Logipi acts as a concentrator for most of dissolved ions and compounds coming from the environment *via* streams, aquifers and hot springs. Additionally, variations in the flow of the Suguta River induce changes in the salinity and composition of the lake waters. For instance, each flooding of the river induces a dilution of the lake brines and a dissolution of the previously deposited salt crusts.

Sedimentology

Materials and methods

In October 1988 no salts deposits were evident on the lake bottom. On October 23 and 24, surficial

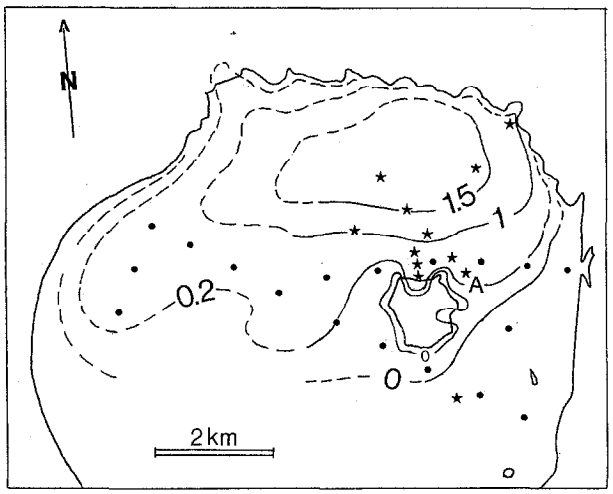


Fig. 7. Location of sediment sampling stations (October, 1988) and schematical map of the black layer thickness (Isopachs in m). Dots: samples directly observed in the field,; stars: collected cores.

lake sediments were cored at 17 stations and examined directly on the boat. A few samples were collected. On October 24 and 25, 12 cores were collected (Fig. 7). They were stored in cool boxes with carbonic ice (dry ice) and sent to France within a few days. Core A (60 cm long) was the only one to be studied in the laboratory by X-Ray diffractometry, SEM imagery and microprobe analysis. Three samples taken from this core (top, middle, and base of the black layer) were analysed for interstitial water content (weight loss at 60 °C after 24 h), organic matter and linked water content (weight loss at 450 °C after 24 h of dessicated sample at 60 °C), organic carbon content following the Anne's method by Ottman (1960), organic nitrogen and N-NH_4^+ with a distillation unit (Büchi 320) and a mineralisation ramp (Büchi 425), and carbonate content (expressed as CO_3^{2-} % of dry weight) by acid attack (HCl N/10). Results are given in Table 4.

Two samples of salt crusts a few millimeters thick were collected in January 1990 and analysed through X-Ray diffractometry.

