How hazardous is the gas accumulation in Lake Kivu? Arguments for a risk assessment in light of the Nyiragongo volcano eruption of 2002

SCHMID, M., et al.
HOW HAZARDOUS IS THE GAS ACCUMULATION IN LAKE KIVU?
ARGUMENTS FOR A RISK ASSESSMENT IN LIGHT
OF THE NYIRAGONGO VOLCANO ERUPTION OF 2002

MARTIN SCHMID 1 · KLAUS TIEFZE 2 · MICHEL HALBWACHS 3 · ANDREAS LORKE 1,4
DANIEL McGINNIS 3 · ALFRED WÜST 1

1. EAWAG, Limnological Research Center, Seestrasse 79, CH 6047 Kastanienbaum, Switzerland
2. pdt GmbH - Physik-Design-Technik - Sensorik & Consulting, Postweg 3A-6A, D 29227 Celle, Germany
3. Université de Savoie, BP 1104 - Savoie Technolac, F 73376 Le Bourget du Lac Cedex, France
4. Now at University of Constance, Limnological Institute, D 78464 Konstanz, Germany

ABSTRACT

Lake Kivu is a special member in the chain of the East African Rift Lakes. Its deep waters contain high concentrations of dissolved carbon dioxide and methane. On the one hand, the dissolved methane has the potential to become an important energy source for the bordering Republic of Rwanda and Democratic Republic of Congo. On the other hand, the high gas concentrations represent a considerable hazard: the conditions in Lake Kivu resemble those in the Cameroonian crater lakes Monoun and Nyos, where disastrous gas outbursts took place in 1984 and 1986. The eruption of the Nyiragongo Volcano to the north of Lake Kivu in January 2002, which led to the flow of about 10^6 m³ of lava into the lake, renewed the question whether such volcanic activity could trigger a devastating degassing from Lake Kivu. The results of an emergency expedition, which was undertaken shortly after the volcanic eruption, revealed no immediate danger caused by the inflowing lava. Although the probability of a catastrophe is rather limited, the possibility of hot lava-induced deep convection, followed by a disastrous gas outburst, cannot be completely ruled out. The present article provides an overview on the current knowledge of the stability of the stratification of Lake Kivu and its influence on the safety of the lake. Risk assessment arguments based on present day conditions are outlined and discussed.

KEYWORDS: Lake Kivu, carbon dioxide, methane, gas eruption, density stratification, Nyiragongo Volcano.

1. INTRODUCTION

Lake Kivu is situated at 1463 m altitude in the western part of the East African Rift Zone between the Republic of Rwanda and the Democratic Republic of Congo. It has a surface area of 2,370 km², a volume of about 560 km³ and a maximum depth of 485 m (Degens et alii 1973, Tietze, 1978, Spigel and Coulter 1996, Lahmeyer and Osac 1998). Highly active volcanoes border the lake. In January 2002, lava flows from the Nyiragongo Volcano destroyed parts of the city of Goma and entered the lake at the northern shore. A lava flow had previously reached the lake shore in 1948, and a flow from the 1977 eruption had stopped before reaching the city of Goma.

The lake contains unusually high quantities of dissolved gases, mainly carbon dioxide (CO₂) and methane (CH₄). The disastrous outbursts of CO₂ from the crater lakes Monoun (Sigurdsson et alii 1987) and Nyos (Kling et alii 1987, Tietze 1992, Evans et alii 1994) in Cameroon have raised awareness that the high gas concentrations in Lake Kivu may be a considerable hazard for the population living on its shores. However, the dissolved gases are not only a hazard but also a potential resource for the local population: the methane contained in the lake could be exploited as an important and partly renewable energy source. The present article summarizes the current knowledge about the density stratification and the gas concentrations in Lake Kivu and their influence on the safety of the lake. Figure 1 gives an overview of the most important characteristics of Lake Kivu.

