Human Health and Vulnerability in the Nyiragongo Volcano Crisis Democratic Republic of Congo 2002

Final Report to the World Health Organisation

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Nyiragongo Volcano with Goma on the shore of Lake Kivu

Cover : The main lava flow which shattered Goma and flowed into Lake Kivu

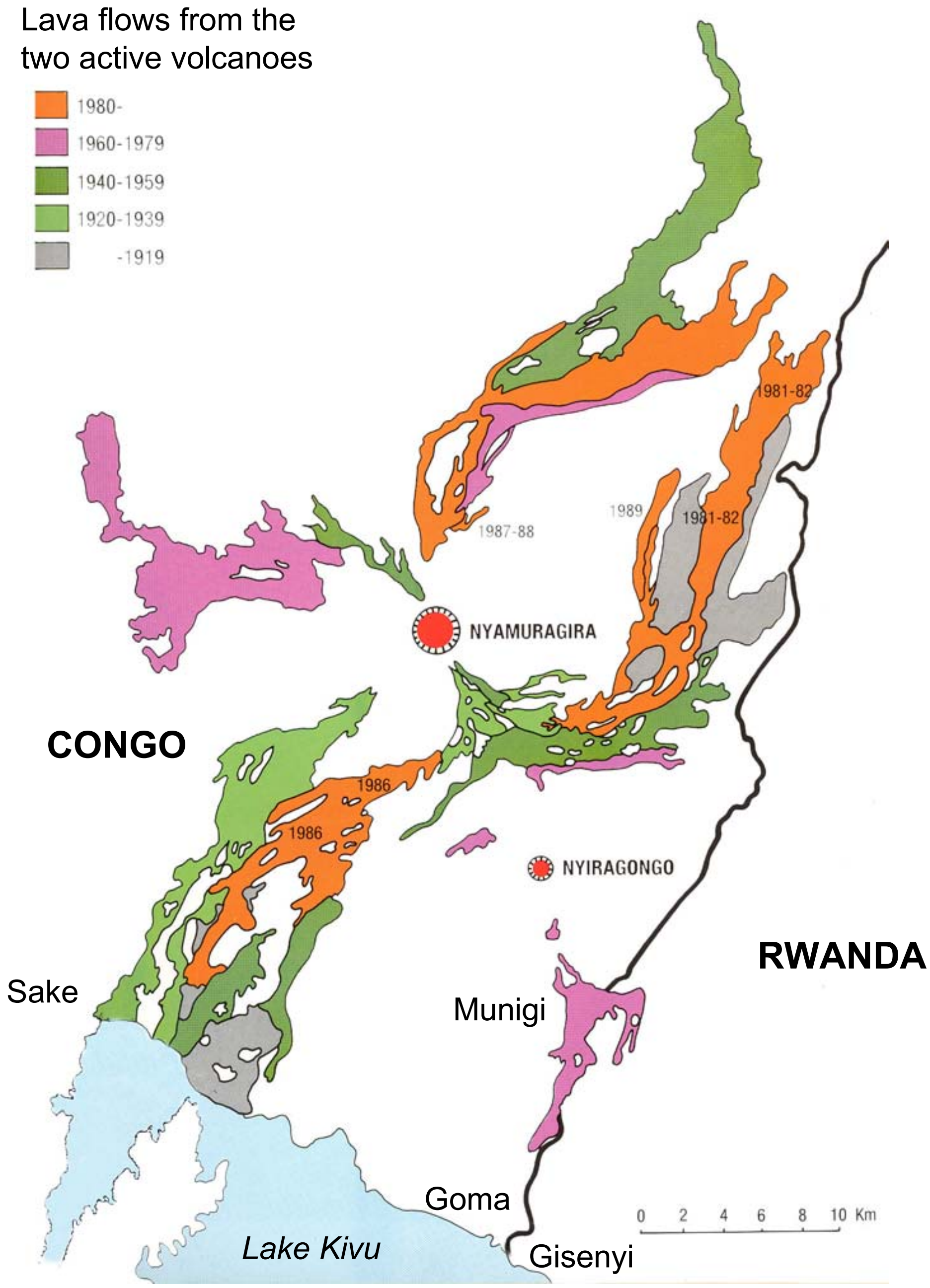

Fig.1. Goma setting and map of area and lava flows

HUMAN HEALTH AND VULNERABILITY IN THE NYIRAGONGO VOLCANO CRISIS DEMOCRATIC REPUBLIC OF CONGO, 2002

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EXECUTIVE SUMMARY

We have undertaken a vulnerability assessment of the Nyiragongo volcano crisis at Goma for the World Health Organisation (WHO), based on an analysis of the impact of the eruption on January 17/18, 2002.

According to volcanologists, this eruption was triggered by tectonic spreading of the Kivu rift causing the ground to fracture and allow lava to flow from ground fissures out of the crater lava lake and possibly from a deeper conduit nearer Goma. At the time of writing, scientists are concerned that the continuing high level of seismic activity indicates that the tectonic rifting may be gradually continuing. Scientists agree that volcano monitoring and contingency planning are essential for forecasting and responding to future trends.

The relatively small loss of life in the January 2002 eruption (less than 100 deaths in a population of 500,000) was remarkable, and psychological stress was reportedly the main health consequence in the aftermath of the eruption. A cholera outbreak was prevented by the rapid intervention of NGO's and other agencies to provide chlorinated drinking water from Lake Kivu.

This report is a contribution for health sector preparedness and the involvement of the health sector in the on-going risk management of this crisis. Some important findings on the vulnerability of the population have emerged which relate to the eruption occurring in a region already affected by a complex humanitarian emergency and these should be considered in emergency planning and preparedness.

1. *Volcanic hazard risks, scientific forecasts and warnings.* According to scientists, the two main hazards of immediate concern in a future eruption of Nyiragongo are: i.) a lava eruption in Goma from fissures located within 1-2 km of the lake shore leading to a major phreato-magmatic explosion, and ii.) a lava eruption in Lake Kivu that disturbs the carbon dioxide and methane stored in the lake at depth, leading to the release of an asphyxiating gas cloud that could disperse over a wide area. Either of these events could lead to catastrophic loss of life. Warning of magma rising beneath Goma or Lake Kivu should be feasible, using a telemeter seismic monitoring network. However, the political and humanitarian situation makes it unlikely that the population will heed warnings of an impending eruption and be prepared to evacuate part or whole of Goma as a precautionary measure. A gas release from Lake Kivu would be most likely localised around the location of a lava emission along the main fissure line from the summit crater to the lake, in other words, near Goma. The evacuation of Goma would therefore also reduce the loss of life expected in a gas release from Lake Kivu.

2. *Cholera risk in Goma.* The devastating cholera outbreak in 1994 in Rwandan refugees in Goma and the neighbouring camp areas was due to the total reliance of the population on Lake Kivu as the only source of drinking water, as the area is built upon the hard rock of old, porous lava flows (there are no wells or rivers). This reliance is unchanged today and the prevention of enteric disease outbreaks in a future eruption has to be a leading priority for the health sector, relief agencies and NGO's. The risk of an epidemic is greatest with an evacuation of Goma, or a return to Goma before its shattered

lifelines are restored (as occurred on January 19, 2002). Preventing an epidemic of cholera is a major priority for the health sector, including international relief agencies and NGO's.

3. *Scientific forecasting and relief agency preparedness and response.* In this vulnerability context, the importance of early warnings of an eruption by scientists will be crucial for the health sector, NGO's and relief agencies so that they can prepare for a mass exodus and prevent a major loss of life from enteric diseases and dehydration. Emergency health measures include the provision of chlorinated water along evacuation routes and in refuge areas, and adequate medical cover for the treatment of cholera and other enteric diseases. Emergency immunisation programmes against measles, meningitis and polio are also likely to be important considerations.

4. *Scientific risk assessment incorporating uncertainty.* A scientific risk assessment will be needed to constrain the hazards from a lava eruption in Goma and an eruption within Lake Kivu, as well as other types of events. The risk assessment will need to incorporate expert opinion on the health hazards, especially cholera, which remains a serious hazard in a mass movement of the population of Goma in response to a volcanic threat. The risks of moving the population out of Goma to reduce the loss of life in an eruption have to be balanced against the risks to life from infectious disease, malnutrition and violence that are likely to accompany a mass exodus. The uncertainty surrounding the two types of risk and their consequences (expressed as numbers of deaths) needs to be constrained using expert judgement and probabilistic analysis of a range of eruption scenarios.

5. *Rapid reoccupation of Goma and cholera.* A repeat lava flow event and evacuation, followed by a rapid return to Goma before activity had declined, as occurred in January, would be especially hazardous, with the possible danger of phreato-magmatic explosions from renewed lava flows. Relief agencies may be very reluctant, on valid safety grounds, to enter Goma to provide chlorinated water supplies, in which case the risk of cholera outbreaks will be high in this scenario.

6. *Societal risk assessment and planning.* The absence of civil institutions and democratically elected government means that there are none of the usual administrative structures by which governing bodies can make decisions on societal risk and long term planning on behalf of the Goma population. This social dysfunction substantially adds to the danger to the population from future eruptions.

7. *Health sector co-ordination.* Recommendations are made for the co-ordination by WHO of the health sector response to the continuing crisis, including emergency planning. This should include close liaison with volcanologists over health hazards from ground gas emissions and ash fall; air and water quality monitoring; as well as crisis risk management.

8. *Specific recommendations.* More specific measures to reduce vulnerability in a future eruption affecting Goma include organisational, logistical and engineering interventions to maintain and chlorinate drinking water and maintain power supplies in the city, and to stockpile and distribute emergency food rations. The possible release and dispersion of gases from Lake Kivu need to be modelled for hazard mapping purposes. Contingency plans should be modified to include the detailed arrangements for health sector interventions to reduce the risk from cholera in an evacuation and resettlement of Goma. Scien-

tists monitoring the volcano should issue regular statements on the activity status of the volcano and undertake a full hazard assessment. A risk assessment should ideally be completed before the end of 2002.

9. *Effect of the volcanic crisis on the humanitarian situation.* The effects of the January eruption and evacuation on the already existing complex emergency were apparently small, but the long-term consequences of the psychological and economic impacts, and the political repercussions surrounding the future of Goma, are possibly yet to unfold. A detailed analysis of the conflict and humanitarian crisis, including the policies towards Goma of outside governments and relief bodies, was outside the terms of reference of this report.

1. Introduction

1.1. *Background*

This analysis of the human health impact of eruptions at Nyiragongo volcano is directed towards the vulnerability and mitigation issues that require to be considered in a risk assessment for future eruptions, including the potential for a catastrophic gas burst at Lake Kivu. The eruption of Nyiragongo on 17/18 January 2002 led to a massive international response following the spontaneous and temporary evacuation of 400,000 people from the city of Goma located on the shore of Lake Kivu.

Within a few days, the United Nations Office for the Coordination of Humanitarian Affairs (OCHA) and the French and British Foreign Ministries sent two scientific teams to evaluate the impact of the eruption. The challenges to the scientists were to rapidly establish the hazards of the lava flows and their associated eruptive phenomena in such a densely populated area. The danger included the wide-scale fissuring and lethal ground gas emissions and, above all, the potential for the eruption to catastrophically release the gases (carbon dioxide and methane) stored in the depths of Lake Kivu. The two teams, who have worked in full collaboration with one another, have published their reports,[1,2] including one by P. Baxter on the health aspects for WHO.[3]

At the time of writing, no further imminent eruptive threat to the population from Nyiragongo has been identified. However, seismic activity continues at a high level and scientists are concerned that tectonic rifting may still be occurring. There is an urgent need to ensure the adequate monitoring of the volcano and to develop contingency planning for a future eruption.

The present report has been compiled following a field visit in March 2002 as a major contribution from the health sector towards the short and long term emergency planning process and the scientific evaluation of the volcanic crisis.

1.2. *Vulnerability*

Vulnerability assessment is a method of evaluating environmental hazards for the factors that amplify their impacts on populations or the environment. It is a fundamental part of making a risk assessment and devising mitigation measures. In this study, we highlight human, infrastructural, geo-environmental and, above all, political vulnerability as the key issues to be considered in the Goma volcanic crisis.

2. Disaster setting

Emergency planning for a major eruption of Nyiragongo presents several unique challenges. These relate to the unusual volcanic setting, the humanitarian crisis which ranks amongst the world's gravest, and the long shadow cast by the events surrounding the genocide and the Rwandan refugee tragedy in Goma in 1994, when tens of thousands of people died from cholera and dysentery.

2.1 *Humanitarian crisis*

The eruption has occurred in a part of the world (Eastern Congo) that is already afflicted by a humanitarian crisis and a chronic complex emergency involving armies and armed groups of at least six countries. Since 1998, two and a half million people have died in the Eastern DCR (Democratic Republic of Congo) from infectious diseases and malnutrition as a consequence of continuing conflict in the region.[4] Goma is the base of the RCD (the Rwandan-based Congolese Rally for Democracy), which controls this eastern part of Congo, and the city's viability has political as well as economic consequences for the region as a whole. Decisions on the short or long-term evacuation of the population because of a renewed threat from the volcano have to be weighed against the hazards to health from disrupting the precarious lives of hundreds of thousands of people.

The volcano is therefore one of a long list of threats to life in Eastern Congo, including conflict and human rights abuses, a range of highly lethal infectious diseases endemic to sub-Saharan Africa, malnutrition, and the long-term mental and physical consequences of poverty. The impoverishment of African populations and the many wars and conflicts on the continent has provided a fertile ground for the spread of HIV/AIDS.[5] At the time of writing, attempts at a peace deal to bring to an end the four-year civil war have been underway in South Africa.

The conflicts have effectively destroyed the civil institutions of Eastern Congo, including those we take for granted in democratic societies. The humanitarian and political situation also has a close bearing on the resources that can be brought to volcano monitoring and the forecasting of eruptive activity, as well as the responses of the population to the communication of volcanic risk and warnings to evacuate in a crisis. The ever-present threat of violence also reduces the physical and mental reserves of the population in overcoming natural hazards. The humanitarian crisis is the major source of vulnerability to be addressed in volcanic risk management. It remains an open question whether the Goma Volcano Observatory can work effectively under such difficult circumstances, even with international support.

2.2 *Volcanic setting*

The two most active volcanoes of the Virunga range are Nyiragongo and Nyramuragira, which lie about 20 km apart (Fig.1). The Virunga Mountains stretch from east to west for about 80 km., and lie in the western branch of the East African Rift Zone that extends from Ethiopia to Mozambique. The eruptions of both volcanoes exhibit the same classical effusive and mildly explosive activity characterized by the opening of long, gaping fissures through which lava emerges at different locations, and these emissions merge to form lava flows several hundred metres wide. This type of eruptive activity is not usually dangerous to life except in the very fluid flows that can move very fast in eruptions of Nyiragongo.

