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January 2002 volcano-tectonic eruption of Nyiragongo volcano, Democratic Republic of Congo

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[1] In January 2002, Nyiragongo volcano erupted 14–34 × 10^6 m^3 of lava from fractures on its southern flanks. The nearby city of Goma was inundated by two lava flows, which caused substantial socioeconomic disruption and forced the mass exodus of the population, leaving nearly 120,000 people homeless. Field observations showed marked differences between the lava erupted from the northern portion of the fracture system and that later erupted from the southern part. These observations are confirmed by new ^{238}U and ^{232}Th series radioactive disequilibria data, which show the presence of three different phases during the eruption. The lavas first erupted (T_1) were probably supplied by a residual magma batch from the lava lake activity during 1994–1995. These lavas were followed by a fresh batch erupted from fissure vents as well as later (May–June 2002) from the central crater (T_2). Both lava batches reached the surface via the volcano's central plumbing system, even though a separate flank reservoir may also have been involved in addition to the main reservoir. The final phase (T_3) is related to an independent magmatic reservoir located much closer (or even beneath) the city of Goma. Data from the January 2002 eruption, and for similar activity in January 1977, suggest that the eruptive style of the volcano is likely to change in the future, trending toward more common occurrence of flank eruptions. If so, this would pose a significant escalation of volcanic hazards facing Goma and environs, thus requiring the implementation of different volcano-monitoring strategies to better anticipate where and when future eruptions might take place.

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1. Introduction

[2] Since its discovery in 1894 [*Durieux*, 2002/2003, and references therein], Nyiragongo volcano is well known for its persistent lava lake activity that has fascinated scientists from all over the world. The volcano is also noted for its foiditic magma composition, which produces extremely fluid lava flows, capable of descending the crater flanks at speeds of up to 100 km h^{-1} [*Tazieff*, 1977; *Le Bas et al.*, 1986]. Such deadly lava flows occurred during the only documented historical eruption of Nyiragongo in 1977 [*Tazieff*, 1977]. Despite the interest scientists have shown in this volcano, very little is still known about its flank or peripheral activity, probably because of the remote location and of the lack of security due to the sociopolitical situation [*Smithsonian National Museum of Natural History*, 1991].

[3] The city of Goma, located ~15 km south of Nyiragongo, was only a small town with 50,000 inhabitants when the 1977 eruption occurred. Following several humanitarian disasters, the Rwandan genocide in 1994 [*Tedesco*, 1995, 2002/2003], and the subsequent civil war that is still ravaging the country (1996 to present), Goma has expanded to the north toward the volcano, with a major influx of people from the very insecure surrounding countryside. Currently, the population of Goma is 500,000. With Nyiragongo volcano located only 15 km from the city, it is impossible to ignore the multiple volcanic hazards that the inhabitants of Goma are now facing. For this reason, we believe it is crucial to study, in great detail, the most recent eruption that occurred on 17 January 2002. It is important to understand whether the flank fracture system, opened in 1977 and further developed during the 2002 eruption up

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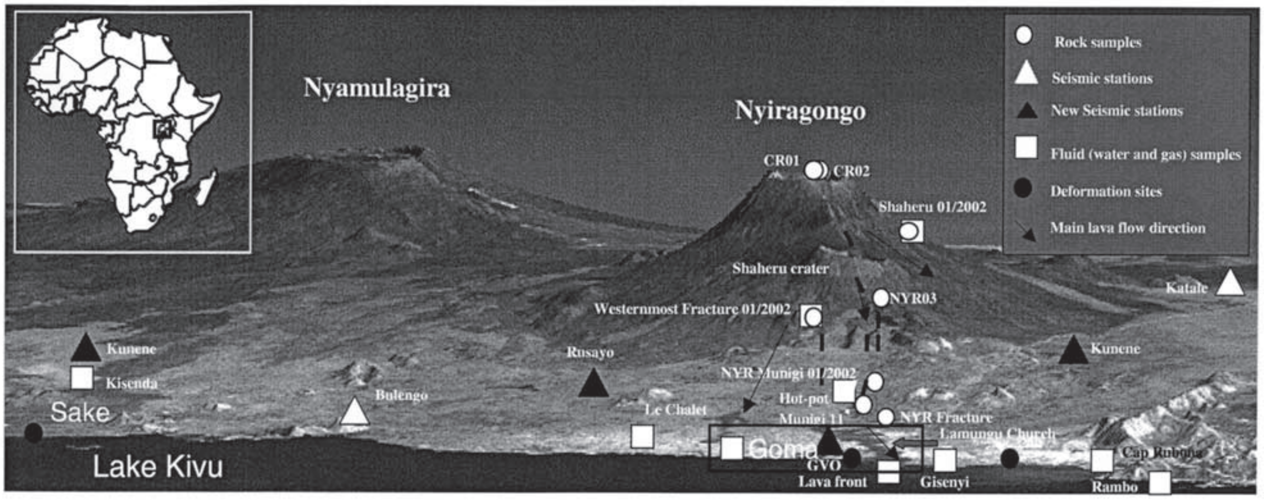

Figure 1a. White circles show rock and white dots show water and gas sampling locations. White triangles show the two seismic stations operating in January 2002 Nyiragongo eruption. Black triangles indicate the new digital seismic network of the Goma Volcano Observatory (GVO) operated in cooperation with the Italian Institute of Geophysics and Volcanology (INGV). Black solid circles indicate deformation measurement sites.

to the outskirts of Goma, may eventually penetrate the city itself. It is also important to better understand the actual plumbing system below Nyiragongo and to determine if the many peripheral cones existing around the volcano, extending up to and within Lake Kivu (the Goma Volcano Observatory (GVO) is built on one of these peripheral cones, Mount Goma, Figures 1a and 1b), represent products of a previous eruptive style, possibly a past eruptive cycle of the volcano, or are still a viable eruptive style for future activity of the volcano. Because of the current activity of the rift and the geological field constraints, Goma and the several villages located at the foot of the volcano are all at risk of future Nyiragongo lava flows.

[4] Our aim here is to document what happened before, during and after the very peculiar 2002 eruption of Nyiragongo, using data collected during field work, by the GVO and visual observations of Nyiragongo's crater. We also show how the activity of the volcano evolved chronologically, using a combination of data collected by the GVO and eyewitness accounts provided by local people. Our objective is also to address our understanding how Nyiragongo volcano works, using different data sets, on a local scale and in the broader framework with respect to the activity of the East African Rift system.

[5] Because of the difficult human and social situation in North Kivu particularly in Goma, and also because of the complications faced during our fieldwork after the eruption, not all the data we planned to gather were obtained. Despite these challenges, the experience we gained, the data collected and local witnesses' stories allowed us to start understanding what happened in the weeks and days that preceded the eruption, and also contributed to monitoring and forecasting the activity of the volcano. The available data also permit us to develop

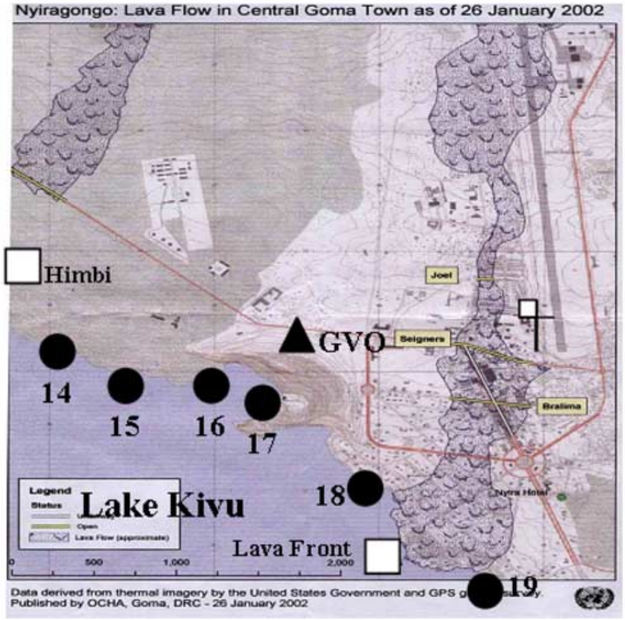

Figure 1b. Map of the two lava flows that invaded and devastated the city of Goma, the eastern one reaching Lake Kivu and the second one at the only existing east-west road axe joining Goma to Sake on the west. For few days, Goma was divided into two parts, Goma east and Goma west. Some days after the eruptions, although the lava was still hot, three different accesses, Seigners, Bralima and Joel, were opened again by the German International Organization GTZ to allow people to rejoin their families and restart life and business. Symbols are the same as in Figure 1a. Deformation measurement sites are as in Figure 4.

