Feature

Taming the killer lakes of Cameroon

A chain of volcanoes, some of them still active, extends from the Atlantic Ocean into the highlands of Cameroon. Mount Cameroon, located at the edge of the continent, erupted in 1999 and 2000 and spewed lava part-way down its flanks, cutting off a coastal road. A number of the now extinct (or dormant) volcanic craters on the continental part of the line are filled with water, forming crater lakes. These lakes have achieved mythical status in local tribal lore. Lacking a written history, prior to the arrival of the colonial powers, much of our understanding of past natural phenomena relating to the lakes is based on these myths.

G. Nelson Eby[1] and William C. Evans[2]

[1]Department of Environmental, Earth, & Atmospheric Sciences, University of Massachusetts, Lowell, MA, USA. email: Nelson_Eby@uml.edu

[2]United States Geological Survey, 345 Middlefield Rd, M/S 434, Menlo Park, CA, USA

In Cameroon, a chain of volcanoes (the Cameroon Volcanic Line) extends from the Atlantic Ocean in a north-east direction into the highlands of the country (Fig. 1). This part of Cameroon's Northwest Province (the Grassfields) is populated by multiple ethnic groups. There are three major language groups, and societies are organized along patriarchal or matriarchal lines. Despite these differences, similar themes in creation and migration myths are shared across many of the groups. Central to these myths are the concepts of good and evil water. An exploding lake is dominates one migration myth, while others speak of evil lakes that transfer from one location to another. Much of our understanding of past natural volcanic phenomena in Cameroon is based on these myths.

Exploding lakes

Lake Monoun On the night of 15 August 1984, myth became reality when a gas eruption at Lake Monoun killed 37 people in the immediate vicinity of the lake. Villagers living in the area reported that a loud boom came from the lake at about 11:30 PM. Subsequent reports of people dying on the road by Lake Monoun led to a police officer and doctor visiting the area at about 6:30 AM. They found a number of casualties along a low part of the road passing the lake. At the time they reported the presence of a low-lying whitish cloud that had an acrid smell. A number of dead animals were also found in the area. Rumours about the event spread rapidly throughout the region. The cause of the accident was ascribed to either purposeful activities by humans (such as clandestine military activities or the dumping of hazardous chemicals), or natural volcanic phenomena. At the request of the government of Cameroon and the US Agency for International Development, Haraldur Sigurdsson (University of Rhode Island) led a team to investigate the cause of the disaster.

Lake Monoun occurs within the Foumbot Crater Field, part of the Cameroon Volcanic Line. The lake was formed when a prehistoric lava flow formed a dam. Subsequent volcanic activity produced two craters in the floor of the lake. The lake is elongated in a SW-NE direction, and is approximately 1.5 km long and 0.5 km wide. The western crater has relatively gentle-slopping walls and reaches a depth of 50 m while the eastern crater has steeply dipping walls and reaches a depth of 96 m.

Several observations were made immediately following the event: 1, the vegetation at the east end of the lake was flattened and the damage pattern suggested that there was a wave that rose 5 m above the lake's normal water level; 2, there was a 100 m long scarp at the eastern end of the lake, at the edge of the crater, indicating that a significant landslide had occurred; and 3, the normally clear surface waters were reddish brown in colour.

Dr Sigurdsson and his colleagues arrived at Lake Monoun seven months after the event. They investigated the chemistry and mineralogy of the bottom sediments and the chemistry of the water column. They found no chemical signatures indicative of anthropogenic inputs to the lake. They observed that water samples collected at depth

