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NATURAL HAZARDS ASSOCIATED WITH LAKE KIVU AND ADJOINING AREAS OF THE BIRUNGA VOLCANIC FIELD, RWANDA AND ZAIRE, CENTRAL AFRICA
FINAL REPORT

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NATURAL HAZARDS ASSOCIATED WITH LAKE KIVU AND ADJOINING AREAS OF THE BIRUNGA VOLCANIC FIELD, RWANDA AND ZAIRE, CENTRAL AFRICA: FINAL REPORT

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EXECUTIVE SUMMARY

The Birunga Volcanic zone (Western African Rift Valley), is a site of complex extentional rifting that has resulted in episodic basaltic volcanism. Large amounts of carbon dioxide (CO_2) associated with the volcanism discharge from springs and dry vents (mazukus). When the springs discharge into nearby Lake Kivu, the CO_2 accumulates in saline, bottom waters were it is biologically cycled. Hazards associated with earthquakes, volcanism, and CO_2-buildup in Lake Kivu are the primary geologic hazards in the Rift Valley near the boundaries of Rwanda, Zaire, and Uganda. A volcanologist and geochemist were sent to this area for two weeks to evaluate the hazards associated with the Birunga volcanism and the dissolved gases in Lake Kivu. The results of the field and laboratory investigations are:

- Lake Kivu is the only lake sampled that contains a sufficient amount of dissolved gas (CO_2 and CH_4) to pose a threat to human lives if released. Concentrations of these gases are in part controlled by biologic processes, and may change dramatically over short intervals of time.
- Mazukus (terrestrial gas vents) are common around Lake Kivu and discharge CO_2 that can accumulate in low lying areas (e.g. basements, sunken gardens, depressions in lava flows, etc.). Concentrations are high enough in these depressions to kill animals and, presumably people.
- Volcanic hazards in the Lake Kivu area include lava flows, littoral eruptive vents, and subaqueous eruptive vents. The lava flows from the Virunga volcanoes are extremely fluid and travel long distances very quickly, leaving little or no time for evacuation. Future eruptive activity near Lake Kivu would undoubtedly result in extremely destructive explosions because of the interaction of magma and groundwater. Eruptive activity into the bottom waters of Lake Kivu could initiate degassing of dissolved gases in the lake by destabilizing the water column.
- Recommendations for remediating these hazards include monitoring of the chemistry of dissolved gases and water in Lake Kivu -- especially if CH_4 mining is initiated; monitoring volcanic activity (both short-term and long-term plans considered); educating the local population about geologic hazards; establishing a warning system and evacuation plan in the event of a disaster, and providing specialized training for local scientists and technicians.

INTRODUCTION
Regional Geography and Geologic History

Lake Kivu, on the Western Branch of the East Africa Rift (Fig. 1), occupies two downfaulted rift basins separated in part by Idjwi Island (Ebinger, 1989). Modern Lake Kivu was formed in the last 15,000 years (Degens and others, 1973) by growth of the Birunga volcanoes (also known as Virunga volcanoes) north of the lake. Flows dammed an ancient tributary of the Nile River and caused the local drainage to direct water southward for eventual discharge into the Indian Ocean (Degens and others, 1973). Morphometric, geochemical, and other features of Lake Kivu are summarized in Table 1. Lake Kivu is meromictic -- its bottom waters (monimolimnion) are isolated from its circulating surface waters (mixolimnion) due to density differences of the two water masses (density stratification). The waters in the monimolimnion contain large amounts of magmatic carbon dioxide (CO_2) and biogenic methane (CH_4). Some of the CH_4 is currently being extracted from the lake water and used to supply power to a brewery in Gisenyi, Rwanda. Much more extensive CH_4 mining is being proposed by C.E.P.G.L. (Communite Economique de Pays des Grandes Lacs) -- a joint organization among Rwanda, Zaire, and Burundi.

The area around Lake Kivu is a site of complex extensional rifting that has been the locus of earthquakes and episodic basaltic volcanism for over 10 million years. This volcanic activity began with the eruption of primarily tholeiitic basalts on the south end of Lake Kivu, and continues on the north end of the lake (Birunga Mountains; Fig. 2) with the primary eruption of highly alkalic basalts (Villeneuve, 1980). This volcanic activity has produced the very large amounts of carbon dioxide dissolved in waters of Lake Kivu and has created very active and dangerous volcanoes. The direct and indirect hazards associated with these continuing tectonic and volcanic processes have been summarized by Katabarwa and others (1987) and by Newhall and Tuttle (1988).

BACKGROUND

Lake Kivu, bordered by Rwanda, Zaire, and Burundi (Fig. 1), is a large reservoir for dissolved CO_2 and CH_4 gases. The loss of 1700 lives after the 1986 release of CO_2 from Lake Nyos, Cameroon (features summarized in Table 1), caused great concern because of the potential for a larger disaster at Lake Kivu (two million people could be affected). In 1988, at the request of U.S. Agency for International Development, Office of Foreign Disaster Assistance (USAID/OFDA), Newhall and Tuttle (1988) prepared a report summarizing potential geologic hazards (earthquakes, volcanism, and lacustrine gas accumulation) associated with the Lake Kivu area and the neighboring Birunga Volcanic Zone. A thorough bibliography of work prior to 1988 is provided in their report and illustrates the paucity of geologic-hazard assessment studies in the Kivu/Birunga area.

In the fall of 1988, the Rwandan Government requested USAID/OFDA to fund a field study to characterize the hazards

associated with CO_2 and CH_4 gases in Lake Kivu and with eruptions from volcanoes in the Birunga group. An OFDA-sponsored team was assembled by the U.S. Geological Survey; team members are John P. Lockwood (volcanologist) and Michele L. Tuttle (geochemist). William C. Evans (chemist) worked on the project, but was unable to participate in the 1989 fieldwork.

During our brief trip to the Lake Kivu area (31 July - 10 August 1989), we were accompanied and assisted by Drs. Katabarwa and Bariyanga (National University of Rwanda), Dr. Zana (Lwiro, Zaire), and Mr. Bavukahe (Regional Centre de Recherches Geologiques et Minieres, Zaire).

LOCATIONS STUDIED AND SAMPLED
Lakes and Springs

The time allotted for sampling Lake Kivu was too short for a thorough study; we collected data at only one station, and this not more than 1 km from shore. We were able to obtain a good profile for water chemistry and two deep-water gas samples. Lacs (Lakes) Vert and Karago were also sampled. Lac Vert, Zaire is a lake that serves as a local water supply for small villages within the area and is located within a small crater just east of Kabuno Bay in Lake Kivu (Fig.2). Lac Karago is located east of the rift valley and was formed from the damming of a river valley by a lava flow (Fig. 2). In May, 1988, its surface level reached an all-time high, 3.5 m above the previous 2 year maximum, causing concern in light of the tragedy at Lake Nyos (for a detailed report on flooding effects and remediation recommendations, see Katabarwa, 1989).

We also visited and sampled two thermal springs on the shores of Lake Kivu and one near Lac Karago (Fig. 3). The two springs by Lake Kivu are spatially separated by a small ridge and are no more than 100 m apart. Water and gas samples were also collected from Mpenge soda spring, located 1 km southeast of Ruhengeri, Rwanda (Fig. 3).

Mazuku (Terrestrial Gas Vents)

Significant emission of gas on the northern shore of Lake Kivu is evidenced by the presence of toxic gas in houses in the area around Gisenyi, Rwanda, and mazukus near Sake and Goma, Zaire. Mazuku (or "Mazuto") is a Swahili word referring to low-lying areas where animals mysteriously die owing to unknown causes. These are also the fabled "elephant graveyards" of

Africa where elephants "go to die." In Zairian folklore, mazuku are "evil winds" which travel and kill people by night.

During our stay, we visited three mazuku in Zaire and Rwanda where animals are known to have died. One was a natural depression in the 1938-40 Nyamuragira pahoehoe flow southeast of Sake, Zaire, one was in a low-lying garden of a private residence near the lake Kivu shore in Gisenyi, Rwanda, and one was a deep pit in the floor of the RWANDEX coffee-packing factory in Gisenyi (Fig 3). The mazuku near Sake was littered with the skeletal remains of dogs, goats, birds, and insects. At this locality (LK-89-95; Fig. 3) a source of dense gas was observed in a particularly deep pit, where flaming kerosene-soaked rags would be instantly extinguished. The gas was observed to be colorless and marked by only a faint, "sweetly organic" smell. This same smell was noted within the Gisenyi mazuku. Conversations with local residents revealed that the mazuku were most dangerous after heavy rains -- as if the toxic gas were perhaps forced out of the ground at accelerated rates when ground voids were filled with water. In many cases, houses have been totally or partially abandoned because of gas accumulations.

Volcanic Rock and Charcoal

In order to better characterize direct volcanic hazards, samples of volcanic lava flows and tephra north and east of Lake Kivu were collected from 12 localities -- five samples were chemically analyzed (localities in Fig. 3). Carbonized roots and twigs were recovered from beneath volcanic deposits at two localities for radiocarbon dating of prehistoric eruptive activity (Fig. 3).

WATER AND GAS GEOCHEMISTRY
Results
Water Temperature

A temperature profile (Fig. 4) was obtained in Lake Kivu as described in the methods (Appendix B). Our temperatures are between 0.10 and 1.2 °C lower than those taken in 1971 (Degens and others, 1973), in 1975 (Tietze, 1978), and in 1986 as part of the C.E.P.G.L. study (Fig. 4). Our low values arise from the inability to calibrate the thermistor in the field because of equipment damage during transport. Our temperature data are internally consistent, however, and values relative to one another are accurate. The similarity in the shape of the profiles in Figure 4 shows that the thermal structure of the water column has changed little since 1971. According to calculations in Tietze (1981a), maximum stability (density-gradient/density) in the water column occurs between 260 m and 275 m, the depth interval where the temperature gradient is steepest (Fig. 4). The significance of the differences among the 1971, 1975, and 1986 profiles is difficult to assess because each was measured with equipment from different groups.

A temperature profile was also obtained in Lac Karago. Again, these temperatures are not calibrated; however, the

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values are accurate relative to one another and to those measured in Lake Kivu. Lac Karago is essentially isothermal below 6 m, and is much cooler than Lake Kivu because of its higher elevation (surface water in Lac Karago is 4.54 degrees Celsius colder than that in Lake Kivu); we saw no evidence for thermal-spring input.

Temperatures in thermal springs were taken with a field thermometer (accurate to ±.5°C). The thermal spring temperatures are: Men's thermal spring, 55°C to 67°C depending on which discharge pool measured; Women's hot spring, 65°C; Karago thermal spring 73°C.

Water Chemistry

Methods used to determine chemical and isotopic compositions of lake- and spring-water samples are summarized in Appendix B. Results of these analyses are reported in Table 2. All chemical data are tabulated as mg per kg of water (ppm) or μg per kg of water (ppb) and isotopic data as per mil (‰) relative to the Standard Mean Ocean Water standard (SMOW).

The ternary plot in Figure 5 summarizes the chemical signature of the lake and spring waters as proportions of cations on a molar basis. The cation composition of the thermal springs in both the Lake Kivu and Lac Karago area is dominated by sodium plus potassium, whereas the mineral spring (Mpenge) is much more enriched in iron and magnesium. Both surface and bottom waters in Lac Vert have an identical signature to that of the thermal springs (sodium plus potassium enriched), but are from two to four times more dilute than the spring waters (Table 2).