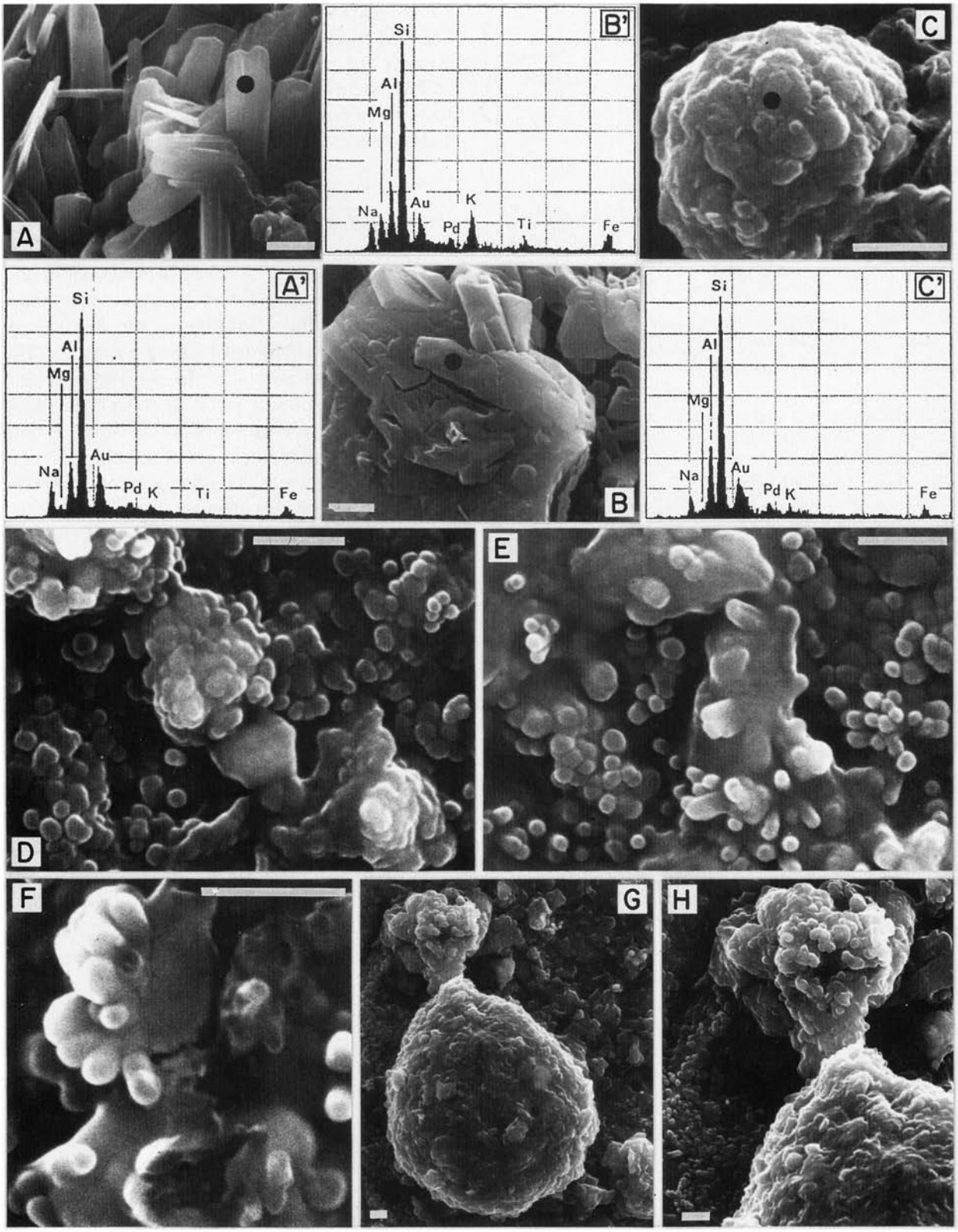
Results and discussion

There was no sharp interface between water and sediment, but under the very turbid water, there was a zone of black mud that became denser with depth and contained fish (*Tilapia?*) remains. The very thin superficial sediments were smooth and black. They lay on a hardened reddish layer which prevented the penetration of coring tubes. A map of the approximate thickness of the black layer is given Fig. 7. It reaches a maximum thickness (around 1.5 m) in the deepest part of the basin. The black layer disappears southwards and the reddish layer is directly overlain by microbial mats on which flamingos feed.

X-Ray diffractograms of the black sediments were very difficult to interpret because of the interference of many mineral species and because of the relatively low peaks heights with respect to the background. Most of them must have been zeolites with clay minerals and, probably, sodium silicates. Neither pyrite nor carbonates were detected. SEM imagery (Fig. 8A, B, C) and microprobe analyses (Fig. 8A′, B′, C′) tended to confirm the above interpretation. Such minerals would be expected from an environment of this kind (Eugster, 1967, 1970; Maglione, 1974; Zins-Pawlas, 1988). The sedimentary particles include clay minerals (Fig. 8A), several forms of zeolites

Table 4. Analyses of core A (for location see Fig. 7).

