556.082

DIRECT MEASUREMENTS OF THE IN-SITU DENSITY OF LAKE AND SEA WATER WITH A NEW UNDERWATER PROBE SYSTEM

by

KLAUS TIETZE

Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover

(Federal Institute for Geosciences and Natural Resources, Hanover)

Abstract

In general, the in-situ density of lake or sea water is usually calculated indirectly from in-situ measurements of electrical conductivity, temperature, pressure, and probably other parameters determined in-situ or by sampling. However, since none of the equations of state that have been set up are valid for all marine areas, direct measurement of the in-situ density is desirable. This paper describes direct measurements of the in-situ density of lake water using a newly developed underwater probe system. This underwater probe system has been tested in the Mediterranean Sea and used in Lake Kivu (Central Africa). The standard deviation of the individual values of the measurements is $\pm 5 \cdot 10^{-5}$ g/cm^3, and the resolution is $\pm 5 \cdot 10^{-6}$ g/cm^3. Further refinement of both the sensor and probe system and the calibrating and monitoring methods, could improve the precision by about a factor of ten.

1. *Introduction*

For many oceanographic and limnologic problems knowledge of the in-situ density of sea or lake water is essential. Usually it is calculated indirectly from in-situ measurements of electrical conductivity, temperature, pressure, and probably other parameters determined in-situ or by sampling (see. *e.g.* KROEBEL [5], HINKELMAN [3]).

However, since none of the known equations of state are valid for all lakes and marine areas (see *e.g.* DIETRICH *et al.* [2], ROHDE [6]), direct measurement of the in-situ density is desirable, especially in the case of peculiarly stratified water bodies such as the Red Sea (DEGENS & ROSS [1]), Lake Kivu in Central Africa (TIETZE [9, 11]), the Ocra basin in the Gulf of Mexico (SACKETT *et al.* [7]) and others.

In 1973 to 1977 a project was carried out which required exact data of the in-situ density distribution in Lake Kivu. The project was aimed at the development of the unique methane gas deposit contained in this lake (TIETZE [8, 11]). Around $63 \cdot 10^9 m^3$ of methane at STP are dissolved physically together with other gases by hydrostatic pressure in the deep waters. The gas is held in the water by a stable density stratification. The in-situ density values were needed for a computer simulation for future exploitation of the deposit. At that time the "water and gas body" within Lake Kivu had only been inadequately investigated. An equation of state of its waters was not known and thus an indirect method of determining the density was not applicable.

For this reason, during 1973—1974 an underwater probe system was developed for direct measurement of the in-situ density of lake and sea water (TIETZE [9, 10]). The system was then tested out in the spring of 1974 in the Mediterranean Sea. Following this, in 1974/75, a measuring survey lasting around three months was carried out on Lake Kivu. Some results of these measurements are presented in this paper and shortly discussed in the following sections.

2. *Short Description of the Underwater Probe System*

The underwater probe system contains two AGAR-density sensors* together with sensors for temperature, conductivity and pressure as well as a special flow system for the density sensors. The sensing element used in the AGAR-density sensor is a thin-walled magnetic tube clamped at one end. The complete tube is immersed in the liquid to be measured. The tube is stimulated electromagnetically which causes it to oscillate elliptically. The resonant frequency of oscillation depends on the density of the liquid flowing through and around the oscillating tube. The density of the liquid can then be calculated directly from the measured resonant frequency using a parbolic calibration equation. When calibrating the sensor and evaluating the measurements, temperature and pressure coefficients must be considered.

In order to be able to use the AGAR density sensor in lakes and in the sea, some improvements had to be made and the construction of some additional instruments were necessary. This included fitting a special flow and filtration system. A detailed description of the probe system is given by TIETZE [9].

Using this underwater probe system, measurements down to 650 m in dept are possible. In principle the density sensors could be adapted for greater depths down to several thousand meters.

* JORAM AGAR & CO. LTD, Alresford, Hampshire, Britain.