2. DENSITY STRATIFICATION OF LAKE KIVU

The most important factor determining the density stratification of lakes is usually the water temperature T. The density ρ(T) of fresh water as a function of temperature can be calculated with the equation of state of Chen and Miller (1986). The water temperature of tropical lakes is always above the temperature of maximum density of 4°C, and density decreases with increasing temperature. When the lake is heated at the surface, the density of the surface water decreases and a stable stratification develops with lighter water overlying heavier water. Conversely, when the surface is cooled, the density increases, the stratification destabilizes and the surface layer is convectively mixed. Wind supplies additional energy for mixing. In other East African lakes, the convective mixing typically reaches depths of 50-200 m once a year during the dry season due to evaporative cooling of the surface water (e.g., Spigel and Coulter 1996). The stratification in the deeper layers of these lakes can be sustained by occasional inputs of cooler water from rivers. This means that most shallow East African lakes are completely mixed every year, whereas in deep lakes the lower water column is permanently stratified and may never or only rarely be reached by seasonal convection.

This simple concept, however, is not sufficient to...
describe the stratification in Lake Kivu. Here, temperature increases with depth below 80 m (Fig. 2), and the stratification would not be stable if the effect of temperature on density were not more than compensated by the effect of dissolved substances. The concentration of dissolved salts, mainly bicarbonates of magnesium, potassium and calcium, increases from 1 g kg\(^{-1}\) at the surface to 6 g kg\(^{-1}\) at 450 m depth. The influence of these salts on the water density can be estimated with the following equation:

\[
\rho(T, S) = \rho(T) \cdot (1 + \beta \cdot S)
\]

The coefficient of haline contraction, \(\beta\), was estimated at 0.75 \(\cdot\) 10\(^{-5}\) kg g\(^{-1}\), based on the measured ionic concentrations, with the method developed by Wüest et alii (1996) for Lake Malawi. This means that an addition of 1 g l\(^{-1}\) salt increases the water density by approximately 0.75 g l\(^{-1}\). The salinity \(S\) [g kg\(^{-1}\)] is calculated from the conductivity at 20°C, \(\kappa_p\) [mS cm\(^{-1}\)] (Fig. 2), with a polynomial function that is also deduced from the ionic composition (Wüest et alii 1996).

Finally, there is the effect of the dissolved gases on the water density, which is opposite for the two main gases in Lake Kivu: \(CO_2\) increases the density of water with a contraction coefficient \(\beta_{CO_2}\) of 0.284 \(\cdot\) 10\(^{-5}\) kg g\(^{-1}\) (Ohsumi et alii 1992), while \(CH_4\) decreases the density with \(\beta_{CH_4}\) = -1.25 \(\cdot\) 10\(^{-5}\) kg g\(^{-1}\), calculated from the partial molar volume of methane of ca. 36 cm\(^3\)/mol (Stoessell and Byrne 1982, Lekvat and Bishnoi 1997). The total density is then approximated by adding the effects of salinity, \(CO_2\) and \(CH_4\):

\[
\rho(T, S, CO_2, CH_4) = \rho(T) \cdot (1 + \beta \cdot S + \beta_{CO_2} \cdot CO_2 + \beta_{CH_4} \cdot CH_4)
\]

The contributions of temperature, salinity and the dissolved gases to the density are shown in Fig. 3, which demonstrates clearly that the stable stratification in Lake Kivu is mainly due to the stabilizing salinity gradient.

The square of the Brunt-Väisälä frequency \(N^2\),

\[
N^2 = -\frac{g}{\rho} \frac{\partial \rho}{\partial z}
\]

is commonly used to describe the stability of the lake stratification. For Lake Kivu, the average density gradient is almost 1 kg m\(^{-3}\) per 100 m depth, and consequently the large-scale \(N^2\) is about 10\(^{-4}\) s\(^{-2}\). In lakes with weaker stratification, the potential density, which includes the effect of adiabatic temperature change, has to be used to calculate \(N^2\), but for Lake Kivu this difference is negligible.