Over geological time the eruptions of the Virunga volcanoes eventually blocked the flow of the ancestral river of the River Nile in its path to the Mediterranean and the natural damn created Lake Kivu. Today, the flow of water out of the lake is to the south and is artificially controlled at Bukavu. The geomorphology of the lake, including its great depth and proximity to an active volcanic centre, underlie its present hazardous, gas-laden state. The Nyiragongo lavas that form the hard and porous bedrock of the area, with the setting of Lake Kivu, also constrain the other main hazard that overshadows Goma – cholera – as will be discussed below.

Nyiragongo is an exceptional volcano, and one that can have an exceptional impact on people's lives. Often concealed by cloud, Nyiragongo has been reluctant to yield its secrets. The earliest European explorers were drawn to the red glow of its crater against the night sky, and an expedition eventually forged a way through almost impenetrable vegetation to reach the summit in 1894. The mystery of its "column of fire" was not revealed until 1948, when the volcanologist Haroun Tazieff climbed down into the crater below its vapour clouds to find a vast, incandescent lake of molten lava. For the local people, as Tazieff learned, the volcano was a resting place for the souls of their ancestors.[6] Today, scientists still have much to learn about its eruptive behaviour.

Until the latest eruption, the hazard of Nyiragongo was thought to be limited to the hydrostatic pressure of the lava lake and the risk of breaching the thin wall of the crater. The very fluid lava flows were not considered to be a major threat to Goma. However, the massive fissuring of the flank of the volcano in January 2002, extending 18 km from the crater to Goma, is strongly suspected by scientists to have a tectonic or rifting origin, at least in part, which implies that the volcano has moved to a new and more hazardous state, with the risk in future eruptions of fractures and lava emissions arising in Goma itself, or even deep within Lake Kivu. A destabilization of the waters of Lake Kivu in such an eruption could lead to a massive out-pouring of the gases carbon dioxide and methane that lie stored deep in the lake.

The activity of the two volcanoes has not been comprehensively monitored by scientists before, though a telemeter seismic network installed by a Japanese team in 1994 during the refugee crisis functioned until it was destroyed in the refugee mass movement in November 1996. Scientists recognize that a high level of monitoring is now needed if adequate warning of a future major eruption is to be provided and a potentially large loss of life is to be prevented. The Goma Volcano Observatory has had its technical capacity reduced during the humanitarian crisis, particularly over the last two years when staff have worked without any salary.

2.3. *Eruptive history of the volcanoes*

Nyiragongo previously erupted in 1977 when 40-300 people may have died in villages over run by the very fluid lava which broke out of the crater without warning from a fracture high up on the south east flank of the volcano.[7] The lava flow halted at 2 km from Goma airport. The volcano was made notorious by this event, with its future hazard defined by its unique potential for the sudden release of lava of a very fluid type due to its highly alkalic composition. Little is known about Nyiragongo's previous eruptive history, though no eruptions have been reported between the first climbing of the volcano in 1894 and the disastrous eruption in 1977. However, Goma is built on its previous lava flows (a major one has been dated 800 yr BP).[8]

In contrast, Nyramuragira volcano erupts on a much more frequent basis and a new eruption could occur any time in the near future. It erupted over 20 times in the 20th Century and its crater also held a lava lake until 1938. On three such occasions the lava from the mountain has flowed into Lake Kivu from fractures on its southern flank (Fig.1): in 1912, from the Karisimbi crater; in 1938, from the Tahambene crater; and, in 1948, from the Muhuboli crater.[6] The lava flows from Nyramuragira do not threaten Goma. Large lava fountains are associated with the flank eruptions of Nyramuragira. These are associated with large ash emissions, which the prevailing winds blow towards the west.

The recent volcanic activity most related to the present crisis occurred in 1994 when Rwandan refugees settled in camps on the slopes of both volcanoes. Episodic lava-lake filling at Nyiragongo began on 23 June, the first such activity since 1982 when the lake first refilled after the 1977 eruption. The rise in the lava lake level increased the risk of a flow breaking out down one of the flanks as in 1977. Then, Nyramuragira erupted between 4 and 17 July when lava fountains on the western flank also produced glassy tephra, which blanketed an area of more than 30 km^2 towards the western side, and killed large numbers of cattle grazing on the ash-covered grass.[9] The area of Masisi, renowned for its cattle farming before the recent devastating conflicts, was particularly affected.

These events raised international concern over the hazard of the two volcanoes to the settled refugees. A hazard assessment was conducted by volcanologists[9] and reported by Tazieff in a letter to *Nature*: his advice was to ignore the risk from Nyiragongo.[10] The concern was that the number of refugees who would die as a result of another mass movement, this time to escape from the volcanic hazard, would be potentially at least two to three orders of magnitude higher than would be claimed by an eruption of the volcano. However, no epidemiological evidence to support this conclusion was presented. This matter is addressed in the next section.

2.4. *Cholera - the other great hazard*

The spectre of a recurrence of epidemics of cholera and other enteric infections in an evacuation of the present population of the Goma area, whether in a volcanic crisis or for other reasons, such as conflict, continues to haunt relief workers, and has to be weighed in any risk assessment of a future eruption of Nyiragongo volcano. This hazard is directly related to the geo-morphology of the area (the flanks of the two volcanoes) and Lake Kivu as the main source of drinking water in Goma.

In July 1994 around one million Rwandan refugees fled into North Kivu from the ethnic violence and civil disturbance in Rwanda in which 500,000-1000,000 civilians, mostly ethnic Tutsis, died. The speed and scale of the influx of these ethnic Hutus overwhelmed the world's response capacity. The name of Goma will be forever linked to the Rwandan genocide of 1994 and the huge humanitarian crisis that was provoked when the refugees fled for their lives across the border with Zaire (now Congo) and established camps near the city – at Mugunga (the largest), Katale, Kibumba and Munigi. About 200,000 refugees also took shelter in the main city area (Fig.2).

The refugees, already exhausted and undernourished, fell victim to a massive epidemic of cholera and dysentery. In the first month of the influx, an estimated 50,000 refugees had died. These and subsequent events have been reported and debated in the medical literature and a discussion of the issues involved is necessary here as they are highly relevant to the volcanic risk assessment. This is because the evacuation of populations is fundamental to mitigation in volcanic crises, but it is also usually a poorly managed process, even in developed countries.

2.5. *Cholera epidemic, July 1994, and lessons learned from the mass movement of refugees in November 1996*

In 1994, most of the refugees entered through Goma between July 14 and 17, and the cholera epidemic began almost immediately. During the first month after the influx, almost 50,000 refugees died, most in the streets of Goma, in explosive epidemics of diarrhoeal disease caused by *V. cholerae* 01, biotype El Tor, and followed by *Shigella dysenteriae* type 1 (See Appendix 1). Acute malnutrition rates among children under 5 years old ranged between 18 and 23%. As graves could not be dug in the lava rock, bodies were picked up by trucks for subsequent mass burial. A well co-ordinated relief programme was associated with a steep decline in death rates by the second month of the crisis.[11] Most of those who survived had moved out of the town to camps at Munigi, Kibumba, Katale and Mugunga (Munigi closed in August; camps were later opened at Kahindo and Lac Vert).

The centre of the outbreak was probably Goma. Many of refugees were located by Lake Kivu, but as there was no available way to purify and transport sufficient quantities of water most of the refugees consumed untreated water. The lake was pH 8 (the organisms can only multiply in alkaline media, but are killed in fresh water). By 31 July, bloody diarrhoea (*S. dysenteriae* type 1) surpassed watery diarrhoea (cholera) in terms of numbers of cases – almost 40% of all deaths during the first month after the influx were associated with bloody diarrhoea. The high death rate, which was almost entirely attributable to diarrhoeal disease, was unprecedented for refugee populations up to that time. Many refugees failed to reach health facilities, and the relatively few health workers on the scene were overwhelmed.[12] Of those health-workers involved many lacked the requisite skills in rehydration.[13] The speed of transmission and the high clinical attack rate were linked to the crowding, poor personal hygiene, and the debilitation of this refugee population.[11] The refugees arrived exhausted and many died in the first days from dehydration without any diarrhoeal illness.[14] Secondary contamination of other water sources and containers also probably occurred. The situation was exacerbated by the lava on which Goma was built, which made digging latrines impossible.

It took three weeks after the influx for the international community's response to have an impact and institute routine refugee relief measures. By early August a standardized health surveillance system was established. Between 1 and 16 August, 162 patients with suspected meningitis were reported, predominantly Group A, the commonest outbreak strain in this African region. A mass immunization programme was instituted in one camp to combat the outbreak there. Measles immunization, vitamin A supplementation and water distribution were some of the measures instituted in each camp. Food distribution was a problem because of the lack of security in the camps and the control over the refugee population by Rwanda political and military leaders.[11]

Following further conflict, from Nov 16-24, 1996, nearly half a million Rwandan returnees from the five Goma camps entered Rwanda through Gisenyi on their way back to their communes. Another outbreak of diarrhoeal disease occurred, but in striking contrast to the 1994 catastrophe, the numbers of deaths in this mass movement from non-violent causes was very low, although precise numbers could not be estimated.[15] This was partly a reflection of the population's better health status before the migration and the immunity acquired in the 1994 cholera outbreak (when probably all the refugees had been infected). Eight relief agencies based in Gisenyi since 1995, including MSF and MERLIN, were in a position to respond, making available rehydration facilities at transit centres and way stations along the route. Even so, facilities were less well prepared than they could have been and some of the deficiencies of 1994 resurfaced again.[16] The refugee exodus was at a rate ten times higher than that planned for and none of the aid agencies on the ground had had any prior knowledge that such a massive movement was about to take place (though MSF stated it was prepared with relief stocks in place in Rwanda and Europe.[17] In consequence the pressures on the aid agencies present were immense and health facilities were overwhelmed with consultations from patients with watery diarrhoea and dehydration, as well as other conditions (in 1994 over 30 agencies had been involved in establishing cholera treatment centres alone). An unknown, but probably important, number of the diarrhoeal cases were cholera.

The health risk from contaminated food and drinking water in Goma is exacerbated by these local geological features:

- the lake is the main, if not only, supply of drinking water, but the sanitation system of the area presents a constant source of potential contamination of the lake with cholera and shigella organisms which are not rapidly destroyed by the fresh water with its alkaline pH
- the hard lava rock on which Goma is built contributes to the spread of disease, as it resists the construction of deep sanitation systems or latrines (which readily overflow down towards the lake in the wet seasons)
- the eruptions of Nyiragongo do not produce much ash and so the lava rock is not covered by deep, fertile soil derived from ash falls; what soil exists comes mainly from the slow degradation of the lava
- the porous nature of the terrain built up by successive layers of erupted lava means that rivers and wells do not exist in the area; the decision in 1994 to move the refugees that had transformed Goma into a huge refugee site to new camps north of the city, rather than west along Lake Kivu, was effectively a “death sentence” on many people[18]

In an interview given to the *New Scientist* (10 November 2001, 44-47), Michael Toole admits that in 1994 an emergency measure should have been to consider a low-tech solution such as “hiring a thousand people to throw chlorine in every bucket of water. We probably could not have prevented the cholera outbreak, but we could have postponed that explosive spread until we were ready to cope with it.” This lesson, borne from extreme experience, should be etched on every contingency plan for Goma.

3. The 17-18 January 2002 eruption and its aftermath

The eruption began without warning at 08.35 local time on 17 January and by the end of the day Goma had been shattered by two lava flows that covered at least 13% of the city and destroyed the homes of 100,000 people. The mass exodus of the population of the city started in the late afternoon, with about 300,000 crossing the border to Rwanda in the east whilst about 100,000 people moved west, along the lake in the direction of

Sake/Masisi and Bukavu in the west. By 21 January, most of these people had returned to Goma, with approximately 30,000 persons left scattered in the Goma area and in two camps in Rwanda[19] felt earthquakes continued for days afterwards, a reminder that the volcanic activity might not be over, but the eruption had officially ceased on 18 January, though for several days afterwards lava continued to flow into Lake Kivu at the delta created by the main lava flow.

3.1. *Premonitory signs*

The eruption had been preceded by a number of premonitory signs in the months and weeks beforehand, such as increased fracturing and fumarolic activity on the upper southern slopes of the volcano and an increasing level of seismicity, especially between 4 – 17 January. Strong earthquakes (magnitude 3.5-4.5) were felt on 7 October, and on 4 and 7 January. The last event triggered fumarolic activity that was observed by local inhabitants. The GVO observed new fumarolic activity in the old Shaheru crater and from new cracks in the inner walls of the Nyiragongo crater following the 7 October earthquake. After the 4 January earthquake, the measured seismic activity remained at a high level. The onset of the eruption was preceded by almost 8 hours of very low seismicity and it started without any detectable preceding signal at 0835 local time.[1, 2]

A sudden re-opening of the 1977 eruption fracture at 2800 m elevation allowed the lava lake in the summit crater to drain out violently. In the following hours the fracture system and the eruption of lava propagated down slope for 20 km. towards Goma and Lake Kivu, producing a series of fissure vents that can be seen to end only 1.5 km from the Goma city airport. Two major lava flows (up to 2 m. thick and 100-400 m wide) destroyed most of the business centre as well as the housing of 120,000 people. The main lava flow crossed part of the Goma airport runway and entered Lake Kivu, forming a new lava delta about 200 m. wide and 120 m. long, with a lava tube extending as far as 80 m in depth.[1, 2, 20]

3.2. *Evacuation.*

People left the upper flanks of the volcano and headed towards Goma to escape from the lava eruptions, which had made a swath through the remoter villages. People in Goma were spectators of the events until the lava flows began to enter the city towards the late afternoon, when they too began to leave by the roads east and west out of the city. Lava invaded the airport at around 1600, and was at the Cathedral by two hours later. We were reliably informed that the mood of the population changed from expectancy to rapid exodus when lava vents were seen to develop within the city in advance of the main lava flow (this observation is a critical one, and requires further confirmation. We were shown the location of these vents at the roundabouts at Seigners and Bralima, 500 m or more from the end of the airport runway).

Most people left the city by foot and their passage eastwards over the border to Rwanda was unimpeded. Car traffic was held up for two hours by the border guards. Nevertheless, most of those who left got away before late evening. As many as 400,000 persons left, whilst a substantial number of people stayed behind in the area of the town between the lava flows and also in the western part of the city. Thousands of people spent the night in safety on Mt Goma, where an unparalleled view of the eruption was obtained. Video footage of the lava flows entering the city was made from this vantage point.