Lac Karago has the lowest proportion of sodium and potassium and the highest of calcium. The lake surface water is essentially identical to that of lake inflow with respect to both its chemical signature and salinity. Although the proportion of sodium plus potassium decreases slightly in the bottom water, its salinity remains identical to that of the surface water.

The chemical signature of Lake Kivu water is intermediate between Lac Vert (and the thermal springs) and Mpenge soda spring. Lake Kivu surface water contains a smaller proportion of calcium relative to deep water, probably due to calcium removal during carbonate precipitation in the upper water column (Botz and others, 1988). The concentration of most elements increases as a function of depth within the lake,; salinities at 300 m are 3.5 times that of surface water.

The minor- and trace-element chemical results in Table 2 are not discussed in detail in this report. The variability in concentrations reflects the source of solutes, redox potentials, and biological processes. In general, concentrations are directly proportional to salinity.

Degens and others (1973) report major-element results for Lake Kivu samples collected in 1971. Lake Kivu water samples were collected in 1986 and analyzed for major chemistry as part of a study for the C.E.P.G.L. Figures 6 and 7 compare depth profiles of chemical concentrations from the study by Degens and

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others (designated 1971), the CEPGL study (designated 1986), and this study (designated 1989). In surface water, cation concentrations have changed little since 1971. At depths from 100 to 300 m, concentrations of all major cations have increased (Fig. 6). Tietze's interval of maximum watercolumn stability (1981a) occurs at the depth where the steepest concentration gradient of many elements begins (Figs. 6 and 7). Sulfate concentrations have decreased at depths between 100 to 300 m since 1971 (Fig. 7). The increase in cations and the decrease in sulfate have been offset by large increases in alkalinity (mostly bicarbonate; Fig. 7) to maintain charge balance. The chance that these concentration differences over time are due to horizontal variability is small; Degens and others (1973) showed that concentrations are relatively uniform at any given depth independent of the geographic location on the lake.

The δD and $\delta^{18}O$ values are plotted in Figure 8 along with Craig's (1961) "meteoric surface water" line. Lac Vert and Lake Kivu waters above 300 m depth are the most enriched in deuterium and ^{18}O; their enrichment is predominantly due to intense evaporation. The $\delta^{18}O$ and δD values reported by Tietze (1978) for Lake Kivu surface water and bottom water (270 m) are similar to our values and follow the same trend of ^{18}O and D depletion with depth (Fig. 8). δD values where not reported by Degens and others (1973), however, their $\delta^{18}O$ values for Lake Kivu (>400 m depth) and local meteoric water are shown on the $\delta^{18}O$ axis and agree with our values and those of Tietze (1978). The relative depletion in deuterium and ^{18}O in Lake Kivu's bottom water relative to its surface water reflects addition of thermal waters from below. Degens and others (1973) expect that this thermal water has similar isotopic compositions as the local meteoric ground water represented by the spring data; however, Lake Kivu's thermal waters contain a greater proportion of Fe and Mg than those of the thermal springs reported in Degens and others (1973) and sampled in our study (Fig. 5).

Gas Chemistry

No gas was found in either Lacs Vert or Karago. Methods used to collect and analyze the gas samples from Lake Kivu, Mpenge soda spring, and dry gas vents are discussed in Appendix B. The compositions of the effervescing gas in the soda spring and the mazuku vapors are shown in Table 3 as volume-percent (equal to mole-percent). The gas compositions in Table 3 for the 200 m and 300 m depths in Lake Kivu represent volume-percent of the total gas exsolvable from these samples. In Table 4 the Kivu gases are given in the absolute concentrations of μmol-gas/kg-fluid and are compared to the results of other studies. Some of the values from earlier studies are averages, derived from graphs, or calculated from information published in reports.

A critical question regarding the gases in Kivu is whether they are at steady-state concentrations as previously suggested by Tietze and others (1980) or are changing with time in response to input rates and evolving lake structure (see Degens and others, 1973). Following the disastrous gas bursts from

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Lakes Nyos and Monoun, Cameroon, a hypothesis was developed that gas concentrations can slowly build up in meromictic lakes until a mechanical disturbance triggers a sudden massive release (Kling and others, 1987). The possibility that gas concentrations in Kivu might be slowly increasing is now of greater concern. In addition to CO_2 and CH_4, which make up approximately 99 percent of the dissolved gas, we measured several trace constituents; the concentrations of some of these have not been previously reported.

The gas dissolved in highest concentration in Kivu is CO_2. Our measured CO_2 concentrations are higher at both depths than all previously reported values (Table 4). Of particular interest in this comparison are the data of Tietze and others (1980) which represent the most recent measurements (1974, 1975) comparable to ours. The analytical methods used in that study are similar to ours in that pressurized containers of deep water are degassed in a controlled manner to allow measurement of dissolved CO_2 concentrations separately from dissolved inorganic carbon (ΣCO_2) concentrations. Differences between the two data sets are much greater than analytical uncertainties in the methods and are not attributable to lateral inhomogeneities in the water column (multiple sampling across the northern basin by CEPGL in 1986 shows that horizontal variation is negligible). In the 15-year period between the studies, the CO_2 concentration has apparently increased 24 percent at 300 m and more than doubled at 200 m. Increases of this magnitude are alarming because they show that significant changes in gas chemistry can occur on a time-scale of years.

Although CO_2 is the dominant gas in Kivu, CH_4 contributes a much greater proportion to the total gas pressure. This results from the lower solubility of CH_4 in water; it is about 25 times less soluble than CO_2. Changes in CH_4 concentrations, therefore, have a much greater effect on the degree of gas saturation than do changes in CO_2. Although we have found significant increases in CO_2 concentrations, our CH_4 values at both depths are similar to previous values (Table 4). In addition to CH_4, we found trace quantities of ethane (C_2H_6) and propane (C_3H_8). Tietze and others (1980) and Degens and others (1973) also detected these gases, which probably derive from the breakdown of organic matter in the lake sediment.

Tietze and others (1980) reported dissolved N_2 concentrations as a function of depth and give a concentration range of approximately 235 to 565 µmol/kg-fluid with no discernable trends as a function of depth. They suggested that, at all levels, the lake was in equilibrium with atmospheric N_2, which at the elevation of Kivu, would require a concentration of about 410 µmol/kg. Our measured N_2 values are within the range reported by Tietze and others (1980) but below the average value expected for atmospheric saturation.

Although N_2 is resistant to biological modification, it is not entirely inert once dissolved in the lake water. The atmosphere does contain a number of totally inert gases that, like N_2, have distinct equilibrium solubilities in water. We measured the concentrations of two of these gases, Ar and He.

The Ar is particularly useful because sources other than the atmosphere are usually unimportant in lake-water systems. It is of interest that the Ar values at both depths are less than the 10.6 μmol/kg-fluid expected for equilibrium with the atmosphere. Because the equilibrium solubility of atmospheric He in lake water is so low (0.002 μmol/kg), only a small fraction of the He we measured can be derived from the atmosphere. Unlike Ar, He can have important sources other than the atmosphere. The He isotopes in Lake Kivu confirm that there has been a significant addition of mantle-derived He to the lake (Schoell and others, 1988).

All three mazukus contained CO_2 at potentially lethal levels (Table 3). Although a distinct odor was associated with gases at all three dry vents, we are as yet unable to detect any toxic gas other than CO_2 or to identify the odorous compounds. Two of the samples contained C_5 and C_6 hydrocarbons suggesting that buried organic material is decomposing in response to geothermal heat. The thermal breakdown of organic material, particularly that buried by high-temperature lava flows, would produce an enormous variety of organic gases, many of which would be odorous.

Implications of Lake Kivu Results

The most significant change observed since the 1971 study of Degens and others (1973) is the almost complete removal of sulfate from the water column while concentrations of other solutes have increased in roughly proportional fashion (Figs. 6 and 7). In order to explain how these changes may have occurred, we must consider the sources of these constituents.

The increase in most solutes with depth led Degens and Kulbicki (1973) to propose that most dissolved salts are transported into the lake by saline, CO_2-rich thermal fluids entering from below. This establishes a stratification of water layers based on density that prevents the rapid mixing of the saline thermal fluids to the surface. Migration of the water layers or partial mixing between layers may occur on the time scale of years. Thermal "jets" in the lake may locally promote the mixing process. One such jet was invoked by Degens and others (1973) to explain a sharp reversal in their temperature profile around 225 m (Fig. 4). We found no evidence of a thermal jet affecting our profile, and suggest that the increase in solutes since 1971 is due to continued input of saline fluids at depth, causing the slow water-layer migration or partial upward mixing. The proportional increase in all cations (Fig. 7) indicates that the chemical composition of the thermal fluids has not changed since 1971, supporting a continuation of the transport process proposed by Degens and others (1973). However, changes in anion concentrations cannot be entirely explained by simple transport processes.

Chloride is normally considered to be a conservative anion in most lake systems and would be expected to show the same proportional increase as the cations in the proposed transport scheme. Unfortunately, we were unable to evaluate changes in

chloride concentrations since 1971 as Degens and others (1973) did not report them. A comparison with the 1986 profile (Fig. 8) shows increases at depths >100 m, but decreases at shallower depths; more data on chloride concentrations are needed before a time-dependent trend can be defined.

The decrease in sulfate from 1971 to the present may be attributable to bacterial reduction of sulfate to H_2S in the anoxic water column. During sulfate reduction, organic carbon, which is abundant in Lake Kivu, is converted to bicarbonate. Therefore, we can invoke this process to explain both the decrease in water-column sulfate and, in part, the very large increase in bicarbonate relative to the increase in cations. Although we did not observe increases in H_2S concentrations in the water column, H_2S can be quickly removed by precipitation of insoluble sulfide minerals. Sphalerite (ZnS)-bearing globules have been identified as particulates in the water column, and pyrite (FeS_2) comprises up to 15 percent of the sediment (Degens and Kulbicki, 1973; Degens and others, 1973). The H_2S produced during sulfate reduction is [34]S-depleted relative to the sulfate and, as reduction progresses, the sulfate reservoir becomes increasing enriched in [34]S. If sulfate reduction was the only process affecting the sulfate isotopic composition, we would expect sulfate $\delta^{34}S$ values to increase with depth. Instead, the $\delta^{34}S$ values of the dissolved sulfate decrease with increasing depth ($\delta^{34}S$ values relative to CDT standard are 9.7‰ at the surface and 8.3‰ at 300 m). This decrease with depth must reflect a relatively [34]S-depleted sulfate dissolved in the thermal recharge fluid and shows that the processes involved in sulfate reduction are complex. Because sulfate and bicarbonate enter into biological processes, they should not be used to infer changes in the chemistry of the incoming thermal fluid with time.

