

**THE JANUARY 2002 ERUPTION OF
NYIRAGONGO VOLCANO (DEM. REPUB. CONGO)
AND RELATED HAZARDS:
OBSERVATIONS AND RECOMMENDATIONS**

FINAL REPORT OF THE FRENCH-BRITISH SCIENTIFIC TEAM

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Dr Patrick ALLARD (Laboratoire Pierre Süe, CNRS-CEA, Saclay, France)
Dr Peter BAXTER (University of Cambridge, United Kingdom)
Prof Michel HALBWACHS (Université de Savoie, Chambéry, France)
Dr Jean-Christophe KOMOROWSKI (Institut de Physique du Globe de Paris, France)

Submitted to :

Ministry for Foreign Affairs, Paris, France
Foreign Office, London, United Kingdom
and
respective Embassies in Democratic Republic of Congo and Republic of Rwanda

Confidential copies to:

J. DURIEUX, P. PAPALE, D. TEDESCO, O. VASELLI, UN-OCHA volcano crisis response consultants
Goma Volcano Observatory, Democratic Republic of Congo
MINERENA, Kigali, Republic of Rwanda
C. NEWHALL, President of World Organization of Volcano Observatories (WOVO)
C. JAUPART, Director, Institut de Physique du Globe de Paris (IPGP)
D. MILLER, United States Geological Survey Volcano Disaster Assistance Program

EXECUTIVE SUMMARY

This report summarises the key findings of the French-British ("Concorde") team of scientists sent to evaluate the source mechanism and the impacts of the January 2002 eruption of Nyiragongo Volcano, Democratic Republic of Congo. The team began its fieldwork on 22 January in collaboration with three other volcanologists sent by UN-OCHA and local volcanologists of the Goma Volcano Observatory (GVO), together with the support of staff experts from the MINERENA (Rwanda).

On January 17-18, 2002, Nyiragongo volcano (1.52°S, 29.25°E; summit elevation: 3469 m a.s.l.) erupted suddenly, emitting lava flows from several vents located on its S and NW flanks (GVP/USGS Weekly Volcanic Activity Report, January 18, 2002). The eruption began from a fracture at about 2800 m elevation and propagated downslope up to a series of fissure vents at an elevation of 1700 m, located only 1.5 km NE of the Goma city airport. Two major lava flows (up to 2 m thick and 100-400 m wide) covered and destroyed about 20 % of the city of Goma, including parts of the airport, most of the business centre and the housing of an estimated 120,000 people. The main flow entered Lake Kivu, ca. 18 km S of the crater, into which it spilled down for a few days. The eruption forced the rapid exodus of 300,000 to 400,000 persons, most into neighboring Rwanda. ***This is the first time in history a volcanic eruption producing only lava flows has impacted a city of such a size and made such a large number of people homeless.*** In a previous eruption in 1977, extremely fluid, fast-moving (up to 60 km/h) lava flows drained from the summit lava lake of Nyiragongo and entirely covered several villages, killing an estimated 70 persons but without reaching Goma (Smithsonian Institution, Global Volcanism Program, Volcanic Activity Reports, 1971-2000; Tazieff, 1979).

The 2002 eruption raised high international concern because of the destruction of the city of Goma and the exodus of hundreds of thousand people. Apart from the immediate threat to life from the volcanic activity, the displacement of such a large number of people, even for a short time, could have widespread humanitarian consequences. The majority of displaced persons began to return in Goma within two days, before the lava flows had safely cooled and fires had stopped. Latest UN Figures report that 147 people were killed (of whom 60 to 100 died in an explosion of the Goma central petrol station on January 21), 350,000 people affected, 30,000 displaced, and 14,000 homes destroyed by the eruption. Around 470 injured people were reported to have suffered burns, fractures and gas intoxication.

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. The eruption started at 08.25 local time on 17 January. A sudden re-opening of the 1977 fracture high up on the volcano allowed the lava lake in the summit crater to drain out violently. Within the next hours the fracture system and the eruption propagated down slope, reaching Goma. The open fracture system, trending N-S, has been carefully mapped and extends over more than 20 km distance from the top of the volcano down to Goma. The main lava flow going through the city entered Lake Kivu, forming a new lava delta about 800 m wide and 120 m long at most. Investigations with a submersible showed that sub-water lava tubes had formed, extending as far as 80 m in depth. Fires on the lava flows were mainly caused by the combustion of organic material. However, widespread smell of hydrocarbide gas and earthquake-related gas-derived explosions that occurred at several locations in Goma away from lava flows were verified to be provoked by ground emanations of methane and carbon dioxide, whose actual origin is under study.

At 20.51 local time on January 22, a series of earthquakes triggered a general collapse of Nyiragongo summit crater floor and lava terraces, generating four hours of phreato-magmatic explosive activity (marked by intense seismic tremor) and heavy ash fall over the upper SW flanks of the volcano. Light ash fall also affected Goma and Gisenyi. This collapse deepened the crater to about 700 m (instead of 320 m previously) below its rim and intermittent explosive activity at its bottom persisted in the weeks after. A strong seismic activity, associated with fracturing events, has persisted both during and after the eruption, creating building damage and a few casualties in Goma and Gisenyi cities. Despite a gradual decline, the seismicity has remained at abnormally high levels in the days and weeks following the eruption, with earthquake shocks felt more than 100 km away (Kigali). Such an intense post-eruptive seismic activity and ground fracturing, together with ground subsidence of several tens of centimeters detected along the northern shore of Lake Kivu but also at greater distance further south (Bukavu) and west (Idjwi island), provide evidence that the 2002 Nyiragongo eruption has most likely been triggered by a major rifting event of tectonic origin. This rifting event is still ongoing.

These telluric phenomena and the volcanic eruption then raised concern about a potential lethal gas burst from nearby Lake Kivu that is known to contain an immense amount of carbon dioxide and methane dissolved in its deep water layers. A major disturbance to the stratification of the lake water could lead to an overturning and a catastrophic, deadly release of the gases. Such a disturbance might be provoked by earthquakes beneath the lake, lava flows entering the lake from above, or fracturing and eruption occurring beneath the lake - a risk that needs to be seriously evaluated.

Although lava flow emissions ceased within about 24 hours of the start of the eruption, the still hot lava flows remain a direct or indirect source of danger for the local people, in particular for children. Moreover, the continuing seismicity

maintains the threat of a resurgence of fracturing and lava emission, together with the risk of toxic ground gas emissions and the risk of destabilising the lake. A new eruption of Nyamuragira volcano, 14 km north-west of Nyiragongo, could result in additional troubles to the area.

The present report contains a number of key recommendations for mitigation, volcanic risk management and scientific action. The following recommendations are those considered to be of the highest priority and requiring urgent consideration by governments :

- Develop contingency planning and response measures to be taken on the short-term in the event of an increase in hazardous seismic and volcanic activities.
- Strengthen the monitoring and logistic capabilities of the Goma Volcano Observatory (GVO) and provide it with access to electronic communications to facilitate contact with foreign scientists and external sources of expertise.
- Instigate a coordinated scientific effort to study and monitor the hazards presented by Nyiragongo and Nyamuragira volcanoes, with the rotating input of one volcanologist-coordinator from Europe. In particular, carefully assess the hazards from ground gas emissions, especially in Goma, and set up systems for their continuous monitoring in relationship with the state of volcanic activity.
- Promote a scientific assessment of gas-burst hazard from Lake Kivu and the risk of an eruption triggering such an event. The dispersion and behaviour of the gas cloud must be modelled. Mitigation measures need to be established for the populations at risk.
- Undertake a formal risk assessment which takes into account the vulnerability issues and humanitarian and conflict context. This would serve as the evidence base for future government policy for the region. WHO should coordinate a health hazard and human vulnerability assessment.

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1. BACKGROUND AND OBJECTIVES

With the agreement of the governments of the Democratic Republic of Congo and the Republic of Rwanda, the French Ministry for Foreign Affairs and the British Foreign Office requested on January 19 that a team of four scientists from both countries depart on 48 hour's notice to Goma to evaluate the impact of the eruption of Nyiragongo volcano on January 17/18, 2002. The team of French-British scientists left Paris on Monday January 21 with the French-British ministerial delegation led by the respective Ministers H. Védrine and J. Straw, who began an official tour of the countries involved armed conflicts in Africa's Great Lakes region in a joint effort to promote peace.

The French-British ("Concorde") scientific team comprised the four authors of this report. They rapidly joined local scientists of the Goma Volcano Observatory (GVO) and three volcanologists from Italy and France mandated by UN-OCHA in Goma (J. Durieux, P. Papale and D. Tedesco, reinforced by O. Vaselli a few days later). The objectives were: i) to assess the source mechanisms and impacts of the ongoing phenomena and to contribute to the volcano hazard and risk assessment, ii) make recommendations for the upgrading of the monitoring network in the short- and long-term, and iii) propose a framework for future scientific research studies on volcano-tectonic activity in this region.

The itinerary and field activities of the team members are summarised in Appendix 1.

2. MAIN OBSERVATIONS

We describe below the observations made by the French-British scientific team, supplemented with data and observations collected by other scientists from the GVO and the UN team, as well as with information provided by the local populations. We conclude that the January 2002 eruption of Nyiragongo volcano was most likely the consequence of major, still ongoing extensional movements of the Kivu branch of the East African Rift.

A) VOLCANIC AND SEISMIC ACTIVITY

1. *Precursory signals*

The January 2002 eruption of Nyiragongo volcano was not unpredictable. It was heralded by a number of precursory phenomena detected since March 2001 by volcanologists of the GVO, which were reported to the local authorities and the volcanological community (Global Volcanism Network) but which, unfortunately, received little attention. These phenomena included:

- Anomalous seismicity (type C long-period events and tremor), which persisted after the February-March 2001 eruption of Nyamuragira volcano*, 15 km north-west of Nyiragongo (Figure 1), and increased gently over the rest of the year. We highlight here GVO's observations in March 2001: " *...While the intensity of the [Nyamuragira] lava flows decreased in mid-March, registered seismicity was at similar levels to December 2000, shortly before the eruption began. This is an unusual pattern for Nyamuragira; tremor usually ends at the same time as the eruption. Local volcanologists believe this indicates lava and pressure remaining within either Nyamuragira or Nyiragongo...*" (Bull. Global Volcan. Network., Smithsonian Institution, 26/03/01). In fact, while Nyamuragira had stopped erupting long-period events and volcanic tremor became predominantly registered at the Bulengo seismic station (15 km W of Goma) and minimally, or not, at the more remote (40 km) Katale station, located closer to Nyamuragira (Akumbi, GVO, pers. comm.). This observation supported the idea of seismo-magmatic processes occurring at or closer to Nyiragongo. This was later confirmed by the registration of two swarms of earthquake shocks (fracturing events) in the Nyiragongo area in October 2001 and then on January 4, 2002, 13 days prior to the

* *Nyamuragira* is Congo's most active volcano, with forty eruptions since the mid-twentieth century. It is a massive basaltic shield volcano, with a volume of 500 km³, that rises across a broad valley NW of Nyiragongo volcano. Extensive lava flows from Nyamuragira cover 1500 km² of the East African Rift. The 3058-m-high summit is truncated by a small 2 x 2.3 km summit caldera that has walls up to about 100 m high. Historical eruptions have occurred within the summit caldera, frequently modifying the morphology of the caldera floor, as well as from the numerous fissures and cinder cones on the volcano's flanks. A lava lake in the summit crater, active since at least 1921, drained in 1938 (source: Global Volcanism Program, Smithsonian, Washington DC, USA).

eruption onset. The January 4 earthquakes were accompanied by a darkened plume and rumbling sounds on top of Nyiragongo (Akumbi and Kasareka, GVO, pers. comm.).

- A reactivation of the former 1977 eruptive fracture running above Shaheru crater (2700 m a.s.l. and ~2 km S of the summit; see Map 3). A new fumarolic vent formed at about 2800 m elevation along this fracture in October 2001. New cracks and increased fumarolic activity were also detected in the southern inner wall of the summit crater, upstream of Shaheru. In November 2001, new fumaroles appeared on the northern floor of Shaheru crater itself.
- A growing seismicity between January 4 and 17, that included several felt earthquakes and volcanic tremor. On January 16, a few hours before the eruption onset, an abnormally strong smell of sulfur dioxide was also noticed by the pilot of a small private aircraft flying north of Nyiragongo (Ted Hoaru, pers. comm.).

