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## Birth of a lava lake: Nyamulagira volcano 2011-2015

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## UNIVERSITÀ DEGLI STUDI DI TORINO

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31 **Birth of a lava lake: Nyamulagira volcano 2011-2015**

32  
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56 **ABSTRACT**

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

76

77 **Keywords:** Nyamulagira, lava lake, heat flux, SO<sub>2</sub>, magma supply rate, stress field

78

79 **INTRODUCTION**

80 Lava lakes are rare features, with only a few currently active on Earth. No lava lake has directly  
81 been observed during its early development, and the opportunity to follow the “re-birth” of a lava

82 lake should also be regarded as a very rare one (i.e., Patrick et al. 2013). The Virunga Volcanic  
83 Province (VVP), at the northern end of the Kivu Basin (Western branch of the Eastern African Rift;  
84 Fig.1a) is characterized by eight volcanoes, and the two youngest and most westerly ones,  
85 Nyiragongo and Nyamulagira (Democratic Republic of Congo; DRC), currently host two  
86 independent lava lakes (Fig. 1).

87

## 88 **Figure 1**

89

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

94 In particular, after 1938, the volcano behaved as a closed degassing system (no gas was being  
95 vented between eruptions) that erupts when a threshold volume or pressure is reached. Hence, the  
96 dikes cross-cutting the volcanic edifice fed two distinct types of eruptions (Wadge and Burt, 2011):  
97 *i*) eruptions fed by dikes perpendicular to the East African Rift Valley (*rift-perpendicular*; i.e.  
98 occurring along the NNW fissure trending zone; Fig. 1a) characterized by small volumes and short  
99 durations; *ii*) eruptions fed by dikes trending sub-parallel to the rift (*rift-parallel*) lasting more than  
100 90 days and pouring out larger volumes of lava. However, a significant change in the eruptive style  
101 of the volcano was noted in late June 2014, when, after 76 years, a small lava lake was first  
102 observed within the eastern pit-crater (Campion 2014; Smets et al. 2014; Fig. 1b).

103 Analysis of satellite-based thermal and SO<sub>2</sub> data coupled with periodic field surveys, allowed us  
104 to track the gradual development of this lava lake, which we found to have started more than two  
105 years earlier, in March 2012. By combining the magma budget of the recent activity (IR-derived  
106 and SO<sub>2</sub>-derived) with those recorded during the previous 35 years of activity, we propose a model

107 for the lava lake's formation and we discuss the hazard related to the new eruptive regime now in  
108 place at Nyamulagira.

## 109 **METHODS**

110

### 111 *Thermal emissions*

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

126

$$127 \quad VRP = 18.9 \times A_{PIX} \times \sum_1^{n_{alert}} (L_{4_{alert}} - L_{4_{bk}}) \quad (1)$$

128

129 where  $A_{PIX}$  is the pixel size (1 km<sup>2</sup> for the resampled MODIS pixels),  $n_{alert}$  is the number of alerted  
130 pixel(s),  $L_{4_{alert}}$  and  $L_{4_{bk}}$  are the 4  $\mu\text{m}$  radiance of the alerted and background pixel(s), respectively  
131 (see Coppola et al. 2015 for more details). Finally, by manually checking the processed images, we

132 discarded all the cases where the thermal signal was undoubtedly attenuated or completely masked  
133 by the presence of clouds (Coppola and Cigolini 2013).

134

135 *Erupted magma flux (VRP-derived)*

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

138

$$139 \quad TADR = \frac{VRP}{c_{rad}} \quad (2)$$

140

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

148

149 *Sulphur emission rates*

150 Measurements of the  $\text{SO}_2$  emission rates were obtained from the satellite images of OMI (Ozone  
151 Monitoring Instrument, operating in the UV) and ASTER (Advanced Spaceborne Thermal  
152 Emission and Reflection radiometer, operating in the visible and Thermal Infrared). For OMI, the  
153  $\text{SO}_2$  emission rate was calculated by applying the traverse method (Campion et al. 2012; Campion  
154 2014) to the  $\text{SO}_2$  column amount images OMI\_ $\text{SO}_2$  product, released in near-real time by NASA  
155 using the linear fit algorithm (Yang et al. 2007). The ASTER images were processed with the band  
156 ratio algorithm (Campion et al. 2010) to derive  $\text{SO}_2$  column amounts, and then processed with the