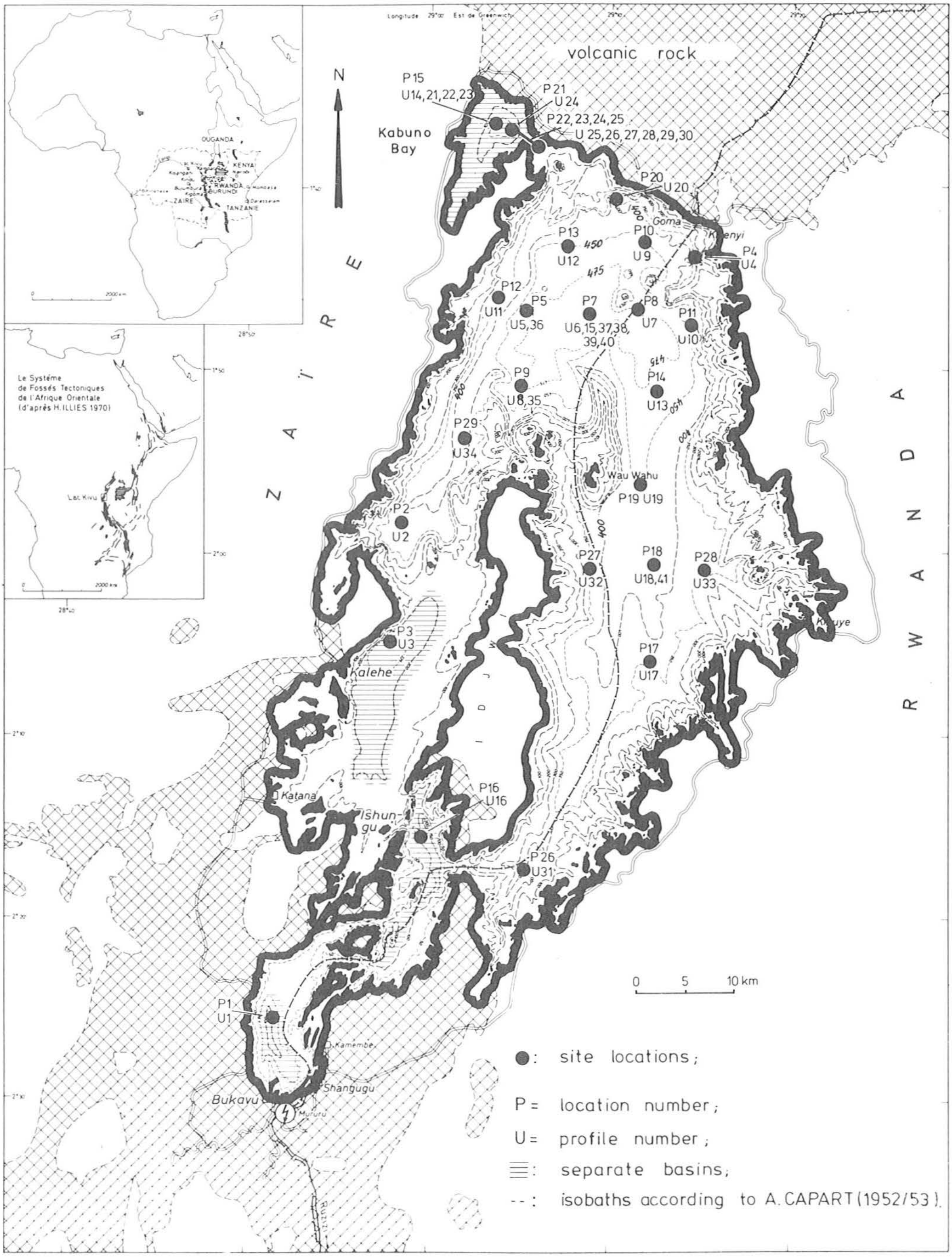

Fig. 1: Lake Kivu with locations of sites where profiles were measured with the underwater probe from 14 November 1974 fo 28 January 1975.