2. Chronology of the eruption

- According to GVO, Nyiragongo started erupting at 08:25 local time (06:25 GMT) on January 17, and not at 05:00 as was initially quoted by news agencies (e.g. Agence France Presse, Relief Web, Jan. 17). Earthquake-related sudden opening of the 1977 fracture system running from 2800 m into Shaheru crater triggered a drainage of the surmounting lava stored in the summit crater. The presence of chilled lava "nests" (lava boulders) perched at 6-8 m height in preserved trees at distance of up to 30 m from the eruptive fracture above Shaheru indicates a powerful hydrodynamic squirting out of the lava column during this initial phase. Very fluid lava flows, only 10-15 cm thick at their source, ran across the forested southeastern slopes of Nyiragongo and rapidly cut the road going from Goma to the north (Rutshuru). The lava also filled the 800 m wide Shaheru crater, forming a 3 m thick lava pond. The high fluidity of the outpouring lava is attested by the high-stand marks left by the lava flow on trees up to a height of 1,5 m. Field evidence suggest that this initial upper drainage activity gradually decreased in strength as the height of the lava column diminished and other fractures opened downslope.
- Within the next hours the fracture system and the eruption actually propagated down to the base of the volcano. Two sets of parallel eruptive fractures, about 300 m apart, first opened through the southern flank of Shaheru cone (Figure 4, photo 14) and extended downslope forming a series of grabens (~5-10 m wide) across banana fields, villages and even older volcanic cones (Figure 3, photos 2, 3). Between 10:00 and 11:00 local time (08:00-09:00 GMT), lava flows issued from a series of eruptive vents between about 2300 and 1800 m elevation along this system (Figure 4 and photos 10-11), devastating several villages in their course. Between 14:00 and 16:20 local time (12:00 and 14:20 GMT) the propagation of magma within a conduit radial to the volcano (dike) continued simultaneously with the southward propagation of fractures towards Goma, down to an elevation of 1580 m a.s. l., to form a line of vents SE of Monigi village only 1.5 km NE of Goma airport. The timing of lava emission from the upper (16:00) and lower (16:20) parts of the Monigi fracture zone implies a lava speed of ~3 km/hour in the conduit. These lowest fractures produced intense spattering activity and the voluminous lava flow which ran through the airport and the heart of Goma city and finally entered lake Kivu during the night.
- In the meantime, another eruptive fissure opened at 15:30 (local) at a higher elevation (2250 m) further south-west (2 km west of Kibati). Eyewitness accounts report that this fissure initially produced passive effusive activity feeding pahoehoe lava flows. However, our field inspection shows the presence of a scoria fall deposit over 500 m around the vent, which indicates that the activity did evolve at least momentarily to a phase of lava fountain emitted from a fissure that eventually produced a line of hornitos/spatter cones. Lava flow activity then resumed to produce voluminous, ropy aa-type lava flows, 1-2 m thick, that cascaded down the slopes of the volcano in many directions (Figure 4, photo 12). These feeded a flow advancing towards Monigi and formed the second main flow that eventually reached Goma by the west, stopping a few km from Lake Kivu.
- 47 people were reported killed directly by the eruption and as many as 350,000 people fled from the advancing lava, principally towards nearby Rwanda to the east. After 2 days the majority of them however returned to Goma, despite hazards from hot lava and burning materials. In fact, despite the lack of in situ observers, it seems that lava emission stopped in the early morning of January 18, which means that the eruption lasted ≤ 24 hours as a whole. However, molten lava continued to flow in tunnels and tubes along the main flow that had reached Lake Kivu and spilled into it for a few days more. This created a new lava delta about 800 m wide and 120 m long at most along the shore which, according to recent submersible investigations (see below), extends down to about 80 m depth in the lake. The two lava flows that invaded Goma were initially reported to have covered from 50 to 80% of the city area, but our estimate is closer to 20%. They actually destroyed part of the airport, the whole business and commercial centre, and the housing of approximately 120,000 people. From 60 to 100 people died on January 21 during the explosion of the central petrol station surrounded by hot lava and around 470 were reported injured with burns, fractures and gas intoxication.

3. *Erupted lava volume*

The total amount of lava emitted during the eruption is not yet known accurately. The two main flows that devastated Goma were 100-400 m wide and 2.0-2.5 m thick on average. Lava flows on the intermediate and upper slopes of the volcano, while variable in width, generally have a smaller thickness averaging ca. 1 m and 0.5 m, respectively. Based on preliminary helicopter-borne mapping of the areal extent of lava flows and ground-based measurement of their thickness, **we estimate a bulk erupted volume of between 20 and 30 millions m³**, including the lava that cascaded into lake Kivu (≤ 1 million m³, according to M. Halbwachs). Even though preliminary, this bulk estimate is an order of magnitude lower than the figure of 200 millions m³ early mentioned by news agencies. It suggests that the 2002 eruption of Nyiragongo may have been about twice larger than the 1977 eruption (from 13 to 20 millions m³ emitted in only one hour; Tazieff, 1979; Pottier, 1978; J. Durieux, pers. comm., 2002). However, its longer duration suggests a lower average effusion rate than in 1977, which was a chance to limit the death toll and might be related to a broadly more degassed state of the lava previously stored in the summit crater (whereas in 1977 this contained a very active and gassy molten lava lake ponding 100 m higher in elevation). This latter inference is consistent with the greater proportion of aa-type lava flows produced by the 2002 eruption and also with the modest amount (~30 kilotons) of emitted sulfur dioxide detected by the space-borne TOMS on January 17 (NASA, Earth Observatory web report). Let emphasize, however, that a maximum duration of 24 hours for the eruption would imply an average effusion rate of 230-350 m³ per second, that is 10-30 times greater than typical effusion rates at a basaltic volcano such as Mt. Etna, Italy. This highlights the extremely high fluidity of the nephelinite lavas feeding Nyiragongo. Improved assessment of the bulk erupted volume will be achieved when accurate space-borne imaging of the entire lava flow field will become available.

4. *Crater collapse and explosive activity*

According to J. Durieux (UN-OCHA), the solidified lava floor of Nyiragongo summit crater – lying at 320 m below the rim since 1996 – was still in place on January 21, three days after the end of eruption, but was cut by a N-S smoking graben. It is most likely that this chilled crater floor, although thick enough to resist, had been weakened by the lava drainage on January 17-18. Its collapse occurred during the night of January 22 to 23. A detailed report by eyewitnesses located in Rusaya (8 kilometers SW of the summit) indicates that collapse started at 20:51 local time on Jan. 22, in coincidence with a series of felt earthquakes. It was accompanied and followed by roaring sounds and glowing above the crater and, soon after, by hot ash falls over Rusaya which accumulated a reported 10 cm thick ash layer. Intense and continuous seismic tremor registered by GVO over the next four hours suggests a post-collapse period of phreato-magmatic explosive activity and ash emissions. Light ashfall also took place over Goma and Gisenyi during that night. A helicopter flight on January 24 allowed us to observe the ash cover on the SW forested flank and to assess the extent of collapse in the summit crater of Nyiragongo. The crater was now about 700 m (instead of 320 m) deep below the rim, with a blocky and fuming narrow bottom over-surrounded by remnants of the former crater floor to the east and, minorily, to the west. Its changes in morphology correspond to an estimated bulk volume of **~30 millions m³** removed during previous molten lava drainage and subsequent (unquantified but likely secondary) ash emission. This figure compares strikingly well with the estimated bulk volume of lava flows, suggesting that these mainly derived from the drainage of lava stored in the crater. Field evidence of greater spattering activity on the lowest eruptive fractures may imply that those drained the deeper, less degassed lava ponding in the crater and, possibly, some other lava coming from the volcanic conduit. Intermittent phreato-magmatic explosive activity inside Nyiragongo crater has persisted after the collapse. At 09:10 (local) on January 24, just a few minutes after our helicopter had overflown the crater, we could see a dense cloud puffing above the volcano (Fig. 4, photo 13). Then, on January 27 we discovered fresh impacts and fresh tree-destructions in the forest on the upper north flank. Finally, phreato-magmatic activity in the crater could be directly observed on February 3 by one volcanologist of GVO (M. Kasareka) who had climbed to the summit.

4. *Fracture system*

- **One most significant feature of the 2002 Nyiragongo eruption has been the development of a large fracture system cutting the volcano over 20 km from north to south and reaching to within 1 km of Goma city (see Map 3 and photos in Plate 3).** Eruptive vents and also new phreatic (explosion-caused) craters were formed in some places along the fractures. Our field observations, combined with careful compilation of eyewitness accounts based on our interviews, as well as the detailed work of GVO scientists and social workers coordinated by UN-OCHA (D Garcin), confirm that opening of fractures and emission of lava flows occurred simultaneously or in close succession during the eruption. The overall propagation velocity averages 2 km/h. However, massive post-eruptive fracturing could also be observed in some places and can be correlated to the intense seismicity felt after the eruption (see below). Two weeks after the eruption intense steaming was persisting along several sections of the fracture system. The fissures were very dangerous, especially for children playing close to them, as they were large enough to fall in.

- The system of fractures is spectacularly developed in the Monigi area (1700 m elevation), where it consists of a down-dropped zone about 25-50 m wide with up to 20 m of vertical downward displacement along vertical walls that extends across the topography for about 2 km (Fig. 3, photos 1,6,8). Several fractures with 1-3 m opening run parallel on either side of the main fault system and extend out to a distance of 100-300 m from the axis. The fault system developed through several villages (Kasenyi, Buganra) causing significant damage and collapse of several houses and huts (Fig. 3, photos 5,9). Continuous steaming (60-80°C) was occurring along the faults. Locally, steam vents formed 10-15 m deep craters.
- In this same Monigi area, glassy fluid pahoehoe lava was extruded in the fractures from a dike 0.5-0.8 m wide. Withdrawal of magma from the dike during its southward propagation, as confirmed by eyewitness accounts, left a drained lava tube (Fig. 3, photos 6,7). In a few locations lava spatter was ejected up to 15 m away from the fracture indicating temporarily more gas-rich lava venting. Fracturing occurred over a short time between 10:00 and 13:00 local time, from North to South, cutting through thick scoria cone deposits as well as massive lava flows several meters thick (Fig. 3, photos 6,7). Where no collapse has occurred fracture depth reaches 5-10 m. The fracture system transects the western banana and grass-covered flanks of the Mubara cinder cone spreading over an area of 100-200 m where it consists of several sub-parallel fractures but with increasingly lower vertical displacements of 2-3 m to 0.2-0.5 m. Instability of the western part of Mubara Hill could lead to future subsidence and collapse, particularly as a result of torrential rains, renewed seismicity, as well as ground deformation linked to tectonic and/or volcanic activity.

5. *Seismicity*

A second major feature of the 2002 Nyiragongo event is the intense (felt) seismic activity that occurred during but mainly after the eruption. This syn- and post-eruptive seismic activity included a large number of tectonic earthquakes of magnitude 3.5 or larger. The strongest earthquake, with magnitude 5, struck at 00:14 (GMT) on January 20 (B. Presgrave, USGS, National Earthquake Information Center, WebRelief). This intense seismicity was registered by the two seismic stations operated by GVO (Bulengo and Katale, no data transmission), complemented since Jan. 24 by one portable MEQ-800 seismometer brought from France (IPGP) and installed temporarily near the emergency operation center in Goma. In the two weeks after the eruption the cities of Goma and Gisenyi were shaken by frequent felt earthquakes (Fig. 3, photo 4), some of which caused building damage and occasional deaths (8 in Gisenyi). Several of these shocks were felt up to Kigali (120 km) and Bukavu (60 km). The number of earthquakes gradually declined with time but has remained at abnormally high levels during all our stay and onwards (UN-OCHA WebRelief reports). At the time of completion of this report, earthquake shocks are still being felt intermittently. Such a high and long-lived seismic activity could not be just a post-eruptive seismicity due to ground compaction after lava drainage and rapidly led us to consider the likelihood of an ongoing tectonic crisis in the East African rift. The seismic network that operated during the eruption and up until January 30 did not allow an accurate assessment of the location and depth of earthquakes. However, the short time intervals between the arrival of P and S seismic waves as measured on seismograms (S-P arrival time difference) indicated a local or proximal location for many shocks. Moreover, the persistence of numerous long-period events and sequences of tremor after the eruption (Fig. 4, photo 15) raised concern about the possibility of continuing magma intrusion at low elevation. The actual significance of these signals is not yet fully understood; part of them may be due to persisting phreato-magmatic activity inside Nyiragongo summit crater or/and magma refilling in the volcano conduit system, but this has to be confirmed.

7. *Ground subsidence*

A third major observation done after the eruption is the verification of a large ongoing subsidence of the whole Kivu-Nyiragongo rift area. On January 28, a 20 km long east-west survey in boat by D. Garcin (UN-OCHA) along the northern shore of lake Kivu revealed impressive relative changes of the lake level, previously marked by green algae. These changes demonstrated a marked subsidence of the shore over a distance of about 15 km, with a maximum of 37 cm at Goma harbour that closely coincides with the N-S axis of the fracture system cutting Nyiragongo slopes (Figure 5). The deformation was steeper towards the eastern side of the rift and disappeared on its bordering fault (Gisenyi). This ground subsidence was further confirmed to be active on February 7 and to affect areas at much greater distance from the volcano, such as the Idjwi island (40 cm) to the west. More recent measurements (D. Tedesco and J. Durieux, pers. comm.) indicates that the subsidence may now amount close to one meter at Goma harbour and extends up to south of Lake Kivu (16 cm at Bukavu). In contrast, no subsidence apparently occurred at lake Tanganyika, further south (M. Halbwachs). These ground deformations, together with the high post-eruptive seismicity and fracturing, provide evidence of a major rifting event in the Kivu area and strongly suggest a tectonic, rather than purely magmatic source mechanism for the 2002 eruption of Nyiragongo.

B) GAS EMANATIONS

The eruption of Nyiragongo was accompanied by gas emissions of different origins which raised concerns over possible toxic effects and explosions.

- **Fires on lava flows:** During the eruption and on subsequent days the population of Goma experienced volcanic gas emissions from the lava flows. Mixtures of gases were released from the combustion of plants and burning materials (houses, cars, petrol tanks, etc.) engulfed by the flows. Flames of burning gas and vegetation were observed by us and analyzed in different parts of the flows, both inside and outside the city. On 23 January, soon after arriving at Goma, we measured a temperature of 500°C for blue flames that were burning on the still hot lava flow about 200 m from our hotel (Hotel Masque). The air in cracks near the flames contained about 2% methane, the smell of which was readily detectable in the area. We were told that on the day before these flames had been 1.5 m high and were orange. This suggests that the fire was originally caused by the burning of organic matter inside the flow and the flames resulted from the combustion of distillates of vegetation. Slow combustion of vegetation and organic matter was widespread after the eruption in all the areas affected by Nyiragongo lava flows.
- **Methane:** Abnormal smells of hydrocarbide gas were reported in many parts of the city, prompting us to investigate their origin and potential risks. Using a portable infrared spectrometer allowing in situ gas analysis, we found that the smells were due to methane- and CO₂-rich gas emanations from the ground which occurred in areas distant by 300 m up to 800 m from the lava flows and which, therefore, had no relationship with organic matter fired or heated by the flows. These emanations, with methane concentrations of a few per cent and sometimes approaching the 5% flammability threshold in air (Table), were found both at the open air (through pavements of Goma streets and in gardens) and in buildings (garages, hotel, airport tarmac). At the Belgian School, we measured methane levels < 1%, though a faint hydrocarbide smell was present in some rooms. On 24 January we measured methane levels at the airport where there was concern that the restarting of flights might be too dangerous. There were strong odours of methane near a drain system for rainwater about 200 m from the lava flow edge, which had not been detected by workers before the eruption. Methane was found in the air along the ground at this location, but at levels < 1%. However, at a nearby concrete roof over a drain the methane content was 2%, together with 2% carbon dioxide. The threat posed by toxic gas emissions was again highlighted recently by GVO with the discovery of a long fissure under the Kanisa La Mungu church in the very centre of the town (WebRelief, March 4). Carbon dioxide emissions that came through the crack were strong enough to cause two women cleaning the church to faint. The church has since been sealed off. According to GVO similar fractures are scattered throughout the area.

