Temperature Steps in Lake Kivu: A Bottom Heated Saline Lake

FRED C. NEWMAN[1]
Department of Earth and Planetary Sciences, Massachusetts Institute of Technology, Cambridge 02139

(Manuscript received 5 July 1974, in revised form 10 October 1975)

ABSTRACT

Vertical profiles of temperature microstructure in Lake Kivu were obtained with "mini-microstructure recorders" developed by C. S. Cox and William Johnson at Scripps Institution of Oceanography. The profiles reveal three depth intervals containing many isothermal layers typically 0.25–2 m thick and of increasing temperature increments 0.01–0.03°C from layer to layer. Approximately 150 such layers appear in a single profile.

We assume double-diffusive convection and apply the results of Huppert and of Turner to calculate an upward heat flux of 0.71 to 1.6 W m^{-2} and a corresponding upward salt flux equal to one-fifth of the average salt output of the lake's only outflow. The chief source of heat and salt is probably geothermal springs in the lake bottom.

1. Introduction

Lake Kivu (2°S, 29°E) is an East African rift lake about 100 mi north of Lake Tanganyika. Of chief interest to this article is the northern basin of the lake (see map, Fig. 1) of nearly 500 m depth where step-like temperature microstructure was observed. The lake has one outflow, the Ruzzizi River, with an annual output to Lake Tanganyika of 3.2 km^3 per year and a "salinity" of 0.7‰ (Degens *et al.*, 1973). "Salinity" in this article will refer to the total mass of dissolved solids per kilogram of water, but the proportional composition of these dissolved solids is not implied to be the same as that of seawater. The lake is heated from below (Fig. 2) and salt-stabilized (Fig. 3). It is suspected that the source of heat and salt is geothermal springs at the bottom of the lake. Such springs exist on the perimeter of the lake and in Kabuno Bay. Also a feature thought to be a plume from a bottom spring was detected with sub-bottom profiling gear in the northern basin. At that time Von Herzen obtained a continuous temperature profile using a modified bottom heat flow recorder and observed that the temperature increased with depth in an irregular fashion suggesting four convecting layers of order 50 m thickness (Degens *et al.*, 1973). The aim of this work was to explore these layers and interfaces with a high spatial resolution temperature microstructure recorder.

Measurements were made with free falling temperature "mini-microstructure recorders" developed by Dr. Charles Cox and Mr. William Johnson at Scripps Institution of Oceanography (Fig. 4). This instrument is similar in concept to that described in Gregg and Cox (1971), but less sophisticated in overall design and does not measure conductivity. The instrument records the time rate of change of temperature from independent flake thermistors mounted on the nose and one wingtip. The actual "gross" temperature is also recorded from the nose thermistor. As the time constant of these thermistors was of order 25 ms, features 1 cm in size could be resolved.

2. Temperature profiles

A profile of the gross temperature taken at station 5 is shown in Fig. 5. A comparison of this with other such profiles as well as with that of Deuser (Fig. 2) shows that the gross character of the temperature profile has been quite constant over a number of years. In addition, Fig. 2 shows that the dependence of temperature on depth is horizontally quite uniform over most of the northern basin. One exception to this was found in the profile from station 17 (Fig. 5, inset) at approximately the location where the geothermal plume is thought to have been observed the previous year. The profile resembles the others except for a 0.028°C maximum in temperature, about 12 m thick at 220 m depth, demonstrating the presence of a layer of warmer water. The previously mentioned Von Herzen profile, which was obtained a year earlier from a site ~5 km north of our station 17, exhibits a similar feature of ~15 m thickness at the same depth. It seems quite reasonable to suppose that this feature is a layer of warmer, more saline water neutrally buoyant at this depth and fed by a plume from a bottom geothermal spring.

---

[1] Present affiliation: Atlantic Oceanographic & Meteorological Laboratories, NOAA, Miami, Fla. 33149.

