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The Cenozoic volcanism in the Kivu rift: Assessment of the tectonic setting, geochemistry, and geochronology of the volcanic activity in the South-Kivu and Virunga regions

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1	The Cenozoic volcanism in the Kivu rift: Assessment of the tectonic setting,
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3	and Virunga regions.
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13	Key words: East African Rift, Kivu, Virunga, tholeiitic, alkaline and potassic lavas, K-Ar age
14	dating
15	
16	ABSTRACT
17	
18	The Kivu rift is part of the western branch of the East African Rift system. From Lake
19	Tanganyika to Lake Albert, the Kivu rift is set in a succession of Precambrian zones of
20	weakness trending NW-SE, NNE-SSW and NE-SW. At the NW to NNE turn of the rift
21	direction in the Lake Kivu area, the inherited faults are crosscut by newly born N-S fractures
22	which developed during the late Cenozoic rifting and controlled the volcanic activity. From
23	Lake Kivu to Lake Edward, the N-S faults show a right-lateral en echelon pattern.
24	Development of tension gashes in the Virunga area indicates a clockwise rotation of the
25	constraint linked to dextral oblique motion of crustal blocks. The extensional direction was
26	W-E in the Mio-Pliocene and ENE-WSW in the Pleistocene to present time.
27	The volcanic rocks are assigned to three groups: (1) tholeiites and sodic alkali basalts in
28	the South-Kivu, (2) sodic basalts and nephelinites in the northern Lake Kivu and western
29	Virunga, and (3) potassic basanites and potassic nephelinites in the Virunga area. South-Kivu
30	magmas were generated by melting of spinel+garnet lherzolite from two sources: an enriched
31	lithospheric source and a less enriched mixed lithospheric and asthenospheric source. The
32	latter source was implied in the genesis of the tholeiitic lavas at the beginning of the South-
33	Kivu tectono-volcanic activity, in relationships with asthenosphere upwelling. The ensuing
34	outpouring of alkaline basaltic lavas from the lithospheric source attests for the abortion of the

35 asthenorpheric contribution and a change of the rifting process. The sodic nephelinites of the 36 northern Lake Kivu originated from low partial melting of garnet peridotite of the sub-37 continental mantle due to pressure release during swell initiation. The Virunga potassic 38 magmas resulted from the melting of garnet peridotite with an increasing degree of melting from nephelinite to basanite. They originated from a lithospheric source enriched in both K 39 40 and Rb, suggesting the presence of phlogopite and the local existence of a metasomatized 41 mantle. A carbonatite contribution is evidenced in the Nyiragongo lavas. 42 New K-Ar ages date around 21 Ma the earliest volcanic activity made of nephelinites. A 43 sodic alkaline volcanism took place between 13 and 9 Ma at the western side of the Virunga 44 during the doming stage of the rift and before the formation of the rift valley. In the South-45 Kivu area, the first lavas were tholeiitic and dated at 11 Ma. The rift valley subsidence began 46 around 8 to 7 Ma. The tholeiitic lavas were progressively replaced by alkali basaltic lavas 47 until to 2.6 Ma. Renewal of the basaltic volcanism happened at ca. 1.7 Ma on a western step 48 of the rift. In the Virunga area, the potassic volcanism appeared ca. 2.6 Ma along a NE-SW 49 fault zone and then migrated both to the east and west, in jumping to oblique tension gashes. 50 The uncommon magmatic evolution and the high diversity of volcanic rocks of the Kivu 51 rift are explained by varying transtensional constraints during the rift history.

52

53 **1. Introduction**

54

The Kivu Rift is the middle part of the western branch of the East African Rift system (**Fig.** 1). This branch separated from the main rift to the north of Lake Malawi and outlined a westward curved path from Lake Rukwa to Lake Albert. The rift valley is discontinuous in displaying a succession of deep lacustrine basins and structural heights commonly overlain by volcanic rocks, *i. e.* from south to north: Rungwe volcanic area, Rukwa and Tanganiyka basins, South-Kivu volcanic area, Kivu basin, Virunga volcanic area, Edward basin, Toro-Ankole volcanic area, and Albert basin.

The East African rift system is commonly explained as the result of one or two mantle plumes beneath Afar and Kenyan Plateaux (Ebinger and Sleep, 1998; Rogers et al., 2000; Furman et al., 2006). It is assumed that the plateaux are dynamically supported by convective activity in the underlying asthenosphere (Ebinger et al., 1989), providing heat transfer for partial melting of the sub-continental lithospheric mantle. Numerous chemically distinctive, but dominately alkaline sodic volcanic provinces emplaced along the entire length of extensional fracture systems across the Ethyopian and Kenyan domes. In return, the western

69 wranch displays limited and localized volcanic products with a great diversity of chemical 70 compositions including potassic lavas which are rare in the eastern branch. Moreover, the 71 time and space distribution of these various lavas, from oversaturated to undersaturated, sodic 72 to potassic and per-potassic, is problematical and hardly understandable. No "conventional" 73 timing of the magmato-tectonic evolution of the rift can be evidenced. Which kind of rift may 74 provide such a diversity of magmatic rocks with unclear time-related setting? What happened 75 in the western branch of the East African Rift system? 76 To document this question, it is necessary to constrain the volcano-tectonic evolution, to 77 comfort the geochemical data, and to obtain numerous age markers. Many years ago, we 78 sampled and studied all the volcanic rocks of the South-Kivu and Virunga areas (Pouclet, 79 1973, 1976, 1980; Pouclet et al., 1981, 1983, 1984; Marcelot et al., 1989). We provided the 80 first significant age data set and discovered the North Idjwi nephelinites, the oldest lavas of 81 the rift (Bellon and Pouclet, 1980). Since that time, a lot of papers were published, some of 82 them providing new and accurate geochemical data (references therein in section 3). 83 In this study, we expose an updated synthesis of the volcano-tectonic features of the Kivu 84 rift on the base of unpublished maps of the Kivu Lake area, Kahuzi horst, Tshibinda Volcanic 85 Chain, Virunga area, and West-Virunga area (Figs. 2 to 6). We complete the analytical data 86 set if necessary for some badly known volcanic series (**Table. 1**) and investigate the 87 magmatological characteristics of the various volcanic series on the base of a revised 88 nomenclature. We perform seventeen new K/Ar age measurements (Table 2) and improve the 89 geodynamical history of the Kivu rift. We discuss about the varying behaviour of the rift 90 tectonic constraints, the subsequent conditions of magma genesis from heterogenous mantle 91 sources, and the role of carbonate metasomatism. 92

