Birth of a lava lake: Nyamulagira volcano 2011–2015

Published version:

DOI:10.1007/s00445-016-1014-7

(Article begins on next page)

Coppola, D., Campion, R., Laiolo, M., Cuoco, E., Balagizi, C., Ripepe, M., Cigolini, C.,Tedesco, D. (2016) Birth of a lava lake: Nyamulagira volcano 2011-2015. Bullettin of Volcanology, 78:20

http://link.springer.com/article/10.1007/s00445-016-1014-7

Published: Feb 29, 2016

Birth of a lava lake: Nyamulagira volcano 2011-2015

Coppola, D.[1*], Campion, R.[2], Laiolo, M.[1,3], Cuoco, E.[4], Balagizi, C. [4,5], Ripepe, M.[3], Cigolini, C.[1,6], Tedesco, D.[4,7,8]

[1]*Earth Science Department (DST), University of Turin, Italy*

[2]*Instituto de Geofísica, Universidad Nacional Autónoma de México*

[3]*Earth Science Department (DST), University of Florence, Italy*

[4]*DISTABIF, Second University of Naples, Caserta, Italy*

[5]*Geochemistry and Environment Department, Goma Volcano Observatory, Goma (Democratic Republic of Congo)*

[6]*NatRisk, Centro Interdipartimentale sui Rischi Naturali in Ambiente Montano e Collinare, University of Torino, Italy* [7]*International Organization of Migrants, Geneva, Switzerland*

[8]*Istituto Nazionale di Geofisica e Vulcanologia, Roma, Italy*

* *Corresponding Author: Diego Coppola. Email: diego.coppola@unito.it*

ABSTRACT

Since 1938, Nyamulagira volcano (Democratic Republic of Congo) has operated as a classic pressurized basaltic closed system, characterized by frequent dike-fed flank eruptions. However, on June 24th 2014, an active lava lake was observed in its summit, after a period of 76 years. The small lava lake is now exposed at the bottom of a pit-crater and is rising and growing. Based on satellite-derived infrared (IR) data, SO_2 fluxes, and periodic field surveys, we provide evidence that the development of the lava lake was gradual and occurred more than two years before it was first observed in the field. Notably, this process followed the voluminous 2011-2012 distal flank eruption and was coeval with weakening of the central rock column below the summit. Hence, the opening and development of the pit-crater favoured the continuous rise of fresh magma through the central conduit and promoted the gradual "re-birth" of the Nyamulagira lava lake. Budgeted volumes of magma erupted and magma degassed at depth indicate that the formation of the lava lake is due to the draining and refilling of a shallow plumbing system (1-2 km depth), probably formed at the time of the rift-parallel 2011-2012 distal eruption. We thus suggest that the transition from lateral to central activity did not result from a substantial change in the magma supply rate but, more likely, from the perturbation of the plumbing system (and related stress field) associated with the distal eruption. The processes observed at Nyamulagira are not unique and suggest that rift-fissure eruptions, in addition to triggering caldera collapses or lava lake drainages, may also induce a progressive resumption of central vent activity. Current activity at Nyamulagira represents a tangible and major hazard for the population living at the base of its southern flank.

Keywords: Nyamulagira, lava lake, heat flux, SO_2, magma supply rate, stress field

INTRODUCTION

Lava lakes are rare features, with only a few currently active on Earth. No lava lake has directly been observed during its early development, and the opportunity to follow the "re-birth" of a lava lake should also be regarded as a very rare one (i.e., Patrick et al. 2013). The Virunga Volcanic Province (VVP), at the northern end of the Kivu Basin (Western branch of the Eastern African Rift; Fig.1a) is characterized by eight volcanoes, and the two youngest and most westerly ones, Nyiragongo and Nyamulagira (Democratic Republic of Congo; DRC), currently host two independent lava lakes (Fig. 1).

Figure 1

Nyiragongo is well known for its quasi-permanent lava lake (Fig. 1c; Tedesco et al. 2007; Spampinato et al. 2013; Burgi et al. 2014), whereas Nyamulagira is considered the most active volcano in Africa. A total of 27 flank eruptions have occurred on Nyamulagira since 1938 (Smets et al. 2010), when its lava lake was abruptly drained from the summit pit-crater (Fig. 1b).

In particular, after 1938, the volcano behaved as a closed degassing system (no gas was being vented between eruptions) that erupts when a threshold volume or pressure is reached. Hence, the dikes cross-cutting the volcanic edifice fed two distinct types of eruptions (Wadge and Burt, 2011): *i*) eruptions fed by dikes perpendicular to the East African Rift Valley (*rift-perpendicular*; i.e. occurring along the NNW fissure trending zone; Fig. 1a) characterized by small volumes and short durations; *ii*) eruptions fed by dikes trending sub-parallel to the rift (*rift-parallel*) lasting more than 90 days and pouring out larger volumes of lava. However, a significant change in the eruptive style of the volcano was noted in late June 2014, when, after 76 years, a small lava lake was first observed within the eastern pit-crater (Campion 2014; Smets et al. 2014; Fig. 1b).

Analysis of satellite-based thermal and SO_2 data coupled with periodic field surveys, allowed us to track the gradual development of this lava lake, which we found to have started more than two years earlier, in March 2012. By combining the magma budget of the recent activity (IR-derived and SO_2-derived) with those recorded during the previous 35 years of activity, we propose a model for the lava lake's formation and we discuss the hazard related to the new eruptive regime now in place at Nyamulagira.

METHODS

Thermal emissions

Thermal emissions at Nyamulagira and Nyiragongo volcanoes have been detected using infrared data provided by the Moderate Resolution Imaging Spectroradiometer (MODIS). The MODIS instrument, aboard the Terra (EOS AM) and Aqua (EOS PM) satellites, offers a temporal coverage (~ 4 images day^{-1}), spatial resolution (1 km in the IR bands), and an adequate spectral coverage (the "fire" channel at 3.9 μm), which enables monitoring thermal emission over a wide range of volcanic activity (Rothery et al. 2005; Wright and Pilger 2008; Coppola and Cigolini 2013). In particular, we used the MIROVA system (Middle InfraRed Observation of Volcanic Activity; www.mirovaweb.it ; Coppola et al. 2015) by running the hot-spot detection algorithm for three distinct regions of interest namely, the Nyamulagira summit area (5 x 5 km), the Nyamulagira NE sector (20 x 10 km), where the 2011-2012 lava flow emplaced (Fig. 1), and the Nyiragongo summit area (5 x 5 km). Nyiragongo activity has been analyzed in order to provide a useful reference for the thermal flux radiated by its well established active lava lake. Hence, for each MODIS image where one or more hot-spot pixel(s) were detected, we calculated the radiant heat flux in terms of *Volcanic Radiative Power* (*VRP*):

$$VRP = 18.9 \times A_{PIX} \times \sum_{1}^{nalert} \left(L_{4alert} - L_{4bk} \right) \quad (1)$$

where A_{PIX} is the pixel size (1 km^2 for the resampled MODIS pixels), *nalert* is the number of alerted pixel(s), L_{4alert} and L_{4bk} are the 4 μm radiance of the alerted and background pixel(s), respectively (see Coppola et al. 2015 for more details). Finally, by manually checking the processed images, we discarded all the cases where the thermal signal was undoubtedly attenuated or completely masked by the presence of clouds (Coppola and Cigolini 2013).