3. *Measurements*

Lake Kivu is situated in Central Africa in the western branch of the East African Rift Zone. It consists of a main basin and four smaller subsisidiary basins which are separated from the main basin by rises in the lake floor. The separate basins are Kabuno Bay and the basins near Bukavu, Ishungu and Kalehe (see Fig. 1). The total water surface is around 2,400 km², the maximum water depth is 485 m and the total water volume is approx. 580 km³.

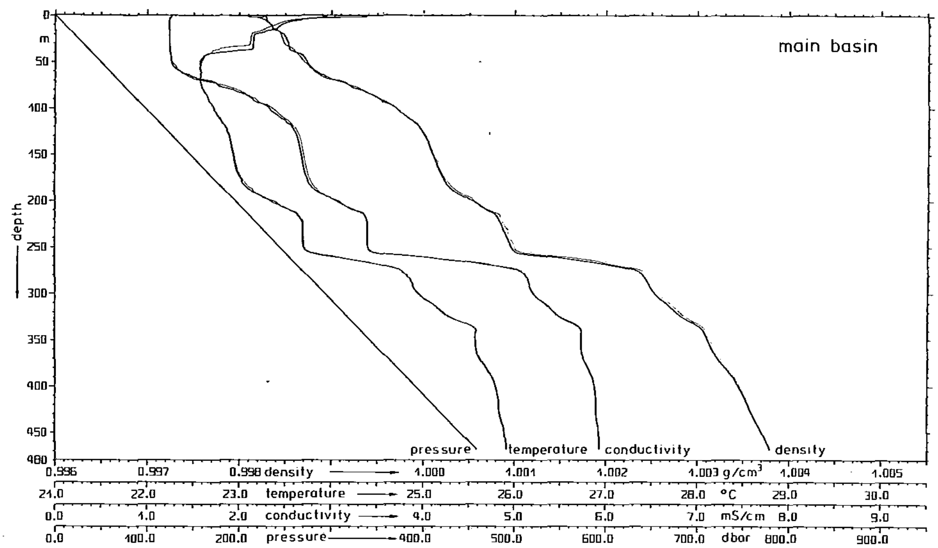

Fig. 2: Vertical profiles of the in-situ density, temperature, conductivity, and pressure (location 9, profile U 35; 23 January 1975); – = lowering, – = lifting of the underwater probe.

The in-situ density, temperature, conductivity and pressure were measured at 28 positions with 40 vertical and one horizontal profile, systematically spread throughout the lake. The locations of the measuring sites are shown in Fig. 1. Fig. 2 shows a typical vertical profile from the main basin of Lake Kivu. The measurements indicate that the stratification pattern is stable below a depth of 50 m apart from fine structure variations. However, above 50 m there are strong variations due to weather conditions. For this reason Fig. 3 shows several measurements down to 50 m at various locations and points of time. In contrast to this, in Fig. 4 which relates to 200—300 m, only fine structure variations can be seen. Fig. 5 shows the gradients from the profile measurements in Fig. 2, plotted with ten times greater resolution.

Fig. 6 and 7 show profiles from the separate basins Bukavu and Kabuno Bay. The conditions in these subsidiary basins are different from those in the main basin. Fig. 8 shows curves for various parameters averaged from 23 profiles, all measured in the main basin under comparable conditions, together with a curve of density normalized for the effects due to pressure.

The measurements are discussed in section 5 of this paper.

4. *Accuracy*

The calibration of the density sensors was made using known NaCl solutions. These solutions were measured with a high precision hydrostatic gauge. The results showed a standard deviation of $\pm 6 \cdot 10^{-6}$ g/cm³ relative to pure distilled water (the absolute standard deviation of the official tables for the density of distilled water is $\pm 5 \cdot 10^{-6}$g/cm³, WAGENBRETH & BLANKE [14]). The temperature sensor was calibrated using official calibration thermometers (accuracy $\pm$ 0.01 °C); the conductivity sensor was calibrated with standard KCl solutions (the error due to the solution composition is neglectable); the pressure sensor was calibrated with a pressure gauge (adjustable to $\pm$ 0.03 ‰).