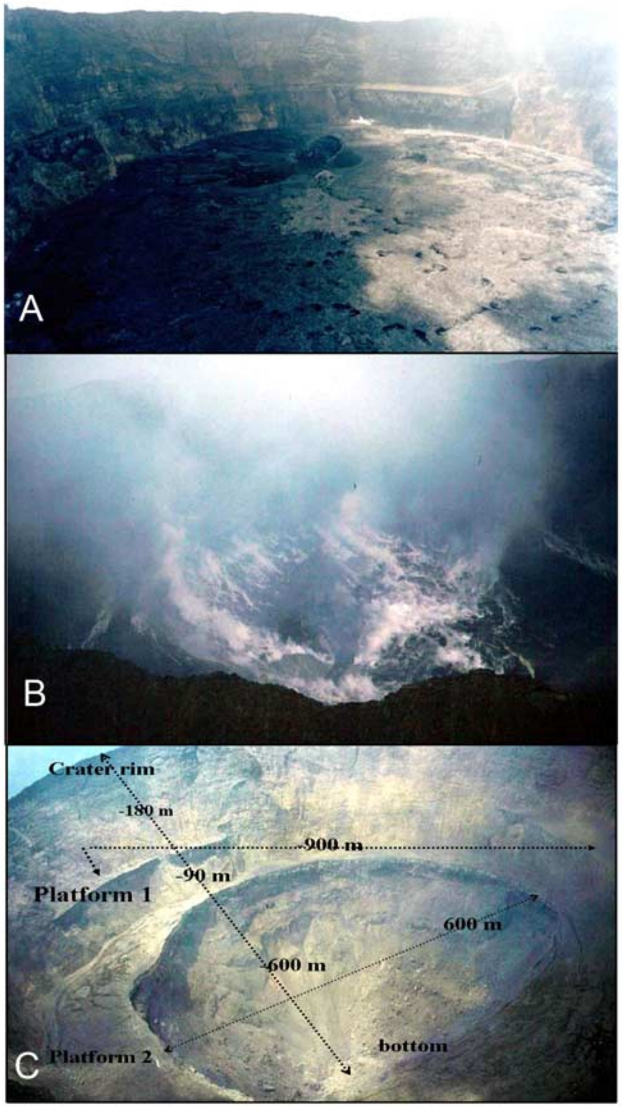

Figure 2. (a) Platform 2 inside the Nyiragongo crater on 5 August 1995 (photo DT). The crater floor was about 270 m below the crater rim. The lava lake activity stopped after just 1 year of activity. (b) Presence of fumarolic activity from annular fractures within the crater before the collapse of the crater floor that occurred on the night of 22 January, 5 days after the 2002 eruption, taken from the helicopter on 21 January 2002. (c) New crater morphology in February 2002 after crater floor collapse. Dimensions are indicated.

a model of how the future activity at Nyiragongo volcano may evolve.

2. The 2002 Eruption of Nyiragongo

2.1. Precursory Signals

[6] The five-station seismic network maintained by the GVO was vandalized during a civil war lasting from 1996 to present. Only two of the original five seismic stations survived (Figure 1a). Beginning in December 2000, volcanic tremor was recorded. On 6 February 2001, Nyamulagira volcano, located about 15 km NW of Nyiragongo, erupted. Following the Nyamulagura eruption, seismic activity, volcanic tremor and long-period earthquakes continued to be recorded by the two surviving stations (Bulengo and Katale; Figure 1a, operational since 1994). The recorded activity was considered by GVO as an indication of high fluid and/or lava pressure within the system [*Global Volcanism Network Bulletin*, 2001]. However, using data from only two seismic stations did not allow understanding of whether the activity was related to Nyamulagira or to Nyiragongo.

[7] On 7 October 2001, an earthquake of magnitude 3.5–4.0, located in the Nyiragongo area, followed by high-amplitude volcanic tremor, was recorded by the seismic network and strongly felt by the local population. During two visits to Nyiragongo in late 2001 (29 October to 1 November and 8–10 December), GVO researchers witnessed several changes/anomalies: (1) a small, dark ash plume was emitted from the small 1995 spatter cone within the crater (Figure 2a); (2) emissions of water vapor from the 1977 eruptive fracture, located above the Shaheru crater (Figure 1a) 2 km south of the summit crater at 2700 m above sea level (asl), and (3) similar water vapor emissions from concentric cracks on the floor of the 1995 lava lake in the central crater of Nyiragongo (Figure 2b). Variations in ground temperatures, typically 5–9°C, up to 28°C were recorded, and anomalous temperatures of ~50°C were measured in cracks upslope of the Shaheru crater.

[8] On 4 January 2002, a seismic event, with characteristics similar to that of 7 October 2001, occurred. Witnesses from villages on the eastern flank of Nyiragongo volcano reported that the earthquake was accompanied by emissions of a dark plume and by rumbling sounds from the central part of Nyiragongo. Volcanic tremor remained at a high level until 16 January 2002 but the eruption itself was preceded by almost 8 hours of perfect calm without tremors or long-period earthquakes. On 16 January 2002, a few hours before the eruption commenced, a strong smell of sulphur was reported ~1000 feet above the volcano by the pilot of a TMK local airline flying north of Nyiragongo (T. Hoaru, personal communication, 2002).

2.2. Chronology of the Eruption

[9] The eruption started at 0825 local time (LT) (0625 UT) on 17 January 2002 with the reopening of the 1977 eruptive fracture system [*Tazieff*, 1977]. The eruptive fracture started at an altitude of 2800 m, between the central cone of Nyiragongo and the Shaheru crater (Figure 1a).

[10] The drainage of still-molten lava stored in the summit crater after the 1995 lava lake activity opened the eruptive sequence. The presence of lava "nests" chilled in tree branches at a height up to 5 m, located up to 30 m from the eruptive fracture above Shaheru, suggests a lava fountaining activity during the initial phase. Very fluid lava flows ran across the forested SE flanks of Nyiragongo and rapidly cut the road north from Goma to Rutshuru. The low viscosity of the lava is inferred from the ≤1.5 m highstand marks left by the lava flow on trees, compared with the thickness of the solidified flow, which is only 5–15 cm.

[11] Within the next hours the fracture system and associated eruptive activity 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 1a) and then extended downslope forming a series of grabens (~5–10 m wide) across banana fields, villages, and older peripheral volcanic structures. Between 1000 and 1100 LT, lava flows erupted from a series of vents at an elevation between ~2300 and 1800 m, devastating several villages. Between 1400 and 1620 LT the propagation of magma along a dike radial to the volcano continued simultaneously with the southward propagation of fractures toward Goma, down to 1580 m asl, forming a line of spatter cones SE of Munigi village and only 1.5 km NE of Goma airport. These vents produced intense lava fountains and a voluminous lava flow that ran through the airport and central Goma and finally reached Lake Kivu late in the evening.