Like sulfate and bicarbonate, CH_4 is controlled by biological processes. Most investigators have proposed that the CH_4 in Kivu is formed bacterially in the water column and/or in the lake sediment (e.g. Schmitz & Kufferath, 1955; Deuser and others, 1973), and through the use of isotopes, Tietze and others (1980) and Schoell and others (1988) have studied Lake Kivu's carbon cycle. The low ^{14}C value for the CH_4 shows that the major carbon source for CH_4 formation is apparently CO_2 dissolved in the incoming thermal fluids. There are two possible biologic pathways for the conversion of CO_2 to CH_4, CO_2 reduction and acetate fermentation. In both pathways, the CO_2 is fixed into organic compounds in the photic zone. Organic material, sinking down through the anoxic deep water, is available as a hydrogen source for CO_2 reduction or as a carbon source for fermentation. The $\delta^{13}C$ value of the organic material sinking to the sediments is about -21‰ relative to PDB standard. Based on tests using Lake Kivu sediments, Shoell and others (1988) suggest that the $\delta^{13}C$ values would be -45‰ and -64‰ for CH_4 formed by acetate fermentation and CO_2 reduction respectively. A $\delta^{13}C$ of -58‰ for the CH_4 in Lake Kivu shows that both CO_2 reduction and acetate fermentation contribute

significantly to CH_4 production. Our measured $\delta^{13}C_{CH4}$ values (near $-58‰$, Table 3) also support the model of a mixed pathway.

Deuser and others (1973) measured higher CH_4 concentrations in 1971 than those reported by Schmitz and Kufferath (1955). This lead Deuser and others to propose that CH_4 concentrations had increased at a rate of approximately 1 percent per year since 1955. However, Tietze and others (1980), measured concentrations in 1975 similar to those reported in 1955 and described the lake as a steady state system with CH_4 concentrations remaining stable over time. Although our results agree well with those of Tietze and others (1980), it is conceivable that the higher CH_4 concentrations measured in 1971 reflect a temporary deviation from steady-state conditions. Deuser and others (1973) reported carbon isotopic compositions of $-45‰$ for CH_4 in Lake Kivu in 1971, a value expected if fermentation were the sole pathway of CH_4 formation. Because sulfate can inhibit bacterial CO_2 reduction, fermentation would be favored in the presence of the high sulfate concentrations such as those measured in 1971 (Degens and others, 1973). Given the high dissolved inorganic- and organic-carbon concentrations in Kivu, changes in relative rates of CH_4 formation by the two pathways could cause significant changes in CH_4 concentrations, although the fractional change in the large CO_2 reservoir would be small. Simply a change in bacterial populations may be the source of the difference between data sets collected just three years apart. Abrupt changes in biological populations have occurred in the past as seen in sediment cores (Haberyan and Hecky, 1987).

The CO_2 in Lake Kivu is associated with Rift magmatism (Degens and others, 1973; Tietze and others, 1980). Because it enters the lake bottom dissolved in the saline thermal fluids, increases over time in cation concentrations at given depths should be accompanied by increases in CO_2. This effect is seen in our actual observations at 200 m and 300 m (Table 4). However, if only water-layer migration or mixing processes were involved, the relative increases in CO_2 and the cations should be equal. At 300 m, this is nearly the case. At 200 m, however, the increase in CO_2 is slightly larger relative to the increase in cations. These differences are expected because CO_2 concentrations are affected by biological processes, surface losses, and redox reactions that alter pH. After allowing for these effects, there is no indication of a change in the CO_2 concentration in the thermal fluids or in the CO_2 source. Our $\delta^{13}C$ values (Table 3) are similar to those measured in 1974 (Tietze and others, 1980), and are compatible with the CO_2 having mainly a magmatic origin.

SPECIFIC HAZARDS
Lake Kivu

The increase in CO_2 at depth since the study by Tietze and others (1980) has caused a small increase in dissolved-CO_2 pressure, about 0.4 atm at 200 m and 0.5 atm at 300 m. Total dissolved-gas pressure (CO_2 + CH_4 + N_2) is now 3.2 atm at 200 m

and 14.8 atm at 300 m. These pressures are 15 percent and 48 percent of ambient saturation pressures respectively. As noted earlier, the high solubility of CO_2 in water makes the total dissolved-gas pressure rather insensitive to changes in CO_2 concentration. Although the increase in dissolved-CO_2 pressure may appear to be trivial, the fact that CO_2 can serve as a carbon source for CH_4 formation makes it a matter of concern. If all the CO_2 added to the lake since 1971 was converted to methane, dissolved-gas pressures would have risen 8.8 atm and 11.8 atm above the pressures we measured at 200 and 300 m. Total dissolved-gas pressures would then be approaching dangerously high values -- 57 percent (200 m) and 86 percent (300 m) of ambient saturation pressures.

At present levels of saturation, degassing could not occur unless deep water were transported many tens of meters upward. Only a major disturbance (i.e. large subsurface landslide, lava flow into the lake bottom, fissure eruption on the lake bottom, etc.) could provide the energy needed to trigger degassing. At this time, however, it is not known how close to saturation levels gas pressures can approach before catastrophic degassing becomes likely, nor is it known if Lake Kivu is capable of the sudden, massive, types of gas emission like Lakes Monoun and Nyos. One key question that can be addressed by the dissolved Ar data is whether or not degassing has occurred previously from Lake Kivu. Atmospheric Ar will tend to dissolve in meteoric water (water in contact with the atmosphere such as rain, stream, or lake water). As mentioned earlier, water at the elevation and temperature of Lake Kivu should contain about 10.6 μmol/kg-fluid of Ar at equilibrium saturation with the atmosphere. The lake surface should be saturated with Ar as should the incoming thermal fluids, which are certain to be geothermally heated meteoric water (juvenile water is considered to be an insignificant portion of such thermal fluids; Craig, 1963). Because it is inert, the only effective way to remove Ar from the subsurface water is by the venting of exsolved gas bubbles from the lake. If our two samples are representative of deep water in general, then a major amount of Ar has been lost from the water column. This could have been a long-term effervescence or a catastrophic release as at Lake Nyos where virtually all dissolved Ar was stripped during recent gas bursts. This gas loss could have been prehistoric and hence unrecorded. Haberyan and Hecky (1987), using data from sediment cores, hypothesize that extreme subaqueous hydrothermal events during the last 5,000 years have caused lake overturn, which would undoubtedly strip the Ar from the water column. If such events mixed dilute surface water downward, then it is possible that the increased concentrations of most solutes represent the gradual return of the lake to some more-heavily stratified condition, allowing gas concentrations to build to higher and more dangerous levels.

The proposed large-scale mining of CH_4 from Lake Kivu may significantly affect the stability of Lake Kivu's water column. The current proposed mining technique would return the extracted bottom water to a depth below the chemocline so as to minimize

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instability due to density differences between the surface and bottom water masses. A variety of chemical reactions will occur within the extracted water unless it is kept at the ambient redox potential (oxidation state), temperature, and pressure of the depth from which it is removed. The cumulative effect of these reactions on water chemistry and subsequently on lake stability is impossible to assess with our data, nor can we estimate them because of our limited knowledge of the proposed mining techniques. Tietze (1981b) has briefly summarized a mining method that should maintain stratification based on density. His report, however, does not discuss the above chemical reactions that could significantly affect stratification.

Mazukus

These dry gas vents for toxic amounts of gas are a peculiar kind of hazard. Although all three vents we tested had distinct odors, the only gas as yet identified at lethal concentrations is CO_2. These types of vents occur in parts of the world where there is a large regional flux of CO_2 from below the earth's surface. The CO_2 is commonly transported in groundwater because of its high solubility and issues at soda springs such as Mpenge. If, however, insufficient groundwater is present to dissolve the CO_2, a dry gas vent (mazuku) can result. CO_2 is heavier than air and will accumulate in depressions such as basements or excavations below ground. Therefore, when vents occur in such depressions, CO_2 concentrations can reach lethal levels.

Lava flows

The active Birunga volcanoes (Nyamuragira, Nyiragongo, and Bisoke; Fig. 2) are characterized by the dominance of effusive (lava flow) activity over explosive behavior. Pouclet (1976) has shown that the Rittmann Explosive Index (volume of tephra to total volcano volume) for Nyamuragira is 15-20 percent -- a low value which shows the preponderance of lava flow activity. We estimate that the Rittmann Index is even lower for Nyiragongo. Most Birunga lava flows are of alkalic to highly alkalic composition (Table 5, this study; Marcelot and others, 1989; Pouclet, 1980), which causes extreme fluidity. This results in lava flows that can travel long distances very quickly, thus leaving little time for the evacuation of populations in threatened areas, especially on steep slopes. The only flank eruption of Nyiragongo in historical time occurred in 1977 and generated a nephelinite flow which covered 20 km^2 in less than one hour and killed about 70 people (Tazieff, 1977). Tazieff estimated the initial velocity of this flow at 100 km/hr on Nyiragongo's steep upper slopes.

The fast-growing city of Goma, Zaire (est. 1980 population: 40,000) is entirely constructed on a young prehistoric nephelinite pahoehoe flow erupted from the south slope of Nyiragongo (the Coulee du Buyinga of Thonnard and others, 1965). This flow is thin (commonly less than 1 m thick) and shows

textures indicative of rapid emplacement. To evaluate the age of this flow, carbonized roots were collected from the base of this pahoehoe near Mont Goma (Lk-89-04, Fig. 3) using techniques described by Lockwood and Lipman (1980). The radiocarbon age on these roots was 740 ±110 yrs, which according to the tree ring-based calibration system of Stuiver and Reimer (1986) indicates that the flow was emplaced between AD 1208-1374 (maximum probability of actual eruption about AD 1270). The velocity at which this flow was emplaced is unknown, but it is probable that it covered the area of present Goma very quickly. If such an eruption were to occur in the future without adequate warning, the loss of life in Goma would be extensive.

Littoral Eruptive Vents

About a dozen prehistoric eruptive vents are present along the north shore of Lake Kivu (Thonnard and others, 1965). Future eruptions from new vents similar to these pose a previously unrecognized volcanic hazard for areas immediately north of Lake Kivu, as the interaction of ground water and magma can result in extremely violent explosive activity. Mont Goma is a prehistoric tuff-ring between Goma and Lake Kivu whose breached south rim forms an excellent harbor for the city. Its formation (estimated here to have occurred within the past few thousand years) was marked by the formation of extensive "base-surge" deposits (formed by violent steam explosions) which devastated an area of several square kilometers around the cone. The extent of these deposits is unknown because of later coverage by the Buyinga flow.

It was not possible to date the Mont Goma tuff-ring, but charcoal was recovered from beneath tephra of an older scoria cone along Lake Kivu's northeast shore south of Gisenyi (LK-89-02), Fig. 3). This cone showed no evidence of explosive phreatic activity, and evidently formed before the formation of modern Lake Kivu. The radiocarbon age of this sample was 10,040 ±240 years (Table 6), too old for calculation of a calibrated age.

The presence of Lake Kivu has greatly increased the geologic hazards of the area, not only because of the indirect hazards associated with dissolved gases in lake waters, but also because of its control on the level of ground water in the area. Any future eruptive activity which occurs at low elevations within a kilometer or two of the Lake Kivu shore could result in violently explosive behavior due to magma/ground water interactions. Such violent explosions would devastate areas of several square kilometers surrounding the vents.

Sub-aqueous Eruptive Vents

Eruptive activity occurring in Lake Kivu at water depths in excess of 50-100 meters will not be explosive, because of the effect of confining pressure of the overlying water. Such activity would be extremely hazardous, however, because of the possibility that the density of deep lake waters would be

sufficiently reduced by rising temperature to induce local overturn of gas-charged waters.