During evalution of the results, the depth of the underwater probe for each of the measurements was calculated from the pressure and a vertical integration of the density curve. The depth error of each measurement related to the standard deviation of calibration was $z = \pm 0.5$ m. Treating this depth error as part of the errors in density, temperature and conductivity respectively, and assuming the error in depth to be zero, the absolute standard deviation of the individual values presented here are:

$\Delta\varrho_{abs} = \pm 5 \cdot 10^{-5}$ g/cm³ for the density,
$\Delta t_{abs} = \pm 0.02$°C for the temperatur and
$\Delta c_{abs} = \pm 0.03$ mS/cm for the conductivity.

For a more detailed discussion of the measurement accuracy see TIETZE [9]. Further refinement of the density sensor and probe system, and the calibration and monitoring methods could improve the precision of the density measurements by about a factor of ten.

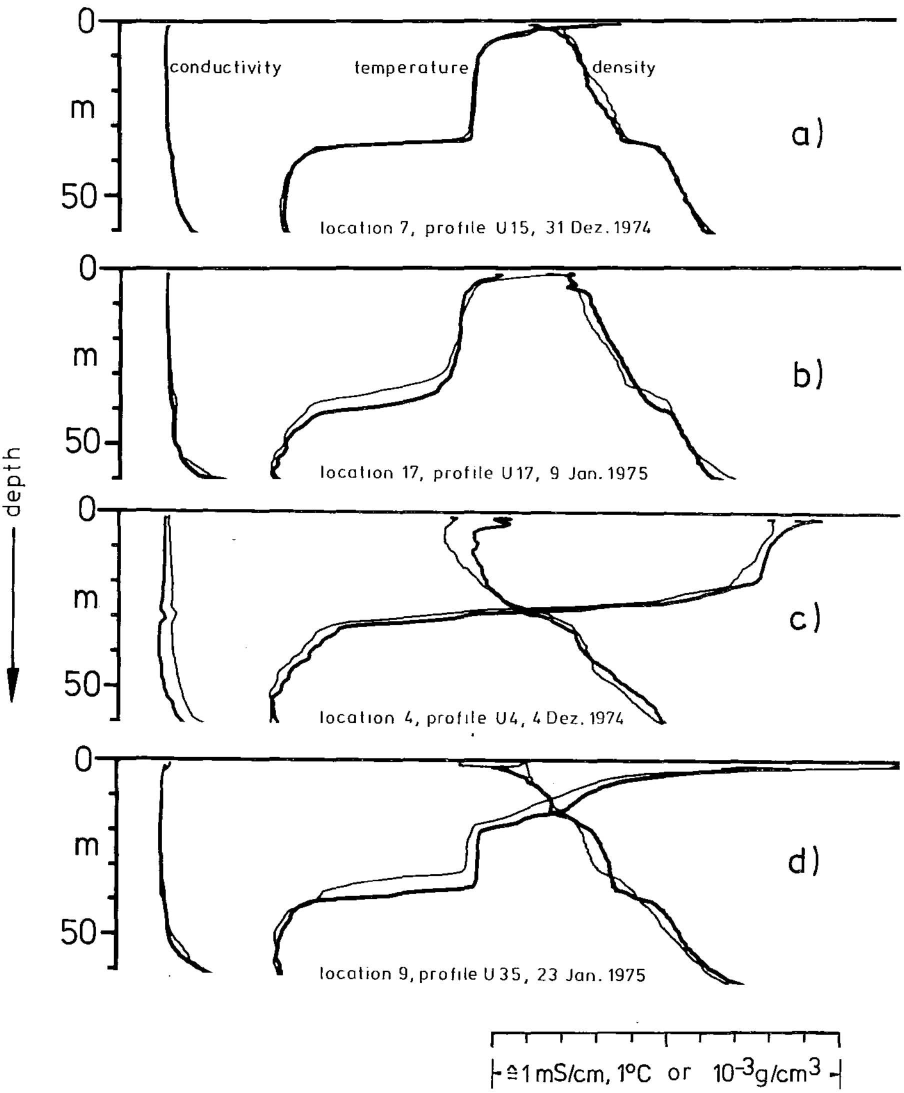

Fig. 3: Variation of the parameters to a depth of 50 m in the main basin; – = lowering, – = lifting of the underwater probe.

