

***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  
Kigali, Rwanda*

***Submitted to***

**SOLIDARITES, Aide Humanitaire d'Urgence**

***105 av Gambetta, 75020 , PARIS.***

## SUMMARY

Nyiragongo volcano, in the eastern RDC (République Démocratique du Congo) 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 flows running 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, village located at only 1.5 km NE of Goma airport, a voluminous lava flows ran through the airport, destroy the central part of Goma city and enter lake Kivu (cf. Fig. 1).

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 clearly indicates that the lava flow which destroyed a part of Goma is 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. Then it must be concluded that the possibility of lava extrusion directly inside of the lake cannot be definitely excluded in future since all the area have been made more fragile by the important fracturing effect of the present rifting phenomenon.

A new type of hazard is now to be taken seriously under consideration in relationship with the existence of high concentration of dissolved gas in the water at depth in the lake. It is necessary to recall here the disaster of Lake Nyos in Cameroon in 1986. In this case, the level of dissolved gas (carbon dioxide) reached a saturation level at some depth of the lake. Bubbles appeared which draw up the over-saturated water and triggering an avalanche process. The whole lake overturned, which resulted in a huge gas burst. Then a mass of dense carbon dioxide just flew as a liquid in the surrounding valley and asphyxiated all the population (1800 casualties).

It must be recalled that the situation at Kivu is quite different from the one at Nyos on a quantitative point of view. At present for instance, the concentration of dissolved CO<sub>2</sub> at a depth of 210 m amounts 10 liters of gas per liter of water at Nyos, the saturation being reached at 14 Lgas/Lwater. The saturation level is then 71.5%. In the case of lake Kivu, and for the CO<sub>2</sub>, the most dangerous layer, located at approximately 280 m depth, shows a concentration of 1.6 Lgas/Lwater, that is a saturation level of 8%. It must be nevertheless consider that the situation is more critical regarding the presence of methane in the lake Kivu. At a depth of 290 m the saturation level amounts 57%. It must also be recalled that the amount of gas dissolved in lake Kivu is by three order of magnitude larger than the amount of gas presently in lake Nyos (300 billions of cubic meters in lake Kivu as compared with 300 millions of cubic meters in lake Nyos).

The existence of a lava flow being running down inside of the lake Kivu is not unprecedented. The figure 2 revealed that historically, large amount of lava reaches the lake on extended area, mainly located on its North-West shore and in the gulf of Kabuno. Moreover it must be pointed out that the water stratification of the gulf of Kabuno presents a particular feature as compared with the main lake Kivu basin (the density at

150 m depth is higher than the density in the main basin at 485 m depth) that could indicate that the level of dissolved gas inside the gulf of Kabuno is by far higher than the one in the main basin.

Nevertheless, the area where the lava flow from the Nyamuragira reached the lake presents a maximum depth and an average slope of the ground which are much lower as compared with those existing in the present Goma lake flow. In fact, the slope of under water ground is exceptionally steep in the vicinity of Goma and reaches the dangerous 300 m depth area eruption at a distance of only 1 km apart from the shore.

Lake Kivu is situated about 18 km S of the Nyiragongo volcano in the western branch of the tectonically and volcanically active East African Rift Zone. It covers an area of around 2400 km<sup>2</sup>, the maximum depth is 485 m and the water volume amounts to 500 km<sup>3</sup>. 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<sup>3</sup> (STP) of carbon dioxide,
- 55 km<sup>3</sup> (STP) of methane,
- 5 km<sup>3</sup> (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 m<sup>3</sup> (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.

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 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. 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<sup>3</sup>,
- 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;

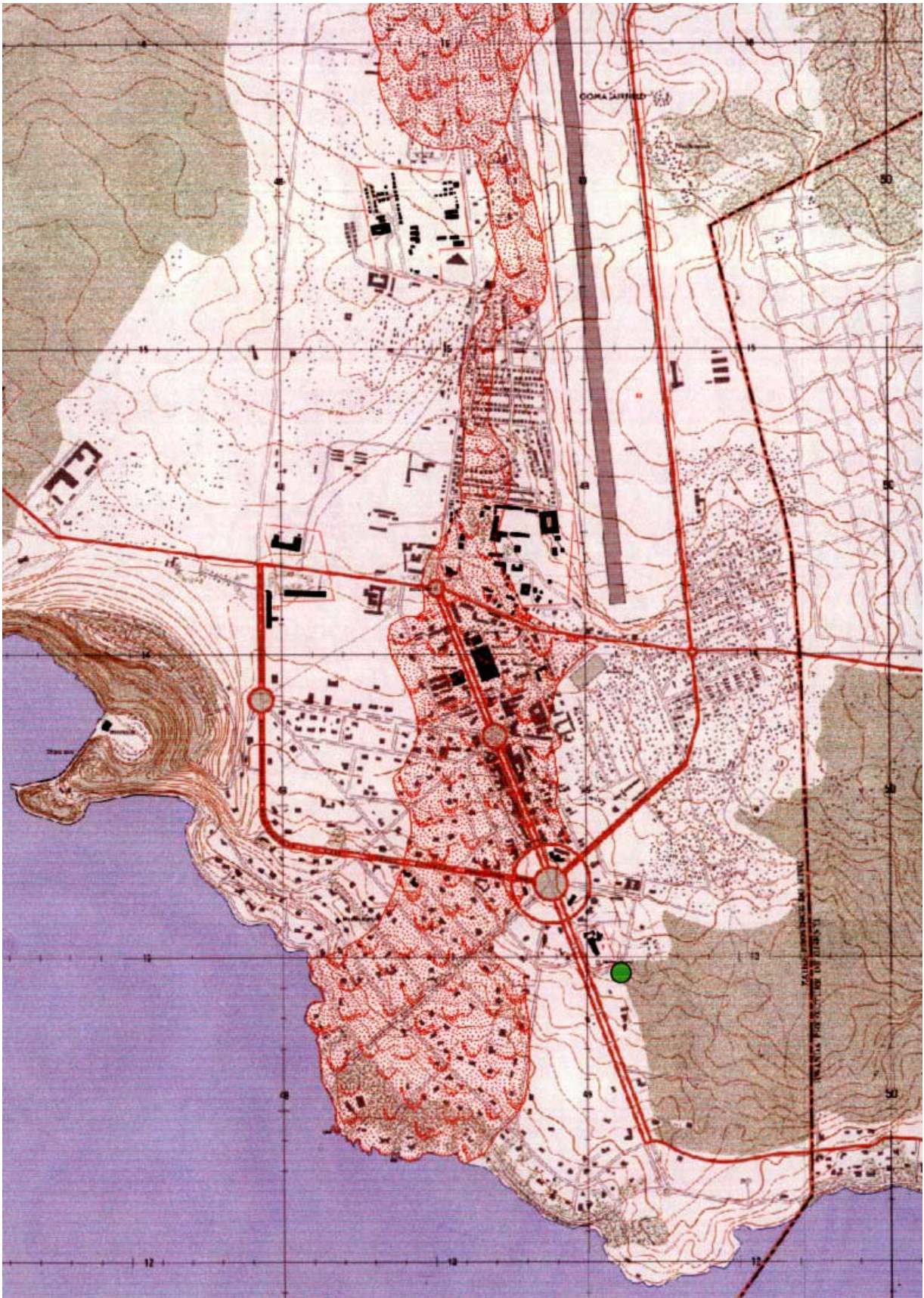
- that long term changes in the lake since the measurements of Tietze in 1974/75 have led to some changes in the stratification pattern as well as in absolute parameter values; it seems that this fact led to a slightly higher stability of Lake Kivu than 27 years ago.

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.

***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 km<sup>2</sup> 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).