Earthquakes

Evaluation of earthquake hazards in the Birunga Volcanic zone was outside the scope of our field visit; however, it is impossible to separate them from hazards associated with volcanism in a rift setting. Newhall and Tuttle (1988) present a summary of earthquake activity in the Western Rift Valley near Lake Kivu.

RECOMMENDATIONS
Lake-Water Monitoring

1) In view of the fact that there have been apparent increases in most solutes in Lake Kivu, it is important that additional stations be sampled to determine whether or not changes have affected the entire lake. The assessment of lake stability will depend on this critical information. Sampling and analytical methods should be similar to those in this study in order to distinguish real changes from the variability that would be introduced by using different techniques.

2) One goal of a monitoring system on Lake Kivu is to determine whether or not there is an increase in gas content with time. Monitoring of a single location within Lake Kivu where deep-water samples can be obtained periodically should be adequate to evaluate changing water chemistry and degree of gas saturation at various lake levels. Widely spaced sampling dates may be adequate to monitor the slow physical processes such as mixing and migration of water layers. The influence of biological processes on gas content, however, can be quite rapid as suggested by the differences between the 1971 and 1975 sampling expeditions. In the absence of frequently spaced sampling, these short-term, biologically mediated changes will not be apparent or may be misconstrued as long-term effects within the lake. Some form of frequent (i.e. seasonally or yearly) monitoring of gas contents should, therefore, be done by local scientists. The hardware for such monitoring is relatively inexpensive (Appendix B).

3) It is important to pursue the possibility that one or more gas bursts may have occurred from Lake Kivu in prehistoric times. Precise measurements of all dissolved inert atmospheric gases should be made at various depths and stations. If the low Ar values we measured are substantiated, then a prior gas release of some type is strongly indicated. Geological, anthropological, and other lines of evidence should also be sought.

4) If large-scale CH_4 mining is undertaken in Lake Kivu, it is critical that a network of stations continuously monitor the water column for changes that may signify a decrease in stability (e.g. changes in dissolved-gas pressures, temperature, or conductivity). These stations need to be distributed throughout the lake in order to access the effect of mining on a lake-wide basis.

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Mazuku Monitoring

Presumably most existing hazardous mazuku locations are already known, and they can be either avoided or properly ventilated. A much greater danger is attached to new excavation projects, particularly if confined. We recommend that construction workers involved in excavations be familiar with the hazards of CO_2. Inexpensive "Dräger tubes" could be used to test for problem areas. Failing this, the use of a flame test would be helpful (flames are extinguished in high CO_2 environments). It should be noted that lethal CO_2 concentrations can exist without any telltale odor and at dangerous concentrations in environments where flames are not readily extinguished.

Volcano Monitoring

The variety of volcano-related hazards which threaten the inhabitants in the Lake Kivu area (lava flows, explosive phreatic eruptions, and volcanic heating and overturn of deep lake waters) make a basic monitoring system essential. There are two aspects to successful volcano-monitoring: 1) adequate monitoring equipment, and 2) well-trained local personnel to carry out the collection of data and preliminary analysis. The monitoring system should be integrated with seismic and deformation monitors already in place in Zaire (Kasahara, 1983; Kasahara and others, 1982; Zana and others, 1988). Previous work has indicated that eruptions of the Birunga volcanos are preceded by increases in seismic activity (Berg and Johnson, 1959; Shimozuru and Berg, E., 1961).

Initial hardware needs for monitoring the volcanoes of the Kivu area can be modest (Appendix B). As experience is gained, however, establishment of a formal volcano observatory in the north Kivu area should be considered.

Warning Systems and Evacuation Planning

As monitoring capability is established, and confidence in the ability to provide early warning of volcanic eruptions or lake instability is gained, consideration should be given to establishment of a network of warning sirens to alert inhabitants of threatened areas as to the danger. To save lives in the event of a dangerous eruption, all residents must know what is expected of them if a warning is sounded: which way to run, how far, and how long to stay away. This will require a massive public education effort.

Monitoring Training

Experience has shown that the "expeditionary" method of volcano- and lake water-monitoring by foreign advisors does not suffice for early warning. The basic monitoring must be done by dedicated local technicians and scientists who can continuously evaluate volcano and lake behavior, spot fast-developing changes, and distinguish between routine variability and ominous change. Accordingly, training of local technicians and

scientists in basic monitoring techniques is critically needed. A volcano-monitoring training course is presently being taught during summer session at the University of Hawaii at Hilo's Center for the Study of Active Volcanoes (CSAV), and would be appropriate for "hands on" training of technician-level students. Additionally, training of senior Rwandan and Zairian scientists in volcano monitoring and data analysis is possible through participation in the University of Hawaii course described above in addition to an extended visit to the Hawaiian Volcano Observatory.

Lake-water sampling can be carried out by a local technician supervised by a senior scientist. Training in interpreting field and analytical data on lake-water measurements, however, is needed for senior scientists. This type of training is possible through programs available from the U.S. Geological Survey (Denver). The Water Resources Division Training Center is located at this facility and offers a large number of key classes on water/gas geochemistry. In addition, the facility maintains a multitude of chemical laboratory facilities providing maximum exposure to the types of analyses and interpretation needed in a monitoring scheme for Lake Kivu.

CONCLUSIONS

The volcanoes of northern Rwanda and eastern Zaire pose threats to the lives of local inhabitants. These threats can be lessened by basic volcano and lake-water monitoring to determine when volcanoes are stirring to life and when lake waters are reaching critical concentrations of gases. To conduct effective monitoring, local technicians and scientists must be trained in the development and initiation of continuous monitoring of active volcanoes and frequent monitoring of gases in Lake Kivu.

The volcano-monitoring system described in Appendix B provides Rwandan authorities with a basic observation capability and would be able to detect changes in volcanic behavior. However, for full interpretation of these changes, a more sophisticated Volcano Observatory should be established in order to monitor the entire Lake Kivu/Birunga area. Such an Observatory would have to be international in scope, involving representation from each of the three countries bordering Lake Kivu (Rwanda, Zaire, and Burundi), as well as perhaps Uganda. A multi-national organization such as CEPGL (Communite Economique des pays des Grandes Lacs) might be a good coordinating agency for such an Observatory.

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APPENDIX A -- SAMPLING AND ANALYTICAL METHODS

Water Methods

Temperature was measured with a calibrated thermistor-ohm meter combination interconnected by 4-conductor cable; accuracy is 0.1°C and precision generally 0.01 °C. Our precision for any particular depth was affected because our boat was not anchored and the wind made it difficult to position directly over the site and to keep the thermistor cable perfectly vertical.

Water samples were collected with a van Dorn bottle and filtered through 0.45 μm filters in the field. Specific conductance and pH measurements were obtained in the field. Alkalinity by potentiometric titration (end point graphically determined) was measured as soon after collection as possible. Samples for major cations were acidified in the field using HCl and analyzed in the laboratory by induction-coupled plasma spectrophotometry. Samples for anions were analyzed in the laboratory by ion chromatography. Major ions in water collected in the pressurized cylinders were analyzed similarly after the gases were removed. Values for standards and blanks were acceptable and replicated analyses were within ±10%. Most charge balances (measured by cations meq/l:anion meq/l ratios) were within ±10% of 1.0.

The $\delta^{18}O$ was determined by use of a water-CO_2-equilibration technique at 25 °C; measurements were made on a Finnigan MAT 251 mass spectrometer. δD was determined by use of the uranium reduction technique at 850°C; measurements were made on the Finnigan spectrometer. All $\delta^{18}O$ and δD isotope values are reported relative to SMOW and reproducible to within 0.1‰ for oxygen and 1‰ for deuterium. The sulfur isotopic composition of the sulfate was determined by its precipitation with barium and thermal decomposition of the $BaSO_4$ to SO_2. The isotopic composition of the SO_2 was measured using a high resolution, six inch, 60 degree sector mass spectrometer. The $\delta^{34}S$ values are reported relative to the Cañon Diablo troilite standard and reproducible to ±0.1‰.

Gas Methods

Gas bubbles in the soda spring and gases from mazukus were collected in pre-evacuated pyrex tubes. Samples of lake water suitable for gas analysis were collected in pre-evacuated stainless steel cylinders equipped with check valves. When lowered to the desired depth, the cylinder valve is triggered by a sliding messenger. After filling, the check valve holds gas pressure until the cylinder is retrieved at the surface where backup plugs are installed. In the laboratory, gases are extracted and analyzed by gas chromatograph. The CO_2 is purified, dried, and analyzed for isotopes by mass spectrometry. The CH_4 is combusted over CuO and analyzed for isotopes as CO_2. The methods are similar to those described in Evans and others (1988).

Whole-Rock Analysis

Whole-rock chemistry was determined on volcanic rock samples by X-ray fluorescence spectrophotometry. The procedures for sample preparation and analyses are in Taggart and others (1981). The precision of the technique is approximately ±5 percent relative standard deviations.

Radiocarbon Dating

One radiocarbon date was obtained from the University of Arizona's Accelerator Mass Spectrometry Laboratory (Donahue) and one from the U.S. Geological Survey's Radiocarbon Laboratory (Rubin).

APPENDIX B -- EQUIPMENT COST ESTIMATES

Lake Kivu

The expertise to sample and carry out monitoring activities on Lake Kivu are available in country. Drs. Katabarwa and Bariyanga at the Université Nationale du Rwanda (Butare) have already implemented surface surveys of many of the crater lakes around the Birunga Volcanic Zone, Rwanda. Similar expertise is available in Zaire through Dr. Zana (Lwiro). However, equipment is needed to sample waters at depth within the lakes in order to perform the critical monitoring needed to further understand the hazards associated with gases dissolved in Lake Kivu (see Recommendations section) and evaluate potential hazards in other volcanic lakes within the region. The required sampling equipment is inexpensive (cost estimated below).

Cost of required lake-sampling equipment:

van Dorn water sampler and messengers	$500
Field pH meter and 2 electrodes	$600
Field thermistor, 500 m cable, probe	$1200
500 m cable + hand winch with depth gauge	$1500
12 stainless steel gas samplers (@$300)	$3600
Gelman sample filter and pump	$400
500 filters (.45μm)	$150
Miscellaneous (Sample bottles, acid, etc.)	$500
Total estimate	$8450

Birunga Volcanos

The basic volcano-monitoring hardware for two seismic/hydrophone remote stations are given below (costs prepared by R. Koyanagi, Hawaiian Volcano Observatory). These two stations are to be operated near the shore of Lake Kivu -- perhaps near Gisenyi and Kibuye. Signals from these stations would need to be relayed back to a central recording/data analysis center (perhaps in Gisenyi?), and would also need to be coordinated with seismic stations presently installed near Nyiragongo and Nyamuragira by the Centre de Recherches Geologiques et Minieres (Zaire).

Cost of required volcano-monitoring equipment:

Analog 4-channel recorder	$6,000
Telemetry radios (2)	$3,000
Electronics package (4)	$4,000
Antennaes (3)	$1,500
Solar panels (2)	$1,000
Geophones (2)	$2,000
Hydrophones (2)	$2,000
Misc. supplies	$2,500
Total estimate	$22,000*

*The above estimate does not cover travel and subsistence costs for technical advisors during equipment installation.