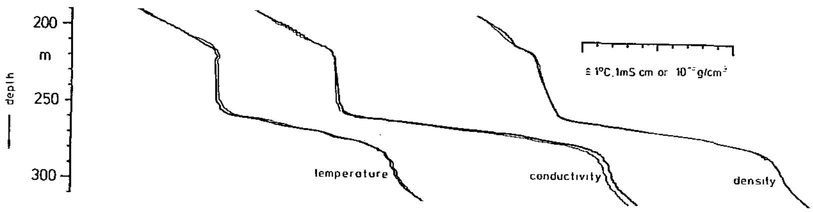

Fig. 4: Fine structure of the distribution of parameters within the layer with the largest gradient (location 5, profile U5; 5 Dez. 1974); — = lowering, - = lifting of the underwater probe.

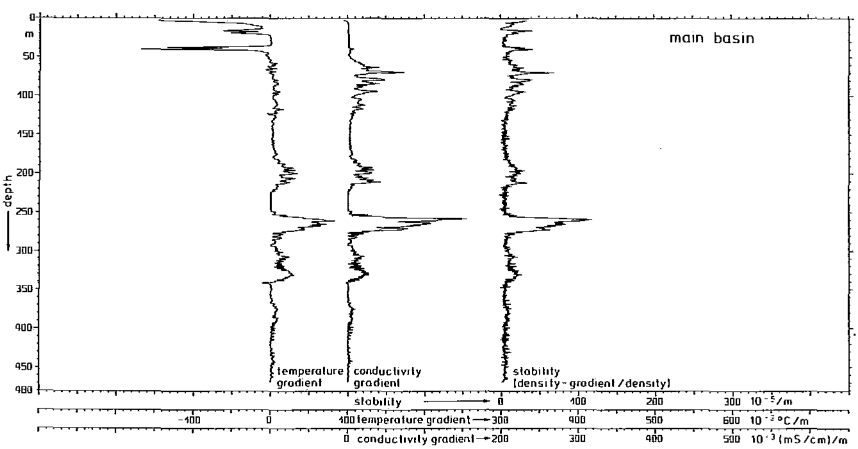

Fig. 5: Vertical profiles of stability (density gradient/density) and of temperature and conductivity gradients (location 9, profile U35; 23 Jan. 1975). The resolution is greater than in Figure 2 by a factor of 10.

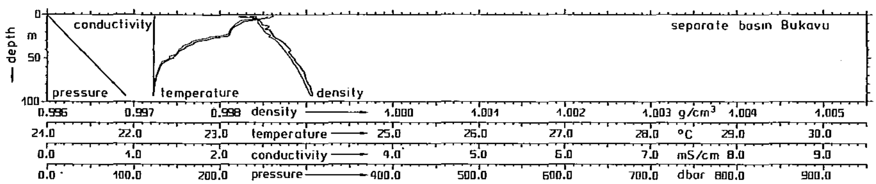

Fig. 6: Vertical profiles of the in-situ density, temperature, conductivity, and pressure in the separate basin Bukavu (location 1, profile U1; 21 November 1974); – = lowerting, – = lifting of the underwater probe.

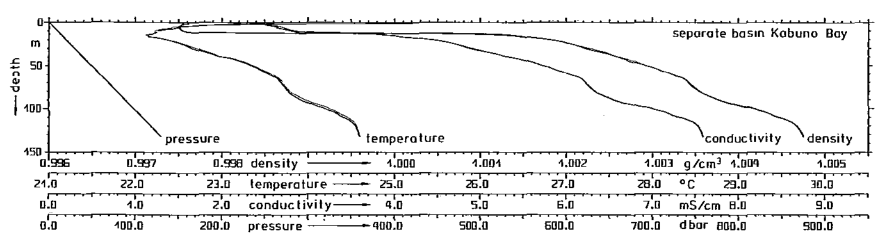

Fig. 7: Vertical profiles of the in-situ density, temperature, conductivity, and pressure in the separate basin Kabuno Bay (location 15, profile U 22, 14 January 1975); – = lowering, – = lifting of the underwater probe.