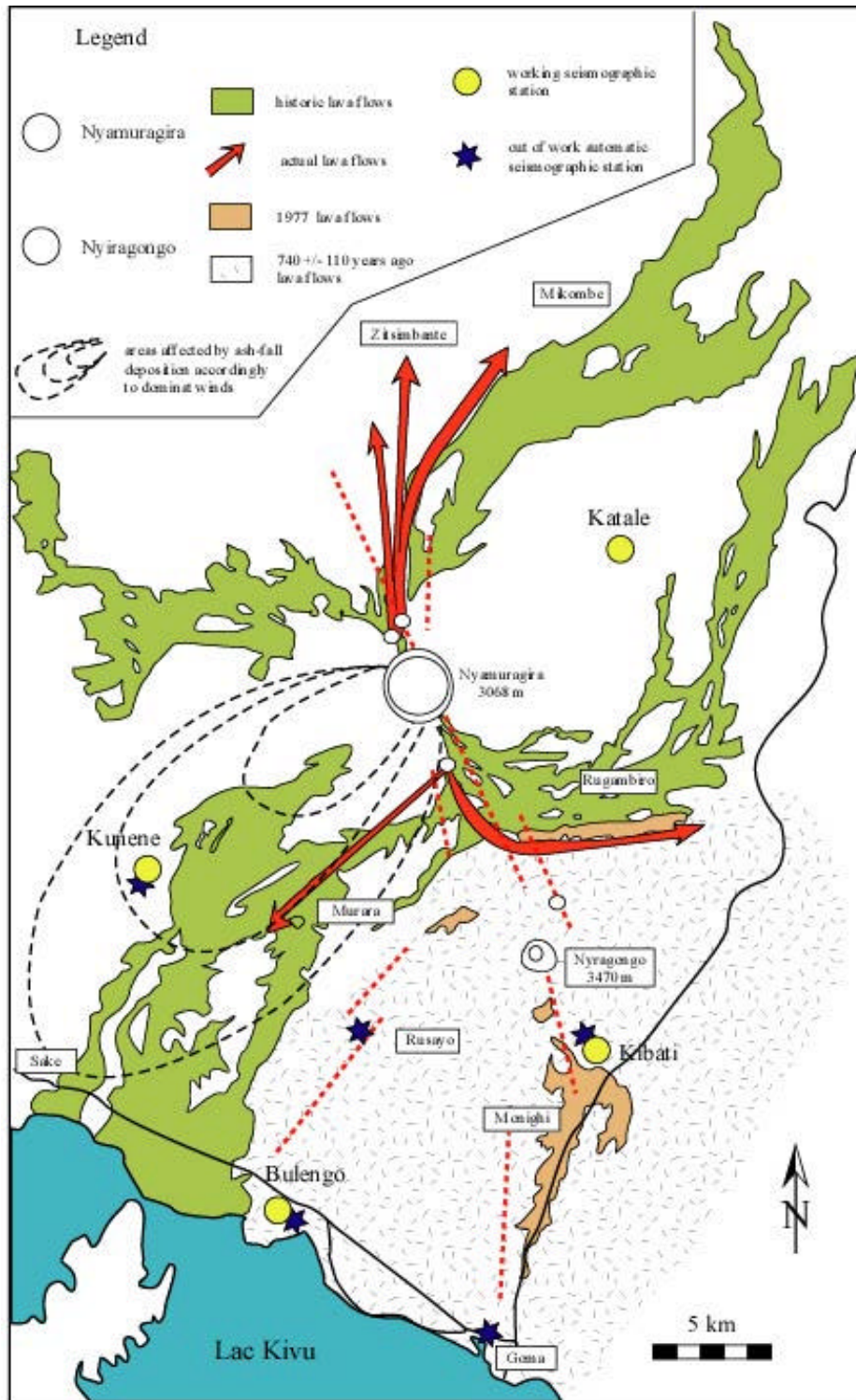
There are some new warnings that the seismic activity could shift below Lake Kivu and that then a major outburst from the lake is to be feared (Tedesco 2002, Interview with International Federation of Red Cross and Red Crescent Societies), but the recommendations which were drawn by representatives of 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 through 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”**

