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PATRICK DENNY
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The vertical temperature used as a guide to the internal hydromechanics of a lake at times be misleading. It is since a sharp change in depth, i.e., a thermocline, in the density of water, upon which stratification of water temperature change is greater than but HUTCHINSON (1957) the limitation of such a rigid suggested the following minimum rate of decrease in water temperature gradient, in which the water temperature gradient can be seen in Fig. 1 that tempera-
LAKE MAHEGA: A MESOTHERMIC, SULPHATO-CHLORIDE LAKE IN WESTERN UGANDA

JOHN M. MELACK and PETER KILHAM

ABSTRACT

In May, 1971, Lake Mahega had pronounced mesothermy (40.0° C at one metre). Solar heating of a bloom of bacteria and the blue-green alga, Synechococcus bacillaris Butch., probably caused the high temperature. A total ionic concentration gradient increasing from 192,600 mg·litre−1 at the surface to 415,200 mg·litre−1 at three metres stabilized the thermally inverted water. Nearly equal amounts of chloride and sulphate accounted for about 90% of the anionic composition. Sodium was the major cation. Crystals of the triple salt, northupite (Na₅₂P₂O₇·MgCO₃·NaCl) and of thenardite (Na₂S·9H₂O) were mixed with the surface sediment. We believe it is possible that primary northupite deposition is occurring. Lake Mahega is also the first mesothermic, sulphato-chloride lake reported for East Africa.

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INTRODUCTION

Lake Mahega (0° 01′ S, 29° 58′ E) is an extremely saline crater lake located in the western Rift Valley, Uganda (Fig. 1). The small lake is 0.16 km² in area and lies at an altitude of 925 metres above sea level (UGANDA GOVERNMENT 1965). The crater rim is between 120 and 215 metres above the lake, and a dry forest (LOCK 1967) covers the inner slopes. In May, 1971, the maximum depth of water was 4.1 metres. Each year localized storms bring between 60 and 90 centimetres of rain, usually during the months of March through May, and September through November (LOCK 1967). HOLMES and HARWOOD (1932), DOORNKAMP (1970), and BISHOP (1970) have described the regional geology. The only previous description of Lake Mahega was a chemical analysis of the water (ARAD and MORTON 1969).

METHODS

We sounded the basin with a weighted line and collected water samples with a two-litre Van Dorn bottle, and mud samples with an Ekman dredge. Temperature was measured to an accuracy of ±0.1° C on
May 23 with a mercury thermometer and on May 30 with a thermister and Wheatstone bridge circuit made by Yellow Springs Instruments. We estimated transparency with a Secchi disc 20 centimetres in diameter.

Oxygen, hydrogen sulphide, pH and turbidity were measured in the field with a Hach Model DR-EL Portable Water Engineers Laboratory (ANON). Oxygen was underestimated owing to the severe effervescence during acidification (WALKER et al. 1970). Conductivity, sodium, potassium, calcium, magnesium, sulfate, chloride, alkalinity, silicon and fluoride were measured three months after collection at Duke University. Water samples were collected and stored in polyethylene bottles. Sodium, potassium, calcium, magnesium and silicon were determined by atomic absorption spectrophotometry using a Perkin-Elmer 303 spectrophotometer (methods described in PERKIN-ELMER 1964). Sodium, potassium, calcium and magnesium were analysed in an air-acetylene flame; silicon and sometimes calcium were done in a nitrous oxide-acetylene flame to preclude the formation of refractory compounds (SLAVIN 1968). When necessary, calcium and magnesium were determined by EDTA titration (AMERICAN PUBLIC HEALTH ASSOCIATION 1965). A Cotlove Chloridometer (Laboratory Glass and Instruments Co.) which employs a silver ion titration was used for determining chloride. Total alkalinity was determined by titration to the bromocresol green-methyl red end-point (AMERICAN PUBLIC HEALTH ASSOCIATION 1965). Sulfate was determined using an ion exchange method (MACKERETH 1963). Fluoride concentrations were estimated electrometrically by an Orion Specific electrode on a Philips Pholysys were used.

The mineral then examined using an Olympus microscope. Megascopic crystals of the lake water were also dissolved and an other.

