Investigations in Lake Kivu (East Central Africa) after the Nyiragongo Eruption of January 2002,

Specific study of the impact of the sub-water lava inflow on the lake stability

FINAL REPORT OF THE INTERNATIONAL SCIENTIFIC TEAM

March 9, 2002

Authors:

Prof. Michel HALBWACHS
Université de Savoie & Coordination de la Recherche Volcanologique, CNRS – INSU
F-73376 Le Bourget du Lac Cedex, France

Dr. Klaus TIETZE
PDT GmbH – Physik • Design • Technik – Sensorik & Consulting
D-29227 Celle, Germany

Dr. Andreas LORKE
Applied Aquatic Ecology (APEC), Limnological Research Centre (EAWAG)
CH-6047 Kastanienbaum, Switzerland

Dr. Clément MUDAHERANWA
Ministry of Energy, Water and Natural Resources

Submitted to

ECHO - Humanitarian Aid Office

European Community Humanitarian Office.
Communauté européenne - ECHO
1 rue de Genève
B- 1049 BRUXELLES

SOLIDARITES, Aide Humanitaire d'Urgence
105 av Gambetta, F - 75020 , PARIS.

SUMMARY

The Nyiragongo volcano, situated in the western branch of the tectonically and volcanically active East African Rift Zone (United Republic of Kivu) erupted suddenly on the 17th of January at 08:25 local time (06:25 GMT). The eruption began from the re-opening of the 1977 fracture, emitting very fluid lava, flowing down from 2800 m across the forest and cutting the road from Goma to Butembo to the North. This very violent lava emission is interpreted in relation with the draining at high velocity of the lava column filling the crater of the volcano. In this way, this eruptive event appeared as quite similar as the former 1977 eruption. Within the next hours, a series of eruptive vents appeared between 2300 and 1800 m elevation on the southern flank of the volcano. At 16:00 h local time, on the continuation of the fracture system, and at an elevation of 1580 m, from a line of vents SE of Monighi, a village located only 1.5 km NE of Goma airport, a voluminous lava flow ran through the airport and destroyed the central part of Goma city.

This later extrusion of an important amount of magma, outpouring at a distance of 13 km from the crater of the volcano (and only 4 km from the lake shore) revealed the totally unusual characteristic of the present eruption. This observation indicates that the lava flow which destroyed a part of Goma is probably not related to the draining of the permanent magma column existing inside of the volcanic pile (as it was the case during the last 1977 eruption) but is extruded from a deep magmatic source.

During these disastrous days lava flows reached Lake Kivu (see Fig. 1), which is situated about 18 km S of the Nyiragongo volcano. The lake covers an area of around 2400 km^2, the maximum depth is 485 m and the water volume amounts to 500 km^3. The maximum sediment thickness beneath the northern part of the lake is around 500 m. During the last few thousand years, a varying density stratification has existed within the lake waters, formed and sustained by several processes such as heat influx, hydrothermal activity and climatic variations. In the main basin of the lake anoxic conditions prevail below a depth of about 50-70 m. The water-density stratification, which is remarkably stable due to its dynamic features, functions like a flexible lid, trapping gases migrating upwards from the Earth's mantle as well as gases generated in the sediments beneath the lake.

The gases, physically dissolved under pressure, remain in the deep water because mixing extends from the surface only down to a depth of about 50 m. The strongest density gradient occurs at around 250-280 m depth and thus the highest concentrations of dissolved gases are found below this. In the course of time huge amounts of gases have accumulated in the waters of Lake Kivu, existing there like the gas in a bottle of champagne. The main gases in place are

- 250 km^3 (STP) of carbon dioxide,
- 55 km^3 (STP) of methane,
- 5 km^3 (STP) of nitrogen, and
- traces of many other gases.

The stability of the water-density stratification is relatively high. The lake reacts against disturbances in a dynamic, self-sustaining way, especially by generating internal waves, which dissipate any influx of energy over large parts of the lake. Additionally, normal

and double-diffusive convection, as well as hydro-thermal and pressure-driven currents, are active within the stratification.

The extensive measurements made during a research expedition of 1974/75 (Tietze 1978) and their comparison with earlier measurements suggested that Lake Kivu was at that time in a quasi-stationary stage. This is due to the fact that all external and internal forces and other influences acting on the system nearly balance each other. Thus for a lake, the losses of water, dissolved substances, heat and momentum, for example, are nearly equal to the corresponding influxes. It also means that the vertical and horizontal distribution of the major parameters, the pressure conditions and therefore the system of currents within the lake vary only slowly with time.

The amount of methane generated within the sediments beneath Lake Kivu has been estimated to be about 120 million m³ (STP) per year. A similar amount of methane is transported yearly by several natural processes through the stratification to the 50 m thick surface layer (biozone) where it is oxidised to carbon dioxide and water.

In January 2002, hot lava flowed into the lake, bringing people to fear, that a large outburst of the gas dissolved in the stratified Lake Kivu waters could lead to another serious disaster. But the natural risk of a disastrous gas outburst posed by the huge amounts of gases dissolved in the waters of the main basin of Lake Kivu is low due to the relatively low saturation of the lake waters with gas and the self-sustaining nature of the non-linear dynamics of the stratification. But because the impact of such an unlikely event could be serious, the whole lake should be monitored with an early warning system, to detect possible natural changes in advance.

No dangerous gas concentration sufficient to cause a spontaneous gas outburst (like in lakes Nyos and Monoun in Cameroon 1986 /1984) had built up in the water column of Lake Kivu up till the last few measurements were made in about 1990. This is probably also true of the period up to the present. A disastrous gas outburst from the waters of the main basin of Lake Kivu would require a very strong volcanic or tectonic occurrence or some other unlikely events.

It was now the question if the present disastrous rifting process which was accompanied by strong tectonic and volcanic events is such a serious impact that it could trigger a disastrous gas outburst out of the Lake Kivu waters. After the large Nyiragongo eruption we felt it to be necessary to investigate soon how strong this large inflow of lava into the lake affected its stratification and stability. Therefore a short expedition was carried out in February 2002 for 4 days on the lake.

We investigated

- with a GPS-system the distribution of the lava on the lake shore,
- with divers and underwater cameras which depth in the lake the lava reached,
- with two underwater probes what influence the lava inflow had on the lake stratification and thus on the lake stability in the vicinity of the lava and far away from this area.

The investigations showed

- that the width of the lava stream at the lake shore has been roughly 600 m,
- that the lava reached a depth between about 70 m and 100 m,
- that the volume of lava which entered the lake is about 1 Mm^3,
- that the disturbance of the water stratification was mainly limited to the area near the lava inflow and there down to about 120 m,
- that small signs of the lava inflow could be found within the stratification far away from this area, just in the middle of the lake,
- that besides from this short term changes in the lake previous measurements which suggest a temperature rise in the upper part of the lake (above 250 m) due to the global greenhouse effect could be confirmed,
- that compared to the measurements of Tietze in 1974/75 the stratification below 250 m changes in some cases: several gradients in gradient layers became sharper and some intermediate layers developed more to real mixed layers.

The new data which are limited in quality due to time and cost constraints must be analysed now in detail. As overall interpretation it could be said at this stage

- that the impact of the lava inflow into the lake was limited by lake internal mechanisms laterally mainly to the region near Goma, and to a depth region down to about 120 m; it seems that this impact was far away from generating a gas outburst from Lake Kivu waters;
- that if the lava would had reached deeper parts of the lake, a hazardous situation would had been built up;
- that long term changes in the lake since the measurements of Tietze in 1974/75 have led to some changes in the stratification pattern as well as in absolute parameter values; it seems that this fact led to a slightly higher stability of Lake Kivu than 27 years ago.

To verify these findings a longer expedition with carefully calibrated underwater probe systems, as well as with sampling under pressure and controlled degassing of the samples is necessary.

When, as feared, the seismicity moves from the volcanoes to a region below Lake Kivu, then it must be concluded that the possibility of lava extrusion directly inside of the lake cannot be definitely excluded in the future since all of the area has been made more fragile by the important fracturing effect of the present rifting phenomenon.

The existence of a lava flow being running down inside of Lake Kivu is not unprecedented. Figure 2 revealed that historically, large amounts of lava reaches the lake on extended areas, mainly located on the North-West shore and in the Gulf of Kabuno. It may be pointed out that the water stratification of the Gulf of Kabuno presents a particular feature as compared with the main basin of Lake Kivu (the density at 150 m depth is higher than in the main basin at 485 m depth and the gas concentration is higher there than in corresponding depths in the main basin. Due to several circumstances (see Tietze 1978) the eruption risk from the Gulf of Kabuno basin is higher than for the main basin).

It may be pointed out here, that the possibility of a huge gas outburst from Lake Kivu where all or most of the gas dissolved in it would reach the atmosphere, is very low, but that the impact of such an event on the whole Lake Kivu region of about 10 000 km² could be very strong. Naturally the possibility for small or medium gas outbursts with limited consequences is higher. Therefore not only the monitoring of this lake but also an exploitation of its gas and thus its controlled degassing is absolutely necessary, as pointed out by Tietze since 1974. A systematic overview about these problems including the equilibrium and stability of Lake Kivu is given in Tietze (2000).

There are some new warnings that the seismic activity could shift below Lake Kivu and that then a major outburst from the lake is to be feared (Tedesco 2002, Interview with International Federation of Red Cross and Red Crescent Societies), but the recommendations which were drawn by representatives of large organisations for this case, to evacuate the population of Goma to Bukavu, are not adequate. A possible evacuation of inhabitants of the Kivu region must be outside the Lake Kivu catchment area because such a large gas cloud would flow via Bukavu to Lake Tanganyika (see Tietze 1978, 1991).

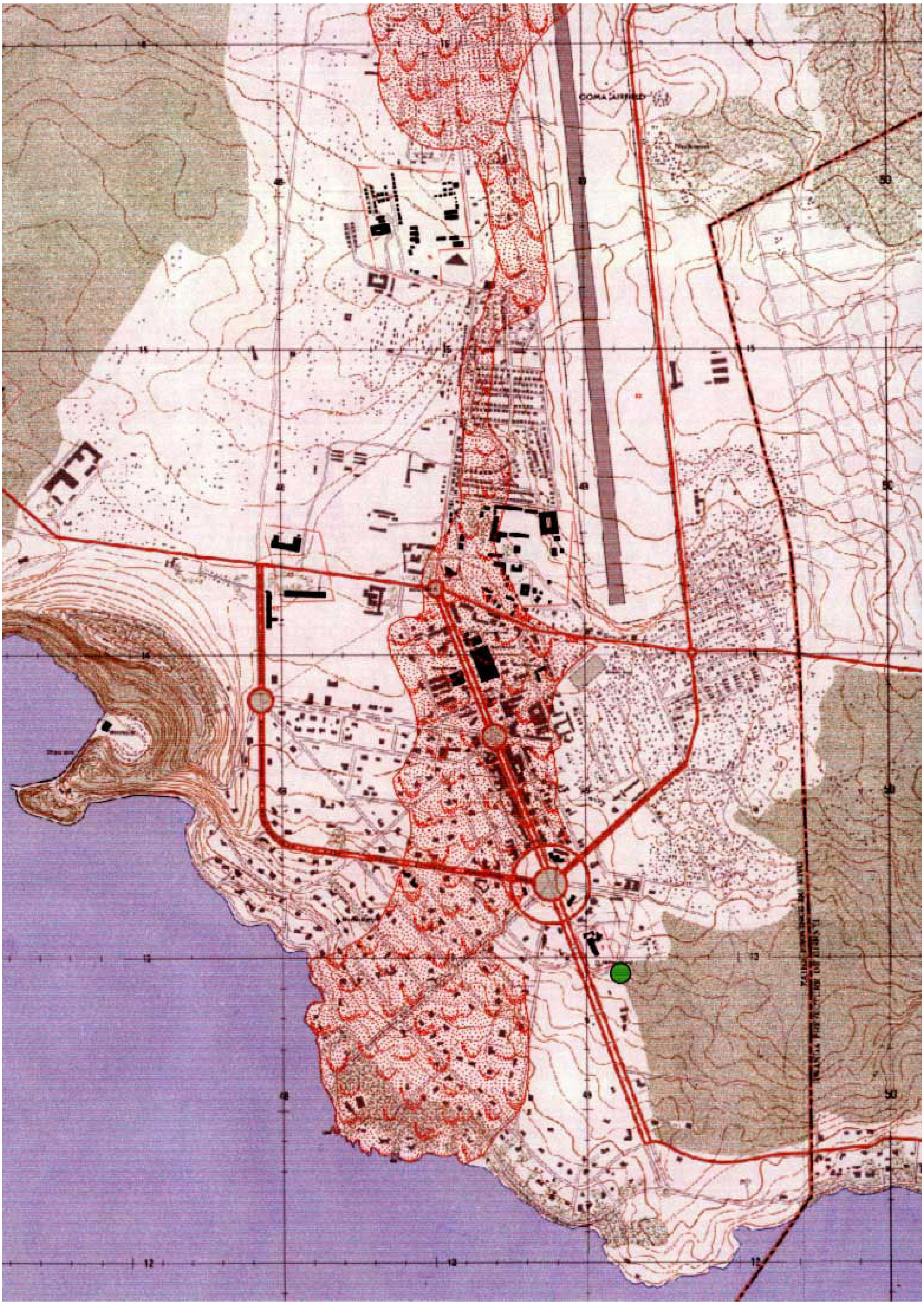


Figure 1: map of the lava flow inside of the town of Goma

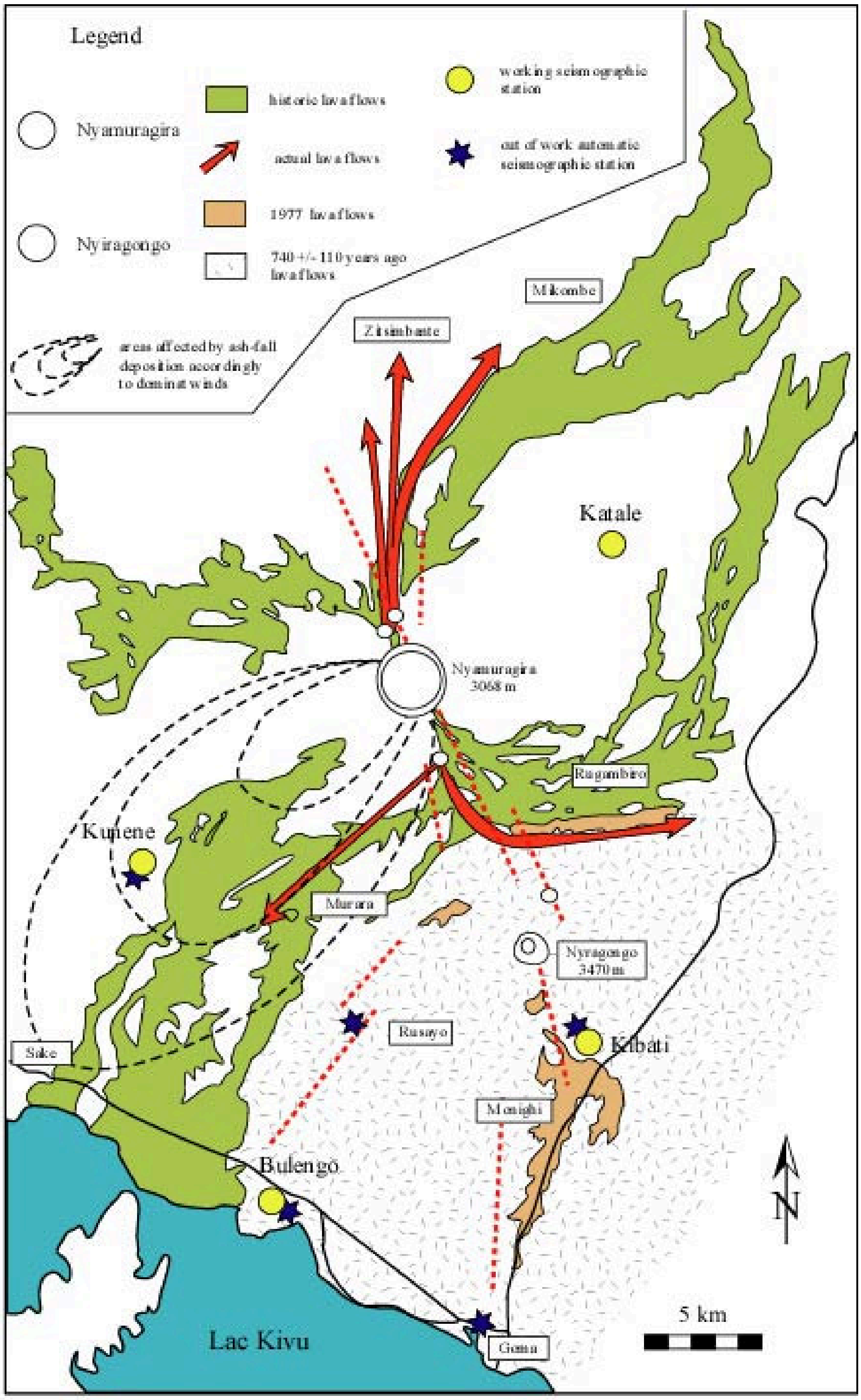


Figure 2 – Schematic map of the Virunga volcanic area after the February 6, 2001 eruption of the Nyamuragira

RESULTS OF INVESTIGATIONS TO STUDY THE DISTRIBUTION OF THE SUB-WATER LAVA FLOW

The hazard of lava flows entering and disturbing density-stratified lake waters has never been previously investigated. A huge mass of hot lava could engender some disturbance in the stratification of the lake and trigger a gas burst, resulting in a lethal cloud of carbon dioxide and methane over an unknown area around the lake. In order to assess the problem, we organised sub-water investigations of the lava flows that entered Lake Kivu, first (January 24 and 25) with the help of scuba divers from UN-OCHA and, as a second step (February 7-10), using a submersible (Fig. 3) that came from France with the financial support of the NGO Solidarités and the EC-ECHO organisation.