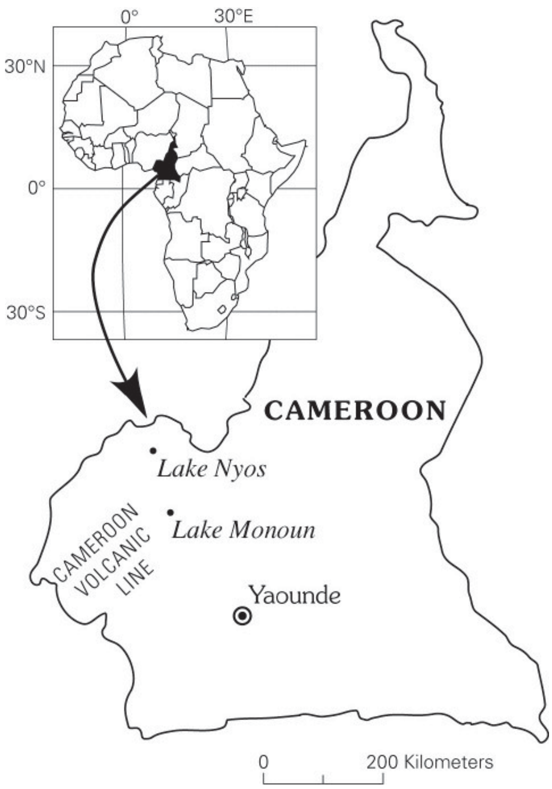

Fig. 1. Location map for the Cameroon Volcanic Line and the Lakes Monoun and Nyos.

Fig. 2. Lake Nyos, September 1990. At the right of the picture note the water flowing across the pyroclastic dam forming a waterfall.

vigorously effervesced when brought to the surface, and then precipitated copious amounts of ferric hydroxide. The dissolved gases were carbon dioxide (CO_2 ~97 per cent) and methane (CH_4). Other gases only occurred in trace amounts.

The deep waters of Lake Monoun are anoxic, as evidenced by the presence of methane, and iron is stable as Fe^{2+}. When the deep waters are exposed to air the iron is oxidized to Fe^{3+}, leading to the precipitation of ferric hydroxides. The source of the iron in the lake was inferred to be wind blown lateritic dust. Based on chemical equilibrium reactions the pressure of CO_2 in the deep waters could be as great as 10 atm (compare this to the normal atmospheric pressure of CO_2 of 0.0035 atm). It was concluded that a landslide into the crater triggered an overturn of the deep water. The CO_2, which was dissolved in the water at amounts far exceeding atmospheric pressure, effervesced leading to an explosive eruption of the lake (much like shaking a carbonated beverage bottle and then releasing the cap). Carbon dioxide gas is denser than normal air and toxic at concentrations exceeding 10 per cent. This cloud of CO_2 gas spilled out of the lake into surrounding low areas and proved fatal to humans and animals. The reddish-brown colour of the lake water noted after the event was due to the oxidation and precipitation of the ferrous iron dissolved in the deep waters. The disaster, hence, was due to a natural, but unusual, phenomenon.

Lake Nyos On 21 August 1986, nature repeated itself when a gas eruption at Lake Nyos (Fig. 2) led to more than 1700 deaths. Two or three violent explosions were reported between 9 and 10 PM. One local resident ventured to the edge of the high cliffs overlooking the lake and reported seeing a fountain of mist that looked like smoke coming up out of the lake, followed by a huge surge of water washing up the southern shore. Fortunately he then ran toward the hilltop village and escaped the suffocating cloud.

After the event, the hilltop villagers ventured down to find that their friends and relatives near the lake had died. Unconsciousness had obviously come quickly giving them little time to react. The lucky few survivors who recovered after many hours of unconsciousness remembered passing out within seconds of sensing an acrid cloud. The extent of damage to the surrounding vegetation suggested that a 15–20 m high wave ravaged the southern shore (Fig. 3). In addition, as was the case for lake Monoun,

Fig. 3. Wave damage at the southern end of Lake Nyos. August 1986.

the water had a reddish-brown colour for several weeks after the event. The magnitude of the disaster, plus the recent event at lake Monoun, led to an immediate international response.

Lake Nyos occupies a young maar crater. With a maximum depth of 210 m, it is much deeper than Lake Monoun and the deep waters are at much greater pressure (note: one can calculate this pressure from the equation: hydrostatic pressure = water density × acceleration due to gravity × depth). The hydrostatic pressure at a depth of 210 m is ~20 atm. Therefore, at saturation, Lake Nyos can hold a significant amount of CO_2. A stream valley draining northward from the lake provided a natural channel way for the Nyos gas cloud. The village of Nyos, where the greatest number of deaths occurred, lies at the bottom of this valley. A conspicuous 80-metre high landslide scar on the cliffs that loom over the lake marks the apparent trigger for the overturn of the deep water, but a variety of alternative hypotheses have been advanced to explain this overturn.