[12] Another eruptive fissure opened at 1530 LT at a higher elevation (2250–2000) about 1.5 km west of the main fracture system (2 km west of Kibati; see Figure 1a). Eyewitnesses reported that this fissure initially produced passive effusive activity feeding pahoehoe lava flows. However, the presence of a scoria deposit around the northernmost portion of the vent indicates that the activity did include a phase of lava fountaining that eventually produced a line of hornitos and spatter cones. Effusive activity then resumed to produce aa-type lava flows, 1–2 m thick, that flowed down the southern flanks of the volcano and formed the second main flow that reached western Goma, stopping on the main Goma-Sake road (Figure 1b).

[13] The death toll during the eruption was reportedly 170, and as many as 350,000 people fled the advancing lava, mainly eastward to nearby Rwanda. Lava emission appears to have stopped during the night of 17 January 2002, hence the eruption lasted $\leq$12 hours. However, molten lava continued to flow toward (and then into) Lake Kivu for a few more days. This lava created a delta approximately 800 m wide and 120 m long (Figure 1b) which, according to submersible investigations [*Halbwachs et al.*, 2002], extended into the lake up to a depth of 60 m. Lava flows destroyed one third of the airport runway, Goma's main business and commercial center, and the homes of ~120,000 people. Between 60 and 100 people died on 21 January as a result of an explosion at a gas station surrounded by hot lava and about 470 were reported injured with burns, fractures and/or gas intoxication.

2.3. Sulfur Dioxide Emissions

[14] Nyamulagira is well known for degassing significant quantities of sulfur dioxide (SO_2) during its frequent effusive eruptions, but prior to the January 2002 eruption, there had been very few quantitative observations of gas emissions from Nyiragongo. Emissions during each of Nyamulagira's 14 eruptions since 1980 have been measured by the NASA Total Ozone Mapping Spectrometer (TOMS) instruments [*Carn et al.*, 2003; *Carn and Bluth*, 2003]. Phases of elevated degassing have occurred in the past at Nyiragongo, most notably in the 1970s [e.g., *Le Guern*, 1987; *Carn*, 2002/2003], but the most vigorous episodes preceded the launch of the first TOMS mission in late 1978. Any subsequent degassing (e.g., during reactivation of the lava lake in 1994) did not produce SO_2 concentrations large enough to be measured by TOMS, and the first ground-based or airborne measurements of SO_2 emissions from Nyiragongo were not attempted until 2004.

[15] SO_2 emissions during the 17 January 2002 eruption were measured from space by the TOMS instrument on the Earth Probe (EP) satellite [*Carn*, 2002/2003]. A cloud containing ~9 ± 3 kilotons (kt) of SO_2 was detected extending WNW from Nyiragongo at 1108 LT on 17 January. Infrared (IR) cloud top temperatures derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra satellite indicate that the eruption cloud rose close to the tropopause (~14–17 km), though SO_2 had dispersed to below EP TOMS detection limits by the following day. The eruption, and most likely the SO_2 emissions, continued after the EP TOMS over passed, and extrapolation yields an estimated total SO_2 discharge during the eruption of 15–31 kt. Interpretation of several satellite data sets in conjunction with the eruption chronology indicates that the eruption plume emerged ~25–45 min after the onset of flank lava flows, which argues against significant preeruptive volatile overpressure and supports a regional tectonic trigger for the eruption [*Carn*, 2002/2003]. Inferred SO_2 emission rates during the first ~2 hours of the 17 January 2002 eruption (~850–1700 kg s^{-1}) are significantly lower than peak rates measured during recent eruptions of Nyamulagira (as high as ~10,000 kg s^{-1}) [*Carn and Bluth*, 2003]. This is most probably a consequence of lower lava effusion rates at Nyiragongo and/or substantial preeruptive degassing of the erupted magma batch in Nyiragongo's long-lived summit lava lake, but could also be partly attributed to scrubbing of SO_2 in the eruption plume, co-emission of hydrogen sulfide (H_2S), and/or lower sulfur concentrations in Nyiragongo magmas.

3. Posteruptive Events

3.1. Seismicity

[16] Arguably the most important feature of the January 2002 eruption is the intense, and unusual, seismic activity recorded mainly after the effusive activity. About 100 tectonic earthquakes (M > 3.5) located between Goma (the lake shore) and Nyiragongo were recorded during the 5 days following the eruption. The strongest earthquake (magnitude 5) struck at 0014 (UT) on 20 January 2002 [*Tedesco et al.*, 2002]. The seismicity was locally recorded by two GVO seismic stations (Bulengo and Katale, Figure 1a), complemented after 24 January 2002 by one additional seismometer brought from France [*Komorowski et al.*, 2002/2003]. This seismic activity impacted Goma and Gisenyi but was also clearly felt as far away as Bukavu (60 km south in DRC), Kigali (Rwanda, 120 km east) and Kampala (Uganda, 150 km NE). The number of earthquakes gradually declined with time but remained at abnormally high levels [*Tedesco et al.*, 2002].

[17] The seismic network in operation during the eruption and until 30 January 2002 allowed neither an accurate assessment of the location nor the depth of earthquakes. However, the small difference in the arrival times of P and S waves indicated epicenters close to seismic stations. Seismic events showed a significant range of magnitude, frequency contents, and S-P times, suggesting several different origins. Seismic signals showed a typical sequence of tectonic events followed within minutes to hours by long-period events and volcanic tremor often lasting more than 10 hours (Figure 3). Such a sequence, which is similar to

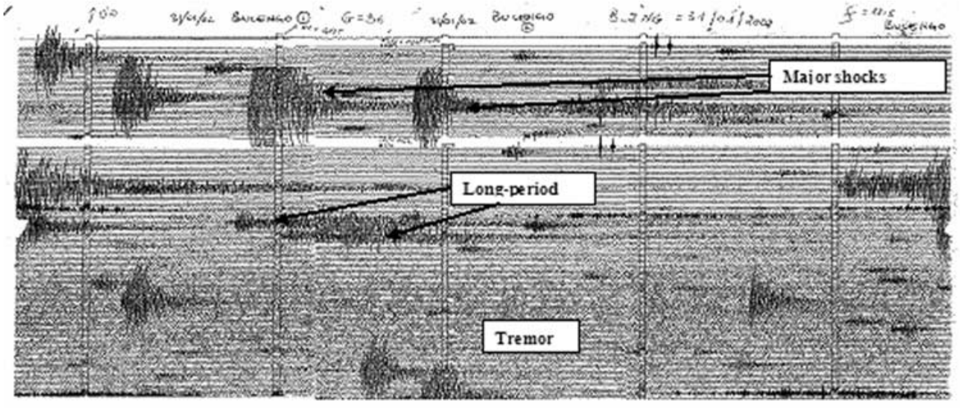

Figure 3. Typical seismogram a week after the eruption (31 January 2002). Three types of earthquake are visible: major tectonic shocks, long-period quakes, and volcanic tremor.

that recorded during the year preceding the eruption, suggests fracturing of rocks followed by intrusion of fresh magma and movement of juvenile fluids.

[18] During the first days of February 2002, the estimated location of epicenters seemed to cluster in two different areas. One cluster was located along the system of N-S fractures running between the crater and Lake Kivu, and the second was located near the town of Sake (Figure 1a), close to the western border of the rift [*Tedesco et al.*, 2002].

