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The potential for catastrophic dam failure at Lake Nyos maar, Cameroon

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Abstract. The upper 40 m of Lake Nyos is bounded on the north by a narrow dam of poorly consolidated pyroclastic rocks, emplaced during the eruptive formation of the Lake Nyos maar a few hundred years ago. This 50-m-wide natural dam is structurally weak and is being eroded at an uncertain, but geologically alarming, rate. The eventual failure of the dam could cause a major flood (estimated peak discharge, 17000 m^3/s) that would have a tragic impact on downstream areas as far as Nigeria, 108 km away. This serious hazard could be eliminated by lowering the lake level, either by controlled removal of the dam or by construction of a 680-m-long drainage tunnel about 65 m below the present lake surface. Either strategy would also lessen the lethal effects of future massive CO_2 gas releases, such as the one that occurred in August 1986.

Introduction

Nyos, a deep maar lake of explosive origin in northwestern Cameroon (Fig. 1) is infamous, owing to a catastrophic voluminous release of carbon dioxide gas that killed an estimated 1700 people in August 1986 (Kling et al. 1987). Our present report draws attention to another potentially hazardous situation still associated with Lake Nyos.

Lake Nyos has an area of 1.49 km^2, is 208 m deep, and has a water volume of about 132 million m^3. The lake waters are dominantly impounded by granitic bedrock to the east, south, and west (Kling et al. 1987, Fig. 2), but to the north the upper 40 m of the lake is bounded by a narrow natural dam composed of friable pyroclastic deposits. The natural spillway across the dam's crest is the lake's only surface outlet (Fig. 2).

During the rainy season (May–October), lake level rises, and a 15-m-wide stream flows across the 45 m width of the natural dam, then drops over a 25-m-high overhanging cliff. During the dry season (November–April), the lake level drops 1–2 m, and no water flows over the dam. The burst of gas from the lake in August 1986, generated large surface-water waves, and one 6-m-high wave washed over the dam. Remarkably, the dam withstood this wave overtopping without eroding and breaching; many natural dams might have immediately failed (Costa and Schuster 1987).

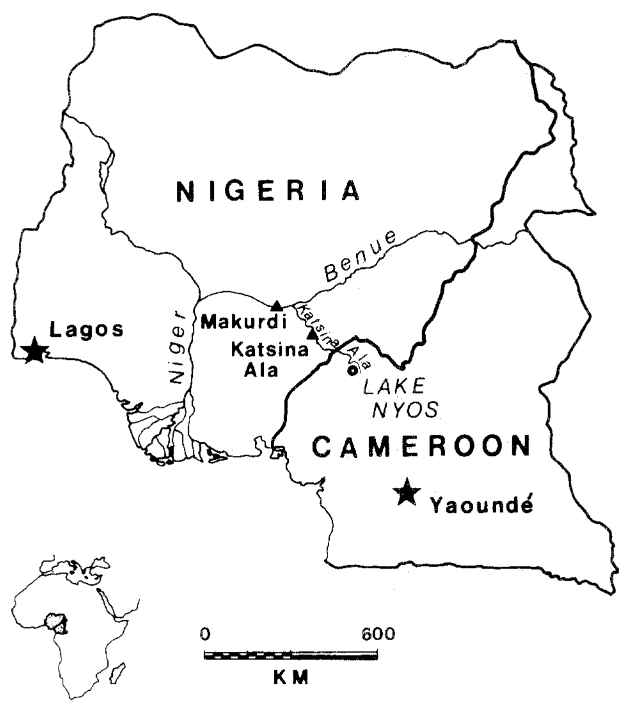

Fig. 1. Nigeria and Cameroon, showing locations of Lake Nyos, important cities, and major downstream drainages

Fig. 2. Lake Nyos natural dam. View northeastward

Natural dam description

The natural dam at Lake Nyos is composed of pyroclastic surge deposits, emplaced by the violent phreatomagmatic eruptions that formed the lake basin about 400 years ago[1]. These deposits consist of lithic debris ejected by pyroclastic surges during the crater-forming event. They range in texture from silty ash to coarse breccia and are for the most part poorly consolidated and poorly sorted. Large lithic clasts are mostly derived from the quartz monzonite bedrock, but also include juvenile alkali basalt and ultramafic xenoliths, carried to the surface from subcrustal depths. The fine silt and sand-size material consists entirely of commutated fragments and crystals from these rocks.