93 2. Volcano-tectonic features of the Kivu Rift

94

95 2.1. Background

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97 The Kivu Rift is linked with a large lithospheric swell centred in the Lake Kivu region. It 98 encompasses two volcanic areas: the South-Kivu area to the south, around the city of Bukavu, 99 and the Virunga area to the north, close to the city of Goma (Fig. 1). The main structural 100 features consist of interplayed two fault patterns: a NW-SE trending fault set and a NE-SW to 101 NNE-SSW trending fault set. Some of these faults are reworked fractures of the Precambrian 102 crust which played as normal faults when a large uplift event affected the eastern Congo. The

103 NW-SE faults control the rift section from Lake Rukwa to north of Lake Tanganyika. They 104 are inherited from Palaeoproterozoic Rusizian and Ubendian structural patterns. Clearly, the 105 rift extends along the Ubendian Belt, a prominent NW-SE crustal structural weakness 106 between the Archaean Bangweulu Block and the Tanzania Craton (Boven et al., 1999; Tack et 107 al., 2010). The NE-SW faults dominate the Lake Kivu region. They belong to the 108 Mesoproterozoic Karagwe-Ankole Belt and are overprinted, to the west of Lake Kivu, by 109 NNE-SSW faults of the Neoproterozoic Itombwe Synclinorium which reoriented the rift 110 direction (Villeneuve, 1987: Villeneuve and Chorowicz, 2004). At the NW to NNE turn of rift 111 direction, from Tanganyika to Kivu lakes, the two fault sets are crosscut by newly born N-S 112 fractures constituting a third set, which developed during late stage of the rift tectonic process. 113 The rift is asymmetric. The western edge is larger and higher than the eastern edge, and east-114 facing faults are more abundant than the west-facing ones. Similar half-graben structure is 115 described in the Tanganyika rift and explained by the flexural cantilever model (Kusznir and 116 Ziegler, 1992), implying isostatic response of the lithosphere to a continental extension by 117 planar faulting in the upper crust. The E-W crustal extension is estimated to be less than 16 118 km (Ebinger, 1989a, b). The offset of the rift axis between the Tanganyika and Kivu lakes is accommodated by oblique-slip transfer faults along the Rusizi valley. Besides, we explain the 119 120 southwestern segment of Mwenga by a southwestward propagation of the rift, based on age 121 dating of the basaltic lavas (see geochronological section).

122 The South-Kivu volcanic area is centred at the crossing of the NW-SE and NNE-SSW fault 123 sets in a classical accommodation zone (Ebinger et al., 1999). It consists of abundant lava 124 flows of olivine tholeiites and sodic alkali basalts, and of few trachy-phonolitic extrusions, all 125 being dated from late Miocene to Pleistocene. The Virunga volcanic area is located at a 126 WSW-ENE dextral shift of the rift, and also in an accommodation zone. It consists of eight 127 large strato- and shield-volcanoes, Nyamuragira (3,058 m), Nyiragongo (3,470 m), Mikeno 128 (4,437 m), Karisimbi (4,507 m), Visoke (3,711 m), Sabinyo (3,634 m), Gahinga (3,500 m), 129 and Muhavura (4,127 m), from south-west to north-east. Mikeno and Sabinyo are the oldest 130 volcanoes and are dated, respectively, to late Pliocene and to Early Pleistocene. Nyiragongo 131 and Nyamuragira are presently active. The other volcanoes were active from Middle 132 Pleistocene to recent time. Two different magmatic suites are displayed: leucite-bearing 133 basanites and evolved lavas at Nyamuragira, Karisimbi, Visoke (pro parte), Sabinyo, Gahinga 134 and Muhavura, and leucite-melilite nephelinites and nepheline-leucitites at Nyiragongo, 135 Mikeno and Visoke (pro parte) (Pouclet et al., 1981, 1983, 1984). In addition, remnants of 136 basaltic lava flows, dated to Miocene, are preserved at the upper western edge of the rift. They

predated the major fault motion of the rift shoulder and the building of the great volcanoes ofthe main Virunga area (Pouclet, 1975, 1977).

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140 2.2. Main features of the Lake Kivu and South-Kivu volcanic area

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142 2.2.1. Tectonic pattern

143 The tectonic evolution of the Kivu rift is witnessed by the Lake Kivu structural and 144 sedimentological features. Dating the sedimentary deposition pattern is the best way for 145 defining the tectonic events. Oscillations of the water level are related to climatic phases but 146 also to tectonic pulses and lava damming of outlets. For these reasons, we draw the tectonic 147 map of the Lake Kivu of the Figure 2, after the bathymetric map and the geophysical data of 148 Degens et al. (1973) and Wong and Von Herzen (1974). The Kahuzi Mountain is another key 149 sector for timing the doming of the rift and the subsidence of the rift valley, because it is the 150 source of the Lugulu flows, a large lava pile running down to the west (Fig. 1). For that 151 reason, a field work was done and we draw a sketch map of the volcanic source area in the 152 Figure 3. The youngest volcano-tectonic activity took place in a western upper step of the rift, 153 east of the Kahuzi horst and built a chain of strombolian volcanoes. We mapped this chain in 154 the Figure 4, in order to illustrate its tectonic relationships.