The first step of the investigation took place on the 24 and 25 of January with the help of Dominic GARCIN, a scuba diver from the UN-OCHA living in Goma. Nine dives were performed all along the shore near the lava flow, at an average depth of 20 m (maximum 35 m depth). The visibility was very poor (1 m maximum) resulting from the presence of tiny particles in suspension (dust, sediment, ashes?). The most salient discovery was the observation of 3 distinct lava tubes, approximately 2.5 m diameter, which appeared to continue at a greater depth along the steep slope of the lake. The diver also reported the existence of several large-dimension tongues of massive lava disappearing into the depths of the lake.

It should be observed that, surprisingly, the advance of a molten lava flow inside of the water is not a very violent process. In fact the molten lava is instantaneously protected from solidification by a thin film of solid lava of very low thermal conductivity that allows the lava flow to move forwards under water over relatively large distances. In this way - although very improbable - the assumption that the recent submarine lava flow might possibly reach deep layers of the lake was not absolutely to be excluded.

In the case a massive body of hot lava could have reached the 300 m gas-rich layer, a slow convective water motion might be provoked. Thus gas-bearing water may have reached a depth where it will become over-saturated in gas and an ex-solution process would be able to occur. In this case an avalanche catastrophic event could not be totally excluded, with a huge amount of lethal gas being released into the atmosphere (Lake Nyos, Cameroon, 1986: 1800 casualties).

In view of those considerations, and despite the very low probability of such evolution, we decided to ask for a deeper investigation of the sub-water lava flow topographical extension. A little wire-controlled submersible named "spéléonaute" was sent from France, which is able to dive to a 400 m depth and to film the bottom of the lake though a swivelling waterproof camera (see Fig. 3).

We were working for 3 full days using the submersible and carried out 10 dives. Beside the exceptional usefulness of the "spéléonaute" at distance, we were faced with some strong difficulties in our observations. On the one hand, the visibility in the free water was limited by the presence of thin particles which diffused the light of the projectors. On the other, the bottom of the lake was covered by a thin layer of light, impalpable sediment. When the submersible got close by the bottom of the lake, those sediments were raised up by the propeller of the submersible. This effect appeared both as a disadvantage and as an advantage since it allowed us to wash the covered-up rocks from the sediment layer.

Our observations are summarized in Fig. 4
On photos 1 to 9 taken at a depth of 20 m, we were able to clearly identify fresh lava blocks or gravels resulting from the explosion of some lava body in contact with water. Photos 7 to 9 were taken using the spotlight, as the earlier ones were taken with natural light.
Photos 10 to 14 were taken at a depth of between 58 m and 72 m. In spite of the poor visibility, some photos (10 and 14) clearly showed the presence of fresh lava blocks.
Unfortunately, during 3 dives performed at 100 m depth, the tape recorder was not in use. Nevertheless, we were able to distinguish some lava formation which appeared to be old (judging by its colour and shape)
Photos 15 to 18 were taken at the maximum depth of 215 m. In the investigated area, we only found a few sandy places with sometimes larger size deposits.

Our conclusion from this survey (while not absolutely certain) is that, in the investigated area (in front of the main lava flow advance), the lava front is located between 70 m and 100 m depth.

Fig. 3 - The submersible spéléonaute from the "Fontaine de Vaucluse Spéléological Association"

PHOTO 1

PHOTO 2

PHOTO 3

PHOTO 4

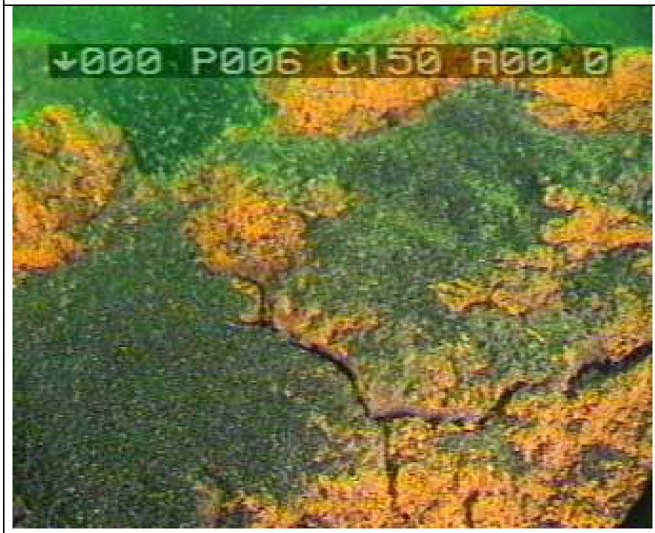


PHOTO 5

PHOTO 6

PHOTO 7

PHOTO 8

PHOTO 9

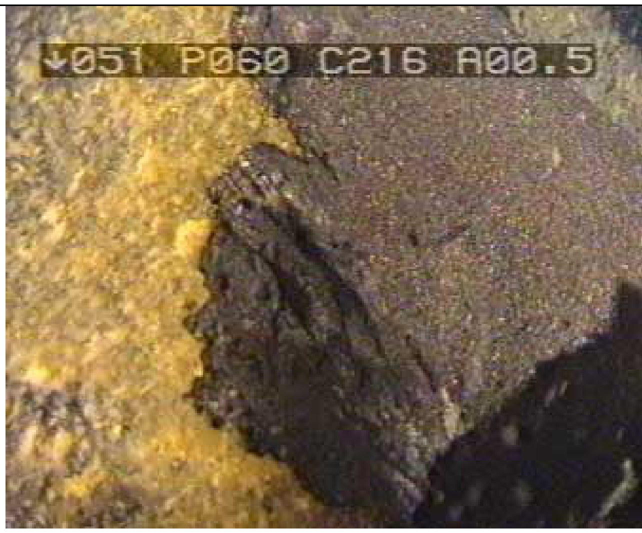


PHOTO 10

PHOTO 11

PHOTO 12

PHOTO 13

PHOTO 14

PHOTO 15

PHOTO 16

PHOTO 17

PHOTO 18

Figure 4 – photographs of the sub-water investigation in the lake

RESULTS OF INVESTIGATIONS TO STUDY THE IMPACT OF THE LAVA INFLOW ON THE STRATIFICATION AND STABILITY OF THE LAKE

This report gives an overview of the measurements and preliminary results from the international expedition to Lake Kivu in February 2002. During this expedition we

- measured the horizontal distribution of the lava on the shore of the lake,
- take some non pressurised samples of lake water for several laboratory investigations, and
- measured the parameters pressure, temperature, electrical conductivity, pH, oxygen-concentration and light transmission on 40 vertical profiles, distributed systematically on horizontal profiles over the northern part of the lake.

The main objective of our measurements was to get vertical profiles of the parameters temperature, electrical conductivity, pH, oxygen concentration and light transmission as function of pressure on a horizontal network to investigate the impact of the inflowing lava on the stratification and stability of the lake water

- near the lava inflow at Goma to investigate the direct impact and
- in the deep part of the lake to investigate how the disturbances were distributed over large parts of the lake.

We measured for these investigations several vertical profiles on a horizontal profile from Goma near the lava to the island of Idjwi through the deepest part of the lake. Additionally we measured two deep profiles in the deep channels at both sides of Idjwi (see Fig. 5). But most of the profiles were relative short. We measured many of them near the lava inflow, parallel to the shore as a „network“ (see Fig. 6). Due to time and cost constraints there have been also several problems with both underwater probes which we had on the lake.

Due to the short period of time the measurements were only analysed partly and hence no comprehensive results can be presented here. The focus of this report is on the description of the measurements carried out and the presentation of first and preliminary conclusions. ***However it will be shown, that the inflowing lava left clear signatures especially in the temperature and turbidity of the lake, but had no significant effect on the overall stability of the density stratification. The signatures were found in a depth range between 50 to 120 m indicating that this is the depth range of maximum impact.***

Equipment & Methods

CTD Profiles

Two different CTD (Conductivity-Temperature-Depth) probes were used for the measurements: a *Seabird* SBE-19 and a *Richard Brancker* XR-420. The SBE-19 probe was measuring oxygen concentration, pH and light transmission in addition to the standard parameters electrical conductivity, temperature and pressure.

Water samples

Water samples were collected using a Niskin sample bottle. Since the samples were not collected “under pressure” dissolved gases became oversaturated after bringing the sample to the surface and gassed out, making any gas concentration measurements from these samples impossible. Water samples were kept as untreated “raw” samples, as filtrated samples for the estimation of the main ion composition using ion chromatography, as filtrated samples with added acid (to avoid precipitation of heavy metals after re-oxygenation) and as untreated samples filled up in gas proof copper pipes for isotope partitioning estimates. In addition to these analyses the dissolved and total concentrations of nutrients will be estimated. No results of chemical analyses are available at the present time.

Calibrations

Due to technical problems only the first two profiles measured with the RBR probe could be processed so fare. The remaining data cannot be recovered from the instrument or are showing artificial spikes on the measured profiles which must be eliminated by an electronic treatment of the records. Both problems will be solved by the manufacturer and the data will be available soon.

Additionally we had problems with the calibration of the underwater probes. It was not possible to calibrate them in a water bath before we travelled and no check of the system was possible in the field. We hope to be able to calibrate the underwater probes now after the expedition. Therefore, before this calibration is carried out, only a relative comparison with the data of Tietze (1978, 1981) is possible.

Also after we have made up for the calibration we cannot be completely sure about a possible drift in the electronics and thus an absolute comparison with the data of Tietze (1978, 1981) is only partially possible. These data, measured in 1974/75 were measured under a very strict calibration treatment before, during and after the measurements. These calibrations were additionally directly connected to official standardised calibration of the German Metrological Institute, the Physikalisch-Technische Bundesanstalt (PTB) in Brunswick. Thus these data are the most accurate data ever measured in Lake Kivu from an absolute point of view (absolute accuracy = accuracy) as well as from a relative point of view (relative accuracy = precision). Because only an absolute comparison can give information about the modifications in the lake, a similar rigorous calibration of the instruments to be used in the planned next expedition to Lake Kivu is essential.

Mapping

The actual locations of the measurements in geographical coordinates (latitude / longitude) were estimated using a GARMIN GPS. For the estimation of distances and mapping of the results an electronic map by LAHMEYER & OSAE (1998) was used. This map bases on a Gauss-Krüger projection using a modified Clarke 1880 ellipsoid, a coordinate system origin of [E: $5*10^5$ m, S: $1*10^7$ m] and a scaling factor of 0.9999. The same parameters were used for a transformation of the measured GPS coordinates into this coordinate system. However, a discrepancy between the measured and transformed coordinates and the map coordinates in the range of about 100 m was found. This discrepancy becomes most obvious in the mapping of the new shoreline, formed by the inflowing lava (Fig. 6), which lies partly behind the former shoreline on the map. We hope to overcome these co-ordinate transformation problems by contacting Lahmeyer International AG and OSAE for a synchronization of the transformation parameters.

Measuring and sampling sites

A summary of all CTD profiles is given in Table 3.1 and a summery of the water samples in Table 3.2. The locations of the profiles and water samples relative to the city of Goma and the lake morphology are shown in Fig. 5 and Fig. 6.

In general the following CTD casts were measured:

- a transect consisting of 8 CTD profiles between the lava inflow in the Idjwi Island was measured from the surface down to 150 m depth (profile #3 to #10);
- a set of profiles close to and around the lava inflow area (#11 to #25);
- four deep profiles down to the bottom of the lake with depth > 450 m (#2, #27 - #29);
- one profile in the Bay of Kabuno (#30);

For the profiles #2 to #25 both CTD probes were used simultaneously and whereas the profiles #26 to #30 were measured using the SBE, the RBR probe was fixed to the submarine (ROV). As noted above these data are not available yet.

Preliminary Results

The transect

The main motivation for measuring the eight profiles along the transect between the lava inflow and Idjwi Island was to find “signatures” of the hot lava in the vertical and lateral distribution of the measured parameters. In fact these “signatures were found in temperature as well as in light transmission as a measure of turbidity of the water.

Fig. 7 shows the temperature profiles measured along the transect. The first three profiles, measured within one kilometre away from the lava show distinct “disturbances” in the temperature between 50 and 150 m depth. Away from the lava (up to 14.14 km for profile #8) these disturbances are confined to a thin layer of 3 to 5 meter thickness between around 80 m depth with higher temperature. In contrast the last two profiles, measured at 20.49 km and 25.84 km away from the lava show no such features at all and exhibit a smooth temperature gradient. In general it can be expected that warming of the water by hot lava produced these features, indicating a range of influence between 50 and 120 m depth. These warmed up layer spread horizontally by advection.

Similar and more pronounced lateral features were found in the profiles of light transmission as shown in Fig. 8. The light transmission can be interpreted as turbidity or particle concentration in the water, with lower values of light transmission for more turbid water. The profiles show a strong lateral gradient with increasing values of light transmission (decreasing turbidity) with increasing distance from the lava (see small inset plot in Fig. 8). As an interesting effect it could be observed that the profiles look just like parallel shifted, indicating that the turbidity is decreasing equally throughout the entire measured water column (uppermost 120 m).

In addition to the lateral gradient the profiles show similar features like the temperature with “disturbances” between 50 and 120 m depth, smoothing out with increasing distance to the lava, confirming that this depth range was and is still influenced by the lava inflow. The source of the increased turbidity is unclear up to now. It can be expected, that ashes or small lava particles with low settling velocities are producing this turbidity.

The deep profiles

Fig. 9 shows CTD profile #2 as an example for a deep profile measured in the main basin down to a depth of 463 m, 11.3 km off the lava inflow. The profiles of all parameters show six well-mixed zones (30 to 50 m thick) between 0 m and 460 m depth, separated by strong gradients in temperature and conductivity. Dissolved oxygen vanishes at 50 m depth. The slight increase in measured oxygen concentration below 250 m is most probably an artefact of the measurements, produced by the existence of H2S.

As an interesting feature the light transmission is decreasing sharply at each density gradient and recovers slowly within the well mixed layers. At a first glance these spikes can be interpreted as settling particles with densities close to the density of the water. By hitting a density gradient these particles will stop sinking and accumulate on the density interfaces, until the particle concentration itself produces a significant contribution to the density and convection transports the particles further down. However, it is not clear whether these particles were produced or brought by the inflowing lava, or if they originate from biological production in the surface layer of the lake.

Comparison with former measurements

A preliminary comparison with the profiles of Tietze (1978, 1981) measured in 1974/75 leads to the following results:

- All profiles measured near the lava inflow at Goma show a „restlessness“, that means fluctuations in the data which have to be interpreted as continuous disturbance of the water body in the upper 150 m. With more and more distance from the shore the fluctuations were reduced and a layer of about 3 to 5 m width with slightly higher temperature and salinity formed in about 80 m depth and distributed over large parts of the lake until the island of Idjwi where the layer was resolved due to the higher natural turbulence in the multiple channels near Idjwi. Therefore we measured also two profiles in the deep channels at both sides of the Idjwi island to clarify if the layer in 80 m depth – which is remarked in the profiles as a temperature-salinity peak -- is present also in larger distances or not. Unfortunately we had no measuring system with a winch and direct online-reading, but only a recording system which had to be later transferred to a computer system. Therefore these profiles could not be analysed up to now.

  This temperature-salinity peak in 80 m depth is in our opinion an indirect sign that the lava which flows into the lake reaches depth below 80 m, perhaps 100 m. Thus in the lake region near Goma, wormer water rises up, disturbs the overall stratification and builds up a several meter thick layer which distributed over large parts of the lake – to be seen in the records as a peak. This peak shows the effects of rising water masses.

  This is something like the opposite of a peak found by Tietze (1978) in 1974/75 in about 40 m depth which also distributed over large parts of the lake. But this peak was an effect of water of higher density falling down from about 12 m depth at the threshold between the separate basin Gulf of Kabuno and the main basin. This is due to the fact that the water density in the Gulf of Kabuno is much higher than in the main basin. If the wind drives surface water from the main basin in the separate basin Gulf of Kabuno, water from the Kabuno basin with a much higher density flows in about 12 m depth above the threshold into the main basin. While „falling down“ it mixes with the surrounding water of the main basin, thus leading to fluctuations in the parameter distribution and finally it forms a thin layer in about 40 m depth, represented by a temperature-salinity peak, which could be measured in the records of 1974/75 more than 10 km away from the threshold.

Both mentioned peaks were distributed over large parts of the lake. But additionally the records of 1974/75 as well as those of 2002 show peaks and staircase structures which are limited in their time and place distribution. These are normal signs of hydrothermal activity as well as of double-diffusive convection (TURNER 1965, BRANDT & FERNANDO 1985) which are position and time dependent. To find out if the heat, salt and gas influx which produces many of such fine structure effects is higher now then 27 years ago, a comparison of the fine structure of the former with the new profiles is necessary.

The effects mentioned in the upper paragraphs are due to the inflow of lava into the lake or to other short term events.

The comparison of the data of Tietze (1978, 1981) with our new data show also two long-term effects:

- The one effect is most likely connected to the global greenhouse-effect, which leads to an increase of the temperature at the surface of Lake Kivu. This effect could be seen also in the records from DAMAS (1937) to KISS (1966) to Tietze (1978) to TECHNIP & BRGM (1986) until our recent measurements. With increasing depth the difference of the temperature from new to old measurements decreases. This is an effect of the turbulent exchange which leads with time to an transport of heat from the „heat source“ at the surface to deeper parts of the lake.