All of these density calculations are based on a small database, namely the ionic composition of a water sample from 150 m depth collected in February 2002, which agrees well with previous chemical analyses by Degens et alii (1973), the conductivity profiles measured after the Nyiragongo eruption in February 2002 (Lorke et alii, 2004), and the concentrations of \(CO_2\) and \(CH_4\) measured in 1974/1975 by Tietze (1978). Vertical profiles of in-situ density were measured in 1974/1975 with a specially developed underwater probe system for in-situ density (Tietze 1978, Tietze 1981). After correcting for the compressibility effect of pressure, these can be compared to the calculated density. For example at 460 m depth, the deepest measured point, the calculated density of 1,002.0 kg m\(^{-3}\) is about 0.3 kg m\(^{-3}\) larger than the corresponding in-situ measured value of 1001.70 ± 0.04 kg m\(^{-3}\). This difference is within the range of the sum of possible changes during the last 30 years, the uncertainty of the calculations and the error of the in-situ measurements.

3. Gas concentrations and partial pressures

Detailed profiles of the concentrations of dissolved gases in Lake Kivu (Fig. 4) were measured in 1974/1975 (Tietze 1978). The total gas content of Lake Kivu was estimated by Tietze (2000) from these concentration measurements and the bathymetry of Lahmeyer and Osae (1998) to 55 km\(^3\) sTP \(CH_4\) (volume of the gas at standard temperature of 0°C and pressure of 1 atm) and 250 km\(^3\) sTP \(CO_2\).

The large amount of gases trapped in the stratified waters of Lake Kivu is a considerable hazard for the population living on its shores. If by some mechanism
a large amount of deep, gas-rich water were lifted to a depth where the gas concentration would be oversaturated, a sudden degassing of CO$_2$ and CH$_4$ from the lake could be triggered. CO$_2$ has a higher density than air, and consequently a layer with a lethal CO$_2$ concentration could be formed over the lake. The 250 km$^2$ of CO$_2$ dissolved in Lake Kivu would be sufficient to cover the whole lake with a >100 m thick layer of CO$_2$. Considering the dense population at the shores of the lake, an eruption of a small portion of this CO$_2$ could be devastating. Similar events with catastrophic consequences occurred at two Cameroonian crater lakes: in 1984 at Lake Monoun where 37 people were killed (Sigurdsson et alii 1987), and in 1986 at Lake Nyos where the CO$_2$ flowed down the valleys and asphyxiated more than 1700 people (Kling et alii 1987, Tietze 1992, Evans et alii 1994, Kusakabe et alii 2000). At Lake Kivu, the consequences of a gas eruption could even be aggravated by the flammability of the CH$_4$.

The minimal requirement for a gas eruption is that the sum of the partial pressures of the dissolved gases locally exceeds the hydrostatic pressure such that bubbles can be formed. To a first approximation, the partial pressure $p$ of a gas can be calculated by multiplying the concentration of dissolved gas with the Henry coefficient $H$ [atm (mol $1^3$)] at standard pressure and the in situ temperature:

$$p_{CO_2} = H_{CO_2} \cdot [CO_2]$$

$$p_{CH_4} = H_{CH_4} \cdot [CH_4]$$

However, there are three second-order effects that should not be neglected for the case of Lake Kivu (Weiss 1974, Stoessel and Byrne 1982, Lekvam and Bishnoi 1997): (1) for real gases, the concentration in the solution is not determined by the partial pressure but by the fugacity $f$, which approaches the partial pressure at low pressures but becomes significantly less than the partial pressure at higher pressures; (2) gas solubility decreases with increasing hydrostatic pressure; (3) gas solubility decreases with increasing salinity. The partial pressure of CO$_2$ is thus calculated from:

$$f_{CO_2} = H_{CO_2}(T,S,R) \cdot [CO_2] \cdot e^{\beta_{CO_2}(T) + \gamma_{CO_2}(T)/R \cdot T}$$

$$p_{CO_2} = f_{CO_2} \cdot e^{-\beta_{CO_2}(T) + \gamma_{CO_2}(T)/R \cdot T}$$

where $P$ is the pressure, $P_a$ is the standard atmospheric pressure, $v_{CO_2}$ is the partial molal volume of dissolved CO$_2$, $\gamma_{CO_2}(T)$ is the second virial coefficient of CO$_2$ (which has a negative value) and $R$ is the universal gas constant (Weiss 1974). The calculation of the partial pressure of CH$_4$ is analogous.

