Chapter 1
Lake Kivu: Past and Present

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Abstract Lake Kivu, located in the Eastern African Rift, in a dramatic volcanic scenery, has fascinated the local people, inspiring legends; the explorers of the nineteenth century, inspiring romantic reports; and the scientists of the twentieth and twenty-first centuries, inspiring limnological and geochemical research. For some, Lake Kivu is a "killer lake", containing vast amounts of carbon dioxide and methane in its deep, anoxic waters, and it has been compared to Lakes Nyos and Monoun, whose eruptions caused massive animal and human death in Cameroon. Fortunately, methane gas exploitation can help to reduce the eruption risk and at the same time supply an important amount of energy for the benefit of local development. However, the management of the lake resources, including methane harvesting and fisheries, is complex, and particular care must be taken during gas exploitation in order to avoid any negative impacts on the ecosystem and the goods and services provided by the lake.

In this chapter, the history of research on Lake Kivu is summarized, and the major findings that resulted from expeditions by British, Belgian, American, and German researchers are presented.

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1.1 The Beauty and the Beast

> … und plötzlich standen wir auf dem felsigen Ufer einer gewaltigen Wasserfläche. Eine frische Seebrise wehte zu uns herüber, und tosende Brandung, wie die des Meeres, rauschte uns entgegen. Der Wasserspiegel erstreckte sich unabsehbar und unbegrenzt für unser Auge weithin nach Süden. Zu den bisher von uns geschauten Wundern dieser herrlichen Länder, zum Kigeri und Kirunga, hatte sich ein drittes gesellt, der Kivu.[1]

Many travellers must have reacted in the same way as Count von Götzen (1895), when their eyes first opened on Lake Kivu. Yet this romantic view is in strong contrast with a local legend about the creation of the lake (Pagès 1920): A farmer was given a bull by the god Imana, but had to promise that he would keep the donation secret. While he was away from his home, his wife betrayed the secret. Imana punished the farmer by inundating his land, and only a few islands jutted out of the vast expanse of water that was now Lake Kivu. It is plausible to assume that this tale relates to the lake's turbulent geological history which is rich in volcanic activity and lake level changes. Indeed, Lake Kivu is both a beauty and a beast, the spectacular landscape and the blue colour of its waters may easily distract from the fact that huge amounts of gases are hidden beneath its surface, with the potential of creating one of the largest natural disasters in the history of humanity.

The catastrophic gas eruptions that occurred in Lake Monoun in 1984 (Sigurdsson et al. 1987) and in Lake Nyos in 1986 (Kling et al. 1987; Sigvaldason 1989) demonstrated the destructive potential of limnic gas eruptions. The deep waters of these lakes are fed by springs containing large concentrations of dissolved carbon dioxide (CO_2). Because of the permanent stratification, the gases cannot escape to the atmosphere, and the lakes are continuously charged with CO_2-rich water until the gas pressure reaches the hydrostatic pressure at some depth (Tietze 1992). At this point, CO_2 bubbles can nucleate and grow and thus lead to a gas eruption from the lake (Zhang and Kling 2006). As the CO_2 released is denser than air, it displaces the air on the lake surface and downstream of the lake, asphyxiating people as well as animals (Kling et al. 1987).

A similar situation is found in Lake Kivu, but on a much larger scale. However, in Lake Kivu, the gas pressure is mainly due to the dissolved methane (CH_4) which is much less soluble than CO_2 (Schmid et al. 2004). A gas eruption from Lake Kivu would therefore be caused primarily by the dissolved CH_4. Still, the erupting gas mixture would be composed mainly of CO_2 that would be stripped from the water by the CH_4 bubbles. Such a gas eruption from Lake Kivu would potentially have much more dramatic consequences as in Lake Nyos or Monoun. However, currently the maximum total gas pressure in the lake, calculated from the gas concentrations (Fig. 10.1) as described by Schmid et al. (2004), reaches only about 55% of saturation.

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[1] English translation: … and suddenly we stood on the rocky shores of a huge expanse of water. A fresh lake breeze blew toward us, and roaring waves like those of the sea, swept towards us. The water surface extended far southward, invisible and infinite for our eyes. To the previous wonders of these marvellous countries, to the Kigeri and the Kirunga, a third one was added: the Kivu.

Schmid et al. (2004) estimated that a large magmatic eruption within the lake would be required to trigger a gas eruption. But a more thorough analysis of this risk still remains to be done, while CH_4 concentrations seem to be increasing in the deep waters of the lake (Schmid et al. 2005; Pasche et al. 2011).