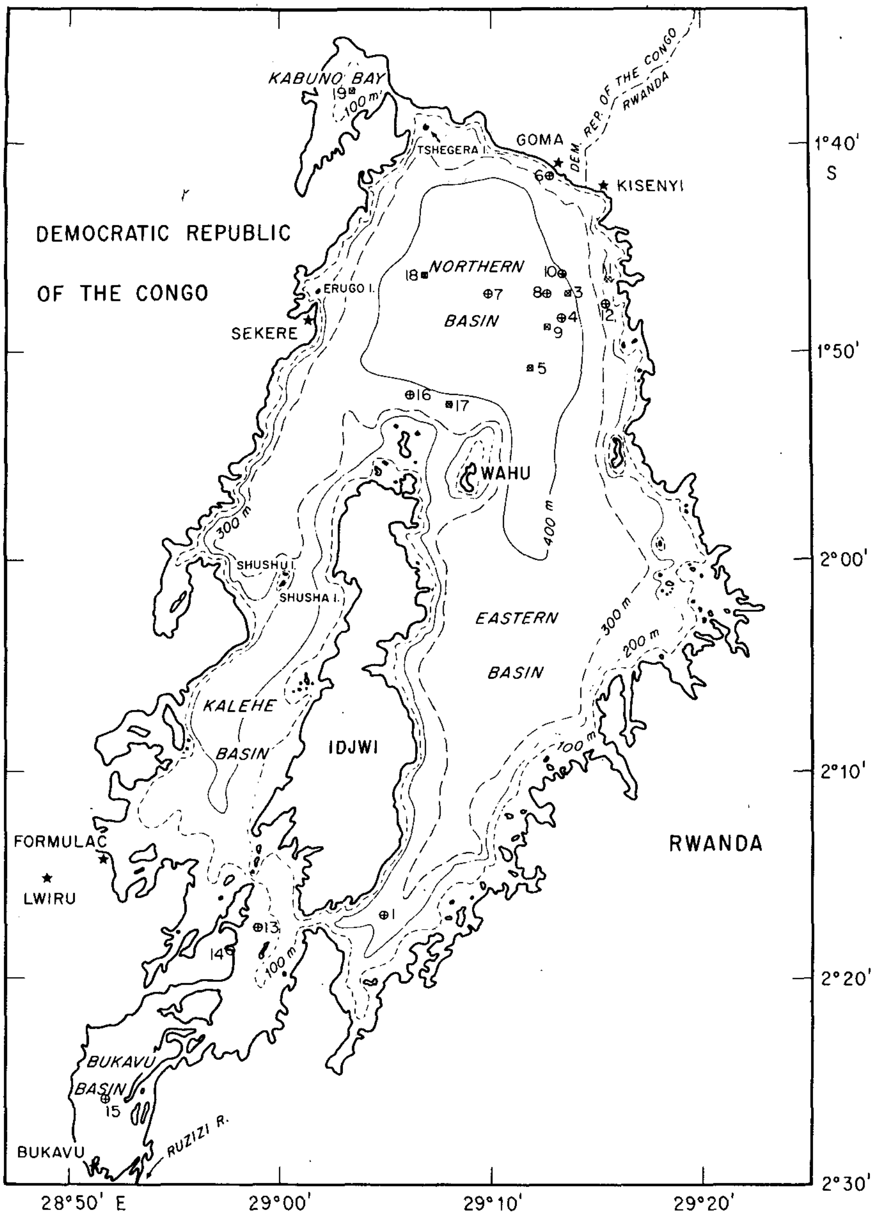

FIG. 1. Map of Lake Kivu showing all stations taken by Degens *et al.* in 1972. Microstructure profiles were obtained at stations 3, 5, 9, 17, 18, 19.

3. Microstructure profiles

The Cox recorder profiles show a warming surface layer overlying the cooler remnant of a seasonally produced mixed layer. The remainder of the profile shows temperature increasing at a variable rate. Three regions (B, C, D in Fig. 5) of distinctly higher mean gradient were found to be rich in microstructure in all profiles obtained. The vertical temperature gradient records for the regions B, C and D at stations 5 and 9 are shown in Figs. 6, 7 and 8 respectively. In addition, there is a less spectacular region (A) of fewer layers and smaller (~0.005°C) temperature steps in the vicinity of 150 m depth. In all regions it is immediately apparent that the gradient is concentrated in thin sheets separated by isothermal layers of somewhat greater thickness. The interface thickness, determined from the gradient spike signal corrected for instrument response characteristics, is about 10 cm in almost every case of a well-formed interface. The sheet-layer scheme repeats with frequencies of 0.5 to 4 per meter varying somewhat with station and depth range. There is no apparent coherence of layering between stations 5 and 9, probably because the space and time separations, 5 km and 1 day, of the stations were too great. [Observations of layers in several circumstances (Bethell, 1972) indicate their ratio of