Erupted magma flux (VRP-derived)

MODIS-derived *VRP* have been converted into erupted magma flux (Time Averaged lava Discharge Rate; TADR in $m^3\ s^{-1}$) by using the radiant density approach (Coppola et al. 2013, 2015):

$$TADR = \frac{VRP}{c_{rad}} \qquad (2)$$

where c_{rad} (the radiant density) is a best-fit empirical parameter that expresses the relationship between volumetric (*TADR*) and thermal (*VRP*) flux. This approach has been successfully applied to the recent eruptions of Nyamulagira (Coppola and Cigolini 2013) by using a value of c_{rad} equal to $3.5 \times 10^8\ J\ m^{-3}$, considered representative of the low-viscosity lavas that erupted from this volcano. A bulk lava vesicularity of ~15% (Wadge and Burt 2011) has been also assumed for the erupted lava ($\rho_{DRE} = 2600\ kg\ m^{-3}$; $\rho_{lava} = 2200\ kg\ m^{-3}$), and for converting the obtained TADR into dense rock equivalent (DRE) erupted magma flux.

Sulphur emission rates

Measurements of the SO_2 emission rates were obtained from the satellite images of OMI (Ozone Monitoring Instrument, operating in the UV) and ASTER (Advanced Spaceborne Thermal Emission and Reflection radiometer, operating in the visible and Thermal Infrared). For OMI, the SO_2 emission rate was calculated by applying the traverse method (Campion et al. 2012; Campion 2014) to the SO_2 column amount images OMI_SO_2 product, released in near-real time by NASA using the linear fit algorithm (Yang et al. 2007). The ASTER images were processed with the band ratio algorithm (Campion et al. 2010) to derive SO_2 column amounts, and then processed with the same traverse method to obtain the SO_2 emission rates. OMI's ground resolution (13 x 25 km at nadir) is too coarse for distinguishing the sources of the SO_2 emissions within the Virunga Volcanic Province, but its relatively high imaging frequency gives a suitable time resolution for real monitoring. Conversely, the high ground resolution of ASTER allows quantifying the emissions of Nyamulagira and Nyiragongo separately (Campion 2014), but only a few images are sufficiently cloud-free over the period of interest. Based on the analyzed ASTER images here, we assume an average SO_2 emission of ~10 kg s^{-1} due to the degassing of Nyiragongo lava lake.

Outgassed magma flux (SO_2-derived)

Measurements of the discharged SO_2, combined with an estimate of the amount of molten sulphur in the lava, have been used to constrain rates of magma supply ($Q_{[SO2]}$) within the shallow degassing and outgassing system (Kazahaya et al. 1994; Shinohara 2008). Here, we used a simplified approach on the basis of the following relationship:

$$Q_{[SO2]} = 10^6 \frac{E_{SO_2}}{2\Delta S \rho_M} \qquad (3)$$

where E_{SO_2} (kg s^{-1}) is the sulphur degassing rate, ρ_M represents the bulk density of the magma entering the degassing zone (ρ_{DRE} = 2600 kg m^{-3}) and ΔS (ppm) represents the total degassed sulphur, calculated as $\Delta S = S_{mi} - S_{ig}$ (where S_{mi} and S_{ig} are the sulphur concentration in the melt inclusions and in the interstitial glass, respectively). We assume negligible retention in vesicles of volatiles degassed from the melt represented by the interstitial glass. Sulphur content in melt inclusions (S_{mi}) of recently erupted materials from Nyamulagira span from 1300 to 2500 ppm (Head et al. 2011). Here, we used ΔS equal to 2500 ppm to represent pre-eruptive volatile composition and complete sulphur degassing and outgassing (S_{ig} = 0).

Integrating the sulphur degassing rate with time equation 3 has allowed us to convert the total mass of SO_2 emitted during distinct eruptions into volume of outgassed magma as summarized in Table 1.

High-resolution multispectral images

High-resolution images shown in this work (i.e., Fig. 1, 2 and 4) were acquired by a series of multispectral imagers: Operative Land Imager (OLI) and Enhanced Thematic Mapper Plus (ETM+), carried on Landsat satellites, and Advanced Land Imager (ALI), carried on EO-1 satellite (all data courtesy of USGS and available at http://earthexplorer.usgs.gov/). All the images have pixel resolution of 30 m and, where not specified differently, were shown in false colour by using the following band combinations: OLI (bands 7-6-5), ETM+ (bands 7-5-4) and ALI (bands 10-9-8).

Field Surveys

Periodic field surveys at Nyamulagira volcano have been carried out since 2009 by helicopter, thanks to the support of the United Nations Organization Stabilization Mission in the DR Congo (MONUSCO). Since 2013, observations have also been directly carried out in the crater of Nyamulagira once or twice a month, always by helicopter. The team has comprised researchers of the Goma Volcano Observatory, Dario Tedesco and other international scientists. This area is a high risk sector due to the presence of armed groups and it is impossible, due to the lack of security, to make detailed field surveys.

SPACE- AND FIELD-BASED OBSERVATIONS

On November 6, 2011, after 644 days of rest, one of the longest (~140 days) and most voluminous (>200 Mm^3) eruptions of Nyamulagira volcano started on the eastern flank of the main edifice (Coppola and Cigolini, 2013). In contrast to the previous eruptions (i.e. Smet et al. 2010; Wadge and Burt 2011), the new eruptive fissure did not open along the main NNW trending rift zone, but along a perpendicular (ENE-oriented) direction, and about 12 km from the volcano summit (Fig. 1). Lava and gas emissions reached their peak values (> 100 m^3 s^{-1}) within the first days of activity (Fig. 2d), when intense lava fountains, 300 m high, built a new spatter cone (V_1 in Fig. 2d) and fed a lava flow extending 11.5 km northward (Fig. 2b). Although initially very intense, the effusion of lava during the first days of activity declined gradually with time and was accompanied by a reduction in sulphur emissions, which is a typical result of syneruptive outgassing (Fig 2d). This initial eruptive phase (hereby defined *phase I*) was characterized by lava emission lasting about three weeks and erupted about 60 Mm^3 of magma (Fig. 2e), similar in every way to the "archetypal" eruption style of Nyamulagira (i.e. Wadge 1981; Wadge and Burt 2011).