Managing Lake Kivu is therefore a difficult challenge, as the beast needs to be tamed without destroying its beauty. The gases need to be removed from the lake to avert the danger of an eruption. At the same time the goods and services provided by the ecosystem, in particular the fishery, need to be preserved. To complicate matters further, Lake Kivu is also unique in its limnological and geochemical features. A thorough understanding of these complexities is essential as a base for sustainable management of the lake. This book aims at presenting the current knowledge about the physics, biogeochemistry and ecology of Lake Kivu, based on research conducted at Belgian universities (University of Namur, University of Liège, University of Brussels) and at Eawag, Switzerland, in collaboration with the "Institut Supérieur Pédagogique" of Bukavu, DR Congo, and the National University of Rwanda at Butare, in the beginning of this twenty-first century.

1.2 History of Lake Kivu Research

Well hidden in the highlands of East Africa, Lake Kivu for a long time escaped the attention of European explorers, even though it had already been the centre of a local trading system between Rwanda and societies living to the west of the lake (Newbury 1980). It seems that the first account of the existence of Lake Kivu was reported by J. H. Speke (1863), but the first European to see Lake Kivu was Gustav Adolf von Götzen, after his famous crossing of Rwanda with a caravan of 620 people, among which 400 carriers. He left a detailed account of his expedition (von Götzen 1895), which describes the difficulties of exploration at that time, but also conveys his amazement at discovering the marvels of this part of Africa. The scientific interest in the East African Great Lakes further increased with the English expeditions at the beginning of the twentieth century (Cunnington 1920). An inventory of several lakes attracted attention on the poverty of Lake Kivu fish fauna: only 23 species, among which 4 endemic, were recorded at that time. The low fish diversity was attributed to high salinity.

A first analysis of water samples from Lake Kivu as well as from hot springs south of Gisenyi was published by Hundshagen (1909). However, it is only in the 1930s that a Belgian expedition, led by Hubert Damas (Fig. 1.1; Damas 1937), gathered the first comprehensive limnological data from Lake Kivu. Among other things, Damas' publication presents detailed evidence of the meromictic character of the lake and of the presence of large amounts of dissolved gases and nutrients in the deep waters. Damas' work was remarkable in many respects: whereas other scientists involved in research projects on East African lakes at the beginning of the twentieth century were largely motivated by the opportunity of making inventories of the flora and the fauna, Damas – a zoologist from the University of

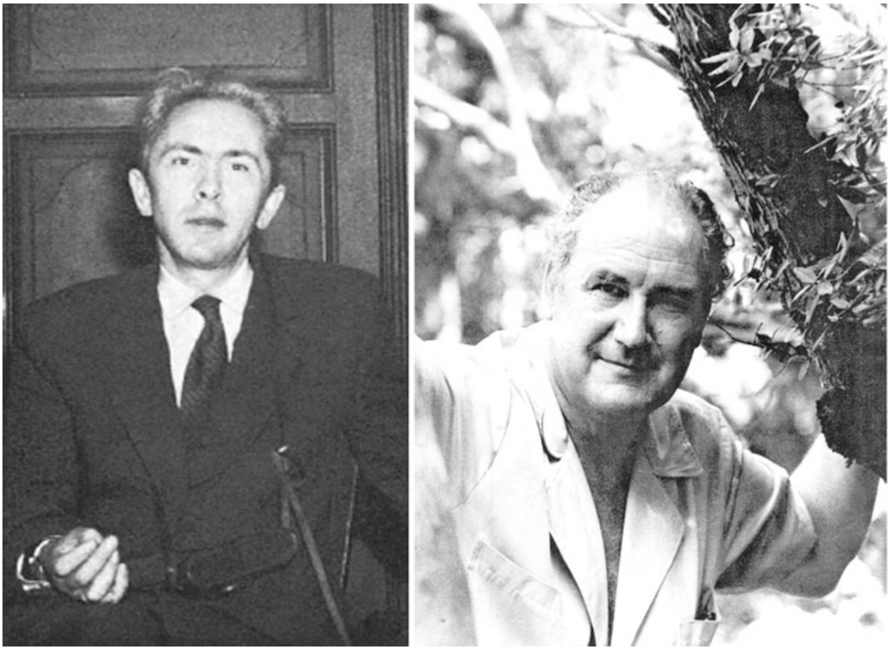

Fig. 1.1 Left: Hubert Damas (1910–1964), professor at University of Liège (Belgium); right: André Capart (1917–1993), director of the Royal Institute of Natural Sciences (Belgium)