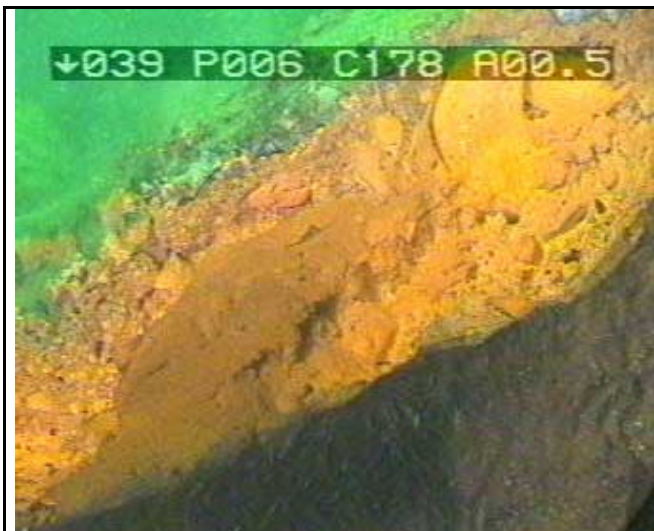


PHOTO 1



PHOTO 2

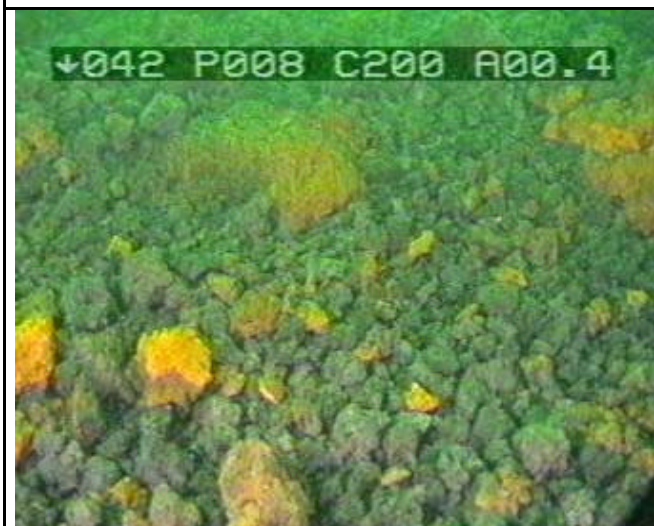


PHOTO 3

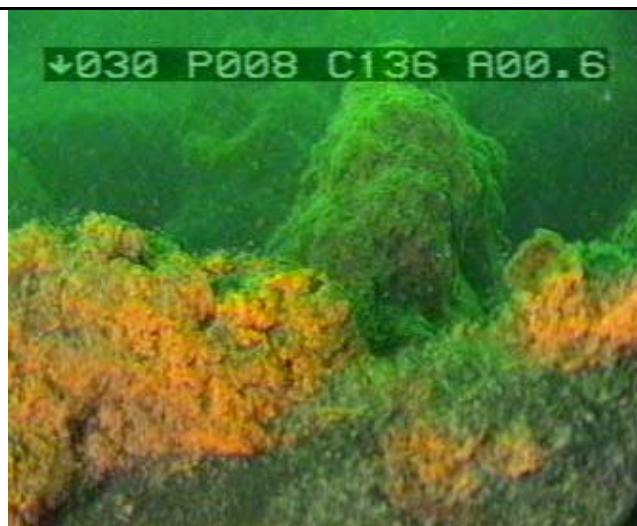


PHOTO 4

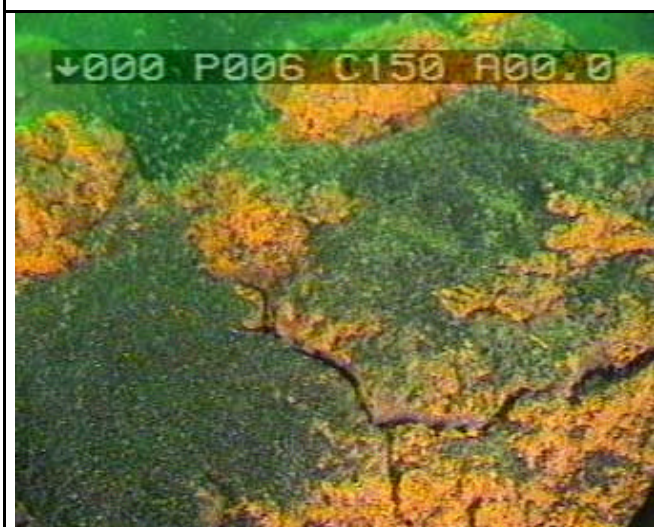


PHOTO 5

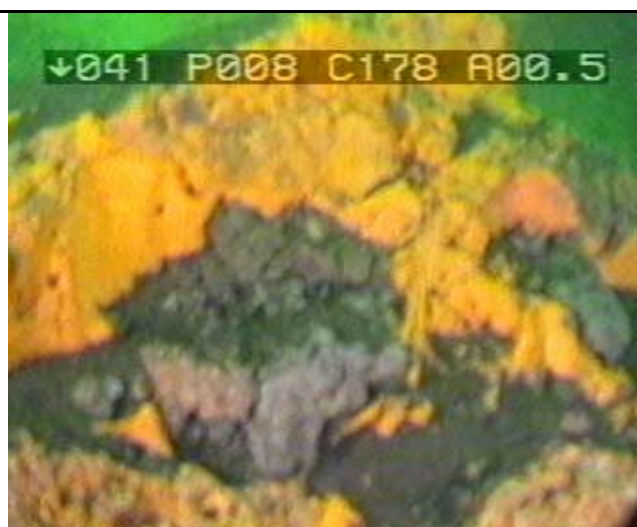


PHOTO 6





PHOTO 7



PHOTO 8



PHOTO 9

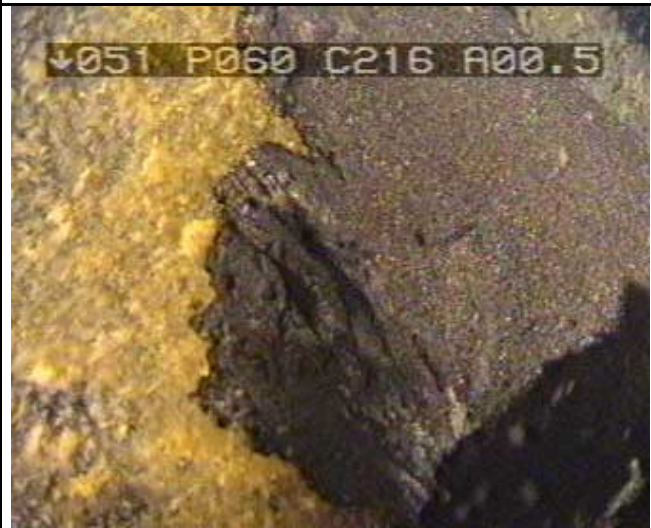


PHOTO 10

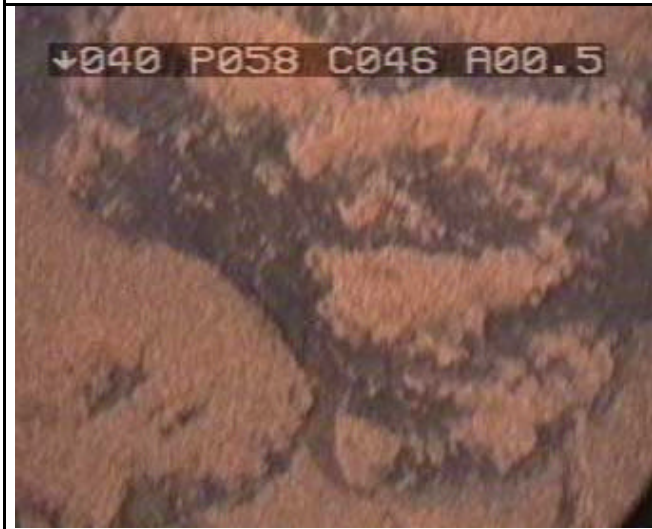


PHOTO 11



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



## 2. 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 far. 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 changes 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:  $5 \cdot 10^5$  m, S:  $1 \cdot 10^7$  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 summary 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 H<sub>2</sub>S.

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, warmer 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 than 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:

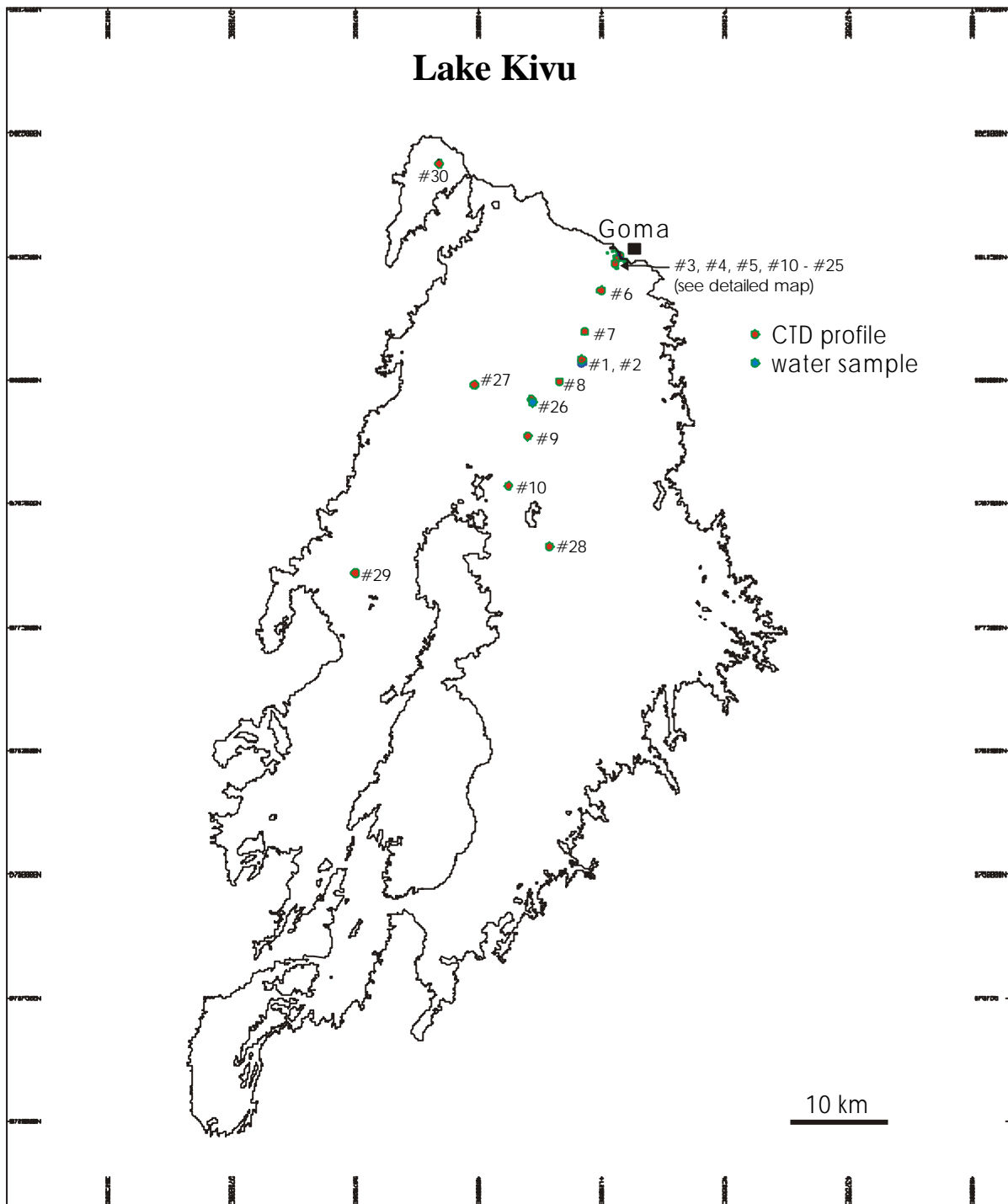
- The one effect is most likely connected to the global greenhouse-effect, which leads to an increase of the temperature at the surface of Lake Kivu. This effect could be seen also in the records from DAMAS (1937) to KISS (1966) to Tietze (1978) to TECHNIP & BRGM (1986) until our recent measurements. 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.

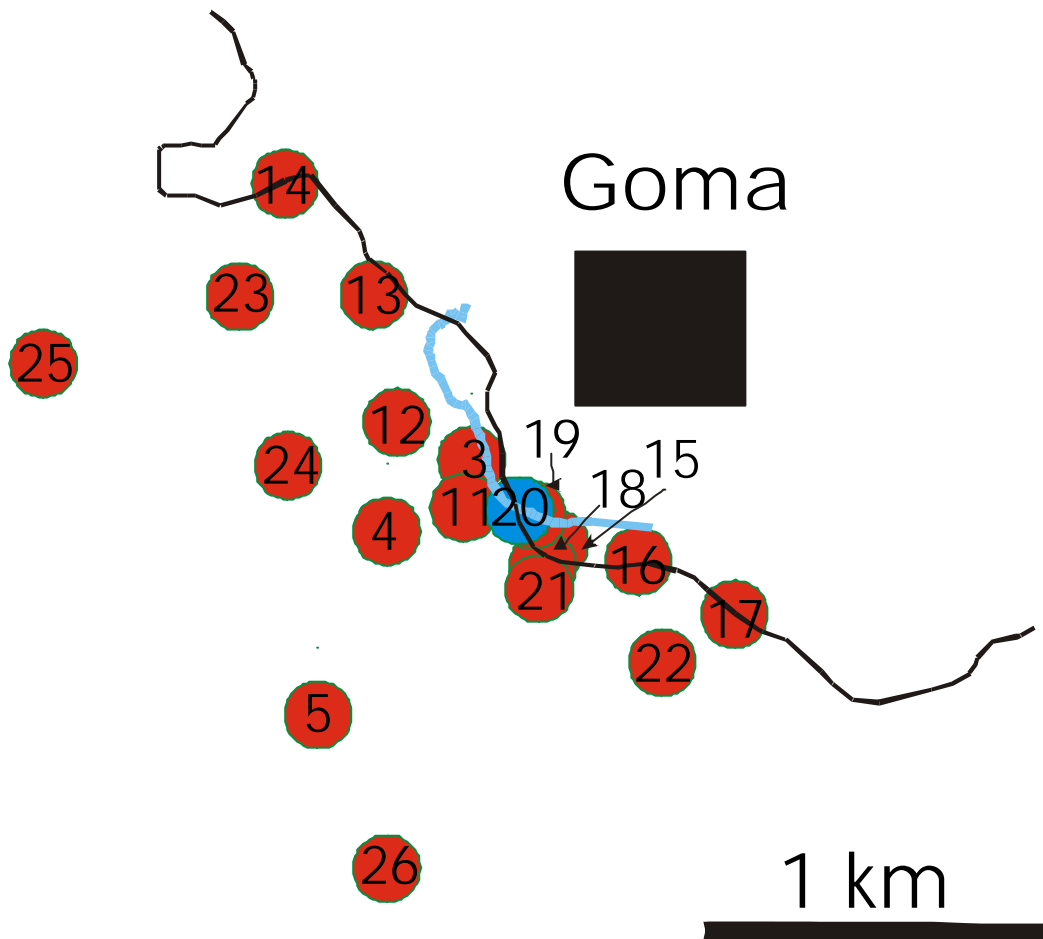
## Outlook

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.