RESULTS

We visited Katwe 1971, and made measurements between both days. The occasional cat appeared or existed on both days. The temperature.
Orion Specific Ion Meter with the appropriate electrodes. Conductivity was measured on a Philips PR9501 meter. The water analyses were within 6% of chemical balance.

The mineral crystals were powdered and then examined in a Norelco X-ray diffractometer using Cu-Kα radiation. Only large (>2 mm) single crystals were studied. These megascopic crystals were found on the bottom of the lake in a mud matrix. Crystals were also dissolved in de-ionized distilled water and analysed quantitatively.

RESULTS

We visited the lake on May 23 and 30, 1971, and made our collections and measurements between 1300 and 1430 hours on both days. The surface was calm except for occasional cat's paws of capillary waves and appeared orange in color. Mesothermy existed on both visits (Fig. 2). On May 23 the temperature increased from 32.8°C at the surface to 38.1°C at two metres and decreased to 37.2°C at three metres. The temperature on May 30 was 31.0°C at the surface, increased to 40.0°C at one metre and decreased to 37.0°C at 3.5 metres.

Coinciding with the maximum temperature at one metre on May 30 was a turbid, green layer of unidentified bacteria and the blue-green alga, *Synechococcus bacillaris* Butch.* The location of the bacteria in anoxic, H₂S containing lighted water (see below) suggests they were photosynthetic sulphur bacteria (PENNING 1967, TRUPER and GENOVESE 1968). On May 30 the turbidity expressed in Jackson Turbidity

*This organism was identified by Dr. R. R. L. Guillard who has two *Synechococcus bacillaris* clones in culture. One clone (48 Syn) is reddish-orange while the other (Syn) is blue-green. These organisms were isolated from coastal sea water. *Anacystis nidulans* and *Agmenellum quadruplicatum* are probably the same organism.

![Figure 2. Vertical profiles of temperature (°C) on May 23, 1971 (○) and May 30, 1971 (●).](image-url)
Units was 47 in the surface water, increased to about 600 at one metre and decreased to 69 and 80 in the faintly orange water at two and three metres respectively. A very turbid layer did not exist on May 23. Secchi disc visibility was 0.33 metres. The oxygen concentration on May 23 was 0.8 mg/litre at the surface and 0.0 at one, two and three metres. Unfortunately, we did not measure oxygen on May 30 but the large amount of H₂S at one metre and below implies anoxia (Table 1).

Samples of surficial sediment smelled of H₂S and were brownish grey and gritty. Crystals of the triple salt, northupite (MgCO₃Na₂CO₃NaCl) were common in the sediment. We also found a few thenardite (Na₂SO₄) crystals. Table 2 presents a summary of the X-ray powder diffraction spectra we obtained for each mineral. Data from entries No. 5-0631 (thenardite) and No. 19-1213 (northupite) of the powder diffraction file (JOINT COMMITTEE ON POWDER DIFFRACTION STANDARDS 1971) were used in identifying these minerals. Chemical analyses of the crystals supported our identifications.

The chemistry of Lake Mahéga water at four depths is presented in Table 1. These data indicate that it is a sulfato-chloride lake. Table 3 gives the percentages of the dissolved solids relative to the total dissolved solids at each of the four depths. Fig. 3 shows the major anionic composition of the closed basin lakes in the Katwe volcanic field (Fig. 1). Lake Mahéga was 125% more concentrated when it was sampled by ARAD and MORTON (1969). Water samples were only collected on May 23 so we do not know if chemical changes occurred between sampling dates.

DISCUSSION

The observed changes in the relative ionic proportions of the lake water between the surface and the bottom indicate that magnesium and sulphate may be precipitating out of solution. Because northupite and thenardite are presumed to be in a stable chemical equilibrium with the bottom water, the precipitation of these evaporite minerals may explain the ionic proportions of magnesium and sulphate. Sulphate reduction, however, may also be important in the removal of sulphate.