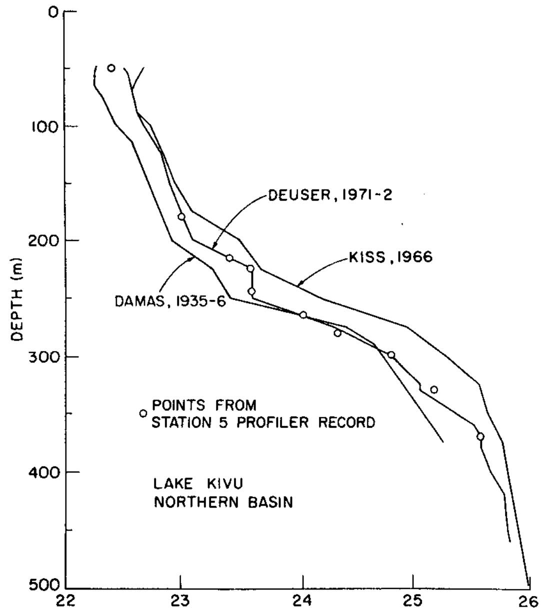

Fig. 2. Temperature data from previous investigators with points from this work for comparison. The Kiss data probably suffer from a systematic error.

horizontal to vertical scales seldom exceeds 1000.] The temperature increment across an interface "sheet" is typically 0.01–0.03°C. A portion of the station 5, region B, gross temperature record (Fig. 9) shows rather graphically the temperature steps associated with the temperature gradient signal spikes. In region D of the station 9 record (Fig. 8) some of the gradient peaks are smaller and the associated sheets appear to have split or somehow formed two to four thin sheets. A similar phenomenon has been reported by Neshyba *et al.* (1971) and by Woods and Wiley (1972) as an effect of billow turbulence due to the Kelvin-Helmholtz instability. For these layers, assuming a stability ratio $\beta\Delta S(\alpha\Delta T)^{-1}$ equal to 2, we calculate a 2×10^{-4} m s^{-1} velocity difference for an interface to become turbulent. We have, however, no evidence as to whether or not such shear might have existed.

That the pattern of vertical microstructure is uniform across the northern basin seems to be confirmed by additional records obtained as follows. One instrument malfunctioned in such a way as to begin recording near the bottom of the drop while returning to the surface, but only from the nose thermistor. Since the instrument does not invert while floating to the surface, the nose thermistor sees only microstructure freshly stirred by the instrument body. Comparison of these records (stations 17 and 18) with the return portion of those from stations 5 and 9 show the amplitude, depth, range and visual character of the stirred microstructure to be very similar.

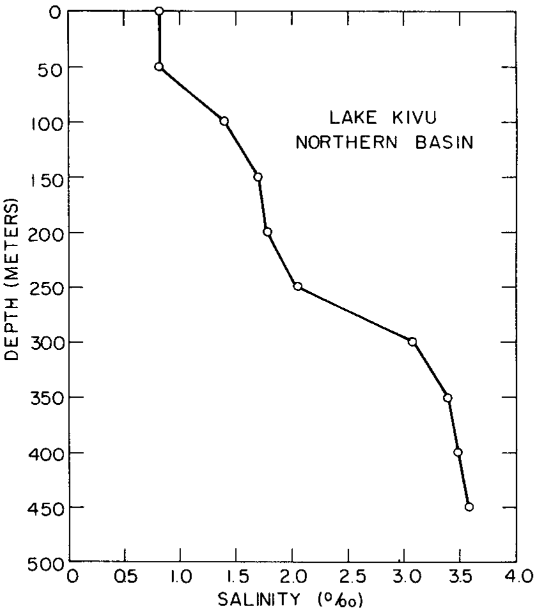

Fig. 3. Salinity profile of the northern basin of Lake Kivu. Data supplied by courtesy of E. Degens (1971 measurements).

Of particular interest is a nearly isothermal layer (Fig. 10) between regions B and C. This layer is 16 m thick and increases 2.7×10^{-3} °C in temperature from top to bottom, exactly the calculated adiabatic effect for water of this salinity, temperature and depth. Hence this layer is uniform in potential temperature and is probably in a state of convection. Region B including this layer now appears very similar to con-