The pyroclastic rocks that form the dam can be divided into upper and lower units (Fig. 3). The upper unit, which is moderately consolidated and thin bedded, forms the resistant surface over which Lake Nyos waters cascade during the rainy-season. This surface has been little eroded since its formation a few hundred years ago, except for some accentuation of the N. 40° E.-trending joints that cut the upper unit (to 30 cm width and a meter depth – Fig. 4). This unit is uniformly about 6 m thick in the outlet area; it unconformably overlies the lower unit and thins gradually to the northeast.

The lower unit is poorly consolidated, coarsely and irregularly bedded, and is readily eroded. Cross-bedding and dune structures are well-developed, especially in the lower half of this unit. Fluid "cow pie" and breadcrust bombs are found in the lower third of the section and beds of glassy basaltic scoria to 50 cm thickness are present at the base in most exposures. Rocks of this unit crumble easily, and where exposed, they are eroded back beneath the overlying upper unit (on both faces of the natural dam). The unit is as much as 30 m thick on the northeast shore of Lake Nyos, but originally extended no more than a few hundred meters beyond the maar rim. These

[1] The estimated maar age of "a few hundred years" (Kling and others, 1987) has been confirmed by a preliminary radioacarbon age of 400 ± 100 yr B.P. (0.4 ka) on charcoal collected from the base of the pyroclastic section (M. Rubin, U.S. Geological Survey, Reston VA, written communication, 1988)

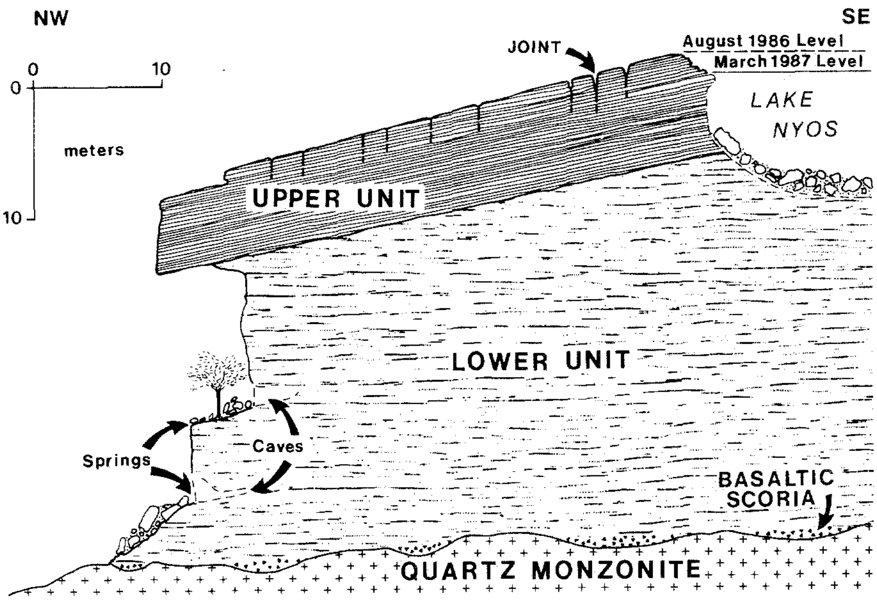

Fig. 3. Cross section of the natural dam, showing upper and lower units of pyroclastic deposits as of March, 1987 (bathymetric data unavailable). Physical dimensions of the dam and surface positions of joints are based on a field survey

deposits filled and blocked an ancestral streambed carved into granitic bedrock beneath the top of the present dam. Had these friable deposits not been covered by the resistant upper unit during the last stage of the Nyos crater-forming eruption, they would have been eroded away long ago.

Fig. 4. Upper surface of dam, showing well-developed joints. View southwestward

Dam stability

The downstream face of the dam, hidden by a waterfall during the rainy season, was examined in March 1987, when dry-season weather and seepage had lowered the lake level to 1.7 m below the dam lip (Fig. 3). The resistant upper unit caprock of the natural dam is undermined wherever its margins are exposed. In response to this undermining, the upper unit fails as large blocks controlled by the N. 40° E.-trending joint system (Fig. 4). The base of the waterfall is littered with giant blocks of upper unit ash.