In late November 2011, however, the effusive activity increased again and accompanied propagation of the eruptive fissure about 500-1000 m downslope and the progressive building of two other elongate spatter- and scoria-cones, named V_2 and V_3 (Fig. 2c). This renewed effusive activity (*phase II*) was not accompanied by a coeval increase in sulphur emission (except for short pulses concomitant with the opening of vents V_2 and V_3; Fig. 2d), which suggests the eruption of a relatively SO_2-depleted magma. The effusion from V_2 and V_3 diminished throughout December 2011 and January 2012, showing a gently declining trend that persisted until the end of February 2012. At this time, the lava flow field had already reached its final length with a DRE volume of about 210 Mm^3. *Phase II* was thus characterized by a long lived (~100 days) and voluminous (~150 Mm^3) effusion of relatively outgassed magma (Fig. 2e).

Figure 2

A major change in the eruptive dynamics occurred on February 23rd, 2012, when a series of shallow explosion quakes was recorded below the pit-crater (stars in Fig. 2 and 3). Field observations made a few days after the explosions revealed the presence of meter-scale lithic blocks within the whole summit caldera, though no evidence of juvenile material (i.e. fresh scoria, ash, Pele's hair) was found. On the other hand, spectacular ring faults (with vertical displacements of several meters) appeared within and around the pit-crater (Fig. 4h), indicating subsidence above a partially open, or emptying, reservoir at very shallow depth. These explosions marked a change in the sites of venting at Nyamulagira, which shifted from the distal flank vent(s) to the summit pit-crater (Fig. 3).

Figure 3

During the following weeks: (*i*) the effusion rate at the lateral vent(s) (and related thermal anomalies) sharply decreased and then ceased entirely on March 28th 2012 (Fig. 3a; Coppola and Cigolini 2013); (*ii*) small thermal anomalies gradually appeared within the pit-crater (Fig. 3a and 4); and finally, (*iii*) intense outgassing from the summit caldera was observed (Fig. 3b and 4; Campion 2014).

Figure 4

There were no thermal anomalies within the pit-crater during the weeks before the summit explosions (Fig 4a) and first detected by MODIS a couple of weeks later (on March 14th, 2012; Fig. 3). A small, shallow heat source was confirmed by Landsat ETM+ image (March 28th, 2012), with a 60-90 m diameter hotspot visible on the southern side of the pit-crater (Fig.4b); the hotspot suggests that explosions of February 2012 opened a central magma path, providing a "window" into Nyamulagira's uppermost magmatic system.

In following months the pit-crater's morphology evolved by multiple rockfall collapses, in "onion skin" mode, within the summit vent and then by thermal and chemical erosion of the crater walls (Fig. 4h-i). During 2013 summit outgassing persisted well above the emission rates of Nyiragongo (Fig. 3b), and distinct pulses alternated with intermittently detected small thermal anomalies (0.5-5 MW) at the bottom of the pit-crater (Fig. 3a and 4c). In April and early June 2014 thermal anomalies exceeded 10 MW for the first time, suggesting a heat source at the surface (Fig. 3a). On June 24th visual observations confirmed the presence of a lava lake (~ 50 m diameter) at the bottom of the pit-crater (~ 500 m depth; Fig.4d), with the lava lake well exposed at the surface (Fig. 4l) producing suddenly increased heat flux, up to ~ 200 MW.

A field survey on November 1st, 2014 showed that level of the lava lake had drastically increased (~325 meters below the pit-crater rim) and continuous and large collapses of the pit-crater walls were still occurring. Molten lava was visible through two “skylights” (< 50 m diameter each) while most of the lava lake was apparently covered by a layer of solidified lava and welded scoriae (Fig. 2m). On November 26th, 2014, MODIS detected the highest radiant flux (440 MW) since the appearance of Nyamulagira’s lava lake (Fig. 3a). Possibly, this increase reflected the rupture of the solidified layer and/or a further enlargement of the lake surface that persisted throughout the first months of 2015 (Fig. 4n). As a comparison, during 2012-2015, the well-established (~200 m diameter) Nyiragongo’s lava lake produced a VRP of 1000-1200 MW as shown in Fig. 3 (cf., Spampinato et al. 2013).

RE-FORMATION AND DEVELOPMENT OF NYAMULAGIRA LAVA LAKE

In order to (re)-form and maintain an active lava lake, three main conditions must be continuously satisfied:

- the magma supply within the shallow plumbing system must be steady (or quasi-steady) and within a specific range of critical values (Francis et al. 1993). Intermittent or very low supply rates will be not able to maintain an open central magma pathway and the summit convecting magma column. Conversely, high supply rates will produce overflows from the pit-crater rim / summit crater and effusive activity, as did the ones observed at Erta Ale volcano on 2010 (i.e., Field et al. 2012);

- the magma plumbing system must be able to accommodate the descending magma mass by recycling, intruding, and/or cumulating processes (Francis et al. 1993, Harris et al. 1999);
- the local tectonic setting (including the stress field and mechanical properties of the edifice) must enable the top of the magma column to reach the free surface without triggering flank failure or lateral magma injection (Battaglia et al. 2011), with consequent drainage of the lake itself (i.e., Tedesco et al. 2007).

After the opening of the pit-crater (February 23rd, 2012), the above conditions were operative at Nyamulagira volcano and persisted throughout the development of the new lava lake.

We estimated that between March 2012 and April 2015, about ~3.3 Mt of SO_2 were released by Nyamulagira volcano with a time averaged emission rate of ~35 kg s^{-1}. According to equation 3, we thus calculate that the DRE volume of magma that outgassed at shallow depth in this period was about 235 Mm^3 (~2.3 m^3 s^{-1}).

Our data indicate that the magma input rate to the growing lake was only slightly higher than the long-term supply rate when eruptions were episodic (see next chapter). This suggests that the transition from lateral to central activity did not result from a substantial change in the magma supply rate but, more likely, from a perturbation of the plumbing system (and related stress field) associated with the 2011-12 distal eruption.