Source of the carbon dioxide

What is the source of the CO_2 – organic, from the decay of organic matter, or inorganic? All modern carbon contains ^{14}C, a radioactive isotope of carbon produced by interactions in the atmosphere between nitrogen and the cosmic ray flux. Any living organism is in equilibrium with atmospheric carbon, and is therefore slightly radioactive. At the present time, the expected radioactivity would be approximately 13.56 dpm/g (decays per minute per gram of carbon). Once an organism dies, it no longer exchanges carbon with the atmosphere and the radioactivity decreases with a half-life of 5700 years. This, of course, is the basis of the radiocarbon dating method widely used in anthropology and archaeology, among other fields. Magmatic carbon contains no ^{14}C. The dissolved carbon in Lake Monoun has an activity of 1.48 dpm/g. Hence, we can calculate the per cent modern (organic) carbon in the lake by dividing the observed activity by the expected activity (13.56 dpm/g) and multiplying by 100. The result is approximately 11 per cent modern carbon. That is, most of the carbon in the lake does not come from the decay of organic matter. A similar calculation for Lake Nyos yielded a value of less than 1 per cent modern carbon.

There are also two stable isotopes of carbon, ^{12}C and ^{13}C. Chemical, physical and biological processes will change the relative abundance of these two isotopes. Thus different sources of carbon have different isotopic ratios. Calculations using stable carbon isotopes also indicate that these lakes contain very little organic carbon. Finding magmatic helium in the lakes (using He isotopes) also supports a magmatic origin for the CO_2 in the lakes.

Hence, we can conclude that the CO_2 is of magmatic origin. The absence of significant amounts of sulphur and halogens, typically associated with high-temperature volcanic gas emissions, suggests that the direct injection of volcanic gases is not the source of the CO_2. The CO_2 is apparently derived from the slow degassing of magma at depth, the CO_2 diffusing along fracture zones into the lakes.

Will carbon dioxide continue to accumulate in the lakes?

If the CO_2 is derived from the degassing of magma at depth, will the gas continue to build up in lakes Monoun and Nyos? Once again revisiting local myths, the stories of exploding and evil lakes suggests that these gas releases have occurred in the past and can be expected to occur in the future. Monitoring of Lake Nyos since the 1986 gas eruption has shown a steady increase in CO_2 in the deep waters of the lake (Fig. 4). A similar situation has also been found at lake Monoun.

What geological hazards are associated with the lakes?

The geological hazards associated with these lakes are of two types. In the case of both lakes Monoun and Nyos, the catastrophic release of CO_2 is an ever-present danger, as indicated by the increase in CO_2 in the deep waters. Lake Nyos has an additional hazard. The crater is located in granite, but a pyroclastic dam (Fig. 2), approximately 40 m thick, impounds the water at a higher level. This natural dam is developing fractures (Fig. 5) and shows potential for

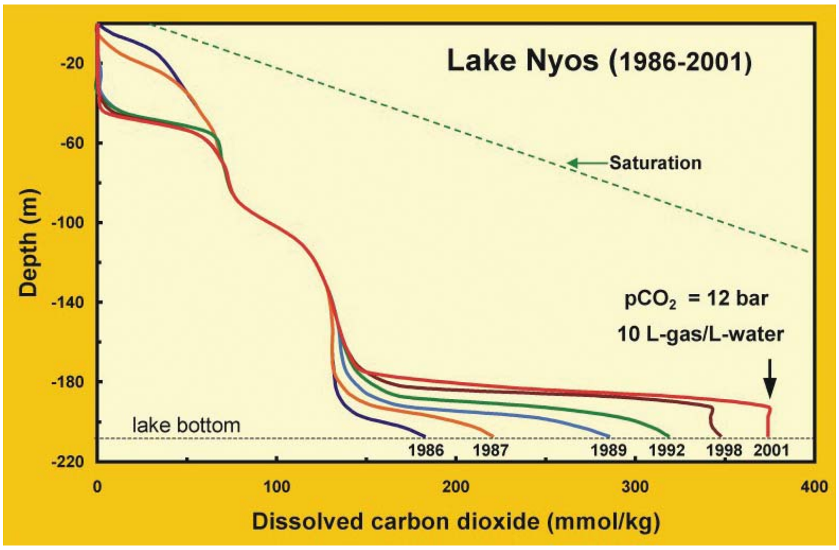

Fig. 4. Change in CO_2 concentrations in the deep waters of Lake Nyos.