155 The Lake Kivu is made of a northern basin and two western and eastern basins. The 156 northern basin is a tectonic trough including 400 m of lacustrine sediments. According to the 157 sedimentation rate, the basin may be dated back to about 5 Ma (Degens et al., 1973). The 158 sediment substratum is at around 600 m of elevation. The mountainous edges reaching 3,000 159 m, the relative vertical motion is calculated at 2,400 m (Pouclet, 1975). The western and 160 eastern basins, on both sides of the Idjwi Island, were former valleys, with rivers flowing 161 down to the northern basin. These valleys were flooded after the damming of the lake 162 northern run-off, which resulted from building of the Nyiragongo and Nyamuragira 163 volcanoes, in the late Pleistocene. The maximum water level reached 1,650 m, at the Bukavu 164 shelf level, ca. 10,000 years ago (Denaeyer, 1954; Pouclet, 1975, 1978). Then, it lowered in 165 furthering the excavation of the Rusizi canyon. The Lake Kivu southward overflow is 166 recorded in the Lake Tanganyika sediments at 9,400 yr BP (Haberyan and Hecky, 1987) or 167 10,600 yr BP (Felton et al., 2007). The early Holocene high water level coincided with the 168 formation of sub-lacustrine flank volcanoes in the Virunga area, at the northern shore of the 169 lake. But this high level cannot explain the formation of the under-water hyaloclastite vents of 170 South-Idjwi which are much older and thus related to a previous lacustrine basin (Pouclet,

171 1975, 1978). The present-day level of 1,462 m is stabilized by the hydroelectric dam of172 Bukavu.

173 The deep northern basin is crosscut by SW-NE tectonic steps (cross-section A-B, Fig. 2). 174 The southern part consists of an alternation of horsts and basins trending SSW-NNE (cross-175 section C-D). All the fractures play as normal faults with horst uplifting, graben sinking, and 176 tilting of the steps. The western edge culminates at Mount Kahuzi (3,308 m), which is a 177 Neoproterozoic intrusive complex of acmite- riebeckite-bearing granite, syenite, and quartz-178 porphyry microgranite, as well as the neighbouring Mount Biega (2,790 m) (Ledent and 179 Cahen, 1965; Kampunzu et al., 1985). These intrusions are dated between 800 and 700 Ma, 180 according to the ages of neighbouring similar alkaline intrusions in the western edge of the 181 rift (Van Overbeke et al., 1996; Kampunzu et al., 1998a). 182 The Kahuzi Mountain is the source area of important flows (Fig. 3). At its western and 183 southern feet, basaltic flows poured out in westward direction from a fracture system, in the 184 Miocene to Pliocene time. Four main lava flow units are distinguished. Doleritic facies are 185 localized along NW-SE fractures, at the southern to south-western foot of the massif, 186 indicating the feeder sites. Heating of the Kahuzi area by rising of this basaltic magma is 187 probably responsible for rejuvenation to 134 and 55 Ma of K-Ar ages of the Kahuzi rocks 188 (Bellon and Pouclet, 1980). At present, the Lugulu flows consist of a reverse topographic 189 relief of elongated hills. The lava flowed down to the west, but not to the east. They poured 190 out during the doming stage of the rift and predated the formation of the rift because they are 191 cut by the major faults of the rift scarp. Indeed, to the eastern foot of the Kahuzi heights, on 192 the Tshibinda step (Fig. 4), the Quaternary Tshibinda basaltic flows overlie metasediments of 193 the Precambrian substratum, which is devoid of any older lava cover. We thus conclude that a true rift valley did not exist across the swell at the Kahuzi lava flowing time, and lavas only 194

195 flowed down to the western slope of the dome.

196 The rift valley initiated in the latest Miocene. East of the western higher steps, Late 197 Miocene lavas are preserved in the Kavumu lowland where they are partly overlain by the 198 Tshibinda Quaternary flows (detailed in the following section). They widely flooded to the 199 Lake Kivu and to the Bukavu and Bugarama grabens, and also poured out in the SSW 200 segment of the rift, the Mwenga graben (Figs. 1 and 2). The western basin of the Lake Kivu is 201 the continuation of the Bukavu Graben. The Idjwi Island is the northern prolongation of the 202 Mushaka horst that separated the Bukavu and Bugarama-Bitare grabens. There is not a single 203 rift valley. However, the deepest part locates in the eastern basin of the lake, where the main 204 rift axis can be assumed to be, in the continuation of the Bitare-Bugarama Graben (Fig. 1).

Fault associated mineral hot springs are abundant (Fig. 2). Many of the faults are more or less
presently active as illustrated by the Frebuary 3, 2008 earthquake along the Luhini Fault (Fig. 4).

- 208
- 209 2.2.2. Volcanic activity

210 The South-Kivu volcanic activity mainly consisted of basaltic flow piling from fissural 211 eruptions, in the Late Miocene to Late Pliocene (10 to 2.6 Ma; Kampunzu et al., 1998b). In 212 the Pleistocene, a renewed strombolian volcanic activity has built the chain of Tshibinda 213 (Bellon and Pouclet, 1980) (Fig. 4). In the stacked lava field, the old volcanic vents can be 214 localized by their feeder dykes and by interbedded pyroclastic materials, which locally gain a 215 few metres in thickness. Occurrences of intercalated tephra are common, but well-preserved 216 scoria cones are absent or limited to the recent Tshibinda volcanic chain. Some metre-sized 217 basaltic dykes are present in the western (Congo side) and eastern (Rwanda side) upper steps 218 and also in the Mwenga area. They are trending N-S to NE-SW. These features are consistent 219 with linear basaltic eruptions along cracks fringed with small scoria cones. Trachy-phonolitic 220 extrusions are only known in the Bukavu Graben, into and close to the upper-Rusizi canyon. 221 They are dated from 6.14 Ma to 5.05 Ma (Pasteels et al., 1989). In this area, we number five 222 decametre- to hectometre-sized bodies, which intruded a lower basaltic pile and are overlain 223 by flows of olivine basalt and hawaiite.