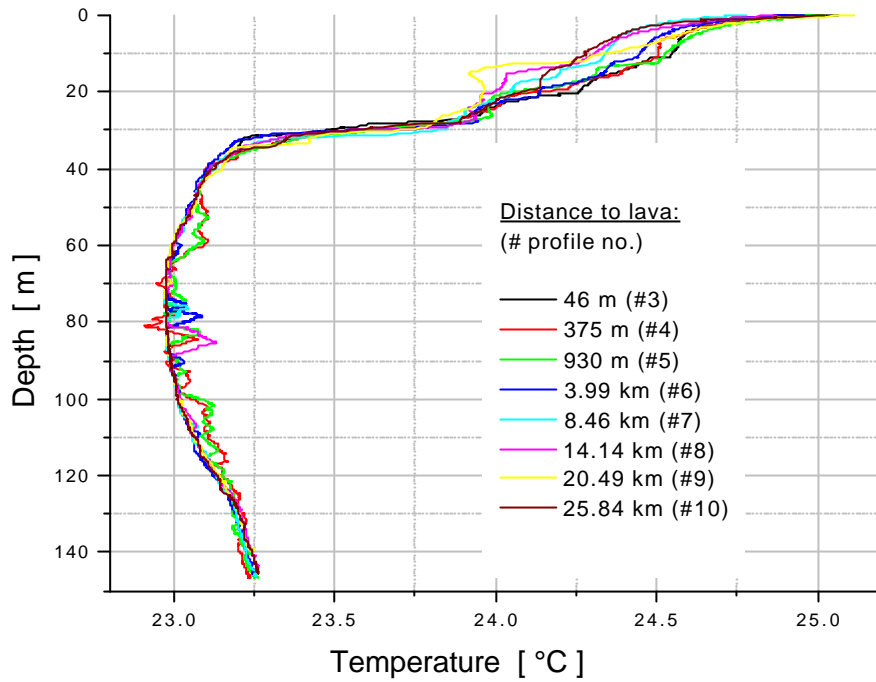


**Fig. 5 : Map of Lake Kivu with indicated CDT and water sampling stations**

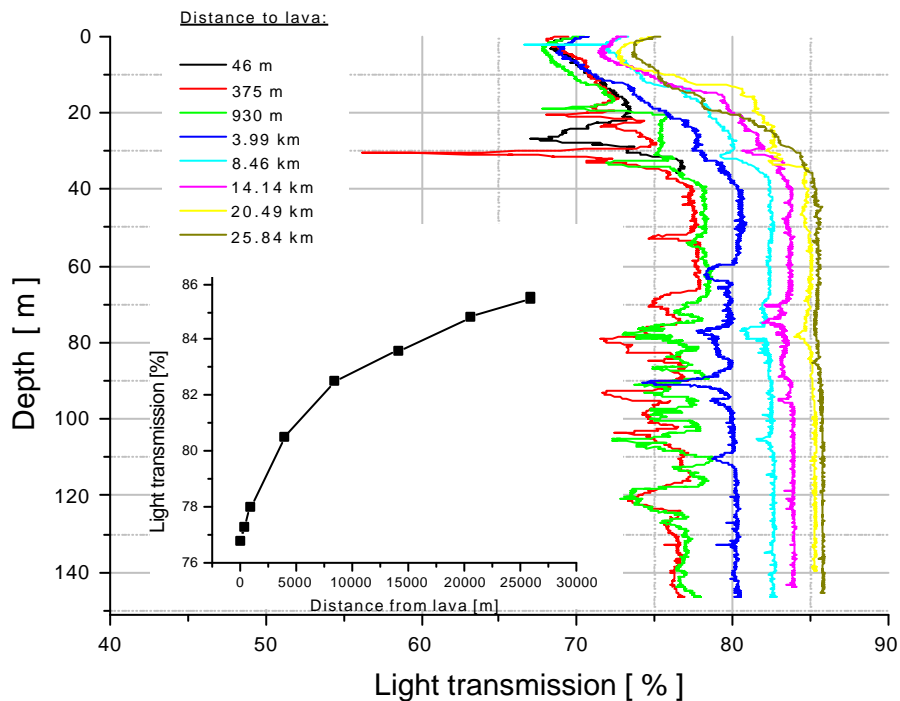


**Figure 6: Detailed map showing the area around the lava inflow. CDT and water sampling stations as well as the GPS based mapping of the new shoreline created by the lava**

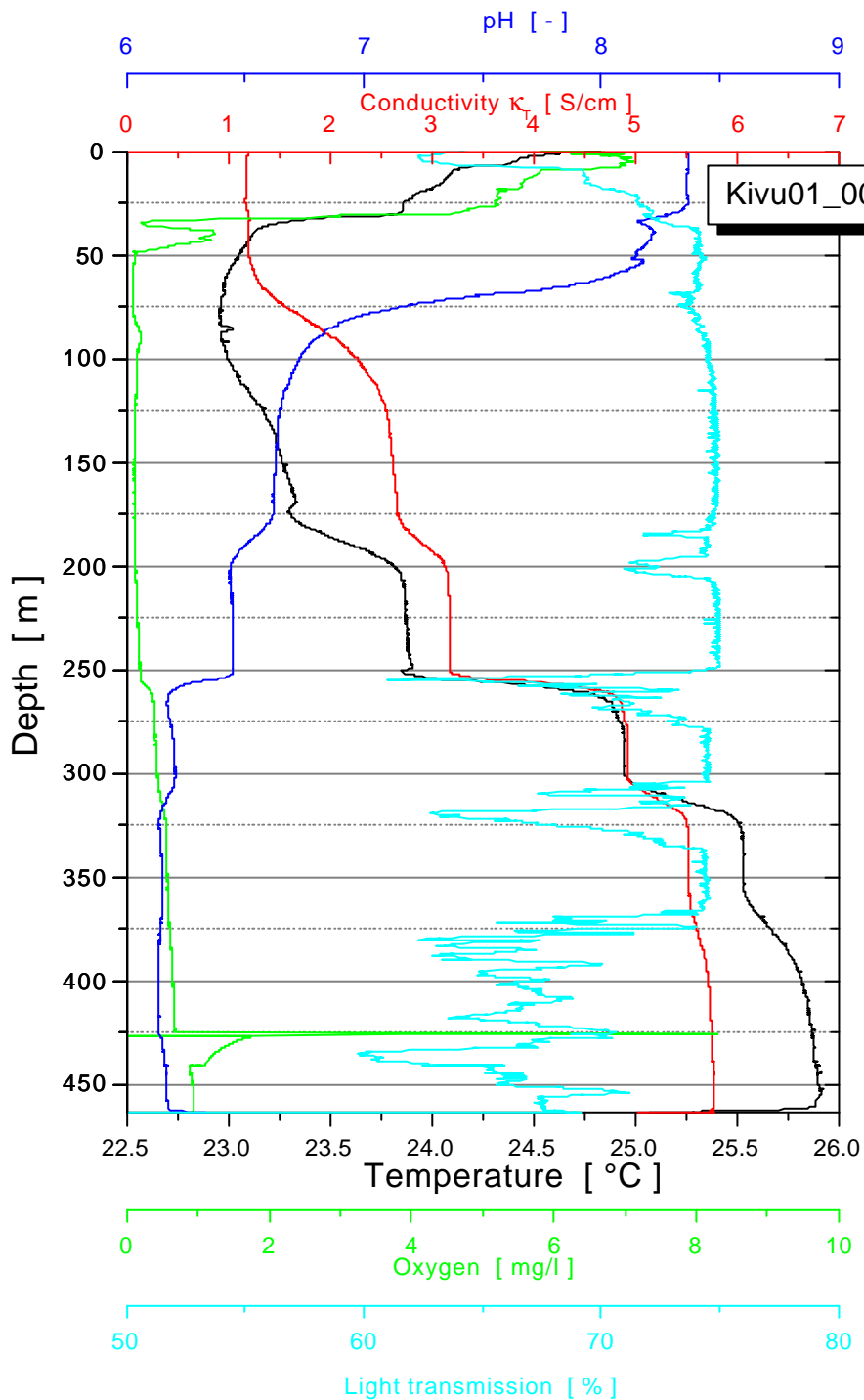




**Figure 7: temperature profiles along the measured transect between the lava inflow and Idjwi Island**



**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**

## 5. CONCLUSIONS

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

- The lava inflow 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 km<sup>2</sup> 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 and 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. 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 km <sup>2</sup>
lake area	≈ 2400 km <sup>2</sup>
lake level (above sea level)	1462-1463 m
discharge rate	≈ 3.2 km <sup>3</sup> /a
maximum depth	485 m
volume	≈ 500 km <sup>3</sup>
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 (Congo). 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.