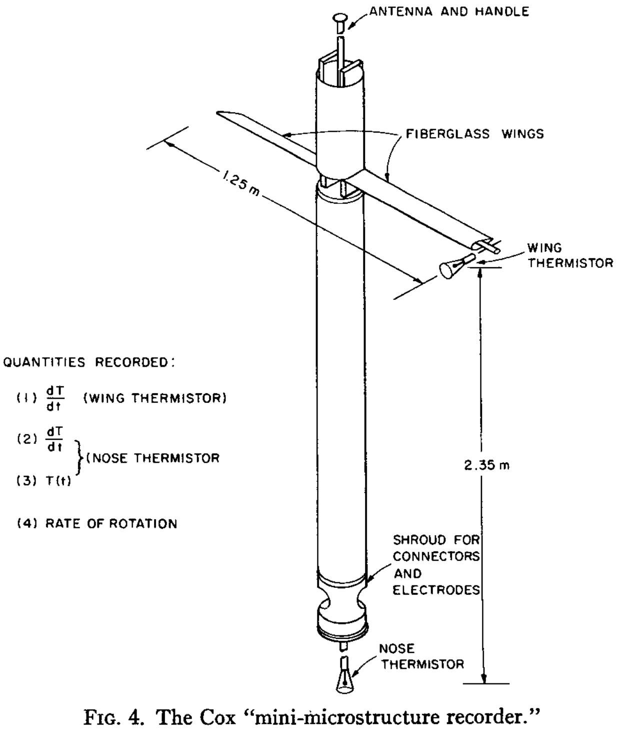

Fig. 4. The Cox "mini-microstructure recorder."

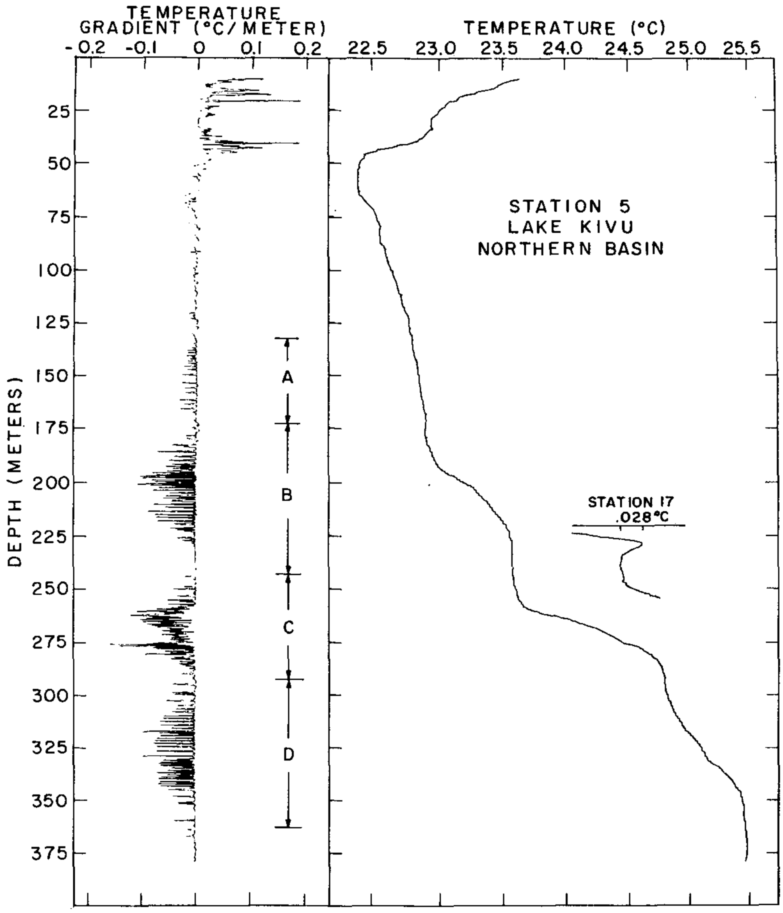

FIG. 5. Simultaneously recorded profiles of temperature and temperature gradient showing occurrence of step-like structure in regions of high mean gradient. Low apparent amplitude, compared to Figs. 6–8, is due to an averaging interval of 25 cm.

ditions as they evolved in Turner's experiment (1968) with a stable salinity gradient heated from below. In this experiment, many layers formed with the bottom layer approximately 10 times thicker than the rest. Later discussion of our observed layer thicknesses, however, leaves the relationship between Turner's experiment and these observations open to question.