The video from Mt Goma shows the clouds of ash and smoke from burning vegetation around the vents and flows on the volcano being convected into the air during the day, and the progression of both lava flows into the city in the evening and night. The lava flows lit up the scene after nightfall, and they were accompanied by intense fires of buildings, especially at the lava flow fronts. The fires were clearly most intense in the main lava flow that struck the commercial centre. There were audible explosions, possibly as cars and petrol stations exploded.

3.3. *Rapid reoccupation of Goma*

Lava continued to move along the middle of the main flow next day, although the edges had solidified. This flow acted as a barrier to the return of the population from the east. It was not until the 19 January that the population was able to return across the flow in large numbers, and then only in one place where the lava was still very hot ("le pont de feu"). Video footage shows a remarkable scene of people flooding over this narrow part of the flow and running to prevent their feet from getting burned (a few minor foot burns were treated at Goma hospital).

Many earthquakes (around 250) were felt on the 19 January, with 10 large ones, some of which caused at least two houses to collapse. These continued on a frequent basis for about a week, and acted as a deterrent to some people returning to the city

Buildings consumed in the fires were still smouldering and the air would have been contaminated with residual smoke and dust from the fires, including light amounts of volcanic ash, and capable of producing high concentrations of fine particles in the ambient air.

3.4. *Mechanisms of eruption*

Two types of lava eruption are hypothesized by scientists.[1,2] On the higher flank (the ancient Shaheru crater area) the lava appears to have drained mainly under hydrostatic pressure from the summit crater. Lower down in the Munigi area, the eruption appears to have been more gas driven. The lava from high up travelled with velocity of tens of kilometres per hour and solidified to a depth of 5-15 cm, though marks on trees indicate that it flowed to a depth of 1.5 m. (Fig.3). In contrast, the lava in the Munigi area moved more slowly (tens or hundreds of metres per hour), and solidified and flowed at a depth as great as 3-4 m in some places. The latter flows were much less hazardous to life, as they could be easily avoided, but were more destructive (Fig.4). Analysis of samples of lava from the different locations shows no major mineralogical differences in their composition as would be expected if their sources had been different (i.e, crater lava lake *versus* magma chamber), and the total lava volume emitted was 20-30 million m^3, about the volume of lava in the crater lake before the eruption. The findings indicate that most, if not all, the lava drained from the crater lake out through the fissures, even as far as fissures in Goma itself.[1,2]

The source of the lava has major hazard implications for the future and further research will be needed to verify if a supply came from a magma conduit at a low level on the volcano. The mechanism for the release of lava in the 1977 eruption was more clearly a drainage phenomenon, with radial fissuring around the summit crater and a high level of very fluid lava in the lake. The lava lake level in January 2002 was not as high as in

1977, and the surface was solidified. In January 2002, the opening of fissures lower down and directed towards Goma may reflect a new evolution for the volcano with eruptions caused by rifting. The observations of intense post-eruptive seismicity and widespread ground subsidence in the Kivu rift, together with both the synchronism of the eruption with volcano fracturing over 20 km., and the broadly consistent volumes of bulk lava flow and crater collapse, means that the evidence is presently in favour of rifting causing the fractures, rather than some hydrostatic phenomenon.[1] The future hazard for Goma and Lake Kivu is for lava to be erupted from a magma chamber or deep conduit in an extension of the rifting. For various reasons (see below), this type of eruption would be more dangerous than either the 1977 or January 2002 events.

4. Review of the acute health impact

A preliminary study of the health impact of the eruption was undertaken soon after the event.[3] In 11-22 March, we undertook a more comprehensive field study to collate the available information on the impact of the eruption on human health. Interviews were held with local officials, the staff of the city's utilities, and workers for NGO's and international agencies in Goma. The results of the epidemiological surveillance of attendances at primary health care facilities were studied. We worked with scientists from the GVO in assessing ground gas emissions in the city and its environs, and the impact of the lava flows on buildings was also considered. Investigations of air and water quality were performed. An ash sample from the 22 January crater explosion was kindly supplied by the GVO and sent for analysis. A visit to the town of Masisi was made to learn more about the impact of ash falls from the volcanoes on human and animal health. Visits were made to Sake and camps for displaced persons. A helicopter flight was arranged with MONEC to photograph Goma from the air and over-fly the volcanoes with scientists from the GVO.

4.1. *Human casualties of the eruption*

Before the eruption, the main public hospitals in Goma were the Goma Hospital – Hopital Général de Reference (200 beds), the Charité Maternelle (100 beds) and the CBK- Virunga Hospital, which was destroyed by the lava. Goma Hospital is located at the base of Mt Goma, and was the only public hospital that remained open during the crisis. A medical team at Gisenyi Hospital also worked through the eruption. Primary health clinics are the main access points for health care. The patients are normally expected to pay for hospital and health clinic treatment, though charges for health care were wavered in the two months after the eruption, when use of the facilities markedly increased as a result. We interviewed three hospital doctors, one of whom was a foreign surgeon attached to an NGO, who had continued working in Goma Hospital in the days during and after the eruption.

- About 120 patients were in Goma Hospital on 17 January, but between 1900 and 2200 hr the patients began to leave spontaneously (some could barely walk) to the safety of Mt Goma, despite reassurances from the hospital team that the lava flows did not endanger the hospital; 30 patients remained. During 17-18 January, there were 18 deliveries (the expected number was 10-12, suggesting that heavily pregnant women stayed behind in the evacuation, and the stress of the event may have been responsible for the triggering of premature labour).

- There was remarkably little evidence to support earlier reports of a large loss of life in the eruption or in the explosion of the gas station on 22 January, when siphoned petrol leaked onto the hot lava flow, and it seems likely that the original numbers were over-stated. Three people wounded in the gas station explosion were treated at the hospital, perhaps 20 others died (initial reports suggested 100). One informant said that the eruption had led to eight people receiving burns injuries and around 70 people were killed altogether, including in the petrol station explosion and the looting, but there were no reliable records available.

- A mother and child were known to have died taking refuge in a house that was overwhelmed with lava and caught fire (Fig.5), but other deaths in Goma were likely to have been few, if any. The number of patients treated for burns from the lava flows was also few, and the burns were minor. However, the number of deaths in the villages high up on the volcano, such as Mujoga, where the very fluid lava travelled at speed and made a swath through the houses, is unknown. Again, only a few deaths appear to have been reported (the eruption occurred after daybreak and the people were also aware of the need to rush to higher ground to protect themselves from the fast-moving lava).

- Some deaths were allegedly caused by armed men engaged in looting in the evacuated parts of the city. Two or three people were treated for gunshot wounds at the hospital.

- The felt earthquakes (magnitude 3.5-4.5) were a considerable source of stress to the remaining and the returning people, as they caused buildings to shake (two collapsed in Goma) and engendered fears of a larger earthquake or further eruptions. These fears delayed the return of the population, who would otherwise have chosen to return even sooner. About 20 people sustained minor injuries from this cause and were treated at Goma Hospital. Several deaths and numerous injuries were reported in January from the collapse of buildings due to the earthquakes in Gisenyi, but we could not confirm this.

- Minor road traffic accidents were common during the evacuation and about 20 people were treated for minor injuries (no deaths from this cause were reported).

- Numerous minor explosions shattered small areas of concrete flooring and paving stones around the city, and not just on the ground within close proximity to the lava flows, where methane can be emitted as the flows compress gases from the incomplete combustion of vegetation and debris through the ground. A smell of methane pervaded many parts of the city in the one to two weeks after the eruption and the presence of this gas at low levels was confirmed in the January mission.[1, 3] As reported previously, we consider that the methane was rising up from deep sediment layers through invisible fault lines as a result of the strong earthquake activity after the eruption. Carbon dioxide at low concentrations was found to be emanating with methane from the ground at some of these explosion locations.

- Carbon dioxide building up in sufficient amounts from diffuse ground emissions or erupting from the extensive fissures could cause asphyxia. Beneath a church in Goma, which had been burned out by fire triggered by the radiant heat from the main lava flow abutting against two sides of the building without levelling it, a small fracture had formed in the ground and two explosions had damaged two separate places on the inside floor. Two women had passed out, or at least had claimed to have been overcome by gases, at the incident locations. We heard of no other reports of ground gas emissions within the city affecting health, and no one appears to have been seriously injured in any of the explosions.
- Steam emanations occurred whenever rain fell on the cooling lava flows. Heavy rain fell on 7 February and at the same time, or soon afterwards, two people were killed (or seriously overcome) whilst walking across the lava (at two separate locations) whilst it was still steaming not far from the village of Munigi. This hazard of hot lava flows is not widely recognised, but it arises when steam is present in sufficiently copious amounts to displace the normal air and lead to asphyxia.
- Psychological stress from the eruption was considered by local doctors to be a much more significant health problem than injuries from the lava flows. As well as fear of the direct threats to life, the main problem for tens of thousands of people was the complete destruction of their homes and all their possessions in the lava flows, as well as the economic impact on the community from the loss of shops and trade in the devastated parts of the city.
- For several days irritant dust and fine debris from the fires remained suspended in the air and this was considered by the clinicians to be a causal factor in the increase in chest and eye complaints which were seen at the hospital and in the primary care clinics.

4.2. *Epidemiological surveillance.*

The WHO office had been devastated in the main lava flow. On 30 January WHO staff met to discuss infectious disease control priorities. The major epidemic-prone diseases (cholera, measles, malaria and dysentery) are endemic and were therefore expected to spread following the overcrowding and displacement. The background nutritional status of the population was already low and people were living in greater concentrations in houses and camps in stressful circumstances. The pre-eruption vaccination coverage for measles in Goma was only 40%, and so UNICEF and WHO initiated a measles vaccination campaign that began on 6-7 February and took about a week to complete in the city and was extended to include the camps. The epidemiological surveillance programme showed a large increase in total attendances at the two hospitals and 18 functioning primary health care centres after the eruption (Fig.6), falling at the end of February (free health care started on the 21 January and stopped on 1 March). Most of the increased attendances were children, with a disproportionate increase in the number of patients with respiratory diseases between 23 January and 5 February (peaked 23-26 January), declining to a more normal level by mid-February. A marked disproportional increase in attendances for eye complaints also occurred in the days following the eruption. As indicated above, a reduction in air quality after the eruption may have been at least partly responsible for these increases. No significant increases in cases of cholera or other diarrhoeal diseases, meningitis or measles were found.

Why was there no outbreak of enteric disease after the 17 January eruption? Possible reasons include:

- the evacuation occurred at a time of the year that is low risk (during the dry months of January and February).
- the evacuation was for a short time (for most people, two to three days).
- chlorination of water, though delayed, was begun in time, and was more extensively provided than even before the eruption
- the population was not markedly malnourished, nor was it exhausted, compared to July 1994
- the evacuation was not motivated by armed conflict and its impacts (but the threat of looting and violence was one of the main reasons why people rushed back to their homes on 19 January and before the area was considered safe)

4.4. *Displaced persons*

Of the 120,000 persons who have lost their homes, about 15,000 were in camps in the Goma environs. The largest was Itig camp near the airport, containing around 7000 people, where the houses were made from recycled galvanized metal sheets collected from the lava flow debris (Fig. 7). Other camps are the ESCO, near Lac Vert, and Kituku. There is a plan to resettle 40,000 people from Goma at a new development near Lac Vert, not far from Sake (this plan, which is going ahead anyway under local political direction, should be reviewed following a formal scientific risk assessment).

4.5. *Air quality*

Concerns about air quality are very common amongst lay people following volcanic eruptions, particularly in those who suffer from asthma and other chronic lung conditions.

- The high altitude of the crater (3,489 m.) means that the volcano acts like a huge stack, so that plume emissions get carried away from ground level around the volcano. We confirmed the absence of pollution of the air in Goma by sulphur gases, markers for volcanic plumes, which were at the detection limits for the small network of diffusion tubes we placed at the WHO and OCHA offices, and GVO.
- Ash emissions are unusual at Nyiragongo. On 22 January, a limited ashfall occurred on the south and east flanks of the volcano following a collapse/phreatic explosion in the crater. An analysis by the British Geological Survey of a sample of this ash confirms the low silica composition (with absence of crystalline silica), and a small amount of residual fluoride was found in a water leachate analysis (4.6 ppm.). Sulphate was raised in both acid and water leachate (about 8000 ppm.), which might also be relevant for toxicity to grazing animals. Analysis of freshly collected and stored samples will be needed in future ash falls.

- The ash was very fine: 32 wt.% of the ash was less than 10 microns diameter, and most of the ash particles were therefore capable of being inhaled into the lungs, with about 10 wt.% within the respirable range (< 4 microns). Fine ash also has a higher potential for adsorbing fluoride and sulphate, and being more toxic to animals.
- A concern about air quality in Goma, particularly in dry weather, was the effect of the dust generated by traffic driving on roads created after the eruption by bulldozers levelling the rough surface of the lava flows. Measurements of PM_{10} concentrations at the roadside (using a DustTrak analyser) showed rapid rises and falls with vehicle movements, but the effect on the ambient air was small and lasted only briefly (Fig.8). The background air quality in Goma, as measured in the WHO office garden, was good (< 50 µg /m^3). This was helped by the fresh winds blowing from Lake Kivu and occasional rainfall, which dampened down the dust.

4.6. *Drinking water quality*

REGIDESO, the Goma water company, found a raised fluoride level (4.8 ppm) in a water sample from near the lava flow on 21 January, but it fell to normal levels subsequently. Water samples collected by the UN–OCHA team in late January also found evidence of slightly raised fluoride levels (2.2-7.5 ppm); but at the lava front the level was 17 ppm.[2] The fluoride levels need to be monitored as they may alter with renewal of volcanic activity affecting the lake.

Water samples were obtained for analysis by the British Geological Survey in March from the lake and from two streams in Sake which were used for drinking water. The significant findings were, in the lake water, fluoride levels of 1.91 and 2.00 ppm (pH 9.0) and, at Sake, 3.33 and 3.83 ppm. (pH 7.4).

Fluoride is unlikely to have been a major health hazard in the area before – there is no obvious evidence of dental fluorosis amongst the population, which would be expected with chronic contamination of water with fluoride levels of 3-5 ppm and above (WHO Guideline Value: 1.5 ppm). However, the fluoride levels in drinking water in the area clearly need monitoring. Fluoride contamination of drinking water from ground sources is not uncommon in the East Africa Rift Zone.