3.2. Crater Collapse and Explosive Activity

[19] The solidified lava lake surface inside Nyiragongo's summit crater, lying 280 m below the rim since 1995 [*Tedesco*, 1995, 2002/2003], was still present on 21 January 2002, 3 days after the eruption, although it was cut by a series of annular rings of fumaroles (Figure 2b). The crater collapsed during the night of 22–23 January 2002. A detailed report by eyewitnesses in Rusayo (8 km SW of the summit) suggests that collapse started at about 2051 LT on 22 January, in connection with a series of felt earthquakes. It was accompanied and followed by roaring sounds and flames above the crater and, soon after, by emission of ashes, which fell over Rusayo and the southern flank of Nyiragongo. Intense and continuous seismic tremor over the next 4 hours suggested a postcollapse episode of phreatomagmatic explosive activity (which most likely involved only magmatic gases as the juvenile component) and ash emissions. Light ash falls also occurred over the Goma-Sake road during the same night and, in the following morning, in Goma. On 24 January, during a helicopter survey, an ash deposit was observed to mantle the forested SW flank of the volcano. Meanwhile, an assessment of the extent of collapse in the summit crater (Figure 2c) was also carried out. The depth of the inner crater had increased from 280 m before the eruption to ~900 m, with an inverted cone geometry (Figure 2c). Sporadic explosive activity occurred after the main collapse. A dense cloud rose above the volcano at 0910 LT on 24 January 2002 shortly after a helicopter overflight. On 27 January 2002, fresh impacts and complete destruction of trees were observed in the forest on the upper northern flank of the volcano.

3.3. Gas and Fluid Emanations

[20] Noticeable hydrocarbon odors occurred days after the eruption in several parts of Goma. Measurements with a portable IR spectrometer and with more precise preevacuated flasks, later analyzed in the laboratory, revealed that these odors were accompanied by CH_4 and CO_2 (both odorless) in areas up to 800 m from lava flows [*Tedesco et al.*, 2002; *Allard et al.*, 2002; *Vaselli et al.*, 2002/2003]. The emanations therefore had no clear or direct relationship with organic matter burned or heated by the flows. In several cases, orange-blue flames were witnessed directly on or beside the lava flows. Methane concentrations of a few per cent and sometimes approaching the 5% flammability threshold in air were found both in open air (discharged through pavements, in gardens and close to the airport runway) and indoor sites (garages, hotels) [*Tedesco et al.*, 2002; *Allard et al.*, 2002]. In some cases, the gas discharge occurred very violently with gas explosions, destroying concrete pavements several centimeters thick. The threat posed by toxic gas emissions has been subsequently highlighted by the discovery of a long fissure under the Kanisa LaMungu church in central Goma [*Tedesco et al.*, 2002]. Carbon dioxide emissions from church floor cracks were strong enough to cause two cleaning ladies to faint. The church was subsequently sealed off.

[21] It is noteworthy that most of the CO_2 emissions and gas bursts occurred in areas that are broadly aligned with the N-S fracture system cutting the volcano (Figure 1a) and where surface gas emanations often persisted. The strong odor of hydrocarbons associated with the explosions, and the elevated concentration of methane measured at several burst sites, strongly suggest a methane-driven origin. Subsurface methane concentrations must have been locally high enough to trigger spontaneous ignition of the methane-containing gas mixture. Because most of the investigated explosions occurred far from lava flows, we can disregard derivation from the combustion of organic matter. Two possible sources can be hypothesized: (1) methane stored in Lake Kivu (see below) that could diffuse into a more fractured subsurface medium related to concurrent tectonic and volcanic activity or, more likely, (2) deeper methane-

Table 1. Chemical Composition of Gas Samples Collected in January 2007 From Fumaroles, Lake Kivu Bubbling, CO_2-Rich Gas Emissions (Mazuku) and Methane Power Plant Near Gyiseni

Name	Sampling Day January 2002	Type	CO_2, %	H_2S, %	N_2, %	CH_4, %	H_2, %	Ne, %	He, %	O_2, %	Ar, %	CO, ppm
Fracture	26	weak fumarole	20.88	0	62.20	0.00660	0.22	0.001320	0.000300	15.84	0.74	0
West fracture	26	weak fumarole	7.42	0	72.67	0.00012	0.00	0.001560	0.000400	18.93	0.86	0
Hot pot	26	weak fumarole	65.73	0	31.53	0.00032	0.01	0.000242	0.000578	2.42	0.31	0
Lava front	26	lake bubbling	63.59	0	16.61	0.59670	14.50	0.000445	0.000447	4.45	0.24	77.6966
Cap Rubona	27	methane plant	81.79	0.04	0.50	17.45384	0.00	0.003426	0.018032	0.004	0.002	0
Himbi	27	Mazuku	44.35	0	42.35	0.00011	0.00	0.000910	0.000720	12.71	0.47	0
Bulengo	27	Mazuku	37.33	0	50.20	0.00011	0.00	0.001110	0.000600	11.23	0.60	0
Nzulu	27	Mazuku	57.46	0	33.95	0.00009	0.00	0.000780	0.001940	8.10	0.40	0

rich gas pockets, possibly of sedimentary/organic origin, stored in sediments filling the North Kivu rift. We suggest that such deep gas reservoirs, stored at low temperature but relatively high pressure in sediments underlying the volcanic layers, may be continuously degassed throughout the region along tectonically controlled fractures. This degassing might have been favored by the sudden development of the fracture system and continuous ground shaking after the eruptive event. In fact, local subsurface accumulation of methane to concentrations greater than 5 vol % may have triggered spontaneous explosions of methane-rich gas in contact with oxygen following major earthquakes. Otherwise, we emphasize that methane is only weakly abundant (0.1%) in persistent CO_2-rich emanations, locally named mazukus (“evil’s winds”) [*Vaselli et al.*, 2002/2003], that occur throughout the area on old, fractured lava flows.

[22] Interesting phenomena also occurred on the shore of Lake Kivu in the area of Himbi (Figures 1a and 1b). Local residents reported that during the night and early morning of 16–17 January 2002, crabs and crayfish acted abnormally by approaching the surface and trying to jump out of the lake. On 20–21 January, dead fish and bubbling spots were also observed in a small bay next to the Chalet Hotel. The temperature of the lake increased slightly and a brown-black discoloration covered an area of several square meters. Contemporaneously, a smell of rotten eggs (suggesting the presence of H_2S) was noticed. A similar phenomenon was witnessed by one of the authors early in the morning (at about 0230 LT) on 30 January after an M 4.5 earthquake. Again, local residents reported breathing difficulties and a strong smell of rotten eggs. In both cases, “normal” conditions were reestablished in a few hours. Soil-gas measurements made at the time of the 30 January event with Dräger tubes indicate CO_2 concentrations up to 20%.

[23] A geochemical survey was carried out in several lava-producing fractures and open cracks (Table 1), namely, (1) Shaheru Fracture, from where the very first batch of magma emerged, (2) Munigi, and (3) the western fracture (Figure 1a). Measurements revealed H_2O as the main component with variable contents of CO_2 (up to 20 vol %) and CH_4 (up to 0.007 vol %). These samples were strongly diluted by air contamination. Values of $\delta^{13}C$-CO_2 were as low as −8‰ (PDB), suggesting the presence of an organic component capable of diluting and masking the magmatic contribution after the eruption. The former was later displaced, with the $\delta^{13}C$-CO_2 value increasing to −3‰ in 2003 [*Vaselli et al.*, 2002/2003]. The presence of “baked” organic matter was also detected in Munigi at an incandescent “hot spot” with a temperature of 880°C, located a few tens of meters from the main lava flow. Here, CO_2 and CH_4 contents were 66 and 3.2 by vol % in dry gas, respectively, whereas the $\delta^{13}C$-CO_2 value was −20.8‰ (PDB-Pedee Belemnite Formation). Sublacustrine bubbling gases collected a few meters from the lava front within Lake Kivu were characterized by the presence of CO_2 (65 by vol %), H_2 (14.5 by vol %), CH_4 (0.6 by vol %) and a relatively small atmospheric component (N_2, O_2 and Ar) (Table 1). Sulphur species, extremely soluble, were dissolved within the lake and were not detected. The relative enrichment in H_2, together with other poorly soluble gases, implies that either (1) the gases were affected by scrubbing processes in the lake water as magmatic fluids were released from the lava or (2) the gases were juvenile, related to a possible vent near or even within the city of Goma. We consider it highly unlikely that such a fluid and gas-poor lava, after flowing for more than 10 km, would still degas mainly juvenile fluids with an extremely low atmospheric component. Although more detailed studies should be performed, these data allow us to hypothesize the presence of a “hidden” eruptive fracture (or direct feeding of juvenile gases) beneath the city of Goma, dangerously close to Lake Kivu.