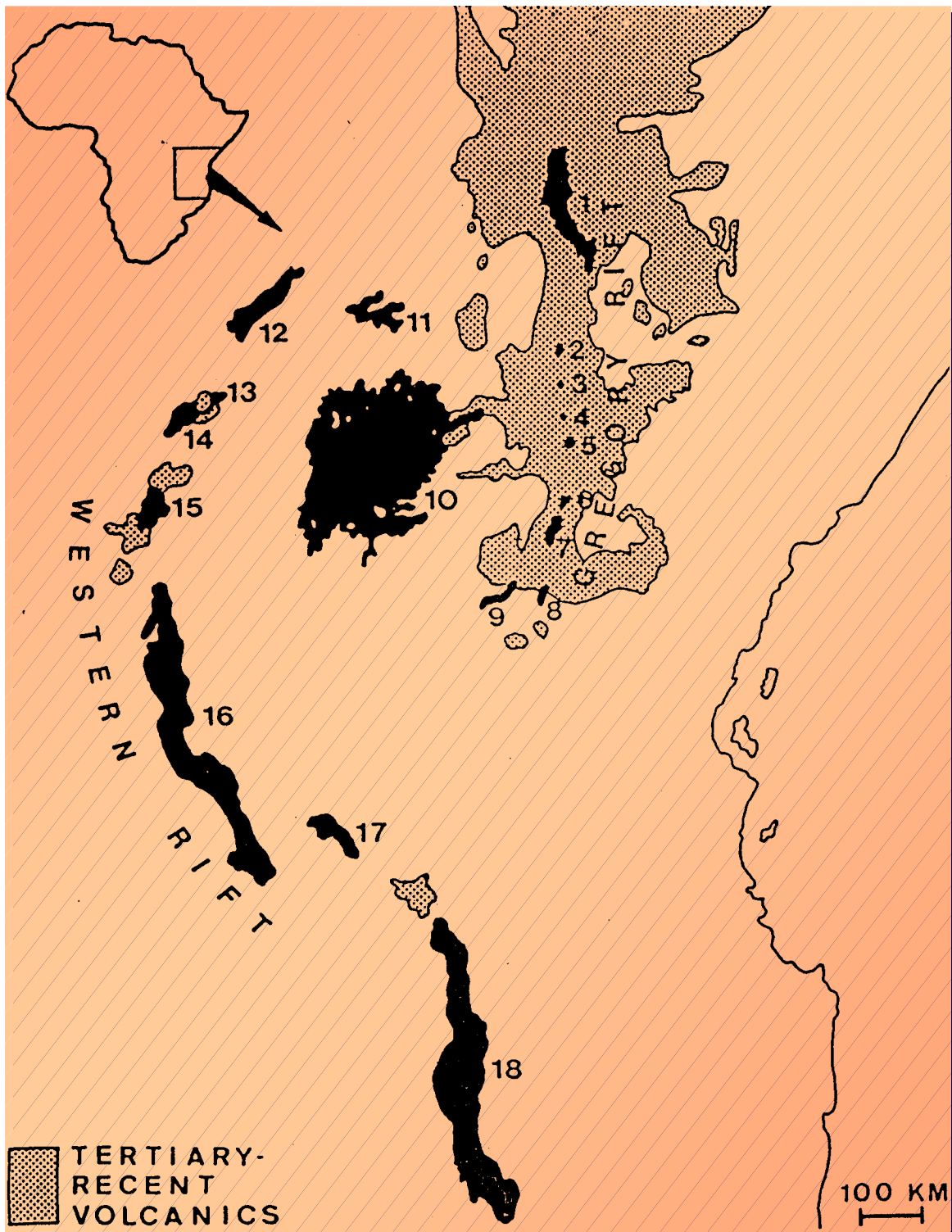
Rain water falling on the high mountains surrounding the Lake Kivu region infiltrates into the ground and recharges the present groundwater. The groundwater flow pattern is determined by the hydraulic pressure conditions, which in turn depend on the topography and the geological features, as well as 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 m<sup>3</sup> of gas-bearing water per year from a depth of 300 m using the natural gaslift principle, demonstrating the unusual quality of the engineering performance. Thus the extracted quantity of methane is around 1.5 million m<sup>3</sup>(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 is given in TIETZE (2000). Unfortunately the limited precision and accuracy of several investigations led to confusing results. Therefore the governments of Rwanda, Zaire 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).

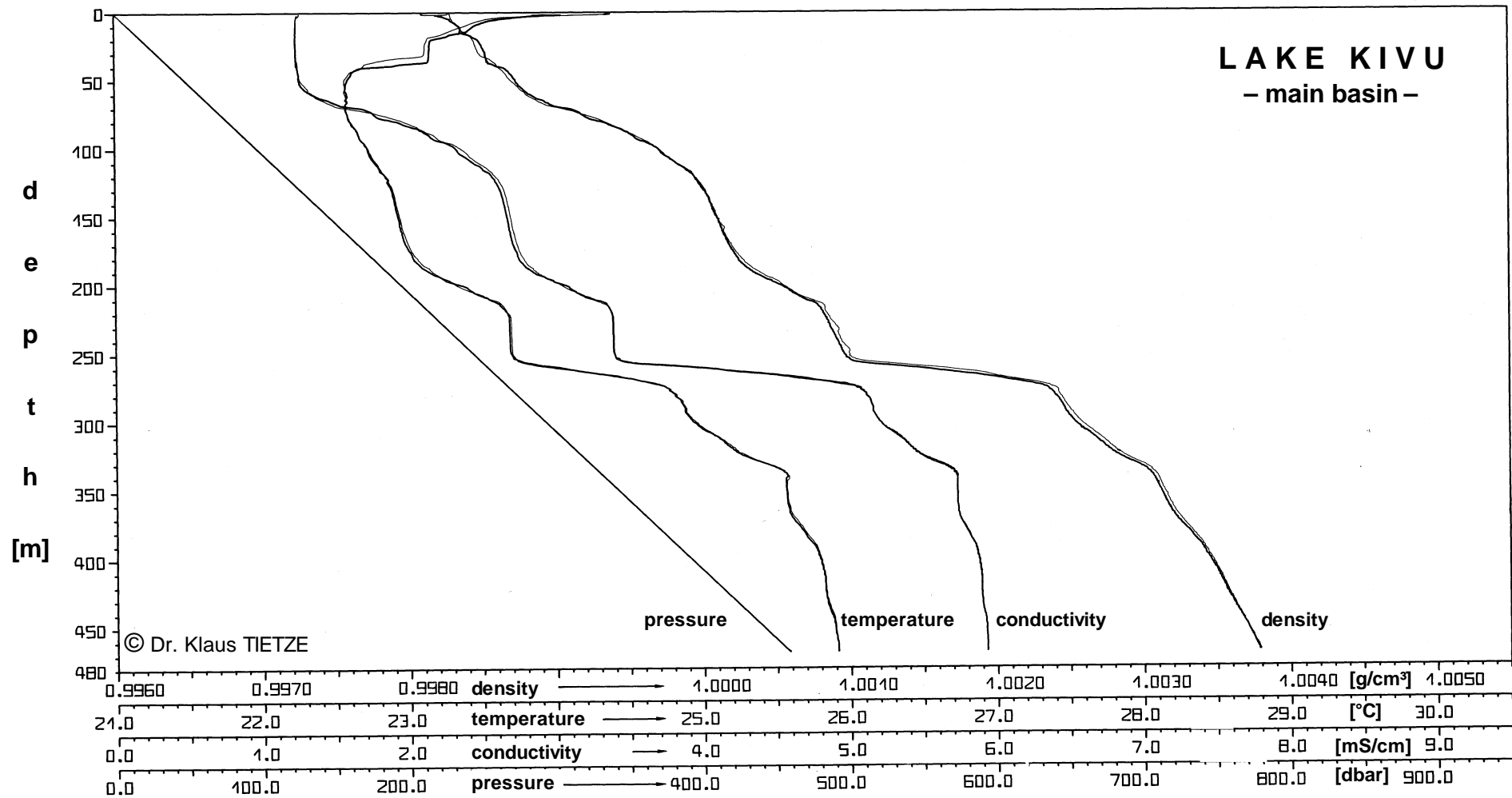
During the research expedition to Lake Kivu in 1974/75 and in the subsequent laboratory investigation on samples, as well as during computer modelling the following work was done, much of it for the first time:

- 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.