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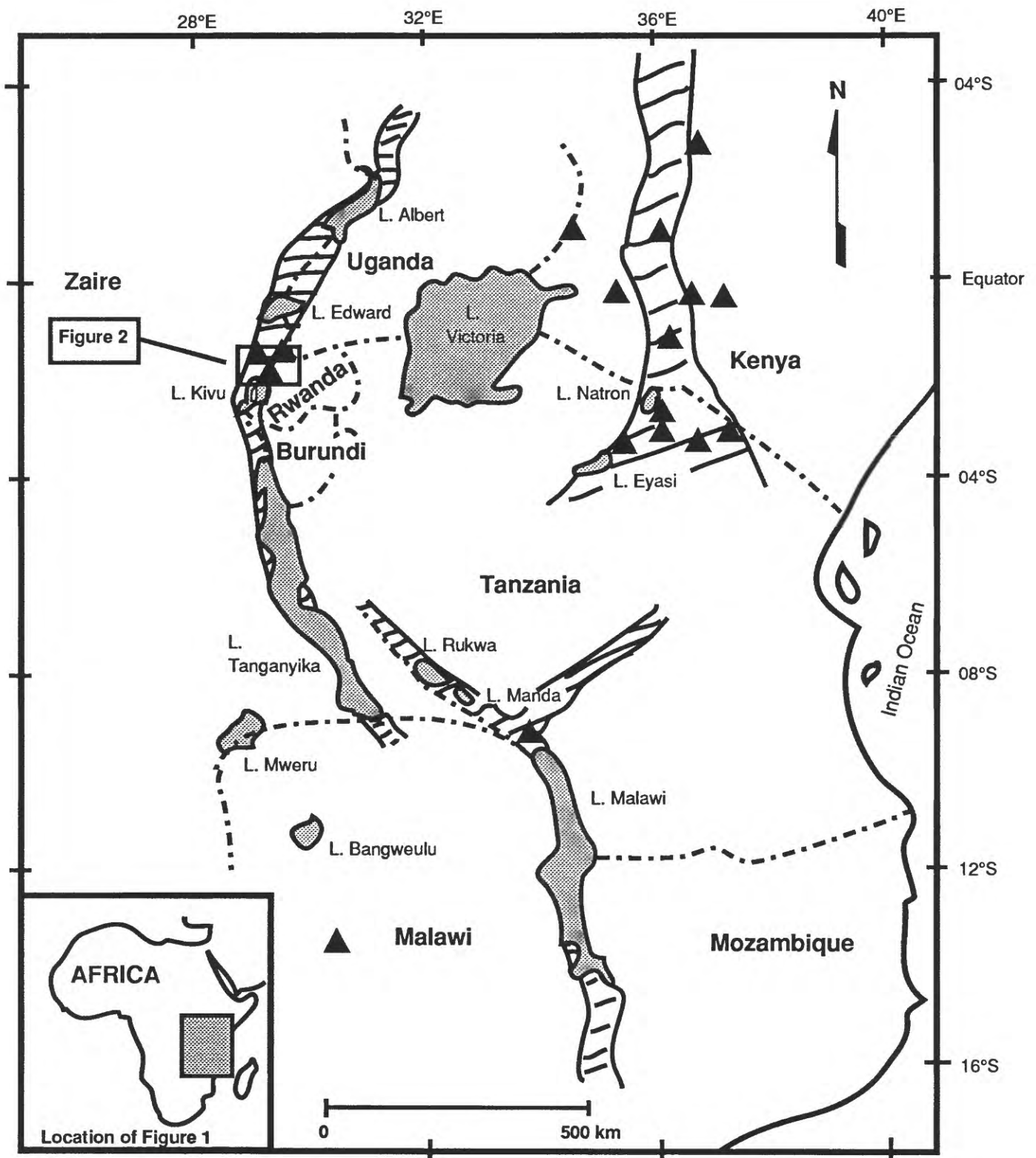
Figure 1. The major "Great Lakes" of East Africa, rift valleys (lined areas), Quaternary volcanoes (filled triangles), and location of Figure 2 (after Ebinger, 1989).
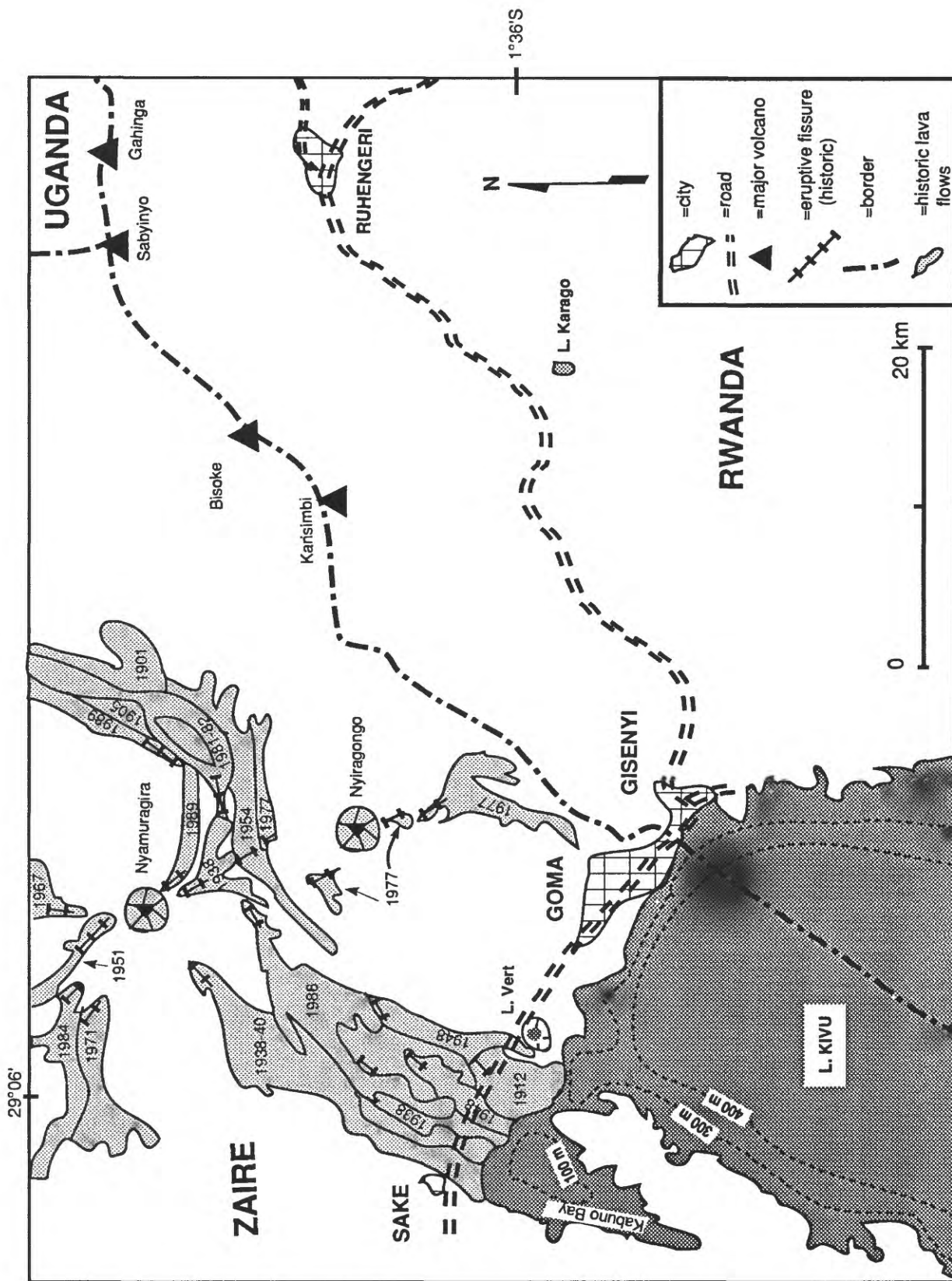
Figure 2. Major volcanoes and generalized distribution of 20th. century lava flows are shown (generalized after Kasahara and Tanaka, 1988; unpublished data of N. Zana and J. Katabarwa). Bathimetry from Degens and others (1973).
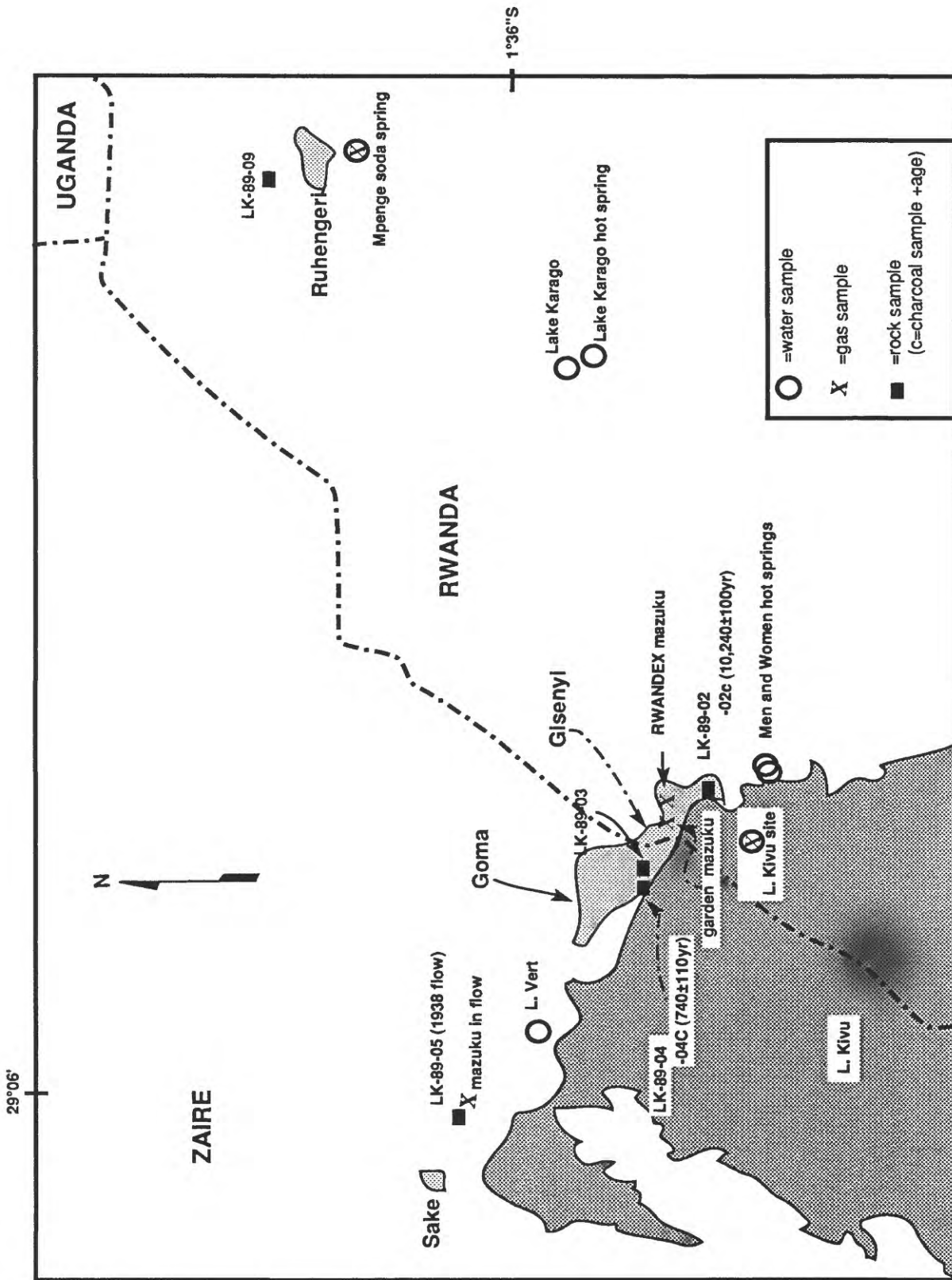
Figure 3. Location of water, rock, and charcoal (c) samples in the north Lake Kivu area.