- The other effect is connected to the „heat, salinity and gas sources“ at the bottom of Lake Kivu. These sources changed the stratification in the time since 1974/75 in such a way that the overall temperature and salinity changed absolutely only a little, but the relative distribution led to sharper gradients within the gradient layers and to an extent of mixed layers. That means that the stratification of Lake Kivu has developed more to an ideal stepwise structure due to turbulent transport of heat, salt and gas from the bottom into the different layers. The effect of „sharpening“ the gradients could be also partly due to the fact that from two sides, from the surface and from the bottom heat is transported into the opposite direction and balanced just nearly the half maximum depth of the lake.

The long-term effects explained in the paragraphs above led to a slightly higher stability of the stratification of Lake Kivu compared to those 27 years ago.

Outlook

The analysis of the collected data is not finished by far due to the short period of time and the availability of the chemical analysis and part of the probe data. Further analysis will include:

- comparison of the measured chemical parameters (main ion composition) with former measurements,
- estimation of the vertical density stratification by incorporation of the measured ion composition and gas concentration estimates from former measurements,
- characterization of changes in the stratification of different parameters compared to former measurements,
- estimation of the introduced heat by the lava – if possible – and characterization of the effect of that heat on the overall heat budget of the lake,
- characterization of the double-diffusive mixing regime and comparison with historical data,
- estimation of the effect of global warming on the heat budget and stratification of the lake,
- estimation of renewal and exchange rates of the deep water body on the basis of the isotope measurements,
- synchronization of the map coordinates with Lahmeyer International and OSAE for a proper mapping of the changed shoreline and bathymetry.

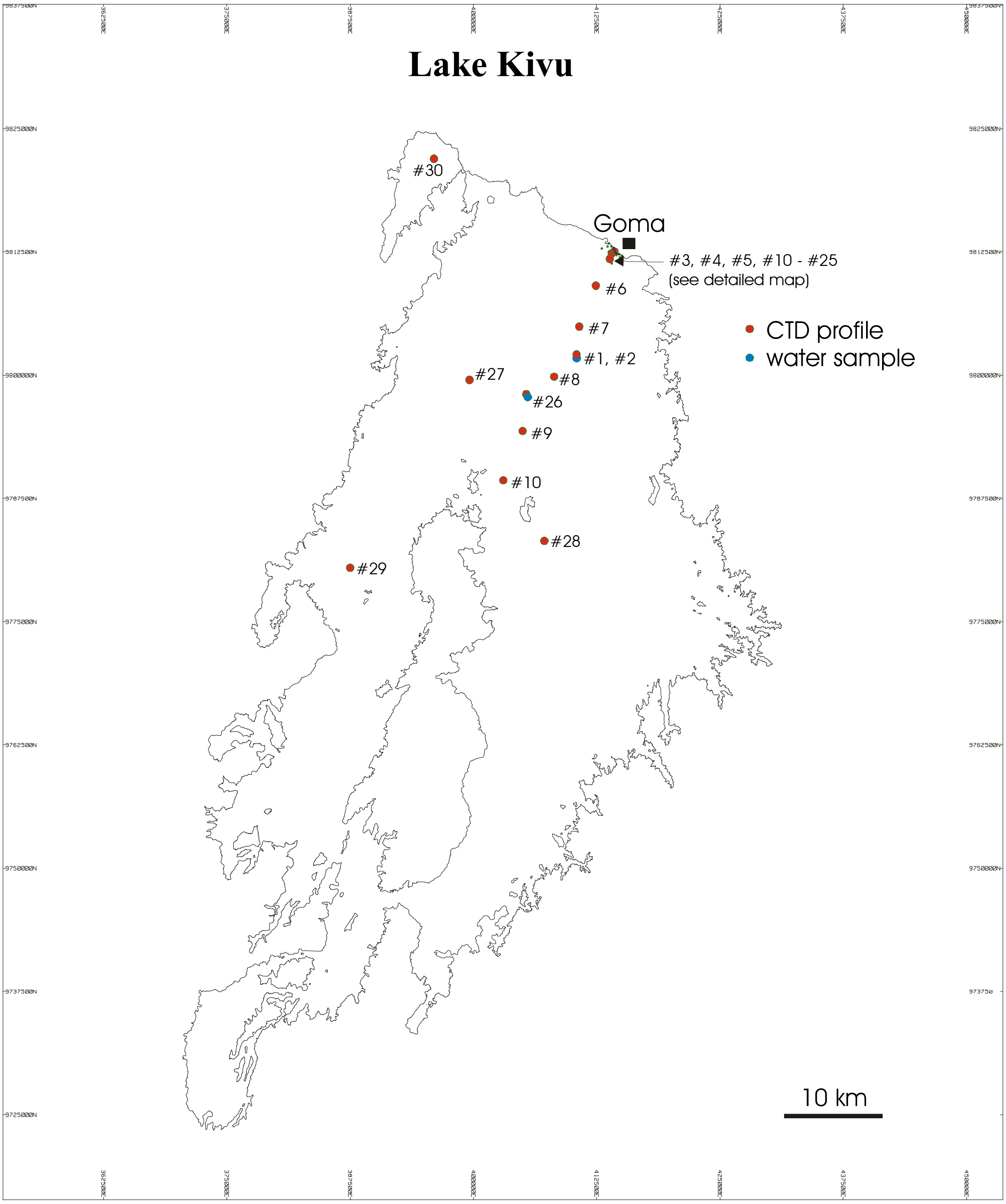


Fig. 5 : Map of Lake Kivu with indicated CDT and water sampling stations

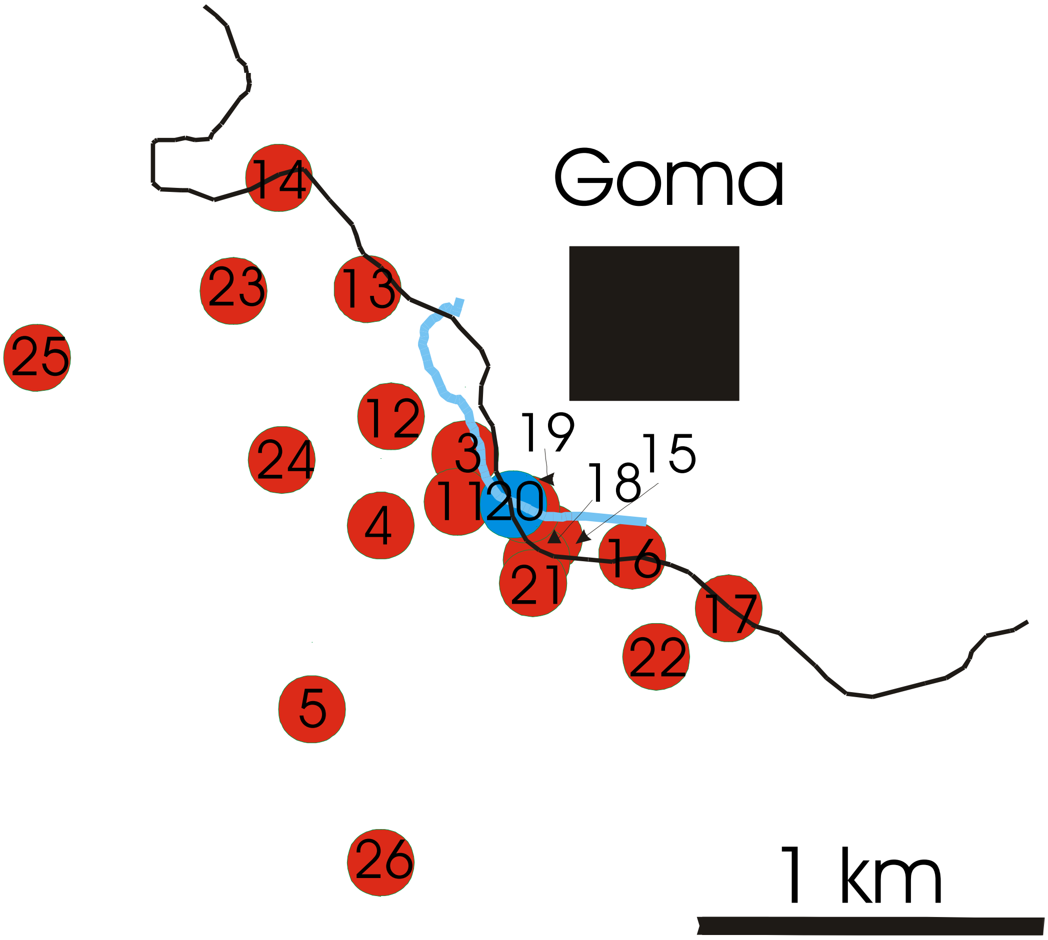


Figure 6: Detailed map showing the area around the lava inflow. CDT and water sampling stations as well as the GPS based mapping of the new shoreline created by the lava

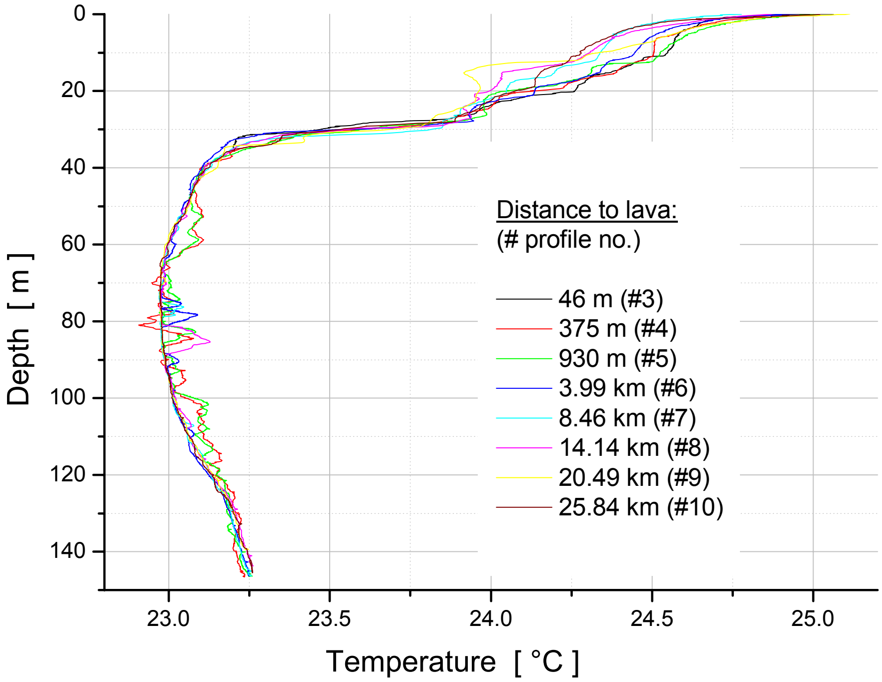


Figure 7: temperature profiles along the measured transect between the lava inflow and Idjwi Island

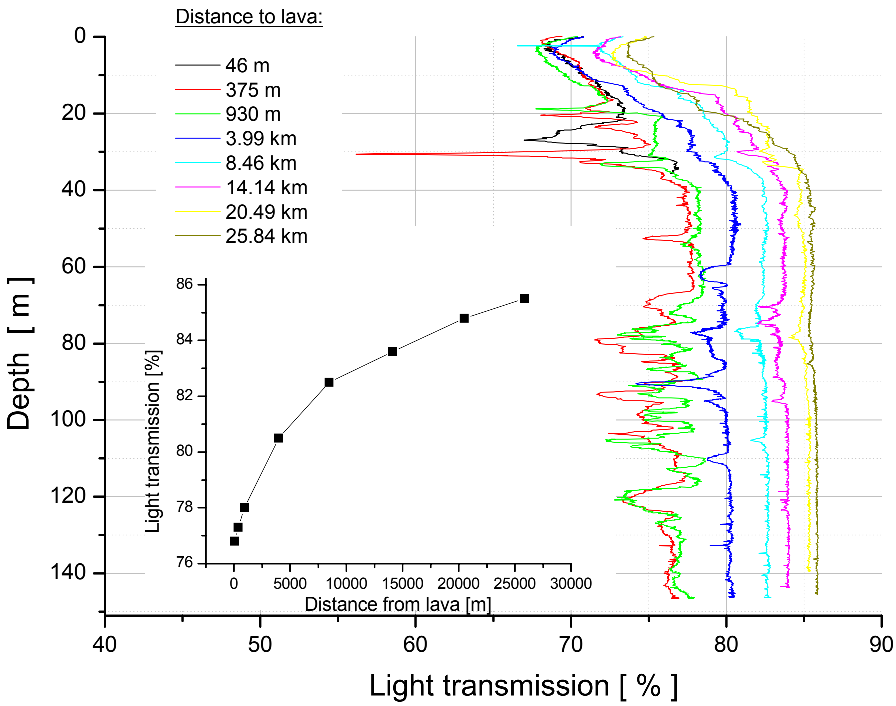


Figure 8: light transmission profiles measured along the transect. The inset shows the bulk light transmission as a function of the distance from the lava

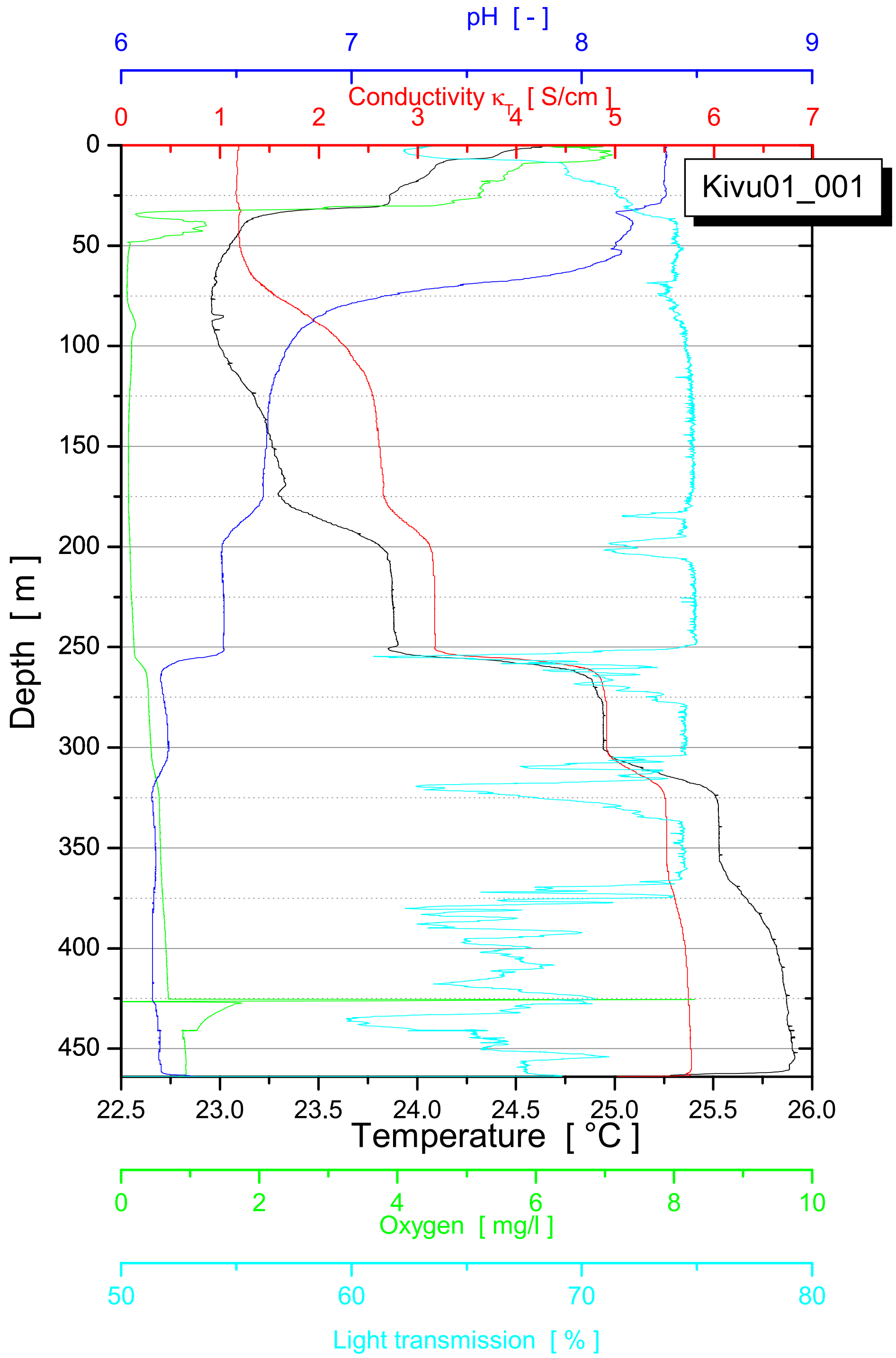


Figure 9: Vertical profile of temperature, conductivity, oxygen concentration, light transmission and pH measured in the main basin down to 465 m depth

CONCLUSIONS

Our measurements and their comparison with those of Tietze (1978,1981) led to the following overall interpretation:

- The lava inflow into Lake Kivu reached most likely only depths down to about 100 m. Therefore the stratification of Lake Kivu was disturbed by this event only between the surface and about 120 m depth and mainly in a limited area near Goma. Far away from Goma the lake was only disturbed in a minor way. Thus it seems that the lake was during this event not near to a gas outburst. But if the lava inflow would have been much longer and stronger, so that lava would have reached depth of more than 250 m, a serious situation would have build up.