Gas-driven explosions: These were an other remarkable feature of this eruption. Numerous gas bursts were reported to have occurred during but mostly *after* the eruption, principally on January 20-22 during the most intense seismicity. Eyewitnesses indicated us that such phenomena followed shortly strongly felt earthquakes and were accompanied by a strong smell of hydrocarbide gas. In several places, distant from the lava flow by 300-400 m, these gas bursts have ripped through cement and stone pavement in houses and streets of Goma (map). We saw places where inside floor tiles and outdoor paving had been displaced and shattered over small areas. In Botembo Avenue smells of methane were common after the eruption in a row of offices. In one place the paving had been displaced upwards and we measured 5% carbon dioxide and 3-4% methane in air by the tile gaps. Inside one office we also found 1% carbon dioxide and 2.6% methane. Not far away was a garage where an explosion on January 21 had blown apart a concrete floor 10 cm thick and destroyed everything. However, four days later we found no more gas anomaly there. A similar explosion had occurred in the back kitchen of our hotel, breaking up its concrete floor in a spectacular manner over a distance of 4 to 6 m. Several other sites of gas-driven explosions were investigated. According to our information, no one had been injured or killed by these explosions. It is noteworthy that most of the gas bursts occurred at places or in areas that are broadly aligned with the N-S fracture system cutting the volcano (see map) and where ground gas emanations were often persisting. Although these explosions occurred at the time of felt earthquakes, the associated ground movement was not severe enough to have been responsible for the observed localized type of damages.

The strong gas smells associated with the explosions and the elevated concentration of methane measured at several of the spots are strong evidence of a methane-driven origin of the explosions. Sub-surface methane concentrations in the ground must have been locally high enough to allow spontaneous ignition of the methane-containing gas mixture. Further study will be necessary to elucidate the origin of that methane. Because most investigated explosions occurred far away from the lava flows, we can immediately exclude its derivation from the combustion of organic matter. There remain two possible sources: i) methane stored in lake Kivu (see below), that could diffuse into a more efficiently fractured substrate in relation with the tectonic and volcanic activity or, more likely, ii) deeper methane-rich gas, of possibly mixed mantle and sedimentary derivation, that may be stored in sediments filling the North Kivu rift. We suggest that such deep gas, stored at low temperature but high pressure in sediments underlying the volcanic cover, may be continuously degassing through the area along tectonically controlled

fractures. Its increased degassing might have been favoured by the development of the fracture system linked to the intense seismo-tectonic activity and the eruption. Local sub-surface accumulation of methane to concentration greater than 5% in volume may have triggered spontaneous explosions of methane-rich gas upon contact with oxygen following major earthquakes. Otherwise, we emphasize that methane is weakly abundant in the permanent mofettes ("mazuku") that occur in the area through old lava flows, such as those we analysed to the west of Goma (CO₂: 93.2 %, CH₄: 0.07% by volume).

We actually witnessed a small methane burst on January 27, while inspecting ground fractures in Monigi which displayed persistent incandescence and very high temperatures (we measured 970°C on Jan. 24). These sites are located in the middle of a small village and constitute a major attraction for cooking and for children who play nearby. The fracture, through which no lava had erupted, was formed parallel to the main eruptive fractures but through thick old lava flows. We infer that incandescence is caused by the presence at depth of relict heat from the magma body (diike) that fed the nearby lava flows which covered Goma (within 1 km). The gas burst occurred at about 2 m distance from the site where maximum incandescence had persisted for a week and where scientists were measuring temperature and collecting gases. Most likely, the scientific fieldwork brought air in contact with a pocket of methane which then spontaneously burst. A few fist-sized blocks of old lava were popped up to a distance <1 m, but without causing any injuries to the numerous bystanders. At another site, minor bursts occur every few minutes as wind goes through the fractures.

Finally, minor explosions of phreatic origin occasionally occurred in different places, such as the lava delta, when lava flows entered lake Kivu, and also Goma when bulldozing the lava flows suddenly depressurized steam produced by the high temperature of lava flows along the ground.

C) LAKE KIVU AND ITS GAS HAZARD

Lake Kivu (485 m deep) is known to contain an immense amount of both carbon dioxide (1000 times that in Lake Nyos, Cameroon) and methane stored in solution in its waters. In the case of a major disturbance of the gas-charged water (density) stratification of this lake, a huge gas burst with catastrophic consequences is possible. Concerns about such a hazard were raised when the lava flowed into the lake, together with the opening of new fractures, the strong seismicity and the unknown possibility of an underwater extension of the eruption.

- **Surface manifestations:** We received reports of a variety of manifestations which were observed at the surface of the lake after the eruption. On January 20-21, in coincidence with felt earthquake shocks, the lake water was seen uprising along the shore at 9 km to the west of Goma ("Le Châlet", Quartier Himbi) and, in three separate areas, the water became dark and warm, with gas bubbles and associated nauseous (hydrogen sulfide) smell. Many dead fish were seen in and around these areas. Similar phenomena were reported in other sectors of the lake's shore. Additionally, yellow flames were reported to have been seen on occasion at the surface of Lake Kivu well away from the lava flow, suggesting some methane burning. We were also told of smells and unpleasant experiences reported in swimmers on Lake Kivu before the eruption, which had been ascribed to gas emissions. These reports need to be followed up by a survey of gas concentrations at the lake surface, which was not possible during our short stay.
- **Underwater investigations:** The hazard of lava flows entering and disturbing the lake waters has not been extensively studied previously. The hot lava could disturb the stability of the lake by introducing convection of the waters and trigger a gas burst resulting in a lethal cloud of carbon dioxide and methane flowing over an unknown area around the lake. In order to assess the problem, M. Halbwachs organized underwater investigations of the lava flow that entered into Lake Kivu, first with the help of scuba divers from UN-OCHA and, in a second stage (February 7-10), using a submersible sent from France with the support of EC-ECHO. Local divers reported the presence of hot water (40-60°C) surrounding the lava delta and of a lava tube system extending down to at least 35 meters below the lake surface. The water around the delta was sampled for subsequent analysis in laboratory. Gas bubbling could be observed locally, but its limited extent suggested that neither the gases, nor the solidified lava presented a risk for the local water supplies. In contrast, potential hazard from the lava tubes required investigations at greater depth. Despite the poor visibility due to abundant particles in suspension, the surveys with the submersible revealed that the lava flow and tubes had descended to about 80 m depth in the lake by the shore at Goma. Fortunately, such a depth is much smaller than the critical depths of 200-300 m at which Lake Kivu's waters contain more abundant dissolved carbon dioxide, closer to the saturation limit. The data gathered during these surveys are still being processed.
- **Study of the physico-chemical stratification of Lake Kivu:** in order to evaluate the influence of the hot mass of lava that entered into Lake Kivu on its physico-chemical stratification, a series of vertical soundings with physico-

chemical sensors were undertaken during the first half of February. These measurements were performed by two limnologists: Klaus Tietze, specialist of the Lake Kivu (PDT GmbH, Celle, Allemagne), and Andreas Lorke (EAWAG Laboratory, Lucerne, Switzerland), in collaboration with M. Halbwachs. The following parameters were measured: depth, temperature, pH, electrical conductivity, turbidity (transparency to white light), and dissolved oxygen content. 40 vertical soundings were made: five down to 450 m depth; eight down to 150 m between Goma and Idjwi island, 20 km from the coast; and one in the Kabuno gulf, to the west, which contains as much CO₂ as Lake Nyos, in Cameroon. Water samples were also collected at different depth (25, 150 and 450 m, as well as at 10 m close to the lava delta) in order to measure their chemical and isotopic composition. Preliminary results suggest a change in the water stratification since the last measurements by Klaus Tietze 20 years ago. A new homogenous water layer was found between 200 and 250 m (probably due to a double diffusion mechanism), together with some temporal and spatial variations in the distribution of temperature around these homogenous layers. Near the lava delta the temperature and turbidity profiles show some perturbations between 50 and 120 m depth. Away from the delta, the temperature anomalies are confined within a thin (3 m) layer of slightly warmer water at about 80 m depth. The turbidity is rather low close to the lava flows but increases rapidly away from it.

3. CONCLUSIVE HAZARD ASSESSMENT

The French-British scientific team and the group of volcanologists advising the UN mutually agree to conclude that the 2002 eruption of Nyiragongo has likely been triggered by a major episode of tectonic extension along the Kivu rift system. This rifting event is revealed by the observed on-going regional subsidence and by the important post-eruption felt seismicity associated with persistent fracture opening down to lake Kivu. A pure temporal coincidence between the volcanic eruption and the tectonic events is considered unlikely. Given the wide areal extent and the cumulated energy of the processes in action, a tectonic origin of the eruption is the most reasonable interpretation. It is also consistent with the low level of volcanic activity at Nyiragongo prior to the eruption (the lava lake in the summit crater was solidifying since 1996), which reduces the likelihood of a pure magmatic source mechanism.

It is envisaged that initially smooth extensional movements gradually reactivated the weakest (hottest) upper part of the 1977 fracture on the volcano between October 2001 and January 2002, into which some magma may have possibly infiltrated. Sudden rifting and fracture opening over 20 km distance on January 17-18 suddenly drained out the lava stored in the summit crater and, possibly, some magma from the volcanic conduit. The contribution of magma diking to downward propagation of the fractures was probably of secondary importance compared to tectonic forces; both the observed complete emptying of lava ducts and the post-eruption widening (rather than compaction) of many fractures lend support to this idea.

If true, a tectonic, rather than magmatic origin of the 2002 Nyiragongo eruption has important implications for the assessment of current and future hazards in the area. If the extensive N-S fracturing of the volcano finally stops and the fractures gradually get closed, one may expect a gradual sealing of the volcanic conduit and the renewal of a lava lake in the summit crater within the next decade. Such a perspective is reassuring for Goma on the short term but, on a longer term, will re-create conditions similar to those before 1977 and 2002. If, to the contrary, fracturing of the volcanic pile further continues or/and the fractures remain opened, then the dynamical conditions in the magma conduit/plumbing system might be modified and could promote future lava flow emissions from fissures on the low slopes, possibly within Goma. In that scenario, Nyiragongo would experience a new period of activity more similar to that of Nyamuragira since 1938 and could threaten Goma and its surroundings from more frequent flank eruptions. Clearly, the issue will depend on the evolution of the present rifting process. One may expect that this latter will progressively reduce with time, as did the frequency of earthquakes after the eruption. If, rather, tectonic extension and ground subsidence and fracturing continue, the potential risks of new lava emissions but also of destabilisation of the gas-laden waters of Lake Kivu will have to be seriously considered. Finally, a new eruption of nearby Nyamuragira is likely in the foreseeable future as this volcano erupts frequently anyway. Any hazard assessment must therefore take into account the effusive and mildly explosive activity of both volcanoes.

As general guidelines, we list below the main hazards that we considered in our initial assessment and which will need incorporating in a more thorough and probabilistic hazard assessment we recommend below for the Goma-Lake Kivu area:

Volcanic:

- i. continued fracturing of the ground with ground collapse and steam vents
- ii. ground movements due to post-eruptive readjustments

- iii. slope instability (creep, slumping, small avalanches) in areas recently strongly and deeply fractured, in the case of renewed deformation of the ground, or renewed strong shallow-depth seismicity, but also likely in the case of torrential rains.
- iv. Nyiragongo partial edifice collapse in the case of renewed major tectonic rifting and/or eruptive activity following the present phase of significant fracturing of the edifice
- v. steam explosions at the lava delta, in areas of thick ponding of lava flows, and in steaming fractures following torrential rain storms
- vi. methane bursts in Goma and in areas of active fracturing superimposed with areas of strong permanent CO₂ outgassing with potential lethal concentrations
- vii. renewed lava flows (fast thin flows and slower more voluminous flows) from lateral fissures (one main axis or many fractures radial to the volcano) including lava fountains with explosive activity
- viii. renewed crater lava lake activity
- ix. instability and collapse of summit crater walls
- x. ash falls and local ballistic showers linked to phreato-magmatic explosions from the summit
- xi. scoria fall over a localized area in case of fissure lava fountain activity
- xii. formation of new adventitious lateral small volcanic cones in particular near Goma, on the new fracture system, and even below the surface of Lake Kivu.

Seismic / tectonic:

- i. felt volcanic earthquakes (strong and shallow-depth causing fractures and ground movement)
- ii. felt tectonic earthquakes with possible superficial rupture (formation of fractures, escarpments, faults, collapsed areas)
- iii. continuing rifting episodes with wide-field regional deformation

Lake Kivu:

- i. increased degassing of CO₂ and methane in areas peripheral to Lake Kivu.
- ii. overturn of CO₂ and methane charged waters of Lake Kivu with associated local to regional spreading of a CO₂ dense cloud and spontaneous ignition of methane in the atmosphere<;
- iii. lake seiche (sudden oscillation of lake water level) associated with tectonic seismic activity in the lake vicinity, or slumping of the lake shore, or slumping of the lava delta.

Health aspects:

- i. *Mortality.* The loss of life in the main lava flow event (47 deaths as officially reported) was low. However, many more deaths could have occurred but have gone unrecorded in the villages high up on the volcano where the volcano flows were very fast. The eruption occurred during daylight hours, and a short but sufficient warning of the encroaching lava was given to the population of Goma, so that they were able to evacuate the city in time. The humanitarian crisis dictated that people returned to the shattered city as soon as the flows had stopped and before they had cooled sufficiently.
- ii. *Methane.* Methane gas pervaded the city air at mostly low, non-dangerous levels. This gas came partly from lava flows burning vegetation inside the hot lava, but mainly from ground emissions associated with fractures bringing up methane and carbon dioxide from deeper in the crust. Fires on the lava flows were possibly due to the burning of organic distillates, or methane. Methane is not toxic but its flammability limits of methane in air are 5.0-13.4 % by volume. The main danger is thus from fire and explosion. Rarely, when in the presence of other products of fermentation, can it ignite spontaneously; in most instances a flame or spark is needed. In Monigi, experience has shown that hot methane-rich gas could ignite spontaneously in contact with air (blue flames). While limited in scale, the immediate proximity of the methane-bursting fractures from huts with dried-palms roofs and to many children playing nearby could raise concern for injuries and onset of small fires.
- iii. *Explosions.* Explosions were due to localized pressurization of methane and carbon dioxide from deep sources, probably sediment layers, acting against an impermeable layer, such as concrete. The gases moved along fractures in the course of the eruption or as a result of earthquake activity. Spontaneous ignition of a methane gas mixture as a cause of the explosions cannot be ruled out.