For the case of Lake Kivu, e.g., at 400 m depth, (1) the partial pressure is 22% larger than the fugacity for CO$_2$ and 7% larger for CH$_4$, (2) the hydrostatic pressure effect increases the partial pressure for both gases by 5% and (3) the salinity effect increases the partial pressure by 2.5%. In total these corrections increase the calculated partial pressures at 400 m depth by 32% for CO$_2$ and by 16% for CH$_4$. Figure 5 compares the vertical profiles of the partial pressures of CH$_4$ and CO$_2$ calculated from the measurements by Tietze (1978), to the hydrostatic pressure. Here we assume that the total gas pressure is the sum of the partial pressures of the gases. Even though the CH$_4$ concentrations are 5 times lower than those of CO$_2$, CH$_4$ contributes 80-90 % to the total gas pressure, because it is far less soluble than CO$_2$. The observed gas concentrations are nearest to saturation at 285 m depth, where the partial pressure is about 1.32 MPa, which corresponds to the hydrostatic pressure at 126 m depth (Fig. 5). The risk of an eruption of these gases from the lake will be discussed in section 6.

The source of the methane in Lake Kivu has been studied with isotope methods by Tietze et alii (1980) and Schoell et alii (1988). They concluded that the CO$_2$ is of magmatic origin, and that two thirds of the methane is produced by bacteria reducing this magmatic CO$_2$, with hydrogen from the degradation of sedimentary biomass, whereas one third is produced from organic carbon during the fermentation of organic material in

---


FIG. 3. Vertical profile of water density at atmospheric pressure, including the cumulative effects of temperature $T$, salinity $S$ and the concentrations of CO$_2$ and CH$_4$. There is an additional effect of pressure (not shown) on the in-situ density. For the local stability of the stratification, this pressure effect has to be removed.
the lake sediment (Fig. 1). Tietze (1978) estimated that the CH₄ flux through the gradient zone at 260 m depth is 170 mol s⁻¹. Under the assumption that the gas concentrations in the lake are in a steady state, the residence time of the methane in the lake would then be about 400 years. Jannasch (1975) calculated a residence time of 430 years based on an estimation of the methane oxidation rate at the oxic/anoxic interface. The large residence time suggests that significant changes in the gas concentrations are not to be expected within a few years. However, the steady state assumption has not been proven and could only be ascertained by a long-term monitoring of the gas concentrations in the lake. Tuttle et alii (1990) presented some measurements which seemed to indicate significant changes in gas and salt concentrations within decades. On the other hand, the temperature profile showed only small changes below 250 m between 1975 and 2002 (Lorke et alii 2004).

4. Eruption of the Nyiragongo Volcano in January 2002

The eruption of the Nyiragongo Volcano on 17 January 2002 resulted in a lava flow through the city of Goma and into Lake Kivu (Fig. 1). There was concern that this lava flow into the lake might cause a release of gas from the lake. For this reason, an emergency expedition was undertaken three weeks after the eruption to study the influence of this lava flow on the stratification which yielded the following major results (Lorke et alii 2004):

About 10⁶ m³ of lava had entered the lake and reached a depth of about 100 m. In the upper 140 m, the observed temperature profiles showed disturbances of up to 0.1°C, which were more frequent in the profiles near the lava. These signals were obviously caused by the lava and could be observed up to a distance of 14 km from the lava. No significant changes in the overall stratification were observed, and the temperature at greater depths was not affected. The light transmissivity of the water increased with distance from the lava which indicates that a substantial amount of particulate matter was brought into suspension by the lava flow and by the deposition on the lake surface. The overall stability of the lake was not significantly affected, and it was concluded that a much stronger event would be necessary to trigger a gas outburst from the lake.