The analysis of pre-eruptive seismicity suggests that 10 months before the 2011-2012 eruption, earthquakes were consistent with a deep (10 - 30 km) magmatic intrusion in the area beneath Nyamulagira (Bondo et al. 2015). After April 2011, hypocenters migrated upward and were associated with magma intrusion at shallower depths (~5 km), as also observed during previous eruptions (Mavonga et al. 2010; Wauthier et al. 2013). Increasing seismic activity culminated in energetic seismic swarms on September 2011 and finally on November 5th, 2011, just one day before the onset of the eruption (Kyambikwa Milungu et al. 2013). At this time, both deep and shallow seismicity extended several kilometres along the ENE direction, thus suggesting lateral propagation of a dike that would feed the eruptive fissure(s) (Bondo et al. 2015).

Notably, the dike/eruptive fissure of 2011-12 eruption was perpendicular to dominant axis of volcanic activity since the early 1990s (the NNW fissure trending zone; Fig. 1; cf. Wadge and Burt, 2011) and was parallel to the alignment of the older central volcanoes ENE (065°) (see Fig. 1a). Preliminary InSAR data, made by the GORISK team (see GORISK Web site: http://www.ecgs.lu/gorisk/volcanoes/nyamulagira/eruptive-activity/november-2011-eruption/4) also suggests that the 2011-12 eruption produced the largest deformation detected at Nyamulagira since early 1990s, characterized by a 20 km wide subsidence probably associated with withdrawal of magma from a large deep reservoir (Albino et al. 2013).

Moreover, a temporary seismic array, operative between March 2012 to April 2013 (i.e. after the end of the effusive activity), detected several tectonic earthquakes beneath Nyamulagira and Nyiragongo volcanoes, at depths of 10-12 km and 7-10 km, respectively (Wood et al. 2015). Lower crustal seismicity (>10 km depth) was also recorded during two intense swarms, in May and November 2012. The latter were interpreted as deep magmatic intrusions beneath the alignment of Nyiragongo and Karisimbi volcanoes although no surface deformation was detected in InSAR data (Wood et al. 2015).

The exceptional 2011-12 rift-parallel eruption was thus associated with an important perturbation of Nyamulagira’s plumbing system (and related stress field) that are likely to have favoured, and possibly induced, the reactivation of a central magma pathway below the summit caldera. Nonetheless, the close link between the shallow explosion quakes, the end of the lateral effusion and the almost coeval appearance of summit thermal anomalies (Fig 3) clearly suggests the existence of a “hydraulic connection” between the diminishing transport of magma through a lateral dike and the rise of new-fresh magma within the central feeding system.

The above analyses and observations give us the opportunity to propose a basic "draining-refilling" model (Fig. 5) whereby the re-birth of the Nyamulagira lava lake occurred in response to the modified stress field associated with the 2011-12 lateral eruption. In particular, we suggest that the injection of the 12 km long dyke along the ENE direction, the partial withdrawal of magma from a deep (> 5 km) undegassed magma chamber (*phase I*; Fig. 5b), and the emplacement of a lateral dike cross-cutting the upper portion of the conduit have somehow perturbed the stress field acting on the volcano edifice. Hence, the new stress conditions favoured the drainage of outgassed magma residing at shallow depths (1-2 km) that had probably accumulated during the previous eruption(s) along the NNW zone (Fig 5c). A gravity-driven magma discharge dynamic (Ripepe et al. 2015) produced the waning trend observed during *phase II*, and triggered the onset of the pit-crater collapse (Fig. 5d-e). Then, the flank eruption progressively ceased and the continuous supply of more deeply sourced magma slowly refilled the damaged shallow plumbing system (Fig. 5f). At this point, the floor of the pit-crater may have been excavated to sufficient depth that it provided a "window" into the uppermost magmatic system as it refilled. Hence, the lava lake slowly crept upwards and enlarged in area as the system approached its pre-flank-eruption pressure state (Fig. 5g).

Figure 5

LONG TERM ERUPTED – OUTGASSED MAGMA BUDGET

The draining-refilling model proposed implies that by December 2011, at least 150 Mm^3 of outgassed magma had accumulated in the uppermost portion of the plumbing system (1-2 km beneath the summit). This probably occurred within a shallow storage zone (i.e. constituted by small sill-like reservoir(s) and/or interconnected magma pockets or dikes).

The existence of such pockets under Nyamulagira caldera is still debated (i.e. Toombs and Wadge 2012; Wauthier et al. 2013), but sub-surface (1-2 km depth) small-volume (< 1 km^3) magma storage zones have been reported at Piton de la Fournaise and Kilauea volcanoes (Poland et al. 2009, 2014; Peltier et al. 2009, 2015). At Piton de la Fournaise, for example, superficial transient storage zones, composed of small magma pockets scattered between the volcano's summit and sea level, have been shown to form and develop during periods of frequent effusive activity (Lénat and Bachèlery 1999). The draining of these shallow magma reservoirs during distal eruptions was thought to trigger pit-crater collapses inside the Dolomieu crater like those in 1986 and 2002 (Hirn et al. 1991; Longpré et al. 2002). Similarly, Kīlauea's summit caldera recently experienced the "re-birth" of a lava lake (within the so-called "Overlook crater") throughout a sequence of events very similar to those currently observed at Nyamulagira (Patrick et al. 2013; Poland et al. 2014). These include: (*i*) lateral magma injection (>10 km) and magma withdrawal to feed intrusions and eruptions along a rift-parallel zone; (*ii*) upward migration of a central collapse front; (*iii*) pit-crater opening through explosion(s) involving lithic blocks (no juvenile material); (*iv*) strong magmatic outgassing; (*v*) gradual rise and growth of a lava lake through episodic collapse of the crater walls, impulsive outgassing, and occasional weak explosive events. The similarity in the processes observed at Piton de la Fournaise, Kilauea, and Nyamulagira (Campion 2014) supports the existence of a transient shallow storage zone also beneath the summit caldera of Nyamulagira, whose draining and refilling dynamics form the basis of the proposed model.

Satellite-based measurements of SO_2 and erupted magma volumes since 1980 (Bluth and Carn 2008; Head et al. 2011; Smets et al. 2010, Wadge and Burt 2011; Coppola and Cigolini 2013; Campion 2014, this study), allowed us to constrain the outgassed-erupted magma partitioning during the last 35 years of activity at Nyamulagira (Fig. 6). The analysis of 17 eruptions (Table 1) reveals that only two of them were characterized by a clear SO_2 deficit, namely the 1991-1993 and the 2011-12 eruptions (Fig. 6). It is worth noting that these two unique SO_2-poor eruptions represent the most voluminous (> 200 Mm^3), long lived (> 100 days) *rift-parallel* eruptions of the past decades, and their deficit in sulphur emissions probably reflects the drainage of the central, shallow, and outgassed portion of the plumbing system. Conversely, all the other eruptions display a variable outgassed-erupted partitioning, spanning from syneruptive outgassing (i.e. 1980, 1984, 1986, 1987, 1996, 2000, 2001, 2010) to SO_2 excess, which has been frequently observed at Nyamulagira volcano (i.e. 1981, 1989, 1994, 1998, 2002, 2004, and 2006 cf. Bluth and Carn 2008; Head et al. 2011).