4. Calculation of the upward flux of heat and salt

The results of Huppert and Turner apply to high Rayleigh number convection (i.e., "deep" layers and low rates of heating). That the layers observed in Lake Kivu lend themselves to analysis according to Huppert's and Turner's results may be shown by calculating a Rayleigh number from typical observed values ($\Delta T = 0.02$°C, $h = 100$ cm). An expression for the Rayleigh number is

$$\mathrm{Ra} = (g\alpha/\kappa\nu)\Delta T h^3, \tag{1}$$

where:

Ra	Rayleigh number
g	acceleration due to gravity
α	thermal coefficient of expansion
κ	thermal conductivity
ν	kinematic viscosity
ΔT	temperature difference across a layer
h	layer thickness.

This yields $\mathrm{Ra} \approx 10^8$ for the typical observed layer. In addition, Huppert (1971) describes convecting layers at high Rayleigh number as having only thin boundary layers at the interfaces and nearly isothermal central regions. The profiles of temperature gradient show that almost all of the observed layers conform well to this description.

According to Huppert (1971), the expression for calculating the heat flux is derived as follows. In a system of thermally convecting layers at high Rayleigh number and without salt, the Nusselt number is defined as

$$\mathrm{N} \equiv H_{sp}/H_{\mathrm{mol}} = c\mathrm{Ra}^{\frac{1}{3}}. \tag{2}$$

Here H_{mol} is the molecular (diffusive) heat flux up through a layer calculated according to the temperature difference between the upper and lower layer

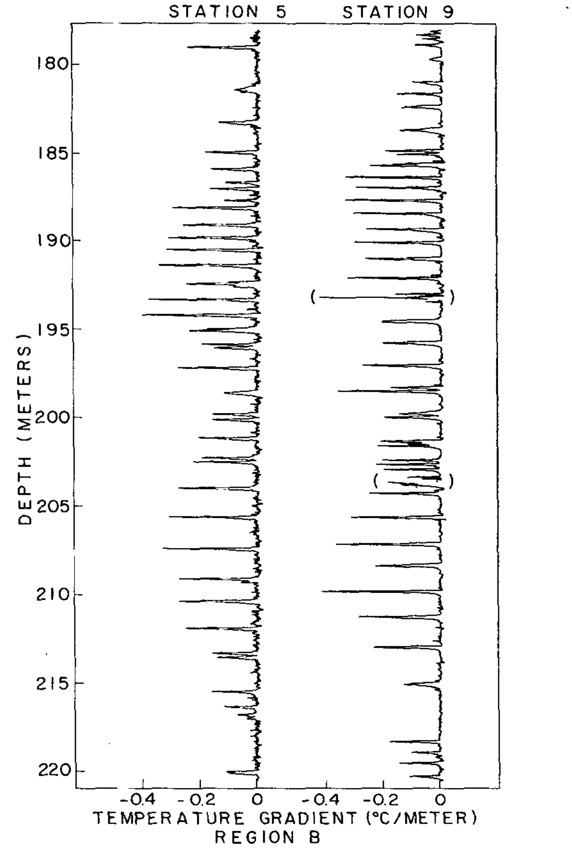

FIG. 6. Temperature gradient records from region B, stations 5 and 9. Parentheses indicate faulty portions of the original tape recording.

boundaries, c is an experimental constant equal to 0.085, and H_{sp} is the heat flux across a perfectly conducting solid plane located at the position of an interface. Huppert has fitted the data from Turner's (1965) experiments with a two-layer double-diffusive system heated from below to the analytic expression

$$H=3.8(\alpha\Delta T/\beta\Delta S)^2 H_{sp}, \qquad (3)$$

where H is the heat flux between two layers undergoing double-diffusive convection, ΔS and ΔT are the changes in salinity and temperature across the interface, and β is the coefficient of density change with salinity. By substituting (1) and (2) into (3) and using $H_{\mathrm{mol}}=k_T\Delta T h^{-1}$ (k_T is the molecular diffusivity for heat) one obtains

$$H=0.32(\alpha\Delta T/\beta\Delta S)^2(g\alpha/\kappa\nu)^{\frac{1}{3}}k_T\Delta T^{\frac{4}{3}}. \qquad (4)$$

The corresponding salt flux according to Turner (1965) is

$$F_s=0.15(\alpha/\beta)H, \quad \beta\Delta S/\alpha\Delta T\geqslant 2, \qquad (5)$$

and [expressing the straight line through Turner's (1965) data in his Fig. 7]

$$F_s=\alpha H/\beta[1.85-0.8(\beta\Delta S/\alpha\Delta T)],$$
$$1\leqslant\beta\Delta S/\alpha\Delta T<2. \qquad (5a)$$

Results of the calculations are given in the following table:

	H (W m^{-2})	$F_s\times10^8$ (kg m^{-2} s^{-1})	Overall stability $\beta\Delta S/\alpha\Delta T$
Region B	1.6	8.6	1.3
Region C	0.96	1.1	2.1
Region D	0.71	1.3	1.9

One comment is in order before reviewing the results of the calculations. Salinity had to be calculated from data on concentrations of major cations and their known compound forms. Since these data are from Nansen bottles spaced at 50 m, only the average vertical salinity gradients are known in depth ranges B, C and C where microstructure is observed.