Fig. 5. Fractures in the pyroclastic dam at Lake Nyos.

failure. The failure of this dam would cause both significant downstream flooding and a catastrophic release of CO_2.

Mitigation of the geological hazards

Multiple approaches have been used to address the geological hazards. The initial response of the Government of Cameroon was to prohibit settlement in the Lake Nyos area. The remaining residents were evacuated from the town of Nyos and the area was fenced. This solution had a very short lifetime as the presence of dwellings and good arable land led to the return of inhabitants.

Given that a prohibitive solution did not work, alert systems were put into place near the lakes that would allow for sufficient warning for an evacuation to occur. The alert system consists of a CO_2 monitor that is solar powered with a battery backup (Fig. 6). CO_2 is a good absorber of infrared radiation. The absorption of infrared radiation by air passing through the monitor is used to measure the CO_2 content. When the CO_2 concentration exceeds 0.5 per cent, both lights and sound are used to signal an alert. The Lake Monoun monitor is located in the low area next to the road where a number of deaths occurred during the 1984 gas disaster. The Lake Nyos monitoring station is located on the pyroclastic dam. Meetings were held with local residents to plan a proper evacuation response to an alert.

Plans to remove the gas

Scientists began seeking a more permanent solution to the problem of exploding lakes soon after the Nyos disaster occurred. They knew that it would be impossible to stop the steady influx of magmatic CO_2 at the lake bottom and focused instead on methods for preventing the gas from accumulating in the water column. One early suggestion was to drop explosive charges into the lakes and try to stimulate the release of more CO_2 while the surrounding area was evacuated. This idea was quickly rejected, in part out of fear that the explosions might induce a failure of the natural dam at Nyos. Removal of the gas would have to be done gradually and at a controlled rate. The easiest way to accomplish this seemed to be through piping.

In principle, piping the gas out of the lakes seems straightforward. A pipe is suspended vertically in the lake and extends down into the gas-rich waters at depth. The top of the pipe is fixed securely to an anchored raft (Fig. 7). Initial pumping removes surface water from the pipe and brings the gas-rich water up to a level where bubbles can nucleate. Once bubbles form, the reduction in density of the water–gas mixture leads to buoyant upflow and suction of additional water into the bottom of the pipe. Soon, a self-sustaining fountain shoots out the top of the pipe, and pumping is no longer needed (Fig. 8). Because no external energy sources or moving parts are required, piping was universally endorsed as the method of choice for gas removal.

From plans to pipes

After initial tests in the early to mid-1990s demonstrated the feasibility of the method, no funding for a permanent pipe installation materialized until the 1999 and 2000 eruptions at Mount Cameroon reawakened public awareness of volcano-related hazards. Pressure for hazard mitigation resulted in a grant from the US Office of Foreign Disaster Assistance to install one permanent pipe in each lake. The Government of Cameroon provided in-country support, and Data Environment of France performed the installations.

Deployment of the degassing pipes was certainly not as simple as envisioned. Frictional forces on the walls caused the first pipes tested to be driven partially up out of the water, even lifting weighted rafts and pulling up heavy anchors. The need to shut down the flow in case of problems meant that valves would be installed, bringing problems of corrosion

Fig. 6. CO_2 monitoring system at Lake Monoun.

Fig. 7. Raft supporting the pipe at Nyos. Control equipment on raft in the background.

Fig. 8. 45 m high fountain on Lake Nyos.

and the need for an external power source in an area far past the end of transmission lines. An unanticipated, but not surprising, occurrence was the rapid build-up of ferric oxyhydroxide coatings on the rafts and valves (Fig. 9). After less than two years of operation, more than 800 kg of these coatings were chipped off the Nyos raft, just in time to prevent its sinking. Operational methods were eventually adjusted, and one pipe now functions nearly continuously in each of the two lakes.