Figure 6

All these data suggest that the upper portion of the Nyamulagira's plumbing system has been recurrently fed and replenished especially by short-lived *rift-perpendicular* eruptions that occurred along the NNW fissures. These eruptions, often characterized by a strong SO_2 excess, may have left batches of residual (unerupted) degassed magma (i.e., sill-like magma pocket and slowly cooling dikes) that were occasionally drained during major *rift-parallel* eruptions (as possibly occurred on 1938-40, 1948, 1991-1993 and 2011-2012).

Two additional features are identified from the cumulative trends of outgassed and erupted magma over the most recent decades (Fig. 6):

- Although each single eruption may be characterized by a variable gas-magma partitioning, the ratio between outgassed and erupted magma volumes seems to be relatively constant over the latest 35 years, and roughly equal to 1.25 (cf. Fig. 6c). We infer that since 1980, about 1.5 km^3 of magma has been erupted (Mean Output Rate; $MOR_{,DRE}$ =1.3 m^3s^{-1}) while 0.5 km^3 has been cycled back (stored or intruded) in the plumbing system after outgassing (at mean rate of 0.4 m^3s^{-1}) .
- The transition from closed-system degassing, preceding the flank eruption, to an open-system centrally outgassing system (late February 2012) does not seem to follow, or to be followed by a substantial change in the long term magma supply, which conversely seems to have continued at the same rate since 1980 (about 1.8 m^3 s^{-1} DRE; Fig 6c). As emphasized by Campion (2014), this

dynamic supports the idea that the present-day plumbing system of Nyamulagira efficiently releases high amounts of gases, without enhancing accumulation of degassed volatiles at depth.

Table 1

The exceptionality of the 2011-2012 eruption lies in the opening of a central outgassing path that inhibited onset of the typical “pressure-cooker” dynamic whereby eruption occurs when a threshold in volume or pressure is reached (Wadge and Burt 2011).

This open, outgassing, condition was probably reached also between 1930 and 1938 when efficient magma convection and outgassing sustained the lava lake for about 9 years (Pouclet, 1975).

PRESENT ACTIVITY AND RELATED HAZARDS

The historical records that report activities similar to the current one provide clues for evaluating the hazard posed by the re-formed lava lake and for inferring some plausible eruptive scenarios.

Between 1913 and 1938, the eruptive activity in the summit caldera on Nyamulagira was persistent (Pouclet 1975) with a marked increase since 1930, when a lava lake was first observed (Hoier, 1939). The lava lake was drained 9 years later, in 1938, during Nyamulagira’s longest historical eruptive event (868 days; Verhoogen 1939; Pouclet 1975). Eruptive fissures related to this event opened on the SW and S flanks and caused the rapid emptying of the lava lake with consequent collapse of the eastern pit-crater. The effusive activity produced the largest historical lava flows of Nyamulagira (volume > 200 Mm^3; area > 67 km^2; Wadge and Burt 2011), which quickly reached Lake Kivu (Kabuno Gulf) and damaged the main road of the region (see Fig. 1).

So far, Nyamulagira volcano has never been locally considered a threat for the population living in the area. We can count dozens of villages and two important urban areas in the Nyamulagira-Nyiragongo area: the cities of Goma and Sake have more than one million and nearly 100,000 inhabitants, respectively (cf., Fig.1 and 7). The presence of such a large population increases the risk related to future volcanic events. In particular, the opening of eruptive fissure(s) located within the southern sector of the volcano (Sake side) may trigger the rapid drainage of the lava lake, as occurred previously at Nyamulagira and Nyiragongo volcanoes.

Figure 7

Based on the current sulphur output rate (~42 kg s^{-1}), we estimated that between March 2012 and December 2014, at least 270 Mm^3 of magma outgassed and was probably stored at a shallow depth. This volume of magma is similar to that drained in 1938 and is potentially available for the next flank eruption.

Together with the extremely acidic gases (SO_2-HCl-HF-rich) and ash and Pele's hairs, the major hazard is related to lava flows that may reach highly populated areas (as during the 1938 eruption; Fig. 7). An additional risk results from the presence of more than one thousand United Nations personnel, the F.I.B. (Force Intervention Brigade), located on the shores of Lake Kivu, just one kilometre from the southern side of the city of Sake (Fig 7).

It is thus clear that an eruptive event, such as those that occurred in 1938 and/or 1948, would cause a massive migration of people to the eastern and/or western side of North Kivu, in areas used, nowadays and in the recent past, by the so-called internal displaced people (IDP's) due to the current civil war.

Nyamulagira lava flows directed towards the southern side of the volcano may have indirect, mainly economic, impacts on a much larger number of people. Only one road (in very bad condition) exists between Sake and Goma (N2 in Fig. 7). Today more than 60% of fresh food and

80% of charcoal (used for cooking by more than 95% of the population) comes from the western side of the rift, the Sake area (World Food Program 2010). However, both in 1938 and 1948, the road was covered by lava, inhibiting transportation. In case of a major eruptive event with similar damage, there could be a serious shortage of food causing possible social instability.

Current warning systems rely on the occurrence of seismic swarms of low-to-moderate magnitude (usually not felt by humans) a few hours or one-two days before the eruption. The onset of such precursors gives a rather limited time to alert the population, particularly those living in remote areas. Therefore, the presence of a lava lake poses several new issues in terms of volcanic risk at Nyamulagira.

CONCLUSIONS

Flank effusive activity associated with large magma withdrawals has been generally associated with caldera collapse and/or with the "drainage" of active lava lakes (Geyer et al. 2006; Tedesco et al. 2007). In contrast, the recent activity at Nyamulagira provides clear evidence that the above phenomena could also induce the reverse process: i.e. the re-birth of a lava lake. We thus propose that the gravity-driven drainage of a shallow (1-2 km depth) outgassed magma body (or multiple small interconnected magma pockets) has been induced by the eruption of deep undegassed magma along a lateral rift-parallel dike. This process triggered the collapse of the summit pit-crater and promoted the subsequent development of a convecting magma column within the edifice. By analysing the outgassed and erupted magma volume ratio over the last 35 years, we suggest that other long-lived, rift parallel eruptions may have systematically drained this transient shallow plumbing system of Nyamulagira.