- Two long-term effects led since 1974/75 to a slightly higher stability of the stratification in Lake Kivu: The Greenhouse effect led to a little higher temperature in the upper part of the lake down to about 250 m depth and dynamic effects driven by heat, salt and gas sources at the lake bottom led to a sharper density distribution in the gradient layers below 250 m and to an extend and better development of homogeneous (mixed) layers in the deep waters of lake Kivu.

- This short preliminary expedition could only deal with overall features from the lava inflow. It is necessary to accelerate now the Lake Kivu research with the goal to exploit the Kivu gas and thus to eliminate by degassing of the lake the small but possibly serious hazard of a gas outburst from the lake waters.

It may be pointed out here, that the possibility of a huge gas outburst from Lake Kivu, where all or most of the gas dissolved in it would reach the atmosphere, is very low, but that the impact of such an event on the whole Lake Kivu region of about 10 000 km² could be very strong. Naturally the possibility for small or medium gas outbursts with limited consequences is higher. Therefore not only the monitoring of this lake but also an exploitation of its gas and thus its controlled degassing is absolutely necessary, as pointed out by Tietze since 1974. Now the importance and necessity of a monitoring system for Lake Kivu as proposed by Tietze (2000) is evident. This system could be used as early warning system as well as a regulation system for the exploitation of the Kivu gas.

ACKNOWLEDGEMENTS

Our team is grateful for the various help in the organisation of the survey as well as the invaluable assistance in the field provided by:

- His Excellency Mr. Marcel BAHUNDE, Minister of Energy, Water and Natural Resources of the Republic of Rwanda,
- Mr. Emmanuel NSANZAMUGANWA, General Secretary, Ministry of Energy, Water and Natural Resources of the Republic of Rwanda,
- Mr. Jose GOHY, French Embassy Attaché in the Republic of Rwanda, Kigali,
- Mr. Hugues TEMPLE-BOYER, Solidarités Goma,
- Mr. François GOEMANS, EC-ECHO Goma,
- Mr. Dominic GARCIN, UN-OCHA, Goma,
- Mr. J.J.F. de VOS, Bralirwa, Gisenyi,
- Mr. Matthieu VALENS, Bralirwa, Kigali,
- Mr. Digne RWABUHUNGU, Communauté Rwandaise de Belgique,
- Mr. Charles NYIRAHUKU, Unit for the Promotion and Exploitation of Lake Kivu Gas
- Mr. Raymond FRADIN and Mr. Roman BUNIAK, Association Spéléologique de la Fontaine de Vaucluse.

APPENDIX 1: LAKE KIVU AND ITS ENVIRONMENT

Lake Kivu is situated within the western branch of the East African Rift Zone (see Figure A1.1), which is a tectonically and volcanically active area. The strong tectonic activity is due to magma rising from the Earth's mantle. This followed drifting and break-up of the African Plate, which led to the formation of the rift valleys (SCHLÜTER 1997).

Active volcanoes are situated in the vicinity of the lake, for example the Virunga volcanoes in the north. Other high mountains surround the lake, forming a large catchment area. Data on the lake are given in Table A1.1.

Table A1.1

Some data on Lake Kivu.

(Data taken from DEGENS et al. 1973 and TIETZE 1978)

catchment area	≈ 7000 km²
lake area	≈ 2400 km²
lake level (above sea level)	1462-1463 m
discharge rate	≈ 3.2 km³ / a
maximum depth	485 m
volume	≈ 500 km³
depth of thermocline	
wet season	20-30 m
dry season	40-50 m
oxygen: max. depth limit	50-70 m

The water level of Lake Kivu is held approximately constant at 1462-1463 m elevation above sea level by the Mururu power plant near Bukavu (URK). Water is discharged from Lake Kivu via the Ruzizi River into Lake Tanganyika, which is 772 m above sea level (NATIONAL GEOGRAPHIC 1981) and thus around 690 m lower than Lake Kivu. The lake consists of a large main basin and four smaller separate basins. All basins except the Bukavu basin contain different amounts of gas, which is associated with anaerobic conditions between various depths and the bottom.

Rain water falling on the high mountains surrounding the Lake Kivu region infiltrates into the ground and recharges the present groundwater. The groundwater flow pattern is determined by the hydraulic pressure conditions, which in turn depend on the topography and the geological features, as well as on the heat flux in the ground. The groundwater first descends deep underground under considerable hydraulic pressure. In this hot volcanic region, it is heated up and chemically dissolves various soluble substances from the rocks underground. It also chemically and/or physically dissolves various substances migrating upwards from the Earth's mantle, like carbon dioxide and other magmatic gases. The water containing these dissolved substances then rises due to the pressure and thermal conditions underground and enters the bottom and sides of Lake Kivu as hydrothermal springs.

The quantity of substances dissolved has varied with time. As a result, different concentrations of dissolved substances have been fed into the lake at different times, giving rise to water layers with different densities. These layers became superimposed within the lake, creating a preliminary form of the present-day density stratification. Stratified lakes are environments with dynamic, non-linear, self-sustaining properties. They show a multiplicity of currents, oscillations, internal waves and different exchange processes as reactions to external and internal driving forces and disturbances. These driving forces and disturbances at the edges of and within the lake acting over a long period of time formed the present-day density stratification.

The special kind of density stratification of the water in Lake Kivu is the essential reason for the existence of an unusual phenomenon of great scientific and economic interest: Dissolved gas was discovered in Lake Kivu by Damas in 1935 (DAMAS 1937) and later investigated by several other researchers (see TIETZE 1978, 2000). They found huge amounts of methane and other gases physically dissolved in molecular form in the deep waters of Lake Kivu, in the same way as gas is dissolved in a bottle of champagne.

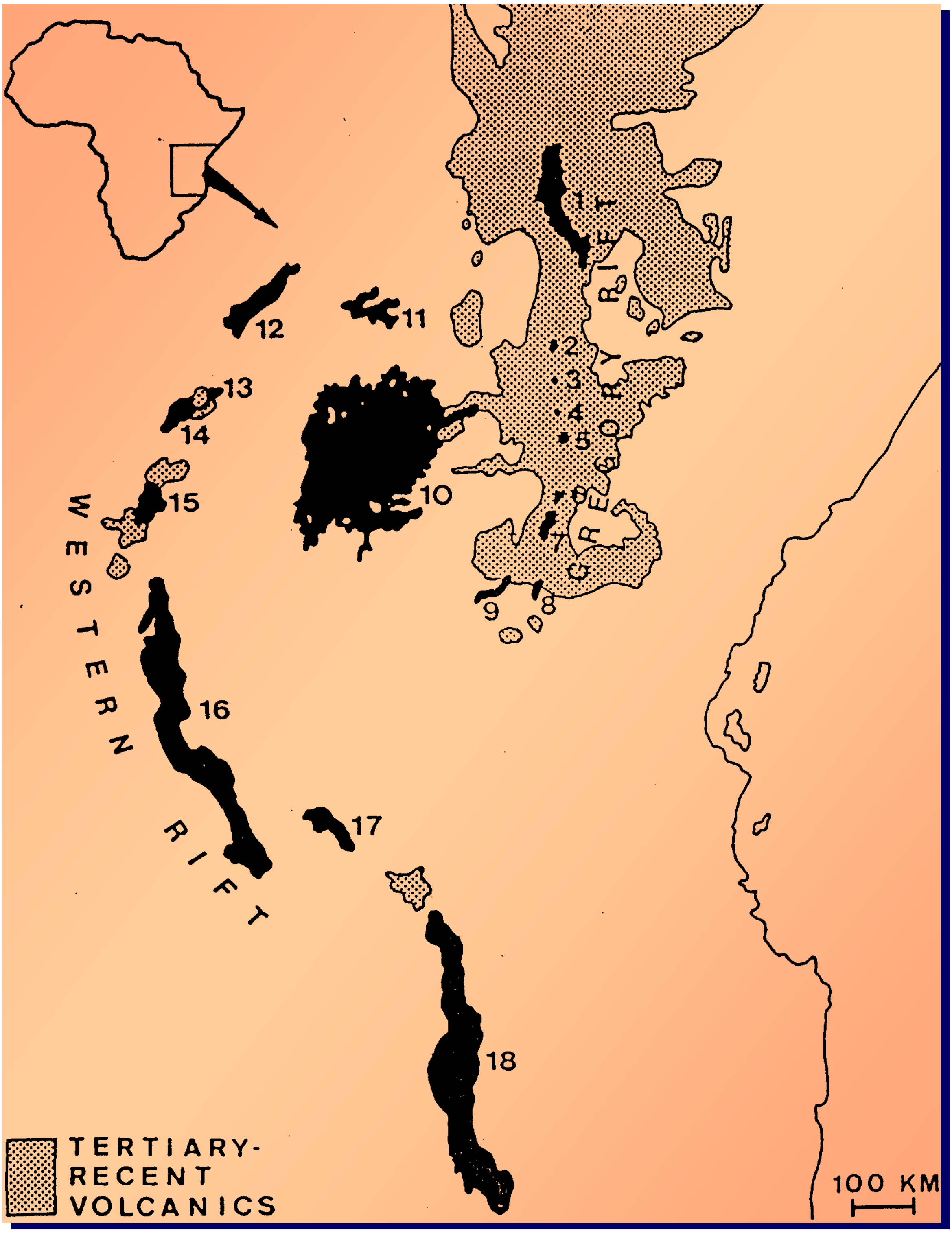


Figure A1.1

Geographical setting of the lakes in the East African Rift System.

(Figure taken from SCHLÜTER 1997)

LAKES:
(1) Turkana / (2) Baringo / (3) Bogoria / (4) Nakuvu / (5) Naivasha / (6) Magidi / (7) Natron / (8) Manyara / (9) Eyasi / (10) Victoria / (11) Kyoga / (12) Albert / (13) Georgi / (14) Edward / (15) Kivu / (16) Tanganyika / (17) Rukwa / (18) Malawi-Nyasa

APPENDIX 2. FORMER SCIENTIFIC EXPLORATION OF LAKE KIVU AND ITS UNUSUAL METHANE GAS ACCUMULATION

In 1935, when DAMAS (1937) discovered gas dissolved in the deep waters of Lake Kivu, he did not know which gas he had found. Around 20 years later SCHMITZ & KUFFERATH (1955), CAPART (1960) and others found out that, besides huge amounts of carbon dioxide, large quantities of methane were dissolved below 275 m in the waters of Lake Kivu, forming an exploitable deposit. These at that time excellent scientific studies led to the construction of a small production plant by UCB (UNION CHIMIQUE BELGE 1954-1971) about 40 years ago. Since then the plant has been extracting approximately 5 million m³ of gas-bearing water per year from a depth of 300 m using the natural gas lift principle, demonstrating the unusual quality of the engineering performance. Thus the extracted quantity of methane is around 1.5 million m³ (STP) per year.

Several other researchers investigated the water and gas body of lake Kivu in the following time with large time gaps. A systematic review of the investigations in given in TIETZE (2000). Unfortunately the limited precision and accuracy of several investigations led to confusing results. Therefore the governments of Rwanda, Kivu and Germany decided to send a scientific research expedition to study Lake Kivu in detail. One major objective was to gather very precise, accurate and complete data on the lake within the framework of a technical co-operation project.

This project comprised three parts as follows

- an economic, market and energy study (BREITENGROSS & KAMPHAUSEN 1973),
- a technical study concerning the production plants and the handling of the gas (PREUSSAG 1972), and
- a scientific study of Lake Kivu and its methane gas deposit. This includes
  - a comprehensive research expedition (for which special new measuring systems were developed),
  - detailed laboratory work, and
  - intensive computer modelling of large scale exploitation of the methane (for which special production simulation models were developed),

  leading to a plan for safe and environmentally sound development of this unusual methane gas deposit (TIETZE 1974; TIETZE & SCHRÖDER 1974, 1975; TIETZE & MAIER-REIMER 1977; SCHOBERTH & TIETZE 1978; TIETZE 1978; TIETZE et al. 1979, 1980; TIETZE 1979-2000; SCHOELL, TIETZE & SCHOBERTH 1988).

During the research expedition to Lake Kivu in 1974/75 and in the subsequent laboratory investigation on samples, as well as during computer modelling the following work was done, much of it for the first time:

- systematic, highly precise and accurate measurements of major parameters such as in-situ density, temperature, electrical conductivity, pressure and concentrations of various gases and other substances including stable and radioactive isotopes,

- development of a model of methane genesis based on in-situ and laboratory measurements, as well as on experiments on unusual bacteria discovered in the lake sediment, using various isotope-labelling methods,
- development of a reconstruction of the lake dynamics and determination of the size of the gas deposit,
- development of an optimal, safe and environmentally sound method of extracting the gas from the lake on a large scale, using three newly developed two- and three-dimensional computer models and the basic data obtained.

These data (TIETZE 1978) are very precise and accurate due to the high standard of calibration in the laboratory as well as in the field, based on official standardisation (German Official Metrological Institute, the Physikalisch-Technische Bundesanstalt (PTB) in Brunswick). Because these data on the water of Lake Kivu and the gas dissolved in it are not only the most precise and accurate, but often the only data that cover the entire vertical profile of the lake, and in some cases the only data available, these data and the associated theories and computations have been recognized internationally as the basic scientific work on the water and gas body of Lake Kivu, features. Therefore in this report our new data were compared with the data of TIETZE (1978), measured 1974/75 that means about 27 years ago .

The profile measurements made in 1974/75 with the underwater probe system were distributed systematically over the whole lake. This was necessary to be able to get mean values of the different parameters. Mean values are much closer to the quasi-equilibrium than single-profile measurements, which are always disturbed in different ways by different amounts.

Figure A2.1shows one vertical profile of parameters measured in the main basin of Lake Kivu. The gas concentration profiles in Figure A2.2 show the same distribution with depth as the density and most of the other parameters. The concentrations of the main dissolved gases each show a maximum near the lake bottom of about 0.35 m^3 (STP) methane / m^3 water and about 6 times this for carbon dioxide. The percentages of the different gases dissolved in the lake water as a function of depth are shown in Figure A2.3.