224 The Pleistocene chain of Tshibinda consists of numerous well-preserved scoria cones and 225 lava flows (Fig. 4). The chain is named after the Tshibinda site, in its southern end, where the 226 first scoria cones were discovered (Meyer and Burette, 1957). The cones are set at the border 227 of the Tshibinda step, at the eastern foot of the Kahuzi upper shoulder. The chain is 33 km-228 long in a SSW-NNE direction, from Tshibinda to Leymera. During our mapping, we 229 numbered sixty strombolian cones, 50- to 150 m-high. Most of them are opened and have 230 supplied lava flows. A few flows run to the west, in following the slope of the tilted step, but 231 most of them came down the fault scarp and spread towards the eastern lowlands. A 232 prominent feature is the alignment of vents along SSE-NNW fractures (N 160° trend) in the 233 Tshibinda and Tshibati sectors. This fracture system is consistent with a NE-SW left-lateral 234 strike slip constraint, and an ENE-WSW extensional strain. We dated the Tshibinda chain 235 activity from 1.9 to 1.6 Ma (Bellon and Pouclet, 1980). Younger ages have been suggested

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238 2.3. Main features of the Virunga volcanic area

but not proved (Pasteels et al., 1989).

239

240 2.3.1. Tectonic pattern

The Virunga volcanic area is located between the Kivu and Edward lakes on a structural height or shoal between two troughs (Fig. 5). The continuation of this shoal beneath the Nyiragongo and Nyamuragira volcanoes is based on sedimentological, volcanological and geophysical evidence (Pouclet, 1975). Its level averages 1,200 m, while the nearest higher topographical Mount Muhungwe rift edge reaches 2,990 m. Thus, the relative vertical motion of the rift floor is around 1,800 m. Subsidence of the Lake Kivu bottom reached approximately 600 m below the shoal level.

248 The tectonic pattern is linked to right lateral shift of the rift axis between Kivu and Edward

249 lakes, which is underlined by the SW-NE Tongo, Muhungwe, and Rutshuru faults.

250 However, motion along these faults is dominantly vertical. This motion is evidenced by the

uprising of sedimentary terraces at the foot of the Tongo scarp to the west, and along theRutshuru Fault to the east as shown in the Figure 6. These terraces contain Early to Middle

253 Pleistocene littoral sediments of the Lake Edward. They recorded an uplifting of 1,000 m

along the Tongo Fault, and of 500 m along the Rutshuru Fault (Pouclet, 1975). Taking into

account a vertical motion of 500 m before the Early Pleistocene sediment deposition, the total

vertical motion of the Tongo Fault is calculated around 1,500 m. The south-eastern side

257 registered a vertical motion of 1,000 m at the Muhungwe Fault. This motion in evidenced

258 along the N-S Kisenyi Fault, in the continuation of eastern border of the Lake Kivu northern

trough. Meanwhile, at the eastern end of the Virunga area, vertical displacements are limited

to a few hundred of metres along N-S and SSE-NNW faults.

The structure and nature of the volcanic substratum are constrained by the trends of the volcano-tectonic framework and the composition of the volcanic xenoliths. In the Virunga area, underlying cliffs moulded by lavas can explain some major topographic uneven differences. It is the case for the N-S west-facing scarp between the Karisimbi-Mikeno volcanoes, in the upper eastern side, and the Nyiragongo-Nyamuragira volcanoes, in the lower western side. This scarp is in the continuation of Rwandese east-Kivu Fault (Fig. 1) and

is connected with the eastern fault of the Kirwa sedimentary terrace (Fig. 5). It is named the

268 "Virunga Fault". This fault has right-lateral en echelon segments, as shown by shift of the

269 Kirwa Fault to the fault of the low Rutshuru terrace. A sub-parallel less important scarp

270 separates the Mikeno to the Karisimbi-Visoke, and is linked to a fault at the north-western

border of the Precambtian substratum, south of the Rutshuru Fault. It is named the "Mikeno

Fault". A third scarp is located between Sabinyo and Gahinga. To the lower southern flank of

Nyiragongo, a transverse WNW-ESE scarp is merely related to a fault between the Virungashelf and the northern basin of Lake Kivu.

275 Two types of volcanic fractures are distinguished. Some fractures show radial distribution 276 on the flank of the largest volcanoes. But many others are aligned independently of the 277 volcano building shape. A SW-NE trend of fractures locates in the prolongation of the east 278 fault of the M'Buzi peninsula. It reveals a major fault between Nyiragongo and Nyamuragira, 279 the "Kameronze Fault", which is ascertained for many reasons. Firstly, the M'Buzi block is 280 extended below the lava cover, according to gravimetric data (Evrard and Jones, 1963). 281 Secondly, the xenoliths of Nyiragongo consist, solely, of granite rocks, while those of 282 Nyamuragira are made of metashales, quartzites, and micaschists. Thus, the two volcanoes 283 were emplaced in two geologically different steps of the rift floor. Thirdly, there is a 284 deepening of focal depth of tectonic earthquakes from west, in the Nyamuragira area, to east, 285 in the Nyiragongo area (Tanaka, 1983). Fourthly, the Kameronze fractures have provided 286 original lava, the rushayite, an ultrabasic olivine-rich melilitite, which is unknown in the rest 287 of Virunga. This rare lava could be originated from a deep cumulate zone of the Nyiragongo 288 magma chamber or from an independent reservoir (see discussion in section 3.4.). Thus, the 289 Kameronze Fault separates the low granitic step of Nyiragongo to the upper meta-sedimentary 290 step of Nyamuragira. The two neighbouring volcanoes have very different lava compositions. 291 Their different setting in two distinct crust compartments may explain their different way of 292 magma feeding. A SSW-NNE fracture set is partly in the continuation of the Kameronze 293 Fault to the north-east. But, its related eruptive vents produced Nyamuragira-type lavas. An 294 important SW-NE fissural complex is located between Visoke and Sabinyo. In the same 295 direction, main fractures crosscut the Mikeno, Visoke, and Sabinyo edifices. This complex is linked to a SW-NE major fault emplaced between the Mikeno NW-base and the Karisimbi-296 297 Visoke step, parallel to the Muhungwe Fault of the rift edge. 298 Undeniably, the most important present-day fracture system is the great NNW-SSE 299 fracture zone or weakness zone of Nyamuragira that crosscuts the caldera and the shield

300 volcano, reaching 20 km in length (Pouclet and Villeneuve, 1972; Pouclet, 1976, 1977). In