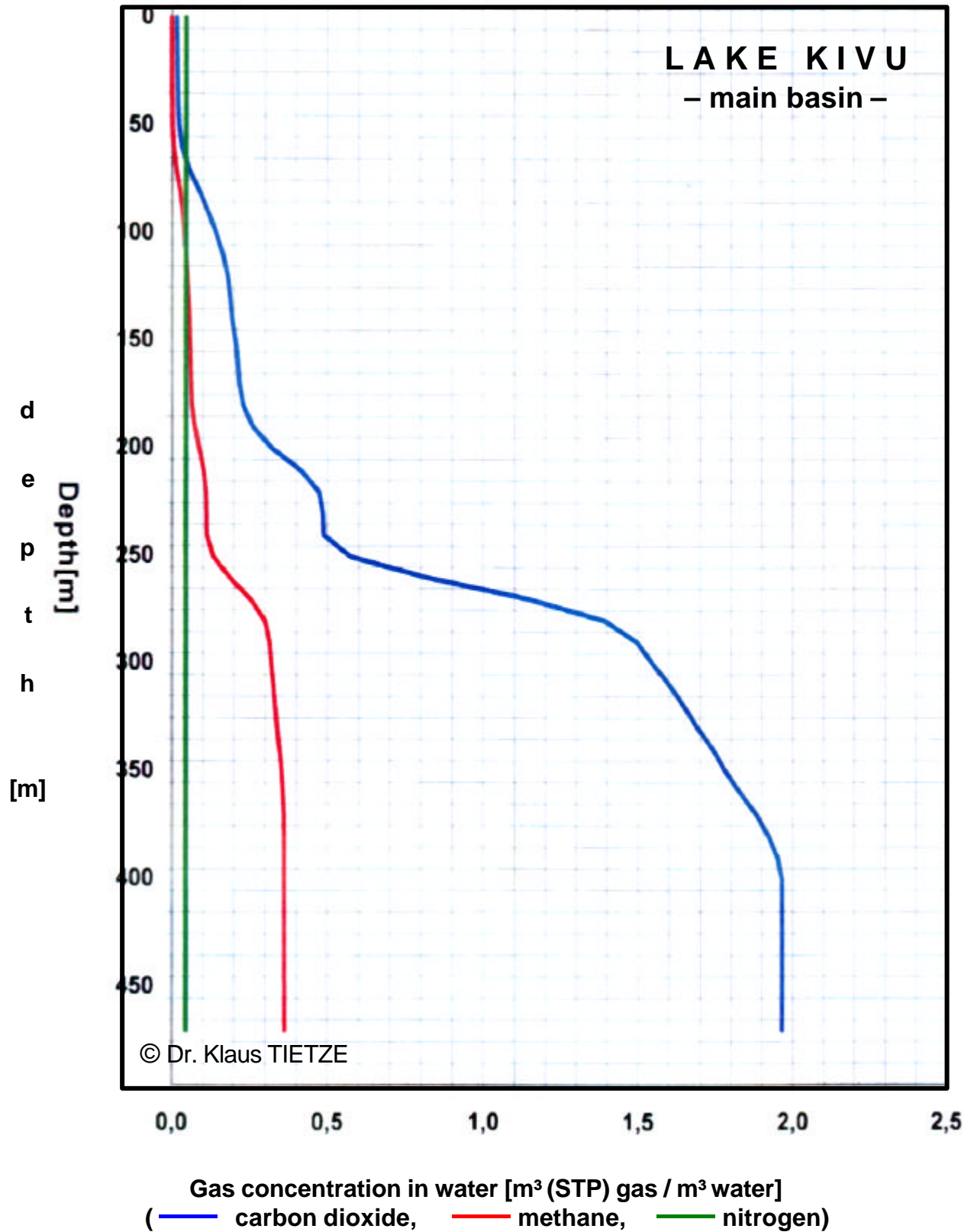
Figure A2.1 shows one vertical profile of parameters measured in the main basin of Lake Kivu. The gas concentration profiles in Figure A2.2 show the same distribution with depth as the density and most of the other parameters. The concentrations of the main dissolved gases each show a maximum near the lake bottom of about 0.35 m<sup>3</sup> (STP) methane / m<sup>3</sup> 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).

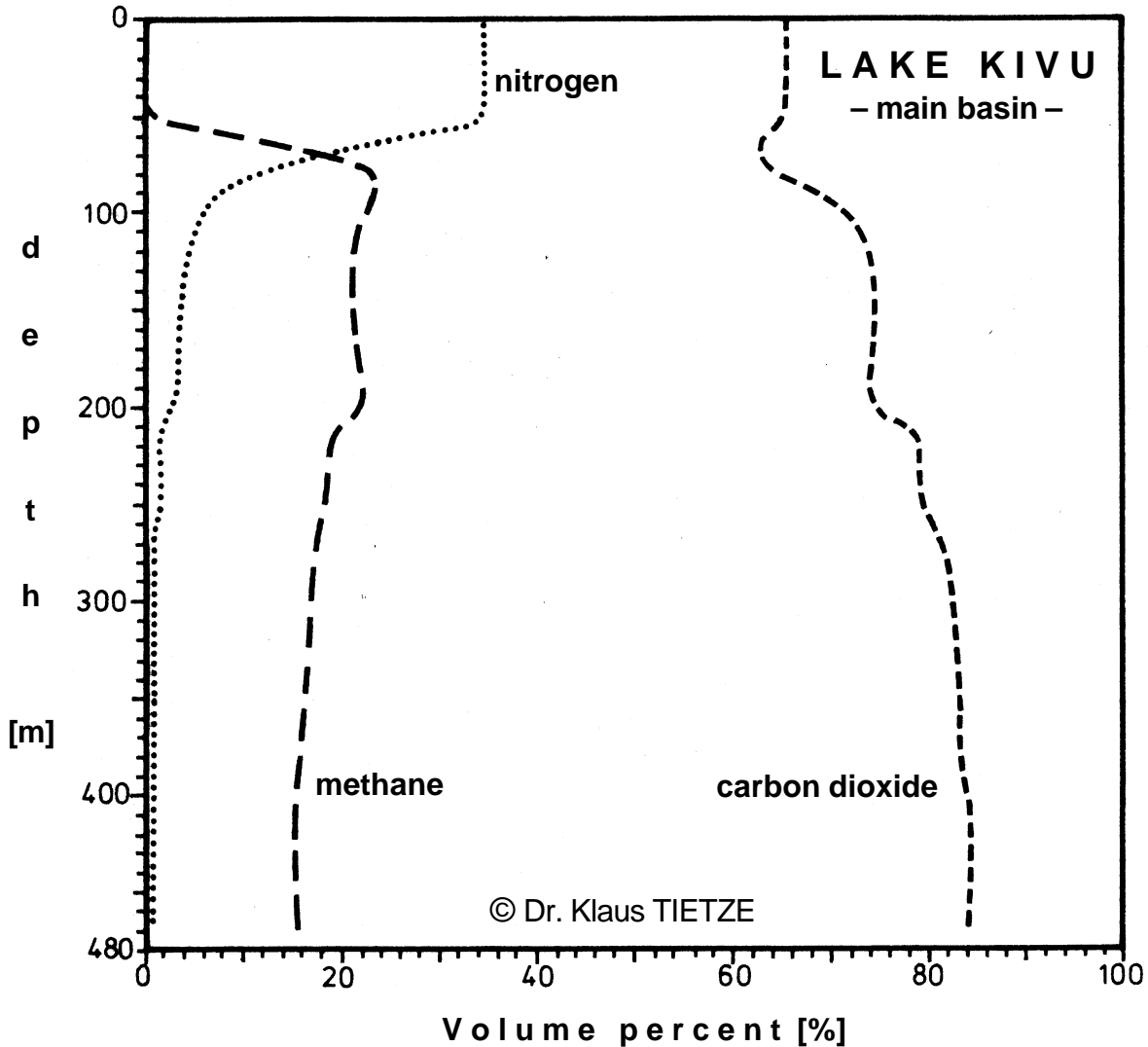
(Figure taken from TIETZE 1978)



**Figure A2.2**

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)