Level	Weight loss at 450 °C %	Org. C %	Org. N %	NH_4^+ $\mu g\, g^{-1}$	C/N	Water content %	Carbonates as CO_3^{2-} %
Top (mud)	10.62	0.30	0.05	0.040	5.8	54.9	7.30
Middle (30 cm)	9.52	0.34	0.05	0.026	7.1	52.6	6.50
Base (60 cm)	10.13	0.24	0.04	0.068	5.9	51.7	7.41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among which probable clinoptilolite (Fig. 8B). No pyrite, which is easily recognizable through SEM, was detected.

The analysed aluminosilicates display noticeable amounts of Na and variable amounts of Mg and K but are devoid of Ca. The scarcity of Ca^{2+} in the water and absence of Ca-carbonates in the lake sediments suggest that most of the calcium released by weathering in the hydrological basin is trapped before reaching the lake. In numerous neighboring areas the pebbles and granules lying on the soil are discretely coated on their lower side with a thin carbonate crust, probably of bacterial origin. Thus, calcium must be retained upstream from the lake by the inconspicuous but widespread precipitation of carbonates in and at the surface of the soils. Some of the magnesium released from the mafic formations of the basin may behave in the same way.

It is worth noting that most of the aluminosilicates display noticeable Fe contents. Given the absence of sedimentary pyrite, in such an alkaline environment Fe seems to be preferentially linked to aluminosilicates rather than to sulfides even though the lake water contains large amounts of Fe and bacterial activity produces hydrogen sulfide.

The black sediments are very poor in organic matter (Table 4). It is even possible that a large part of organic matter remains in solution in the pore water of sediments. Thus, the black color of sediments is probably due to the presence of Fe in the lattices of silicates or aluminosilicates.

Caution should be taken in interpreting C/N ratios (Table 4) because the concentration of nitrogen is low and any small errors in its measurement will considerably change this ratio. Nevertheless, the three values obtained are low which tends to indicate a microbial origin for the organic matter in sediment and/or a preferential early biodiagenesis of carbohydrates that produces large quantities of carbonate and bicarbonate ions (Zajic, 1969; Castanier, 1987). This is in accordance with the high alkalinity of the lake waters.

A large number of sedimentary particles of the black layer seem to be composed of bacterial cells coated with cocoon-like mineral matrix (Fig. 8F) which often form more or less spherical (Fig. 8C, D), plate-like or urchin-like (Fig. 8E) bio-mineral assemblages which seem to be usually composed of aluminosilicates (Fig. 8C′). These could be amorphous compounds such as those that accumulate in the early stages of the formation of bacterially-produced carbonate bio-mineral assemblages (Castanier, 1987; Castanier *et al.*, 1988).

During the course of SEM exploration a very strange structure was discovered (Fig. 8G). It is composed of an avoid body and a cone-shaped appendix which are separated on the micrograph but seem to have been linked together. A close-up (Fig. 8H) shows that the appendix is hollow and its wall is made of several layers of mineralized bacterial cells. Here is not the place to discuss further this obviously biological structure. In our opinion, it has to be placed, with similar structures we have found in other modern environments (Castanier, 1987, and unpublished studies) and with fossil counterparts known from Precambrian times (Schopf & Walter, 1983), among a group that might be termed 'metaprokaryotes'.

The reddish layer overlain by the black sediment has a similar mineralogical composition as shown by X-Ray diffractometry but it is likely that the iron has been released from silicates or aluminosilicates to form oxides or hydroxides.

Fig. 8. Some nannofacies of sediments in core A and microprobe analyses. Black dots indicate analyses points. Scale bars are 1 μm. A: Probable clay minerals; B: Probable zeolite (clinoptilolite?). Notice the round body being included in crystal (possible bacterial body); C: Mineral assemblages. The round body could be of biological origin and constituted of amorphous compounds; A′, B′ & C′: microprobe analyses of mineral particles; D: Globular or more or less tetrahedral bio-mineral assemblages. E: First stage of bio-mineral build-up. Numerous bacterial cells are trapped in mineral assemblages which are probably composed of amorphous compounds; F: Some bacterial cells have been separated from tiny bio-mineral assemblages during SEM preparation which lets appear they are coated by a rigid mineral matrix or cocoon; G: *Incertae sedis* biological structure with an ovoïd body and an appendix. H: Close up of preceding micrograph showing detail of the appendix and structure of its wall.