- 301 many parts, this tectonic zone is a trench, 15 to 30 m wide and 20 to 30 m deep, limited by
- 302 two parallel sub-vertical fractures. It is associated with slightly parallel secondary fissures, on
- the NNW and SSE upper flanks. It extended from Nyamuragira to the Nyiragongo area,
- 304 across the Kameronze Fault, with large fissures at the NNW flank of this Nyiragongo. This
- 305 tectonic system, having an axial direction of N 155°, can be considered as a mega tension

306 gash. In the NNW flank of the Nyamuragira caldera, there is a spectacular fan-shaped 307 succession of fissures where thirteen eruptive events took place since the year 1900. 308 In addition, the Nyamuragira shield is crossed by N-S faults. In the northern wall of the 309 caldera, a N-S fault shows a two metres-displacement of the lava pile and is intruded by a 310 dyke. The fault motion has occurred after the setting up of the initial summit cone, but before 311 the caldera collapse (Pouclet, 1976). In the SW upper flank, a N-S fault was active during the 312 1938 eruption that drained a large volume of lava from the caldera. The western flank of the 313 shield displays a morphological lowering of 30 to 40 m. A less important lowering of the SSE 314 flank is due to a N-S fault associated with the Kameronze Fault. Important N-S fractures also 315 concern the southern flank of Nyiragongo. They were responsible for draining of the caldera 316 lavas during the dramatic 1977 and 2002 eruptions (Pottier, 1978; Komorowski et al., 2002). 317 It is concluded that the N-S fractures, not only controlled the structural pattern of the Virunga 318 substratum (Virunga and Mikeno faults), but also play a present-day important role in the 319 tectonic constraints triggering volcanic eruptions.

320

321 2.3.2. Volcanic activity

322 The Volcanic activity began in the Late Miocene. The oldest lavas are preserved as 323 residual basaltic flows, above the western edge of the Bishusha-Tongo area as depicted in 324 Figure 6. They are dated between 12.6 and 8.6 Ma (Bellon and Pouclet, 1980; Kampunzu et 325 al., 1998b). They predated the 1,500 m vertical motion of the Tongo fault system, and then, 326 the rifting process and the main volcanic activity of the Virunga area (Pouclet, 1977). For 327 these lavas we use the term "pre-Virunga" magmatic activity because there is an important 328 time gap and a drastic difference of composition between these Miocene lavas and the 329 Quaternary Virunga lavas. We numbered and sampled a dozen of scattered outcrops of 330 basaltic rocks at small hills in the Bishusha area, above and along the Mushebele scarp, and 331 above the Tongo scarp (Fig. 6). They belong to different dissected and highly eroded lava 332 flows, as it is attested by the various petrographical compositions (olivine basalt, basanite, 333 hawaiite, mugearite, benmoreite) and frequent doleritic textures of the mafic rocks. The lava 334 setting is controlled by NW-SE and NNW-SSE fractures, the same directions that were used 335 by the two recent Mushari fractures of satellite eruptions of Nyamuragira. No field 336 relationships between the flows, in term of succession order, can be inferred. In addition, a 337 thick blanket of tephra coming from the numerous Nyamuragira flank eruptions overlies the 338 entire area.

At the middle flank of Mount Mushebele, an olivine basalt lava flow seems to be overlain by a hawaiite flow that crops out at the top of the scarp. However, the hawaiite is dated at 12.6 ± 0.7 Ma (Bellon and Pouclet, 1980) and the basalt at 10.8 ± 1.7 Ma (Kampunzu et al., 1998b). The 12.6 Ma age was questioned because the hawaiite being at a higher altitude than the basalt must be younger (Kampunzu et al., 1983). There is an alternative explanation: The two lavas are separated by an important normal fault and the hawaiite was tectonically displaced above the basalt.

346 The other lavas of the west Virunga area are the Mweso valley flows and the Pinga flows 347 (Fig. 1). The Mweso flows poured out in the Mokoto Bay. Their source is hidden by the 348 recent flows of Nyamuragira (Fig. 6). The lavas extended along 32 km in the valley, from 349 Mokoto to the NNW end of the flow system. Our sampling shows that the petrographical 350 composition remains constant: olivine basalt with microphenocrysts of skeletal olivine and 351 aggregated phenocrysts of diopside and labradorite. At the Pinga area, residual basaltic flows 352 are pointed out in the Pinga village and 35 km west of this village, in the Oso valley, (De La 353 Vallée-Poussin, 1933). These lavas cannot belong to the Mweso flow, for topographical 354 evidences, but recalls the Numbi lava for their western position out of the rift. More accurate studies are needed for precising their petrographical and chemical compositions. 355

The volcanic activity of the Virunga main area began with Mikeno, in the middle part of the shelf between the Kivu and Edward troughs. This volcano was active around 2.6 Ma and maybe until 0.3 or 0.2 Ma (Guibert et al., 1975). The old age of Sabinyo, the second oldest volcano, is only attested by its erosional feature similar to that of Mikeno. Its base is totally

360 covered by lavas from Gahinga and Visoke. It was active around 0.1 Ma (Bagdasaryan et al.,

361 1973; Rançon and Demange, 1983; Brousse et al., 1983; Rogers et al., 1998). Thus, the

362 erosion of Sabinyo may be recent and due to violent volcano-tectonic activities. Gahinga and

363 Muhavura are dated between 0.29 and 0.03 Ma (Rançon and Demange, 1983; Rogers et al.,

1998), but recent activities are suspected (Brousse et al., 1983). Visoke consists of two

365 superposed stratovolcanoes (Ongendangenda, 1992). The upper one is as old as 0.08 Ma

366 (Bagdasaryan et al., 1973). Its last eruption in 1957 produced the adventive cone of Mugogo

367 on the lower north flank (Verhaeghe, 1958). Karisimbi is made of a shield volcano overlain

368 by two successive upper flank large cones (De Mulder, 1985). It is dated between 0.14 and

369 0.01 Ma (De Mulder et al., 1986: De Mulder and Pateels, 1986). Nyiragongo and

370 Nyamuragira emplaced since 12 ka on the lower steps of the Virunga shelf (Pouclet, 1978).

371 Nyiragongo is a combination of three stratovolcanoes, from south to north: Shaheru,

372 Nyiragongo main cone and Baruta. Shaheru, the first volcano of the complex, may be as old373 as 0.1 Ma (Demant et al., 1994).