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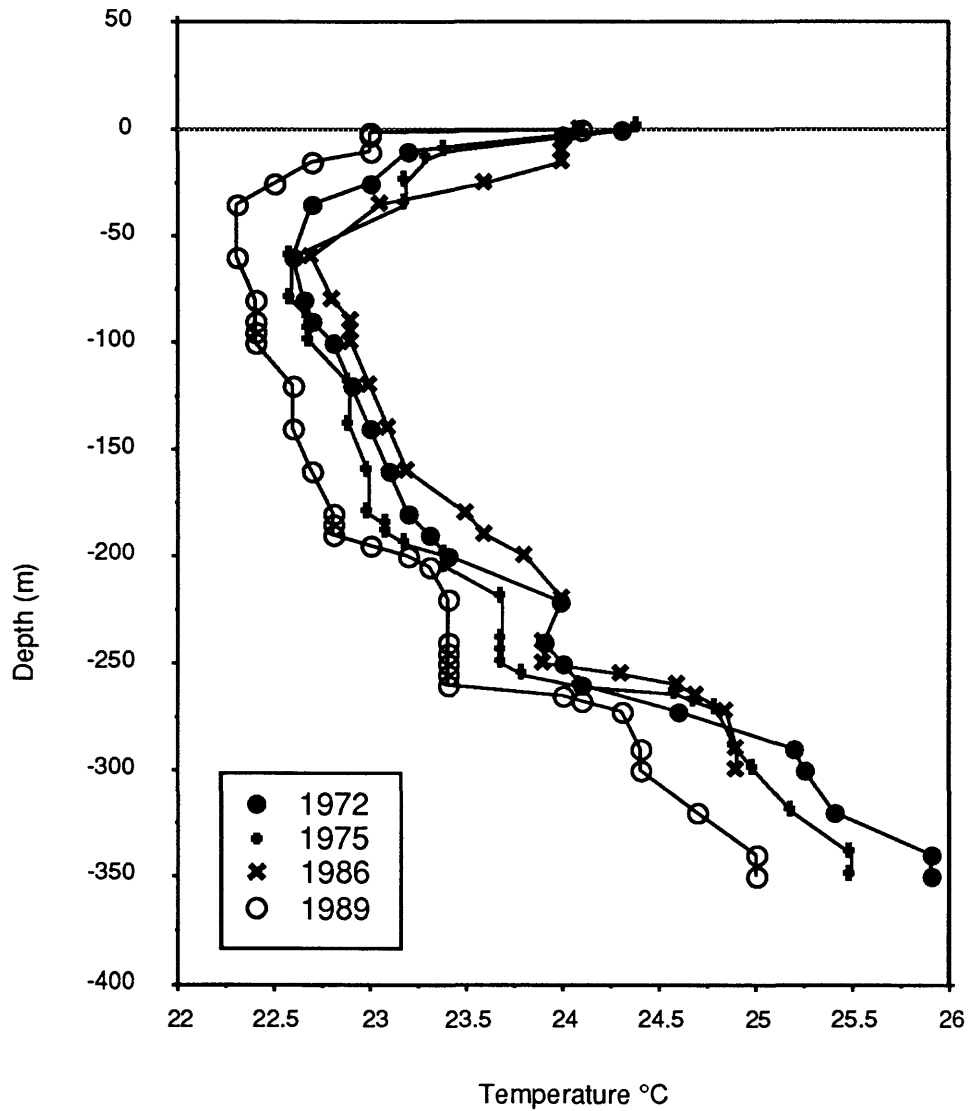
Figure 4. Temperature profile for Lake Kivu August
1989, January-February, 1986 (unpublished
data, C.E.P.G.L.), January, 1975 (Tietz,
1978), and spring, 1971 (Degens and others,
1973).
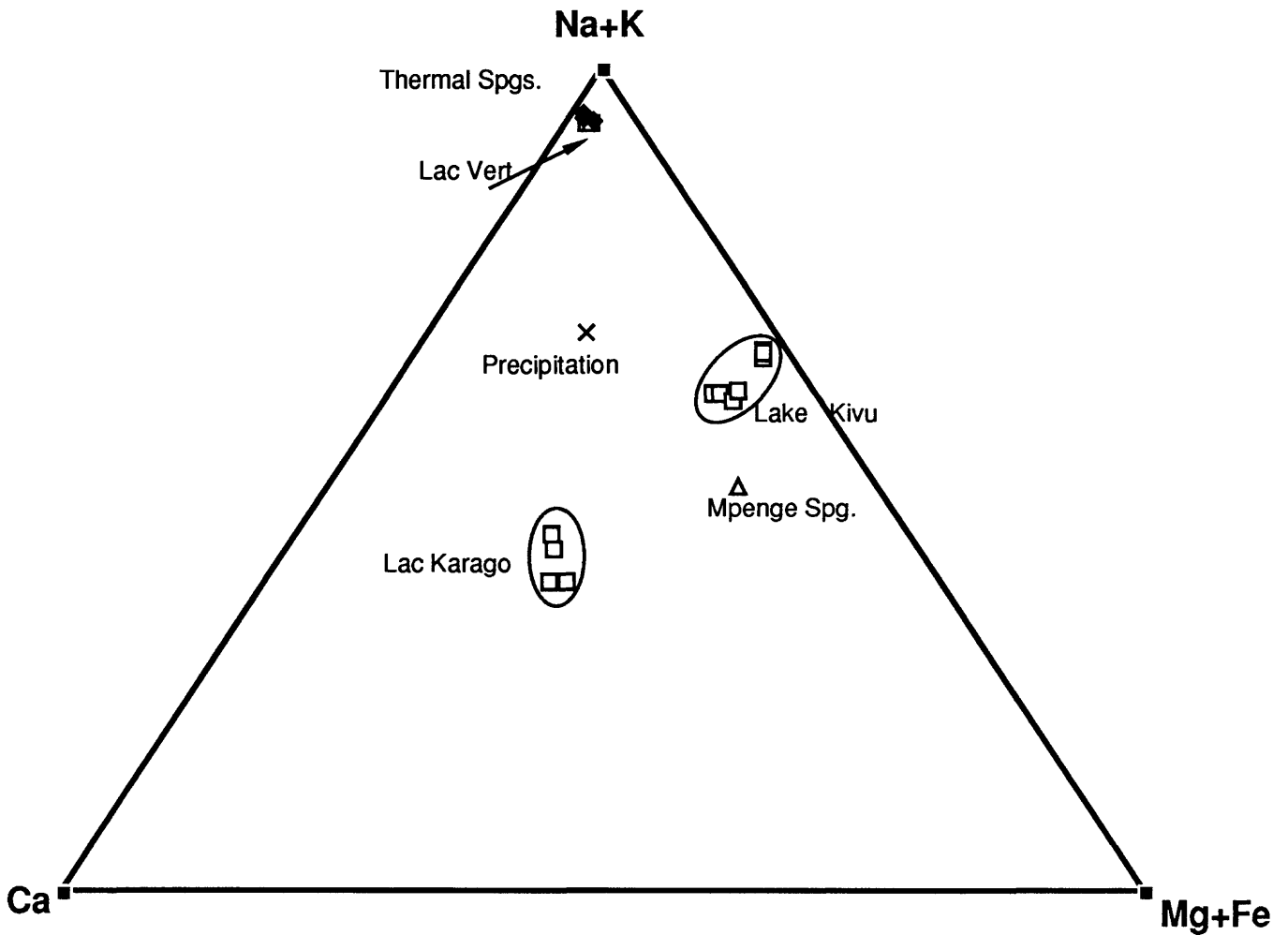
Figure 5. Major cation composition (mole fraction) of the lakes
(open squares), thermal springs (filled squares), soda
spring (open triangle), and precipitation (x) collected
in August, 1989.