4.7. *Ground gas emissions*

An important concern in the eruptive events of 17 January and thereafter has been the potential for emissions of carbon dioxide from fissures and from the soil. Other dangerous gases that needed to be excluded include methane, hydrogen sulphide and carbon monoxide. The potential for carbon dioxide emissions has been known for a long time, as there are numerous dry gas vents in the area, especially near Lake Kivu, that emit carbon dioxide, and occasionally lead to deaths in humans. The vents are known in Swahili as *Mazuku* (places with "evil winds"), and the depressions are often the locations of dead animals and birds that have been killed by the gas

Another issue was the minor explosions linked to methane ground gas in Goma in the days after the eruption, the scattered fires on the lava flows and the pervading smell of methane in the air of the city.[1, 3]

A repeat survey with GVO volcanologists using a portable infra-red gas-analyser (Geotechnical Instruments, GA45) in March showed that there were no longer any significant gas emissions in Goma. The lava fissures at Munigi showed no emissions, but carbon dioxide was being diffusely emitted at several steaming locations in the ground nearby the fissures there. A survey of several well-known *Mazuku* on the outskirts of Goma and towards Sake was performed. The high carbon dioxide levels emitted at these sites were confirmed (Fig. 9). In addition, several dangerous sites were confirmed within the ESCO camp area and these were cordoned off on WHO advice – one low lying area was going to be used as a cemetery which would have proved very hazardous for the grave-diggers (Fig.10).

Persons swimming on the shore of Lake Kivu occasionally report feelings of suffocation or being overcome, and sudden deaths in local and expatriate individuals occur sporadically. There are possibly numerous places where carbon dioxide is emitted from the lava rocks by the edge of the lake. A survey at two houses whose gardens adjoined the water showed potentially lethal levels of carbon dioxide at the water surface where people swam. In still conditions swimmers could lose consciousness and drown without warning. A full survey of the lake edge for gas emissions is warranted (Fig.11).

Mapping and monitoring of the ground gas emissions is an urgent objective of the volcanologists.

5. Lava flows and the impacts of the eruption on the infrastructure of Goma

A city has not been devastated by lava flows before and the impacts of the two flows in January need to be carefully considered for future emergency planning. An eruption of Montagne Pelee, Martinique wiped out the city and 28,000 of its inhabitants in 1902, but the devestation was caused by pyroclastic flows. In Colombia in 1984, 23,000 people died in the town of Armero and neighbouring settlements when they were destroyed by volcanic mudflows (lahars) triggered by an eruption of Nevado del Ruiz volcano.[21]

The most obvious difference between the two lava flows is that the western one had cooled much more than the main one by the time it reached Goma. Wooden houses very close to the edge of the former lava flow survived, whilst the radiant heat from the larger flow ignited all adjacent buildings or their interiors. The main flow also continued flowing into the lake for several days through the lava tube and the centre of the flow was still moving on 18 January in Goma. Two lava vents were reported to have opened in Goma and these might explain the differences observed between the two flows. What is apparent is that the flows contained two quite different properties – the slower moving, rough (aa-type), and the smooth (pahoehoe type) that could move faster and apparently be extruded under pressure in tongues from lateral vents in the main aa flows. The interpretation of the lava flow behaviour and how the different types of lava formed during the phases of the eruption requires study by volcanologists. The impact of the flows on the city's infrastructure and the implications for vulnerability studies are now described.

5.1. *Water supplies*

The water network across the city was broken by both lava flows (Fig.12). Both the main supply pumping stations for the city, Lac Kivu and Turquoise, were out of action because the power supplies had also been disrupted by the eruption. REGIDESO began attempts to restore supplies. Diesel generators were set up at both stations and Turquoise began to supply 10% of the network (in the east part of Goma only) by 20 January. On 19 January, five chlorination sites had been established at the Lake on the west side of the city, and these were increased to seven (20 January), 12 (21 January), 17 (22 January) and a maximum of 22 by 23 January (AMI-KIVU). Water haulage (tankers and bladders) did not get underway until 21 January (ICRC and OXFAM). Lac Kivu station came back on line on 23 January, supplying 30-40% of the network. The rest of the pipe network damaged in the eruption was being restored during the time of our visit with the help of ICRC, with an east-west connecting pipe being laid in the still-hot main lava flow. In the meantime, the more distant villages, like Munigi, were being supplied by bladders.

People who were unable to collect water from the piped system after the eruption would have taken water from the lake. Probably not all of this would have undergone chlorination because the chlorination sites were not all up and running until 23 January. About 30,000 people stayed in the west part of the city during the eruption, and this area is not on the network. There would have been insufficient fuel to boil all the drinking water needed.

In the villages people can walk many kilometres a day to fetch water from water supply points (standing pipes, bladders and trucks) and Lake Kivu (maximum distance between the lake and farthest dwellings is about 15 km). In the remotest villages, e.g., Mujoga, people also rely on rock basins containing stagnant rainwater.

The potential for outbreaks of diarrhoeal diseases from drinking contaminated water was therefore present immediately after the eruption, the risk falling rapidly in the first few days as potable water supplies were restored. Chlorination stations were rapidly reintroduced by the lakeside, the main source of water to Goma.

The water intake pipe for the Lac Kivu station is only a few metres away from the edge of the lava flow. The effect of the lava flow on the water near the inlet was checked by REGIDESO, who sent water samples to a laboratory in Kigali. A slight increase in turbidity was found in the sample for 21 January, which lasted for about a week. The fluoride concentration on 21 January was measured at 4.8 ppm, but it then fell to 1.5 ppm, which is the WHO guidance value.

Significantly, on week 14 in the post eruption epidemiological surveillance, the cutback in large-scale water distribution in the western part of the city, as a part of the return to normal, was associated with an increase in reported cases of gastro-enteritis. Six out of seven stool samples were positive for Ogawa-type cholera vibrios. All the patients reported that they had failed to chlorinate water taken from Lake Kivu. Preventive measures were rapidly instituted, the number of chlorination points was increased and REGIDESO and ICRC were requested to urgently complete repairs to the water supply system.

5.2. *Sanitation*

Houses in Goma have latrines dug into the ancient lava flows from Nyiragongo on which the city is built. Due to the hardness of the rock, the depth of latrines is generally less than ideal, not more than 1.5-2 m. In the rainy seasons (July-December and March /April), heavy rains can flush waste water from the latrines into the lake. These months are those of highest risk for diarrhoeal diseases. After the eruption, most of the people whose homes were destroyed by the lava took up occupancy with families in homes that were undamaged. The houses became occupied by as many as three families, which placed even greater loads on the existing latrines. New pits had to be dug to take the effluent, and these were often rudimentary. Occupants have to pay to have the pits emptied.

Thus, the lava flows, by displacing thousands from their homes and causing overcrowding, could have indirectly increased the already high level of risk to health from diarrhoeal diseases by adding to the potential for contamination of the lake with sewage from the overflowing latrines. The old lava rock is porous and the potential for the drainage of latrines to flow into the ground soil and then into the lake requires further investigation.

5.3. *Food supplies*

The main impact of the lava flows on the supply of food was on access to food stocks. Emergency supplies of food (BP5 – dried food and biscuits for three to five days) had not been stockpiled before the eruption. An on-going two-year programme under the auspices of the World Food Programme for the supply of food to displaced and other vulnerable persons was in progress. There were 1300 tonnes of stock in a warehouse in the western part of Goma, and this could not initially be accessed from the east because of the city being divided by the two lava flows. By 20 January, the emergency supply of food began to be co-ordinated, and on 21 January the distribution of beans, flour, oil and cereal became possible. It took five days to distribute the food to those in need in Goma, and after 25 January the distribution switched to hospitals, camps and to people living outside Goma. The distribution of food had been delayed because of the need to get stocks from Kigali and other centres. Only a small amount of food had been stored at Gisenyi. The BP5 supplies did not arrive until the 28 January, but in the end they were not distributed.

The specific problems faced with the food supplies were as follows:

- The list with the names of families was destroyed in the eruption and there was no back-up record. The lists had to be made up by the Heads of the quarters where people had moved to and this was done with inadequate knowledge. With up to three families in the same dwelling, some families (in particular, the hosts) got double rations, the others had none, especially as food was given out to 10 families at a time.
- The NGO partners had to be quickly increased from three to nine to distribute the food. This is a difficult task in disaster relief and the new NGO's were not experienced enough: violence broke out at times.

- There was insufficient wood or charcoal for fires (houses keep stocks of charcoal, but these had been lost in the destruction of houses in the lava flows), and so the poorest people would exchange food for other goods, such as clothing, and so would not receive enough calories. Charcoal was distributed with the food, and small stoves, to enable high calorie meals to be cooked.
- When new NGO's arrived they gave out food to their allotted population groups who became angered when they received less than those families in the main distribution.
- There was a lack of flexibility at the border with Rwanda on allowing food to pass through.

In summary, the distribution of emergency rations did not occur and there was a delay up to four days before food became available and released to the population. It is not evident that this delay has had any major impact on the nutritional status of the population of Goma, but it could have helped to weaken the resistance to infectious disease in pre-existing malnourished persons. Preliminary estimates by UNICEF were that 20% children were suffering from moderate malnutrition, 3% of whom were severe.

5.4. *Power supplies*

The Headquarters of the Société Nationale d'Electricité (SNEL) is at Bukavu and prior to the eruption all the electrical power to Goma came from Kivu. The Bukavu officials cut off the power supply to Goma at 1900 hours on 17 January in order to minimize the risk of fires from the cutting of overhead high-tension lines by the lava flows. The lava flows cut two main power lines and transformers that supply electricity across the city. These had not been possible to repair because of a shortage of money. Looters had taken poles and cables. As a result, the eastern side of Goma was dependent at that time on power from Gisenyi.

In January and February the power was provided free to the population, and there was, in consequence, no funds to pay Gisenyi for the power and so the supply had become a precarious one (there was also no money to pay salaries to the SNEL staff). Normally, 30 megawatts is needed in Goma, but they could only supply 20 megawatts, so supplies tended to be cut off in a rotation around the city and its environs. Problems continued with the system being overloaded and unstable for the power supply to the water pumping stations of REGIDESO, one of the two hospitals and the flour mill, for example. The areas where displaced people were living required new distribution systems. A serious problem of security existed for areas of the city, which could not be illuminated at night, particularly along the lava flows. Discussions were on-going with NGO's and international agencies, such as ECHO, to provide the necessary funding.

It took three days to reinstate the power supply after the eruption for the following reasons:

- Staff had to wait for the lava flow to cool down before they could cross back into the city
- Demand did not take off until 3 days after the eruption by when many people had returned

- Staff were dispersed and tools and equipment had been burned and destroyed in the eruption (or looted)
- A lack of fuel to drive around, so staff had to work on foot

From the health viewpoint the most significant aspect to the delay in restoring supplies was the delay incurred in restarting the city's water pumping stations. Future planning should consider ways of isolating power lines in areas impacted by lava so that the supply to the rest of the city can be maintained.

5.5. *Urban form (Fig. 14)*

Goma lies spread out along the edge of Lake Kivu and comprises mostly small dwellings around intersecting roads. There are no large industrial complexes or major storage facilities for chemicals or flammables, except for fuel at gas stations and the airport. The commercial centre was destroyed by the main lava flow, which also over-ran the runway and put the airport out of action for days after the eruption. When it reopened in January large aircraft could not be accommodated. This reduced the access to the area for emergency supplies, which had to be brought in by road from Kigali or Bukavu, which have the closest airports.

Access in and out of the city is relatively free-moving using the single main roads out to the east and west, but these could easily become congested during an evacuation of the population except that they would mostly move on foot. The roads would be inadequate for large loads of traffic. The evacuation route for most people living on the south flank of Nyiragongo would be through Goma.

Goma does not contain high-rise or densely packed buildings, so fires set off by the lava flows did not spread much further than the lava flow edge. In some places short tongues of pahoehoe lava flowed from the sides of the main flows into topographical depressions and ignited nearby houses (Fig.15). On the video a large ball of fire lasting a few seconds came from an explosion near the main lava flow. The lack of fires spreading further in the city was an unexpected finding and significantly reduced the overall hazard.

6. Future eruption scenarios

6.1. *Lava eruptions*

Volcanologists have suggested the following future eruption scenarios, which should be considered in the light of the above findings in the January eruption:

- Refilling of the lava lake and a recurrence of a an eruption from a flank of the volcano (as in 1977)
- Extension of the rifting and fissure eruptions of lava from the magma chamber – into Goma and possibly even within the lake (danger of gas release)
- Lava flows from fissures within Goma (in either of the previous two types of eruption) interacting with the water table close to the lake to trigger large phreatomagmatic explosions, with a worst scenario involving a base-surge, or pyroclastic flows, causing devastation over several square kilometres within the city (8). Little seems to be known about the hydrology of the region or the structure of the

volcanic edifice by the lake; this is important as an effusive flow of lava may just cool on its surface and not explode, even in close contact with groundwater

- The above scenarios accompanied by large ground gas emissions of carbon dioxide

Although contingency planning should include all these scenarios, volcanologists have not yet evaluated the likelihood of these.

These scenarios are also good reasons for not returning to the city after an eruption until the activity has clearly declined. The other hazards include the delayed explosion of flammable stores, intensely hot lava flows emitting steam in heavy rains, strong earthquakes leading to building collapse, the methane explosions, no means of sterilizing drinking water, raised fluoride levels near the lake water intakes for the city, lack of food and fuel, continuing movement of lava and extruded tongues of lava from lateral vents, and the unpredictability of the whole situation. In January, the major fear of some volcanologists was a major phreato-magmatic explosion from an eruption of lava in the heart of Goma.

6.2. *Lake Kivu and gas release scenarios*

The presence of large quantities of methane and carbon dioxide stored at depth in Lake Kivu has been recognized and puzzled over by scientists since the early 1960s,[22] if not before. The carbon dioxide is now known to be magmatic in origin and the methane is formed by fermentation in deep sediments at the bottom of the lake as well as by bacterial conversion of the carbon dioxide. The threat of an underwater volcanic eruption causing a violent outpouring of gases was considered by Tuttle, Lockwood and Evans in a USGS Open File Report following a brief field visit to the lake by the authors in 1989[8] and it was not published. These concerns were rekindled by the lava flow into the lake in January. The impact on the lake waters was investigated by Halbwachs and colleagues in February/March[20] who found that the lava tube descended 80 m. into the lake, but presented no risk to the lake stability.