This probably occurred in a period when the lake dried out completely for a long time.

The salt crust which covered the lake on January 1990 comprised two parts. The outer one was composed of halite, the inner one was trona (Na_2CO_3, $NaHCO_3$, $2H_2O$). These crusts are dissolved when floods occur and, according to satellite imagery, they cover the basin northward starting from the southern bank.

Microbiology

Materials and methods

On October 20–26, 1988, samples for counting living bacteria were collected aseptically in the field early each morning. The culture media were inoculated in the field laboratory within 3 h in order to obtain reliable counts.

Water samples were collected at the following points (Fig. 5 & 7): station 43 in the lake; PL 1 and PL 2; PB 1 and PB 2; SV 1, SV 2 and SV 3; NV 1 and NV 2. Sediment samples were: Core A (mud and sediment); SV 1 and SV 3; NV 1 and NV 2; and a piece of silicified wood from Central Island.

The media inoculated for counts were: for heterotrophic strict aerobic bacteria, the solid medium 2216E (Oppenheimer & Zobell, 1952); for heterotrophic aerobic bacteria able to precipitate carbonates (here after called carbonate-precipitating, bacteria), the solid medium of Castanier (1987); for heterotrophic strict and facultative anaerobic bacteria a liquid culture medium described by Marty (1981) prepared following the technique of Hungate (1969) and inoculated following the method of the most probable number (MPN) (McCrady, 1918); and for the sulfate-reducing bacteria the liquid medium of Marty & Garcin (1987) prepared following the technique of Hungate (1969) and inoculated following the method of the most probable number (MPN) (McCrady, 1918). After 15 days incubation at room temperature counts were performed by the Service of Microbiogeology in Nantes. Results are given Table 5.

As bacterial carbonate precipitation may be

Table 5. Bacterial numerations on water (W) and sediment (S) of lake samples and surrounding inflows. Counts are numbers of living cells in 1 ml water or 1 g sediment. For location of samples see text and Figs 5 & 7.

Sample	Heterotrophic aerobic bacteria		Heterotrophic anaerobic bacteria	
	Total	Carbonate-precipitating	Total	Sulfate-reducing
St. 43 (W)	1300000	675000 (52%)	600	6 (1%)
Core A (mud)	2320000000	39500000 (2%)	20000000	1300000 (7%)
Cora A (S)	3860000000	52100000 (1%)	600000	6000 (1%)
PL 1 (W)	36700000	6540000 (18%)	700000	6000 (1%)
PL 2 (W)	385000000	50000000 (13%)	20000	2500 (13%)
PB 1 (W)	76700000	16500000 (22%)	5000	6 (<1%)
PB 2 (W)	1080000000	600000000 (56%)	700000	250 (<1%)
SV 1 (W)	32900000	4400000 (13%)	1300	0 (0%)
SV 1 (S)	72000000	14500000 (20%)	12000	25 (<1%)
SV 2 (W)	140000000	17500000 (13%)	25000	0 (0%)
SV 3 (W)	395000000	68800000 (17%)	1100000	60 (<1%)
SV 3 (S)	333000	269000 (81%)	20000	25 (<1%)
NV 1 (W)	30000000	4360000 (14%)	1100000	600 (<1%)
NV 1 (S)	388000000	105800000 (27%)	250000	20000 (8%)
NV 2 (W)	161000	63700 (40%)	200000	250 (<1%)
NV 2 (S)	3790000	2100000 (55%)	60000	0 (0%)
Silicified wood	24800000	17500000 (71%)	700000	2500 (<1%)