All values for upward heat flux are considerably higher than the bottom heat flux (0.017–0.17 W m^{-2}) measured by Von Herzen in 1971 (Degens *et al.*, 1973). There must be an additional source of heat within the lake to account for this large discrepancy. At present, the two possibilities are bottom geothermal springs and exothermic methane production by bac-

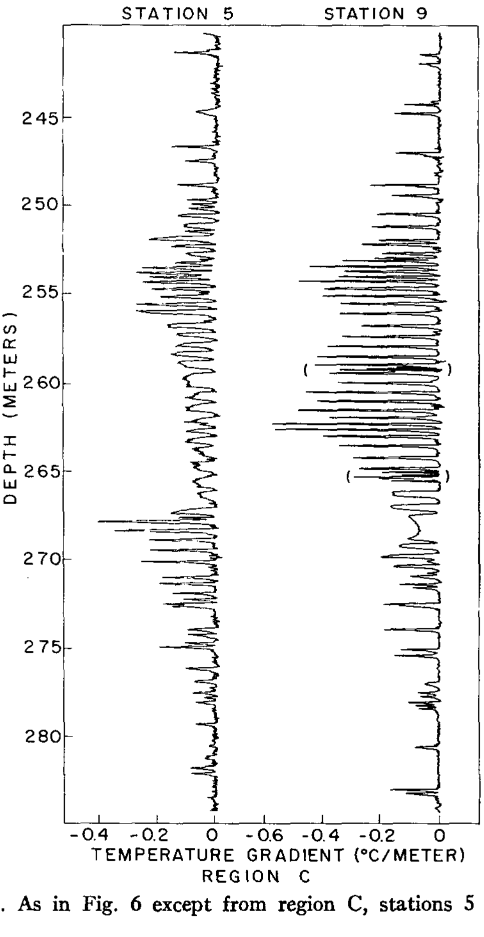

FIG. 7. As in Fig. 6 except from region C, stations 5 and 9.

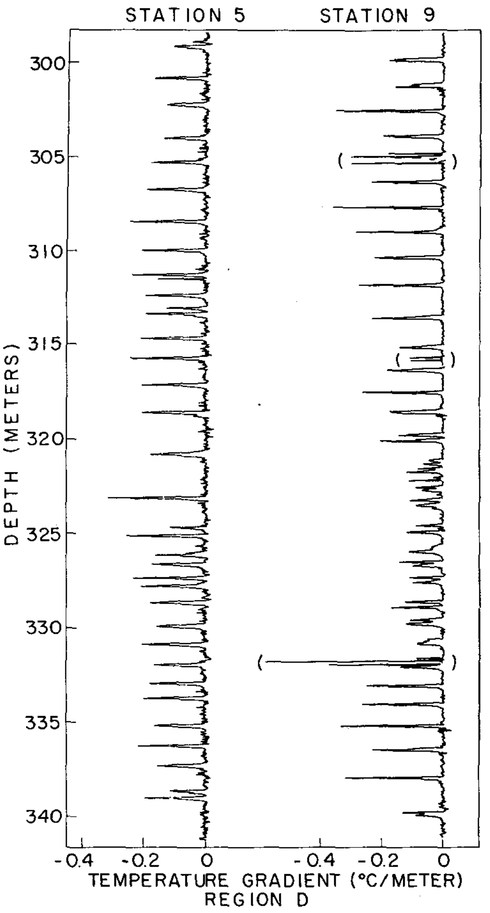

FIG. 8. As in Fig. 6 except from region D, stations 5 and 9.

teria in the water column (Deuser *et al.*, 1973). Deuser points out that the heat generated by methane production is just sufficient to account for the net increase in the temperature of the lake in the last 30 years (see Fig. 2). Since we still require an upward flux of heat, it seems that geothermal springs are required in addition. Solar heating is not significant here because Secci disk measurements show no significant solar energy penetrates below about 60 m.[2] Its effects together with those of seasonal mixing are thus confined to the surface layer.