The lower unit portion of the dam face is a zone of continuous water seepage. Several caves, 1-3 m in diameter, extend at least 10 m into the lower unit face (Fig. 3). These caves are apparently formed by seepage erosion, although no sediment was noted in the spring waters during our investigation. The caves' rate of advance toward the lake is unknown, but they obviously have the potential to cause failure of the dam by "piping" (Costa and Schuster 1987).

The largest springs (estimated flow of a few l/sec) are associated with these caves, and are concentrated at two horizons — one 4 m above the dam base and the other about 12 m above the base (Fig. 3). Waters from the lower springs leave red-orange deposits of iron hydroxides, both as stream precipitates and as centimeter-long "stalactites" where water issues from overhangs. Waters from the upper springs are clear and leave no precipitates along their flow paths. The absence of iron hydroxide in the upper dam spring waters suggests that these springs are derived from above the mesolimnion[2]. The stream that flows from the combined springs is stained red orange for more than 100 m downstream. These iron oxide precipitates demonstrate that the pyroclastic dam is highly permeable and that waters from Lake Nyos are seeping through the dam.

Chemical analyses of these two spring waters show similar compositions, although the lower spring contains slightly more iron. Both waters are more dilute by a factor of 2 than Lake Nyos surface waters (< 17 m), indicating an additional water source for the springs. A cation plot of deep Lake Nyos waters (> 150 m), surface waters, the two dam-face spring waters, and a range of typical rainfall compositions (Fig. 5) suggests a mixing-line relation, with one end member being deep Lake Nyos water and the other local precipitation. The dam spring waters probably vary along this mixing line depending on the season. During the driest part of winter the dam spring waters are presumably close to lake composition, but during the summer rainy season the springs are diluted by rainfall. The spring waters plotted in Fig. 5 were collected in March, after the summer rains had begun, and are midway between lake water and precipitation in composition.

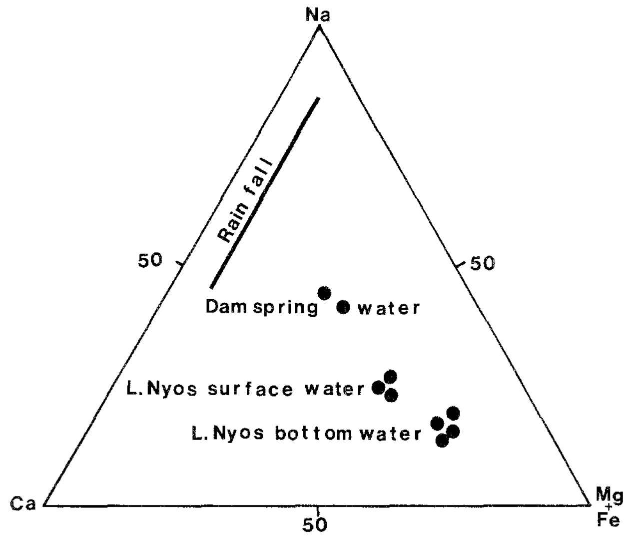

Fig. 5. Major cation proportions (M, molarity basis): 1) in Lake Nyos bottom waters below 150 m (average ionic strength, 0.016 M); 2) Lake Nyos surface waters above 17 m (average ionic strength, 0.0006 M); 3) dam springs (average ionic strength, 0.0003 M); 4) range for rainfall (from Eugster and Hardee 1979). Positions of dam springs shown on Fig. 3

It is surprising that the unconsolidated lower unit ashes do not allow seepage of larger quantities of Lake Nyos water, and that they have not already been eroded away by internal piping. Perhaps these apparently permeable ashes are mantled by relatively impermeable clay-rich sediment at the lake/dam interface, or perhaps cementation by secondary minerals has reduced the dam permeability.

The pyroclastic rocks that form the Lake Nyos dam once extended much farther to the northwest, but erosion by the Lake Nyos outlet stream has removed all but a 45-m-wide remnant of the protective caprock at the dam's narrowest point (Figs. 6, 7). A section of pyroclastic rocks about 600 m long has been eroded away, exposing granitic bedrock along the streambed. Assuming an age of 400 years and a constant erosion rate, the natural spillway has receded at an average rate of 1.5 m/year. This high rate does not apply to the present, however, because the pyroclastic deposits

[2] The upper surface of the mesolimnion (anoxic level) was at 10-m depth when measured in September, 1986.