Because sodium bicarbonate-carbonate lakes predominate in Africa, the dominance by sulphate and chloride in Lake Mahéga makes it very unusual (KILHAM 1971b). The anionic composition of Lake Mahéga is, however, the expected result of the evaporative concentration of a closed basin lake receiving inflows rich in magnesium and calcium (KILHAM 1971a). To assess the amount of evaporative concentration one must know the water balance of the lake. This is not known, but judging from the thick growth of Cyperus laevigatus and thorn thicket on the shore, the lake level is not rising. Based on Penman's method Beadle (LOCK 1957) reported for a location about 20 km from the lake an annual potential evaporation of about 150 cm which was about double the rainfall (ca. 80 cm). Although the method used is not completely appropriate for estimating evaporation from a saline lake, it is the only one available and can be used to support the importance of evaporative concentration in determining the chemistry of the lake.

The acquisition of solutes in the lakes of the Katwe volcanic field (Fig. 1) was studied by ARAD and MORTON (1969). They concluded that the chemical compositions of all the lakes except Kilagata and Murumuli could be explained in terms of the evaporation of the mineral spring waters entering the lakes. Lakes Kilagata and Murumuli were explicable in the same way only if it was assumed that the original source of salts possessed a high SO₄/Cl ratio.
Table 1. Chemical analyses of Lake Mahega (May 23, 1971). Concentrations expressed as mg litre⁻¹.

<table>
<thead>
<tr>
<th>Depth (Meters)</th>
<th>Conductivity at 25°C (µmho/cm)</th>
<th>Total Solids</th>
<th>Na⁺</th>
<th>K⁺</th>
<th>Ca²⁺</th>
<th>Mg²⁺</th>
<th>SO₄²⁻</th>
<th>Cl⁻</th>
<th>HCO₃⁻</th>
<th>PO₄³⁻</th>
<th>SiO₂</th>
<th>F⁻</th>
<th>H₂S</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>124,700</td>
<td>192,600</td>
<td>91,000</td>
<td>11,800</td>
<td>15.2</td>
<td>134.1</td>
<td>61,000</td>
<td>51,500</td>
<td>9,123</td>
<td>9.6</td>
<td>28</td>
<td>3.2</td>
<td>0.1</td>
<td>10.1</td>
</tr>
<tr>
<td>1</td>
<td>145,300</td>
<td>281,500</td>
<td>81,000</td>
<td>16,200</td>
<td>13.6</td>
<td>50.1</td>
<td>96,000</td>
<td>72,200</td>
<td>15,960</td>
<td>19</td>
<td>15</td>
<td>7.6</td>
<td>4</td>
<td>—</td>
</tr>
<tr>
<td>2</td>
<td>155,200</td>
<td>395,100</td>
<td>125,000</td>
<td>24,900</td>
<td>13.6</td>
<td>15.3</td>
<td>110,000</td>
<td>109,800</td>
<td>25,200</td>
<td>110</td>
<td>37.5</td>
<td>28.9</td>
<td>&gt;5</td>
<td>—</td>
</tr>
<tr>
<td>3</td>
<td>156,000</td>
<td>415,200</td>
<td>129,000</td>
<td>26,700</td>
<td>13.2</td>
<td>7.0</td>
<td>116,000</td>
<td>117,000</td>
<td>25,260</td>
<td>132</td>
<td>37.5</td>
<td>28.9</td>
<td>&gt;5</td>
<td>9.1</td>
</tr>
</tbody>
</table>
Table 3. Percentages of dissolved solids relative to the total dissolved solids at each depth.

<table>
<thead>
<tr>
<th>Depth (Meters)</th>
<th>N+</th>
<th>K+</th>
<th>Ca²⁺</th>
<th>Mg²⁺</th>
<th>SO₄²⁻</th>
<th>Cl⁻</th>
<th>HCO₃⁻</th>
<th>PO₄³⁻</th>
<th>SiO₂</th>
<th>F⁻</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>30.6</td>
<td>6.13</td>
<td>0.008</td>
<td>0.070</td>
<td>31.7</td>
<td>26.7</td>
<td>4.74</td>
<td>0.005</td>
<td>0.015</td>
<td>0.002</td>
</tr>
<tr>
<td>1</td>
<td>28.8</td>
<td>5.80</td>
<td>0.005</td>
<td>0.021</td>
<td>34.1</td>
<td>25.7</td>
<td>5.70</td>
<td>0.007</td>
<td>0.005</td>
<td>0.003</td>
</tr>
<tr>
<td>2</td>
<td>31.6</td>
<td>6.30</td>
<td>0.003</td>
<td>0.004</td>
<td>27.8</td>
<td>27.8</td>
<td>6.38</td>
<td>0.028</td>
<td>0.009</td>
<td>0.007</td>
</tr>
<tr>
<td>3</td>
<td>31.1</td>
<td>6.43</td>
<td>0.003</td>
<td>0.002</td>
<td>27.9</td>
<td>28.2</td>
<td>6.33</td>
<td>0.032</td>
<td>0.009</td>
<td>0.007</td>
</tr>
</tbody>
</table>