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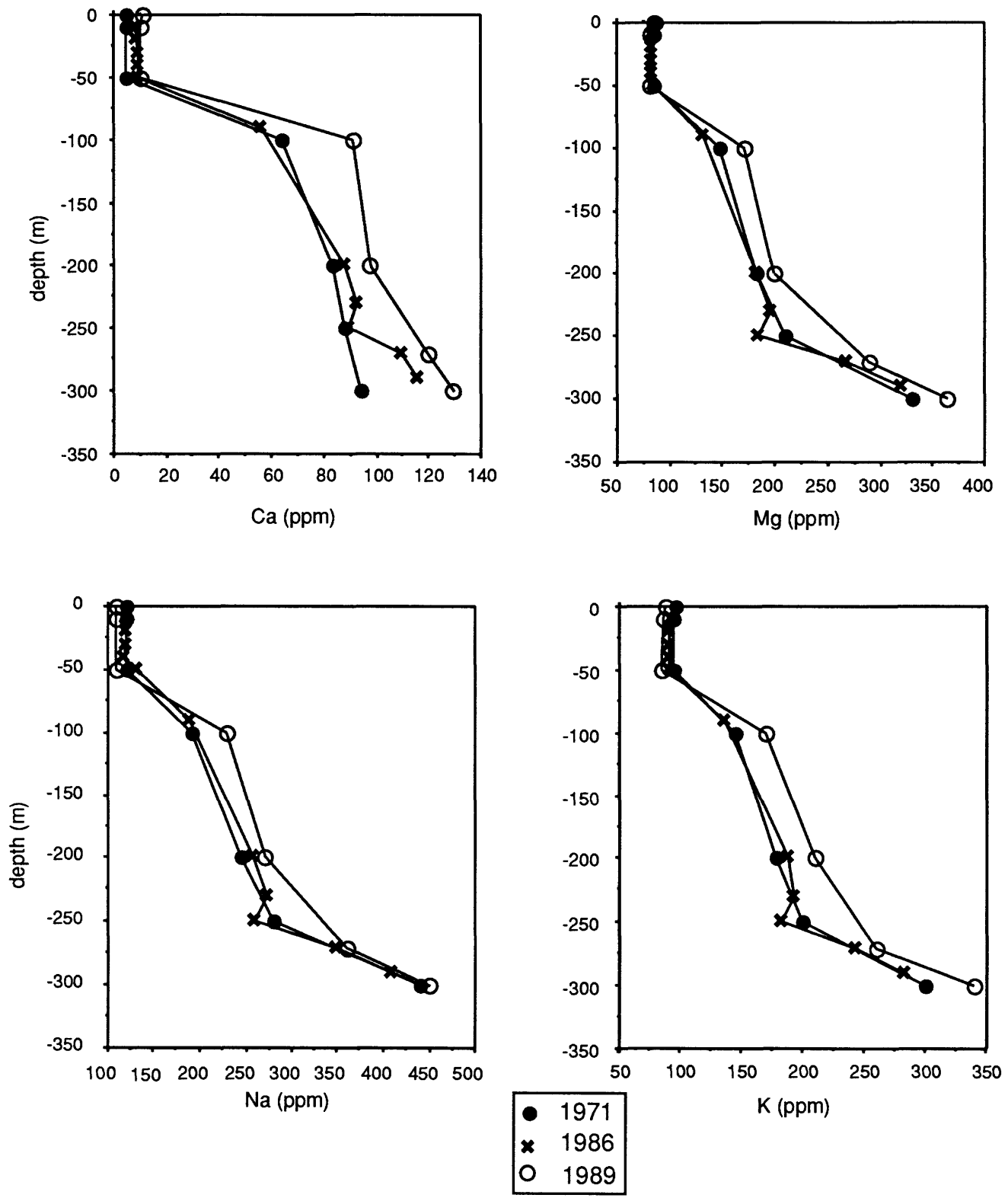
Figure 6. Depth profiles of major-cation concentrations for
Lake Kivu August 1989, January-February, 1986
(unpublished data, C.E.P.G.L.) and spring, 1971
(Degens and others, 1973).
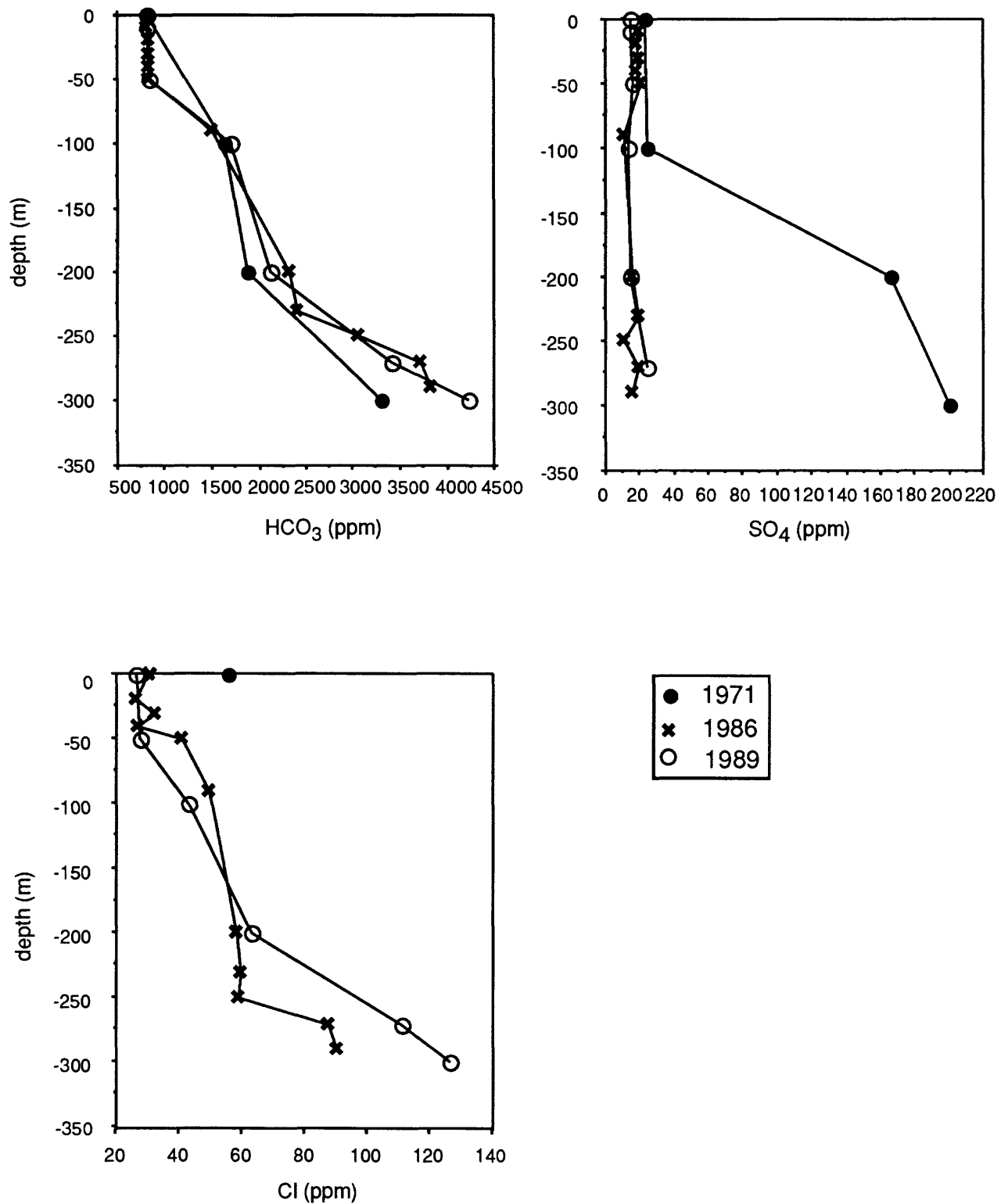
Figure 7. Depth profiles of major-anion concentrations for
Lake Kivu August 1989, January-February, 1986
(unpublished data, C.E.P.G.L.) and spring, 1971
(Degens and others, 1973).
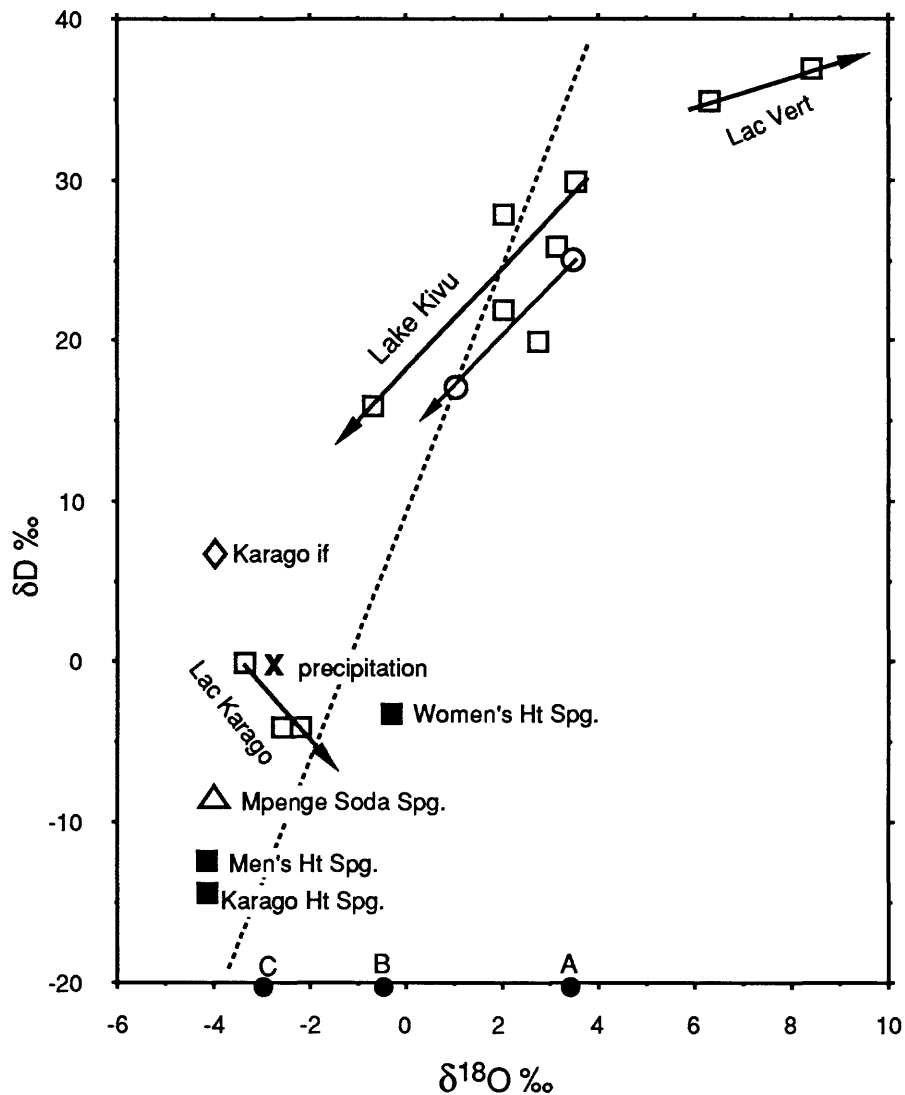
Figure 8. Plot of δD versus δ¹⁸O for lakes (open squares), thermal springs (filled squares), soda spring (open triangle), lake inflow (open diamond), and precipitation (x) collected in August, 1989. All data are reported relative to SMOW standard.

Table 1. Morphometric, geochemical and various other
          features of Lake Kivu, Rwanda/Zaire, and Lake Nyos,
          Cameroon. Data from Degens and others (1973),
          Tietze and others (1980), Tietze (1981); Kling and
          others, 1987; Kling and others, 1989; Kling and
          others, in press)

Feature	Lake Kivu	Lake Nyos
Elevation (m)	1500	1094
Area (km^2)	2060	1.58
Volume (km^3)	580	0.18
Maximum depth (m)	435	208
pH		
surface water	9	6.0
bottom water	7	5.2
Surface conductivity (mS/cm)	6.0	0.1
Water-Column stability (J/m^2)	340,000	64,000

Table 2. Rwanda/Zaire water chemistry and isotopy; +, summation of cation concentrations (meq/l); -, summation of anion concentrations (meq/l).

Sample	Al ppm	Ca ppm	Fe ppm	K ppm	Mg ppm
L. Vert surface	0.3	10	0.3	48	2.6
L. Vert 17m	<.1	10	0.2	49	2.9
L. Kivu surface	0.2	11	<.1	89	85
L. Kivu 10m	0.2	10	<.1	86	82
L. Kivu 50m	0.2	10	<.1	85	82
L. Kivu 100m	0.4	91	<.1	170	170
L. Kivu 200m	0.5	100	0.1	200	210
L. Kivu 200m*	0.3	96	0.7	210	200
L. Kivu 270m	0.8	120	<.1	260	290
L Kivu 300m*	0.5	130	0.4	340	360
L. Karago inflow	<.1	17	<.1	6.9	7.4
L. Karago surface	0.1	16	0.1	6.6	6.8
L. Karago 27.6m	<.1	17	<.1	6.7	7.4
L. Karago 33.3m	0.6	16	0.8	6.9	7.4
Mans Ht Spg	<.1	22	<.1	15	2.5
Karago Ht Spg	0.3	23	0.4	16	2.7
Womens Ht Spg	<.1	40	0.3	40	12
Mpenge Spg	0.5	110	5.8	150	190
Precip	<.1	0.4	<.1	0.5	0.2