- 374
- 375 **3. Geochemical composition of lavas**
- 376

377 Numerous geochemical analyses of South-Kivu and Virunga lavas are available from the 378 literature, though their accuracy is highly variable. Trace element and isotopic data are 379 provided by Mitchell and Bell (1976), Vollmer and Norry (1983), Hertogen et al. (1985), 380 Vollmer et al. (1985), De Mulder et al. (1986), Auchapt (1987), Auchapt et al. (1987), 381 Marcelot et al. (1989), Toscani et al. (1990), Demant et al. (1994), Rogers et al. (1998), 382 Furman and Graham (1999), Platz et al. (2004) and Chakrabarti et al (2009a). These data are 383 reviewed and, when necessary, completed by new analyses (Table 1). The analytical set is 384 used to discuss the petrological features and the magmato-tectonic relationships dealing with 385 the rift formation and evolution. South-Kivu basalts derived from a heterogeneous lithosphere 386 mantle source by variable degrees of melting (Auchapt et al. 1987; Furman and Graham, 387 1999). Both the leucite-basanite and leucite-nephelinite series of Virunga resulted from 388 moderate or small amount of partial melting of mica-garnet-lherzolite lithospheric and/or 389 asthenospheric mantle, with contribution of carbonatite for the more alkaline series (Pouclet, 390 1973; Furman and Graham, 1999; Chakrabarti et al., 2009a). 391 In the South-Kivu and Virunga area, it has been shown in the section 2 that volcanism and 392 doming preceded the rifting, with the Kahuzi and pre-Virunga basalts. Asthenospheric 393 upwelling caused uplift of the lithosphere and partial melting of various sources. However, to 394 document that model, we have to clarify some intriguing questions, because the geochemical 395 data from literature are, in many cases, incomplete and not representative, and sometimes 396 inexact. The questions concern the early and late activity of South-Kivu, the poorly known volcanism of North-Idjwi between South-Kivu and Virunga, and the early activity of Virunga. 397 398 What is the composition of the earliest volcanic rocks in South-Kivu? Is it really tholeiitic?

399 It is necessary to ascertain the existence, the age, and the tectonic location of true tholeiites, in

400 one hand, and the timing of the rift formation, in the other hand. The Quaternary South-Kivu

401 Tshibinda volcanoes erupted simultaneously with some Virunga volcanoes. Their basaltic

402 composition is close to that of South-Kivu lavas. What is their place in the South-Kivu

403 magmatic evolution? The early Miocene North-Idjwi lavas are the oldest dated lavas of the

404 Kivu rift. They are not tholeiites but nephelinites. What is their magmato-tectonic meaning

405 between the South-Kivu and Virunga areas? The Miocene pre-Virunga lavas predated the rift

406 formation, and may be contemporaneous with the first South-Kivu activities. They are very 407 different from the Quaternary Virunga lavas. Their composition, tholeiitic to alkaline, is a 408 matter of debate. What is the true composition of the pre-Virunga lavas? Is it similar to that of 409 the South-Kivu? And, finally, what is the origin of the original features of the Virunga lavas? 410 411 3.1. South-Kivu lavas 412 413 South-Kivu lavas mainly consist of alkali basalts and tholeiites. The first question deals 414 with the true composition of tholeiites and their meaning in the rift evolution. Then, we revise 415 the composition and the nomenclature of the various volcanic rocks. Most of the activities are 416 dated in the Miocene and Pliocene, but a renewal occurred during the Pleistocene in the 417 Tshibinda site. New analytical data are provided for to better constrain this last magmatic 418 event. 419 420 3.1.1. The tholeiite question 421 422 Tholeiite lavas have been pointed out at different parts of the South-Kivu volcanic area and 423 in the pre-Virunga field, with various ages. They are very important in the debate about the 424 tectono-magmatic history of the rift. But, examination of these lavas is problematic. Many 425 "tholeiites" have been defined on the basis of their major element composition (low abundance of alkali elements), without mineralogical arguments. As they are always more or 426 427 less altered, in having high loss on ignition, they could be former alkali basalts secondary 428 depleted in alkali elements. It is tritely verified that altered olivine-rich basalt may display 429 oversaturated norm composition. In addition, it is ascertain for tholeiites by Pasteels and 430 Boven (1989) that many K-Ar ages are questionable, due to alteration (loss of K and/or Ar) 431 and to magmatic argon excess. This tholeite problem leads to three questions: 1) Are there 432 true tholeiites? 2) Is there a space distribution of tholeiites from the border to the rift axis? 3) 433 Is there a time relationship in the tholeiite and alkali basalt production? 434 The criteria for defining true tholeiites are their mineral content, crystallization order, and 435 major and trace element composition. Early olivine phenocrysts are absent. Calcic plagioclase 436 crystallizes before sub-calcic pyroxene. For that reason, the tholeiitic doleritic facies displays 437 intersertal texture. Olivine only exists as residual and corroded xenocrysts. There is a single 438 pyroxene of sub-calcic augite composition, or two coexisting pyroxenes that are augite and 439 ferrous hypersthene. The norm calculation gives variable amount of quartz and more than

440 10% hyperstheme. Trace element pattern of continental tholeiites exhibits moderate 441 enrichment of the most incompatible elements. However, olivine-tholeiites contain 442 microphenocrysts of ferrous olivine and partly syncrystallizing plagioclase and augite leading 443 to intergranular or sub-ophitic textures in doleritic facies. Their norm composition is saturated 444 with variable amount of hypersthene. The most incompatible elements are slightly more 445 enriched than for tholeiites. 446 On the basis of these mineralogical and geochemical criteria, examination of the South-447 Kivu lavas indicates that true tholeiites are present at five sites: West-Kahuzi, South-Idjwi and 448 Mushaka horst, Bitare-Buragama graben, lower-Rusizi (southern continuation of the 449 Bugarama graben), and Mwenga. Olivine-tholeites are present at the same sites, plus the 450 Bukavu graben. The answer to the question of space and time distribution is more 451 complicated. Tholeiites are localized along the rift axis, but also at distant fields, though they 452 are concentrated close to the rift axis. Concerning the chronological setting of tholeiites 453 versus alkali basalts, tholeiites are everywhere overlain by alkali basalts, but the transition is 454 diachronic. For instance, at the Mwenga site, tholeiites are younger than the alkali basalts of 455 Bukavu. On the whole, tholeites predated alkali basalts, and, for that reason, they crop out in 456 the most eroded topographical landscapes. Because the erosion process is variable, the 457 distribution of tholeiites is not known for all the volcanic area.