Table 2. Summary of X-ray powder diffraction data obtained for each mineral. Intensities (I) and d-spaces (d) are given.

<table>
<thead>
<tr>
<th>Mineral</th>
<th>d Å</th>
<th>I</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thenardite</td>
<td>4.65</td>
<td>62</td>
</tr>
<tr>
<td></td>
<td>3.83</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>3.18</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>3.07</td>
<td>57</td>
</tr>
<tr>
<td></td>
<td>2.78</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>2.64</td>
<td>51</td>
</tr>
<tr>
<td></td>
<td>2.33</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>2.21</td>
<td>8</td>
</tr>
<tr>
<td>Northupite</td>
<td>1.92</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>1.89</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>1.86</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>1.84</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>1.80</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>1.68</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>1.66</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>1.60</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>1.59</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>1.55</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>1.51</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>1.50</td>
<td>6</td>
</tr>
</tbody>
</table>

The source of solutes acquired by the mineral springs and surface runoff entering Lake Mahega is the key to understanding the chemical composition of the lake. The most likely sources of the solutes are the recent surficial volcanic rocks and the underlying Precambrian rocks. We favour the hypothesis that the runoff and springs feeding Lake Mahega have acquired their solutes from the weathering of the volcanic rocks in the area because the evaporative concentration of most of the dilute surface waters of the western Rift Valley would produce a lake of similar composition. In comparison to the other lakes in the area, Lake Mahega's dominance of sulfate and chloride resulted from more evaporative concentration. The surface waters of this region contain unusually high proportions of potassium and magnesium because the volcanic rocks they drain contain relatively large amounts of minerals rich in these elements (i.e., leucite KAl(SiO₄)₂ and magnesium olivine Mg₂SiO₄).

Northupite is not a common evaporite mineral but it has been reported as occurring in Lake Katwe, Uganda (ARAD and MORTON 1969), Borax Lake, California (FORD 1932), Searles Lake, California and the Green River Formation (Eocene, Wyoming) evaporite deposits (BRADLEY and EUGSTER 1969). In the Searles Lake deposits it occurs at one layer in a mineral assemblage consisting of northupite, thenardite and trona (EUGSTER and SMITH 1965). This assemblage is not considered primary (i.e., first formed as a precipitate on the bottom of the lake) but if it is, Searles Lake may have once had a composition similar to Lake Mahega.

Few data on the stability of northupite exist but the mineral has been synthesized a number of times (see BRADLEY and EUGSTER 1969). The chemical composition of Lake Mahega water as it changes with depth falls generally near and sometimes within the stability field of northupite.
the Rift Valley would exhibit a distinct composition. In the area, lakes in the near vicinity of sulfate and halite deposits are known to have relatively large proportions of potassium, magnesium, and calcium in these elements. However, the volcanic ash composition of the Lake Mahega waters is relatively large and rich in these elements, suggesting that volcanic ash is a significant factor in the lake's composition.

Common evaporite deposits reported as occurring in Uganda (ARAD and Morton, 1969; Lake, California and Texas) and in the Roraima Mountains (BRADLEY and SMITH, 1971) are not considered as a precipitate in these lakes. However, some of the deposits have a composition similar to the chemical composition of the water. This agreement seems reasonably good considering the differences between the experimental and field conditions. More data are needed to conclusively prove that primary northupite deposition occurs in Lake Mahega, but the chemical composition of the water suggests that northupite precipitation is possible.