unfamiliar to some readers, it is worth offering a few statements about it. Bacteria precipitate carbonates in two ways. First, there is passive precipitation resulting from an increase in the pH of the medium produced by the end-products of bacterial metabolism. This can be brought out by three metabolic pathways. These are: the anaerobic ammonification of amino-acids; the anaerobic and microaerophilic dissimilatory reduction of nitrate; and the anaerobic reduction of sulfate accompagnied by hydrogen sulfide production. Second, there is the active precipitation of carbonates by still poorly known membrane processes. This has been demonstrated under aerobic conditions but still remains conjectural for anaerobic ones (Castanier, 1987). From several experiments carbonate precipitation appears to be the reaction of bacterial populations to an increase in metabolisable organic substrates. When this occurs, the bacterial populations first increase rapidly, causing gradual increases in the concentrations of carbonate and bicarbonate ions and of other end-products of metabolism, and in pH. A steady state is reached within 24 to 48 hours. In these conditions and given the presence of Ca^{2+} and Mg^{2+} in the medium, active carbonate precipitation occurs first and is followed by passive precipitation (Castanier, 1987). The first carbonate particles seem to be generally composed of amorphous, perhaps hydrated, compounds (Castanier *et al.*, 1988). If Ca^{2+} and Mg^{2+} are lacking, the precipitation of carbonates does not occur and carbonate and bicarbonate ions simply accumulate in the medium.

Results and discussions

Primary producers

A large part of microbial primary production seemed to occur on the shoals south of Central Island which were covered by extensive cyanobacterial mats. Cyanobacteria also colonized the hot springs vents, their effluent channels and the beds of peripheral streams. Bacterial populations in the lake itself include methane producing bacteria, the activity of which was demonstrated by methane bubbles as assayed by the flame of a lighter. The color of the lake waters varied widely. In October, 1988, they were dirty pink whereas in November 1985, when the level was a little lower, they were deep green with pink patches. This could have represented purple and green photosynthetic bacteria populations changing in relation to oxygen availability. The surface oxygen content of the water was high for sulphur bacteria but let us recall that the dissolved oxygen content of the lake waters rapidly decreased with depth. Moreover, the microscopic observation of water showed the absence of algal phytoplankters that could have been responsible for the color of the lake water. Lastly, the lake sediments did not contain diatom frustules that might have lived during high stand periods, either because no diatom population developed in the lake or because their siliceous tests were rapidly dissolved. Thus, in Lake Logipi the bulk of primary producers must be prokaryotes.

Heterotropic bacteria

The populations of heterotrophic bacteria were much denser in the inflowing waters, notably the hot spring environments and the seepage zone of the Barrier (Pelicans Bar), than in the lake water itself, presumably because the primary production is higher there. Contrarily they are denser in the lake sediments than in sediments of the surrounding water inflows.

As far as heterotrophic aerobic bacteria populations are concerned, there is a clear increase in the proportion of carbonate-precipitating bacteria downstream, towards the lake where they dominate in water (Table 5). The high percentage of such bacteria in the 'silicified wood' collected on the beach near NV 2 is very typical. This means that the organic substrates in peripheral environments are colonized by carbonate precipitating bacteria and at least partly transformed into carbonate and bicarbonate ions. The same processes occur in the surface waters of the lake itself. In both cases, because of the scarcity of Ca^{2+} and Mg^{2+} in water the carbonate-precipitating bacteria are unable to precipitate carbonates, so that the carbonate and bicarbonate ions contents tend

to increase in the inflowing waters as well as in the lake which accounts partly for their high alkalinity and pH.

The bacterial populations of the lake sediments are very dense with up to nearly 4.10^9 living cells per gram. This contrasts sharply with the low organic matter content of these sediments. In addition, even though carbonate-precipitating bacteria are numerous in sediments, they fall to a few percent of the total bacterial counts (Table 5). The organic matter produced in the lake or coming from the outside apparently is partly recycled into the bacterial populations themselves and partly transformed, through bacterial metabolism, into carbon dioxide and carbonate and bicarbonate ions with very little accumulation of particulate organic matter in the sediments. Lake Logipi appears to be a terminal pool of natural detergent, unable to sediment large quantities of organic matter at its present stage of evolution.