Benefits of piping

Piping must remove gas at a rate that is at least as fast as the natural inflow of gas at the lake bottom in order to be effective at hazard mitigation. The current piping operations accomplish this, and the huge amounts of dissolved gas stored in both lakes are now declining with time. The 203 m long Nyos pipe (14 cm ID) was installed in 2001, and within a few years the drop in CO_2 concentrations was readily detectable. The Monoun pipe was installed in 2003, just as dissolved gas pressures were reaching saturation level in the 55–60 m depth interval (Fig. 10). Within one year, this 73 m pipe has created a small but noticeable margin of safety within this zone.

Fig. 9. Ferric oxyhydroxide build-up on control valves. 800 kg of precipitate had to be removed from the Nyos raft to prevent sinking.

Additional pipes that reach to the lake bottom are planned for both lakes. Although it might seem best to put in as many pipes as possible, piping up the anoxic, Fe^{2+}-rich bottom water too quickly could deplete all the oxygen in the surface water, killing the normal biota in the lakes. The present rate of piping has reduced the surface oxygen levels, but fish have been able to survive in both lakes. Once gas contents in Lake Nyos have been reduced to safe levels, the natural pyroclastic dam can be progressively lowered and removed, eliminating once and for all the threat of flooding.

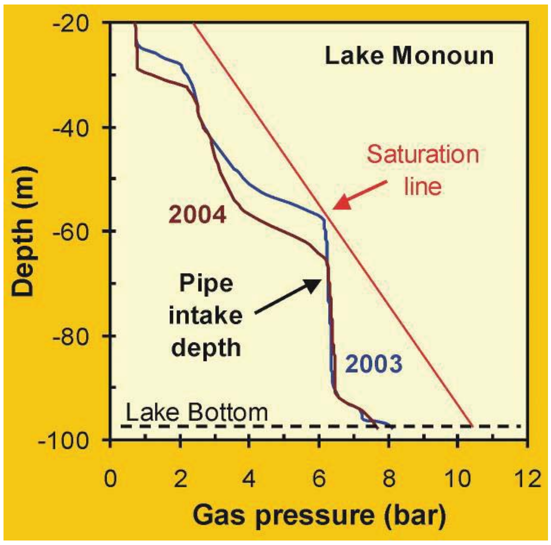

Fig. 10. Dissolved gas pressures in Lake Monoun.

The Nyos and Monoun disasters spurred the completion of a survey of other Cameroonian crater lakes. None contained dangerous levels of gas. The only other lake known to contain gas-rich bottom waters is Lake Kivu in East Africa, where plans for piping are being developed. Copious amounts of CO_2 bubble up into other lakes, such as Lake Mashu in Japan and the Eifel maar lake in Germany, but seasonal overturns prevent long-term stratification and gas build-up in lakes of the Temperate Zone.

Suggestions for further reading

Baxter, P.J. & Kapila, M., 1989. Acute health impact of the gas release at Lake Nyos, Cameroon, 1986. *Journal of Volcanology and Geothermal Research*, v.39, pp.265–275.

Halbwachs, M., Sabroux, J.-C., Grangeon, J., Kayser, G., Tochon-Danguy, J.-C., Felix, A., Beard, J.-C., Villevieille, A., Vitter, G., Richon, P., Wuest, A., & Hell, J., 2004. Degassing the 'killer lakes' Nyos and Monoun, Cameroon. *Eos, Transactions AGU*, v.85, pp.281–285.

Kling, G.W., Clark, M.A., Compton, H.R., Devine, J.D., Evans, W.C., Humphrey, A.M., Koenigsberg, E.J., Lockwood, J.P., Tuttle, M.L., & Wagner, G.N., 1987. The 1986 Lake Nyos gas disaster in Cameroon, West Africa. *Science*, v.236, pp.169–175

Lockwood, J.P. & Rubin, M., 1989. Origin and age of the Lake Nyos maar, Cameroon. *Journal of Volcanology and Geothermal Research*, v.39, pp.117–124.

Shanklin, E., 1989. Exploding lakes and maleficent water in Grassfields legends and myth. *Journal of Volcanology and Geothermal Research*, v.39, pp.233–246.

Sigurdsson, H., Devine, J.D., Tchoua, F.M., Presser, T.S., Pringle, M.K.W. & Evans, W.C., 1987. Origin of the lethal gas burst from Lake Monoun, Cameroun. *Journal of Volcanology and Geothermal Research*, v.31, pp.1–16.