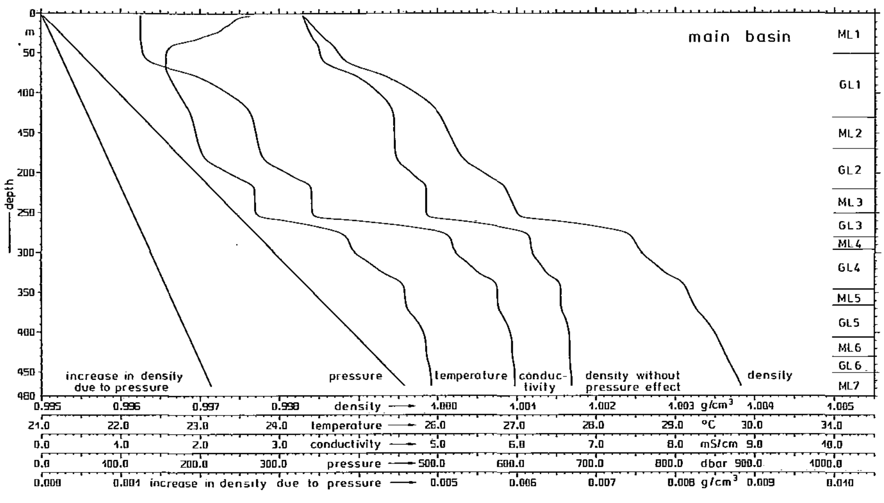

Fig. 8: Average values of the in-situ density, temperature, conductivity, and pressure obtained from 23 vertical profiles in the main basin. Also plotted are the in-situ density minus the density increase due to pressure and the density increase due to the pressure effect alone. ML=mixed layer, GL=gradient layer.

5. *Discussion*

In Fig. 2, pressure, temperature, conductivity and density, measured in-situ, are plotted against depth for one profile from the main basin. Differences between measurements made while the probe was being lowered and those repeated at the same depth when the probe was raised again are small. The results show that layers possessing an exceptional constancy of the measured parameters alternate with other layers with very marked variations within a small interval of depth. The former are called ''mixed layers'' and the latter ''gradient layers''.

A normal situation exists in the lake down to a depth of 50 m. Within this range the temperature decreases with depth. Fig. 3 shows the variation of several parameters in more detail. As can be seen, at a depth of 35 m a temperature gradient layer is present. This gradient layer is called metalimnion. Over a period of time it can vary in depth down to a maximum of 50 m, and it can also vary in structure (see Figs. 3a-d). As with most lakes, Lake Kivu possesses epilimnion, metalimnion and hypolymnion.

As can be seen from the conductivity curve, the water of the lake is mixed down to around 50 m. However, below the 50 m a stable stratification is present. This stratification remains constant apart from time and place dependent fine-structure variations (see *e.g.* Fig. 4).

The density increases down to about 50 m due to the decrease of temperature. Below that it increases due to increasing salt content, although this effect is somewhat reduced since both the temperature and the amount of physically dissolved gases increase at the same time.

Fig. 3 shows the data from the upper 50 m taken from profile measurements at various locations and times. The mixing and stratification in this depth range varies due to weather conditions, which result in both shape and vertical alterations of the metalimnion.

Each complete profile measurement made in the main basin down to the bottom requires approx. three hours. Fig. 3a shows that during this time interval the conditions remained constant whereas in another profile measurement shown in Fig. 3b the dept of the metalimnion changed by around four meters during the three hours. This is the result of a long internal wave. Fig. 3c and 3d show similar variations.