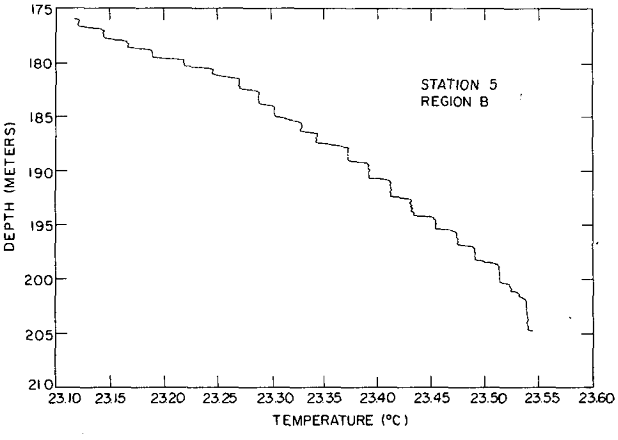

FIG. 9. Temperature steps from station 5, region B, exhibiting well-formed layers and interfaces.

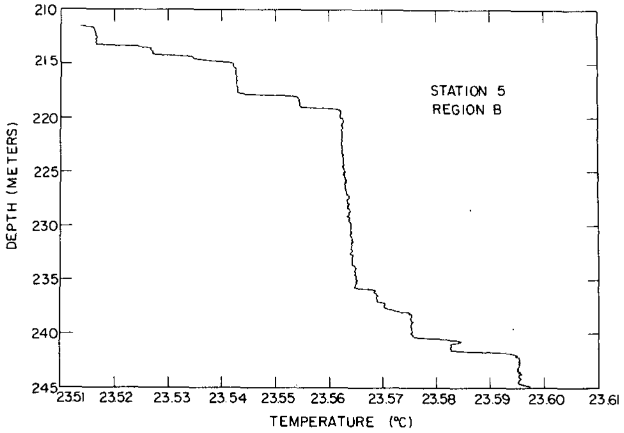

FIG. 10. The nearly isothermal layer between regions B and C, station 5.

To compare the calculated upward salt flux with the average Ruzzizi output, a value for H of 0.88 W m^{-2} was chosen. This value is midway between the fluxes for regions C and D whose layers are apparently stable. Using the area of the lake's 200 m contour (below which most of the layering is observed), 1.4×10^9 m^2, Eq. (5) shows the total annual upward salt flux to be 0.45×10^9 kg. According to Degens *et al.* (1973), the annual output of the Ruzzizi (3.2 km^3 at 0.7‰) is 2.2×10^9 kg or five times the calculated upward diffusive flux. There is considerable variation in the annual output of the Ruzzizi, and some uncertainty in the value of the diffusive salt flux; thus, under the circumstances, agreement within an order of magnitude is probably the best that can be expected.

5. Layer thickness

Finally, it is interesting to compare the observed layer depths with those predicted by Turner's (1968) results. Turner found he could predict the depth of the bottom layer formed in his experiments and that successive layers formed were about one-tenth as thick. His equation is

$$h_c = (\nu R_c/64\kappa^2)^{\frac{1}{4}}(-\alpha g H/\rho C_p)^{\frac{3}{4}}[(-\tfrac{1}{2})g\beta dS/dZ]^{-1}, \qquad (6)$$

where h_c is the critical layer thickness at which layer growth terminates, R_c the critical Rayleigh number at which the thermal boundary layer at the interface becomes unstable causing a new layer to begin forming [2.4×10^4 according to Turner (1968)], C_p the specific heat at constant pressure, and dS/dZ the salinity gradient *before* layers are formed. We equate this to the average salinity gradient of the layering region in

---

[2] H. Jannasch, private communication.

question. Substituting the appropriate values for water at 23.5°C, 1‰, 250 db [$\alpha=-2.42\times10^{-4}$ (°C)$^{-1}$; $\beta=7.51\times10^{-4}$ (‰)$^{-1}$; $\nu=9.25\times10^{-7}$ m^2 s^{-1}; $\kappa=1.4\times10^{-7}$ m^2 s^{-1}; $C_p=4.186\times10^3$ J (kg °C)$^{-1}$; $\rho=10^3$ kg m^{-3}], (6) becomes

$$h_c\ (\mathrm{m})=0.0115\ H^{\frac{3}{4}}\ (dS/dZ)^{-1}, \tag{7}$$

for H in units of W m^{-2} and dS/dZ in units of (‰) m^{-1}. Using $H=0.88$ W m^{-2}, the predicted and observed layer depths (m) are as follows:

	Value of h_c	
Region	Observed	Predicted from Eq. (7)
B	1.20	2.00
C	0.55	0.40
D	1.40	1.40

If the observed layers were formed as the succession of layers above an initial thicker layer (as the thick layer under Region B could suggest) they should be one-tenth the calculated initial layer thickness. Rather, they are the same size, suggesting that each layer is somehow forming under conditions similar to the initial conditions of Turner's experiment (i.e., smooth salinity gradient and uniform temperature). The latter case would then raise the question of how the 16 m layer under region B was formed. Another possibility is layer growth initiated from the sides of the lake as has been seen in laboratory experiments. This seems unlikely in view of the very large ratio of horizontal and vertical scales of the layers. Huppert[3] has suggested that some kind of finite-amplitude instability could be responsible for spontaneous layer formation. Such a mechanism might account for the formation of four separate layering regions.

6. Conclusions

Temperature microstructure profiles from Lake Kivu each exhibit approximately 150 isothermal layers typically 0.5–2 m thick. Typical values of ΔT and ΔS for a single interface are 0.015°C and 0.01‰. Calculations of the upward heat flux using results of Huppert (1971) and Turner (1968) yield values of 0.71 to 1.6 W m^{-2}. The corresponding total upward salt flux is one-fifth of the average salt output of the Ruzzizi River, the lake's only outflow. This is considered satisfactory agreement considering uncertainties in the data and the possibility of sources of salt (e.g., geothermal springs) elsewhere than in the northern basin where these measurements were obtained. Thus, it seems reasonable to conclude that extensive layering observed in the lake's northern basin is due to double-diffusive convection driven by heat from bottom geothermal springs and producing an upward flux of heat (about 20 times the global average through the ocean bottom) and salt.

Acknowledgments. I am grateful to Henry Stommel for suggesting that Lake Kivu might contain some interesting microstructure and to Egon Degens for accommodating me on his expedition at the last minute. Helpful discussions with Herbert Huppert and J. Stuart Turner are gratefully acknowledged. I would like to thank Wilford Gardner for his assistance with the field work. Finally, I am indebted to Carl Wunsch for the opportunity to work in microstructure. This work was supported jointly by the Office of Naval Research under Contract N00014-67-A-0204-0048 and by the National Science Foundation under Contract A30729X.

REFERENCES

Bethell, J. P., 1972: The fine structure of the ocean: A review. SACLANTCEN, Tech. Memo. 184. [Available from the Library of Congress].

Damas, H., 1937: La stratification thermique et chiminque des Lacs Kivu, Edouard et Ndalaga (Congo Belge). *Verh. Intern. Ver. Limnol.*, **8**, 51–68.

Degens, E. T., R. P. Von Herzen, H. Wong, W. G. Deuser, H. W. Jannasch, 1973: Lake Kivu: Structure, chemistry and biology of an East African rift lake. *Geol. Rundsch.*, **62**, 245–277.

Deuser, W., E. T. Degens, G. R. Harvey, M. Rubin, 1973: Methane in Lake Kivu: New data bearing on its origin. *Science*, **181**, 51–54.

Gregg, M. C., and C. S. Cox, 1971: Measurements of the oceanic microstructure of temperature and electrical conductivity. *Deep-Sea Res.*, **18**, 925–934.

Huppert, H. E., 1971: On the stability of a series of double diffusive layers. *Deep-Sea Res.*, **18**, 1005–1021.

Kiss, R., 1966: Le Lac Kivu. *Informations de l'Institute pour la Recherche Scientifique en Afrique Centrale, Chronique de l'IRSAC*, Vol. 1, Depeche Speciale, Bukavu, Zaire, 20–28.

Neshyba, S., V. T. Neal, W. Denner, 1971: Temperature and conductivity measurements under ice island T-3. *J. Geophys. Res.*, **76**, 8107–8120.

Turner, J. S., 1965: The coupled turbulent transports of salt and heat across a sharp density interface. *Intern. J. Heat Mass Transfer*, **8**, 759–767.

——, 1968: The behaviour of a stable salinity gradient heated from below. *J. Fluid Mech.*, **33**, 183–200.

Woods, J. D., and R. L. Wiley, 1972: Billow turbulence and ocean microstructure. *Deep-Sea Res.*, **19**, 87–121.

---

[3] H. Huppert, private communication.