157 same traverse method to obtain the SO<sub>2</sub> emission rates. OMI's ground resolution (13 x 25 km at  
158 nadir) is too coarse for distinguishing the sources of the SO<sub>2</sub> emissions within the Virunga Volcanic  
159 Province, but its relatively high imaging frequency gives a suitable time resolution for real  
160 monitoring. Conversely, the high ground resolution of ASTER allows quantifying the emissions of  
161 Nyamulagira and Nyiragongo separately (Campion 2014), but only a few images are sufficiently  
162 cloud-free over the period of interest. Based on the analyzed ASTER images here, we assume an  
163 average SO<sub>2</sub> emission of ~10 kg s<sup>-1</sup> due to the degassing of Nyiragongo lava lake.

164

165 *Outgassed magma flux (SO<sub>2</sub>-derived)*

166 Measurements of the discharged SO<sub>2</sub>, combined with an estimate of the amount of molten sulphur  
167 in the lava, have been used to constrain rates of magma supply ( $Q_{[SO_2]}$ ) within the shallow  
168 degassing and outgassing system (Kazahaya et al. 1994; Shinohara 2008). Here, we used a  
169 simplified approach on the basis of the following relationship:

170

$$171 \quad Q_{[SO_2]} = 10^6 \frac{E_{SO_2}}{2\Delta S \rho_M} \quad (3)$$

172

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



181 Integrating the sulphur degassing rate with time equation 3 has allowed us to convert the total mass  
182 of SO<sub>2</sub> emitted during distinct eruptions into volume of outgassed magma as summarized in Table  
183 1.

184

#### 185 *High-resolution multispectral images*

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

192

#### 193 *Field Surveys*

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

201

### 202 **SPACE- AND FIELD-BASED OBSERVATIONS**

203 On November 6, 2011, after 644 days of rest, one of the longest (~140 days) and most  
204 voluminous (>200 Mm<sup>3</sup>) eruptions of Nyamulagira volcano started on the eastern flank of the main  
205 edifice (Coppola and Cigolini, 2013). In contrast to the previous eruptions (i.e. Smet et al. 2010;  
206 Wadge and Burt 2011), the new eruptive fissure did not open along the main NNW trending rift

207 zone, but along a perpendicular (ENE-oriented) direction, and about 12 km from the volcano  
208 summit (Fig. 1). Lava and gas emissions reached their peak values ( $> 100 \text{ m}^3 \text{ s}^{-1}$ ) within the first  
209 days of activity (Fig. 2d), when intense lava fountains, 300 m high, built a new spatter cone ( $V_1$  in  
210 Fig. 2d) and fed a lava flow extending 11.5 km northward (Fig. 2b). Although initially very intense,  
211 the effusion of lava during the first days of activity declined gradually with time and was  
212 accompanied by a reduction in sulphur emissions, which is a typical result of syneruptive  
213 outgassing (Fig 2d). This initial eruptive phase (hereby defined *phase I*) was characterized by lava  
214 emission lasting about three weeks and erupted about  $60 \text{ Mm}^3$  of magma (Fig. 2e), similar in every  
215 way to the “archetypal” eruption style of Nyamulagira (i.e. Wadge 1981; Wadge and Burt 2011).

216 In late November 2011, however, the effusive activity increased again and accompanied  
217 propagation of the eruptive fissure about 500-1000 m downslope and the progressive building of  
218 two other elongate spatter- and scoria-cones, named  $V_2$  and  $V_3$  (Fig. 2c). This renewed effusive  
219 activity (*phase II*) was not accompanied by a coeval increase in sulphur emission (except for short  
220 pulses concomitant with the opening of vents  $V_2$  and  $V_3$ ; Fig. 2d), which suggests the eruption of a  
221 relatively  $\text{SO}_2$ -depleted magma. The effusion from  $V_2$  and  $V_3$  diminished throughout December  
222 2011 and January 2012, showing a gently declining trend that persisted until the end of February  
223 2012. At this time, the lava flow field had already reached its final length with a DRE volume of  
224 about  $210 \text{ Mm}^3$ . *Phase II* was thus characterized by a long lived ( $\sim 100$  days) and voluminous ( $\sim 150$   
225  $\text{Mm}^3$ ) effusion of relatively outgassed magma (Fig. 2e).