Below 50 m dept the stratification remains stable apart from numerous fine-structure variations. Fig. 4 shows some of them for depths between 200 and 300 m. The temperature and conductivity peaks that can be seen are typical for one type of fine structure. They can be interpreted as ascending water which forms localized layers directly below the gradient strata, which they evidently cannot penetrate due to the prevailing density conditions. The peaks vary with time and position. They are an indication of hydrothermal activity in the lake. Other typical variations are step-like structures; these were recorded even more frequently than the peaks. These also vary in time and position. They are a consequence of double-diffusive convection, which takes place within a stratified water body when heated from below. This is because heat diffuses 100 times faster than dissolved salt. This mechanism forms small convection cells which become turbulently mixed and bounded by distinct gradient layers (Turner [12, 13], Hubbert [4]). For this reason, transport of dissolved matter is considerable faster than in the case of molecular diffussion. Apart from eddy diffussion, double-diffusive convection is the second major transport mechanism for dissolved substances in this lake.

Fig. 5 shows the gradients calculated from the profile measurements in Fig. 2. This figure is drawn with a resolution ten times greater than that of Fig. 2. Below 50 m the strong correlation of the parameters is clearly visible. In addition to this, it can be seen that, within the mixed layers, the parameter variations with respect to depth are very small. In the case of the layer at around 240 m dept the measured relative variations of the parameters with depth are smaller than:

$\pm 5 \cdot 10^{-6}$ (g/cm^3)/m for the stability,
$\pm$ 0.001 (mS/cm)/m for the conductivity gradient and
$\pm$ 0.001 °C/m for the temperature gradient.

These figures approach the limits of resolution for the unterwater probe.

Up to a corresponding depth, in the separate basins of Ishungu and Kalehe the behavior of the water is similar to that in main basin. In contrast to this, in the separate basins of Bukavu and Kabuno Bay the distribution of the physical parameters differs markedly from that in the main basin. The water of the Bukavu basin is mixed down to the bottom at about 100 m depth (see Fig. 6). However, in Kabuno Bay the main density gradient is approx. 15 times greater than that of the main basin, in fact the mixed surface layer only reaches down to a depth of 12 m (see Fig. 7). Below 12 m the strafication is stable. Fine structure variations in Kabuno Bay are much smaller than in main basin.

Fig. 8 shows the mean values of 23 profiles which have been measured under comparable conditions in the main basin. In addition to the in-situ density, the density normalized for pressure is also shown. The strong correlation of the increases in temperature, conductivity and density is even more clear than in Fig. 2. Averaging the measurements has the effect of smoothing out the fine variations and small inaccuracies of measurement. With the help of these smooth curves it is possible to classify the waters of Lake Kivu into a number of distinct water layers. The water body of the main basin can be divided into seven mixed and six gradient layers; these are shown with their abbreviations on the right-hand side of Fig. 8.

The equation of state was calculated from the smoothed-out curves using the method of multiple regression analysis and average figures for the quantities of gas physically dissolved in the water. The calculations were continued up to the fifth order although a quadratic equation appears to be the most suitable approximation. The equation indicated the influence on density of each of the various parameters; this shows that the greatest influence is caused by the chemically dissolved materials, and in particular by the salts.

Because Lake Kivu is stratified, it reacts to disturbances in a unique way. Disturbances of changes in the dynamic equilibrium can originate from the surface of the lake due to currents and waves caused by wind action, and due to variations in temperature and pressure, and due to evaporation and radiation. Disturbances originating from the sea bed can be caused by the heat flux and by infiltration of hydrothermal water. The lake reacts to all these natural influences:

— by mixing the surface layer down to a depth of 50 m (main basin),
— by eddy currents in the various mixed layers,
— by both double-diffusive and normal convection and
— by oscillations and internal waves in the gradient layers.

6. *Conclusion*

Because none of the known equations of state are valid for all lakes and marine areas, a direct measurement of in-situ density is desirable. Stratified water bodies are particularly of interest for research activities. Their dynamics cannot be completely investicated with conventional underwater probes because the content of dissolved substances can be very different from those in the open sea. Consequently, there is no equation of state known which could be used to calculate the in-situ density. Therefore a new technique must be applied. In 1973—74 an underwater probe system for direct measurements of the in-situ density of lake and sea water was developed. This was tested in the Mediterranean Sea in 1974 and applied in Lake Kivu in 1974—75. Some examples of measurements made in Lake Kivu with this probe are presented and discussed in this paper.