Tietze has performed the most comprehensive study of the gas problem in Lake Kivu. The main descriptive points in his report[23] are as follows:

- Lake Kivu is located in the western branch of the tectonically and volcanically active East African Rift Zone. The lake covers an area of around 2400 km.^{2}, the maximum depth is 485 m. and the water volume amounts to 500 km.^{2}.
- About 10,000 years ago the Nile drainage system was blocked by the Virunga volcanoes, making the lake larger and deeper.
- In the main basin of the lake anoxic conditions exist below a depth of about 50-70 m. where the gases methane and carbon dioxide are physically dissolved under pressure and are unmixed with surface water. The strongest density gradient occurs around 250-280 m. depth.
- The main gases in the deep waters are carbon dioxide (250 km.^{3} STP) and methane (55 km.^{3} STP).

- The stability of the water-density stratification is relatively high. A disastrous gas burst from the main waters would require a strong volcanic or tectonic event

A meeting was held at IPGP, Paris, on 30 April 2002, between the three volcanologists in the French-English "Concorde" team, with P. Baxter and A. Woods, Cambridge University. Woods is a leading expert on fluid dynamics problems in volcanic phenomena, and the purpose of the meeting was to make an initial scoping of the hazard and identify specific research that needs urgent addressing within the time frame of action proposed by the UN OCHA Scientific Co-ordination Committee.

The main conclusions of the meeting were as follows:

- There were no precedents for this type of eruption at other volcanoes
- The underwater lava eruption would need to be large and of long duration to set up a destabilizing convective plume – how large and how long requires further study
- Lava pouring into the lake would be quenched and the heat transfer would be much reduced due to the layer of solidified lava, or crust, which would form a tube
- The hazard assessment would mostly require mathematical modelling, though some laboratory work is also needed
- Modelling the dispersion of the gas cloud would not be too difficult once the initial conditions of the release (including the amount of gas) had been worked out
- It was unlikely that, if a convective plume could be established in a part of the lake, the whole lake would overturn, as at Lake Nyos, Cameroon in 1986. The saturation of the gases was less than that at Nyos. Instead, the gas release, which could still be very large, would be confined to the part of the lake where the eruption takes place
- The probability of an underwater lava eruption and a gas release occurring as well is likely to be remote. However, the consequences are so high as to require emergency planning and preventive action

7. Recommendations for mitigation to be included in a risk assessment

7.1. *Volcano monitoring*

Volcano monitoring needs to be urgently expanded and upgraded by foreign scientists working with the full involvement of the Goma Volcano Observatory which, to date, has been working at a rudimentary state of capacity during the political crisis.

At a meeting with UN OCHA representatives (chaired by Julie Belanger) held in Nice on 24 April, the volcanologists from the Concorde and the UN consultant teams agreed the structure of a Scientific Advisory Committee for advising OCHA on the volcano monitoring that needed to be established using funds provided for the purpose to OCHA by donor countries. The major priorities identified were as follows:

- Observatory logistics - upgrading (underway) the transport, computer and communication facilities of the Goma Volcano Observatory so it could become more fully operational
- Seismicity - upgrading the seismic monitoring network and installing telemetry, including sending one or two seismologists to assist in the interpretation of the on-going level of volcanic and tectonic seismic activity
- Ground deformation (geodesy) - instigate a programme of monitoring ground deformation, using direct measurements, satellite mapping, GPS and EDM techniques, and lake level measurements
- Gas chemistry – ground emission mapping and lake-edge degassing (including lake water chemistry profiles), soil gas flux monitoring
- Lake gas burst hazard – fluid dynamics scoping studies for the destabilization of the lake waters and overturn of carbon dioxide and methane, including modelling the dispersion of the gas cloud
- Lava flow studies - mapping and studying the lava flows of the 17 January eruption
- Public education programmes – as part of communicating on volcanic risk
- Hazard/risk assessment - a group of the scientists involved to prepare a hazard assessment and to hold a meeting late in 2002 to collate information from the above on-going work and to assess the volcanic risk using quantitative probabilistic methods where possible

Some of these priorities will include human health aspects, which will require to be co-ordinated with health sector. Thus, the *ground gas mapping* will have implications for public health – carbon dioxide is being released in potentially lethal levels at the numerous *mazuku* in the area and in places on the lake edge; the *modelling of the lake gas burst* - cloud gas dispersion and its consequences to humans; and the *volcanic risk assessment* will need to be quantified in terms of human casualties and consequences to health. A key input to this analysis will be broad estimates of the number of cases of severe enteric diseases which can be expected in the worst foreseeable scenarios, such as following disruption and emergency relocation of the population in the absence of planned interventions to provide for the adequate distribution of safe food and water.

Some limitations of volcano monitoring (affecting vulnerability) include the following:

- Scientists accept that, generally speaking, volcano monitoring cannot accurately *predict* the timing and size of an eruption, at least in a sufficiently robust and objective way to be a reliable tool for timing the evacuation of populations to prevent major loss of life in a volcanic eruption. Volcanic *forecasting* by scientists allows the sounding of the alert that a volcano's activity is becoming dangerous, and volcanologists can indicate the likely range of eruptive hazards that could ensue and the most probable mode of the eruption and whether it is imminent or not. They can also provide reassurance when signs from the volcano do not necessarily herald a major eruption.

- The limitations of volcano monitoring are more obvious in societies without civil science (e.g., in developing countries where most people are uneducated in science or do not even understand what scientists do), or the political will is lacking to take the necessary action. The tragedy at Nevado del Ruiz volcano, Colombia, in 1984, when 23,000 died in a lahar triggered by an eruption was an example where forecasts by scientists were ignored or mishandled leading to a failure to warn and to evacuate towns at risk.[24] Presently, over 15,000 people in the town of Banos, Ecuador, have refused to leave despite the extreme threat of pyroclastic flows from Tungurahua volcano. The cultural divide between western trained scientists and society becomes even more problematic in a place like Goma, where there is an absence of the government and civil institutions needed to enable scientific knowledge to be communicated to the people in a manner that allows their involvement in decision-making. There are no police, fire or civil protection organizations, or government volcanic crisis committees, which would be found in more advanced democratic societies.
- The other feature of the society is that it cannot be a risk-averse one by the standards of industrialized countries. This was demonstrated after the January 17 eruption with the rapid return of the people to Goma that began even before the lava flow had stopped, and was symbolized well by "le pont de feu" which people streamed across on 19 January, placing the risk from further eruptive activity lower than other life and death priorities. The eruption seemed only a "blip" in their precarious existence. In such a society recommendations for a precautionary evacuation in case the volcano erupts are unlikely to be readily accepted when there are other compelling and more familiar sources of risk in their lives.
- The key to volcano monitoring, as far as the direct threat of Nyiragongo volcano to Goma is concerned, lies in seismic monitoring through a seismic network adequate enough to provide warning of magma rising beneath Goma (or the lake) in relation to further rifting. Signs that magma is rising could, in conjunction with other evidence, lead to a warning to evacuate Goma. The warning may or may not be followed by an eruption, but it might be given far enough ahead to allow officials in Goma, the NGO's and other outside agencies to trigger their evacuation contingency plans. These plans should contain all the components necessary to prevent a humanitarian crisis arising from the mass movement of hundreds of thousands of people into Rwanda or further inside Eastern Congo.
- There is no proven monitoring method for accurately predicting a lake overturn.

7.2. *Forecasts and warnings*

The scientific monitoring and evaluation work will all be useless unless the lines of communication between the GVO scientists, foreign scientists and the appropriate officials, plus the local people, are all in place, and a satisfactory method of warning the people exists in the event of an impending future eruption. The scientific institute in which the GVO is embedded does not appear to be functioning. However, weekly meetings with the Governor have been instigated, as have regular slots for the GVO volcanologists on Radio Okapi. But the effectiveness of this more visible role for the GVO and its effect on its credibility with the population at large have yet to be established and it will be important in the foreign scientific initiatives to review these issues on a regular basis.

7.3. *Evacuation planning*

In the most serious volcanic scenarios, there will be a need for the urgent evacuation of at least a large part of the population of Goma. The January eruption proved that hundreds of thousands of people could leave the city within the space of only a few hours, the vast majority on foot. This was a self-evacuation in the middle of an eruption, rather than a planned one on the basis of advice from the GVO. It has yet to be shown that the population would leave on a planned basis, especially in the context of the continuing political crisis. Key considerations include the threat of physical violence, with people being more vulnerable as evacuees depending on where they go, and the threat to the property they leave behind.

In the absence of the requisite government structures, the NGO's have a critical presence in the dissemination of information. The GVO has to have credibility with these organizations and the international agencies such as WHO, and their credibility is now being enhanced by the visible input of expert foreign scientists.

Consideration needs to be given to making evacuation plans for the hospitals.

7.4. *Emergency planning*

At the time of writing a multi-sectoral emergency plan is being developed.[25] This will not be complete until the eruption scenarios are clarified in more detail, and this will depend on the outcomes of the Risk Assessment Meeting planned as part of the urgent scientific programme of investigation and monitoring. There are three principal volcano scenarios presented in the draft plan that will need to be expanded upon in more detail as part of the Risk Assessment meeting. The draft plan allows for the relocation of between 200,000 to1.5 million people, depending upon the scenario.

As far as Lake Kivu is concerned, the most reasonably foreseeable worst scenario would be for the eruptive fissures to extend into the lake along the same line as the fractures from the Nyiragongo crater to Goma, which opened in January 2002. An underwater lava eruption near Goma would prompt the evacuation of the city and its environs in the same way as for a lava eruption into the city. Further work is needed on the dispersion modelling of the gas cloud to determine the extent of the evacuated area, which will in any event be greater than that needed for the lava flow into the city.

As outlined already in this report, minimising loss of life also means planning and providing for the continuing supply of safe food and water to the population during their exodus, the period of relocation, which may last weeks or even months, and subsequent return to Goma and its environs. An adequate lead time for evacuation therefore includes a sufficient period of warning to allow the NGOs and international agencies to gear up for the emergency, which will be longer than the warning time need for the population to leave under an evacuation plan. Forecasting a volcanic eruption days or weeks in advance is not likely to be possible, so an understanding at what stage and on what basis the warning to the NGOs will be given needs to be elaborated upon and agreed with all parties as part of the Contingency Plan.

The two mass movements of refugees, in 1994 and 1996, were amongst the most dramatic population movements in history. The lessons that need to be considered in volcanic risk management for the present population of the Goma area include the following:

- mass population movements, as in an evacuation of the entire city in a volcanic crisis, are associated with a high risk of explosive outbreaks of cholera and dysentery – these may start almost immediately by drinking unchlorinated lake water
- the risk is increased in populations that are malnourished, weakened by the threat of violence and suffering from exhaustion
- the risk of epidemics of diarrhoeal disease can be reduced, and even eliminated, by ensuring adequate supplies of chlorinated drinking water and food rations at health posts along the evacuation routes
- mortality can be kept at low levels by the provision of adequate rehydration facilities staffed with trained health workers along the evacuation routes
- adequate supplies of chlorinated water and uncontaminated food need to be maintained at all times for when the city is re-occupied (this requires working city infrastructure – water, power and food/fuel distribution)
- the temporary evacuation of hundreds of thousands of people from Goma in a volcanic crisis does not need to be associated with a high mortality from infectious disease epidemics (including measles and meningitis) so long as appropriate contingency planning is in place and providing that there is a lead-time for the aid agencies to send adequate back-up teams of experienced health workers and supplies which can be set up before the exodus occurs.

Siddique et al. considered that the high case fatality rates in the 1994 epidemic were due to a lack of preparedness and training amongst treating staff.[13] They recommended better medical co-ordination as follows:

- Standard guidelines for case-management of cholera and shigellosis for all parties involved in medical relief activities
- Vigorous efforts should be made to promote the use of oral rehydration therapy, and appropriate intravenous fluids should be used to treat dehydration from severe cholera
- Involve experienced members in medical NGOs
- Investigate the sensitivity patterns of local strains of pathogens before ordering large quantities of anti- microbials
- people need to be protected from the threat of human violence and sudden displacement. The overall management of any contingency plan has to take into account the role of local and Rwandan political and military factors, including basic security issues for the operation of the aid and other international agencies.

Thus preparedness should include plans to maintain supplies of chlorinated water from the lake; generators and fuel for the water pumping stations; monitoring of fluoride levels.

Emergency food rations should be strategically stockpiled, together with charcoal fuel and stoves. NGOs should be better prepared for food distribution.

Goma airport cannot be relied upon for the delivery of humanitarian supplies in a future eruption as it may be covered by a lava flow.

Mass casualty planning for the future eruption scenarios (see above) is not feasible in this setting. Injured survivors of eruptions usually suffer from serious burns – a burns team should be sent as required, as skin grafting is often necessary to prevent long-term disability.

7.5. *Land-use planning*

Another important aspect, in the longer term, is mitigating risk by planning the future development of Goma in such a way as to minimize the impact of a future eruption. This approach includes the careful siting of human settlements and key infrastructure, such as hospitals and other buildings of importance, overhead power supplies and sub-stations, the water pumping stations and the water distribution networks, stores of emergency food and other essential supplies, etc., especially in the light of our account above of the January 17 eruption and its consequences.

7.6. *Engineering measures*

Although engineering measures appear on the list of headings under natural disaster mitigation, and are important for preventing floods, for example, there is little scope for measures such as building barriers against lava flows at Nyiragongo volcano. However, a planned degassing of Lake Kivu would be an important undertaking to consider in the light of the successful first attempt at degassing Lake Nyos, Cameroon, by an international team of experts led by Halbwachs (this began in March 2001 and ran successfully until January 2002 when it developed a fault – further funding is awaited to enable this to be rectified). The safety of this procedure at Lake Kivu with such a large population at risk living around the lake would need to be established.

The water supply network needs strengthening and extending; and pipes hardened against lava flows (e.g., laid deeper and using steel pipes). More pumping stations are needed in case the two existing ones are damaged by lava flows.

Latrine pits should be dug deeper, but investigation of their porosity and contamination of the lake is needed.

The electrical grid needs strengthening so that power can be switched along different routes when a line is disrupted by a lava flow.

Tanks of aviation fuel and petroleum should be hardened against lava flows.

Consideration needs to be given to seismic resistance in any future large buildings in Goma because of the hazard of volcanogenic earthquakes.

7.7. *Hazard mapping and risk assessment*

At the UN OCHA Scientific Co-ordinating Committee meeting in April, a plan of work was agreed, the results of which would be fed into a quantified risk assessment by a team of experts meeting in Goma planned for late 2002 (Appendix 2). An essential task for this group would be to define the eruptive scenarios and estimate their probabilities using elicitation and expert judgement methods, as was undertaken for the Montserrat volcanic crisis. The findings could be updated as new information on the volcano was obtained from new scientific work and in the light of developments in volcanic activity.