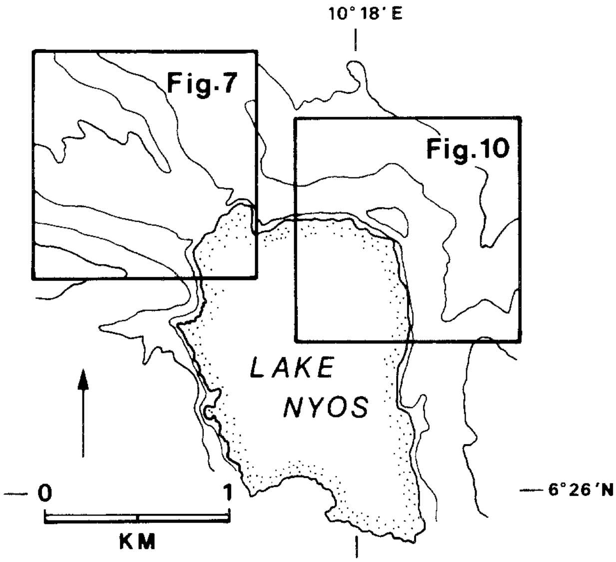

Fig. 6. Locations of Figs. 7 and 10

are thinner and less consolidated farther downstream, and erosion would have initially advanced upstream at a much higher than "average" rate. A slower present rate is also indicated by the vegetation on the dam face (Fig. 3). The presence of large fresh talus blocks of upper unit ash at the dam base does indicate that erosion is still proceeding. We cannot estimate the present erosion rate with any precision, nor do we know what minimum dam width is required to hold back the waters of Lake Nyos. We nonetheless believe that this minimum width will be reached and the dam will fail by natural causes in the not too distant future, possibly within a few decades.

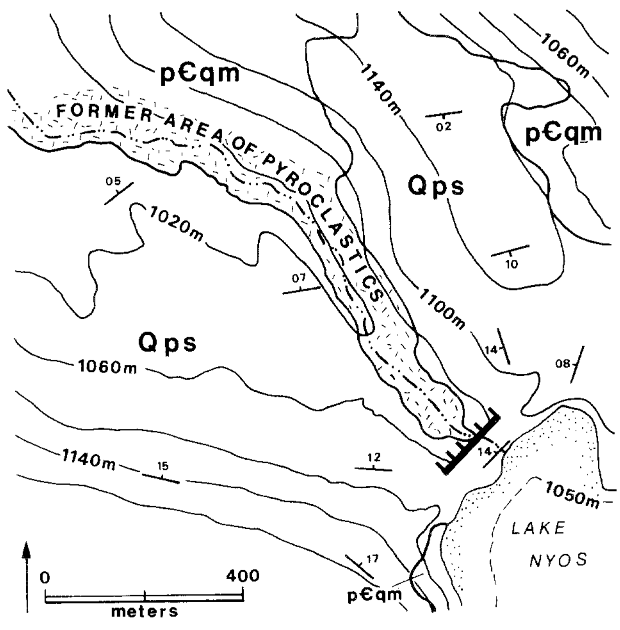

Fig. 7. Geologic sketch map of Lake Nyos dam and adjacent areas. *Qps*, pyroclastic surge deposits; *pCqm*, Precambrian quartz monzonite. *Patterned area* denotes former extent of pyroclastic rocks, removed by stream erosion; *strike-and-dip symbols* indicate attitude of ash layering

Consequences of failure

The inevitable failure of the Lake Nyos natural dam is likely to proceed very rapidly, once the resistant layer of upper unit ash loses its underlying support and begins to fracture. The dam could fail by surface erosion due to wave overtopping during another gas release, to lake overflows in the rainy season, or by piping, if internal flow from seepage increases and causes an increase in internal erosion. A large earthquake in the area could also trigger failure.