- iv. *Carbon dioxide hazard.* No obvious hazard from carbon dioxide emissions from fractures or soils was found or reported. This assessment may change when magma begins to recharge the volcano and refill the lava lake, and further evaluation of this hazard is urgently needed. The presence of carbon dioxide is usually undetectable by the senses, and it is a toxic gas in its own right. 5-10% concentrations and above are highly dangerous when inhaled.
- v. *Ambient air quality.* Air quality in Goma and the impacted villages was not severely affected during, or in the aftermath, of the eruption. Toxic emissions would have been present in the fires triggered by the lava flows in Goma, with smoke inhalation being a risk for people escaping. No information was available on this.
- vi. *Ash.* Ash fall was not a significant problem. However, future ash falls from the two volcanoes should be studied, as it appears that the ash may well have toxic properties or at least be a hazard to grazing animals. A collapse of a rock platform in the crater was probably responsible for the ash emission episode marked by a modest explosion. A major phreatic explosive eruption did not occur as a result of the draining of the lava lake. Abundant ash falls might present an acute respiratory hazard, depending upon the proportion of respirable particles. Toxic ash should not be a hazard to humans, but vegetables should be washed to remove ash before consumption.
- vii. *Fractures.* The fracturing that accompanied the eruption left many gaping cracks in the ground in villages, even below houses (Monigi-Mubara area). The ground is thus unstable, further house collapse could occur, and many of the fractures (up to 10 m deep, 1-2 m wide, and sometimes with high temperature steaming) pose a danger to people approaching the edge and the many children playing nearby. Furthermore, instability of the western part of Mubara hill could lead to future slumping and collapse, particularly as a result of torrential rains, renewed seismicity, as well as ground deformation linked to tectonic and/or volcanic activity.

4. RECOMMENDATIONS

A. General

- i. **Contingency planning.** Urgent consideration is needed to provide support for the GVO and local agencies in developing contingency planning in the event of a renewal, or increase, of eruptive activity. We consider that electronic facilities (computer, scanner, modem, telephone link) should be provided, or be made available, to the GVO so that the local volcanologists can rapidly exchange information with foreign scientists on the state of the volcanic activity. The Alert Level at the time of writing is Yellow, meaning that a further eruption is not imminent. Ground shocks are still occurring occasionally, suggesting to the volcanologists that rifting may still be happening, but not a rapid rise in magma. In any volcanic crisis the state of the activity can suddenly change and move from a quiet into a threatening mode. There is an urgent need to develop emergency planning in the event of an increase in the hazard level of the volcano on an inter-sector basis.
- ii. **Scientific co-ordination.** An internationally co-ordinated scientific effort is urgently needed to investigate the dangers presented by Nyiragongo and Nyramuragira volcanoes which threaten an area already affected by a huge humanitarian crisis. The rotating presence in Goma of one experienced occidental volcanologist keeping close coordination with GVO, UN and the local authorities is badly needed.
- iii. **Volcano monitoring.** The monitoring capabilities of the GVO (GVO) need urgent strengthening to measure and interpret the ongoing activity, both immediately and for the longer term, as Nyiragongo volcano will need monitoring for many years. The new prominent fracture system increases the hazard of flank lava eruptions at low level in the future, as well as flank instability that could eventually trigger some collapse of the upper part of the volcano. Any extension of the fracture system into Lake Kivu could lead to the catastrophic overturning of the water and gases mentioned previously. A comprehensive detailed program of monitoring upgrade must be elaborated between all interested parties and funds allocated for implementation of the most urgent aspects in the very short term. The GVO has training and expertise in monitoring but lacks funds, equipment, and logistic support for it. In addition serious safety issues and political problems have rendered the work of the GVO very difficult. Ideally, monitoring efforts should benefit from future collaborative research-programs in Earth Sciences between research institutions and Government agencies in the area with international partners. Emphasis should be given also to professional training via student and research scholarships.
- iv. **Hazard evaluation and risk assessment.** Comprehensive and integrated studies are urgently needed to include the three main natural hazards (volcanic, limnic/lake, seismic) and all their direct and indirect associated risks including those related to public health, civil aviation, agriculture for the Goma-Gisenyi area, and even wider Lake Kivu area. Particular attention needs to be given to the influence of the specific political, economic, geographic, and cultural factors on risk prevention and mitigation in the future. By any measure this situation is unlike any other volcano crisis

in recent times. A full risk assessment of a future eruption of Nyiragongo and its impact on Lake Kivu will be required by a team of scientists. Nyamuragira volcano and its activity will also need to be included. The potential for loss of life directly as a result of volcanic activity is on a level that must now be regarded as highly significant even in a region (eastern DRC) where 2.5 million people have died from malnutrition and infectious diseases, due to the collapse of the health system and food insecurity, between 1998 and 2001. In 1995, the late Haroun Tazieff, the French volcanologist, proclaimed during the Rwandan refugee crisis that the number of victims of volcanic activity would be at least two to three orders of magnitude smaller than the number that would be claimed by a large scale displacement of the (then) one million refugees in the refugee camp close to the town of Goma (Nature 1995; 376: 394). His eruption forecast has now been overtaken by events, as have the refugee and humanitarian problems. The potential for a much larger loss of life from the volcano, both in absolute and relative terms, now makes the need for a new risk assessment essential. The devastating cholera and dysentery epidemics in the refugee movements in July 1994, in which 50,000 died in the first month after the influx (Lancet 1995; 345: 338-344), should not be allowed to recur in future displacements of the populations, e.g., in an evacuation in a volcanic crisis, with the appropriate involvement of international agencies.

v. **Human risk assessment.** An innovative approach is required to policy-making to ensure it is underpinned by evidence of science in the face of uncertainty about the future impact of the volcanic activity. For example, the value of subjective probabilistic methods for dealing with scientific uncertainty in the absence of frequency data, e.g., for forecasting volcanic activity and human casualties, has been previously shown in the continuing volcanic crisis in Montserrat. The use of these methodologies should be considered to support policy making in the Nyiragongo crisis, where a large population is at risk from volcanic activity. The critical issues include decision-making if the volcanic hazard level rises and if there is a need for a precautionary evacuation of a population out of a danger area. The displacement of large numbers of people may lead to more deaths from infectious diseases and malnutrition than taking the risk of leaving the population in place, unless the volcanic activity becomes immediately threatening, when people will self-evacuate, but not necessarily in sufficient time to minimise loss of life. The evaluation of the hazard of a massive gas release from Lake Kivu, including its mode of dispersion, will also need to be part of this risk assessment.

vi. **Humanitarian crisis.** The humanitarian crisis and conflict situation in eastern DRC must be incorporated in such an assessment. The health impact of the present volcanic emergency, leading to the disruption to life in Goma and its surroundings, should be reviewed, e.g., the consequences of this salient or sudden, disruptive event for water and food supplies and outbreaks of infectious diseases, such as cholera, dysentery and malaria. Emergency planning for a future eruption needs to consider the efficacy of warnings and the response to calls for evacuation in a community that is attempting to survive under a host of different threats, the volcano being but one of these. About 2 million people are already internally displaced in DRC, with some 310,000 as refugees in other countries (WHO data). The benefits of volcano emergency management planning and associated recommendations need to be justified within this context. This places a special challenge on scientists, policy makers and humanitarian agencies alike.

vii. **Sustainability.** In justification, the volcano has introduced a new layer of complexity in an already complex emergency. Volcanic crises are not on-off events (e.g., like an earthquake or flood), as is commonly supposed, but usually present long-term sustainability issues arising, for example, from the threat of on-going volcanic activity and devastation, as is the case here. The commercial and transport importance of Goma to the region may not be the same after the severe damage caused by the lava flows. Rebuilding on the lava in the city may not be an option, and a decline in economic activity there would have implications for the viability of the region.

viii. **Vulnerability assessment.** The natural hazards and their implications for policy need to be assessed in a broader context than just technical aspects of mitigation and epidemiological risk factors. A vulnerability assessment should be undertaken which includes the political and social aspects of the complex emergency, as well as the infrastructural and community characteristics of Goma and the region at risk from the only two active volcanoes (Nyiragongo and Nyamuragira) in the Virunga range. The location of stores of flammable substances is an obvious example of infrastructural vulnerability in the light of the petroleum explosion killing 100 people. The human vulnerability assessment should be co-ordinated by WHO (Appendix 3).

ix. **Alert and warning system.** A system of color-coded alert levels correlated with precursory activity, the various eruptive scenarios, and the areas/population at risk need to be implemented at all times to warn of further eruptions, and allow evacuation planning and mitigation measures to be taken.

x. **Risk prevention.** Significant mitigation efforts need to be undertaken well ahead of any future eruptions. The impact on the city and its infrastructure of renewed lava flow activity requires urgent study for disaster planning. Emphasis must also be given on communication between all parties involved (scientists, authorities, public, media, international scientific community) and preventive information, particularly in the villages isolated and scattered on the slopes of the volcano and threatened by the opening of new eruptive vents, the opening of fractures, and the passage of future lava flows. The traditional village chiefs, as well as the schools, need to be involved, for example.

- xi. **Seismic hazard and risk assessment.** We recommend that such studies be implemented rapidly for the Goma and Gisenyi areas because of the continuing seismicity in the area, the potential for formation of new fractures, the potential for further building damage in buildings already weakened or partially destroyed by numerous felt earthquakes, the characteristics of buildings in the area (materials used, architecture, position with respect to the active rift fault system)
- xii. **Monitoring Lake Kivu and the gas hazard.** The gas hazard from the lake and the best ways of monitoring the stability of the gas-laden waters at depth need urgent investigation. Monitoring the level of the lake is also a rapid and efficient, low-cost way to monitor the ground movements due to either tectonic rifting or/and magma refilling and volcanic activity. The French/English team have requested A. Woods, a fluid dynamics expert at Cambridge University who has a special interest in volcanic flow problems, to make an initial evaluation of the stability of the lake in relation to thermal inputs from lava flows using data provided by K. Tietze, a limnologist who has studied Lake Kivu for many years in collaboration with M. Halbwachs. This would be a major contribution to the initial risk assessment.
- xiv. **Measurement of ground gas emissions.** The hazard of methane from ground emissions in the city requires monitoring. If further explosions and reports of smells continue, the ground gas emissions will need additional investigation. More checks of carbon dioxide emission from the soils in the Goma area are also warranted.
- xv. **Link between Nyamuragira and Nyiragongo volcanoes :** the precursors to eruptions on both volcanoes must be better recorded and understood, especially with respect to the potential link between the activity of the two volcanoes and how that may control the timing, magnitude, duration, and nature of future eruptions. Although Nyamuragira poses much less of a direct threat to populations, potential modification of land-use and city planning in the aftermath of the 2002 eruption will also require a comprehensive hazard and risk assessment for that volcano. In the past, contamination of pastures by volcanic ash with adsorbed acid condensates or volcanic glass shards has led to mass deaths in cattle. Historical lava flows have also entered the western-most part of Lake Kivu. The consequence of similar activity in the past on the lake dynamics must also be addressed.
- xvi. **Investigation of tectonic rift processes.** The relationship between volcanic activity and seismicity warrants monitoring and study of the active rift processes in the area, as these may play a key part in the eruptive activity and the future stability of the volcanic edifice.

B. Specific recommendations

B1. Permanent monitoring systems, short-term upgrade

- i. *Seismic monitoring network* : an upgrade of the network is necessary (number and distribution of the stations, telemetry, data processing).
- ii. *Gas monitoring* : a detailed prospection and mapping of CO₂ and CH₄-rich gas emanations must be undertaken in the Nyiragongo-Goma-Gisenyi area, that will be subsequently used to select sites for the installation of permanent sensors. We recommend the rapid acquisition of a portable infrared spectrometer to conduct such a prospection and, then, the acquisition and set up of buried (protected) radon sensors with solid-state detectors (Barasol probes) allowing to monitor the temporal/spatial variations of the gas flux in the ground in relationship with either volcanic or/and seismo-tectonic events. Addition of hydrogen sensors could be useful at some sites in the near future.
- iii. *Lake Kivu water level* : set up three maregraphs, complementing a network of graduated marks fixed along the coast, in order to survey the evolution of ground level (ongoing tectonic subsidence or possible uplift prior to future magma refilling and intrusion).
- iv. *Phenomenological observations*: set up a reliable network of observers in towns and village surrounding and on the volcano as well as in the Lake Kivu area to collate and report rapidly observations and information related to any new phenomena to the Goma Volcano Observatory. Continue the questionnaire initiated by social workers under the initiative of UN-OCHA (D Garcin) following the eruption. On medium term, install a permanent telemetred videocamera on top of Nyiragongo.

B2. Discontinuous or specific measurements – short-term

- i. Detailed study is needed of the new fracture system and of the recent rifting episode, using both ground-based (EDM + GPS) and space-borne (SAR) sensors for distance/height measurements.
- ii. The routine surveillance and profiling of dissolved gases and chemical substances in Lake Kivu is required to monitor lake waters and their stability.