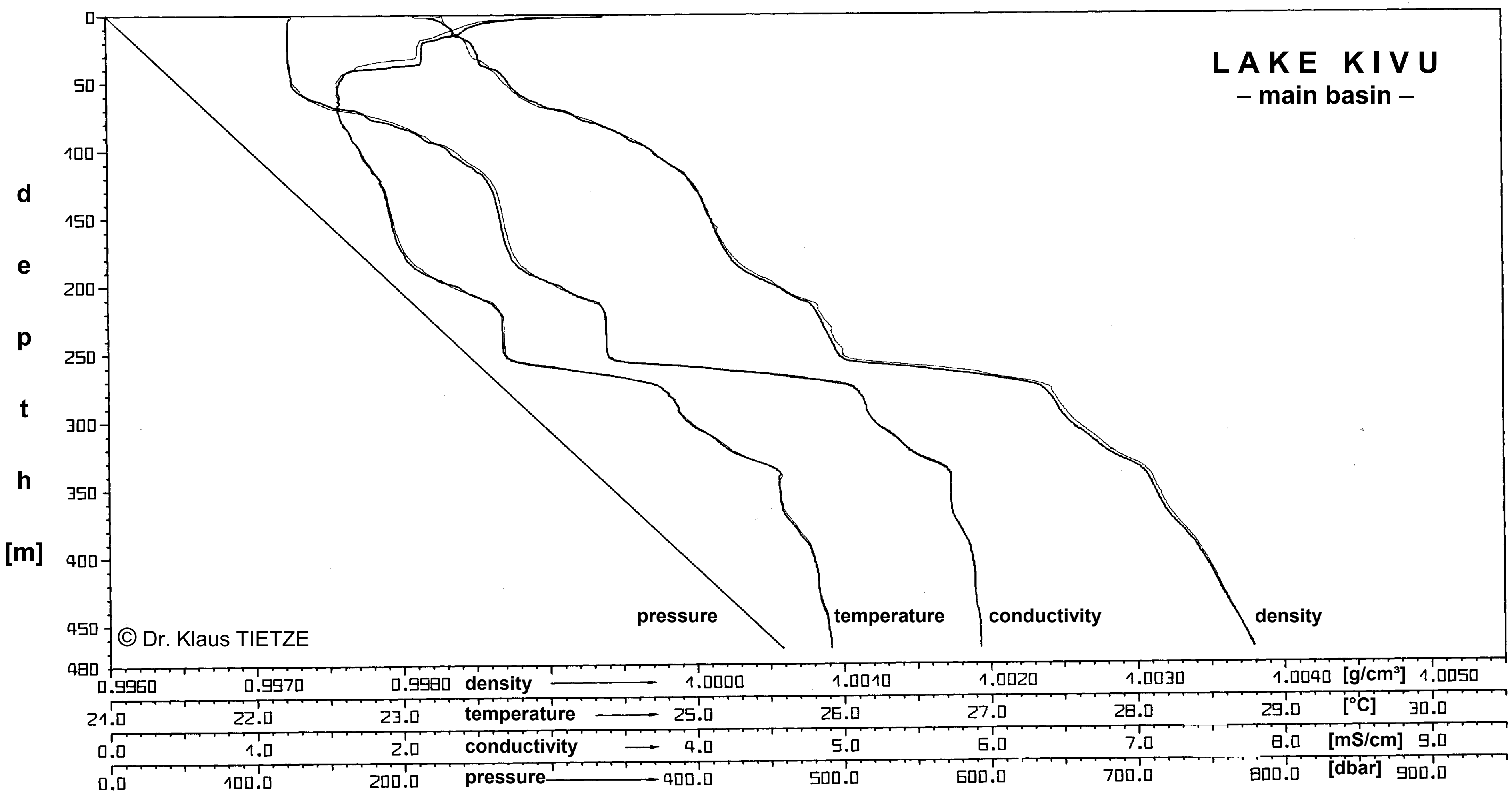
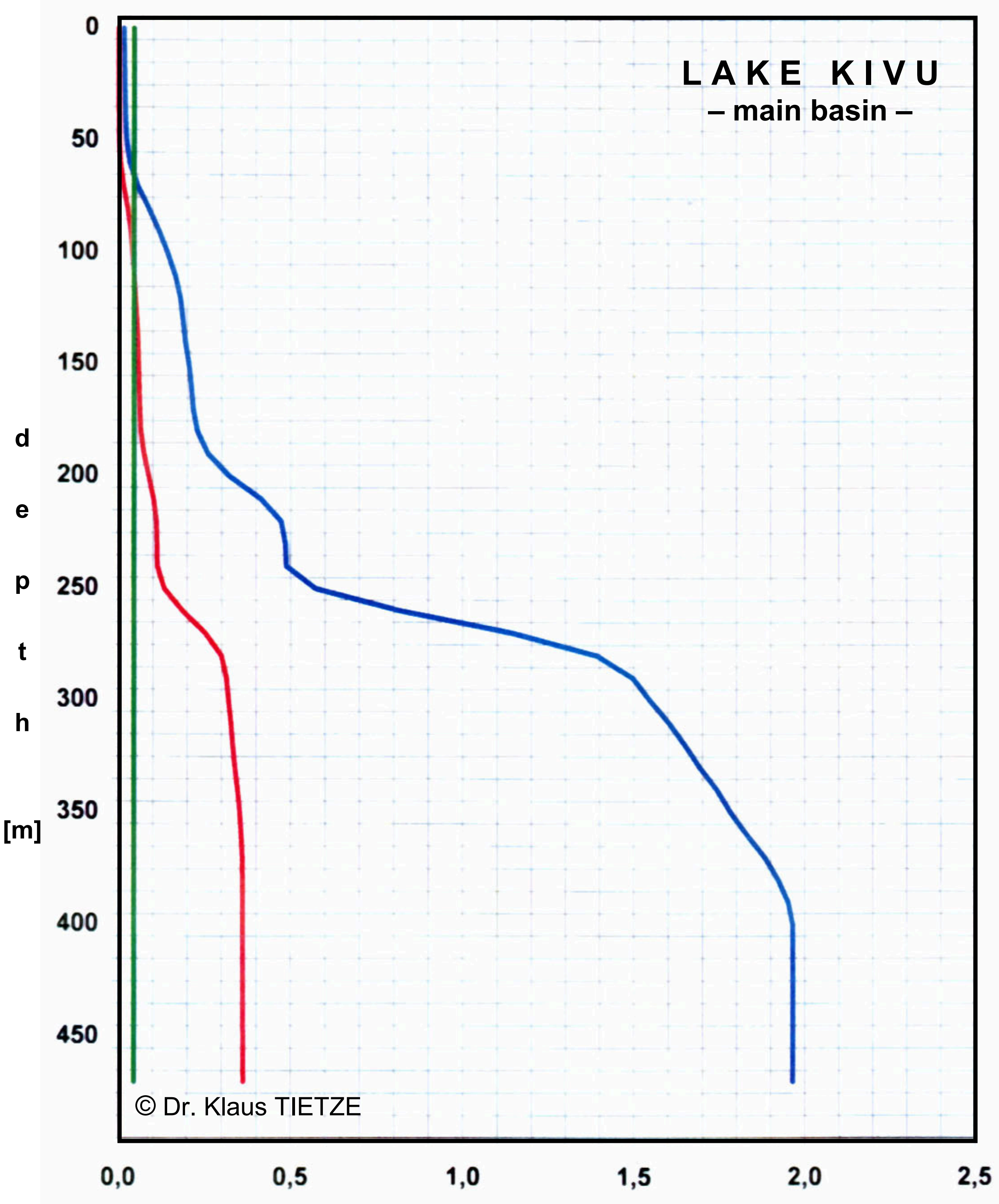


Figure A2.1

Vertical profiles of in-situ measurements of density, electrical conductivity, temperature and pressure in the main basin of Lake Kivu (position 9, profile U35, 23 January 1975, thick line = lowering, thin line = raising of the underwater probe).

(Figure taken from TIETZE 1978)



Gas concentration in water [m³ (STP) gas / m³ water]
(—— carbon dioxide, —— methane, —— nitrogen)

<u>Figure A2.2</u>

Concentrations of physically dissolved methane, carbon dioxide and nitrogen versus depth in the main basin of Lake Kivu (best-fit curves).

(Figure taken from TIETZE 1978)

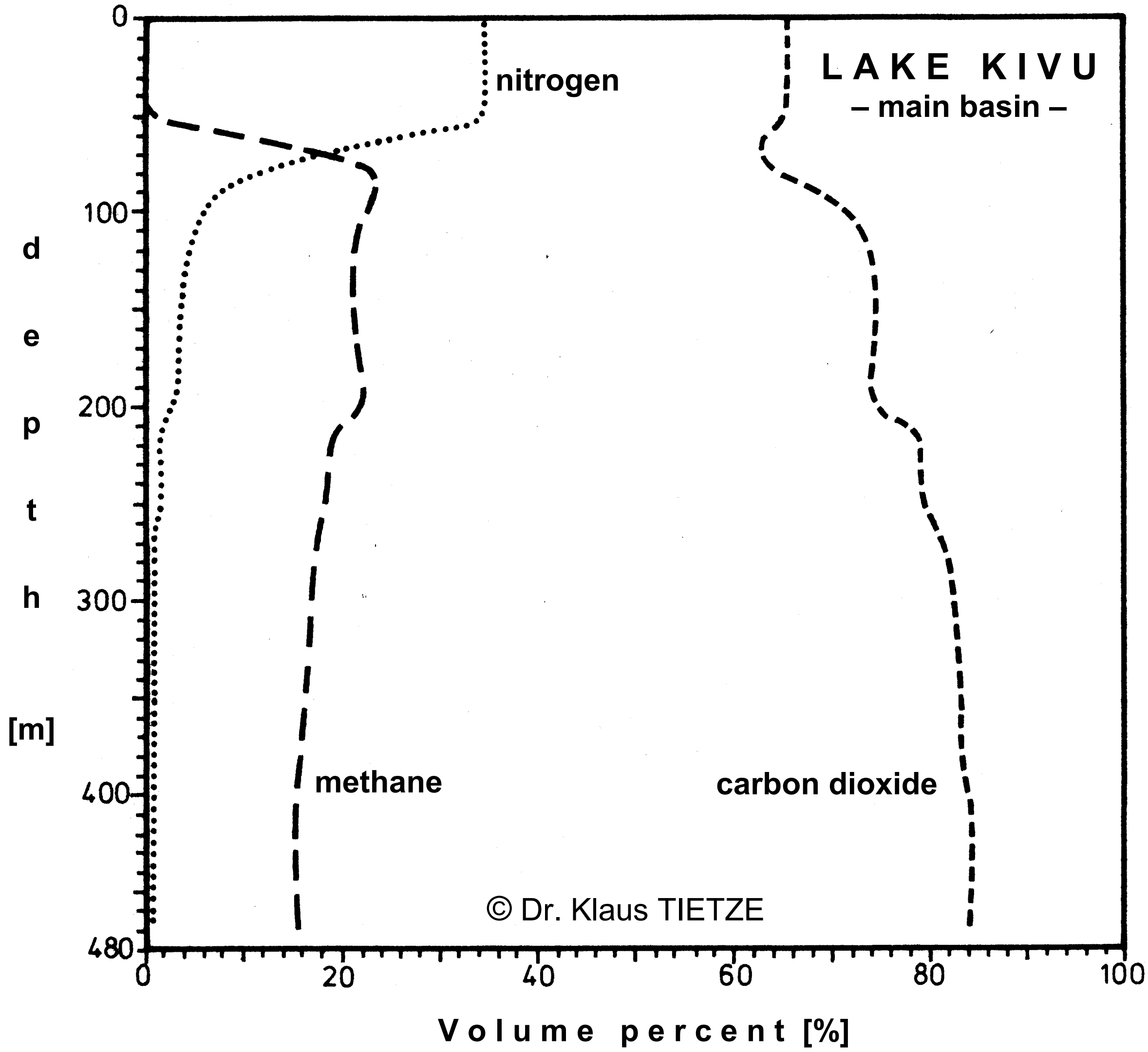


Figure A2.3

Proportions of methane, carbon dioxide and nitrogen dissolved in the water of Lake Kivu (main basin) versus depth, as a percentage of the total volume of dissolved gas present at the corresponding depth.

In this figure the amounts of the various dissolved gases are given as percentages of the total volume of dissolved gases at the corresponding depth. This is equal to the amount of gas which would completely degas from a water sample into a vacuum, which is maintained during degassing, i.e. no gas remains dissolved in the water sample.

(Figure taken from TIETZE 1978)

The gas volumes integrated from the surface downwards are shown in Figure A2.4. The calculations are based on the gas concentration data of TIETZE (1978) and the bathymetric maps by CAPART (1960) (blue lines) and LAHMEYER & OSAE (1998) (red lines). The bathymetric measurements of LAHMEYER & OSAE (1998) were carried out using modern equipment and are therefore assumed to be more accurate than those of CAPART (1960). Therefore the red lines should be used in further work. Thus the total amounts in place are around 5 km³ (STP) of nitrogen, 55 km³ (STP) of methane and 250 km³ (STP) of carbon dioxide. Figures for other gases dissolved in the lake water are given in TIETZE (1978).

Since the methane in Lake Kivu is physically dissolved in the lake water under hydrostatic pressure, this methane gas deposit is significantly different from the usual types of gas fields, where fissures and pores in rock act as a static storage system. In Lake Kivu the methane is held in water layers which form a dynamically stable density stratification and thus act as a dynamic storage system. Owing to this uniqueness, it was not clear how to exploit the methane entrapment without disturbing the density stratification, which not only enabled the methane to accumulate but also secures the continued existence of the methane gas deposit.

Therefore, much effort (see TIETZE & MAIER-REIMER 1977) has been expended to solve the problems connected with safe and environmentally sound exploitation of this unique gas deposit. Even the probability for a large outburst of gas from Lake Kivu is very low, the impact of such an unlikely event could be serious. Therefore not only the monitoring of this lake but also an exploitation of its gas and thus a controlled degassing is absolutely necessary. A systematic overview about these problems including the equilibrium and stability of Lake Kivu is given in TIETZE (2000).

For comparison with other profiles, especially the new ones, it is the best to use averaged former profiles, because they are closer to the quasi-equilibrium than single profiles. Therefore in Figure A2.5 averaged profiles of 23 profiles from 1974/75 (TIETZE 1978) are given, as well as averaged stabilities in Figure A2.6.

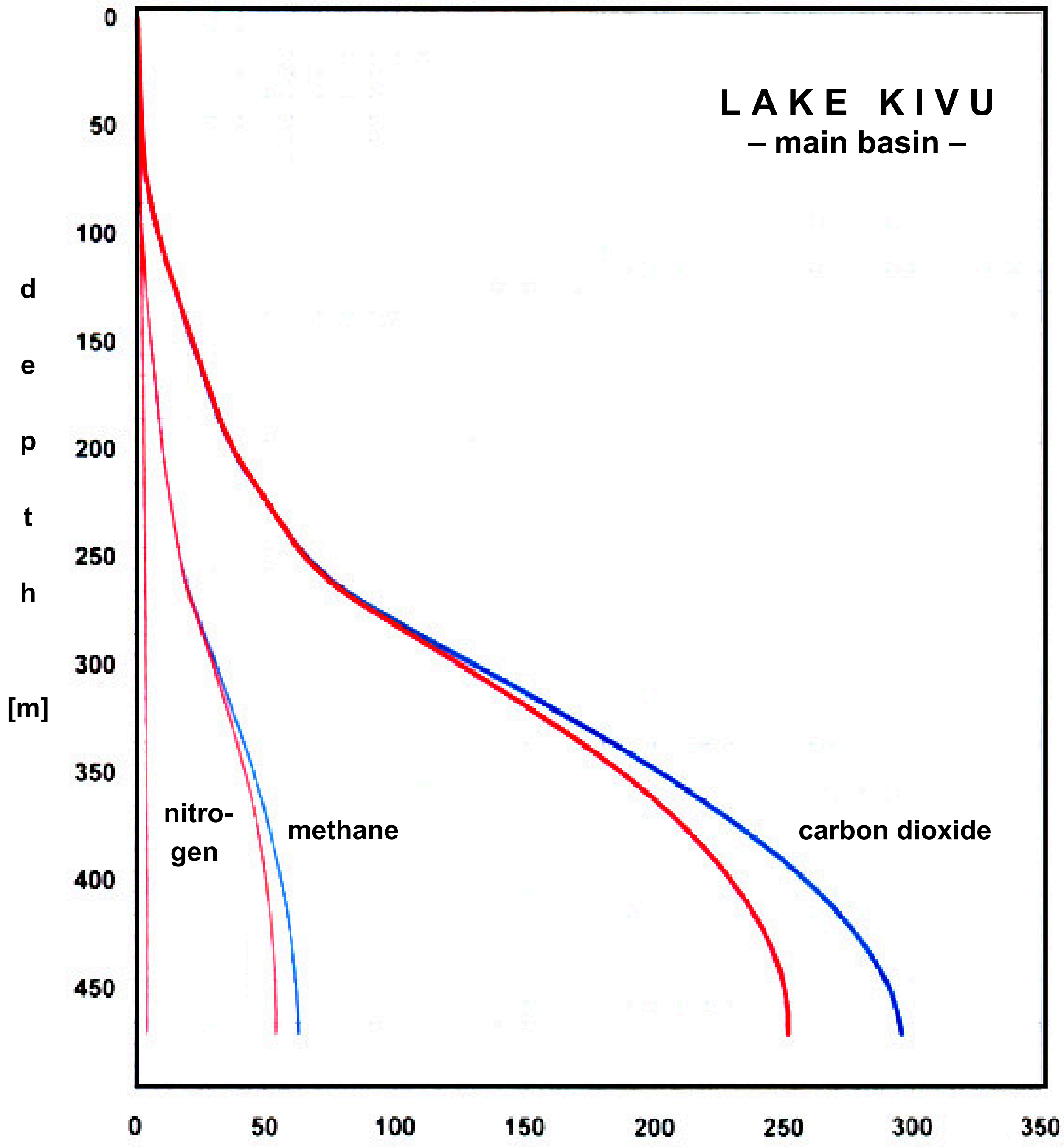


Figure A2.4

Comparison of the integral gas volumes of methane, carbon dioxide and nitrogen dissolved in the main basin of Lake Kivu as a function of depth (cumulative plots).

TIETZE 1978 based on the bathymetric map of CAPART 1960

TIETZE 1998 (LAHMEYER & OSAE) based on the bathymetric map of LAHMEYER & OSAE 1998

(Figure taken from TIETZE 1998 (LAHMEYER & OSAE))