To evaluate the effects of this potential hazard, we modeled a hypothetical failure of the Lake Nyos natural dam, using the US National Weather Service's model DAMBRK (Fread 1980). We assumed for our model that the failure will occur during overtopping, that the dam will be eroded to the underlying bedrock in a trapezoidal breach, with a bottom width of 40 m and a top width of 85 m, and that the full breach will take 30 min to develop. The breach formation time relationships developed by Froehlich (1987) for constructed earthen dams show that breach times are in large part related to the volume of water impounded by the dams and suggest that full breeching for the Lake Nyos dam would occur in approximately 1.1 h. In this case we assumed that the Lake Nyos natural dam has less internal strength than an engineered dam and consequently assumed 30 minutes for complete failure. If the dam were to fail by piping and rapid embankment failure, breach time could be less than 30 min, and the resulting flood levels and peak discharge would be greater than predicted by our model.

On the basis of the crude bathymetric information available for Lake Nyos, we assumed for our model that the lake level will drop 38 m (from Fig. 3), and that 55 million m^3 of water will be released. Using the above failure parameters this model predicts a peak discharge from a hypothetical failure of the Lake Nyos natural dam of about 17 000 m^3/s (Fig. 8), or about twice the flood from the 1899 failure of the South Fork Dam at Johnstown, Pennsylvania. Characteristics of the resulting hypothetical flood were calcu-

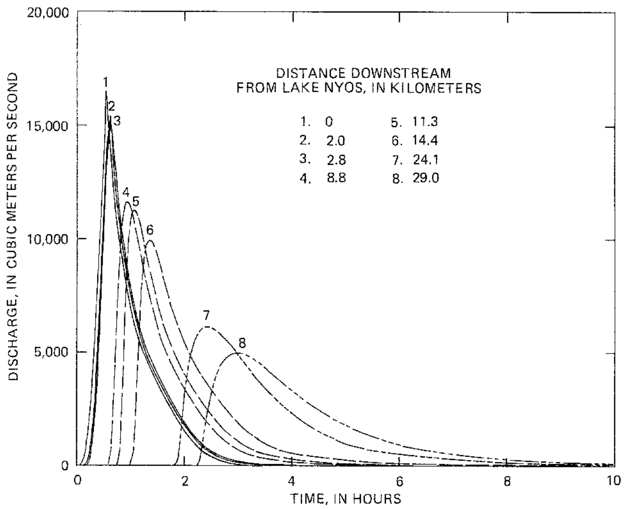

Fig. 8. Calculated hydrographs for hypothetical flood resulting from catastrophic failure of Lake Nyos dam. Individual flood-discharge *curves* refer to stations listed in Table 1

lated for 29 km of the downstream floodpath, using the one-dimensional, unsteady-state streamflow model HYDRAUX (DeLong 1984). This flood was routed for only 29 km because that is the north limit of minimally adequate topographic information (US Defense Mapping Agency, 1985) required to calculate flood characteristics. Available maps of areas farther downstream were at too small a scale for reliable stream cross-section determinations.

The steep first 2 km downstream from the dam (to the Nyos Valley) has a slope of 0.079, and the average slope of the Valley to the junction with the Kumbi River is 0.024. The slope of the Kumbi River downstream of the Nyos Valley is 0.00427. Using this data, our model predicts that the flood would reach stage heights of 6.5–19.2 m above the stream channel downstream (Table 1), depending

Table 1. Routing of flood from hypothetical failure of the Lake Nyos natural dam

Station	Distance downstream from dam (km)	Time of first arrival (h)	Time of peak arrival (h)	Peak discharge (m^3/s)	Flood height (stage) (m)
1	0.0	—	0.50	17000	—
2	2.0	0.10	0.60	15900	14.1
3	2.8	0.15	0.60	15600	7.9
4	8.8	0.60	0.95	12000	16.9
5	11.3	0.75	1.05	11700	6.5
6	14.4	1.00	1.35	10300	9.9
7	24.1	1.85	2.40	6300	15.2
8	29.0	2.25	2.85	5100	19.2

on differences in valley geometry. The *front* of the hypothetical flood wave would travel at speeds of 3.4–5.6 m/s and would take about 2.3 h to travel the 29 km evaluated, whereas the flood *peak* would travel between 0.94 and 3.0 m/s and would take about 3 h to travel this 29 km (Fig. 8). At this distance the flood peak would have attenuated to about 5100 m^3/s.

Data from other historical dam failures indicate that most dam-failure water floods attenuate to 10–20% of their outflow peak discharge by the time the flood reaches 100 km downvalley (Costa 1985). The attenuation rate of the hypothetical flood from Lake Nyos is steep, so that the discharge from a hypothetical dam failure, at a point 100 km downstream, should be no more than 3400 m^3/s, and possibly 1400 m^3/s or less.