Liège, Belgium – was interested in investigating the conditions in which animals lived and developed. In this respect, he was among the leading scientists of that time in tropical limnology, along with Juday, Thienemann, Ruttner, Worthington and Beadle. Although the methods and equipment he used may seem rudimentary compared to the techniques of modern limnology, the publication of the mission conducted in 1935–1936 on Lakes Kivu, Edward and Ndalaga (Damas 1937) remains a model of a limnological study, where the results were presented with precision and interpreted in great detail. Among other things, his observations, combined with geological evidence, contributed to confirm that present Lake Kivu originated from the rise of the Virunga chain in the late Pleistocene. The "old" Lake Kivu was formerly part of the drainage basin of Lake Edward, with which it shares faunal elements, while entire fish families present in Lake Tanganyika are absent from Lake Kivu as well as from Lake Edward (Beadle 1981). Damas understood that the stability of the stratification was due to the increase of salinity below 70 m, but he could not fully explain the increase in temperature. He also noted the horizontal homogeneity in the deep water and observed the main density gradient between 250 and 275 m depth which he speculated to have been caused by a mixing event from the surface during a cold period. Finally, he hypothesized that the gases present at high concentrations in the deep waters were CH_4 or nitrogen, as he excluded CO_2 to be sufficiently concentrated to cause the observed bubbling in deep water samples.

It was Capart and Kufferath (1956) who identified the gases as CO_2 (73.4%) and CH_4 (24.8%), with small amounts of hydrogen sulfide, nitrogen and argon. Schmitz and Kufferath (1955) estimated the total amount of CH_4 to be 57 km^3, and proposed to exploit this enormous source of energy.

Another subsequent Belgian expedition was led by André Capart (Fig. 1.1), then Director of the Royal Institute of Natural Sciences, and reported by Verbeke (1957), on Lakes Kivu, Edward and Albert, often quoted as “mission KEA”. For Lake Kivu, this expedition completed the data reported by the Damas’ mission, with an emphasis on the littoral flora and fauna, particularly on invertebrates. To date, this study remains the most comprehensive inventory of the biota of the lake shore, stressing for instance the peculiarities of the rocky shores and the absence of *Chaoborus* larvae in the benthos. Capart and others (Capart 1960), besides the purely scientific discoveries, had practical objectives regarding the exploitation of the resources of these large lakes which were at that time part of the Belgian colonies. They first contributed to the development of the pelagic fishery of Lake Tanganyika, and then promoted the introduction of the “Tanganyika sardine” *Stolothrissa tanganicae* or *Ndakala* into Lake Kivu, which supported a substantial zooplankton comprising Copepods and Cladocerans, but no fish (Capart 1959, 1960). The project was, actually, after the introduction of the sardine, to introduce *Lates stappersii*, the most abundant piscivorous fish in Lake Tanganyika. After some failed attempts with adult *Stolothrissa*, which died quickly during the transport between the two lakes, juveniles of the two clupeid species present in Lake Tanganyika (*S. tanganicae* and *Limnothrissa miodon*) were released in Lake Kivu (Collart 1960), and only *Limnothrissa* succeeded in adapting to Lake Kivu (Spliethoff et al. 1983). Another dream of Capart and co-workers was to exploit the CH_4 of the deep waters (Capart and Kufferath 1956), and to increase the productivity of the fishery by releasing the nutrient-rich degassed waters into the surface waters. The advent of the independence of Congo and the decolonization that followed put an end to those projects. Still, the pelagic fishery of Lake Kivu developed later on (Chap. 8), even though its yield was lower than that predicted by the Belgian scientists who envisioned a sardine production as high as 35,000 tons per year.

In the meantime, the exploitation of the CH_4 resource was initiated by the construction of a pilot plant by the Union Chimique Belge at Cap Rubona south of Gisenyi in 1962, which delivered energy to a local brewery. However, despite several studies investigating possibilities for a more extensive exploitation of the CH_4 stored in the lake, it took more than 40 years until the next CH_4 extraction pilot plant was constructed.