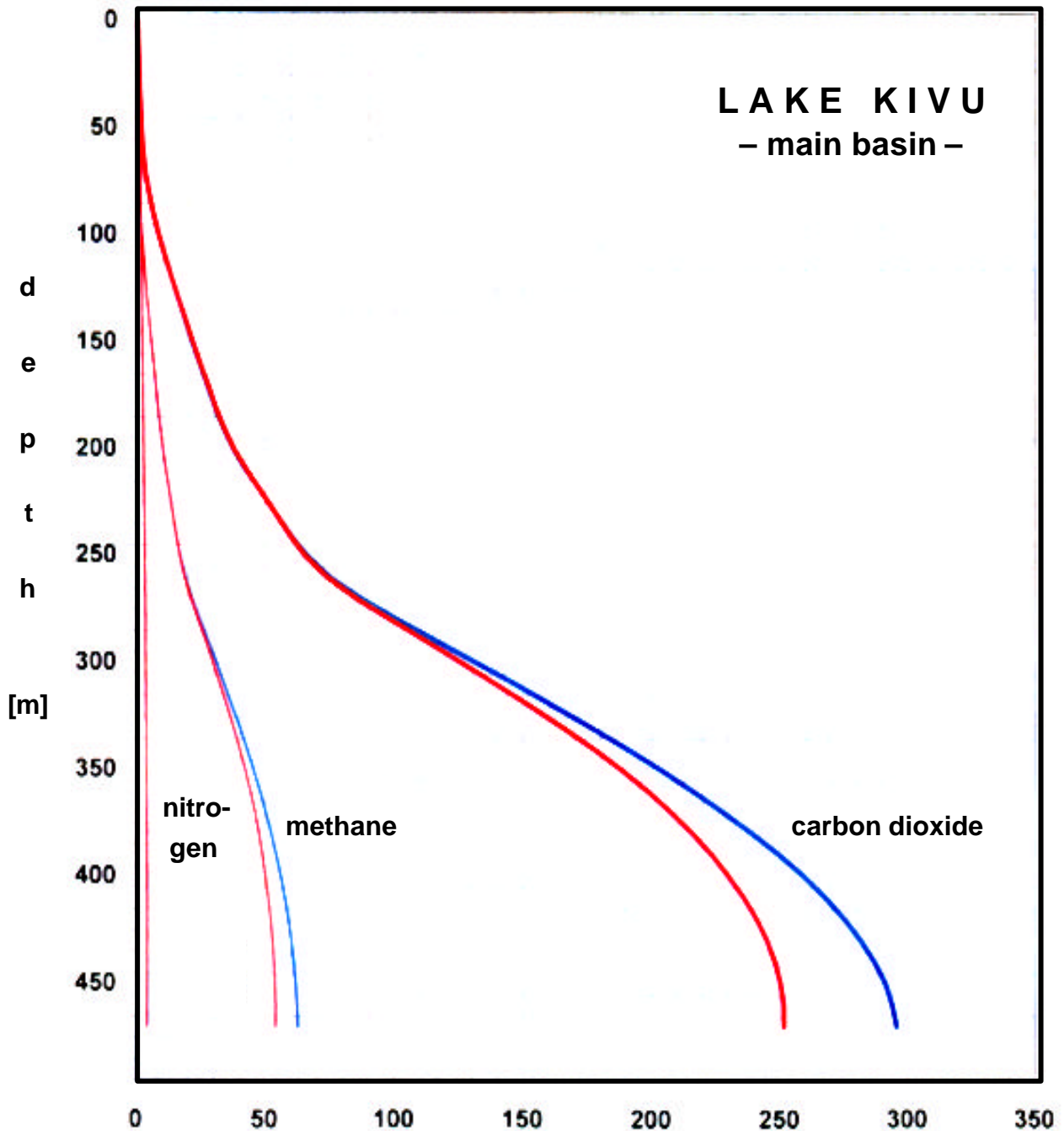


The gas volumes integrated from the surface downwards are shown in Figure A2.4. The calculations are based on the gas concentration data of TIETZE (1978) and the bathymetric maps by CAPART (1960) (blue lines) and LAHMEYER & OSAE (1998) (red lines). The bathymetric measurements of LAHMEYER & OSAE (1998) 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 km<sup>3</sup> (STP) of nitrogen, 55 km<sup>3</sup> (STP) of methane and 250 km<sup>3</sup> (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.

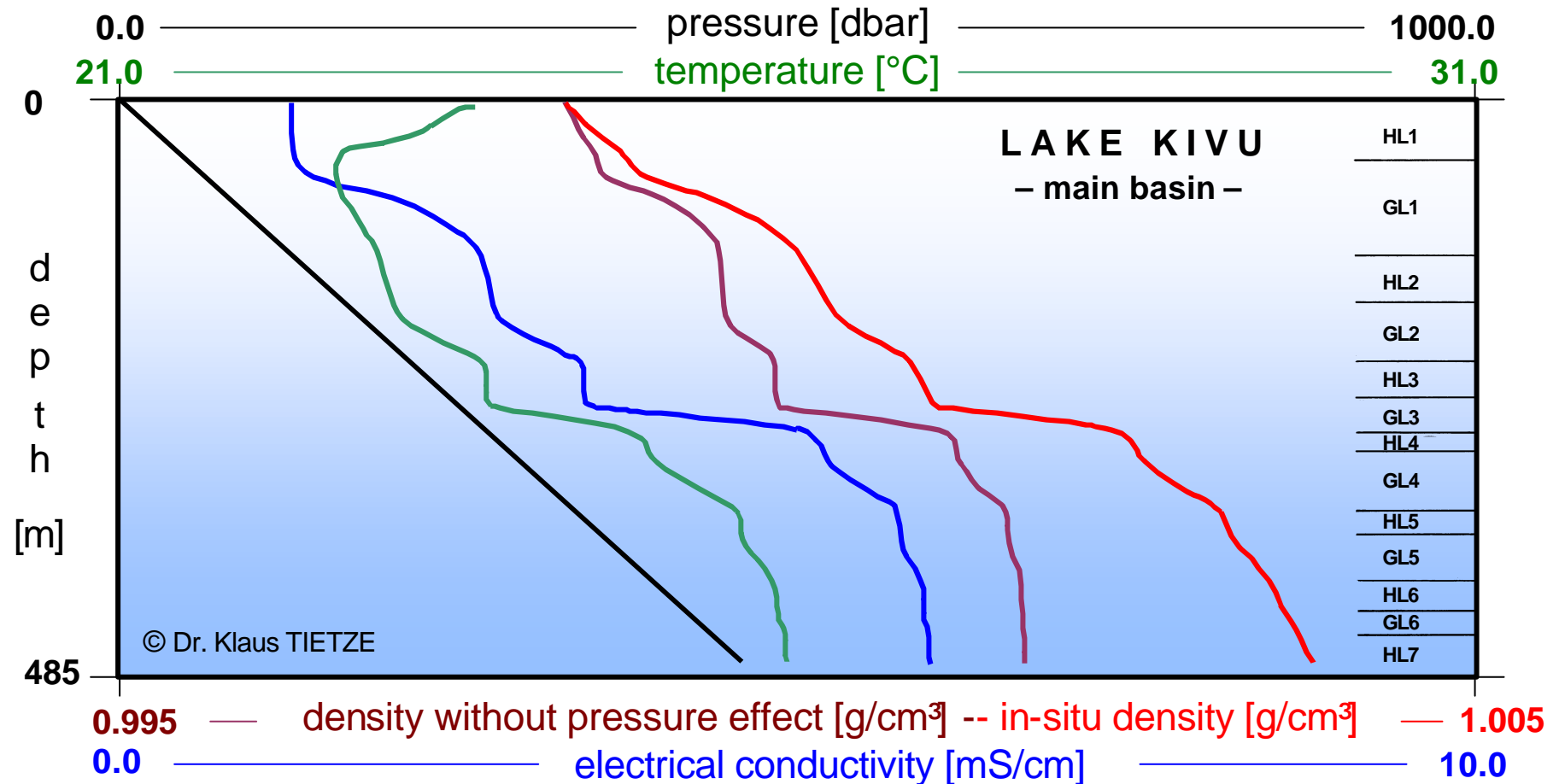


**Figure A2.4**

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))