The hazard map in current circulation needs revision and the eruption scenarios refined for the Goma Contingency Plan. A full hazard assessment has yet to be undertaken.

As far as the present hazard situation in Goma is concerned, the following observations can be made, pending a full hazard assessment:

- the rapid return of the population was unplanned and would not have been recommended by scientists until activity had fallen to a safe level (see 6.1.); however, in any society it is very difficult to obtain full compliance of populations for evacuations in volcanic crises. Here, the primary motivation of the population to return was, paradoxically, security (avoiding conflict).
- a substantial shift in the status of the volcanic activity will be needed to make the people leave Goma; monitoring of the volcano is still at a rudimentary level and there is an urgent need to understand the continuing high level of seismic activity.
- in the meantime, an unexpected and rapid change in activity status to a lava fissure eruption in Goma could result in many casualties; there is no immediate expectation of such a change by volcanologists.
- contingency planning in the event of a renewed eruption activity must continue to be developed.

A probabilistic risk assessment needs to take account of individual and societal risk. Individual risk is the frequency at which an individual may be expected to sustain a given level of harm from the realization of specific hazards – how the hazard affects them. Societal risk concerns the occurrence of multiple fatalities in a single event – the relationship between the frequency and the number of people suffering from a specified level of harm in a given population from the realization of specified hazards.

An example: the individual risk from an eruption occurring over the next year which kills 1000 people in Goma is 1:500 (assuming a population of 500,000 people). This is a relatively small risk by any standards and one that many people would take rather than evacuate. However, a simple way of expressing societal risk is that 1000 people dying in a single event over the same period would be a catastrophe. In democratic societies, government officials and elected representatives are usually concerned about societal risk in their judgements and recommendations in crises – which often places them in conflict with individuals who rightly perceive that their own risk might be small and acceptable to them (wearing car seat-belts is an example). In Goma, individual risk is the current criterion of the people and, in the absence of governmental mechanisms to evaluate and act on societal risk, it is almost inevitable that in a further crisis significant loss of life could occur.

The health risks of evacuating a population the size of Goma for weeks or months should also be evaluated for risk assessment purposes (Appendix 2).

In view of the scientific uncertainties involved any risk assessment must be probabilistic, taking into account a range of possible scenarios and their casualty consequences. A model for this was the methodology used in the Montserrat volcanic crisis (Appendix 2).

In the longer term, the concept of having such a large population living in Goma on a fracture line from the summit of the active Nyiragongo volcano to Lake Kivu and its gas hazard must be formally questioned by scientists for the first – and not the last – time.

What we can conclude at this stage is that vulnerability amplifies the danger to the population of Goma in two main ways. Political vulnerability, which includes the humanitarian crisis, will profoundly affect how the people regard warnings about impending eruptions and their beliefs in taking actions such as evacuation to protect themselves. It is likely that people will ignore warnings and will wait for an eruption to occur before taking action. Human, geomorphological and infrastructural vulnerability will combined or separately increase the danger from cholera and other lethal infectious diseases, if the population does evacuate, or subsequently returns prematurely to a shattered city without the means available of chlorinating water from Lake Kivu.

Decision making on risk is therefore a balance between the two dangers: on the one hand, an eruption without a timely evacuation in Goma and, on the other, an evacuation of the people of Goma which, without adequate preparedness, is followed by a cholera epidemic. The numbers of deaths in both scenarios needs to be balanced, with the scales weighing more heavily in favour of evacuation if the NGO's are prepared sufficiently to cope (Appendix 2). Volcano monitoring, therefore, has an important role in forewarning NGO's and providing them with sufficient lead-time to prepare for the planned or unplanned evacuation of Goma.

8. Summary of vulnerability

8.1. *Political vulnerability*

We have shown above that political vulnerability is a main threat, with consequences for the population in affecting their responses to warnings from scientists on impending volcanic activity. The lack of security and fear of violence, the absence of democratic institutions, are the main issues affecting human vulnerability in this and future volcanic crises. Volcanic risk management is untested in this socio-political context.

8.2. *Human, infrastructure and geo-morphological vulnerability*

Human, infrastructural and geo-morphological vulnerability play the major role in the danger from epidemics from cholera, the other main hazard to the Goma people in this volcanic crisis.

The cutting of water and electrical power networks by the lava flows resulted in increasing the dependence of people on water taken direct from Lake Kivu before chlorination was fully in place. The risk of enteric disease was increased further by the destruction of housing by the flows and the resultant overcrowding. Food and fuel also became scarce, and water could not be boiled.

Although one hospital and two health centres were destroyed, access to health care actually improved after the eruption, with the temporary waving of charges.

Roads were cut which impeded restoration of services, but this was temporary.

The loss of the commercial centre and housing has meant a loss of jobs and disruption of the economy.

The consequences to health in terms of trauma and infections of these impacts were relatively small, especially in comparison to the potential hazards from the lava flows (6.1). Mortality and morbidity were remarkably low in the light of the lava flow hazard. However, the low mortality might make people underestimate the volcanic hazard in the future with consequently higher loss of life

Other consequences of the lava flows were mainly psychological stress from loss of homes, possessions and jobs. Perceptions of the people were that the impact extended to heart attacks, miscarriages and other ailments. This is the first time that a lava flow has impacted on a city and made such a large number of people homeless. The eruption should therefore have a significant effect in aggravating poverty in some social strata, at least.

Security was the main reason for the rapid return of the population: the fear of violence and being controlled in makeshift camps, and the inevitable looting of homes.

Overcrowding increases vulnerability to endemic infectious diseases.

Education of the populace on volcanic hazard is a paramount need.

8.3. *Volcanic eruption superimposed upon complex emergency*

The acute impact of the volcanic crisis on the humanitarian situation has been small, as far as we can tell (a "blip" according to one NGO official). However, the long-term consequences of the psychological and economic impacts of the destruction to private and commercial property, as well as the political issues surrounding the future viability of Goma, may yet unfold.

9. Conclusions and recommendations

9.1. *International scientific effort is needed and should be co-ordinated.* Nyiragongo volcano and the danger to Goma from a future eruption of lava inside the town and/or in the depths of Lake Kivu could result in a major loss of life. This is one of the world's most important volcanic crises. Seismic activity indicates that tectonic rifting is likely to be continuing, and a further rifting event as occurred on 17/18 January, 2002, could trigger a new eruption. Scientific studies are urgently needed to constrain the present volcanic hazard. Co-ordination of the international scientific effort is being provided through UN-OCHA and monitoring of the Nyiragongo and Nyramuragira volcanoes and Lake Kivu must be established as a matter of urgency.

9.2. *The management of the volcanic crisis cannot be undertaken without including the other threats to life in the region, which is already in a humanitarian situation of disaster proportions.* The risk of death and injury from the volcano has to be weighed against the risk from other causes of loss of life due to the vulnerability of the population to daily threats from violence, malnutrition and endemic infectious diseases. The unusual geomorphology of the region means that the population of Goma and the surrounding region is totally dependent on Lake Kivu for drinking water, so that cholera is an ever-present threat. In epidemic form cholera could cause more fatalities than the volcano, and epidemics could be precipitated by lack of preparedness for evacuation, with the mass exodus of hundreds of thousands of people, and/or an uncontrolled return to a city with its lifelines shattered by an eruption.

9.3. *The value of scientific monitoring of the volcano is most likely to lie in providing the international community and relief agencies and NGO's with sufficient lead-time to prepare for a mass movement of the population of Goma when the volcano erupts.* Forecasts and warnings are not likely to be acted upon by the population in the present political and humanitarian crisis. The importance of this is not sufficiently recognised in parts of the international community and needs to be reinforced as an integral aspect of contingency planning. The provision of safe water and adequate food depends almost entirely on outside assistance, which is the life-support system for Goma.

9.4. *The WHO (OPS) should play a lead role for the health sector in co-ordinating planning and response to a renewed volcanic eruption.* Volcanic risk management is currently focused on the Goma Volcano Observatory with support from international scientists. As indicated above, decisions on protecting people from the volcano cannot be made in isolation from the health sector and its state of preparedness to prevent major outbreaks of infectious disease. Risk assessment in this crisis should include the regular input of health experts, together with international relief agencies and NGO's working in Goma. WHO should provide the organisational bridge between the volcano scientists and health experts and health care providers.

9.5. *The WHO should establish its own programme of action in Goma, including monitoring the impact of the volcanic crisis on health and emergency preparedness for a future eruption.* There is sufficient scope for a full-time post based in Goma, and the development of project proposals for work on the health aspects of the crisis:

- Reducing disaster vulnerability and devising mitigation measures in the light of the findings in this report
- Air quality and lake water monitoring should be set up on a routine basis, including acting on feed-back from scientists on ground gas emissions (mapping) and the location of *mazuku* in populated areas or locations of new settlements.
- Ash fall from an eruption of Nyramuragira would need to be studied urgently for any toxic potential on grazing animals and humans.
- Planning for the evacuation of Goma, including its hospitals, and co-ordinating activities with UN-OCHA and the local partners in the health sector in developing emergency preparedness to prevent epidemics of infectious diseases, especially cholera.
- Working closely with GVO and international scientists and UN-OCHA in crisis risk management.
- Daily or weekly mortality in Goma from all causes needs to be included in the epidemiological surveillance programme: routine mortality statistics would also be important in crisis management monitoring.

- Health education of the people needs to be widened to include volcanic risk issues and reinforcing the hazard of drinking unchlorinated or unboiled water.
- Reducing scientific uncertainty in preventive health strategies, e.g., for those factors that would influence the outbreak of infectious diseases in displaced populations from Goma. These include the locations of evacuation areas for the people, which need to be clarified, in conjunction with volcanologists, to ensure their suitability in relation to the volcanic hazards. The resources needed to maintain the temporary infrastructure and prevent the breakdown of chlorination and rehydration procedures, especially along evacuation routes, need to be defined. In the camps, responding to the problems associated with the rapid setting up of immunisation programmes against measles, meningitis and polio, for example.

9.6. *A scientific risk assessment is needed to make recommendations on the state of the volcanic activity and the implications for risk management and planning for the population of Goma.* This should include the potential impact of a gas release from Lake Kivu. Apart from this, the worst reasonably foreseeable event, according to the volcanologists, would be a major phreato-magmatic eruption triggered by a lava emission coming into contact with groundwater in Goma. A hazard analysis of such an event needs to be urgently undertaken.

9.7. *Education of the public and expatriate staff on volcanic hazards is urgently needed.* Brief guidance on the health hazards of gas and ash emissions from volcanoes is given in Appendix 3, which could form the basis of an information leaflet.

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APPENDIX 1

CHOLERA AND NATURAL DISASTERS

1. Communicable disease epidemics are relatively rare after rapid-onset natural disasters unless large numbers of people are displaced from their homes and placed in crowded and unsanitary camps.[26] However, armed conflict and subsequent mass population displacement, involving food shortages and relief camps, are associated with a severe increase in the risk of epidemics. The diseases of overcrowding are enteric diseases, measles and, in the "meningitis belt" of sub-Saharan Africa, meningitis. Effective mass immunisation exists for the latter two conditions. The control of enteric disease is through the provision of adequate sanitation, a supply of potable water and the protection of food. Malaria may also cause high rates of morbidity and mortality among refugees and displaced persons in countries where the disease is endemic.

2. Cholera is an acute illness caused by an enterotoxin elaborated by *Vibrio cholerae* that have colonised the small bowel. In the more severely affected patients, fluids and electrolytes are rapidly lost from the gastro-intestinal tract, leading to hypovolaemic shock, metabolic acidosis and all the signs, symptoms and metabolic derangements associated with the disease. In severe, untreated cases, death may occur within a few hours, and the case-fatality rate (CFR) may exceed 50%. With proper treatment, the rate is 2% or less, regardless of the setting, which is also achievable in epidemics if administered by well-prepared medical and paramedical personnel. In contrast, in Goma in July 1994 the average facility-based CFRs were as high as 22% during the early days of the epidemic, the highest reported for a single day being 40% at Mugunga camp.[11,12] Once adequate relief personnel had arrived and treatment resources were established the CFR dropped rapidly to 2%-3%. The illness may last from 12 hours to seven days, but with prompt and adequate fluid and electrolyte repletion recovery is remarkably rapid. In children complications are both more frequent and severe, and include coma and convulsions, but the outcome is just as favourable as in adults if treated adequately. The mainstay of treatment is intravenous or oral rehydration. Adjunctive therapy with antimicrobials dramatically reduces the duration and volume of the diarrhoea, and results in rapid eradication of the vibrios from the faeces.

3. The disease is spread through the ingestion of food or water contaminated directly or indirectly with the faeces or vomitus of infected persons. The incubation period is from a few hours to a few days, usually two to three days. Although a cholera-like illness may be caused by micro-organisms other than *V. cholerae* (most frequently by enterotoxigenic *E. Coli*, and, of course, *Shigella*) the resulting physiological and metabolic abnormalities are the same and the emergency treatment is identical.[27]

4. Epidemic dysentery caused by *Shigella dysentariae* Type 1 has caused high morbidity and mortality rates among refugees in central and east Africa since 1992. CFRs for dysentery have been as high as 10% amongst young children and the elderly.[26]

APPENDIX 2

VULNERABILITY & RISK ASSESSMENT

1. Vulnerability is a widely used concept in natural disaster management, but if it has to have any practical or scientific meaning it must be expressed in quantifiable terms. An expression for quantifying risk has been applied to disaster planning in volcanology (for example, Barberi et al., 1990):

$$\text{Risk} = \text{hazard} \,.\, \text{value} \,.\, \text{vulnerability}$$

where, in the Goma situation, hazard is the probability of the eruptive event, value is the number of people exposed to the hazard and vulnerability is that fraction of the people exposed that are likely to be killed. Although the population in the area can be precisely counted, the probability of the eruptive event and the fraction of the people exposed that are likely to be killed are always going to be uncertain. Thus the vulnerability is going to be determined by the size and timing of the eruption – the range of the destructive impact, when it occurs in relation to where the population is at that time (e.g., full or partially evacuated, and whether sufficient warning can be given and if it is responded to by the population; if the population has not moved, then whether the eruption occurs during the day or night). The size and timing of the eruption cannot be predicted by volcanologists, and as indicated in the text, the other main determinants of vulnerability to volcanic risk are the political and humanitarian crisis issues which may result in the population taking too little action, too late, in response to the volcanologists' warnings.