In such conditions of alkalinity and pH, the carbon dioxide produced by heterotrophic bacteria must be mostly converted to carbonate and bicarbonate ions. Additionally, a part of it is possibly recycled by primary producers so that probably very little carbon escapes the system as gaseous CO_2 or CH_4.

Anaerobic heterotrophic bacteria are much less numerous than aerobic ones, even in the few restricted environments studied and in the mud at the bottom of the lake. In this mud sulfate-reducing bacteria are fairly numerous, which explains the relatively low sulfate concentration with regard to the salinity in the water of the central part of the lake (Table 1). Bacterial sulfide oxidation probably occurs near the top of the water column but does not prevent a part of the produced hydrogen sulfide from escaping towards the atmosphere as attested by typical odors when travelling over the lake.

Many hydrochemical and sedimentological features of Lake Logipi are related to prokaryotic activity. This is true for all ecosystems but is particularly evident here because the prokaryotic activity is not camouflaged by other biological activity.

Higher organisms

None of the expedition members was a zoologist. Nevertheless, Lake Logipi is such an isolated place that we feel it might be useful to offer our observations on higher organisms.

In October 1988, birds flocks were distributed in two zones. On the southern shoals of the lake, hundreds of flamingos were feeding on microbial mats. The birds were trampling on the mats perhaps in order to break it up into small edible pieces but perhaps also to draw out small larvae or worms. Some insects (Coleoptera) were visible in the very shallow (up to 5 cm depth) shoreline waters. Elsewere observations were impossible because of the very high turbidity of water. We tried to collect zooplankton by means of a zooplankton net pulled by the boat. Under the microscope the collected material revealed no recognizable metazoans, only plant detritus and feathers. The feeding behaviour of flamingos produces round and linear tracks on the surface sediment. In the northern deeper part of the lake a few tens of pelicans were gathered, probably to feed. Indeed there were fish in the lake. Live ones were seen at the water surface and dead ones were occasionally brought to the surface by the boat's turbulence, but none was collected. They were approximately 20 cm in length. In November 1985, the lake was lower, smaller, saltier and probably less oxygenated. Part of the fish population was dead and floating on the surface especially in the northeastern corner of the lake, which attracted vultures. Again, no fish were collected but from photographs taken then, it appears they may be *Tilapia* sp.

The wastes of the lake's numerous birds enrich the lake water with phosphate which favours bacterial activities and with uric acid the bacterial degradation of which gives carbon dioxide and ammonia. These bacterial processes act in the same way as the ammonification of amino-acids which increases pH and enhances the carbonate and bicarbonate ions production. It is difficult to know if such processes are quantitatively significant. Besides, the disturbance and oxygenation of sediments caused by birds activities could be

even more important but birds probably play an important role in the hydrochemical behavior of Lake Logipi.

Conclusions

From its hydrological situation Lake Logipi appears to be an accumulator for mineral ions and dissolved organic and inorganic compounds, even though there could be some recycling through hot springs.

At its present stage of evolution, and given the hydrochemical background, *i.e.* mainly the lack of Ca^{2+} and Mg^{2+} in incoming waters, the microbial processes (organic matter production and consumption) maintain a high alkalinity in the lake waters because they are chiefly responsible for carbonate and bicarbonate ions production.

This induces:

- the precipitation of sodium aluminosilicates (perhaps with sodium silicates) and clay minerals from the silica and alumina saturated brines;
- the crystallization of ephemeral salt crusts (mainly Na-carbonates) at the last stage of brine evaporation;
- the retention in solution and biological recycling of most of the organic matter produced by the system itself or imported.

Both kinds of mineral deposits have to be interpreted in terms of concentration of solutions and in terms of biological activity of the sedimentary environment. As biological processes account at least partly for their genesis, they might be termed bio-evaporites even though, under other conditions, they may form in absence or without the intervention of organisms.