The temperatures we measured in Lake Mahega were peculiar both because the deeper water was appreciably warmer than the surface water and because of the exaggeration of the mesothermy during the week between visits. The high turbidity (ca. 600 NTU at depth, ca. 1 metre) which receives sunlight (Secchi disc visibility 0.33 metres) is evidence which favors solar heating as the cause of the pronounced mesothermy measured on May 30. The deeper water was also probably heated by sunlight although thermal springs and the conduction of geothermal heat from the bottom may have contributed to the heat content. The relatively high turbidity and the high temperature at depth suggest that the lake is a eutrophicated system, with a distinct biological community that is not well understood.
dilute and transparent surface water allowed solar radiation to reach the deeper water but vertical mixing was retarded by the ionic concentration gradient (see Table I). Turbulence was also low because high crater walls around the small lakes shielded it from the wind.

Our visits were at the end of about two months of rain during which relatively dilute water entered the lake. The accumulation of a layer of this less saline water may have produced or at least exaggerated the ionic concentration gradient that we measured. The high evaporation rate during the subsequent dry period may have been sufficient to destroy the gradient and allow mixing. COLE et al. (1967) and ECKSTEIN (1970) reported this process for saline ponds located in Arizona, U.S.A., and Israel respectively.

Lakes with pronounced mesothermy or inverted temperature profiles caused by solar heating are not common and usually occur in arid or semi-arid regions. KALECSINSKY (1901) was the first to study such a lake. He measured a maximum temperature of 36.0° C at 132 metres in the Hungarian lake, Medve See. Additional examples of heliothermal lakes have been described in Antarctica (WILSON and WELLMAN 1962, SHIRTLIFFE 1964), the Americas (ANDERSON 1958, BRADBURY 1971, and BOZNIAK et al. 1969), North Africa (BEADLE 1943), and Israel (ECKSTEIN 1970). Lake Mahega is the first East African lake reported with mesothermy caused by the absorption of solar radiation. Of greater importance than its novelty is the demonstration that rapid solar heating of stratified water can occur in certain regions of East Africa. Recent research in Israel has suggested the possibility of utilizing the heated water in artificially constructed solar ponds for power production or heating purposes (TABOR and MATZ 1965).

**SUMMARY**

Lake Mahega had a mesothermal temperature profile in May 1971. On May 30 the water temperature increased from 31.0° C at the surface to 40.0° C at one metre and decreased to 37.0° C at 3.5 metres.

Solar heating of a bloom (ca. 600 Jackson Turbidity Units) of bacteria and the blue-green alga, *Synechococcus bacillaris* Butch. which coincided in depth (one metre) with the maximum temperature was probably the cause of the mesothermy.

The concentration of total dissolved solids increased from 192,600 mg/litre at the surface to 415,200 mg/litre at three metres. Magnesium and sulphate decreased in relative ionic proportion between the surface and bottom and were probably precipitating. Biological sulphate reduction also may have occurred.

Sodium was the major cation. Nearly equal amounts of sulphate and chloride accounted for about 90% of the anionic composition. Their predominance is the expected result of the evaporative concentration of a closed basin lake receiving inflows rich in magnesium and calcium.

Crystals of the triple salt, northupite (Na$_2$CO$_3$MgCO$_3$NaCl) and of theriaudite (Na$_2$SO$_4$), existed mixed with the surface sediment. We believe it is possible that primary northupite deposition is occurring.

Lake Mahega is both the first sulphato-chloride lake and the first markedly mesothermal lake reported in East Africa.

**ACKNOWLEDGEMENTS**: We wish to thank Dr. John Okedi, Director of the EAFFRO laboratory, Jinja, for providing a base for our African operations; Mr. Michael LaBarbera, N.U.T.A.E., the Staff of Ruhwenzi National Park and the J.B.P. team, Lake George. For help in the field. Dr. R. E. Hecky, Dr. S. S. Kilhan, Mr. S. A. Holdship, Dr. D. A. Livingstone and Miss Sally MacIntyre made helpful comments on the manuscript. Drs. D. S. Heron and D. P. Peacock kindly loaned us the use of a boat. Permission to work in Uganda was granted by the Uganda National Council for Research and Development.

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loosed the use of their X-ray diffractometers. Permission to work in the National Parks of Uganda was granted by Mr. P. Siembwe, Acting Director. Financial support came from National Science Foundation grants GB 8328X and GB 33310 to Dr. Livingstone at Duke University.

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