226

## 227 **Figure 2**

228

229 A major change in the eruptive dynamics occurred on February 23<sup>rd</sup>, 2012, when a series of  
230 shallow explosion quakes was recorded below the pit-crater (stars in Fig. 2 and 3). Field  
231 observations made a few days after the explosions revealed the presence of meter-scale lithic blocks  
232 within the whole summit caldera, though no evidence of juvenile material (i.e. fresh scoria, ash,

233 Pele's hair) was found. On the other hand, spectacular ring faults (with vertical displacements of  
234 several meters) appeared within and around the pit-crater (Fig. 4h), indicating subsidence above a  
235 partially open, or emptying, reservoir at very shallow depth. These explosions marked a change in  
236 the sites of venting at Nyamulagira, which shifted from the distal flank vent(s) to the summit pit-  
237 crater (Fig. 3).

238

### 239 **Figure 3**

240

241 During the following weeks: (i) the effusion rate at the lateral vent(s) (and related thermal  
242 anomalies) sharply decreased and then ceased entirely on March 28<sup>th</sup> 2012 (Fig. 3a; Coppola and  
243 Cigolini 2013); (ii) small thermal anomalies gradually appeared within the pit-crater (Fig. 3a and 4);  
244 and finally, (iii) intense outgassing from the summit caldera was observed (Fig. 3b and 4; Campion  
245 2014).

246

### 247 **Figure 4**

248

249 There were no thermal anomalies within the pit-crater during the weeks before the summit  
250 explosions (Fig 4a) and first detected by MODIS a couple of weeks later (on March 14<sup>th</sup>, 2012; Fig.  
251 3). A small, shallow heat source was confirmed by Landsat ETM+ image (March 28<sup>th</sup>, 2012), with a  
252 60-90 m diameter hotspot visible on the southern side of the pit-crater (Fig.4b); the hotspot suggests  
253 that explosions of February 2012 opened a central magma path, providing a “window” into  
254 Nyamulagira's uppermost magmatic system.

255 In following months the pit-crater's morphology evolved by multiple rockfall collapses, in  
256 “onion skin” mode, within the summit vent and then by thermal and chemical erosion of the crater  
257 walls (Fig. 4h-i). During 2013 summit outgassing persisted well above the emission rates of  
258 Nyiragongo (Fig. 3b), and distinct pulses alternated with intermittently detected small thermal

259 anomalies (0.5-5 MW) at the bottom of the pit-crater (Fig. 3a and 4c). In April and early June 2014  
260 thermal anomalies exceeded 10 MW for the first time, suggesting a heat source at the surface (Fig.  
261 3a). On June 24<sup>th</sup> visual observations confirmed the presence of a lava lake (~ 50 m diameter) at the  
262 bottom of the pit-crater (~ 500 m depth; Fig.4d), with the lava lake well exposed at the surface (Fig.  
263 4l) producing suddenly increased heat flux, up to ~ 200 MW.

264 A field survey on November 1<sup>st</sup>, 2014 showed that level of the lava lake had drastically increased  
265 (~325 meters below the pit-crater rim) and continuous and large collapses of the pit-crater walls  
266 were still occurring. Molten lava was visible through two “skylights” (< 50 m diameter each) while  
267 most of the lava lake was apparently covered by a layer of solidified lava and welded scoriae (Fig.  
268 2m). On November 26<sup>th</sup>, 2014, MODIS detected the highest radiant flux (440 MW) since the  
269 appearance of Nyamulagira’s lava lake (Fig. 3a). Possibly, this increase reflected the rupture of the  
270 solidified layer and/or a further enlargement of the lake surface that persisted throughout the first  
271 months of 2015 (Fig. 4n). As a comparison, during 2012-2015, the well-established (~200 m  
272 diameter) Nyiragongo’s lava lake produced a VRP of 1000-1200 MW as shown in Fig. 3 (cf.,  
273 Spampinato et al. 2013).

274

## 275 **RE-FORMATION AND DEVELOPMENT OF NYAMULAGIRA LAVA LAKE**

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

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

- 284           • the magma plumbing system must be able to accommodate the descending magma mass  
285           by recycling, intruding, and/or cumulating processes (Francis et al. 1993, Harris et al.  
286           1999);
- 287           • the local tectonic setting (including the stress field and mechanical properties of the  
288           edifice) must enable the top of the magma column to reach the free surface without  
289           triggering flank failure or lateral magma injection (Battaglia et al. 2011), with consequent  
290           drainage of the lake itself (i.e., Tedesco et al. 2007).