The standard deviation of the individual values of the measurements is $\pm 5 \cdot 10^{-5}$ g/cm³ and the resolution $\pm 5 \cdot 10^{-6}$ g/cm³. Further refinement of both the sensor and probe system and the calibrating and monitoring methods could improve the precision of the density measurements by about a factor of ten. Using the underwater probe developed for the Lake Kivu survey, measurements can be carried out down to 650 m in depth. In principle the density sensors could be adapted for measurements down to several thousand meters.

Acknowledgement: I would like to thank Mrs. Rehwinkel, Mr. Röben and Mr. Schulze for their assistance. The project was financed by the Federal Ministry of Economic Cooperation.

REFERENCES

1. DEGENS, E. T. and D. A. ROSS, 1969: *Hot Brines and Recent Heavy Metal Deposits in the Red Sea.* Berlin, Springer Verlag.
2. DIETRICH, G., K. KALLE, W. KRAUSS und G. SIEDLER, 1975: *Allgemeine Meereskunde.* Berlin, Gebrüder Bornträger Verlag.
3. HINKELMANN, H., 1963: *Die Ermittlung der Dichte von Seewasser in-situ aus Messungen der Elektrischen Leitfähigkeit, des Druckes und der Temperatur.* Kiel, Habilitationsschrift Universität Kiel.
4. HUBBERT, H. E., 1971: On the Stability of a Series of Double-Diffusive Layers. *Deep-Sea Res.,* **18,** 1005—1021.
5. KROEBEL, W., 1973: Die Kieler Multimeeressonde. *Meteor Forschungsergebnisse,* A12, 53—67.
6. ROHDE, J., 1968: *Funktionale Zusammenhänge zwischen Grössen des Meerwassers und Auflösung formelmässiger Darstellungungen solcher Grössen nach unabhängigen Variablen durch Potenzreihenansatz.* Kiel, Dissertation Universität Kiel.
7. SACKETT, W. M., J. M. BROOKS, B. B. BERNARD, C. R. SCHWAB, H. CHUNG and R. A. PARKER, 1979: A Carbon Inventory for Ocra Basin Brines and Sediments. *Earth and Plan. Sc. Letters,* **44,** 73—81.
8. TIETZE, K., 1974: The Lake Kivu Methane — Problems of Extraction and their Mathematical-Physical Study. *Prints Regional Conference on the Petroleum Industry and Manpower Requirements in the Field of Hydrocarbons, Tripoli,* UN-ECA, 7 p.
9. —»—, 1978: *Geophysikalische Untersuchung des Kivusees und seiner ungewöhnlichen Methangaslagerstätte — Schichtung, Dynamik und Gasgehalt des Seewassers,* Kiel, Dissertation Universität Kiel, 149 p.
10. —»—, 1979: An Underwater Probe System for the Direct In-situ Measurement of the Density of Sea Water, *EOS,* **60,** 578.
11. —»—, 1980: The Unique Methane Gas Deposit in Lake Kivu (Central Africa) — Stratification, Dynamics, Genesis and Development. *Proceedings of the First Annual Symposium on Unconveltional Gas Recovery, Pittsburgh,* SPE/DOE 8957, 275—287.
12. TURNER, J. S., 1965: The Coupled Turbulent Transport of Salt And Heat across a Sharp Density Interface. *Int. J. Heat Mass Transfer,* **8,** 759—767.
13. —»—, 1968: The Influence of Molecular Diffusivity on Turbulent Entraiment across a Sharp Density Interface. *J. Fluid Mech.,* **33,** 639—657.
14. WAGENBRETH, H., und W. BLANKE, 1971: Die Dichte des Wassers im Internationalen Einheitensystem und in der Internationalen Praktischen Temperaturskala von 1968. *PTB-Mitteilungen,* **6,** 412—415.