- iii. COSPEC or similar remote sensing of the SO₂ discharge from Nyiragongo crater should be established as part of the routine monitoring of the activity.
- iv. A study of magmatic volatiles and their behaviour in Nyiragongo magmas (crystal melt inclusions) is needed.
- v. Re-establish the levelling and gravity measurement profiles that were performed in the 1960's (see geological map) including the Gisenyi-Sake profile, Goma-Rushuru profile, and the profile going to the summit of the volcano from Kibati.
- vi. Provide GVO with a practical and operational means to visually record the activity in the summit crater (fracturing, fumaroles, lava lake) by means of a digital photo and video camera, in the hope that in the future an already existing project to install a permanent video camera telemetered to the GVO can succeed.
- vii. Obtain a synthesis of field observations from eyewitnesses that took shelter from lava flows on nearby hills and witnessed the eruption or its precursors and its aftermath (post-eruptive phenomena). Undertake field checks for deposits, structures. Collate a detailed chronology of the eruption including with photos or other documents. Of crucial importance is the spatio-temporal characteristics of the effusive activity, the more explosive lava fountain activity, the fracturing, the emission of very fluid non-voluminous pahoehoe lava flows as well as more viscous but voluminous aa lava flows, the temporal link between fracturing and seismicity, the relationship between activity of the crater lava lake and the onset of the January eruption, and the fumarolic reactivation of the 1977 flank fractures.
- viii. Detailed post-eruption analysis of the seismic data is needed in order to test for seismic precursors, discriminate between different sources of seismicity (eruptive Nyiragongo seismicity, background Nyamuragira seismicity, Nyamuragira 2001 eruptive seismicity, background tectonic local and regional seismicity, and abnormal rifting episodes - local and regional seismicity), and understand processes of magma rise, intrusion, and propagation through the fracture and dike system.
- ix. Elaborate (subcontract) rapidly a photogrammetric aerial survey of the complete lava flow fields of both Nyiragongo and Nyamuragira including the entire lava flow and fracture field of 2002 and the northern shores of lake Kivu to produce 1) a detailed map of the lava flows, 2) a new topographic map to replace the old existing 1965 topographic base map. This is a fundamental database that will be extremely valuable to scientists, government and city officials, and humanitarian and emergency planners.
- x. Elaborate a map of lava flows and fractures of the 2002 based on satellite-derived imagery (ASTER, Landsat, Spot, Radarsat).

B3. Discontinuous or specific measurements – longer-term

- i. *Drilling of cores in sediments of Lake Kivu* : should be done to evaluate the record of possible occurrence of catastrophic gas bursts from the lake in the past thousands of years (associated with important waves and rapid accumulation of terrigenous debris and subaerial vegetation). Correlated investigations of paleobotanical and paleobiological changes in the environment surrounding lake Kivu and the region, and of Quaternary terraces around lake Kivu.
- ii. *Produce a detailed bathymetric map of Lake Kivu and of the lava delta* : to estimate volumes and, more importantly, map deposits and structures in the lake bottom which will be important to incorporate in the modelling of the factors that could promote lake overturn (existence and formation of tectonic fractures, surface ruptures from recent strong shallow seismicity, deformation structures, lake edge and lava delta instability structures, existence of old underwater volcanic vents, deformed sediments)
- iii. *Reconstruct in detail the eruptive chronology of both Nyiragongo and Nyamuragira volcanoes*: geological mapping, dating of volcanic deposits and eruptions including and in particular those from adventitious cones that reach far down the populated slopes of Nyiragongo and Nyamuragira, such as Mount Goma, estimation of erupted volume, geochemistry of volcanic products, eruptive processes, stratigraphy, areas affected). This work will result in an updated geological map including tectonic features and a volcano-seismic hazard map. These documents can then form the basis of any volcano-seismic risk assessment for the area and the development of emergency and land-use planning.
- iv. Install a volcano and rift deformation surveillance network integrated with the other monitoring networks (lake, volcanic and tectonic seismicity, gas, water)
- v. Provide the GVO with the access (infrastructure, training, data analysis) to remote sensing satellite-based data (morphology, thermal, anomalies, gas emissions, and deformation) that would be very useful for surveillance because of

the large size of both active volcanoes, their remote access, the large wide-field signal they tend to produce on such data sets, and the possibility that these techniques offer to evaluate fluxes (heat, gas).

vi. Undertake a spatio-temporal study of the field of fractures, dikes, and adventitious volcanic cones field on the volcano flanks, in the crater wall, and by the shores of lake Kivu to determine the parameters that control frequency of occurrence, orientation, scale of such features and their associated eruptive activity. Results of this study would need to be included in the modelling of potential scenarios of overturn of lake Kivu (determine probability of occurrence of a new fracture, dike, earthquake, or eruptive volcanic vent below lake Kivu using perhaps an approach similar to that developed by an international team of scientists for the hazard and risk assessment for the Nevada Nuclear Storage Site in the United States).

B4. International Scientific meeting

A meeting should be convened by international and governmental agencies to bring together the international scientists and representatives of the appropriate aid/humanitarian agencies and government officials involved in the Nyiragongo crisis, with the purpose of exchanging information and advancing mitigation and other developments.

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APPENDIX 1

Itinerary and fieldwork

January 19 (Saturday)

French Ministry for Foreign Affairs requests that volcanologists from France and the UK go urgently to Goma. Contacts with IPGP, CNRS, University of Savoie and University of Cambridge.

January 20 (Sunday)

Preparation of equipment. Transfers to Paris (P Baxter, M Halbwachs).

January 21 (Monday)

Flight from Paris to Kinshasa (Dem. Rep. of Congo) together with the French-British diplomatic delegation (French government Airbus). Assistance with passports and visas by the first counsellor of the French Embassy in Kinshasa. Meeting and dinner with the cultural and scientific counsellor of the French Embassy (M B Sexe), local representatives of the UN-OCHA and the Rector of Kinshasa University. Brief meeting with the Minister for Health of the DR of Congo.

January 22 (Tuesday)

Flight from Kinshasa to Kigali (Rwanda). Meeting with M. J Gohy, cultural and scientific counsellor at the French Embassy in Rwanda. In the afternoon, first helicopter survey of the scientific team over the Goma area, thanks to OXFAM logistics. Despite bad weather conditions, it was found that (i) most lava flows had stopped, leaving only residual lava spilling into Kivu lake, and (ii) the destruction of Goma city was less (about 15-20% in area) than previously quoted in the press (80%), (iii) Goma was largely reoccupied by population, (iv) smoking from still hot lava flows and burning houses were seen in various parts of the destroyed sectors. In late afternoon, meeting in Kigali with the General Secretary of MINERENA, the director for Energy and the director of the Methane Project, in presence of M. J Gohy. Dinner at M. Gohy's house.

January 23 (Wednesday)

Transfer of the team from Kigali to Goma by road with two 4 x 4 vehicles of the MINERENA. Acquisition of 6 batteries for the IPGP seismograph brought by J C Komorowski. Visit to the Prefet of Gisenyi. Arrival in Goma and meeting with the UN representatives, three colleagues volcanologists mandated by the UN (J Durieux, France; D Tedesco and P Papale, Italy) and Congolese colleagues of the GVO (GVO). Discussions and planning. Strongly felt earthquakes. In the evening, first recognition of lava flows inside Goma and first analysis of gas emanations in the area using a portable infrared spectrometer. Collection of first rock samples from the lava flows. Lodging at Hotel Masque arranged. Several felt earthquakes during the night.

January 24 (Thursday)

Helicopter flight (OCHA) over the lava flows and over the volcano, starting from Goma airport (partly covered by lava). Observation of an extensive fracture system trending north-south and cutting the southern flank of Nyiragongo from just above Goma up to about 2800 m elevation on the summit cone. Lava flows were emitted from different sections of this fracture system. Observation of an other fracture on the upper north-west flank of the volcano which also produced an extensive lava flow through the dense forest. Flying above the top of Nyiragongo revealed a major collapse of the whole inner part of the summit crater. This occurred during the night of January 22 to 23 and was the source of light ashfall in Goma-Gisenyi on 23th and thicker ash deposits observed othe volcano itself. At 09:10 an explosive plume is seen uprising above Nyiragongo crater, just after our passage in helicopter (see photo 13). In late morning, general briefing of the volcanological teams in Goma.

In the afternoon, investigations of the lava flows, gas emanations and the fractures which affected the area the closest to Goma airport (1.5 km to the north). Discussions with the local populations and chronological reconstruction of the events. Finding of incandescent cracks and flames (burning gas) in older lava terrains in the middle of Monigi village, indicating magma intrusion at very shallow depth. Sampling of different lava specimens and measurements of gas emissions. At the same time, an underwater exploration of the new lava delta created on the shore of Lake Kivu was realized with the help of local divers (D Garcin, UN-OCHA). A portable MEQ-800 seismometer from France (IPGP) is installed temporarily in Hotel Masque in Goma, near the emergency operation center, to complement the two working seismic stations managed by the Goma observatory. Contribution to a daily report by the "Volcano surveillance team", delivered to authorities, UN representatives and the press. Continuation of the seismic crisis with felt earthquakes, even though the number and the magnitude of the earthquakes is slowly decreasing.

January 25 (Friday)

Systematic investigations of gas emanations and of reports of gas-explosions and hydrocarbon smells in Goma city by P Allard and P Baxter. Controls and measurements in various places and discovery of sustained emanations of concentrated methane from the grounds (up to 4% by volume). Discussions with local people and accounts of gas-related explosive phenomena following earthquakes. JC Komorowski, P Papale, M Kasereka (GVO) investigate the eruptive vent just west of Kibati and north of Lemera cinder cone. Discovery of a line of eruptive vents and fractures that propagated southward onto Lemera hill forming a 100 m wide graben with 1-2 m downward displacement. Collection of eyewitness accounts from the houses on top of Lemera hill on which people took shelter. Refining of the timing of eruptive activity.

In the afternoon, new assessment of the glowing fractures in Monigi village, where temperatures of up to 970°C are measured. Detailed inspection of the upper fracture system that cut villages and later produced the main lava flow over Goma. Visit and discussion in the field with the Rwandese Minister of MINERENA. Investigations of lava flows at higher altitude towards Kibati village. Investigation of the lava flows and associated devastation in the business center of downtown Goma and of the lava delta by lake Kivu. Collection of rock samples, temperature measurements. Briefing with other colleagues in late afternoon and contribution to the daily volcanological report.

January 26 (Saturday)

Strong earthquake shock at 03:55 local time. Briefing and planning in the morning. Departure of P Baxter to Kigali, with dinner as guest of French Ambassador (back to London on 27th). P Allard goes with people from MINERENA and from GVO to investigate CO₂-rich gas emanations ("mazuku") north-west of Goma (Sake road). Gas measurements and sampling. Analysis of an other gas spot nearby the seismic station of Bulengo and recovery of the seismograms. Inspections and analysis of gas emanations from various fractures and gas-explosion spots in the eastern part of Goma city. An other team with J C Komorowski, P Papale and O Vaselli (newly arrived Italian geochemist) is dropped by helicopter on the westernmost eruptive vent at 1890 m elevation to carry out gas sampling, temperature measurements, rock sampling, and geological observations with measurements on fractures, interview with french TV crew from France 3. Several fractures running about N-S are seen from the helicopter to the NW of the western vent. Aerial survey of the fracture system in Monigi. Reconnaissance of fractures with cm-size surface movements in Goma and Kisenyi that formed during the recent felt earthquake swarms and have orientations correlated with the fracture system developed on the flanks of the volcano. In late afternoon, scientific briefing and contribution to the daily volcanological report.

January 27 (Sunday)

Successive helicopter (OCHA) flights to drop a total of 7 scientists into Shaheru crater (2700 m elevation) on Nyiragongo volcano. Investigations and analysis of the uppermost eruptive fracture which opened first on January 17 and through which most of the lava lake was drained. Rock collection, temperature measurements and gas sampling. One group attempts to climb the volcano to the summit but fails to find the pathway in the forest. The helicopter takes time to be back due to denser clouds, a small to moderate gas plume with vertical thermal uplift is clearly seen above the summit. An earthquake is mildly felt while in the Shaheru crater, it was strongly felt in Goma. Bangs from the summit are heard on three occasions during this time. New helicopter survey by three volcanologists (J Durieux, P Allard and JC Komorowski) over the upper flanks of Nyiragongo: clear visibility of the NW fracture and lava flows and discovery of fresh destructions and impacts in the forest due to explosive block ejections. In late afternoon, new controls of fractures and glowing cracks in Monigi village, a methane gas burst is witnessed in the village, interview with french TV crew from France 3. Temperature measurements, gas sampling, and eyewitness accounts. Inspection of intense steaming at the lava delta on the shore of Lake Kivu that formed following torrential rains and major surface runoffs onto the hot lava because the water-drains are all clogged by lava. Observation of boiling bubbling pools and small phreatic explosions with projection of lava fragments up to 15 m in height. In the evening, briefing and contribution to the daily volcanological report.

January 28 (Monday)

Departure of M Halbwachs to Kigali. P Allard and O Vaselli go with colleagues of MINERENA to control reports of uprising "dark, warm and smelling" waters that occurred after the eruption, between January 20 and 21, along the shore of Lake Kivu 9 km NW of Goma. Confirmation of other similar accounts in correspondance with major earthquakes that shook the area after the eruption. In the afternoon, confirmation of an uprising level of Lake Kivu (or, rather, a subsidence of Lake Kivu's coast) was obtained from local divers, during a profile in boat. Investigations and sampling of gases and thermal water (72°C) along the eastern fault bordering the rift (Rambo, in Rwanda). Then, investigations and sampling of gases and water extracted from the bottom of Lake Kivu (300 m) at the methane-station of Cap Rubona (Rwanda). JC Komorowski accompanied by Mr Eloi, technician in GVO, carries out a detailed field survey of the fracture system between Monigi village and Mubara

cinder cone. Orientation and dimensions of fractures and faults are measured. Rock samples from the dike are collected. Eyewitness accounts allow refined reconstruction of the eruption chronology. In the evening, scientific briefing and contribution to the daily volcanological report.

January 29 (Tuesday)

In the morning, return of P Allard and JC Komorowski to Kigali by road with colleagues of MINERENA. At 16:30, P Allard, JC Komorowski and M Halbwachs meet in Kigali with the Minister of MINERENA, M. Marcel BAHUNDE, and the General Secretary, M. Emmanuel NSANZAMUGANWA, and present the main results and recommendations of the French-British scientific team. At 18:00, participation of the three scientists to a public conference-debate on the Nyiragongo eruption organized by the French Embassy and MINERENA. Presentation of documents, films and debate with the public. At 21:00, dinner at the French Ambassador's home in Kigali, together with the British Ambassador and the Minister of MINERENA.

January 30 (Wednesday)

Departure of P Allard and JC Komorowski to Paris via Addis Ababa.

M. Halbwachs stays in Rwanda for other two weeks to work on a previously planned applied research project with Rwandese scientists and authorities on industrial extraction of methane gas from Lake Kivu, as well as to manage a sub-aqua investigation of lava flows entered in Lake Kivu using a French submersible.

APPENDIX 2

Health hazard assessment

- Determine from the volcanologists, including the GVO, the most recent state of the volcano and its latest activity, including seismicity, felt earthquakes and any extension of the fracture system, and the latest observations on Lake Kivu.

- Assess the latest accounts of explosions, deaths, gassings, fires, smells in and around Goma and the villages.