Lastly, it is necessary to keep in mind that carbonate production and/or precipitation are usual and widespread metabolic processes for bacterial populations in natural environments. Then, let us consider the whole basin of the Suguta River. Calcium and magnesium which are abundant in such a geological environment must be massively trapped in carbonates precipitated at the surface or inside the soils of the slopes because the general bacterial activity is favored by the high temperatures. On the other hand, as rainfall is low, dissolution of carbonates is minor and very little Ca and Mg reach the terminal lake. This allows microbial activity to intensify the accumulation of carbonate and bicarbonate ions in the lake. Weathering processes within the basins (which are partly controlled by bacterial activity) and evaporative concentration are surely causes of the high pH and alkalinity of Lake Logipi and of most soda lakes but the influence of microbial processes on these characteristics must not be underestimated.

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References

Bosworth, W., 1989. Basin and range style tectonics in east Africa. J. Afr. Earth Sci. 8: 191–201.

Castanier, S., 1987. Microbiogéologie: processus et modalités de la carbonatogenèse microbienne. State Doctorate Thesis, University of Nantes, France, 541 pp.

Castanier, S., A. Maurin & J.-P. Perthuisot, 1988. Les Cugnites: carbonates amorphes de Ca et Mg, précurseurs possibles de la dolomite. C. r. Acad. Sci., Paris, 306, II: 1231–1235.

Eugster, H. P., 1967. Hydrous sodium silicates from Lake Magadi, Kenya. Contr. Mineral. Petrol. 22: 1–31.

Eugster, H. P., 1970. Chemistry and origin of the brines of Lake Magadi, Kenya. Mineral. Soc. Amer. Spec. Paper 3: 215–235.

Gwynne, M. D., 1969. The South Turkana Expedition. Scientific Papers I. Preliminary report on the 1968 season. Geogr. J. 135: 331–342.

Hungate, R. E., 1969. A roll tube method for cultivation of strict anaerobes. In Norris and Ribbons (eds), Methods in Microbiology, Vol. 3B, Academic Press, London and New York: 117–132.

Lambiase, J. J. & W. Bosworth, 1991. Structural Controls on Sedimentation in Continental rifts. Geol. Soc. Amer. Bull., in press.

Maglione, G., 1974. Géochimie des évaporites et silicates néoformés en milieu continental confiné. Les dépressions interdunaires du Tchad, Afrique. State Doctorate Thesis, University P. & M. Curie, Paris, 334 pp.

Marty, D., 1981. Distribution of different anaerobic bacteria in Arabian Sea sediments. Mar Biol. 63: 277–281.

Marty, D. & J. E. Garcin, 1987. Présence de bactéries méthanogènes méthylotropes dans les sédiments profonds du détroit de Makassar (Indonésie). Oceanol. Acta 10: 249–253.

McCrady, M. H., 1918. Tables for rapid interpretation of fermentative tube results. Can. J. Publi. Health, 9: 201–216.

Oppenheimer, C. H. & C. E. Zobell, 1952. The growth and viability of sixty three species of marine bacteria as influenced by hydrostatic pressure. J. mar. Res. 11: 10–18.

Ottman, J. M., 1960. Essai de détermination qualitative et quantitative de quelques constituants de la matière organique dans un sédiment marin. Revue Geogr. Phys. Geol. Dynam., Paris, 3, 1: 49–52.

Rodier, J., 1984. L'analyse de l'eau, eaux naturelles, eaux résiduaires, eau de mer. Dunod, Paris: 564 pp.

Schopf, J. W. & M. R. Walter, 1983. Archean Microfossils: New Evidence of Ancient Microbes. In Schoph (ed.), Earth's Earliest Biosphere. Its origin and evolution. Princeton University Press, Princeton: 214–289.

Solorzano, L., 1969. Determination of ammonia in natural waters by the phenylhypochlorite method. Limnol. Oceanogr.: 14–779.

Zajic, J. E., 1969. Microbial biogeochemistry. Academic Press, New York & London, 247 pp.

Zins-Pawlas, M.-P., 1988. Géochimie de la silice dans les saumures et les milieux évaporitiques. Doctorate Thesis, University of Strasbourg, France, 200 pp.