The mechanisms reported in this study shares similarities with those that occurred during the formation and evolution of other lava lakes such as: Kilauea (Patrick et al. 2013), Ambrym (Németh and Cronin 2008), Masaya (Rymer et al. 1998) as well as the neighbouring Nyiragongo lava lake (Tedesco et al. 2007). This suggests that a draining-refilling model at steady-state basaltic volcanoes can easily shift from lateral to central activity thus promoting the (re)-birth of a lava lake or the renewal of volcanic activity at the summit (as in the case of Stromboli, e.g., Calvari et al. 2005, 2010). This process can be tracked by using thermal and SO_2 satellite-derived data that have been shown to be strategic in decoding the renewal of central vent activity at Nyamulagira volcano. The presence of a lava lake at the summit of Nyamulagira is a major hazard due to the large local population and requires further attention and collaborative efforts both in terms of volcano surveillance and information to mitigate volcanic risk.

ACKNOWLEDGEMENTS

MIROVA is a collaborative project between the Universities of Turin and Florence (Italy) and is supported by the Centre for Volcanic Risk of the Italian Civil Protection Department. Additional funds were provided by MIUR; additional funds for improving our computing hardware were provided by Fondazione Cassa di Risparmio di Torino. We thank J.D.L. White, M. Patrick and two anonymous reviewers for their constructive comments that strongly improved this work. We are grateful to G. Wadge and L. Spaminato for their helpful suggestions on an early version of this manuscript. We acknowledge the LANCE-MODIS system (http://lance-modis.eosdis.nasa.gov/) for providing Level 1B MODIS data. Thanks to UN-MONUSCO flights, European Union-Kinshasa (DRC), and I.O.M. for their support.

REFERENCES

Albino F, Kervyn F, Smets B, d'Oreye N (2013) InSAR study on the 2011 eruption at Nyamulagira volcano, D.R.C: lava flow emplacement and post-eruption ground deformation. American Geophysical Union, Fall Meeting: 2013AGUFM.G31A0957A

Battaglia M, Di Bari M, Acocella V, Neri M (2011) Dike emplacement and flank instability at Mount Etna: Constraints from a poro-elastic-model of flank collapse. J Volcanol Geotherm Res 199:153-164

Bluth GJS, Carn SA (2008) Exceptional sulfur degassing from Nyamuragira volcano, 1979–2005: Int J Remote Sens 29 (22):6667–6685. doi: 10.1080/01431160802168434

Bondo SF, Njovu CB, Nshokano JR, Lubula JL (2015) Some seismic aspect prior the November 06, 2011 Nyamulagira eruption, Democratic Republic of Congo. International Journal of Innovation and Applied Studies 10(2):753-766

Burgi PY, Darrah TH, Tedesco D, Eymold WK (2014) Dynamics of the Mount Nyiragongo lava lake. J Geotherm Res 119(5):4016-4122

Campion R, Salerno GG, Coheur PF, Hurtmans D, Clarisse L, Kazahaya K, Burton M, Caltabiano T, Clerbaux C, Bernard A (2010) Measuring volcanic degassing of SO_2 in the lower troposphere with ASTER band ratios. J Volcanol Geotherm Res 194(1):42-54. doi: 10.1016/j.jvolgeores.2010.04.010

Campion R, Martinez-Cruz M, Lecocq T, Caudron C, Pacheco J, Pinardi G, Hermans C, Carn S, Bernard A (2012) Space-and ground-based measurements of sulfur dioxide emissions from Turrialba Volcano (Costa Rica). Bull Volcanol 74(7):1757-1770. doi: 10.1007/s00445-012-0631-z

Campion R (2014) New lava lake at Nyamuragira volcano revealed by combined ASTER and OMI SO_2 measurements. Geophys Res Lett 41 (21):7485–7492. doi: 10.1002/2014GL061808

Calvari S, Spampinato L, Lodato L, Harris AJL, Patrick MR, Dehn J, Burton MR, Andronico D (2005) Chronology and complex volcanic processes during the 2002–2003 flank eruption at Stromboli volcano (Italy) reconstructed from direct observations and surveys with a handheld thermal camera. J Geophys Res (110):B02201. doi:10.1029/2004JB003129.

Calvari S, Lodato L, Steffke A, Cristaldi A, Harris AJL, Spampinato L, Boschi E (2010) The 2007 Stromboli eruption: Event chronology and effusion rates using thermal infrared data. J Geophys Res (115):B04201. doi:10.1029/2009JB006478.

Coppola D, Cigolini C (2013) Thermal regimes and effusive trends at Nyamuragira volcano (DRC) from MODIS infrared data. Bull Volcanol 75 (8):1-15.

Coppola D, Laiolo M, Piscopo D, Cigolini C (2013) Rheological control on the radiant density of active lava flows and domes. J Volcanol Geotherm Res 249:39–48. doi:10.1016/j.jvolgeores.2012.09.005

Coppola D, Laiolo M, Cigolini C, Delle Donne D, Ripepe M (2015) Enhanced volcanic hot-spot detection using MODIS IR data: results from the MIROVA system. In: Harris AJL, De Groeve T, Garel F, Carn SA (eds) *Detecting, Modelling, and Responding to Effusive Eruptions*. Geological Society, London, Special Publications, 426, first published on May 14, 2015, doi: 10.1144/SP426.5

Field L, Barnie T, Blundy J, Brooker RA, Derek K, Lewi E, Saunders K (2012) Integrated field, satellite and petrological observations of the November 2010 eruption of Erta Ale. Bull Volcanol 74(10):2251-2271.

Francis PW, Oppenheimer C, Stevenson D (1993) Endogenous growth of persistently active volcanoes. Nature 366:554–557

Geyer A, Folch A, Martì J (2006) Relationship between caldera collapse and magma chamber withdrawal: An experimental approach. J Volcanol Geotherm Res 157 (4):375-386

Harris AJL, Flynn LP, Rothery DA, Oppenheimer C, Sherman SB (1999) Mass flux measurements at active lava lakes: Implications for magma recycling. J Geophys Res 104 (B4):7117-7136

Head EM, Shaw AM, Wallace PJ, Sims KWW, Carn S (2011) Insight into volatile behavior at Nyamuragira volcano (D.R. Congo, Africa) through olivine-hosted melt inclusions. Geochem Geophys Geosyst 12:Q0AB11. doi:10.1029/2011GC003699

Hirn A, Lépine J, Sapin M, Delorme H (1991) Episodes of pit-crater collapse documented by seismology at Piton de la Fournaise. J Volcanol Geotherm Res 47:89-104

Hoier R (1939) Contribution à l'étude de la morphologie du volcan Nyamuragira. Exploration du Parc National Albert: Institut des parcs nationaux du Congo Belge.