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

293           We estimated that between March 2012 and April 2015, about ~3.3 Mt of SO<sub>2</sub> were released by  
294           Nyamulagira volcano with a time averaged emission rate of ~35 kg s<sup>-1</sup>. According to equation 3, we  
295           thus calculate that the DRE volume of magma that outgassed at shallow depth in this period was  
296           about 235 Mm<sup>3</sup> (~2.3 m<sup>3</sup> s<sup>-1</sup>).

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

302           The analysis of pre-eruptive seismicity suggests that 10 months before the 2011-2012 eruption,  
303           earthquakes were consistent with a deep (10 - 30 km) magmatic intrusion in the area beneath  
304           Nyamulagira (Bondo et al. 2015). After April 2011, hypocenters migrated upward and were  
305           associated with magma intrusion at shallower depths (~5 km), as also observed during previous  
306           eruptions (Mavonga et al. 2010; Wauthier et al. 2013). Increasing seismic activity culminated in  
307           energetic seismic swarms on September 2011 and finally on November 5<sup>th</sup>, 2011, just one day  
308           before the onset of the eruption (Kyambikwa Milungu et al. 2013). At this time, both deep and

309 shallow seismicity extended several kilometres along the ENE direction, thus suggesting lateral  
310 propagation of a dike that would feed the eruptive fissure(s) (Bondo et al. 2015).

311 Notably, the dike/eruptive fissure of 2011-12 eruption was perpendicular to dominant axis of  
312 volcanic activity since the early 1990s (the NNW fissure trending zone; Fig. 1; cf. Wadge and Burt,  
313 2011) and was parallel to the alignment of the older central volcanoes ENE ( $065^\circ$ ) (see Fig. 1a).  
314 Preliminary InSAR data, made by the GORISK team (see GORISK Web site:  
315 <http://www.ecgs.lu/gorisk/volcanoes/nyamulagira/eruptive-activity/november-2011-eruption/4>) also  
316 suggests that the 2011-12 eruption produced the largest deformation detected at Nyamulagira since  
317 early 1990s, characterized by a 20 km wide subsidence probably associated with withdrawal of  
318 magma from a large deep reservoir (Albino et al. 2013).

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

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

333

334 The above analyses and observations give us the opportunity to propose a basic “draining-  
335 refilling” model (Fig. 5) whereby the re-birth of the Nyamulagira lava lake occurred in response to  
336 the modified stress field associated with the 2011-12 lateral eruption. In particular, we suggest that  
337 the injection of the 12 km long dyke along the ENE direction, the partial withdrawal of magma  
338 from a deep ( $> 5$  km) undegassed magma chamber (*phase I*; Fig. 5b), and the emplacement of a  
339 lateral dike cross-cutting the upper portion of the conduit have somehow perturbed the stress field  
340 acting on the volcano edifice. Hence, the new stress conditions favoured the drainage of outgassed  
341 magma residing at shallow depths (1-2 km) that had probably accumulated during the previous  
342 eruption(s) along the NNW zone (Fig 5c). A gravity-driven magma discharge dynamic (Ripepe et  
343 al. 2015) produced the waning trend observed during *phase II*, and triggered the onset of the pit-  
344 crater collapse (Fig. 5d-e). Then, the flank eruption progressively ceased and the continuous supply  
345 of more deeply sourced magma slowly refilled the damaged shallow plumbing system (Fig. 5f). At  
346 this point, the floor of the pit-crater may have been excavated to sufficient depth that it provided a  
347 “window” into the uppermost magmatic system as it refilled. Hence, the lava lake slowly crept  
348 upwards and enlarged in area as the system approached its pre-flank-eruption pressure state (Fig.  
349 5g).

350

## 351 **Figure 5**

352

### 353 **LONG TERM ERUPTED – OUTGASSED MAGMA BUDGET**

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

358 The existence of such pockets under Nyamulagira caldera is still debated ( i.e. Toombs and  
359 Wadge 2012; Wauthier et al. 2013), but sub-surface (1-2 km depth) small-volume ( $< 1 \text{ km}^3$ ) magma