5. Changes in the temperature stratification since 1975

Considering the potential hazard connected with the lake, it is important to carefully observe the temporal development of the lake stratification. Figure 6 compares the temperature profile measured by Lorke et alii (2004) to the observations by Tietze (1978). There were two distinct differences between the two profiles:

- the temperature of the top 250 m of the water column had increased by 0.3 to 0.5°C. This warming was probably caused by the warmer climate in the past decades, since similar trends were also observed in other African lakes. In Lake Tanganyika, for example, the temperature of the top 300 m increased by 0.15 to 0.4°C within the past 50 years (Plisnier 2000), which was suggested to have caused a weakening of vertical mixing and primary production (O’Reilly et alii 2003, Verburg et alii 2003).

- there was a further development of the steps in the temperature profile (Fig. 6), which consist of well-mixed layers with a thickness of 20-50 m and steep gradients in between. The cause of the build-up of these steps needs further examination, but it seems probable that a process called double-diffusive convection is involved. Double-diffusive convection can occur in salinity-stratified lakes which are geothermally heated from below. The different molecular diffusivities of heat and salt can then lead to the formation of well-mixed layers with a thickness of a few decimeters to a few meters (Turner 1973, Fernando 1987, Kelley et alii 2003). Such layers had already been observed in Lake Kivu by Newman 1976 and Tietze 1978, and 30 years later at different
6. Risk assessment

There are three main possible risks in connection with the high gas concentrations in Lake Kivu:

1) the gas concentrations could slowly build up in the deep waters until the sum of the partial pressures would locally approach the hydrostatic pressure. A relatively small uplift of water by a strong internal wave could then trigger a gas eruption similar to those of Lake Nyos and Lake Monoun. To rule out this scenario, the gas concentrations in Lake Kivu should be monitored such that significant changes in the gas concentrations would be observed in time and preventive action could be taken. As a first step, gas concentration measurements with similar accuracy and vertical resolution to those of Tietze (1978) should be performed and the observed changes during the last 30 years should be analyzed;

2) a volcanic event could produce sufficient thermal energy to induce a rising plume that would lift water with high gas concentrations to a level where it is oversaturated and bubbles could form. This could then trigger a self-amplifying plume and finally cause a gas eruption. The observations after the Nyiragongo eruption in January 2002 (Lorke et alii 2004) have shown that the flow of $10^6$ m$^3$ lava into the top 100 m of the lake was far too small to cause such a process. The lava did not reach the depths of high gas concentrations, and even in the upper levels, the large-scale stratification was not significantly affected. Local thermal plumes were probably formed, but they would have been completely harmless due to the low gas concentrations at these depths. To assess the risk associated with a potential subaqueous eruption, the rise height of a plume in the stratified water column of Lake Kivu was calculated with a plume model as a function of the heat flux, the diameter and the depth of a circular heat source. The model, which was originally designed for simulating bubble plumes in lakes and reservoirs (Wüst et alii 1992), includes the effects of the lake stratification and of decreased gas solubility in a heated plume. The heat fluxes needed to produce a plume that reaches the level of saturation of the gas concentrations and consequently to the formation of bubbles within the plume are shown in Fig. 7 (heat fluxes per m$^2$) and 8 (total heat fluxes). Simulations were performed with and without entrainment of ambient water into the plume. Entrainment of cooler water with lower gas concentrations slows the plume down and increases the rise height needed to reach saturation. In the simulations, the plume is always horizontally mixed, whereas in a real plume, especially of large diameter, the core will be less affected by the entrained water than the fringe. Simulations with entrainment consequently yield an upper limit for the heat flux, whereas those without entrainment yield a lower limit. The calculated heat fluxes are $> 5$ MW m$^{-2}$ for all depths and source diameters even without the effect of entrainment. Lorke et alii 2004 estimated the heat input to Lake Kivu by the lava flow in 2002 to approximately $2.4 \times 10^{15}$ J. In March 2001, the eruption of Nyamuragira, the other active volcano north of Lake Kivu, produced a radiative energy transfer to the atmosphere of $1.3 \times 10^{16}$ J within 35 days, which is about half the total heat flux (Wright and Flynn 2004). If the total heat from these events would be introduced into Lake Kivu within one day, the average heat fluxes were 28 GW for the 2002 lava flow and 300 GW for the Nyamuragira eruption. Even without entrainment, these heat fluxes would have to be introduced into the lake at 460 m depth within an area of $<56$ m diameter (lava flow of January 2002) or $<170$ m diameter (Nyamuragira 2001 eruption) to produce a dangerous plume (Fig. 8). We conclude that the probability of such a large and concentrated heat input from a magma source within the lake is low. Of course the energy input necessary for the plume to reach saturation would decrease with increasing gas concentrations in the lake;