[24] We also note that in the village of Sake, ~20 km west of Goma, a new mineral spring discharge (since disappeared; T = 19°C, pH = 6.74) seeped out in the center of the village on the day of the eruption (few hours earlier). Chemical features are similar to other local springs, i.e., with HCO_3 as the dominant anion: 775 mg L^{-1}, Cl and SO_4 concentrations of 14 and 50 mg/L, respectively, whereas concentrations of Na, K, Ca and Mg were less than 100 mg/L (86, 98, 62 and 63 mg/L, respectively). No free gas phase was observed.

[25] A similar feature occurred on the day of the January 1977 eruption, the only other known historical eruption of Nyiragongo, when a water spring appeared on the outskirts of Sake. Considering these unusual events, it seems possible that the fracture system is not only related to the narrow corridor extending from the volcano’s flank to Lake Kivu, traversing Goma. We believe that during eruptions, such as those in 1977 and 2002, the whole region (e.g., the rift), including areas distant from the volcano where new fractures are not visible, is dynamically involved. The week after the 2002 eruption, several tectonic earthquakes clustered in the Sake area (see section 3.1). The coincidence between the appearance of new springs and the historical eruptions, along with the posteruptive tectonic activity centered in this area, supports this hypothesis.

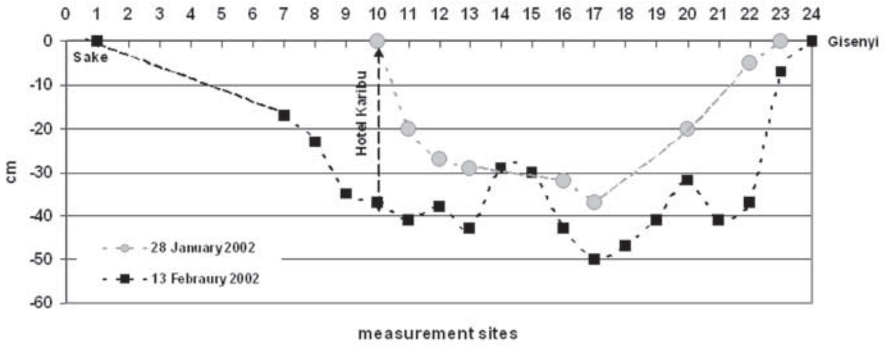

Figure 4. Vertical ground deformation as measured on the line between Gisenyi and Sake 1 week and 3 weeks after the eruption. Maximum deformation (sinking) has been recorded at the Goma Harbour (site 17).

3.4. Ground Subsidence

[26] Immediately following the 2002 eruption, fishermen reported visible variations of the water level in Lake Kivu. This finding was confirmed by women who daily go to the lake shore to collect drinking water and wash clothes. Following these observations a series of water level measurements was initiated in close cooperation with a UN field officer (D. Garcin). The first data were obtained on 28 January 2002, along the lake shoreline from Gisenyi to Sake. Results confirmed a significant subsidence of the ground and rise of the water level. The subsidence was greatest at Goma Harbour (37 cm), corresponding to the main axis of the fracture system, and diminished to the east and west (Figure 4). After these initial measurements, others were systematically taken along the Gisenyi-Goma-Sake axis, as well as around the lake up to tens of kilometers south of Goma, and on Idjwi Island, about 30 km south of Goma in the middle of Lake Kivu (data not included in this article). The measurements show that ground subsidence is an ongoing process affecting the entire rift area in the environs of Lake Kivu. One month after the 2002 eruption, the cumulative maximum measured ground subsidence was 70–80 cm at Goma Harbour and on Idjwi Island. It is important to note that data obtained by radar interferometry [*Poland and Zhang*, 2003] agree with the above field measurements. They show that the Goma area, and more broadly the whole area of the rift, subsided between 14 January and 13 February 2002, while only minor deformation was detected subsequently between February and August 2002.

4. Interpretation of Phenomena

4.1. Eruptive Features

[27] The characteristics of the erupted products and lava flows, together with the available information on the state of the volcano prior to the eruption, suggest different eruptive dynamics in the upper and lower portions of the fracture system. In the northern (Shaheru) portion, the eruptive activity appears to have been driven by drainage of the preexisting, probably partially solidified and mostly degassed lava lake inside the Nyiragongo crater (1994–1995 activity [*Tedesco*, 2002/2003]), as well as part of the upper conduit connecting the lava lake to the deep magma supply system (discussed in section 5). Conversely, we believe that the propagation of "new" gas-rich magma through fractures was the origin of the eruptive activity in the vicinity of Goma (Munigi area), in agreement with *Poland and Zhang* [2003].

[28] Accordingly, the reconstructed eruptive events and the associated eruptive products are different for the northern and southern portions of the fracture system. In the Shaheru area, at an altitude of 2700–2900 m asl, the eruptive style reflected the forcing of magma through fractures by the high hydrostatic load (estimated at ~7–14 MPa) exerted by the partially solidified magma column in Nyiragongo's crater and upper conduit. This initial phase resulted in the development of a wave of lava that was pushed several tens of meters above the vent. It was seen from a large distance by several witnesses. The presence of lava scoria in trees far from the lava flow is consistent with the above reconstruction. The general absence of scoria (apart from a limited amount during the last phases of the eruption) and the lack of spatter or scoria cones around the Shaheru fracture, supports the interpretation that the magma erupted from the fracture was largely degassed. Drainage of magma from the 1995 lava lake and upper conduit system would have destabilized the solidified lava lake surface, which then repeatedly collapsed beginning on the night of 22 January 2002.

[29] In contrast to the Shaheru area, in the southernmost portion of the fracture system (Munigi), and possibly also in the fracture ~1.5 km west of the main system, the eruption of gas-rich magma resulted in the construction of a chain of spatter and scoria cones (Figure 1a). Both the scoria and spatter are extremely inflated and glassy, and commonly display vesicles larger than 10 cm [*Tedesco et al.*, 2002]. In this area, the eruptive activity appears to have been dominated by gas-driven lava fountains with associated lava flows. Local witnesses confirm the occurrence of high lava fountains.