360 storage zones have been reported at Piton de la Fournaise and Kilauea volcanoes (Poland et al.  
361 2009, 2014; Peltier et al. 2009, 2015). At Piton de la Fournaise, for example, superficial transient  
362 storage zones, composed of small magma pockets scattered between the volcano's summit and sea  
363 level, have been shown to form and develop during periods of frequent effusive activity (Lénat and  
364 Bachèlery 1999). The draining of these shallow magma reservoirs during distal eruptions was  
365 thought to trigger pit-crater collapses inside the Dolomieu crater like those in 1986 and 2002 (Hirn  
366 et al. 1991; Longpré et al. 2002). Similarly, Kīlauea's summit caldera recently experienced the “re-  
367 birth” of a lava lake (within the so-called “Overlook crater”) throughout a sequence of events very  
368 similar to those currently observed at Nyamulagira (Patrick et al. 2013; Poland et al. 2014). These  
369 include: (i) lateral magma injection (>10 km) and magma withdrawal to feed intrusions and  
370 eruptions along a rift-parallel zone; (ii) upward migration of a central collapse front; (iii) pit-crater  
371 opening through explosion(s) involving lithic blocks (no juvenile material); (iv) strong magmatic  
372 outgassing; (v) gradual rise and growth of a lava lake through episodic collapse of the crater walls,  
373 impulsive outgassing, and occasional weak explosive events. The similarity in the processes  
374 observed at Piton de la Fournaise, Kilauea, and Nyamulagira (Campion 2014) supports the  
375 existence of a transient shallow storage zone also beneath the summit caldera of Nyamulagira,  
376 whose draining and refilling dynamics form the basis of the proposed model.

377 Satellite-based measurements of SO<sub>2</sub> and erupted magma volumes since 1980 (Bluth and Carn  
378 2008; Head et al. 2011; Smets et al. 2010, Wadge and Burt 2011; Coppola and Cigolini 2013;  
379 Champion 2014, this study), allowed us to constrain the outgassed-erupted magma partitioning  
380 during the last 35 years of activity at Nyamulagira (Fig. 6). The analysis of 17 eruptions (Table 1)  
381 reveals that only two of them were characterized by a clear SO<sub>2</sub> deficit, namely the 1991-1993 and  
382 the 2011-12 eruptions (Fig. 6). It is worth noting that these two unique SO<sub>2</sub>-poor eruptions represent  
383 the most voluminous (> 200 Mm<sup>3</sup>), long lived (> 100 days) *rift-parallel* eruptions of the past  
384 decades, and their deficit in sulphur emissions probably reflects the drainage of the central, shallow,  
385 and outgassed portion of the plumbing system. Conversely, all the other eruptions display a variable



386 outgassed-erupted partitioning, spanning from syneruptive outgassing (i.e. 1980, 1984, 1986, 1987,  
387 1996, 2000, 2001, 2010) to SO<sub>2</sub> excess, which has been frequently observed at Nyamulagira  
388 volcano (i.e. 1981, 1989, 1994, 1998, 2002, 2004, and 2006 cf. Bluth and Carn 2008; Head et al.  
389 2011).

390

## 391 **Figure 6**

392

393 All these data suggest that the upper portion of the Nyamulagira's plumbing system has been  
394 recurrently fed and replenished especially by short-lived *rift-perpendicular* eruptions that occurred  
395 along the NNW fissures. These eruptions, often characterized by a strong SO<sub>2</sub> excess, may have left  
396 batches of residual (unerupted) degassed magma (i.e., sill-like magma pocket and slowly cooling  
397 dikes) that were occasionally drained during major *rift-parallel* eruptions (as possibly occurred on  
398 1938-40, 1948, 1991-1993 and 2011-2012).

399

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

402 • Although each single eruption may be characterized by a variable gas-magma partitioning,  
403 the ratio between outgassed and erupted magma volumes seems to be relatively constant over the  
404 latest 35 years, and roughly equal to 1.25 (cf. Fig. 6c). We infer that since 1980, about 1.5 km<sup>3</sup> of  
405 magma has been erupted (Mean Output Rate; MOR<sub>DRE</sub> = 1.3 m<sup>3</sup>s<sup>-1</sup>) while 0.5 km<sup>3</sup> has been cycled  
406 back (stored or intruded) in the plumbing system after outgassing (at mean rate of 0.4 m<sup>3</sup>s<sup>-1</sup>).

407 • The transition from closed-system degassing, preceding the flank eruption, to an open-  
408 system centrally outgassing system (late February 2012) does not seem to follow, or to be followed  
409 by a substantial change in the long term magma supply, which conversely seems to have continued  
410 at the same rate since 1980 (about 1.8 m<sup>3</sup> s<sup>-1</sup> DRE; Fig 6c). As emphasized by Campion (2014), this

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

413

#### 414 **Table 1**

415

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

419 This open, outgassing, condition was probably reached also between 1930 and 1938 when  
420 efficient magma convection and outgassing sustained the lava lake for about 9 years (Pouclet,  
421 1975).