There are many uncertainties in modeling hypothetical dam failures. Peak discharges are sensitive to breach widths and times of breach development, both of which can only be approximated. Downstream routing of the flood wave is dependent upon the valley roughness and the accuracy of the topographic cross-sectional data, which in our model were less than ideal. Our hypothetical peak discharges and hydrographs assume clear water; we did not consider the role of possible massive sediment entrainment in floodwaters as did Laenen et al. (1988), although this could be a significant factor if debris flows were generated.

Three potentially devastating processes could be set into action by sudden failure of the Lake Nyos natural dam:

Floods

The hypothetical flood described above would rush at a speed of 12–20 km/h down the narrow canyon leading northward from the lake outlet. Upon reaching the flat Nyos Valley, most of the water would turn eastward down the valley, although some may spill westward, past the village of Cha and into the Mbum River drainage (Fig. 9). The presently abandoned town of Nyos, where nearly 1000 people died from CO_2 asphyxiation on the night of August 21, 1986, would be completely swept away. The floodwaters would continue eastward, obliterating the town of Subum, and would here turn northward, down the Kumbi River. About 33 km from Lake Nyos, the floodwaters would reach the Katsina Ala River (Figs. 1, 9) and turn westward, toward Nigeria (Institut Geographique National du Cameroun, 1983). The floodwaters would deepen and move more rap-

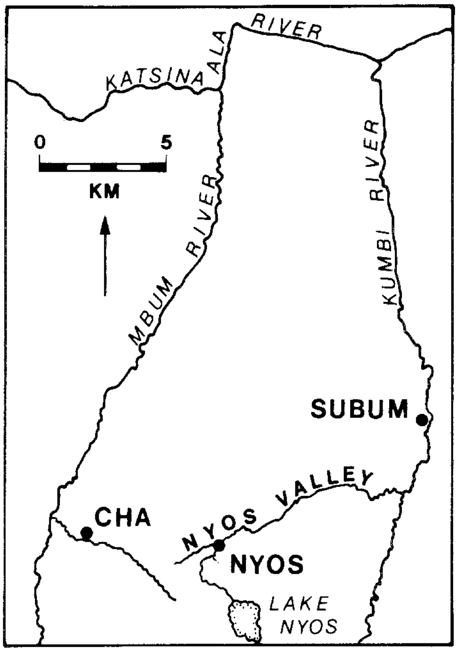

Fig. 9. Area north of Lake Nyos, showing principal drainages and towns mentioned in this report

idly where valleys narrow, and would become more shallow and slow where valleys widen. The flood peak would gradually decrease downstream but could still be 10–20 percent of the original peak discharge 108 km from Lake Nyos at the Cameroon-Nigeria border, where the Katsina Ala descends from the Cameroon highlands to the fertile, densely populated Benue Plain. Effects of the Lake Nyos flood would extend far downstream along the Katsina Ala River, and the flood could impact the low-lying city of Katsina Ala, 225 km from Lake Nyos (US Defense Mapping Agency, 1984; Fig. 1). The Katsina Ala River is a major tributary of the Benue River (Fig. 1); flood effects on the Benue would likely be minor but would depend on the river level, which varies seasonally (Udo 1970). The Benue joins th Niger River 590 km downstream from Lake Nyos, but flooding effects on that great river would be minor.

Debris flows/lahars

Deposits of loose volcanic ash and soil are extensive along the stream leading northward from Lake Nyos. The quartz monzonite bedrock adjacent to the streams is deeply weathered and covered by 1–5 m of clay-rich lateritic soil, and the Nyos Valley is underlain by deep alluvium. Some of this material would be eroded by and incorporated into the advancing floodwaters. Although we suspect that the amount of loose material available is insufficient to form debris flows or lahars, we cannot completely discount the possibility, especially during the rainy season, when sediment is waterlogged.