Re-evaluate the ground gas emissions (carbon dioxide, methane and carbon monoxide) along fault lines in Goma and the fissures in the upper villages.

Study the behaviour of the lava flows in a field survey of their distribution around houses, and consider the implications for future eruptions into Goma.

- Obtain more data on the “methane” explosions around the city, their location and timing.
- Collect drinking water samples to repeat routine anion and cation estimations to monitor the any contamination from lava entering the lake, or the effects of the volcanic activity. Confirm the sources of water supplies in remote areas.
- Check ambient air quality in Goma. The levels of fine particles from drying out of the lava flows and human activity generating dust can be measured in real time using a DustTrak instrument. Diffusion tubes will provide a useful check on sulfur dioxide levels (plume grounding).
- Collect ash samples from the recent fall on the upper flanks and check the properties of the ash.
- Observe houses where people are reported to have died in “volcanogenic” earthquakes, to confirm the nature of damage and to consider the risk of local building typologies in future eruptions.
- Collate information on epidemiological surveillance of the stressed populations, to determine if the rapid displacement triggered any further outbreaks of infectious diseases.
- Survey the town for vulnerability issues which might heighten the risk of casualties in future lava flows.
- Location and state of present hospitals and clinics, including level of care.
- Obtain general information on the nutritional status and health problems identified as on-going amongst refugees/displaced peoples.
- Evaluate reports of gas emissions on Lake Kivu - carbon dioxide and methane measurements out on the lake surface.
- Confirm the numbers and causes of death in the eruptive events of January 17/18, 2002.

APPENDIX 3

Vulnerability Assessment

The concept of a vulnerability assessment is well known in disaster mitigation work, but methodologies for incorporating hazard (probability), vulnerability and human lives in a risk assessment format have not been often used. Advances in numerical modelling, computer power and Bayesian statistics now enable probabilistic risk assessments to be used in volcanic risk management. The methodology was first used in the Montserrat crisis in 1997 for advising the UK government on whether the hazard of the Soufriere Hills volcano was sufficient to warrant evacuation of the island. The technique was used to underpin judgment, not to replace it. A group of scientists defined the main eruption scenarios that would endanger life, assigned probabilities to each of these, and central values and ranges for casualties were estimated, using an elicitation process. The results underwent a Monte Carlo simulation to produce a summary FN curve displaying probability of N or more deaths over the next six months, with the calculation of individual and societal risk values for different locations of the population around the volcano. The methodology and its application is now generally recognized as being a leading development in volcanology.

The method may not be directly applicable to the Nyragongo crisis, but the need for a framework for a formal risk assessment incorporating a wide range of scientific opinion now exists. The complexity of the humanitarian crisis needs to be incorporated in decision-making, and the risk from the volcano weighed against the health risks associated with relocating people in large numbers, either in the long-term or during periods of volcanic unrest, as a precautionary measure. A formal method is more likely to lead to a realistic assessment of risk rather than relying on one or two expert opinions.

Some key steps to beginning this process are suggested as follows:

- An evaluation of the events and health impacts on the population of the latest eruption and its hazards. This information can rapidly perish and should be collected soon.
- Assess the current vulnerability of the population in the aftermath of the eruption to determine what new threats to health have emerged as a consequence of the activity, e.g., the lava flows and disruption to the infrastructure of Goma, and to life in affected villages; the health impact as a result of thousands of people displaced since their homes were destroyed.
- Review the status of the volcanic hazards identified in the initial assessment undertaken by the international team of scientists and as indicated in my main report.
- Develop a framework for a formal evaluation of human, community and political vulnerability to be co-ordinated by WHO. The assessment can be used to inform the development of future mitigation measures, such as forecasts and warnings, community preparedness, infrastructure and land-use planning, emergency response and evacuation planning. The data will also provide an essential input to a formal scientific risk assessment as described in the text of the report.

TABLES – FIGURES –PHOTOS

Figure 1. Map of the deposits and phenomena associated with the January 2002 eruption of Nyiragongo volcano (geologic background taken from Thonnard, R.L.G., Denaeyer, M-E., Antun, P., 1965, Carte Volcanologique des Virunga (1/50 000), Afrique Centrale, Feuille No. 1, published by the Centre National de Volcanologie (Belgique), Missions Gèologiques et Gèophysiques aux Virunga, Ministère de L'Education et de la Culture, Bruxelles, Belgium)

Figure 2. Map of field measurements and collected samples (gas, rocks, water)

Figure 3. Assorted photos of the eruptive deposits (photos 1-9)

Figure 4. Assorted photos of the eruptive deposits (photos 10-15)

Figure 5. Profile of ground subsidence in the Goma area associated with the January 2002 eruption

Figure 6. Map of gas concentration anomalies and gas-driven explosion sites

Photo captions (photos 1-15 by JC Komorowski, IPGP):

1: Fracture and fault system developed on jan. 17 around 14h00 in Monigi village. Continuing strongly felt post-eruptive seismicity further opened the fractures that can reach 2 m in width and 5-10 m deep.

2: Glassy fluid lava erupted on jan. 17 from a dike that reached the surface in the fractures in several places in Monigi between 14h00 and 16h00. Here pieces of fluid lava were ejected as spatter up to 15 m from the fracture.

3: Tube-shaped eruptive dike in Monigi fracture. The dike is about 0,6-0,8 m wide and formed by a glassy outer envelope of lava. Remaining lava drained through the dike conduit southward towards Goma.

4: Smoked drum seismogram from the IPGP MEQ-800 portable station (short period 1 vertical component station, gain: 66, upper filter 10 Hz) installed at the Hotel Masque in Goma, DRC, 12 hour recording period from jan. 28 18h07 GMT until jan. 29 6h35 GMT. Each line represents several minutes (time marks separated by one minute). Seismicity is characterized by several scattered high-frequency volcano-tectonic earthquakes, the largest of which are felt in Goma, a few long period (low frequency) earthquakes as well as periods of low amplitude volcanic tremor (bottom of record) indicating that the volcano is still in a state of unrest with possible injection of magma into the edifice. The high-frequency earthquakes are related to tensional stresses in the volcano (opening and/or readjustments of fractures) as well as to fracturing events of local shallow tectonic origin.

5: Wooden hut destroyed by opening of fractures and associated seismicity on jan. 17 in the village of Buganra, N Monigi.

6: Fracture system N of Monigi. The area between the fractures has been downdropped by about 2 m to form a graben (see tilted trees), steam vents locally from deep pits (5-10 m). Earth cracks parallel to the main depression extend out to about 20-30 m. This feature was formed by extension and collapse consequent to intrusion of magma high into the edifice (pressure opening fractures) and drainage through a dike towards Goma (withdrawal of magma). The very high and abnormally strong high-frequency seismicity that followed the eruption and fracturing in this area suggest also the contribution of a major tectonic event with surface rupture.

7: Central depression in the Monigi fracture-graben system through old scoria fall deposits from Mugara cinder cone located just N. Width is about 25 m and depth 10-15 m. Local steaming indicate that a dike of magma was near the surface and was involved in the formation of this feature.

8: Fracture-depression system in Monigi village. Notice that the center of the depression is bound by fractures and was downdropped by about 2 m.

9: Mud brick-house collapsed on the main fracture/normal fault in Monigi village. Notice the vertical downward displacement of about 0,5 m.

10: aerial view of part of the lava flow field south of Lemera hill and N of Mugara hill. Notice the system of parallel fractures that runs from north (bottom of photo) to south (top of photo) and which produced initially very fluid hot and thin pahohoe lava flows (< 1 m thick, grey color). Later eruptive vents higher up on the volcano produced much more

voluminous aa ropy less fluid black lava flows (1-3 m thick) that reached Goma. Fracturing occurred simultaneously with effusive activity and afterwards.

11: Detail of area in photo 11 showing relationships between the set of parallel fractures (extending over an area 200-300 m wide), grey fluid lava flows, and black less fluid aa-type lava flows.

12: Detail of the large pahoehoe and aa lava flows emitted from the western vent and which fed a large flow that reached Goma to the west but did not reach the lake. Here the two types of lavas were emitted simultaneously. Notice that the flows are thin not exceeding 2 m in thickness.

13: View of a small ash plume on jan 24 2002, at 9h07 local time, that reached 200-300 m above the Nyiragongo crater as we were flying over in a UN helicopter. The plume was probably formed by a collapse of the inner crater wall as the one that occurred in the night of 22-23 january and caused significant ash fall to the W-SW of the volcano and a trace of ash in Goma-Gisenyi. Such collapse are likely related and/or triggered by the strong post-eruptive seismicity.

14: Detail of the set of parallel fractures high on the S side of Shaheru adventive cone located on the S flanks of Nyiragongo volcano. The fractures emitted pahoehoe fluid lava, and show continuous post-eruptive degassing. Several 20-30 m deep explosion craters were formed on the fractures. The fracture system started on the morning of jan. 17, N of Shaheru on the Nyiragongo cone and propagated southward.

15: Smoked drum seismogram from the MEQ-800 portable station (IPGP) installed at the Hotel Masque in Goma, DRC, detail of 12 hour recording period that started on jan. 28 6h52 GMT. 10 days after the end of the eruption, seismicity is characterized here by a period of continuous low amplitude volcanic tremor (bottom of record) as well as by scattered high-frequency earthquakes.

FIGURE 3 - Assorted photos of the activity (photos by JC Komorowski, IPGP). In: Allard, Baxter, Halbwachs, and Komorowski (2002), *The January 2002 eruption of Nyiragongo volcano (DRC) and related hazards: observations and recommendations* - Final report of the French-British scientific team, 23 pp + figures



FIGURE 4 - Assorted photos of the activity (photos by JC Komorowski, IPGP). In: Allard, Baxter, Halbwachs, and Komorowski (2002), *The January 2002 eruption of Nyiragon-go volcano (DRC) and related hazards: observations and recommendations - Final report of the French-British scientific team*, 23 pp + figures

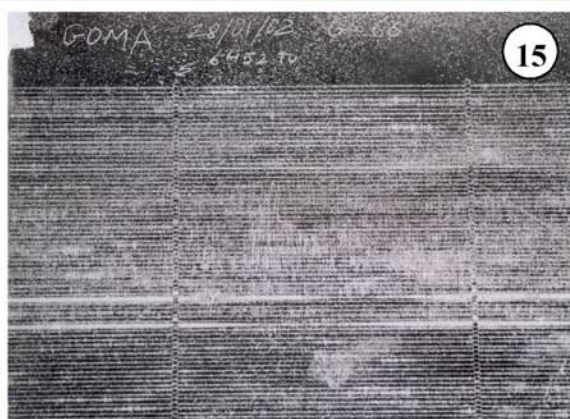
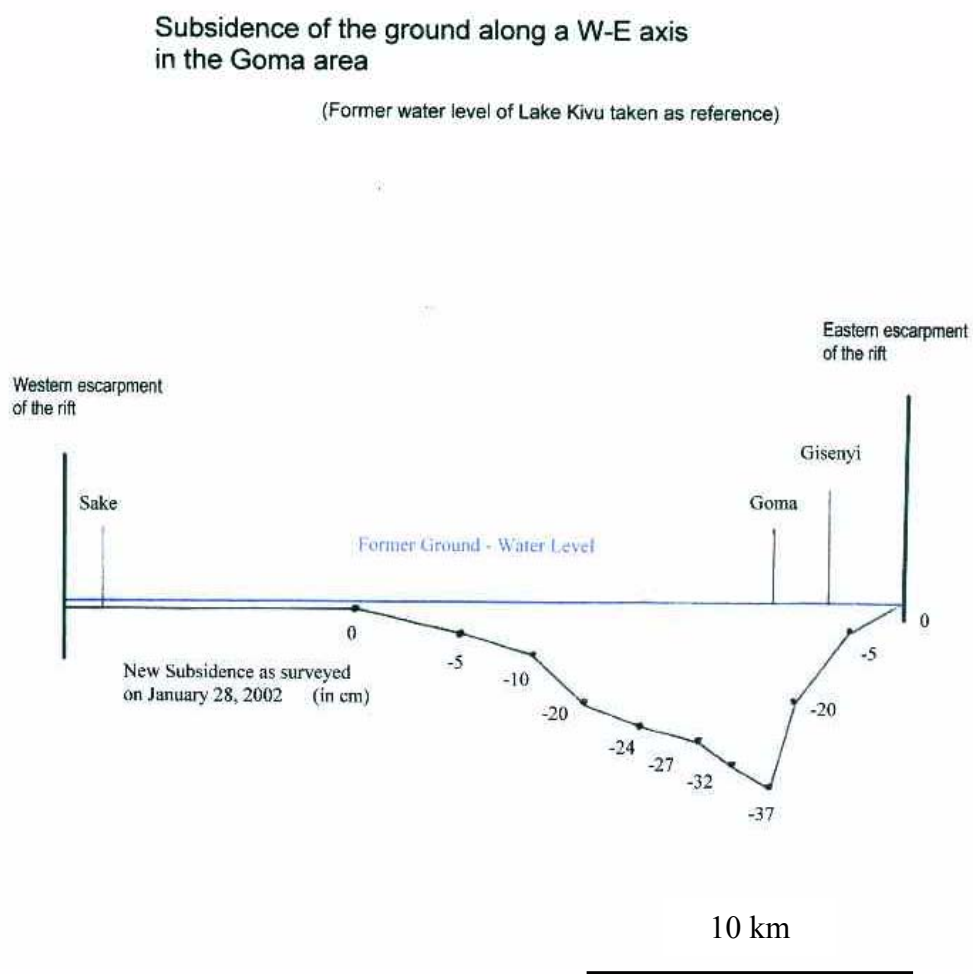


Figure 5: First E-W profiling of ground subsidence along the northern shore of Lake Kivu, 28 January 2002 (D. Garcin, UN-OCHA)