2. One way of reducing uncertainty is for scientists to define more clearly the fraction of the population at highest risk. At present, however, volcanologists would generally plan to evacuate over a wide area because it is not possible as yet to accurately delineate the zone of most danger from a lava eruption in Goma. The problem with this broad population approach is that many have to be evacuated to protect a smaller group at high risk, who cannot be readily identified, and this dilutes the preventive message and the urgency for action in people's perception of their own individual risk (individual *versus* societal risk, as described in the text). This "prevention paradox" is also well known in disease control in public health (and a lack of response to the warnings of volcanologists also has its counterpart in adherence to medical advice – in studies up to 50% of patients may not adhere to their prescribed treatment, even in patients with life-threatening conditions).

3. Actually, the above formula calculates expected numbers of lives lost and is not a probability or estimate of risk (risk is the probability of harm in an adverse event). We can therefore approach the quantification of the volcanic risk through estimating the possible range of expected numbers of deaths using this formula. If scientists cannot as yet reduce the uncertainty of this estimate through better definition of the area to be impacted by the eruption, we can attempt to estimate the uncertainty using a range of expected casualties under Circumstances A and by comparing this result with the range of expected numbers under Circumstances B. We can call this result the Relative Environmental Risk.

4. Using this approach we can then compare the loss of life expected from the eruption if there is no evacuation (Circumstance A) with the loss of life expected if there is a pre-planned evacuation and the hazard is cholera (Circumstance B).

5. In comparing two quite different hazards (the one hazard being the volcanic eruption in Goma when it is not evacuated and, on the other hand, the hazard of cholera if the whole population of the city was displaced because of the threat of an eruption) the most useful comparison is the difference in the absolute numbers of deaths, and not the ratio, or the mortality rates. In epidemiology, relative risk and attributable risk are used in aetiological studies, but they are of little use here. However, a parallel does exist with Evidence–Based Medicine (Sackett et al., 2000) in the use of the terms relative risk reduction (RRR) and absolute risk reduction (ARR) that follows a treatment intervention, when the intervention in this case is evacuation, especially the number of patients that need to be treated (NNT) – evacuated - to prevent one bad outcome (this is also the reciprocal of the ARR%). These figures are presented for two theoretical scenarios below to illustrate their potential use.

Theoretical risk assessment for an eruption in Goma

Scenario1: (i) Estimated threat of 10,000 deaths in Goma from volcanic eruption – no evacuation – worst scenario

(ii) Estimated 1,000 deaths from infectious disease and violence if whole population evacuated as a precaution for several weeks

Population of Goma: 500,000

	No Evacuation	Evacuation
No. killed	10,000 (eruption)	1,000 (cholera, etc)
% deaths	2	0.2
Individual risk	1:50	1:500
Relative risk reduction % (with evacuation)	90	
Absolute risk reduction %	1.8	
No. evacuated to save one life	55	
Total no. of lives saved by evacuation	9,000	

Scenario 2: As above, but 2,000 killed by eruption – moderately severe scenario

	No Evacuation		Evacuation
No. killed	2,000 (eruption)		1,000 (cholera, etc)
% deaths	0.4		0.2
Individual risk	1:250		1:500
Relative risk reduction % (with evacuation)		50	
Absolute risk reduction %		0.2	
No. evacuated to save one life		500	
Overall no. of lives saved by evacuation		1,000	

6. The decision to evacuate the city is obvious, using all the risk indices, if Scenario 1 prevails, but the decision becomes less clear in a scenario with a much smaller but still appreciable number of deaths (1000) from the eruption, unless the health sector agencies are well prepared to respond to prevent the spread of cholera, even on a limited scale, in an evacuation.

7. Finally, the absolute numbers of deaths do not convey the uncertainty which needs to be incorporated in decision making when a variety of eruptive scenarios are possible, with the worst, on general grounds, being the least likely to occur. In the past, disaster managers planned for what was considered to be the "worst reasonably foreseeable" scenario without regard to the uncertainty that was involved. The complexity of volcanic hazards makes this approach unacceptable and it is not overcome by providing broad estimates of the ranges of deaths, as mentioned in the paragraph 3 above. The present high degree of uncertainty of the volcanic impact in an eruption needs to be reduced by further scientific evaluation, but the residual uncertainty, which can be large, also needs constraining. The best way that has been found for doing this, so far, is to produce F/N curves which give the probability of N or more deaths in a given time period, say the next 6 or 12 months, by summarising a number of scenario variables and their distributions using a combination of expert judgement and Monte Carlo methods.

8. An example of the use of F/N curves as derived by scientists for the activity of the Soufriere Hills volcano during the 1997 Montserrat volcanic crisis (MVO,1998). The probabilistic risk assessment was based on Bayesian logical methods and comprised:

- Construction of a logic-tree of events (Fig.1) and eruption scenarios (Fig.2).
- Assignment of probability weights to the various logic trees – statistical analysis of data or formal elicitation of expert judgement with calibration method

- Computation of the probability of exceedance of different casualty figures by Monte Carlo simulation of events using a standard simulation computer package (final outputs in Fig 2 and tables 2-4)
- Sensitivity analysis of the probability of exceedance curve to input parameters

Further information on constructing event (probability) trees in volcanic crises can be found in Newhall and Hoblitt (2002).

Fig.1: Montserrat crisis: logic tree with estimated probabilities for different types of forecasted volcanic activity

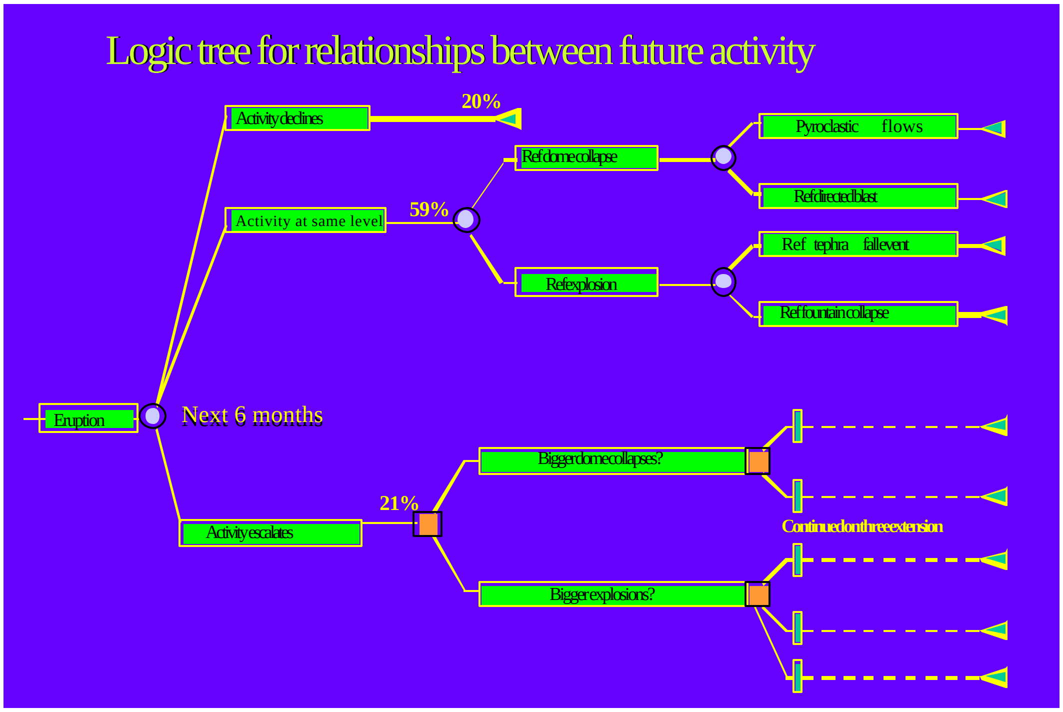


Table 1: Montserrat crisis: hazard scenarios with risk of 5 or more casualties in the next six months

Hazard scenarios with risk of 5 or more casualties in the next six months.

Hazard Scenario	Approximate probability of event	Expected number of fatalities
10 million m^3 dome collapse, flows down Belham	1 : 10	5
30 million m^3 dome collapse, flows down Belham	1 : 125	15
10 x power ref. explosion - fountain collapse surges	1 : 500	100
10 x power ref. explosion - tephra fall in E-W wind	1 : 1,000	10
30 x power ref. explosion - fountain collapse surges	1 : 2,000	190
100 million m^3 dome collapse, flows down Belham	1 : 2,000	115
30 x power ref. explosion - tephra fall in E-W wind	1 : 3,000	40
Collapse with 3 x power ref. explosion causing blast to NW	1 : 4,000	40
10 x power ref. explosion - tephra fall to N and NW	1 : 8,500	40
Collapse with 10 x power ref. explosion causing blast to N	1 : 10,000	80
Other Collapses followed by lateral blast	1 : 10,000 to 1 : 1,000,000	190 plus

Fig. 2: Montserrat crisis: Final F/N curves for different locations of the population according to four evacuation strategies.

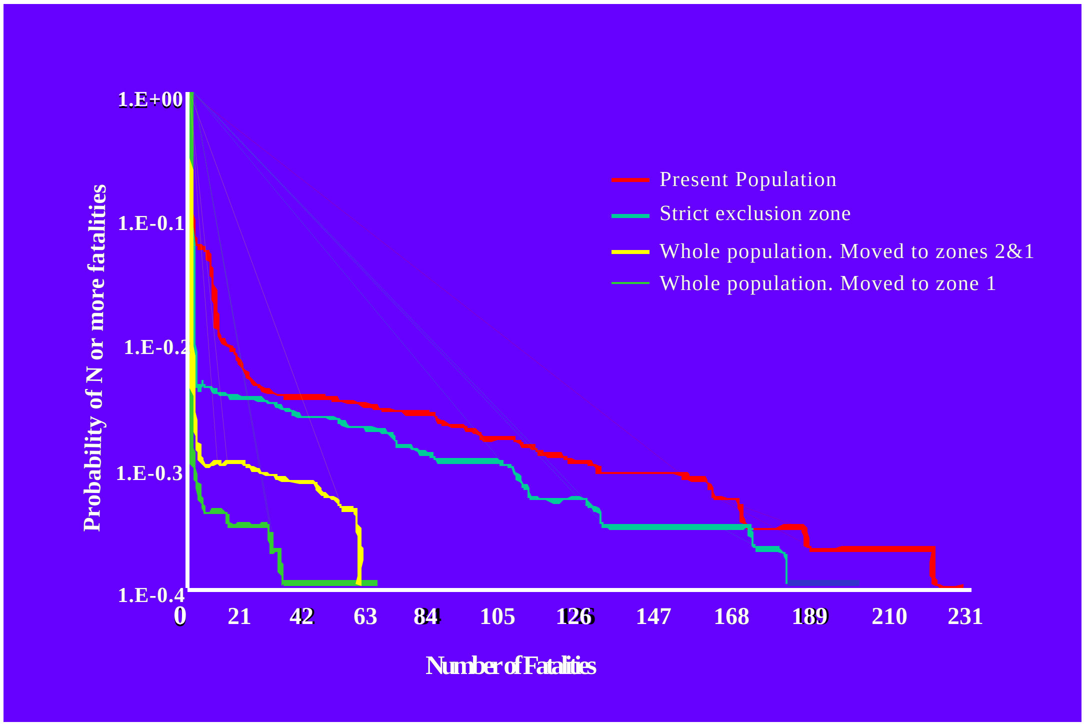
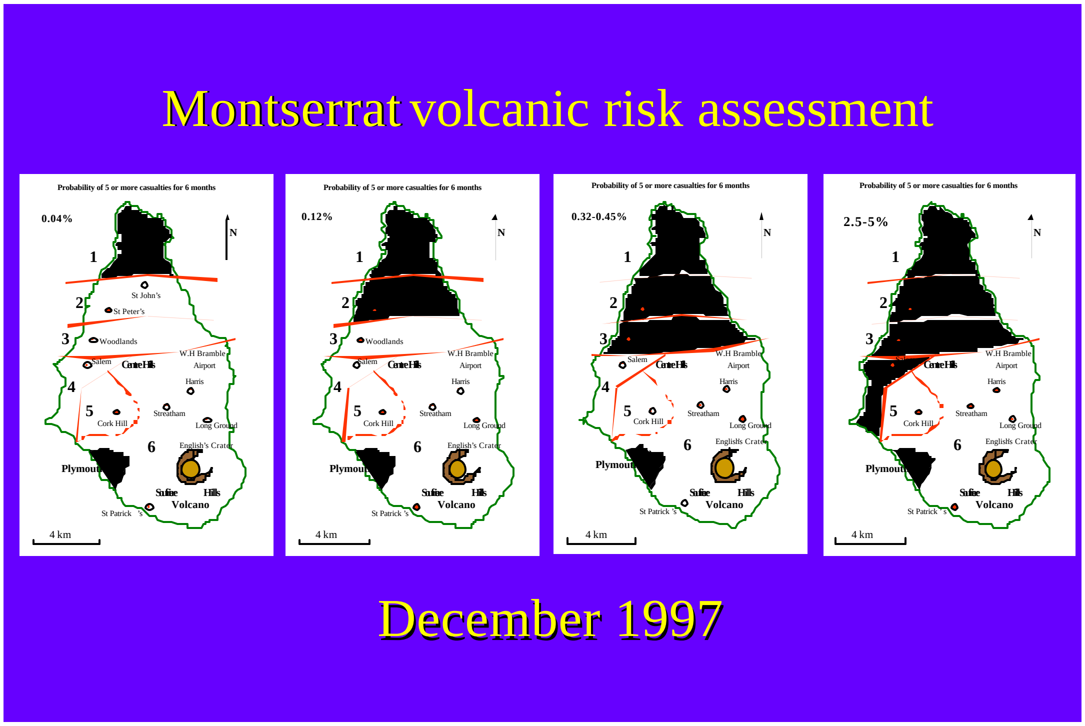


Table 2: Montserrat crisis: Summary of societal risk values for the four evacuation strategies

Probability of N or more fatalities (for six months) for different population distributions

Population model	N=1	N=5	N=10	N=50
Current situation	9-13%	2.5-5%	1.0-1.5%	0.3-1.0%
Strict exclusion	0.35-0.5%	0.32-0.45%	0.26-0.35%	0.2 %
North of Lawyer Õs	0.18-0.22%	0.12 %	0.10 %	0.03 %
All in area 1	0.12-0.15%	0.04 %	0.04 %	0.02 %

Table 3: Montserrat crisis: Summary of individual risk rates for the four evacuation strategies



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APPENDIX 3

HEALTH ASPECTS OF VOLCANIC EMISSIONS

Volcanic ash

1. Ash is produced from the volcanic vent during the eruption and consists of particles with mineral composition usually similar to magma or the erupted lava. Thick deposits of ash make up the soils in many volcanic areas – but not at Goma, because ash falls are sparse from the two volcanoes. In some eruptions the particles can be very fine and easily inhaled, causing respiratory irritation. Particles blown into the eyes by wind can be sharp and scratch the cornea (front of the eye); corneal abrasions are painful but soon heal. Fine ash can also adsorb fluoride from the volcano's gas plume. This is quickly washed off by rain, but grazing animals can die from fluorine poisoning by eating the ash adhering to the surface of the grass. Fluorine on ash is not usually a problem to humans, but ash should be routinely washed off food and filtered out of water before consumption. Ash falls, even light ones, would be very disruptive if they occurred where people were evacuated to temporary camps. Moderate falls will obscure vision for a while and winds will create clouds of dust until dampened down by rain. Fortunately rain is frequent in the wet season in the Goma and Masisi areas. Deaths in cattle in 1994 suggest that fluorine is a major contaminant of the ash from Nyramuragira, which will require further study to confirm this in any future eruption of this volcano. The recent ash falls have all been light and so it is unlikely for large enough deposits to occur in future eruptions to cause the collapse of roofs. This is a major hazard at some other volcanoes around the world.