Depressurization effects on Lake Nyos

The waters of Lake Nyos still contain substantial dissolved carbon dioxide, mostly at deeper levels. The estimated 55 million m^3 of water that would be released by failure of the outlet dam contains about 3.7 million m^3 of dissolved CO_2 at Standard Temperature and Pressure (STP) — only 10^{-7}–10^{-4} of the amount released during the 1986 disaster. This CO_2 would be largely released from the floodwaters during flow and could pose a direct hazard to people and livestock along the upper reaches of the flood path. A greater hazard involves the potential degassing of deeper lake waters. The sudden removal of the upper 38 m of Lake Nyos would reduce hydrostatic pressure on the underlying water by 3.9 atm. Because the CO_2 in these waters ranges from 23 to 32% of saturation (WC Evans, US Geological Survey, 1987, written communication), depressurization alone would not result in supersaturation; but if large internal waves were generated in the lake by the sudden outflow of water, gas release from deeper, unstable waters is possible. Many uncertainties exist regarding the nature of the internal waves that could be generated and their effects on CO_2 solution stability, and so the amount of gas that might be released from deeper waters is unknown. In any event, it is likely to be substantially less than that released in August 1986. Estimates of the volume of CO_2 released from the lake during the 1986 disaster range from 100 million to 1200 million m^3 at STP. Because the area affected by the 1986 disaster has not been reoccupied (as of late 1987), the gas-release hazard is not presently of great significance.

Possible mitigation strategies

The Lake Nyos natural dam could fail any day owing to natural causes, and quite possibly will fail within the next few decades. Several options to lessen or eliminate this hazard are available for consideration by responsible authorities, including:

1) The present evacuation of low-lying areas downstream from Lake Nyos could be continued indefinitely until the dam fails naturally. Additional areas along the Katsina Ala River might also require evacuation, at least during rainy season high water levels.
2) The existing dam could be strengthened by construction of a reinforced concrete "cap" over the natural spillway surface. Such a solution was employed by Dutch engineers to reinforce the outlet area of the crater rim at Ijen crater lake in East Java in the 1920s, and still serves to control crater lake outflow (TA Casadevall, US Geological Survey, written communication, 1988). Such a "cap" or other structural reinforcement would be relatively inexpensive, quick to build, and could help to prolong the dam's natural life by slowing surface erosion, but would not protect against the hazards of "piping" or seismic activity.
3) The dam could be removed by demolition or excavation techniques. A narrow channel blasted through upper unit pyroclastic deposits would probably be sufficient to initiate the failure. By prior calculation of the areas to be affected by floodwaters and possibly by CO_2 gas, all threatened areas could be temporarily evacuated of people and livestock, so that losses would be restricted to property. The resulting flood probably would have a major impact on low-lying areas in both Cameroon and Nigeria, however, and could cause great property damage. The damage could be lessened by conducting the operation during the dry season.
4) The upper 40 m of Lake Nyos could be mechanically drained by large siphon pipes or pumps prior to demolition or removal of the dam.
5) The most sophisticated strategy to eliminate all hazards associated with the natural dam would be to drain Lake Nyos to well below the spillway base by construction of a drainage tunnel through the Lake Nyos crater wall.

Lake drainage to mitigate hazardous situations is not a new technique. The crater lake surface of the East Java volcano Kelut was lowered 53 m by construction of a drainage tunnel through the crater rim in the 1920s, after a lahar-generating eruption killed more than 5000 people in 1919 (Kemmerling 1921; Stehn and Coert 1929). The overtopping and breaching of a natural debris-avalanche dam at Spirit Lake, north of Mount St. Helens, Washington, was prevented by construction of a 3 km-long lake drainage tunnel in 1984-85 (Youd et al. 1981; Sager and Chambers 1985). A 685 m-long tunnel was constructed to drain Thistle Lake (Utah) to prevent a sudden catastrophic failure of a 63-m-high landslide dam that blocked the Spanish Fork River in 1983 (Hansen and Morgan 1985). A suggestion has been made to drain the crater of Galunggung Volcano (West Java), which has been gradually filling with water since it was formed during the 1982–83 eruption (Katili and Sudradjat 1984; Lubis et al. 1988).