458

459 *3.1.2. Composition of lavas*

460

461 To display relative abundances and features of tholeiitic rocks compared with alkaline 462 lavas, a set of representative and accurate chemical analyses is provided in Table 1. Poorly 463 described and altered lavas are eliminated. Thanks to this precaution, we adopt a normative 464 classification slightly modified from Green (1969): 1) quartz-bearing and hypersthene-rich 465 tholeiite, 2) olivine-tholeiite containing olivine and more than 15% hypersthene, 3) olivine 466 basalt containing olivine and less than 15% hypersthene, 4) alkaline-basalt with 0 to 5% 467 nepheline, 5) basanite with 5 to 15% nepheline, and 6) nephelinite having more than 15% 468 nepheline. Classification of the South-Kivu, North-Idjwi, and Pre-Virunga lavas is 469 accomplished using a tetrahedral diagram of normative proportions of Qtz, Hy, Ol, Ne+Le, 470 and Ab+Or (Fig. 7). Compared with the tetrahedral diagram of Yoder and Tilley (1962), 471 diopside is replaced by albite + orthose because the alkali amount is more significant than the 472 calcium content, and the alkali abundance cannot be shown only by feldspathoids. True 473 tholeiites plot in the Qtz - Hy - Ab+Or triangle. In the Ol - Hy - Ab+Or triangle, olivine-

474 tholeiites are discriminated to olivine basalts by Hy normative amount of more than 15 %. In 475 the Ol – Ne – Ab+Or triangle, the alkali basalt - basanite and basanite - nephelinite limits are 476 determined by Ne normative amounts of 5% and 15%, respectively. In this triangle, some 477 basanites of the Mwenga site are characterized by high MgO contents (9-12 wt %). They are 478 rich in olivine, although being not cumulative. Then they are termed "Mg-basanites". 479 Trace element data of the new analyses (Table 1) are completed by those of Auchapt 480 (1987), Auchapt et al. (1987), Marcelot et al. (1989), and Furman and Graham (1999). In the 481 Primitive Mantle normalized incompatible elements diagram (Fig. 8A) tholeiites and olivine-482 tholeiites are moderately fractionated in the light rare earth elements. Their La/Yb ratios range 483 from 8 to 13 and from 10 to 15, respectively. They are not enriched in Ba and Th, and are 484 poor in Rb. Similar patterns are exhibited, with increasing trace element abundances and rare 485 earth element fractionation, from tholeiites to olivine basalts (15<La/Yb<30), alkaline-basalts 486 (20<La/Yb<35), basanites (25<La/Yb<40), and Mg-basanites (40<La/Yb<50). As already 487 suggested by Auchapt et al. (1987), Marcelot et al. (1989) and Furman and Graham (1999), 488 this is consistent with varying degree of partial melting of a lithospheric mantle source, which 489 decreases from tholeiites to Mg-basanites, as shown by the Yb vs. La/Yb diagram (Fig. 9A). 490 Auchapt (1987) has calculated the source composition from a set of tholeiitic and basanitic 491 lavas of the Mwenga area. A first source, moderately enriched, (C1, Table 3) can be assumed 492 for most of the lavas. A second less enriched source (C2, Table 3) is suitable for lavas that are 493 poor in the most incompatible elements.

Having tested the accuracy of the Auchapt's results, we calculated the degrees of partial
melting after the reverse method and the source composition C1, for all the South-Kivu mafic
lavas and using light rare earth elements (LREE). We obtained the following values: tholeiites
and olivine-tholeiites = 15 to 7%, olivine- and alkaline-basalts = 6 to 4%, basanites and Mgbasanites = 3 to 2%. However, to get consistency of partial melting degrees between large ion

499 lithophile elements (LILE) and high field strength elements (HFSE), it is necessary to

500 increase the bulk partition coefficient of heavy rare earth elements (HREE), particularly in the

501 basanite case implying the presence of garnet in the source. This assertion is supported by

502 increasing HREE depletion from alkaline-basalts to basanites characterized by increasing

values of Tb_N/Yb_N normalized ratio from 1.78 to 2.27 locating the melting column in the

504 garnet stability field. Indeed, due to the residual garnet effect, the Tb_N/Yb_N melt ratio passes

505 beyond 1.8 at the spinel-garnet transition (Furman et al., 2004; Rooney, 2010).