In 1971 and 1972, two research expeditions by the Woods Hole Oceanographic Institution, led by Egon T. Degens (Fig. 1.2), focused on the geophysical and biogeochemical properties of the lake. These expeditions provided the most comprehensive compilation of vertical profiles of chemical properties of the lake water in the twentieth century. It was concluded that the deep water of the lake was fed by hydrothermal springs (Degens et al. 1973) and that the CH_4 mainly originated from CO_2 reduction (Deuser et al. 1973). Seismic profiles indicated sediment thicknesses of up to 500 m in the deep part but only a thin sediment layer in the shallower

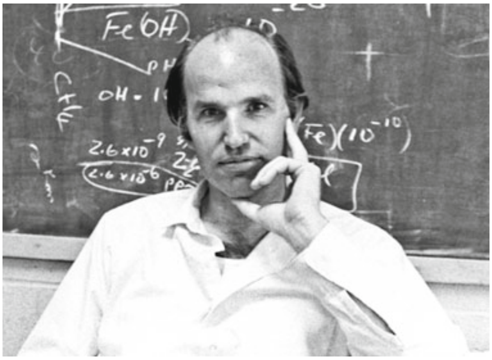

Fig. 1.2 Egon T. Degens (1928–1989), professor at the Woods Hole Oceanographic Institution

parts. The observed variability of sediment thicknesses was attributed to different ages of the different lake basins and lake level fluctuations (Wong and Von Herzen 1974). Several sediment cores were collected which until recently were the only source for paleolimnological information (Chap. 9). These cores were later also used for chemical and biological analyses by other research groups (Haberyan and Hecky 1987; Al-Mutlaq et al. 2008). During the 1972 expedition, Fred C. Newman investigated the fine structure of the temperature profiles in the lake using a recently developed temperature microstructure profiler and thus discovered the unique double-diffusive staircases (Newman 1976; Chap. 2).

In 1974–1975, the German Bundesanstalt für Geowissenschaften und Rohstoffe organized another expedition to the lake which resulted in the PhD thesis of Klaus Tietze (1978). Tietze specifically developed a probe to measure density *in situ* with high precision (Tietze 1981). His work was hitherto the most detailed study on the density stratification, temperature, conductivity and gas concentrations, as well as on the isotopic composition of the CH_4 in the lake. Tietze (Fig. 1.3) estimated the total amount of CH_4 in the lake to 63 km^3 and concluded that it was mostly biogenically produced (Tietze et al. 1980). However, based on a re-analysis of the isotopic data, Schoell et al. (1988) concluded that approximately one-third of the CH_4 was derived from an acetate fermentation process and two-thirds from a CO_2-reducing bacterial process which uses the dissolved CO_2 in the lake water as a carbon source. Following the catastrophic gas eruptions in Lakes Nyos and Monoun, Tietze understood that a similar eruption from Lake Kivu could potentially result in an unimaginable disaster (Tietze 1992). He invested a lot of time and energy in developing strategies for a safe and environmentally sound exploitation of the CH_4 resource (e.g., Tietze 2007 and references therein).

Political instability in the region retarded further research activities on Lake Kivu, until January 2002, when lava from the eruption of the volcano Nyiragongo flowed into the lake. It was feared that this lava flow might trigger a gas eruption from the lake. Subsequently, a dramatic documentary by BBC brought international attention to Lake Kivu, even though the results of an emergency expedition showed that there had been no significant impact by the lava flow on the lake stratification

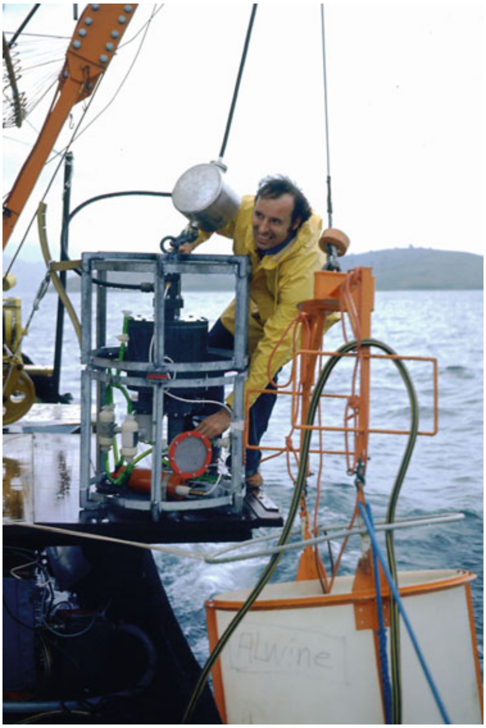

Fig. 1.3 Klaus Tietze during an expedition on Lake Kivu in 1974 (Photo provided by K. Tietze)

(Lorke et al. 2004). Since then, several projects for exploiting the CH_4 gas from the lake have emerged and pilot power plants have been constructed (Fig. 1.4). It is expected that large-scale commercial CH_4 extraction will develop in the next decade and will possibly have important impacts on the density stratification in the lake. The scientific research presented in the following chapters of this book came thus just in time to document the physical, chemical and biological status of the lake before it is entering this new era.