2. There is evidence that fluoride levels in the waters of Lake Kivu temporarily rose close to the lava flow in January. Fluoride levels near the intakes of the water pumping stations need to be monitored during the present crisis.

Volcanic gases

3. Volcanoes commonly emit water vapour, carbon dioxide, sulfur dioxide, hydrogen chloride, hydrogen sulphide and hydrogen fluoride from their erupting craters. These gases, especially sulfur dioxide, can present an air pollution problem, but the height of Nyiragongo should disperse the gases away from the populated areas around the volcano, and dilute the plume before it can ground and fumigate areas downwind. Regular monitoring should be carried out in Goma, especially if the activity increases with the re-entry of lava in the summit crater. This would be especially necessary to reassure people in the area who suffer with asthma.

4. Carbon dioxide is regarded as odourless (it has a very faint acid smell, in fact), and can kill by displacing ordinary air, as at the Mazuku depressions, which of course should all be fenced off. Children are most at risk in these places because very high concentrations of gas can be found at ground level or just a few feet above. Carbon dioxide is denser than air and so accumulates in depressions and on the water surface in some locations by the lake- shore in still weather. It is especially dangerous because it is toxic in its

own right and can lead to rapid loss of consciousness at concentrations over 8-10%, even when there is enough oxygen to breath. This is the explanation for reports of people becoming overcome whilst swimming and even drowning as a result. Swimmers should avoid swimming by the lake-shore during still weather – the shore areas used for swimming should all be checked for carbon dioxide emissions.

5. Gas emissions from the large ground fractures were evidently limited to the time of the eruption.

6. Mapping of the ground gas emissions in the rift area is urgently required.

7. There is no imminent danger of a major gas emission from Lake Kivu. The only preventive measure is evacuation from the Goma area when a major eruption is threatened.

8. There is no benefit to be derived from carrying gas masks in Goma. They will not protect the wearer from carbon dioxide - they would only be useful for working inside the Nyiragongo crater!

9. After the January eruption, methane was present in the air over the city. The gas was escaping from the ground by diffusion and was probably responsible for the minor gas explosions that occurred in houses and on the streets. Unlike carbon dioxide, methane is not toxic, but it is flammable. The risks from this gas were minimal, and there was no evidence it was present in large enough quantities to trigger fires. There were no methane or carbon dioxide ground emissions in Goma found subsequent to the eruption.

Fig.2. Location of refugee camps 1994-96

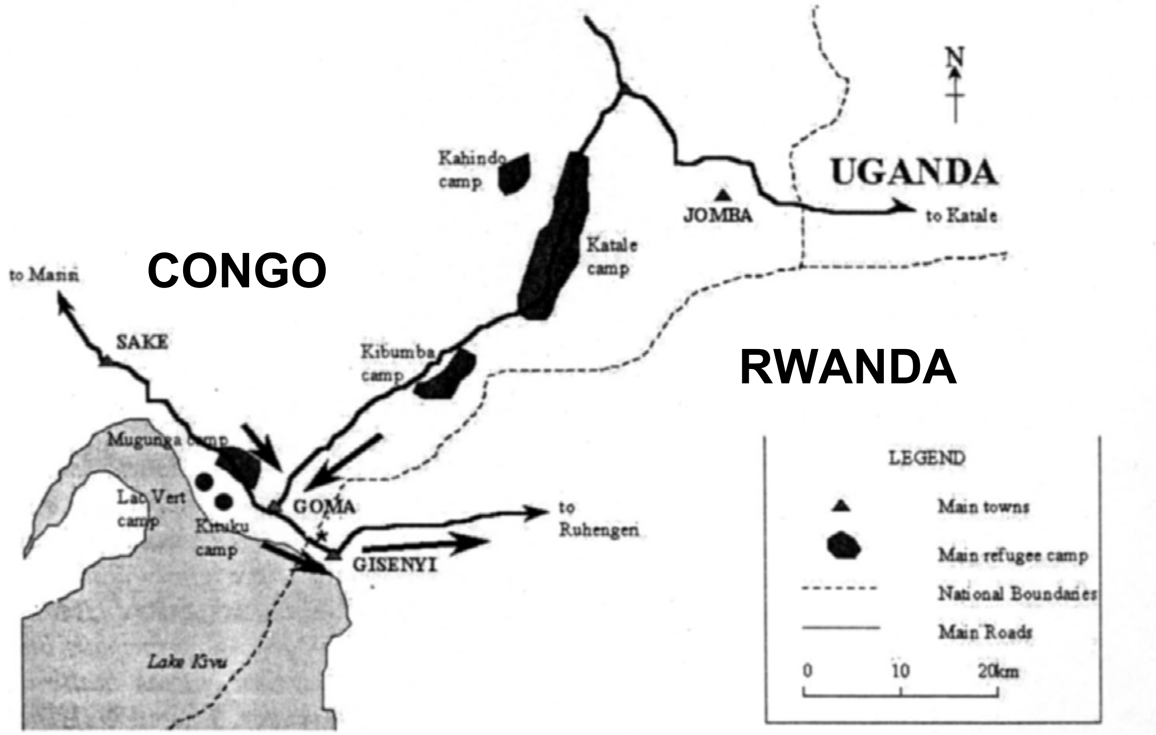

Fig.3. Solidified lava from the January 17/18 eruption.
Upper flanks near Shaheru crater.
The lava flowed at tens of kilometres per hour.
(Jean-Christophe Komorowski)

Fig.4. The smaller lava flow which stopped at the main road to the west of Goma.

Fig.5. A woman and child who died with burns sheltering in a basement
(sparse evidence for mortality in lava flows)

Fig.6. **Principal Consultations per day. Goma, 14-01 to 20-03-02. (Cemubac, WHO, MIP)**

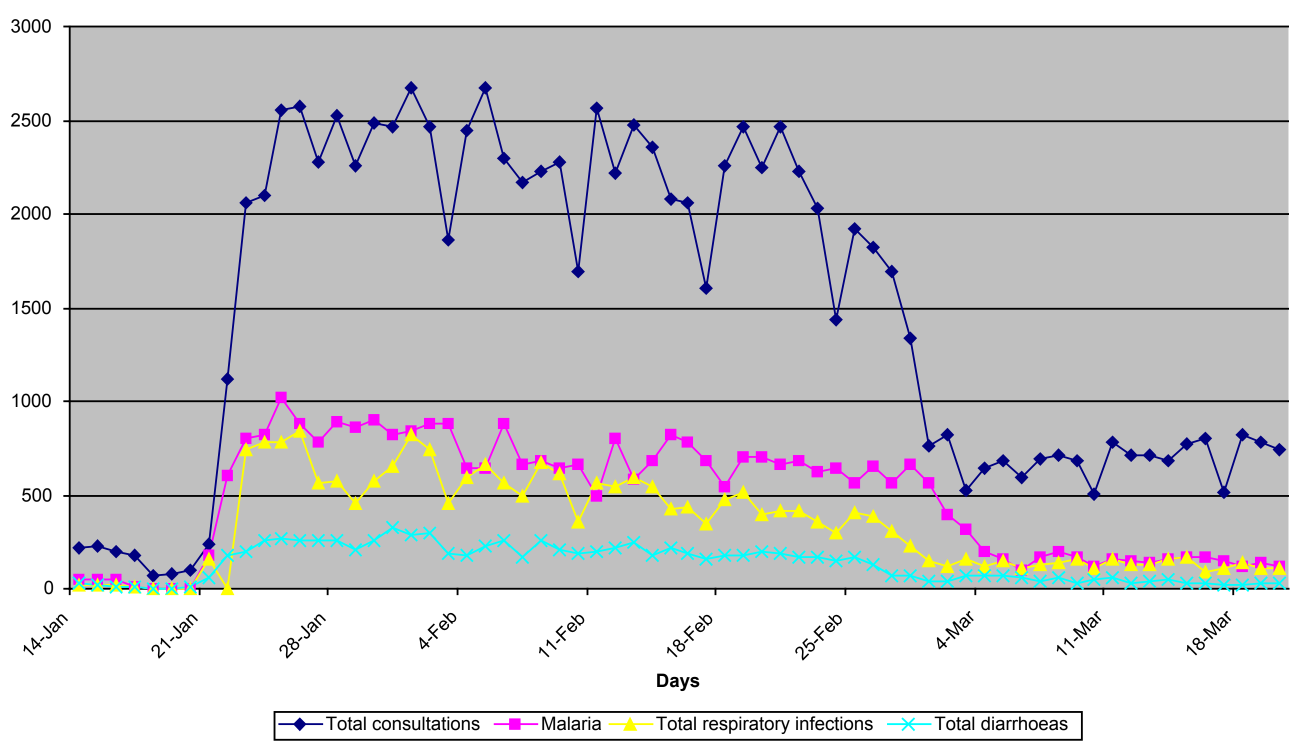

Fig.7. Itig refugee camp with dwellings made from galvanised metal sheets collected from the lava flows that engulfed the city.

Fig.8. Measuring air quality (PM_{10}) at road on levelled surface of lava flow

Fig.9. Measuring carbon dioxide concentrations in air: the gas flows out of the ground fissure at this *mazuku*, where deaths have occurred in the past.

Fig.10. Diffusion of carbon dioxide from the ground in this topographical depression (bottom right) renders it highly hazardous for its planned used as a cemetery.

Fig.11. Two bathers died in this location by the lake edge about three years ago. Carbon dioxide leaks out between the rocks of old lava flows and high concentrations can accumulate on the water surface in still weather

Fig.13. Lake Kivu water pumping station : water intake only metres from lava flow

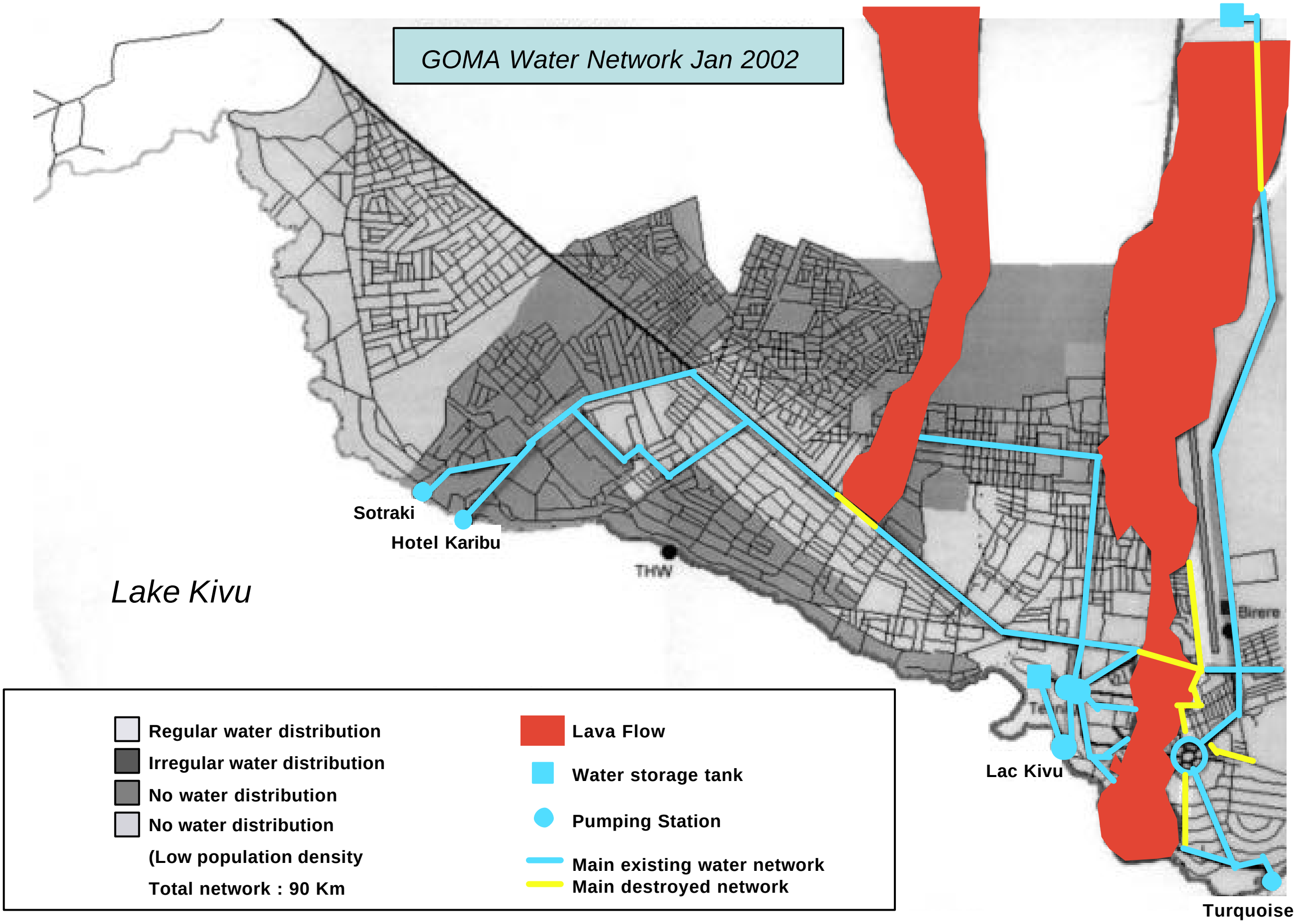

Fig.12. The Goma Water network damaged by the two lava flows *(courtesy IFRC)*

Fig.14. Aerial view of commercial centre of Goma and main lava flow.

Fig.15. Tongues of lava flowed from lateral vents in main flows, igniting and demolishing houses