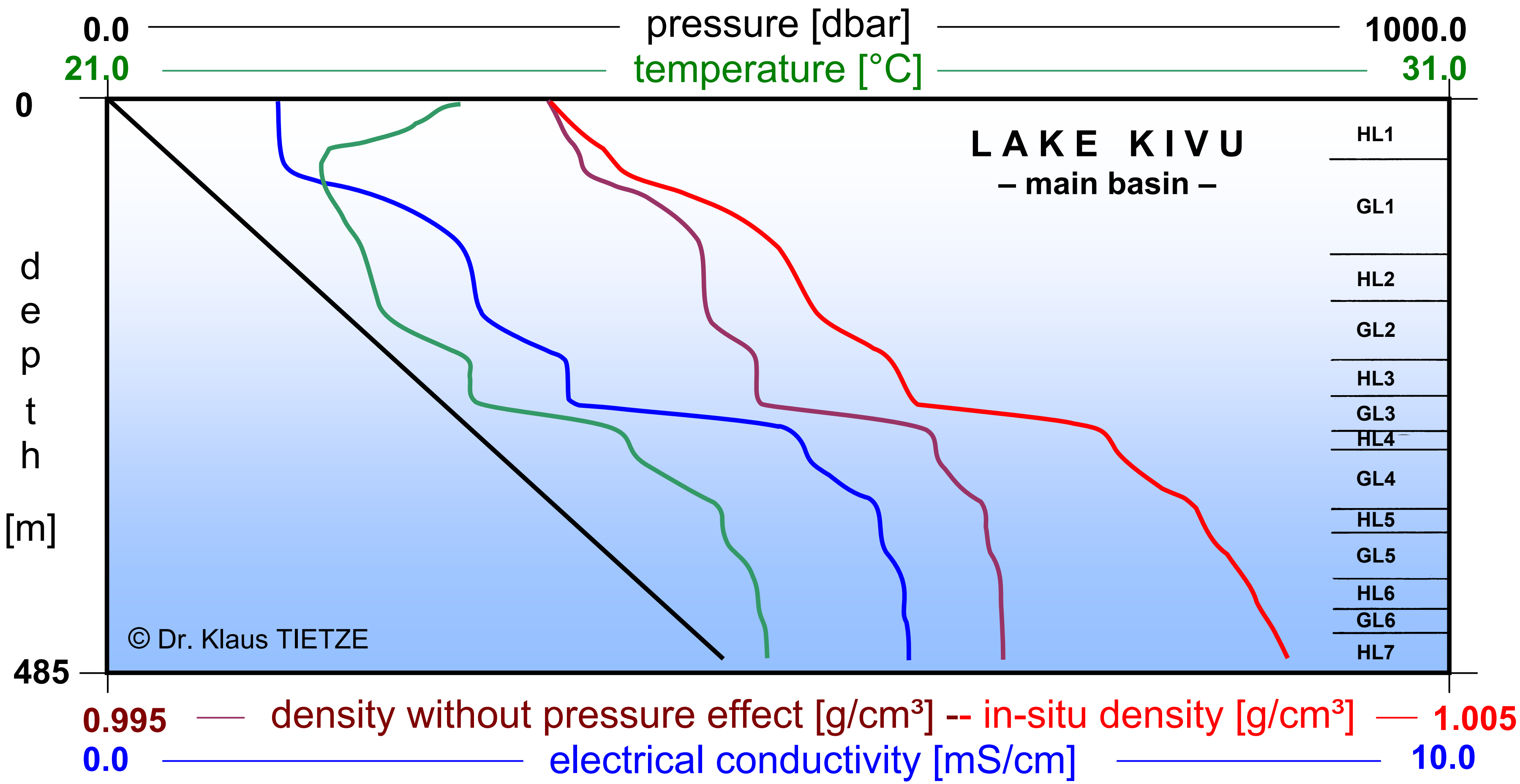
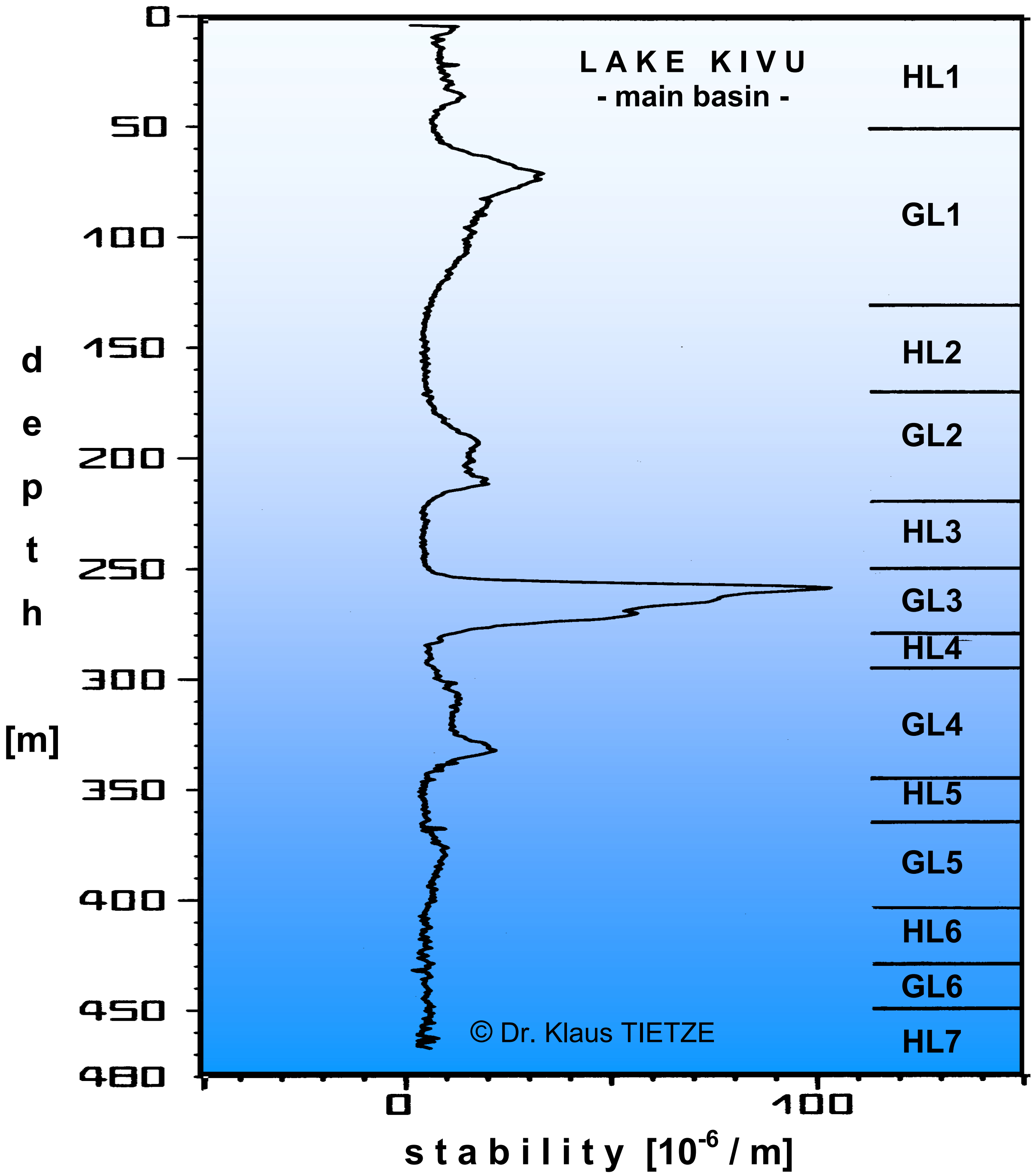


Figure A2.5

Vertical profile of simultaneous in-situ measurements of density, electrical conductivity, temperature and pressure, averaged from 23 profiles in the main basin of Lake Kivu. The in-situ density minus the density increase due to pressure is also plotted. The lake shows a typical stratification pattern, where homogeneous layers (HL) are separated by gradient layers (GL). Measurement period: 24 November 1974 to 26 January 1975 (note that this is a scanned figure: for exact values please see the original figure).

(Figure taken from TIETZE 1978)



<u>**Figure A2.6**</u>

Stability (density gradient / density) as a function of depth in the main basin of Lake Kivu (average of 23 vertical profiles). Homogeneous layers (HL) and gradient layers (GL) alternate in the water column giving the entire lake a high degree of dynamic stability. The resolution in the horizontal direction in this figure is higher than in Figure A2.5 by a factor of 10. (Measurement period: 24 November 1974 to 26 January 1975)

(Figure taken from TIETZE 1978)

Appendix 3. Estimation of the natural risk posed by the amount of dissolved gas in place

The following text is taken from TIETZE (2000):

"On 21 August 1986 a disastrous gas outburst occurred in Lake Nyos in Cameroon, which caused more than 1700 fatalities (FREETH & KAY 1987). The victims died of asphyxiation (BAXTER et al.1989), because a large carbon dioxide cloud had temporarily displaced the oxygen in the atmosphere up to 25 km from the lake. The physical conditions in Lake Nyos and other stratified lakes, which are charged from below with gas, favour the generation of gas accumulations in physical solution in lake water under hydrostatic pressure. If, in a stratified lake, the gas influx rate is higher than its transport rate through the stratification to the surface by eddy diffusion and other transport processes, a hazardous situation will build up. It is then inevitable that gas bursts will take place, normally as "fountain-limnic eruptions" (TIETZE 1987a-f, 1992a-d). They may or may not be disastrous. Water stratification will survive these bursts in a modified form. Thus, cyclic gas bursts of this kind are in a sense pre-programmed, probably with a "stochastic" frequency.

Comparison of the first measurements of the total gas concentration on samples taken in Lake Nyos under in-situ pressure in November 1986 (TIETZE 1987a-d), with later measurements (for example KLING et al.1989, SANO et al. 1990) suggests that the gas content in the relatively small Lake Nyos (area $\approx$ 1.5 km^2) was, around 1990, increasing by at least 5 million m^3 (STP) carbon dioxide per year (FREETH et al. 1990). There is no need for the whole lake to be nearly saturated with gas to create a new outburst. In fact it is not possible for a lake to become totally saturated, since a special physical stratification effect discovered in 1986 (TIETZE 1987a-f, 1992a-d) causes discrete zones at the bases of the gradient layers to become latently over saturated, thus creating potential gas-burst sources at different levels in the lake. Consequently a new gas burst could take place in Lake Nyos in the near future.

Thus, although risk assessment is "the mother of all uncertainties" (BAILAR & BAILER 1999), there is a need to make at least a rough estimate of outburst probabilities from different gas-bearing lakes and ocean basins to compare them. A classification which takes into account many different characteristics of those water bodies will be given later in a special publication by the author. The most important point in such a classification is the estimate of the rate of change of the quasi-equilibrium conditions in gas-bearing lakes and ocean basins in a hazardous direction, as well as the estimate of the probability and possible impact of a sudden external event that might trigger a disastrous gas burst.

A gas outburst from the stratified waters of a lake or ocean basin, which could be disastrous for the local population or for the crews of ships, is, as far as the water body itself is concerned, only an abrupt change to another stable state. Stable density stratification is induced in a water body by external influences and internal mechanisms. The stratification traps gases migrating upwards, and in this way builds up an accumulation of dissolved gases, which at the same time enhances the stratification. When the

stratification becomes destabilised, then it cannot retain all the gas that has accumulated. This may result in minor to major gas outbursts. The main scenarios in which destabilisation of the stratification in gas-bearing lakes or ocean basins could lead to cyclic gas outbursts (TIETZE 1987-1996) are as follows (note: the three scenarios are more or less independent of whether the lake or ocean basin is in short-, medium- or long-term quasi-equilibrium):

SCENARIO A: Spontaneous gas eruption (triggered by a normal event):

- Stratification forms effective gas trap and/or gas influx via the bottom is high.
- Gas concentration of the water builds up and approaches 100 % saturation at the bases of the gradient layers.
- A "normal" external event, such as a storm, induces internal waves, which in turn cause temporary local over saturation in the layers richest in gas.

Result: spontaneous fountain limnic gas eruption with loss of a small or moderate portion of the gas accumulation: disaster if the region were inhabited.
This is most probably what took place in Lakes Monoun (1984) and Nyos (1986).

SCENARIO B: Non-spontaneous gas eruption (triggered by an abnormal event):

- Stratification is less effective as gas trap and/or its effectiveness is reduced by external conditions and/or gas influx from below is moderate or low.
- Gas concentration of the water builds up and reaches moderate values of saturation at the bases of the gradient layers compared to 100 % saturation.
- An "abnormal" external event is required, such as a large landslide into the lake, to cause high internal waves, turbulence and mixing, which in turn cause temporary local over-saturation in the layers richest in gas.

Result: externally triggered fountain limnic gas eruption with loss of a small or moderate portion of the gas accumulation: disaster if the region were inhabited.

SCENARIO C: Non-spontaneous gas eruption (triggered by a catastrophic event):

- Stratification is not effective as gas trap and/or its effectiveness is very reduced by external conditions and/or gas influx from below is low or very low.
- Gas concentration of the water builds up and reaches low values of saturation at the bases of the gradient layers compared to 100 % saturation.

- A catastrophic external event is required, such as a strong earthquake or a volcanic eruption near the lake, to cause very large internal waves, strong turbulence and extensive mixing or just to mix the whole lake from bottom to top and thus let the entire gas accumulation "boil off".

<u>Result</u>: externally triggered major fountain limnic gas eruption with loss of a moderate or large portion of the gas accumulation, or overturn limnic gas eruption with loss of nearly the whole gas accumulation: major disaster (coupled with the trigger disaster) if the region were inhabited.

The natural risk of a disastrous gas outburst posed by the huge amounts of gases dissolved in the waters of the main basin of Lake Kivu is estimated here to be very low for the next few decades and low for the next few centuries (see also TIETZE 2001). This is due to the probably slow change currently taking place in the lake conditions (see Section 4.1), the currently relatively low saturation of the different gases and the self-sustaining nature of the non-linear dynamics of the stratification. But these changes are probably currently accelerating and will accelerate more and more in the future.

<u>FOR THE MAIN BASIN OF LAKE KIVU:</u>

<u>SCENARIO A</u>, can most probably be ruled out for at least a century.

<u>SCENARIO B</u>, for which several possible causes have been repeatedly discussed for a long time, such as strong temperature decrease at the surface, temperature increase at the bottom of the lake, increase in frequency and impact of storms (e.g. TECHNIP et al. 1986) is estimated here to be unlikely in the next several decades (see below). An unknown factor in this estimate is how the climate on the Earth will develop in the future due to the greenhouse effect.

<u>SCENARIO C</u>, together with earthquakes and volcanic eruptions, which trigger this scenario and have been repeatedly discussed for a long time (e.g. TECHNIP et al. 1986), is also estimated here as unlikely in the near future.

Whether Lake Kivu is at the present time in long-term (centuries to millennia) or medium-term (decades to centuries) quasi-equilibrium or whether it is changing from long-term to medium-term quasi-equilibrium, can only be investigated with the help of a new research expedition of similar accuracy to that carried out in 1974/75 and/or an accurate permanent monitoring system (see Flow Diagrams 1 and 2). Unfortunately, most data obtained before and after the expedition of 1974/75 (TIETZE 1978) are not comparable in accuracy and completeness with the data obtained during this expedition (see Chapter 2), so that no reliable conclusions concerning this important question can be drawn yet, before a new extensive research expedition has been carried out. But it may be pointed out that in any case large scale exploitation of the Lake Kivu gas, if carried out in the right way, would – e.g. by reducing the gas-saturation of the lake water while protecting the stratification – generate a quasi-equilibrium that is comparable in effect to natural long-term equilibrium and thus would considerably enhance the safety of the region.

Compared to the probability of a new disastrous gas outburst occurring in Lake Nyos or Monoun in Cameroon, the probability of a gas outburst from the main basin of Lake Kivu is about 10 000 times lower, because it is very different from the other two lakes. Lakes Nyos and Monoun are both small crater lakes, which are situated on the top of volcanic cones. They are at the present time only in very short-term or short-term (years to decades) quasi-equilibrium or in other words, compared to Lake Kivu, they are not in equilibrium. This is due to the fact that large amounts of carbon dioxide infiltrate via the groundwater into these lakes, and therefore the gas concentration in the lake waters increases in time dramatically (e.g. FREETH et al. 1990, TIETZE 1992c, NOJIRI et al. 1992, EVANS et al 1994).

This means that the short-term equilibrium in Lakes Nyos and Monoun is changing fast. These two lakes were nearly saturated at the bases of the gradient layers before the spontaneous gas outbursts of 1984 and 1986 (TIETZE 1987a-f, 1992a-d), which were unavoidable at that time because the gas accumulations in these lakes were not known about. Had they been known about and had funds been available, degassing could have been carried out in time to prevent the disasters, as was proposed first by TIETZE (1987a-f) for the gas remaining in Lake Nyos after the disaster to prevent new outbursts.

Thus Lakes Nyos and Monoun may in the future attain nearly 100 % saturation in certain water layers (TIETZE 1987a-f) in a matter of years to decades. The roughly estimated current probability of a disastrous gas outburst of 1 to 100 will increase to a probability of 1 to 1, meaning that a spontaneous gas outburst will be inevitable if controlled degassing is not carried out before. If the current gas influx does not decrease naturally and if no systematic controlled degassing of these lakes is carried out, they will certainly erupt periodically in the future (TIETZE 1992c). In contrast to this, Lake Kivu is a large under saturated rift lake, which was at the time of the German research expedition in 1974/75 most likely in a slowly changing long-term or medium-term quasi-equilibrium. This means for example that the amounts of gases entering the main basin of the lake at the bottom and the amounts of gases lost within the surface layer nearly balanced out. Therefore, no dangerous gas concentration sufficient to cause a spontaneous gas outburst had built up in the water column, at least up till the last few measurements in 1990.

In Figures 27 and 28 the carbon dioxide and methane concentrations in the main basin of Lake Kivu are compared with the corresponding 100%-saturation curves of the relevant gases. Figure 27 shows that the carbon dioxide concentrations in the marked gradient layers are far away from 100% saturation: i.e. 8% and 3.5%. These layers are also far away from the much shallower depth at which these gas-bearing waters would be over saturated. To reach over-saturation and thus to lead to a gas outburst, the gas-bearing water would have to be raised about 270 m or 220 m, respectively. For methane (see Figure 28) these values are 43% and 10%, and 180 m and 80 m, respectively. The values for the methane can also be considered to be safe within the next decades. However in the case of an extremely high internal wave or some other unlikely event, the methane could exsolve first and would probably trigger carbon-dioxide exsolution. But this would probably soon be smoothed out by the self-sustaining nature of the stratification. Thus a disastrous gas outburst from these under saturated waters in the main basin would probably require a strong volcanic or tectonic occurrence or another unlikely event. But, because the impact of such an event could be serious, the lake should be monitored to detect possible natural changes in advance.

The natural risk of a gas outburst from the Gulf of Kabuno basin in the north-west corner of the lake is probably 100 times higher than for the main basin. The concentration of dissolved carbon dioxide there is relatively high at relatively shallow depths and only one gradient layer exists near the surface (below 12 m depth, see Figure 10), but this gradient layer is around ten times more stable there as the strongest gradient layer in the main basin. To trigger an eruption from this separate basin would require a less strong event than in the case of the main basin. The possible impact would be about 100 times lower there than in the main basin, because the Gulf of Kabuno basin contains less than one percent of the amount of carbon dioxide in the main basin and only small amounts of methane (TIETZE 1978). This basin appears to be in a medium-term quasi-equilibrium.

If a carbon dioxide cloud from a gas eruption from the Gulf of Kabuno basin spread out over the surface water of Lake Kivu, the CO_2 would probably be redissolved to a large extent. In the worst case, neglecting re-dissolution, it was calculated here that the thickness of a carbon dioxide cloud, if it reached the Rwandan border, would be less than 50 cm. In fact it would be redissolved and/or dissipate in the atmosphere before it reached the Rwandan border. But on the Kivu side to the west and south, the risk for the local population in the case of a gas eruption from the Gulf of Kabuno basin is high. Therefore, particular attention has to be paid to this basin when monitoring Lake Kivu. The natural risk of a gas outburst from the Bukavu basin is zero and from the separate Ishungu and Kalehe basins almost zero, because the Bukavu basin contains only insignificant amounts of gas and the gas concentrations in the Ishungu and Kalehe basins are low.