1.3 Outline of the Chapters

The unusual vertical stratification and the physical mixing and transport processes, which are governing internal nutrient cycling in Lake Kivu, are detailed in Chap. 2. The nutrient budget, with estimations of external inputs and internal loading, is treated in Chap. 3, while Chap. 4 deals with partial pressure of CO_2 and CH_4 in the surface waters, mainly driven by the seasonal variation of vertical mixing, and contrasting with the very high concentrations of these gases in the deep waters.

The two following chapters are devoted to the microbial communities, i.e. the prokaryotic and eukaryotic phytoplankton and its ecology in Chap. 5 and the other microbes (bacteria, archaea and microzooplankton) in Chap. 6. Zooplankton and

Fig. 1.4 Gas extraction facility of Kibuye Power 1 (KP1), the first pilot plant for large-scale commercial methane extraction from Lake Kivu that started operating in January 2009 (Photo provided by Kibuye Power Ltd.)

fish diversity, biomass and production are described in Chaps. 7 and 8, respectively. Comparisons are made with other African Great Lakes, highlighting the low diversity and the simplified food web of Lake Kivu, with however a high proportion of endemic fish species.

The historical changes that occurred in Lake Kivu, related to climatic variations over thousands of years, to volcanic events and to very recent changes, are recorded in the sediments (Chap. 9). Finally, Chap. 10 deals with the sources and sinks of the CH_4 present in high concentrations in the deep waters; this chapter also considers different scenarios for sustainable gas exploitation, with the objectives of maintaining the lake stability and ecological integrity, combined with economic viability.

In a final concluding chapter, we synthesize the current knowledge on Lake Kivu and suggest different lines for future investigations of this unique tropical lake.

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The story began earlier, with an encounter of one of us (JPD) with George Hanek on the shore of Lake Ihéma, back to 1989. George was at that time director of the FAO "Isambaza" project, and took interest in the studies by Rose Mukankomeje, PhD student at University of Namur, who attempted to relate primary production with fish production in Lake Muhazi. George Hanek suspected that similar relations could explain the large seasonal variations of fisheries yield in Lake Kivu, evidenced by Michel Lamboeuf. However, it was only more than 10 years later, through a long-term collaboration between ISP-Bukavu and University of Namur, that projects centred on the lake ecology developed. In particular, the UERHA ("Unité d'Enseignement et de Recherches en Hydrobiologie Appliquée") of ISP, led by Prof. Boniface Kaningini Mwenyimali, played a key role, with the objective of establishing a long-term program of limnological research, chiefly on Lake Kivu. In that framework, several cooperation and research projects were initiated, in which African and European scientists and students became involved. Financing came first from University of Namur, then from CUD ("Commission Universitaire pour le Développement", Belgium), from FRS-FNRS ("Fonds de la Recherche Scientifique", Belgium), and the local partnership was extended to NUR (National University of Rwanda at Butare), with Canisius Kanangire, Jean-Bosco Gashagaza and Laetitia Nyina-wamwiza as successive leaders. Financing also came from the Belgian Federal Science Policy Office through the EAGLES (East African Great Lake Ecosystem Sensitivity to changes, SD/AR/02A) project. Mission grants were awarded to several Belgian students by CUD, the "Fonds Léopold III", and the "Fonds pour Favoriser la Recherche en Afrique". Eawag became involved in research on Lake Kivu with an emergency expedition following the eruption of Nyiragongo in 2002, financed by EC-ECHO. Further financial support came from Eawag, UN-OCHA, and the Research Partnership project "Nutrient cycling and methane production in Lake Kivu" (207021-109710) funded by the Swiss National Science Foundation (SNSF) and the Swiss Agency for Development and Cooperation (SDC). The research of Eawag on Lake Kivu was only possible thanks to the dedicated scientific and administrative support of Alfred Wüest and the involvement of Bernhard Wehrli, Beat Müller, Helmut Bürgmann, Flavio Anselmetti, Mike Sturm and Carsten Schubert, as well as the local administrative support by Augusta Umutoni and Charles Nyirahuku. The research carried out in the Belgian universities benefited from the assistance of several people, as Philippe Leroy and Yves Mine.

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