Sample	Na ppm	Si ppm	B ppb	Ba ppb	Be ppb
L. Vert surface	95	9.8	75	12	<1
L. Vert 17m	97	9.2	63	11	<1
L. Kivu surface	110	1.7	61	29	<1
L. Kivu 10m	110	1.6	56	29	<1
L. Kivu 50m	110	2	59	29	<1
L. Kivu 100m	230	26	190	340	<1
L. Kivu 200m	280	34	260	480	<1
L. Kivu 200m*	270	23	250	410	<1
L. Kivu 270m	360	47	350	530	<1
L. Kivu 300m*	460	35	480	520	<1
L. Karago inflow	8	17	15	33	<1
L. Karago surface	8.2	14	15	44	<1
L. Karago 27.6m	6.2	14	17	49	<1
L. Karago 33.3m	6	14	18	87	<1
Mans Ht Spg	260	64	99	190	3
Karago Ht Spg	250	65	97	200	4
Womens Ht Spg	510	43	580	350	11
Mpenge Spg	150	52	81	130	<1
Precip	0.6	<.1	<10	6	<1

*Pressurized cylinder water samples

Sample	Cr ppb	Cu ppb	Li ppb	Mn ppb	Ni ppb
===============	========	========	========	========	========
L. Vert surface	2	<10	19	46	<5
L. Vert 17m	2	<10	21	70	<5
L. Kivu surface	1	<10	50	220	<5
L. Kivu 10m	1	<10	49	60	<5
L. Kivu 50m	<1	<10	49	29	<5
L. Kivu 100m	<1	<10	100	340	<5
L. Kivu 200m	17	<10	150	460	6
L. Kivu 200m*	<1	<10	130	540	<5
L. Kivu 270m	<1	<10	180	510	<5
L. Kivu 300m*	<1	<10	200	670	<5
L. Karago inflow	1	<10	20	<10	<5
L. Karago surface	3	29	16	24	<5
L. Karago 27.6m	<1	<10	16	160	51
L. Karago 33.3m	3	46	16	1000	<5
Mans Ht Spg	2	<10	420	120	<5
Karago Ht Spg	8	45	420	280	10
Womens Ht Spg	<1	<10	440	64	<5
Mpenge Spg	<1	<10	54	340	9
Precip	<1	<10	<4	<10	<5

Sample	Sr ppb	Ti ppb	Zn ppb	+meq/l	F ppm
===============	========	========	========	========	========
L. Vert surface	270	47	4	6.1	4.1
L. Vert 17m	280	11	<3	6.2	10
L. Kivu surface	200	4	4	15	1.8
L. Kivu 10m	200	4	6	14	1.6
L. Kivu 50m	200	3	<3	33	1.2
L. Kivu 100m	2600	<1	<3	40	2.9
L. Kivu 200m	3600	2	6	38	2.5
L. Kivu 200m*	3100	<1	<3	38	2.9
L. Kivu 270m	4500	1	<3	66	5.2
L. Kivu 300m*	4400	120	<3	64	4.7
L. Karago inflow	180	<1	<3	1.9	2.5
L. Karago surface	190	18	5	1.9	0.67
L. Karago 27.6m	200	4	9	13	0.38
L. Karago 33.3m	200	140	8	13	0.9
Mans Ht Spg	540	4	<3	26	7.2
Karago Ht Spg	550	39	13	32	12
Womens Ht Spg	800	5	<3	26	4.9
Mpenge Spg	2300	<1	4	21	1.4
Precip	5	<1	<3	0.06	0.08

Sample	Cl ppm	NO3 ppm	PO4 ppm	SO4 ppm	HCO3 ppm
L. Vert surface	17	0.4	<	1.5	345
L. Vert 17m	34	5.6	<	2.6	366
L. Kivu surface	25	<	<	14.5	820
L. Kivu 10m	28	<	<	14.1	820
L. Kivu 50m	27	<	<	15.7	830
L. Kivu 100m	42	<	<	13	1700
L. Kivu 200m	62	0.1	0.5	15	2130
L. Kivu 200m*	95	nd	nd	nd	2370
L. Kivu 270m	110	1.0	1.8	25	3405
L. Kivu 300m*	125	nd	nd	nd	4230
L. Karago inflow	8.4	7.3	<	9	nd
L. Karago surface	6.2	4.0	<	11.7	81
L. Karago 27.6m	5	0.9	<	10.7	nd
L. Karago 33.3m	6.3	6.6	<	8.3	90
Mans Ht Spg	61	<	<	39	560
Karago Ht Spg	82	1.6	<	61	575
Womens Ht Spg	221	<	<	49	nd
Mpenge Spg	22	5.0	<	42	1935
Precip	1.14	0.3	<	1.46	nd

Sample	- meq/l	pH	∂180	∂D	+meq/-meq
L. Vert surface	6.4	8.3	6.3	35	0.95
L. Vert 17m	7.5	7.9	8.4	37	0.82
L. Kivu surface	15	8.9	3.1	26	1.00
L. Kivu 10m	15	9.0	2.0	28	0.97
L. Kivu 50m	15	9.0	3.5	30	0.96
L. Kivu 100m	29	6.7	2.7	20	1.12
L. Kivu 200m	37	6.6	2.0	22	1.07
L. Kivu 200m*	39	nd	nd	nd	0.98
L. Kivu 270m	60	6.6	-0.7	16	0.87
L. Kivu 300m*	73	nd	nd	nd	0.88
L. Karago inflow		nd	-4.0	7	--
L. Karago surface	1.8	9.3	-3.4	0	1.06
L. Karago 27.6m		7.1	-2.6	-4	--
L. Karago 33.3m	1.9	7.7	-2.2	-4	0.99
Mans Ht Spg	12	6.8	-4.3	-12	1.07
Karago Ht Spg	14	7.4	-4.4	-14	0.93
Womens Ht Spg		6.8	-0.4	-3	--
Mpenge Spg	33	6.6	-4.1	-8	0.95
Precip		nd	-2.7	0	--

Table 3. Rwanda/Zaire gas chemical and isotopic composition. Concentrations in volume percent except where noted. Isotopic compositions relative to PDB standard. na, not analyzed; nd, not detected.

Sample	He*	H2	Ar*	O2*	Air Vol %*	N2*	CH4
Mpenge Soda Spg.	0.0472	<.0001	0.117	0	0.74	6.95	0.0075
Sake Mazuku	0.0016	0.0001	0.432	0	2.03	37.19	2.97
Factory Hole	0.0022	<.0001	<.01	0	83.31	9.71	<.0002
Sunken Garden	0.0026	<.0001	<.01	0	69.67	3.02	<.0002
L. Kivu 200 m	0.0011	<.0008	0.019	<.008	0	0.916	11.3
L. Kivu 300 m	0.00092	<.0002	0.0063	<.002	0	0.358	16.2

Sample	CO2	C2H6	H2S	CO	HCN	SO2	C3H8
Mpenge Soda Spg.	93.32	<.0002	<.0002	<.001	<.001	na	nd
Sake Mazuku	58.37	0.0632	<.0002	<.001	<.001	<.0005	<.0005
Factory Hole	89.83	<.0002	<.0002	<.0005	<.0005	<.0005	nd
Sunken Garden	96.82	<.0002	<.0002	<.0005	<.0005	na	nd
L. Kivu 200 m	87.72	0.012	<.0005	<.0008	na	na	0.001
L. Kivu 300 m	83.22	0.0132	0.206	<.002	na	na	0.0015

Sample	iC4H10**	nC4H10**	C5group**	C6 group**	Sum (vol %)	$\delta^{13}C$ CO2	$\delta^{13}C$ CH4
Mpenge Soda Spg.	nd	nd	nd	2	100.43	-8.5	na
Sake Mazuku	7.58	0.33	2.16	13	99.06	na	na
Factory Hole	nd	nd	0.13	1.1	99.54	-9.2	na
Sunken Garden	nd	nd	nd	nd	99.84	-8	na
L. Kivu 200 m	na	na	na	na	99.97	-6.1	-57.9
L. Kivu 300 m	na	na	na	na	100	-5.7	-57.2

*O2 used to determine % air volume and stoichiometrically correct values of N2, Ar, and He for air contamination.

**in ppm (analyzed by Tom Lorenson, U.S. Geological Survey).

Table 4. Comparison of Lake Kivu Gas Data. Concentrations are in μmol/kg-fluid; --, not reported

Data Set-Depth m	CO_2	CH_4	N_2	C_2H_6	C_3H_8
Kiss-200m	19190	--	--	--	--
Degens-200m	14800*	--	--	--	--
Tietze-200m	11150	3350	410	--	--
This study-200 m	23450	3030	245	3.3	0.4
S&K-300 m	62020	14390	--	--	--
Kiss-300m	24990	--	--	--	--
Degens-300 m	69200*	18740	--	29	9.5
Tietze-300m	67820	14100	410	--	--
This study 300 m	84250	16400	362	13.4	1.5

Data Set-Depth m	H_2S	O_2	Ar	He	H_2
Kiss-200m	--	--	--	--	--
Degens-200 m	--	--	--	--	--
Tietze-200m	--	--	--	--	--
This study-200 m	<1	<2	5.1	0.29	<.2
S&K-300 m	--	--	--	--	--
Kiss-300m	281	--	--	--	--
Degens-300 m	--	--	--	--	--
Tietze-300m	--	--	--	--	--
This study 300 m	209	<2	6.4	0.93	<.2

*calculated from DIC (sum of CO_2) values given in Degens and others (1973)
S&K data from Schmitz and Kufferath (1955). Sampling year unknown.
Kiss data from Kiss (1966). Sampling year unknown.
Degens data from Degens and others (1973). Samples collected in 1971.
Tietze data from Tietze and others (1980). Samples collected in 1975.

Table 5. Major element chemistry of volcanic rocks from the Birunga Volcanic Zone.

Sample No.	Type	SiO2 wt%	Al2O3 wt%	FeTO3* wt%	MgO wt%	CaO wt%	Na2O wt%
=======	=======	=======	=======	=======	=======	=======	=======
Lk-89-02	Scoria	44.5	13.3	12.6	8.3	11.9	3.98
Lk-89-03	Magmatic bomb	39	14.7	13.9	4.49	12.8	5.08
Lk-89-04	Pahoehoe	38.9	14.9	13.6	4.07	12.5	5.11
Lk-89-05	1938 Pahoehoe	45.3	16.1	13.1	5.08	9.83	3.35
Lk-89-09	Pyroclastic flow	60.8	15.1	6.55	2.41	4.37	3.12

Sample No.	Type	K2O wt%	TiO2 wt%	P2O5 wt%	MnO wt%	LOI** wt%	Totals
=======	=======	=======	=======	=======	=======	=======	=======
Lk-89-02	Scoria	0.89	3.39	0.55	0.19	0.78	100.38
Lk-89-03	Magmatic bomb	4.14	3.28	1.78	0.28	0.21	99.66
Lk-89-04	Pahoehoe	5.26	3	1.75	0.3	<.01	99.39
Lk-89-05	1938 Pahoehoe	3.49	3.74	0.67	0.2	<.01	100.86
Lk-89-09	Pyroclastic flow	4.85	1.63	0.46	0.08	0.07	99.44

*Total iron reported as Fe2O3.
**Loss on ignition at 925°C.

Table 6. Radiocarbon dates from the Birunga Volcanic Zone.

Field Sample No.	Laboratory No.	Locality	Radiocarbon ages (yrs. b.p.)	Analyst
=====	=======	========	================	=======
Lk-89-02	AA5334	Gisenyi scoria cone, Rwanda	10,240 ±100	Donahue
Lk-89-04	W6206	Goma nephelinite pahoehoe, Zaire	740 ±110	Rubin

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