An estimate of the overall probability of a disastrous gas outburst from Lake Kivu is very difficult and could not be accurate. But it should be done for comparison with other lakes, ocean basins and the different basins in Lake Kivu itself (see TIETZE 2001). It leads to different probabilities, naturally with large margins of error for the different basins of Lake Kivu:

- $\approx 10^{-4}$ (1 to 10 000) for the Gulf of Kabuno basin,
- $\approx 10^{-6}$ (1 to 1 000 000) for the main basin, and
- $\approx$ 0 for the other basins (Kalehe, Ishungu and Bukavu).

Several decades of experience gained with gas-bearing lakes permits the conclusion to be drawn that, as a rough estimate, Lake Kivu is currently at least in a medium-term quasi-equilibrium (decades to centuries). The probability of a disastrous gas outburst with thousands of victims occurring in the main basin of Lake Kivu may be about 1 to a million for the next several decades. The probability of a non-disastrous gas burst may be slightly higher.

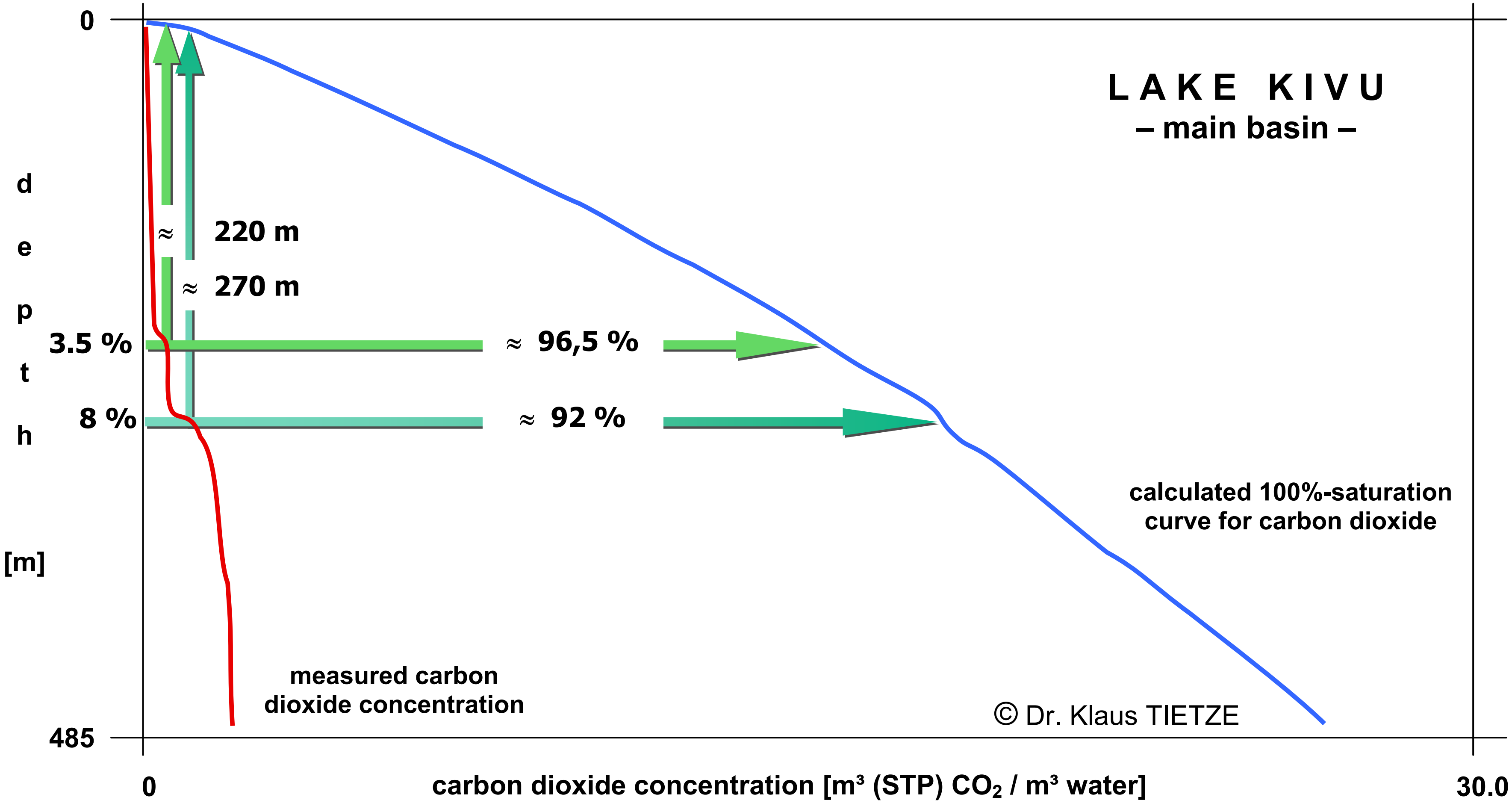


Figure A3.1

Vertical profile of carbon dioxide concentration in Lake Kivu water (main basin) compared with the 100%-saturation curve. The saturation curve is only a first approximation. The formula used must be improved to take more account of the non-linear conditions in the deep water.

(Figure taken from TIETZE 2000)

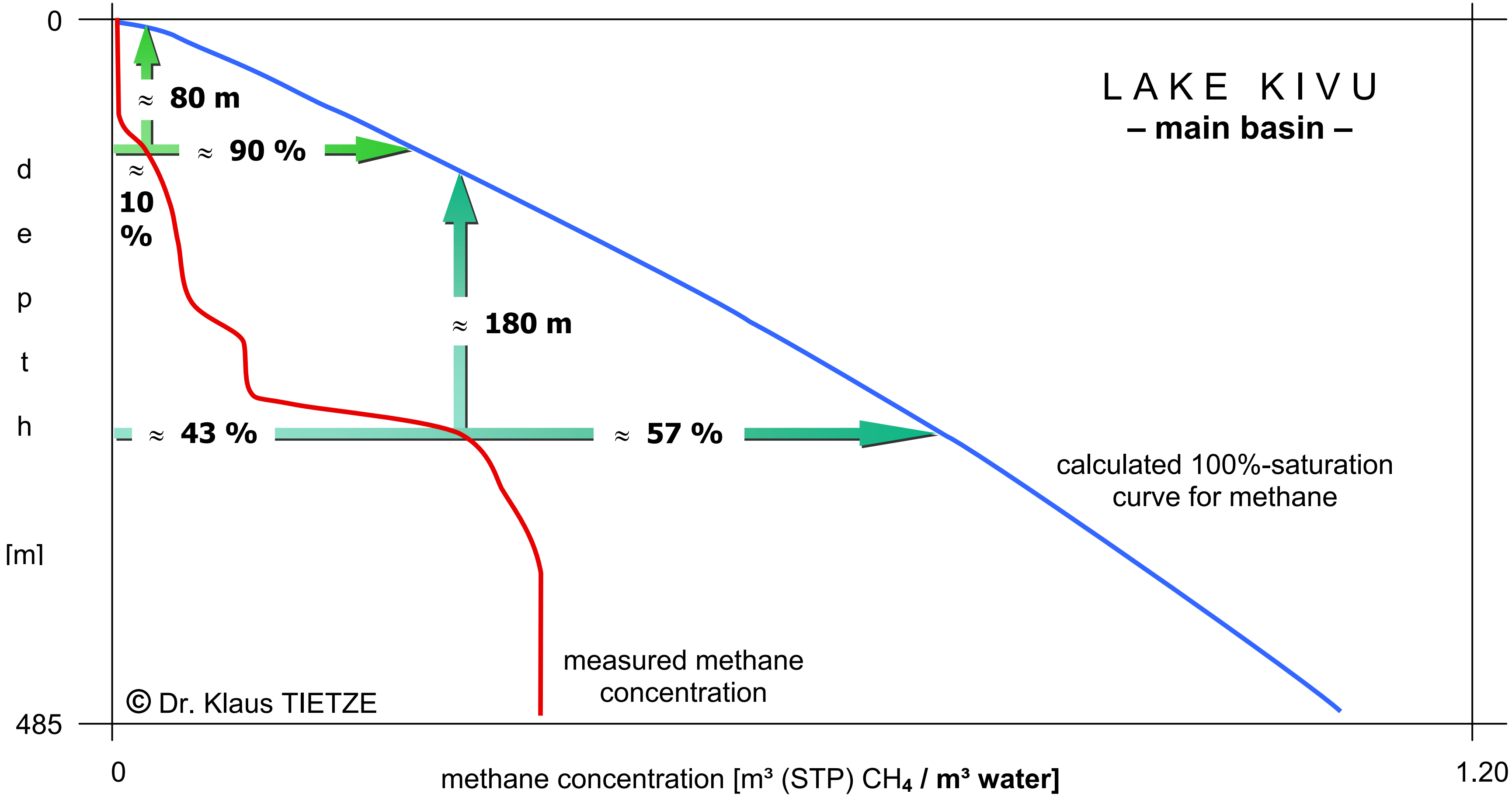


Figure A3.2

Vertical profile of methane concentration in Lake Kivu water (main basin) compared with the 100%-saturation curve. The saturation curve is only a first approximation. The formula used must be improved to take more account of the non-linear conditions in the deep water.

(Figure taken from TIETZE 2000)”

APPENDIX 4. SUMMARY OF THE CTD AND WATER SAMPLING STATIONS

Table 3.1:

Profile #	SBE	RBR	Date	Time	GPS coordinates	Distance to lava center	Profile depth [m]	Bottom ?	Filename	Comment
1	-	x	08.02.02	**12:19**	**S: 01°47.537‘ E: 29°11.742‘**	11.4 km	450 m	-	?	Together with water sample #1
2	x	x	08.02.02	**13:32 start** 14:47 end	**S: 01°47.438‘ E: 29°11.742‘** S: 01°47.537‘ E: 29°11.738‘	11.3 km	466 m	x	kivu01_001	deep profile
3	x	x	09.02.02	**11:52**	**S: 01°41.712‘ E: 29°13.799‘**	46 m	37 m	x	kivu03_000	Transect profile #1
4	x	x	09.02.02	**11:57 start** 12:11 down end 12:17 end	**S: 01°41.827‘ E: 29°13.664‘** S: 01°41.791‘ E: 29°13.691‘ S: 01°41.777‘ E: 29°13.701‘	375 m	148 m	-	kivu03_001	Transect profile #2
5	x	x	09.02.02	**12:34 start** 12:53 down end 13:09 end	**S: 01°42.124‘ E: 29°13.553‘** S: 01°42.056‘ E: 29°13.605‘ S: 01°42.040‘ E: 29°13.626‘	930 m	148 m	-	kivu03_002	Transect profile #3
6	x	x	09.02.02	**13:29 start** 13:52 down end 14:01 end	**S: 01°43.599‘ E: 29°12.794‘** S: 01°43.579‘ E: 29°12.834‘ S: 01°43.578‘ E: 29°12.846‘	3.99 km	148 m	-	kivu03_004	Transect profile #4
7	x	x	09.02.02	**14:16 start** 14:25 down	**S: 01°45.852‘ E: 29°11.883‘** S: 01°45.872‘ E: 29°11.865‘	8.46 km	148 m	-	kivu03_005	Transect profile #5

				end 14:32 end	S: 01°45.876‘ E: 29°11.846‘					
8	x	x	09.02.02	**14:44 start** 15:00 down end 15:05 end	**S: 01°48.607‘ E: 29°10.509‘** S: 01°48.679‘ E: 29°10.352‘ S: 01°48.695‘ E: 29°10.319‘	14.14 km	148 m	-	kivu03_006	Transect profile #6
9	x	x	09.02.02	**15:27 start** 15:38 down end 15:46 end	**S: 01°51.593‘ E: 29°08.086‘** S: 01°51.655‘ E: 29°08.670‘ S: 01°51.688‘ E: 29°08.576‘	20.49 km	148 m	-	kivu03_007	Transect profile #7
10	x	x	09.02.02	**15:56 start** 16:12 end	**S: 01°54.305‘ E: 29°07.734‘** S: 01°54.305‘ E: 29°07.658‘	25.84 km	148 m	-	kivu03_008	Transect profile #8
11	x	x	10.02.02	**11:27 start** 11:33 end	**S: 01°41.789‘ E: 29°13.787‘** S: 01°41.747‘ E: 29°13.796‘			-		In front of lava Tube on probe!!!
12	x	x	10.02.02	**11:38 start** 11:46 end	**S: 01°41.651‘ E: 29°13.680‘** S: 01°41.606‘ E: 29°13.684‘			-		In front of lava
13	x	x	10.02.02	**11:57 start** 12:03 end	**S: 01°41.445‘ E: 29°13.642‘** S: 01°41.400‘ E: 29°13.645‘			-		In front of lava
14	x	x	10.02.02	**12:05 start** 12:17 end	**S: 01°41.265‘ E: 29°13.500‘** S: 01°41.453‘ E: 29°13.741‘			-		In front of lava
15	x	x	10.02.02	**12:34 start**	**S: 01°41.847‘ E: 29°13.933‘**					In front of lava

				12:39 end	S: 01°41.830‘ E: 29°13.931‘					
16	x	x	10.02.02	**12:48** **start**	**S: 01°41.876‘** **E: 29°14.067‘** S: 01°41.853‘ E: 29°14.072‘					In front of lava
17	x	x	10.02.02		**S: 01°41.961‘** **E: 29°14.222‘** S: 01°41.943‘ E: 29°14.223‘					In front of lava
18	x	x	10.02.02	**13:05** **start**	**S: 01°41.883‘** **E: 29°13.914‘** S: 01°41.834‘ E: 29°13.908‘					
19	x	x	10.02.02	**13:19** **start**	**S: 01°41.801‘** **E: 29°13.987‘**					In front of lava Before water sample #2
20	x	x	10.02.02	**13:40** **start** 13:51 13:53 end	**S: 01°41.920‘** **E: 29°13.908‘** S: 01°41.872‘ E: 29°13.911‘ S: 01°41.869‘ E: 29°13.907‘					
21	x	x	10.02.02	**13:58** **start**	**S: 01°42.039‘** **E: 29°14.106‘** S: 01°42.009‘ E: 29°14.115‘ S: 01°41.990‘ E: 29°14.121‘					
22	x	x	10.02.02	**15:36** **start**	**S: 01°41.448‘** **E: 29°13.427‘** S: 01°41.420‘ E: 29°13.410‘ S: 01°41.413‘ E: 29°13.406‘					
23	x	x	10.02.02	**15:52** **start** 16:05 16:10 end	**S: 01°41.721‘** **E: 29°13.505‘** S: 01°41.733‘ E: 29°13.551‘ S: 01°41.738‘ E: 29°13.573‘					

24	x	x	10.02.02	**16:16 start** 16:26 16:31 end	**S: 01°41.556'** **E: 29°13.112'** S: 01°41.598' E: 29°13.186' S: 01°41.633' E: 29°13.230'					
25	x	x	10.02.02	**16:36** 16:45	**S: 01°42.372'** **E: 29°13.663'** S: 01°42.412' E: 29°13.724' S: 01°42.445' E: 29°13.761'					
26	x	-	11.02.02	**09:45 start** 09:59 100m 10:08 200m 10:20 300m 10:33 400m 440m end	**S: 01°49.608'** **E: 29°09.020'** S: 01°49.608' E: 29°09.012' S: 01°49.657' E: 29°09.014' S: 01°49.671' E: 29°09.017' S: 01°49.678' E: 29°09.022' S: 01°49.685' E: 29°09.028' S: 01°49.686' E: 29°09.046'	17.09 km	434 m	x	kivu05_000	Deep profile Before water sample #3 and #4
27	x	-	11.02.02	**12:14 start** 12:24 100m 12:29 200m 12:35 300m 12:42 400m 12:52 13:15 end	**S: 01°48.784'** **E: 29°05.885'** S: 01°48.751' E: 29°05.883' S: 01°48.734' E: 29°05.883' S: 01°48.718' E: 29°05.866' S: 01°48.707' E: 29°05.854' S: 01°48.987' E: 29°05.841' S: 01°48.622' E: 29°05.796'	19.68 km	478 m	x	kivu06_000	Deep profile

28	x	-	11.02.02	 **Start** 14:03 100m 14:06 200m 14:10 300m 400m end	**S: 01°57.642‘** **E: 29°09.981‘** S: 01°57.612‘ E: 29°09.924‘ S: 01°57.607‘ E: 29°09.920‘ S: 01°57.607‘ E: 29°09.896‘ S: 01°57.606‘ E: 29°09.883‘ S: 01°57.593‘ E: 29°09.831‘	30.24 km	408 m	x	kivu06_001	East of island
29	x	-	11.02.02	**15:24** **start** 15:30 100m 15:33 200m 15:36 300m 13:38 down end 15:53 end	**S: 01°59.115‘** **E: 28°59.364‘** S: 01°59.122‘ E: 28°59.351‘ S: 01°59.123‘ E: 28°59.348‘ S: 01°59.128‘ E: 28°59.346‘ S: 01°59.130‘ E: 28°59.347‘ S: 01°59.114‘ E: 28°59.341‘	41.83 km	365 m	x	kivu07_000	W of island
30	x	-	11.02.02	**16:44** **start** 17:04 17:11	**S: 01°36.619‘** **E: 29°03.944‘** S: 01°36.633‘ E: 29°03.971‘ S: 01°36.635‘ E: 29°03.978‘	20.57 km	139 m	x	kivu07_002	Kabuno bay
31	-	x	11.02.02							RBR on ROV in front of lava