[30] In the northernmost portion of the fracture system the erupted magma appears to have been much less viscous than that in the Munigi region. Observations supporting this finding include (1) the thickness of the solidified lava flow, which is only 5–15 cm north of Shaheru compared to ~1.5 m for the active flows in the same area as reconstructed from the thin solidified lava layer surrounding trees (in the

Table 2. The ^{238}U and ^{232}Th Radioactive Series Data Activity Ratios[a]

Sample	^{228}Th/^{228}Ra[b]	^{226}Ra/^{228}Th[b]	^{228}Ra/^{226}Ra[b]	^{228}Th/^{232}Th[b]	^{230}Th/^{232}Th	^{228}Ra/^{232}Th[b]	^{226}Ra/^{230}Th	^{238}U/^{232}Th	^{226}Ra, dpm/g
Shaheru Jan 2002	1.06 ± 0.02	1.55 ± 0.06	0.68 ± 0.03	1.21 ± 0.06	0.99 ± 0.05	1.14 ± 0.06	1.89 ± 0.11	2.31 ± 0.09	6.65 ± 0.08
NYR 03 flow	1.16 ± 0.03	1.49 ± 0.05	0.58 ± 0.01	1.46 ± 0.05	1.40 ± 0.07	1.26 ± 0.07	1.34 ± 0.07	2.20 ± 0.09	9.36 ± 0.12
NYR scoriae CR 02 crater rim 29 Jul 2002	1.15 ± 0.02	1.14 ± 0.03	0.76 ± 0.04	1.51 ± 0.05	1.25 ± 0.05	1.35 ± 0.08	1.37 ± 0.07	2.81 ± 0.12	7.93 ± 0.11
NYR scoriae CR 01 crater rim 3 Aug 2002	1.25 ± 0.02	1.14 ± 0.03	0.70 ± 0.03	1.53 ± 0.05	1.25 ± 0.05	1.33 ± 0.07	1.39 ± 0.07	1.50 ± 0.06	6.46 ± 0.08
Munigi Jan 2002	1.01 ± 0.04	1.52 ± 0.03	0.65 ± 0.03	1.05 ± 0.04	1.26 ± 0.06	1.04 ± 0.06	1.27 ± 0.07	1.48 ± 0.06	6.91 ± 0.09
Westernmost fracture Jan 2002	1.00 ± 0.04	1.52 ± 0.03	0.66 ± 0.03	1.06 ± 0.04	1.24 ± 0.06	1.06 ± 0.06	1.30 ± 0.07	1.72 ± 0.08	5.04 ± 0.07
NYR 11 fracture	1.03 ± 0.02	1.56 ± 0.03	0.62 ± 0.02	1.08 ± 0.04	1.20 ± 0.06	1.05 ± 0.05	1.41 ± 0.07	2.12 ± 0.08	8.72 ± 0.10

[a] Errors are given at 2-sigma level. High-resolution γ spectrometry (^{226}Ra, ^{228}Th, ^{228}Ra) using coaxial and planar HPGe detectors, unspiked α spectrometry (^{228}Th, ^{230}Th, ^{232}Th) and isotope dilution α spectrometry (^{238}U, ^{230}Th) were crossed over to measure activity ratios on seven fresh lava samples. The analyses were carried out in the Laboratory of Radiochemistry of IGAG-CNR (Rome).

[b] Data corrected for the time span between eruption and analysis.

Munigi area, however, the thickness of the solidified lava flow (3–4 m, depending on morphology) is closely comparable with that of the active lava flows); (2) the development of a compound lava flow field in the Munigi area, with the overlapping of individual/composite lava flow units several tens of centimeters to tens of meters long, formation of lava flow levees, lava tunneling, and opening of ephemeral vents (these structural features are absent in the northern lava field, inside and around the Shaheru crater); (3) the high-velocity (order of tens of kilometers per hour) of the lava flows originating from the northernmost part of the fracture system, compared to the relatively low velocity (order of tens or hundreds of meters per hour) of the lava flows originating from the southernmost eruptive vents (the difference in slope between the upper and lower portions of the fracture system can only partly explain this order of magnitude difference in flow velocity); and (4) the lower destructive capability of the lava flows from the northernmost portions of the fracture system. In several cases these flows did not destroy trees but only enveloped them, leaving a 2–5 cm lava "tide mark." In comparison, the lava flows erupted in the Munigi area, as well as those erupted from the westernmost fracture system described above, were highly destructive, causing buildings to collapse, and devastated Goma.

4.2. Information From Short-Lived Isotopes

[31] Evidence of the existence of two different magmas and two different plumbing systems erupted during the 17 January 2002 eruption from different sites of the volcano, is given by U and Th series disequilibria studies.

[32] U and Th series disequilibria, measured on fresh lava samples, allow the timescales of magma transfer and evolution in the crust to be inferred [*Condomines et al.*, 2003]. In particular, radioactive pairs of short-lived members (^{226}Ra, ^{228}Th, ^{228}Ra) can give information about the occurrence of magmatic differentiation processes in the last 7 Ka (^{226}Ra/^{230}Th), 25 a (^{228}Ra/^{228}Th) and 8 a (^{228}Th/^{228}Ra) since the different geochemical behavior between radium and thorium is observed in a number of magmatic processes able to fractionate these radionuclides up to 2 orders of magnitude [*Voltaggio et al.*, 2004]. Theoretically, the use of radioactive disequilibria can be considered as a one-way test, since only "the presence" of radioactive disequilibria implies necessarily the occurrence of magmatic differentiation processes during the previously mentioned timescales.

[33] High-resolution γ spectrometry (^{226}Ra, ^{228}Th, ^{228}Ra, ^{238}U) and unspiked α spectrometry (^{228}Th, ^{230}Th, ^{232}Th) analyses were carried out on seven fresh lava samples. Details of analytical methods are given by *Voltaggio et al.* [1995]. Five samples belong to different locations of the 17 January 2002 eruption (Figure 1a and Table 2) and two are scoriae collected on the crater rim during two episodes of lava fountains in July and August 2002 when the eruptive activity resumed within the main crater.

[34] Three radioactive pairs, ^{226}Ra/^{230}Th, ^{228}Ra/^{232}Th, ^{228}Th/^{228}Ra, and two isotopic ratios, ^{230}Th/^{232}Th, ^{228}Ra/^{226}Ra allow us to constrain the magmatic system during the 2002 eruptive phases. The ^{226}Ra/^{230}Th ratios (1.27–1.89) are significantly higher than those measured by *Williams and Gill* [1992] for Holocene and 1977 lava flows (0.90–1.20) and also higher than those measured for 1972 and 1982 lava lake episodes (0.94–1.00 [*Turekian et al.*, 1996]). Considering the absence of large ^{226}Ra enrichments, *Williams and Gill* [1992] suggested, for Nyiragongo, the absence of subsolidus fluids before magma genesis.

[35] The radioactive disequilibrium between ^{228}Th-^{228}Ra-^{232}Th isotopes is generally caused by differentiation processes occurring in shallow environments (e.g., fractional crystallization of feldspars and feldspathoids or interaction with hydrothermal solutions or geothermal brines) [*Voltaggio et al.*, 2004]. Eventually, different disequilibria between ^{226}Ra and ^{230}Th may occur deep in the crust as a consequence of dynamic melting [*Zou and Zindler*, 2000], equilibrium percolation melting [*Spiegelman and Elliot*, 1993], or during the interaction with metasomatic mantle fluids [*Voltaggio et al.*, 2004].

[36] Data have been corrected for the time span between eruption and analysis using the equations given by *Voltaggio et al.* [1987], as mentioned in Table 2.