Kazahaya K, Shinohara H, Saito G (1994) Excessive degassing of Izu-Oshima volcano: Magma convection in a conduit. Bull Volcanol 56:207–216

Kyambikwa Milungu A, Mavonga Tuluka G, Birimwiragi Namogo D, Etoy Osodundu M (2013) Analyse del l’activitè magmatique du volcan Nyamulagira par la mesure sismique des amplitudes à temps réel (RSAM) durant le période du Mars au 6 Novembre 2011. Book of Abstract, Active Volcanism & Continental Rifting, (AVCOR) International conference 12-15 November 2013, Gisenyi, Rwanda. (http://avcor2013.africamuseum.be/)

Lénat JF, Bachèlery P (1990) Structure and dynamics of the central zone of Piton de la Fournaise volcano. In: Lénat JF (ed) Le volcanisme de la Réunion, Monographie. Cent. De Rech. Volcanol, Clermont Ferrand, pp.257–296

Longpré MA, Staudacher T, Stix J (2007) The November 2002 eruption at Piton de la Fournaise volcano, La Réunion Island: ground deformation, seismicity, and pit-crater collapse. Bull Volcanol 69(5):511-525. doi:10.1007/s0044500600870

Mavonga T, Zana N, Durrheim RJ (2010) Sudies of crustal structure, seismic precursors to volcanic eruptions and earthquake hazard in the eastern provincies of the Democratic Republic of Congo Journal African Earth Sciences 58:623-633

Németh K, Cronin J (2008) Volcanic craters, pit-craters and high-level magma-feeding systems of mafic island-arc volcano: Ambrym, Vanuatu, South Pacific. In: Thomson K, Petford N (eds), Structure and Emplacement of High-Level Magmatic Systems, Geological Society, London, Special Publications, 302:85-99

Patrick M, Orr T, Sutton AJ, Elias T, Swanson D (2013) The first five years of Kilauea’s summit eruption in Halema’uma’u crater, 2008-2013. U.S. Geological Survey Fact Sheet 2013–3116. http://dx.doi.org/10.3133/fs20133116

Peltier A, Bachèlery P, Staudacher T (2009) Magma transport and storage at Piton de La Fournaise (La Réunion) between 1972 and 2007: A review of geophysical and geochemical data. J Volcanol Geotherm Res 184:93-108

Peltier A, Poland M, Staudacher T (2015) Are Piton de la Fournaise (La Réunion) and Kīlauea (Hawai'i) Really "Analog Volcanoes"?, in Hawaiian Volcanoes: From Source to Surface (eds R.

Carey, V. Cayol, M. Poland and D. Weis), John Wiley & Sons, Inc, (ch 23), doi: 10.1002/9781118872079.

Poland MP, Sutton AJ, Gerlach TM (2009) Magma degassing triggered by static decompression at Kīlauea Volcano, Hawai‘i. Geophysical Research Letters 36:L16306. doi:10.1029/2009GL039214

Poland MP, Miklius A, Montgomery-Brown EK (2014) Magma supply, storage, and transport at shield-stage Hawaiian volcanoes, in Characteristics of Hawaiian Volcanoes. (eds. Mp Poland, TJ Takahashi, CM Landowski), US Geological Survey Professional Paper 1801 (ch. 5)

Poppe S, Smets B, Albino F, Kervyn F, Kervyn M (2013) A new volcano-structural map of the Virunga Volcanic Province, D.R.Congo and Rwanda. EGU General Assembly 2013, 7-12 April, 2013. Abstract id: EGU2013-7131

Pouclet A (1975) Activités du Volcan Nyamuragira (rift ouest de l'Afrique centrale), évaluation des volumes de materiaux emis. Bull Volcanol 39 (3):466-478

Ripepe M, Delle Donne D, Genco R, Maggio G, Pistolesi M, Marchetti E, Lacanna G, Ulivieri G, Poggi P (2015) Volcano seismicity and ground deformation unveil the gravity-driven magma discharge dynamics of a volcanic eruption. Nature Communications 6 (6998). doi: 10.1038/ncomms7998

Rothery DA, Coppola D, Saunders C (2005) Analysis of volcanic activity patterns using MODIS thermal alerts. Bull Volcanol 67:539–556

Rymer H, Vay Wyk de Vries B, Stix J, Williams-Jones G (1998) Pit-crater structure and processes governing persistent activity at Masaya Volcano, Nicaragua. Bull Volcanol 59(5):345-355

Shinohara H (2008) Excess degassing from volcanoes and its role on eruptive and intrusive activity. Review of Geophysics 46 (4): RG4005. doi:10.1029/2007RG000244

Smets B, Wauthier C, d’Oreye N (2010) A new map of the lava flow field of Nyamulagira (D.R. Congo) from satellite imagery. Journal African Earth Science 58 (5):778–786

Smets B, D'Oreye N, Kervyn F (2014) Toward another lava lake in the Virunga Volcanic Field. Eos, Transactions American Geophysical Union 45 (42). doi: 10.1002/014EO420001

Spampinato L, Ganci G, Hernandez PA, Calvo D, Tedesco D, Pérez NM, Calvari S, Del Negro C, Yalire, MM (2013) Thermal insights into the dynamics of Nyiragongo lava lake from ground and satellite measurements. J Geophys Res 118 (11):5771-5784

Tedesco T, Vaselli O, Papale P, Carn SA, Voltaggio M, Sawyer GR, Durieux J, Kasereka M, Tassi F (2007) The January 2002 Volcano-Tectonic Eruption of Nyiragongo volcano, Democratic Republic of Congo. J Geophys Res 112:B09202. doi: 10.1029/2006JB004762

Toombs A, Wadge G (2012) Co-eruptive and inter-eruptive surface deformation measured by satellite radar interferometry at Nyamuragira volcano, D.R. Congo, 1996 to 2010. J Volcanol Geotherm Res 245–246:98–122. doi:10.1016/j.jvolgeores.2012.07.005

Villeneuve M (1980) La structure du Rift Africain dans la region du Lac Kivu (Zaire oriental). Bull Volcanol 43:541–551.