- Times are local times (MEZ winter-time + 1hour - **this is SBE+RBR probe time!!!**)
- GPS are WGS84 coordinates in degrees, minutes and decimal minutes; 2nd GPS coordinates as backup available

Table 3.2:

Lake Kivu water samples

Sample #	Date time	Sampling location	Depth [m]	Sample type	Analysis	Comment
1	08.02.02 12:19	S: 01°47.537’ E: 29°11.742’	450	filtrated filtrated + acid raw copper pipe	main ion composition main ion composition isotopes	main basin
2	10.02.02 13:30	S: 01°41.799’ E: 29°13.876’	10	filtrated raw	main ion composition ???	close to lave (30m) water depth: 18m
3	11.02.02 11:15	S: 01°49.687’ E: 29°09.053’	25	filtrated raw copper pipe	main ion composition ??? isotopes	main basin
4	11.02.02 11:30	S: 01°49.679’ E: 29°09.059’	150	filtrated raw copper pipe	main ion composition ??? isotopes	main basin

REFERENCES AND USEFUL LITERATURE

[Citation standard: SPRINGER, Berlin, Heidelberg, New York, Barcelona, Hong Kong, London, Milan, Paris, Singapore, Tokyo]
[If a company is the author of a report or publication, the name of the company is accompanied here by the abbreviation (co)]

BAILAR III JC, BAILER AJ (1999) Risk Assessment – the Mother of All Uncertainties – Disciplinary Perspectives on Uncertainty in Risk Assessment. In: BAILER AJ, MALTONI C, BAILAR III JC , BELPOGGI F, BRAZIER JV, SOFFRITTI M (Eds) Uncertainty in the Risk Assessment of Environmental and Occupational Hazards. Ann New York Acad Sci 895:273-285

BEADLE LC (1974) The Inland Waters of Tropical Africa – An Introduction to Tropical Limnology. Longman Inc, New York, 365 p

BORGINIEZ G (1960) Données pour la Mise en Valeur du Gisement de Méthane du Lac Kivu. Académie Royale des Sciences d´Outre-Mer, Classe des Sciences Techniques, Mémoires in –8°, Nouvelle série XIII(1), Brussels, 110 p

BOTZ R, STOFFERS P, FABER E, TIETZE K (1988) Isotope Geochemistry of Carbonate Sediments From Lake Kivu (East-Central Africa). Chemical Geology 69:299-308

BRANDT A, FERNANDO HJS (Eds.) (1995) Double-Diffusive Convection. Geophysical Monograph 94, American Geophysical Union, Washington, 334 p

BROWNING KA, GURNEY RJ (Eds) (1999) Global Energy and Water Cycles. Cambridge University Press, Cambridge, 292 p

BURKE K, MUELLER G (1963) Dissolved Gases in East African Lakes. Nature 198:568-569

CAPART A (1960) Le Lac Kivu. Les Naturalistes Belge 41:397-417

DAMAS H (1937) La Stratification Thermique et Chimique des Lacs Kivu, Edouard et Ndaleger (Congo Belge). Verh Int Ver Theor angew Limnol 8:51-68

DEGENS ET, KULBICKI G (1973) Hydrothermal Origin of Metals in some East African Rift Lakes. Mineral Deposita 8:388-404

DEGENS ET, VON HERZEN RP, HOW-KIN WONG, DEUSER WG, JANNASCH HW (1973) Structure, Chemistry and Biology of an East African Rift Lake. Geol Rundsch 62:245-277

FOGG PGT, GERRAND W (1991) Solubility of Gases in Liquids – A Critical Evaluation of Gas/Liquid Systems in Theory and Practise. Chichester

FREETH SJ, KLING GW, KUSAKABE M, MALEY J, TCHOUA FM, TIETZE K (1990): Conclusions from Lake Nyos Disaster. Nature 348:201

FYFE WS, PRICE NJ, THOMPSON AB (1978) Fluids in the Earth´s Crust – their Significance in Metamorphic, Tectonic and Chemical Transport Processes. Elsevier, Amsterdam, 383 p

HABERYAN KA, HECKY RE (1987) The late Pleistocene and Holocene Stratigraphy and Paleolimnology of Lakes Kivu and Tanganyika. Palaeogeogr / Palaeoclim / Palaeoec 61:169-197

HALBWACHS M (1993) Purge par Auto-Siphon du gaz Carbonique dissous dans le Lac Monoun (Cameroun): premiers Résultats Expérimentaux. CR Acad Sci Paris 316(II):483-489

HOW-KIN WONG & VON HERZEN RP (1974) A Geophysical Study of Lake Kivu, East Africa. Geophys J R astr Soc 37:371-329

IMBERGER J (Ed) (1998): Physical Processes in Lakes and Oceans. American Geophysical Union, Washington, 668 p

JANNASCH HW (1975) Methane Oxidation in Lake Kivu (Central Africa). Limnol Oceanogr 20:860-864

KANTHA LH, CLAYSON CA (2000) Small Scale Processes in Geophysical Fluid Flows. Academic Press, San Diego, 888 p

KISS R (1966) Le Lac Kivu. Chronique de L´Irsac I(1):20-28

KLING GW, TUTTLE ML, EVANS WC (1989) The Evolution of Thermal Structure and Water Chemistry in Lake Nyos. J Volc Geotherm Res 39:151-165

KRAFFT M & KRAFFT K (1983) La réapparition du lac de lave dans le cratère du volcan Nyiragongo de juin à septembre 1982 (Kivu), histoire, dynamisme, débits, et risques volcaniques. C.R. Acad. Sci. Paris, série II, v. 296, 797-802

KUFFERATH J (1960) Le Méthane du Lac Kivu. Les Naturalistes Belge 41:418-426

LAHMEYER (co), OSAE (co) (1998): Levé Bathymetrique Complet du Lac Kivu. Final Report. République Rwandaise, Ministère des Travaux Publics, Direction de l'Energie et des Hydrocarbures, Kigali, 32 p

LAHMEYER (co), OSAE (co) (1998): Bathymetric Survey of Lake Kivu. Final Report. Republic of Rwanda, Ministry of Public Work, Directory of Energy and Hydrocarbons, Kigali, 18 p

MAMYRIN BA, TOLSTIKHIN LN (1984) Helium Isotopes in Nature. Elsevier, Amsterdam, 273 p

NAKAMURA Y & AOKI K (1980) The 1977 eruption of Nyiragongo volcano eastern Africa, and chemical composition of the ejecta. Bull. Volcanol. Society of Japan, v. 25, no. 2, 17-32

NATIONAL GEOGRAPHIC (1981) Atlas of the World. 5th edition. National Geographic Society, Washington, 383 p

NEWMAN FC (1976) Temperature Steps in Lake Kivu: a Bottom Heated Saline Lake. J phys Oceanogr 6:157-163

NOJIRI Y, KUSAKABE M, TIETZE K, HIRABAYASHI J, SATO H, SHINOHARA H, NJINE T, TANYILEKE G (1992) An Estimate of CO_2 Flux in Lake Nyos, Cameroon. Limnol Oceanogr 38(4):739-752

OECD (1994) Global Change of Planet Earth. Organisation for Economic Co-operation and Development (OECD), Megascience, The OECD Forum, Paris

PEETERS L (1957) Contribution à l'Etude de la Genèse du Lac Kivu. Bull Soc Belg, Etudes Géogr XXVI(1):155-168

POTTIER Y (1978) Première éruption historique du Nyiragongo et manifestations adventives simultanées du volcan Nyamuragira (Chaine des Virunga-Kivu: Décembre 76-juin 77). Musée Royal de l'Afrique Centrale (Tervuren, Belgique) : Rapport annuel du Département de Géologie et de Minéralogie (1977), 157-175

PREUSSAG (co) (1972): Etude Technique Préliminaire – Extraction et Traitement du Méthane Dissous dans le Lac Kivu. Report, Bundesstelle für Entwicklungshilfe / Preussag, Hanover, 149 p

SAARBERG INTERPLAN (co) (1982) Gaz Méthane du Lac Kivu. Etude de Préfactibilité, élaborée pour La Communauté Economique des Pays des Grands Lacs dans le Cadre du Contrat ET/1294, Projet Régional, Tome I & II, Saarbrücken,

SALMON R (1998) Lectures on Geophysical Fluid Dynamics. Oxford University Press, New York

SCHMITZ DM, KUFFERATH J (1955) Problèmes posées par la Présence de Gaz dissous dans les Eaux profondes du Lac Kivu. Académie Royales des Sciences Coloniales, Bulletin des Séances, nouvelle Série 1:326-356.

SCHOBERTH S, TIETZE K (1978) Isolation of Methanogens from Lake Kivu Sediments. International Association of Microbiology Societies. Abstracts of the XII International Congress of Microbiology, Munich, p 160

SCHOELL M, TIETZE K, SCHOBERTH S (1988) Origin of the Methane in Lake Kivu (East-Central Africa). Chemical Geology 71:257-265

SCHLÜTER T (1997) Geology of East Africa. Borntraeger-Verlag, Berlin

STOFFERS P, HECKY RE (1978) Late Pleistocene-Holocene Evolution of the Kivu-Tanganyika Basin. Spec Publs Int Ass Sediment 2:43-55

SUNDQUIST ET, BROECKER WS (Eds.) (1985) The Carbon Cycle and Atmospheric CO_2: Natural Variations Archean to Present. Geophysical Monograph 32, American Geophysical Union, Washington DC, 627 p

TAZIEFF H (1963) Dissolved Gases in East African Lakes. Nature 200:1308

TAZIEFF H. (1977) An exceptional eruption : Mt. Niragongo, Jan. 10th, 1977. Bull. Volcanol. 40-3, 1976-77, 1-12

TAZIEFF H (1979) Nyiragongo, the forbidden volcano (translation from french language text by J.F. Barnard originally published as "Nyiragongo : le volcan interdit", by Editions Flamarion, 1975, Paris), Barron's Educational Series, Inc., Woodbury, New York, 287 pp.

TAZIEFF H (1984) Mt. Niragongo : renewed activity of the lava lake. Jour. Volcan. Geotherm. Res. 20 : 267-280

TAZIEFF H (1988) Lake Nyos – Lake Kivu, Opportunities and Risks for Exploiting Methane. Courier 109:45-47

TAZIEFF H (1995) Nature: 376: 394

TIETZE K (1974) The Lake Kivu Methane – Problems of Extraction and Their Mathematical-Physical Study. Conference Paper, Regional Conference on Petroleum Industry and Manpower Requirements in the Field of Hydrocarbons, United Nations Economic and Social Council, United Nations Economic Commission for Africa, E/CN.14/EP/INF/13, Tripoli, 7 p

TIETZE K, SCHRÖDER L (1975) Rapport Intermédiaire sur le Projet Gaz Méthane du Lac Kivu (Zaïre/Rwanda). Report No 68414, Bundesanstalt für Geowissenschaften und Rohstoffe, Hanover, 25 p

TIETZE K, MAIER-REIMER E (1977) Recherches Mathématiques–Physiques pour la Mise en Exploitation du Gisement de Gaz Méthane dans le Lac Kivu (Zaïre/Rwanda). Report No 76003, Bundesanstalt für Geowissenschaften und Rohstoffe, 2 Volumes, Hanover,180 p

TIETZE K (1978) Geophysikalische Untersuchung des Kivusees und seiner ungewöhnlichen Methangaslagerstätte – Schichtung, Dynamik und Gasgehalt des Seewassers. PhD Dissertation Kiel University, Kiel, VIII p + 149 p

TIETZE K (1980) Expedition zum ungewöhnlichen Kivusee. Umschau in Wissenschaft und Technik, 80(14):438-440

TIETZE K (1980) The Unique Methane Gas Deposit in Lake Kivu (Central Africa) – Stratification, Dynamics, Genesis and Development. Proceedings of the First Annual Symposium on Unconventional Gas Recovery, Society of Petroleum Engineers (SPE) of the American Institute of Mining, Metallurgical, and Petroleum Engineers (AIME) and United States Department of Energy (DOE), Pittsburgh, SPE/DOE 8957:275-287,

TIETZE K, GEYH M, MÜLLER H, SCHRÖDER L, STAHL W, WEHNER H (1980) The Genesis of the Methane in Lake Kivu (Central Africa). Geologische Rundschau 69(2):452-472

TIETZE K (1981) Direct Measurements of the In-Situ Density of Lake and Sea Water with a New Underwater Probe System. Geophysica 17(1-2):33-45

TIETZE K (1981) Permanently Stratified Lakes and Oceans Basins as a Possible Source of Methane for Developing Countries. In: FAZZOLARE RA, SMITH CB (Eds) Beyond the Energy Crisis – Opportunity and Challenge, Volume III (Proceedings of the Third International Conference on Energy Use Management, Berlin), Pergamon Press, Oxford, pp1889-1900

TIETZE K (1987) Results of the German-Cameroon Research Expedition to Lake Nyos (Cameroon) – October/ November 1986. Report No 100470, Bundesanstalt für Geowissenschaften und Rohstoffe, Hanover, 84 p

TIETZE K (1987) A possible explanation of the Lake Nyos (Lake Lwi) gas burst, based on a newly discovered special stratification effect. Conference paper, International Scientific Conference on the Lake Nyos Disaster. Republic of Cameroon, United Nations Economic and Social Council (UNESCO), United Nations Economic Commission for Africa (UNECA), Programme des Nations Unies pour le Développement (PNUD), Yaounde, 3 p

TIETZE K (1987) The Lake Nyos Gas Catastrophe in Cameroon: Cause, Sequence of Events, Consequences. In: GRAF WH, LEMMIN U (Eds) Topics in Lake and Reservoir Hydraulics (Proceedings of Technical Session Cl, XXII Congres, International Association for Hydraulic Research). École Polytechnique Fédéral de Lausanne, Lausanne, pp 93-98

TIETZE K (1991) Potential Hazard and Possible Utilization of Dissolved Gases in Stratified Lakes, Exemplified by Lakes Nyos and Kivu. Verh int Ver Limnol 24(2):1106

TIETZE K (1992) The Need to degas the dangerous Cameroon Lakes Nyos and Monoun and the Main Principles involved. International Union of Technical Associations and Organizations, Bulletin UATI 2:23-26,

TIETZE K (1992) Cyclic Gas Bursts: are they a “usual” Feature of Lake Nyos and other gas-bearing Lakes? In: FREETH SJ, ONUOHA KM, OFOEGBU CO (Eds) Natural Hazards in West and Central Africa. Vieweg-Verlag, Brunswick, pp 97-107

TIETZE K (1992) A Special Physical Stratification Effect: the last Link in the Chain of Causes leading to the Disastrous Fountain Limnic Gas Eruption from Lake Nyos in 1986. Extended Abstract (International Symposium on Hazardous Crater Lakes, International Working Group on Crater Lakes) Institute for Study of the Earth´s Interior, Okayama University, Misasa, pp 9-11

TIETZE K (1996) Artificial Degassing of Gas-rich Lakes – Methods and Dangers. Abstract, Chapman Conference: Crater Lakes, Terrestrial Degassing, and Hyper-acid Fluids in the Environment, Crater Lake, Oregon, 1 p

TIETZE K (1998) Etude de Synthese. In: LAHMEYER (co), OSAE (co) (1998) Levé Bathymétrique complet du Lac Kivu. Final Report, République Rwandaise, Ministère des Travaux Publics, Direction de l'Energie et des Hydrocarbures, Kigali, pp 27-129

TIETZE K (1998) Exploitation of the Methane Layer in Lake Kivu. In: LAHMEYER (co), OSAE (co) (1998) Study Synopsis. Final Report, Republic of Rwanda, Ministry of Public Work, Directory of Energy and Hydrocarbons, Kigali, pp 1-105

TIETZE K (2000) Lake Kivu Gas Development and Promotion-related Issues: safe and environmentally sound Exploitation. Final Report, Republic of Rwanda, Ministry of Energy, Water and Natural Resources, Unit for the Promotion and Exploitation of Lake Kivu Gas, Kigali, pp 1-110

TURNER JS (1965) The Coupled Turbulent Transport of Salt and Heat Across a Sharp Density Interface. Int J Heat Mass Transf 8:759-767

TUTTLE ML, LOCKWOOD JP, EVANS WC (1990) Natural Hazards associated with Lake Kivu and adjoining areas of the Birunga Volcanic Field, Rwanda and Kivu, Central Africa. Report No 90-691, US Geological Survey, San Francisco

UCB (co) (1954) Gaz du Kivu – Rapport des Recherches. Report, Union Chimique Belge (UCB), Brussels

UCB (co) (1971) Gaz du Lac Kivu – Rapport de la Mission confiée á UCB par l`Organisation des Nations Unies pour le Développement Industriel, Contrat ONUDI/UCB No 17/80, Project S75 69/935. Report, Union Chimique Belge (UCB), Brussels

VERBEKE J (1957) Exploration Hydrobiologique des Lacs Kivu, Edouard et Albert (1952-1954) – Recherches Ecologiques sur la Faune des Grands Lacs de l'Est du Congo Belge. Vol III(1), Institut Royal des Sciences Naturelles de Belgique, Brussels, 177 p

Internet Global Volcanism Program, Volcanic activity reports (1971-2001) :
www.volcano.si.edu/gvp/volcano/region02/africa_c/nyamura/var.htm
www.volcano.si.edu/gvp/volcano/region02/africa_c/nyiragon/var.htm