[37] The ^{226}Ra/^{230}Th isotopic ratios of samples from the 2002 eruption are out of radioactive equilibrium, indicating a similar fractionation process affecting the whole magmatic system. The magnitude of this fractionation suggests that it occurred at depth during magma generation and melt transport. A second shallower fractionation (enrichment of Ra over Th) possibly took place in samples collected from the highest part of the volcano: Shaheru crater, NY03 site and later on from CR01 and CR02 crater rim samples. This event is recorded by the ^{228}Ra/^{232}Th values (fractionation event occurred within the last 25 years). The same fraction-

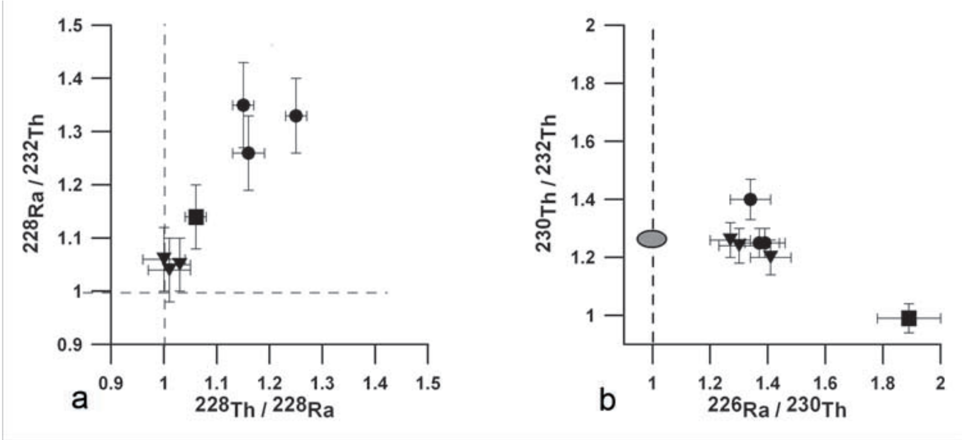

Figure 5. (a) Dispersion diagram of ^{228}Ra/^{232}Thversus^{228}Th/^{228}Ra activity ratios of 2002 Nyiragongo lava samples. (b) Dispersion diagram of ^{230}Th/^{232}Thversus^{226}Ra/^{230}Th activity ratios of 2002 Nyiragongo lava samples. Black triangles, samples from fractures near Munigi village; black circles, samples from main crater and fractures at north of Munigi; black square, Shaheru lava. The grey oval area is related to lava samples analyzed by *Turekian et al.* [1996]. Equilines indicate values at radioactive equilibrium. Error bars are given at 1σ level. It is worthy to note that in Figure 5a, values of lavas and scoriae erupted from the main crater and fractures north of Munigi are clearly out of radioactive equilibrium if compared to those erupted in the southern part of the fracture system (from Munigi to Goma). This result shows two different feeding systems, central and peripheral, and possibly two different magmas. Figure 5b shows that Shaheru lava sample displays ^{230}Th/^{232}Th and ^{226}Ra/^{230}Th activity ratios distinct from all other samples pointing to a different and older batch of magma likely related to the 1994–1995 Nyiragongo lava lake episode.

ation event (enrichment of ^{228}Ra over ^{232}Th and consequent transient disequilibrium between ^{228}Th and ^{228}Ra) is recorded by the ^{228}Th/^{228}Ra values of all these sites, significantly higher than unity (Figure 5a). However, the high ^{230}Th/^{232}Th value at all crater sites (1.24–1.40) is clearly different from that recorded at Shaheru (0.99). It suggests the arrival at surface of a fresh magma characterized by a high Th isotope signature. This isotopic signature is similar to that recorded by *Turekian et al.* [1996] for 1972–1982 eruptive period (1.25–1.27). On the other hand, the highest ^{226}Ra/^{230}Th ratio recorded at Shaheru confirms that the initial phase of the eruption had a "different" magma (Figure 5b) compared to that erupted later. This finding can be explained with the existence within the volcano edifice, and before the eruption, of residual magma related to the 1994–1995 lava lake activity [*Tedesco*, 1995, 2002/2003].

[38] Our data suggest the presence of different feeding systems beneath, and also far from, the Nyiragongo edifice. This has been highlighted by radioactive disequilibrium in ^{228}Th/^{228}Ra and ^{228}Ra/^{232}Th ratios showing that lava and scoria samples collected from the top of the volcano underwent a recent fractionation process, whereas lava samples collected from spatter cones and fractures at the bottom of the volcano do not show such a feature. The different magmatic feeding systems are then located in different areas of the volcano, both vertically and horizontally (Figure 6). The same plumbing system fed CR01 and CR02, Shaheru, and NY3 sites, whereas an independent feeding system fed the downslope volcanic structures at Munigi, westernmost fracture and NYR 11 fracture, much closer to the city of Goma (Figure 6).

[39] The existence of at least two independent feeding systems, one almost beneath the city of Goma, shows that geophysical and geochemical monitoring need to be focused on the Nyiragongo crater, its southern flank and the vents near the city of Goma. The presence of several peripheral volcanic craters close or even within the city of Goma (and Lake Kivu) confirms that our findings are of the utmost importance, and that new volcanic activity far from the main volcanic edifice and near or within the city of Goma (or even Lake Kivu) might resume in the future.

4.3. Reconstruction and Interpretation of the January 2002 Eruption

[40] The above description of events that preceded, accompanied, and followed the January 2002 eruption of Nyiragongo suggests that the regional tectonic setting played a major role in determining the observed phenomena and also triggering the eruption. We suggest that the eruption itself was due to a significant rifting event in the Nyiragongo–Lake Kivu area. On Nyiragongo, the rifting fractured the volcanic edifice, triggering the eruption of magma stored in the upper conduit and lava lake, which in turn initiated deeper magma depressurization, and favored fluid and magma ascent. Therefore magmatic and volcanic processes triggered by rifting coincided to produce the observed eruptive events. We therefore suggest a volcano-tectonic origin for the January 2002 eruption of Nyiragongo. Our conclusion is supported by several arguments, which are examined below.

[41] The most striking feature of the eruption is the generation and propagation of a huge system of fractures down the southern flanks of the volcano. The alignment of