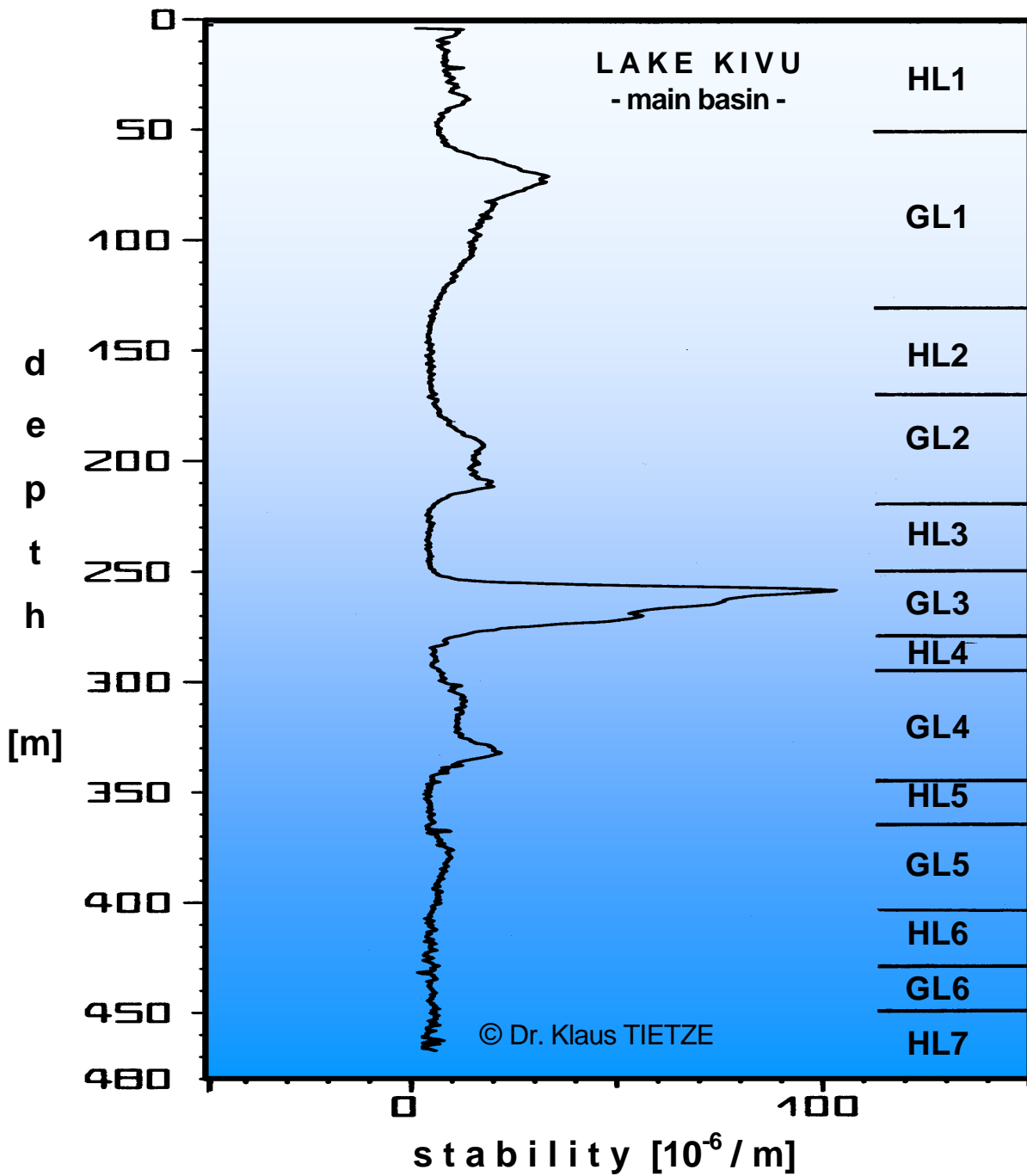


**Figure A2.5**

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)





**Figure A2.6**

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. 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	S: 01°45.852' E: 29°11.883' S: 01°45.872'	8.46 km	148 m	-	kivu03_005	Transect profile #5



				down end 14:32 end	E: 29°11.865' S: 01°45.876' E: 29°11.846'					
8	x	x	09.02.0 2	<b>14:44</b> start 15:00 down end 15:05 end	<b>S: 01°48.607'</b> <b>E: 29°10.509'</b> 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	09.02.0 2	<b>15:27</b> start 15:38 down end 15:46 end	<b>S: 01°51.593'</b> <b>E: 29°08.086'</b> 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	09.02.0 2	<b>15:56</b> start 16:12 end	<b>S: 01°54.305'</b> <b>E: 29°07.734'</b> S: 01°54.305' E: 29°07.658'	25.84 km	148 m	-	kivu03_008	Transect profile #8
11	x	x	10.02.0 2	<b>11:27</b> start 11:33 end	<b>S: 01°41.789'</b> <b>E: 29°13.787'</b> S: 01°41.747' E: 29°13.796'			-		In front of lava Tube on probe!!!
12	x	x	10.02.0 2	<b>11:38</b> start 11:46 end	<b>S: 01°41.651'</b> <b>E: 29°13.680'</b> S: 01°41.606' E: 29°13.684'			-		In front of lava
13	x	x	10.02.0 2	<b>11:57</b> start 12:03 end	<b>S: 01°41.445'</b> <b>E: 29°13.642'</b> S: 01°41.400' E: 29°13.645'			-		In front of lava
14	x	x	10.02.0 2	<b>12:05</b> start 12:17 end	<b>S: 01°41.265'</b> <b>E: 29°13.500'</b> S: 01°41.453' E: 29°13.741'			-		In front of lava
15	x	x	10.02.0	<b>12:34</b>	<b>S: 01°41.847'</b>					In front of lava

			2	<b>start</b> 12:39 <b>end</b>	<b>E: 29°13.933'</b> S: 01°41.830' E: 29°13.931'					
16	x	x	10.02.0 2	<b>12:48</b> <b>start</b>	<b>S: 01°41.876'</b> <b>E: 29°14.067'</b> S: 01°41.853' E: 29°14.072'					In front of lava
17	x	x	10.02.0 2		<b>S: 01°41.961'</b> <b>E: 29°14.222'</b> S: 01°41.943' E: 29°14.223'					In front of lava
18	x	x	10.02.0 2	<b>13:05</b> <b>start</b>	<b>S: 01°41.883'</b> <b>E: 29°13.914'</b> S: 01°41.834' E: 29°13.908'					
19	x	x	10.02.0 2	<b>13:19</b> <b>start</b>	<b>S: 01°41.801'</b> <b>E: 29°13.987'</b>					In front of lava Before water sample #2
20	x	x	10.02.0 2	<b>13:40</b> <b>start</b> 13:51  13:53 <b>end</b>	<b>S: 01°41.920'</b> <b>E: 29°13.908'</b> S: 01°41.872' E: 29°13.911' S: 01°41.869' E: 29°13.907'					
21	x	x	10.02.0 2	<b>13:58</b> <b>start</b>	<b>S: 01°42.039'</b> <b>E: 29°14.106'</b> S: 01°42.009' E: 29°14.115' S: 01°41.990' E: 29°14.121'					
22	x	x	10.02.0 2	<b>15:36</b> <b>start</b>	<b>S: 01°41.448'</b> <b>E: 29°13.427'</b> S: 01°41.420' E: 29°13.410' S: 01°41.413' E: 29°13.406'					
23	x	x	10.02.0 2	<b>15:52</b> <b>start</b> 16:05  16:10	<b>S: 01°41.721'</b> <b>E: 29°13.505'</b> S: 01°41.733' E: 29°13.551' S: 01°41.738'					

				end	E: 29°13.573'					
24	x	x	10.02.0 2	<b>16:16</b> <b>start</b> 16:26  16:31 end	<b>S: 01°41.556'</b> <b>E: 29°13.112'</b> S: 01°41.598' E: 29°13.186' S: 01°41.633' E: 29°13.230'					
25	x	x	10.02.0 2	<b>16:36</b>  16:45	<b>S: 01°42.372'</b> <b>E: 29°13.663'</b> S: 01°42.412' E: 29°13.724' S: 01°42.445' E: 29°13.761'					
26	x	-	11.02.0 2	<b>09:45</b> <b>start</b> 09:59 100m 10:08 200m 10:20 300m 10:33 400m  440m end	<b>S: 01°49.608'</b> <b>E: 29°09.020'</b> 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	-	11.02.0 2	<b>12:14</b> <b>start</b> 12:24 100m 12:29 200m 12:35 300m 12:42 400m 12:52  13:15	<b>S: 01°48.784'</b> <b>E: 29°05.885'</b> 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'	19.68 km	478 m	x	kivu06_000	Deep profile

				end	E: 29°05.796'					
28	x	-	11.02.0 2	<b>Start</b> 14:03 100m 14:06 200m 14:10 300m  400m  end	<b>S: 01°57.642'</b> <b>E: 29°09.981'</b> 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	-	11.02.0 2	<b>15:24 start</b> 15:30 100m 15:33 200m 15:36 300m 13:38 down end 15:53 end	<b>S: 01°59.115'</b> <b>E: 28°59.364'</b> 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	-	11.02.0 2	<b>16:44 start</b> 17:04  17:11	<b>S: 01°36.619'</b> <b>E: 29°03.944'</b> 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	11.02.0 2							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; 2<sup>nd</sup> 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

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