422

#### 423 **PRESENT ACTIVITY AND RELATED HAZARDS**

424

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

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

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

442

#### 443 **Figure 7**

444

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

449 Together with the extremely acidic gases ( $\text{SO}_2$ -HCl-HF-rich) and ash and Pele's hairs, the major  
450 hazard is related to lava flows that may reach highly populated areas (as during the 1938 eruption;  
451 Fig. 7). An additional risk results from the presence of more than one thousand United Nations  
452 personnel, the F.I.B. (Force Intervention Brigade), located on the shores of Lake Kivu, just one  
453 kilometre from the southern side of the city of Sake (Fig 7).

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

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

461 80% of charcoal (used for cooking by more than 95% of the population) comes from the western  
462 side of the rift, the Sake area (World Food Program 2010). However, both in 1938 and 1948, the  
463 road was covered by lava, inhibiting transportation. In case of a major eruptive event with similar  
464 damage, there could be a serious shortage of food causing possible social instability.

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

470

## 471 **CONCLUSIONS**

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

483 The mechanisms reported in this study shares similarities with those that occurred during the  
484 formation and evolution of other lava lakes such as: Kilauea (Patrick et al. 2013), Ambrym (Németh  
485 and Cronin 2008), Masaya (Rymer et al. 1998) as well as the neighbouring Nyiragongo lava lake  
486 (Tedesco et al. 2007). This suggests that a draining-refilling model at steady-state basaltic

487 volcanoes can easily shift from lateral to central activity thus promoting the (re)-birth of a lava lake  
488 or the renewal of volcanic activity at the summit (as in the case of Stromboli, e.g., Calvari et al.  
489 2005, 2010). This process can be tracked by using thermal and SO<sub>2</sub> satellite-derived data that have  
490 been shown to be strategic in decoding the renewal of central vent activity at Nyamulagira volcano.  
491 The presence of a lava lake at the summit of Nyamulagira is a major hazard due to the large local  
492 population and requires further attention and collaborative efforts both in terms of volcano  
493 surveillance and information to mitigate volcanic risk.

494

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505

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650

651

## 652 **Figure Captions**

653

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

664

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

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

672

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

679

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

685

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

692 residual outgassed magma residing at shallow depths; eruption of a SO<sub>2</sub>-depleted magma [*phase III*];  
693 (d) a series of explosion quakes marks the opening of a central magma path through the collapsing  
694 pit-crater; complete cessation of lateral effusive activity; (e) the uninterrupted magma supply causes  
695 the rise of magma column and refilling of the shallow plumbing system; high outgassing from the  
696 summit; (f) appearance of the new lava lake within the pit-crater. Numbers above the lava flow and  
697 the eruptive plume represent erupted and outgassed magma fluxes, respectively.

698

699 **Figure 6** – (a) Erupted (red) and outgassed (blue) magma volumes (DRE) related to the 17  
700 eruptions occurred at Nyamulagira between 1980 and 2012 (data from Bluth and Carn 2008; Head  
701 et al. 2011; Smets et al. 2010; Wadge and Burt 2011; Coppola and Cigolini 2013; Campion 2014,  
702 this study; see Table 1). (b) Balance between outgassed and erupted magma volumes. The 1991-93  
703 and the 2011-12 rift-parallel, long-lived eruptions (black arrows) are the only two events displaying  
704 a strong SO<sub>2</sub> deficit suggesting the drainage of a shallow outgassed magma body. (c) Cumulative  
705 trend of outgassed and erupted magma volume since 1980, about 25% of outgassed magma remains  
706 “unerupted”. Note how the transition from lateral to central activity (gray field) does not seem to be  
707 related to a substantial change in the long-term magma supply.

708

709 **Figure 7** - Detail of the northern shore of the Lake Kivu with the major lava flows that occurred  
710 along the southern flank of Nyamulagira (1938 and 1948) and Nyiragongo (2002). Notably, the  
711 1938 Nyamulagira’s eruption drained the summit lava lake, hosted within the eastern pit-crater  
712 since 1930. The lava field produced by the eruptive fissures on the southern flank quickly reached  
713 the Kabuno Gulf, and cut the main road (N2) connecting Sake to Goma towns. Shaded red and  
714 green areas represent lava fields of Nyamulagira and Nyiragongo, respectively.

715