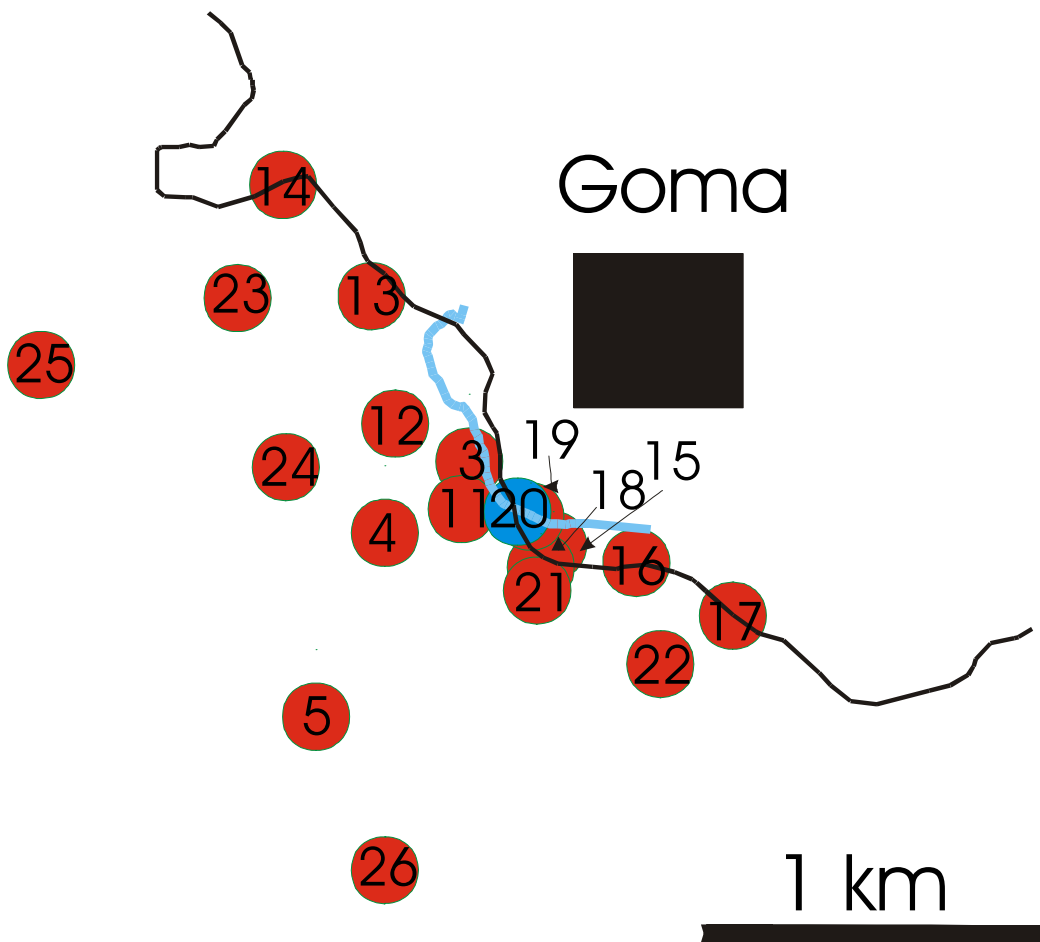


Figure 6: Detailed map showing the area around the lava inflow. CDT and water sampling stations as well as the GPS based mapping of the new shoreline created by the lava (Halbwachs et al., March 2002)

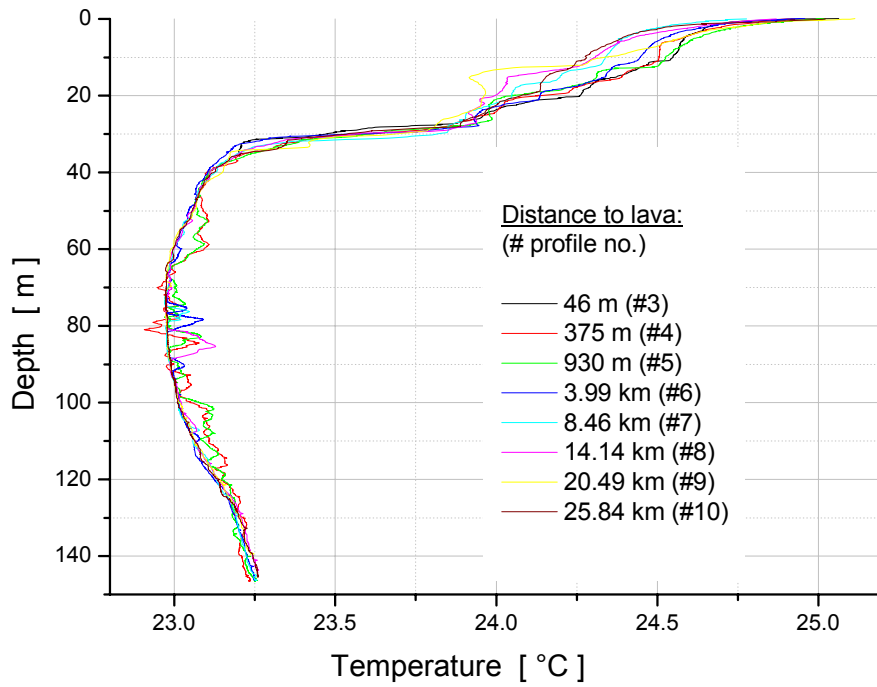


Figure 7: Temperature profiles along the measured transect between the lava inflow and Idjwi Island (Halbwachs et al., March 2002)

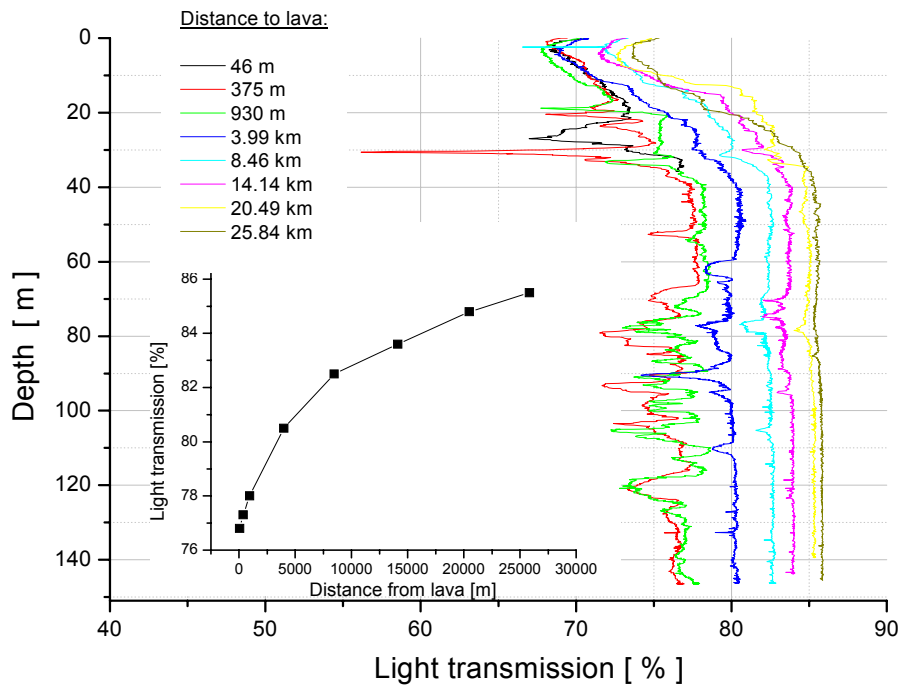


Figure 8: Light transmission profiles measured along the transect. The inset shows the bulk light transmission as a function of the distance from the lava (Halbwachs et al., March 2002)

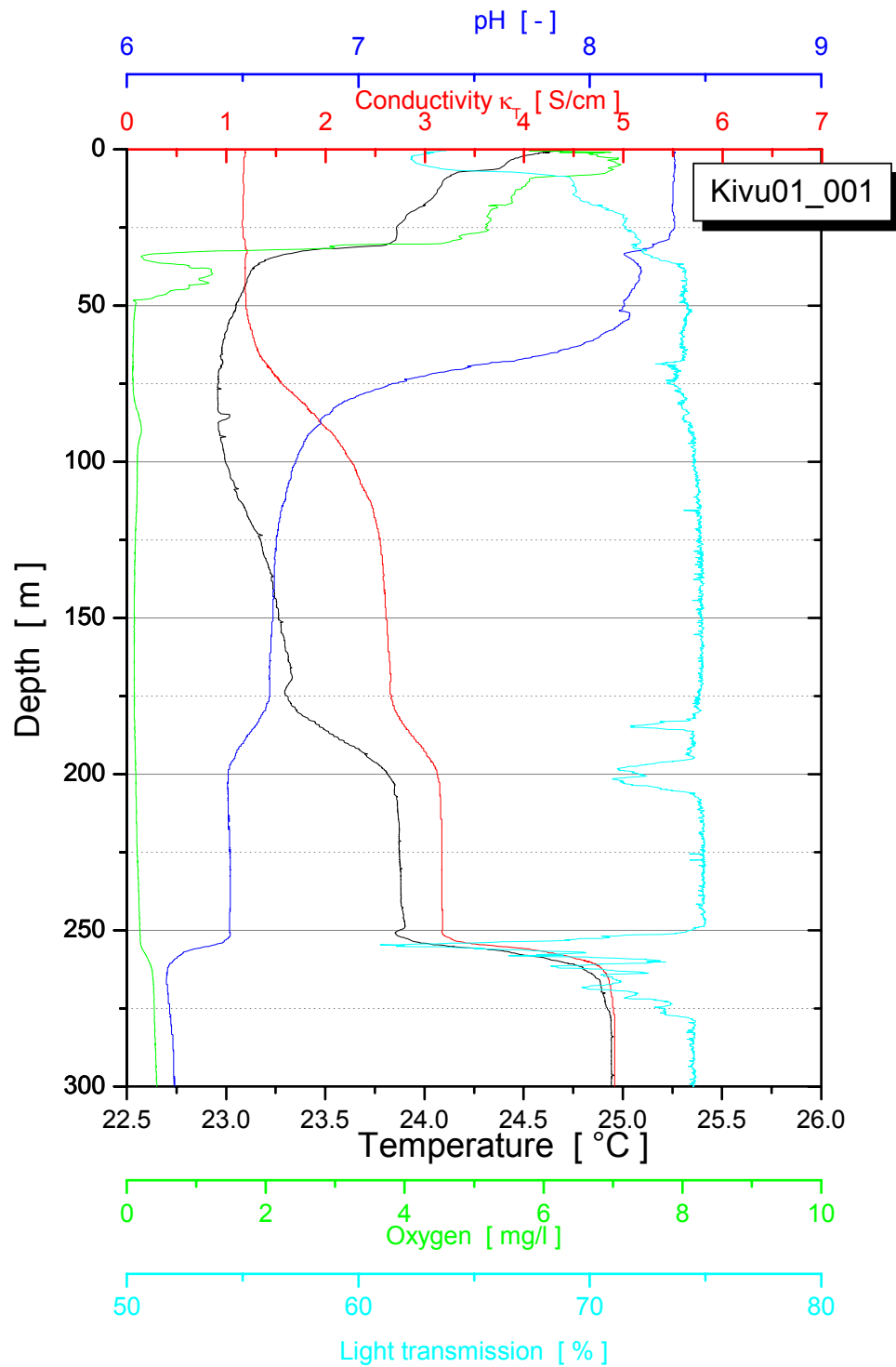
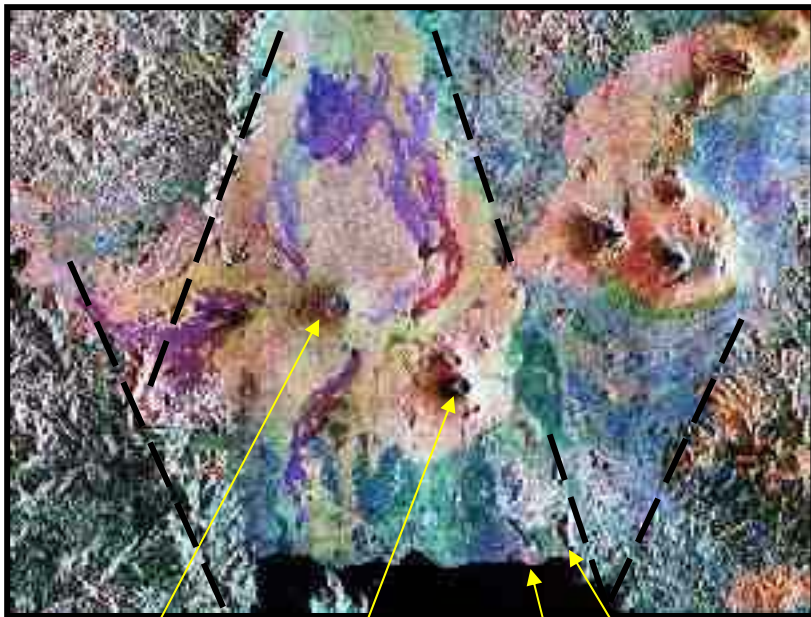


Figure 9: Vertical profile of temperature, conductivity, oxygen concentration, light transmission and pH measured in the main basin down to 465 m depth (Halbwachs et al., March 2002)