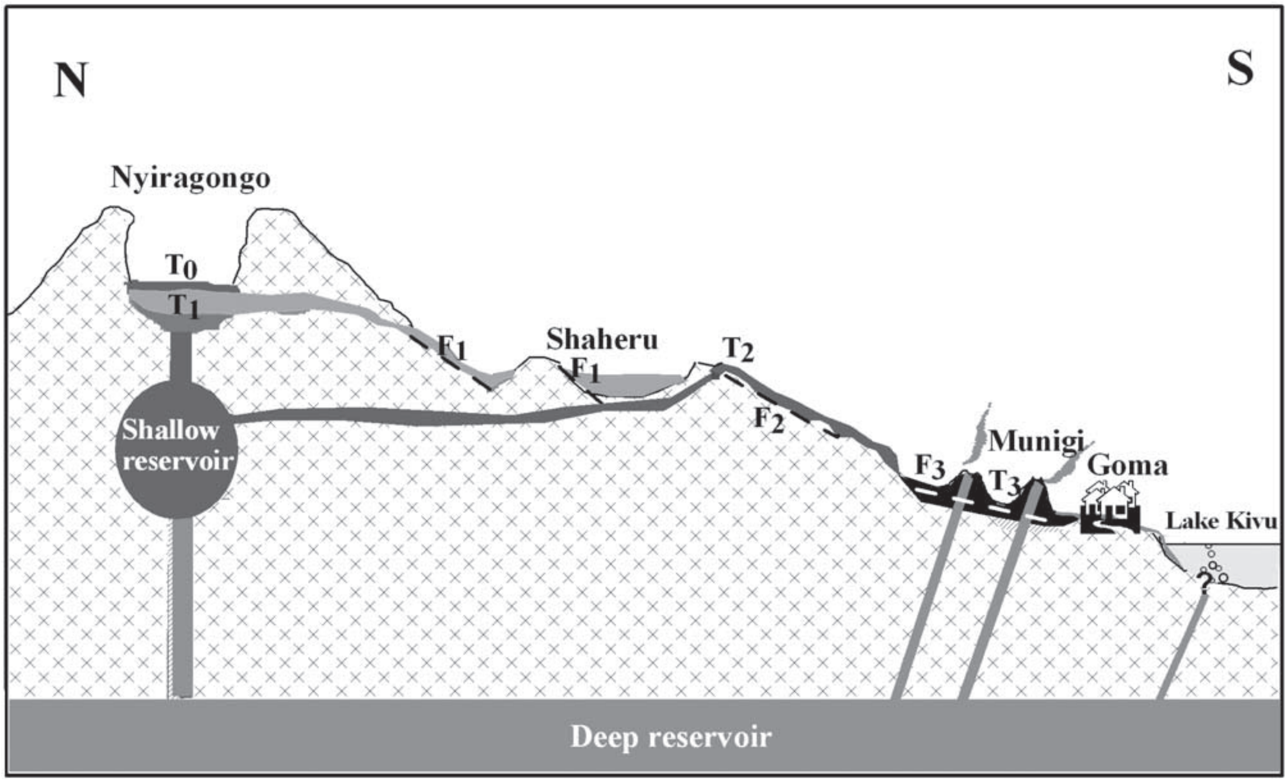

Figure 6. Sketch of the volcanic plumbing system and the sequence of events during the 2002 eruption as inferred from field observations, gas analysis and U-Th disequilibrium series. (1) T_0, old solidified Nyiragongo 1994–1995 lava lake event present at Nyiragongo crater bottom; (2) F_1, fracture between Nyiragongo and Shaheru crater open at T_1 when old (1994–1995) remaining molten lava from the Nyiragongo lava lake flooding Shaheru crater; (3) F_1 continues to extend south at T_2 when first batch of fresh lava possibly from the superficial reservoir erupted from fractures located lower than Shaheru on the Nyiragongo southern flank; (4) F_2 open in the middle and then extend south of Munigi Village, T_3 is the time when fresh lava from the deep reservoir erupted immediately near Munigi village and then from a chain of spatter cones (and within Goma). This lava then enters Goma and into Lake Kivu. The vertical dimension of the sketch is exaggerated 3 times.

the fracture system coincides (within ±5°) with that of the Albert Rift (N15°E) in the Nyiragongo–Lake Kivu area, suggesting a relationship between syneruptive fracturing and the regional tectonic setting. At several locations up to a few kilometers north of Goma, the fracture system shows a clear graben-like structure, with the ground between parallel fractures down thrown by a few tens of centimeters to several meters. Although this could also have been the result of inflation of the southern flank of the volcano under the action of magmatic pressure, it appears more likely connected with the significant subsidence of the northern Lake Kivu area. Future InSAR analysis of the south flank of Nyiragongo in the weeks and months preceding the eruption should help to clarify the relative roles played by inflation (pressurization due to magma rise) and rifting (depressurization due to fracturing). In any case, the major subsidence affecting the northern portion of Lake Kivu is clear evidence that rifting was not confined to the volcano but affected a much larger area. Subsidence occurred mostly after the eruption, but we cannot exclude that it may have started during or before the eruption. In fact, some witnesses report a water level increase during the week preceding the eruption, but this remains unconfirmed due to the absence of measurements in that period.

[42] Seismic activity showed no immediate decreasing trend after the eruption, as would be expected in a purely volcanic event and as has been observed for other historical eruptions of Nyiragongo and Nyamulagira. Most felt earthquakes occurred in the days following the eruption, when subsidence was occurring at its maximum rates. Such intense and long-lived seismic activity cannot be a post-eruptive sequence due to ground compaction after lava drainage. Clustering of epicenters in two different areas, encompassing the northern portion of Lake Kivu along the direction of fracturing, and the western rift south of Sake (Figure 1a), further suggests the involvement of a rifting process in the seismic crisis that accompanied and followed the eruption.

[43] The magnitude of the eruption, in terms of volume erupted, does not seem commensurate with such large-scale fracturing of the volcano. Gas-rich magma appears to have been erupted only from the southernmost (and possibly, westernmost) portion of the fracture system. Much of the erupted magma appears to have been largely degassed, and drained from the volcano rather than erupted violently under

the action of exsolving gases. At several places along the fracture system in the Munigi area, we observed the tops of dykes that had nearly reached the surface before being drained off to lower altitudes as the fracture system propagated. This observation further suggests a relatively passive role of magma during opening and propagation of the fracture system, and strengthens the hypothesis that rifting was the main trigger of the eruption.

[44] Other field data supporting the tectonic style of the eruption is the clear evidence of syneruptive and posteruptive fracturing in several areas of the fracture systems on the volcano, some of which defined noneruptive fractures. These events occurred both on the steep slopes of Shaheru as well as at the foot of Nyiragongo. They show that warm, still-plastic-lava flows entered (instead of being ejected) from fractures. This illustrates that the fracturing was not only preeruptive or syneruptive but also that it continued after the eruptive event.

[45] On the other hand, the fracture system propagated from the near-summit region to the periphery of the volcano. An additional fracture opened on the NW flank of the volcano, in an opposite sense to that of the main fracture system on the south flank (Figure 1a). We cannot therefore rule out the possibility that magmatic pressure influenced fracture propagation, as would be expected in a depressurizing magmatic system due to fracture formation and associated magma intrusion and migration. The eruptive signals recorded in the year preceding the January 2002 eruption show a typical sequence with tectonic events followed by long-period events followed by volcanic tremor, and suggests fracturing of rocks followed by magma movement and fluid migration. Therefore, during the year-long seismic crisis that preceded the eruption, the magmatic-volcanic system was recharged. It seems likely that gas-rich magma erupted from the southernmost vents in Munigi represents magma of deeper origin that slowly intruded into fractures in the months/weeks preceding the eruption.

5. Conclusions

[46] The 17 January 2002 eruption of Nyiragongo represents an interesting case study in volcanology, as well as perhaps an important evolutionary step in the history of the volcano. Eruptions from vents along the volcano flanks have occurred many times in the past, as shown by the presence of several tuff cones along directions radial to the crater and extending mainly toward the south and SW but never in historical times. One of these ancient (undated) tuff cones (Mount Goma) is located within Goma, on the shore of Lake Kivu.

[47] The northern portion of the fracture system active during the January 2002 eruption developed in 1977, when highly fluid lava flows, stopping a few kilometers from Goma, were emitted. In 1977, however, only degassed magma from the lava lake and from the upper conduit was erupted [*Tazieff*, 1977]. In January 2002, the extent of fracturing, the major syneruptive and posteruptive subsidence, and the involvement of gas-rich magma from deeper source regions below the volcano make the eruption unique in the recent history of the volcano. While Nyiragongo has been renowned for the presence of a long-lived lava lake inside its crater for nearly one century [*Tazieff*, 1977, and references within], beginning in 1977, and with much more evidence in 2002, a transition from central crater to rifting activity may be in process. Rifting might therefore become the dominant style of future eruptions at Nyiragongo, posing an increased seismic and volcanic hazard in the Nyiragongo–Lake Kivu area where several hundred thousand people live.

[48] An interesting analogy may be made with Nyamulagira volcano, the "twin brother" of Nyiragongo, located ~10 km NNW of Nyiragongo. Like Nyiragongo, Nyamuragira had a semipermanent lava lake in early 20th century, which was drained during an eruption in 1938, and since then the volcano's eruptions have been mostly on the flanks. This important variation in the eruptive style may help us to better understand what is happening to Nyiragongo and possibly help to forecast future type of activity of the volcano.

[49] Future eruptive scenarios should also take into account the possibility of a new eruptive episode starting close to or even within the city of Goma. The existence of two different plumbing systems (shown by U-Th disequilibria), the new CO_2-gas emanations from a fracture within the city (LaMungu church) and magmatic gases collected from the lava flow within Lake Kivu, concur and agree with the existence of an independent magmatic system beneath the city of Goma. Volcano monitoring should therefore focus not only on the crater and/or flank activity but also on possible activity occurring within the city itself.

[50] **Acknowledgments.** Chris Newhall is warmly thanked to have continuously helped most of us with his experience and suggestions as a chairman of the ISCC. The United Nations–OCHA and the International Committee of the Red Cross are also warmly thanked for giving all of us the possibility to work on this spectacular volcano and for strongly helping in the field with its local facilities

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