Verhoogen J (1939) Les volcans Virunga et 1'éruption du Nyamulagira de 1938 (note préliminaire). Ann Soc Géol Belg 62:326-353

Wadge G (1981) The variation of magma discharge during basaltic eruptions: J Volcanol Geotherm Res 11:139–168

Wadge G, Burt L (2011) Stress field control of eruption dynamics at a rift volcano: Nyamuragira, D.R. Congo: J Volcanol Geotherm Res 207:1–15. doi: 10.1016/j.jvolgeores.2011.06.012

Wauthier C, Cayol V, Poland M, Kervyn F, D'Oreye N, Hooper A, Samsonov S, Tiampo K, Smets B (2013) Nyamulagira's magma plumbing system inferred from 15 years of InSAR,in Remote Sensing of Volcanoes and Volcanic Processes: Integrating Observation and Modelling (eds. DM Pyle, TA Mather, J Biggs J). Geological Society, London, Special Publications, 380.

Wood DA, Zal HJ, Scholz CA, Ebinger CJ, Nizere I (2015) Evolution of the Kivu Rift, East Africa: interplay among tectonics, sedimentation and magmatism. Basin Research (on line first): doi: 10.1111/bre.12143

World Food Program (2010) Fighting Hunger Worldwide - The World Food Programme's Year in Review, 2010. Available on line at:
http://documents.wfp.org/stellent/groups/public/documents/communications/wfp236112.pdf

Wright R, Pilger E (2008) Radiant flux from Earth's sub-aerially erupting volcanoes. Int J Remote Sens 29(22):6443–6466. doi:10.1080/ 01431160802168210

Yang K, Krotkov NA, Krueger AJ, Carn SA, Bhartia PK, Levelt PF (2007) Retrieval of large volcanic SO_2 columns from the Aura Ozone Monitoring Instrument: Comparison and limitations. J Geophys Res 112 (D24):D24S43. doi: 10.1029/2007JD008825

Figure Captions

Figure 1. (a) Map of Virunga Volcanic Province (VVP) within the Western branch of the Eastern African Rift. Thick red lines show major normal rift faults for this sector of the Eastern African Rift (from Villeneuve 1980). The white field indicates the alignment of Virunga dormant volcanoes; thin black lines represent the main eruptive fissures of 1990 through 2010 at Nyamulagira and Nyiragongo volcanoes (modified after Poppe et al. 2013). The yellow field marks the NNW fissure zone lying between Nyamulagira and Nyiragongo volcano in DRC (Democratic Republic of Congo). The "rift-parallel" 2011-2012 eruptive fissure (ENE oriented) and the related lava field (white dashed line) are also shown; (b) A detail of Nyamulagira's summit caldera and (c) Nyiragongo summit caldera, with their respective lava lakes imaged on February 9th, 2015 by the Operational Land Imager (OLI -Landsat 8; Band combination: 754).

Figure 2- (a) Overview of Virunga area as seen by the Enhanced Thematic Mapper Plus (ETM+ Landsat 7) on March 28th 2012; (b) detail of the 2011-2012 lava field; (c) detail of the eruptive

fissure and main vents propagating from SW (V_1) to NE (V_3). DRE fluxes (d) and volumes (e) retrieved for erupted (red) and outgassed (blue) magma recorded during the 2011-2012 eruption (cf., the section Methods). During *phase I* effusive activity was accompanied by a syn-eruptive outgassing, but during *phase II* erupted magma released relatively little SO_2. Explosion quakes (yellow stars) mark the transition from lateral to central activity (see text for details).

Figure 3. (a) Volcanic Radiative Power (VRP) at Nyamulagira and Nyiragongo volcanoes between September 2011 and April 2015. Light gray stems define steady heat flux from the Nyiragongo lava lake. Dark gray stems refer to the 2011-2012 distal eruption of Nyamulagira. Red stems represent the heat flux associated with the thermal activity of Nyamulagira's pit-crater following the explosion quakes of February 23rd, 2012 (yellow stars); (b) Trend of SO_2 emission rates from the Virunga volcanoes during 2011-2014, measured using OMI and ASTER images.

Figure 4 - Re-birth of the Nyamulagira lava lake as seen from space (a-f) and from helicopter surveys (g-n). The gradual rise of the column of magmatic was accompanied by increasing thermal anomalies, strong degassing, and formation of ring faults plus incremental collapse of the pit-crater walls. On June 2014 the lava lake was reported for the first time by field observers. Details on satellite images can be found in Methods; pictures taken by D. Tedesco.

Figure 5 –Re-birth of Nyamulagira lava lake according to the draining-refilling model. (a) Pre-eruptive condition: residual outgassed magma pockets, accumulated along NNW trending zone during previous eruptions, cool within the edifice and form an intrusive complex. Some magma remains in pocket(s); (b) the injection of a 12 km long rift-parallel dike caused the intense eruption of deep-sourced undegassed magma along the distal eruptive fissure(s) [*phase I*]; (c) the plumbing joint between the lateral dike and the central conduit caused the gravity-driven drainage of the

residual outgassed magma residing at shallow depths; eruption of a SO_2-depleted magma [*phase II*]; (d) a series of explosion quakes marks the opening of a central magma path through the collapsing pit-crater; complete cessation of lateral effusive activity; (e) the uninterrupted magma supply causes the rise of magma column and refilling of the shallow plumbing system; high outgassing from the summit; (f) appearance of the new lava lake within the pit-crater. Numbers above the lava flow and the eruptive plume represent erupted and outgassed magma fluxes, respectively.

Figure 6 – (a) Erupted (red) and outgassed (blue) magma volumes (DRE) related to the 17 eruptions occurred at Nyamulagira between 1980 and 2012 (data from Bluth and Carn 2008; Head et al. 2011; Smets et al. 2010; Wadge and Burt 2011; Coppola and Cigolini 2013; Campion 2014, this study; see Table 1). (b) Balance between outgassed and erupted magma volumes. The 1991-93 and the 2011-12 rift-parallel, long-lived eruptions (black arrows) are the only two events displaying a strong SO_2 deficit suggesting the drainage of a shallow outgassed magma body. (c) Cumulative trend of outgassed and erupted magma volume since 1980, about 25% of outgassed magma remains "unerupted". Note how the transition from lateral to central activity (gray field) does not seem to be related to a substantial change in the long-term magma supply.

Figure 7 - Detail of the northern shore of the Lake Kivu with the major lava flows that occurred along the southern flank of Nyamulagira (1938 and 1948) and Nyiragongo (2002). Notably, the 1938 Nyamulagira's eruption drained the summit lava lake, hosted within the eastern pit-crater since 1930. The lava field produced by the eruptive fissures on the southern flank quickly reached the Kabuno Gulf, and cut the main road (N2) connecting Sake to Goma towns. Shaded red and green areas represent lava fields of Nyamulagira and Nyiragongo, respectively.