3) a large amount of gas could be injected into the lake, e.g., by a gas release from the sediments triggered by intruding magma. In this case the rising plume would gain additional buoyancy from the bubbles and the plume rise height would increase. To assess the risk associated with this scenario, the probability of such a gas injection needs to be evaluated and simulations of plume rise heights caused by gas injections need to be performed.

7. Conclusions and outlook

Lake Kivu contains 250 km$^3$ CO$_2$ and 55 km$^3$ CH$_4$, which are a considerable potential hazard for this densely populated region. However, the lava inflow by the Nyiragongo eruption in January 2002 was far from causing a gas
eruption within the lake, and it seems highly improbable that such an eruption could be triggered by a similar lava inflow. A very large subaqueous eruption would be needed to produce a plume that could lead to an eruption. The current knowledge also indicates that the gas concentrations, which were ≤ 48% saturation throughout the whole depth in 1975, change only slowly and that there is consequently no imminent risk of the concentrations approaching saturation. However, the only available detailed profiles of the gas concentrations were made about 30 years ago, and it is important to repeat these measurements to assess the development of the gas concentrations in the last 30 years and the risk of a spontaneous gas eruption. A project that includes such a survey is currently being carried out. In the future, the gas concentrations should be monitored in such a way that significant changes would be observed at an early stage. The most plausible mechanism that could lead to a dangerous destratification in the near future would be a magma-induced injection of gases into the deep waters of the lake. Considering the large population living on the shores of Lake Kivu, the potential impact of a gas outburst from Lake Kivu is enormous. Consequently, even though the probability of an outburst from Lake Kivu currently seems to be low, the volcanic activity in this region must be thoroughly observed and the probability of a subaqueous eruption should be seriously evaluated. The necessity to monitor the development of the gas concentrations in the lake is supported by observations from the sediment record of Lake Kivu: Haberyan and Hecky (1987) have observed several organic-rich layers with different phytoplankton composition within the last 5,000 years of the sediment record. They concluded that these layers resulted from sudden changes in the limnology of the lake due to hydrothermal and volcanic activity.

The total methane content of the lake corresponds to more than 10 times the current annual commercial energy consumption of the Democratic Republic of Congo and Rwanda together (BIA 2003). The methane gas contained in the lake can thus be considered as an important future energy source for the countries bordering Lake Kivu, and there are existing plans for exploiting this huge methane deposit in a safe and environmentally sound way (Tietze 2000). Currently only a small amount of methane is extracted from the lake and used for energy production by a local brewery. An increased exploitation of the methane deposit would reduce the total gas pressure in the lake and consequently the risk of an outburst and would facilitate the implementation of gas concentration monitoring.

Acknowledgements

The authors would like to thank William C. Evans and Samuel J. Freeth for their constructive reviews of an earlier version of this manuscript. The Humanitarian Aid Office of the European Community (echo) funded the 2002 CTD profiles (Figs. 2 and 6).

References


Haberyan K. A. and Hecky R. E. (1987). The late pleistocene and