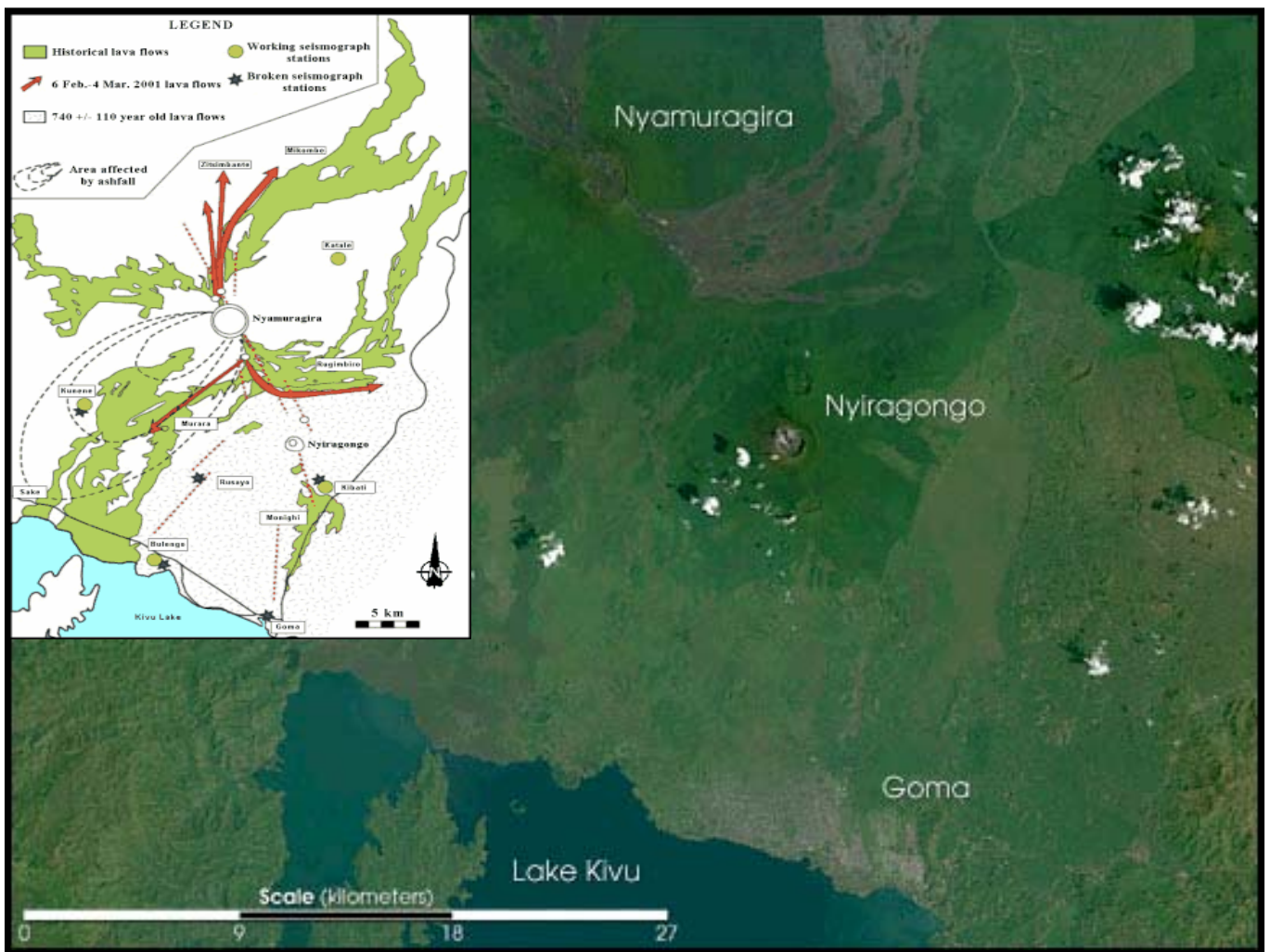
Picture 1:
North-south satellite image of the Virunga volcanic chain (Dem. Repub. of Congo and Rwanda). Nyiragongo strato-volcanic cone, with its 1x1.5 km wide summit crater (3470 m a.s.l.), is seen to the south. Nyamuragira volcano, with its 2x2.5 km wide summit caldera, lies 15 km northwest of Nyiragongo. It is one most active volcano in East Africa. Its more recent lava flows are seen in violet. The western and eastern bordering faults of the rift are clearly visible (broken lines). Goma and Gisenyi cities are located on the shore of lake Kivu.



Picture 2:
SPOT image of Nyiragongo volcano, with its two satellite craters (Baruta to the north and Shaheru to the south). The Jan. 1977 lava flows are indicated by yellow arrows.



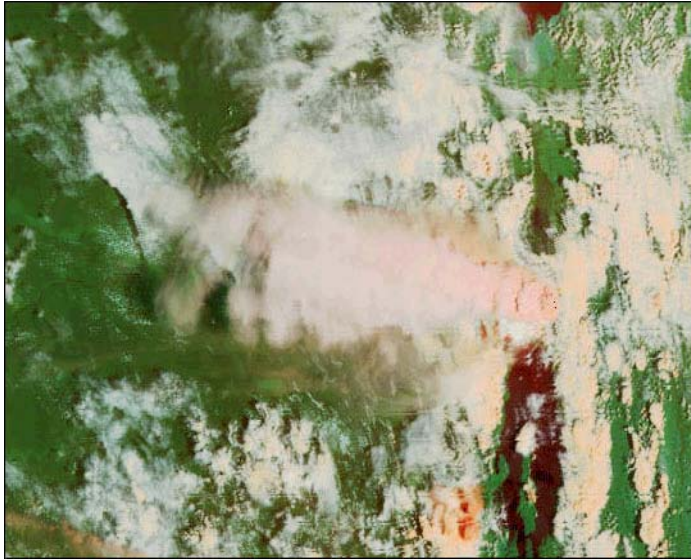
Picture 3:
View of Nyiragongo summit crater and its active lava lake in July 1994 (photo: J. Lockwood, USGS).



Picture 4: Landsat image of Nyiragongo in December 2001, one month prior to its Jan. 2002 eruption, and lava flows erupted from Nyamuragira in February-March 2001 (insert).

This true-color scene was captured by the Enhanced Thematic Mapper Plus (ETM+), flying aboard the Landsat 7 satellite, on December 11, 2001, just over a month before the most recent eruption. Nyiragongo's large crater is clearly visible in the image. (Image by Robert Simmon, based on data supplied by the NASA GSFC)

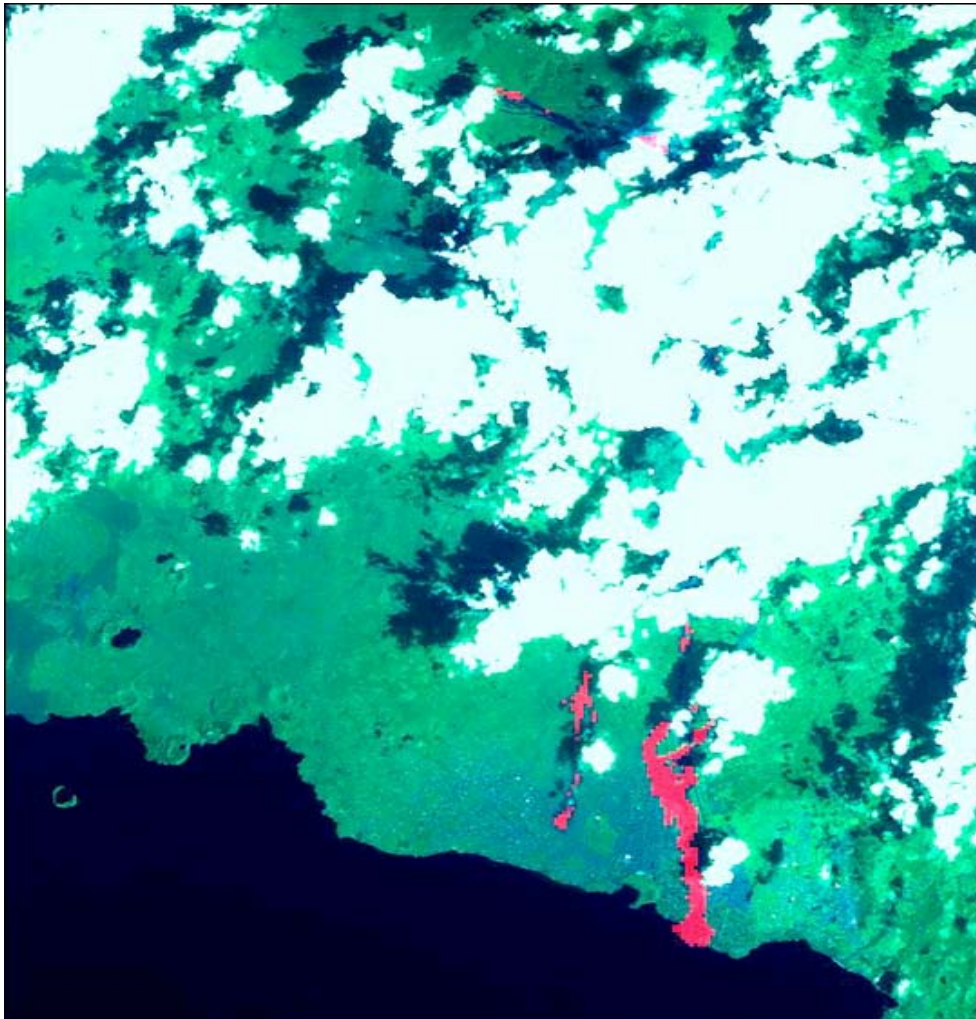
Insert: map of historical lava flows at Nyamuragira and Nyiragongo. Nyamuragira lava flows from 6 February to 4 March 2001 are indicated by red arrows. Also indicated are the 1977 lava flows from Nyiragongo. For a more detailed map of historical lava flows and their ages, see GVN Bulletin v. 19, no. 6. (Courtesy of the Goma Volcanological Observatory)



Picture 5: Eruptive cloud of Nyiragongo on January 17, 2002.

The volcano is ejecting a large cloud of smoke and ash high into the sky and spewing lava down three sides of the volcano. This false-color image was acquired today (January 17) by the Moderate-resolution Imaging Spectroradiometer (MODIS) roughly 5 hours after the eruption began. Notice Mount Nyiragongo's large plume (bright white) can be seen streaming westward in this scene. The plume appears to be higher than the immediately adjacent clouds and so it is colder in temperature, making it easy for MODIS to distinguish the volcanic plume from the clouds by using image bands sensitive to thermal radiation.

(Image courtesy Jacques Descloitres, MODIS Land Rapid Response Team at NASA GSFC).

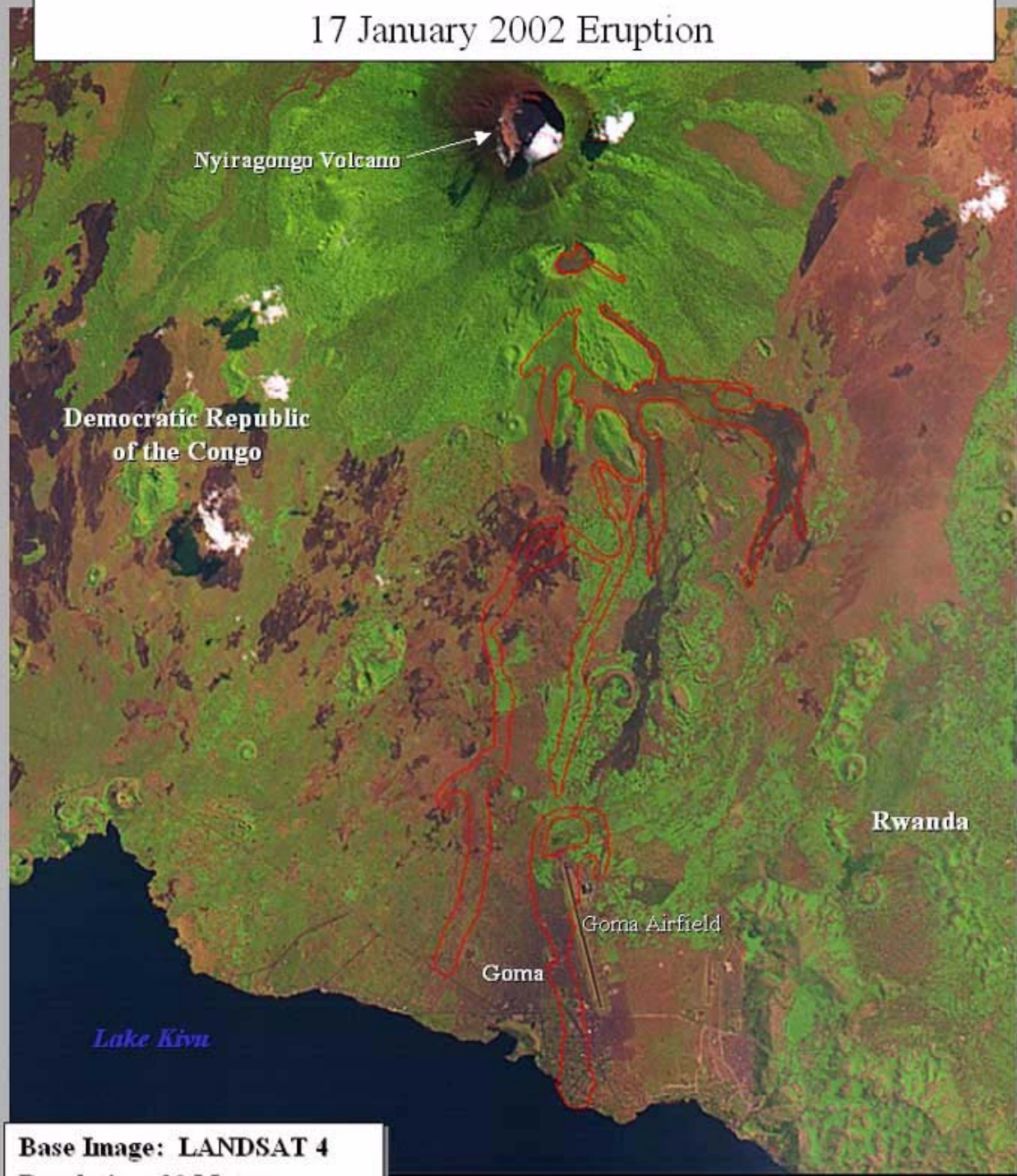


Picture 6: Space-borne ASTER detection of Nyiragongo lava flows on NW and S flanks on January 28, 2002.

This scene was acquired on January 28, 2002, by the Advanced Spaceborne Thermal Emission and Reflection Radiometer, flying aboard NASA's Terra satellite. In this scene, the Nyiragongo volcano itself is covered by clouds, but Goma is visible to the south, situated on the northern shore of Lake Kivu. The bright red ribbons radiating away from the volcano are the still hot lava flows outpoured on the NW (top) and south flanks (down) of the volcano. This false-color image covers an area of 21 by 24 km, and combines a thermal band in red, and two infrared bands in green and blue. (Image by Mike Abrams, NASA/GSFC/MITI/ERSDAC/JAROS, and U.S./Japan ASTER Science Team).

Nyiragongo Volcano Lava Flow Assessment Democratic Republic of the Congo

17 January 2002 Eruption



Base Image: LANDSAT 4
Resolution: 30 Meters
Date: 04 August 1989
Bands: 5 4 3

— Estimated extent of lava flows

Picture 7: Assessment of January 17, 2002 lava flows from Nyiragongo
Source : Government of the United States of America, WebRelief 17/01/02

Picture 9: Photo of the submersible ("speleonaute") used to investigate the extent and impact of Januray 2002 Nyiragongo lavas flowed into Lake Kivu (M. Halbwachs, Feb. 2002)