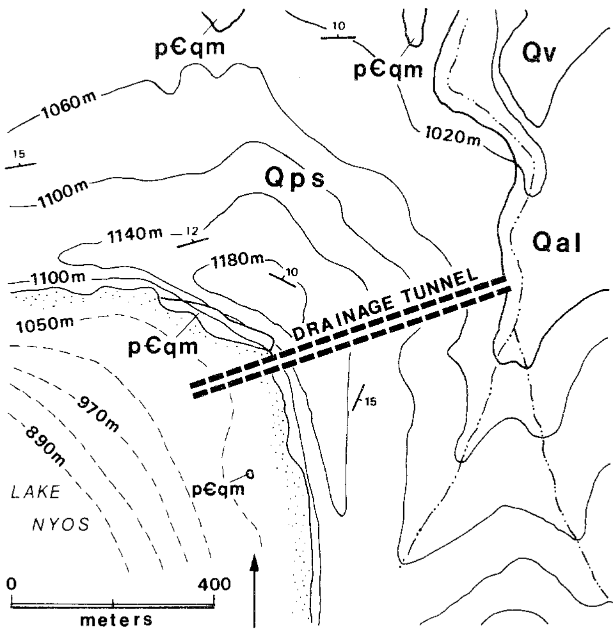

Fig. 10. Geologic map of northeast corner of Lake Nyos, showing location of possible drainage tunnel. *Qv*, pre-maar effusive volcanic rocks, other *Symbols* as in Fig. 7

In the case of Lake Nyos, a 680-m-long drainage tunnel appears to be feasible through the northeast crater wall (Figs. 6, 10). Such a tunnel could be driven almost entirely in the granitic rock that underlies the weak crater rim pyroclastic deposits (Fig. 11), and thus avoid the perils of soft-rock tunneling and the need for extensive support and lining. The tunnel could intercept the lake about 65 m below its current surface.

Such a tunnel would be a relatively expensive, complex, and potentially hazardous project but would have several important benefits:
a) It would completely eliminate all hazards associated with the natural dam — lake drainage would be permanently routed through the tunnel.
b) It would greatly reduce and possibly eliminate future catastrophes from CO_2 gas release, such as the one that occurred in 1986. This would be accomplished by reduction of both the volume and confining pressure of Lake Nyos water, and thus its CO_2 storage capacity, as well as by creation of

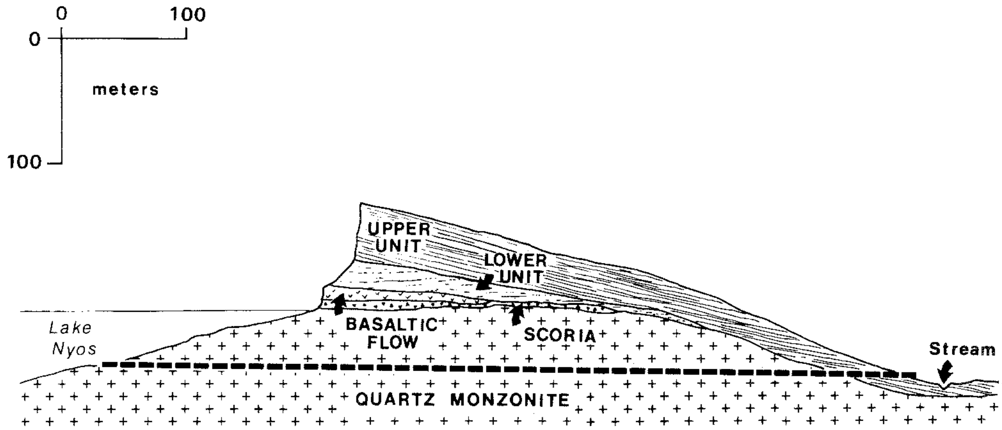

Fig. 11. Geologic cross section through the east rim of Lake Nyos crater, showing location of possible drainage tunnel

a 65-m-deep crater, with a volume of about 65 million m^3, within which any CO_2 released in the future would be largely confined until dissipation.

c) Such a tunnel, if provided with gate valves, could contribute to agricultural development in the Lake Nyos region. Lake levels could be allowed to rise during the rainy season, and the stored water slowly released during the dry season, allowing year-round irrigation in the Nyos area.

Conclusions

The phreatomagmatic eruption that formed the Nyos maar several hundred years ago set the stage for unusual secondary volcanic hazards. The release of accumulated carbon dioxide gas killed about 1700 people in 1986, and may be a recurrent phenomenon. The possibility of catastrophic natural dam failure at Lake Nyos is another secondary hazard with a grave potential for loss of life and property in northwestern Cameroon and, possibly, adjacent Nigeria. Immediate steps to reduce or eliminate this hazard may be called for to avoid a tragedy greater than that of August 21, 1986.

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