- 506 Batch melting is calculated for the enriched source C1 and the less enriched source C2;
- 507 results are shown in the La/Sm versus Sm/Yb diagram (Fig. 9B). Melt curves are drawn for

508 spinel-lherzolite, garnet-lherzolite, and a 50:50 mixture of spinel- and garnet-lherzolite. 509 Modal compositions of spinel-lherzolite (olivine 53%, OPX 27%, CPX 17%, spinel 3%) and 510 garnet-lherzolite (olivine 60%, OPX 20%, CPX 10%, garnet 10%) are after Kinzler (1997) 511 and Walter (1998). Mineral/melt partition coefficients for basaltic liquids are after the 512 compilation of Rollinson (1993). Tholeiites may have resulted from ca. 10% of partial 513 melting of spinel-lherzolite from a moderately enriched source. But, globally, South-Kivu 514 magmas may be generated by melting of spinel+garnet lherzolite, from enriched source 515 between the C1 and C2 calculated compositions, assuming increasing amount of garnet, from 516 tholeiites to basanites. Hence, melting took place in the spinel-garnet transition zone at depth 517 surrounding 80 km. The more abundant garnet content in the basanite source locates its 518 melting in the lower part of the transition zone. Partial melting degree of the C1 source 519 decreases from 20% to 5%, from basalts to basanites, along the 50:50 spinel+garnet-lherzolite 520 curve. Lower degrees of partial melting (8% to 2%) and lower amounts of garnet are 521 determined with the C2 source. But, the large dispersion of plots suggests compositional 522 heterogeneities and/or mixing in the melted sources. 523 Contribution of these different sources has to be tested by using all the incompatible

524 elements. However, chemical bias may be due to crustal contamination and assimilation. This 525 latter process can be evidenced in the Nb/Yb versus Th/Yb diagram (Fig. 10). Crustal effect is 526 suspected in the case of thorium enrichment unrelated to magmatic processes. In this diagram, 527 all the lavas plot in the Mantle array along the partial melting vector. No particular Th-528 enrichment is visible, precluding perceptible crustal assimilation. In addition, Sr-isotopic data 529 of Furman and Graham (1999) do not display Sr anomalous pattern. Hence, the chemical 530 scatter only resulted from magmatic processes, and the analytical data, namely the 531 incompatible element values, can be used to discern magmatic patterns of the different lava 532 suites.

533 To test the behaviour of incompatible elements, bivariate diagrams have been carried out. 534 Results are illustrated in **Figure 11** with three selected diagrams. La versus Yb diagram 535 shows data scatter between two partial melting curves: a low-Yb and high-La curve, and a 536 low-La curve (1 and 2, Fig. 11A). The lack of significant Yb increase is due to garnet effect, 537 mainly in basanites, which are the most LILE-enriched and-HREE-depleted lavas. The high-538 La curve evolves from basanites to olivine basalts and can be related to the enriched C1 539 source. The low-La trend characterizes tholeiites and some olivine basalts; it may be inherited 540 from the less-enriched C2 source (3), as suggested above (Fig. 9B). Fractional crystallization 541 is limited to few tholeites and olivine basalts (see also Fig. 10A). The Ba versus La diagram

542 displays a high-Ba curve, a low-Ba curve and an intermediate high-Ba and high-La pattern (1,

543 2 and 3, Fig. 11B). Nb versus Zr diagram shows a low-Zr curve, a high-Zr curve and an

544 intermediate trend (1, 2 and 3, Fig. 11C). It is concluded that high-Ba and low-Zr values

545 (trend # 1) agree with the enriched source C1 and are best displayed in the Tshibinda

546 Volcanic Chain. Low-Ba and high-Zr values (trend # 2), observed in tholeiitic lavas, comply

547 with the C2 less enriched source. Thus, the double source model can be assumed.

548 Intermediate trends and scattering of plots are explained by varying contributions of the two 549 sources.

550 Existence of two source components is inferred from Sr-Nd isotopes (Furman and Graham,

551 1999). The lavas define a Sr-Nd isotope array between a high ^{143/144}Nd and low ^{87/86}Sr end-

552 member and a low $^{143/144}$ Nd and high $^{87/86}$ Sr end-member. The latter end-member

553 characterizes Tshibinda lavas, and complies with the C1 enriched source, that is the main

source of these lavas. Further isotope features including the East Africa data by Furman and

555 Graham (1999) indicate that this end-member belongs to the continental lithospheric mantle

556 (CLM). In return, the isotopically depleted end-member is allotted to sub-lithospheric source.

557 Its isotope values correspond to an asthenospheric mantle source much more depleted than the

558 C2 source and close to the FOZO composition as redefined by Stracke et al. (2005). Then, the

559 C2 composition is not an end-member, but probably a mixture of asthenospheric and

560 lithospheric (C1) components.

561 In short, diversity of South-Kivu magmas results from interplay of three parameters: 1) 562 mixing of two source components, a lithospheric enriched component and a sub-lithospheric 563 (asthenospheric) less enriched or depleted component; 2) varying degree of partial melting as 564 a function of melt depth; 3) modal composition of the melted source with varying amount of 565 garnet. It is concluded that the South-Kivu magmas were generated in the sub-continental 566 mantle at depth surrounding 80 km (spinel-garnet transition zone) with important degree of 567 partial melting for tholeiites, and slightly below 80 km, with low degree of partial melting for 568 basanites. Olivine- and alkaline-basalts were produced under intermediate conditions. It can 569 be assumed that the magma genesis was initiated by upwelling of asthenospheric hot material 570 and by decompression linked to extensional tectonic regime of the rift area.

571

572 *3.1.3. The Tshibinda Volcanic Chain*

573

According to previous chemical data (Meyer and Burette, 1957; Pouclet, 1976; Guibert,

575 1977; Villeneuve, 1978; Kampunzu et al., 1979; Bellon and Pouclet, 1980; Pasteels et al.,

576 1989), the lavas of the Tshibinda Volcanic Chain (TVC) share the composition of olivine 577 basalt and alkaline-olivine basalt similar to that of the Mio-Pliocene alkaline lavas (Fig. 7). 578 However, on the base of four samples from south of the volcanic chain, Furman and Graham 579 (1999) emphasize significant differences in some trace element abundances between the 580 Tshibinda lavas and the other South-Kivu lavas (higher Th/Nb, Nb/Zr, Ba/La, Ba/Nb), while 581 Sr and Nd isotope ratios show that Tshibinda lavas form an end-member in the South-Kivu 582 suite. 583 To better document the chemical data, we carried out new analyses along the chain (Table 584 1, Fig. 4). Compared with the South-Kivu alkaline lavas, the TVC lavas are significantly less 585 enriched in less mobile HFS elements, but relatively more enriched in Ba (Fig. 8B). These 586 features are exposed in the Nb versus Zr and Ba versus La covariation diagrams of Figure 11. 587 Tshibinda magma resulted from 4 to 2.5% of partial melting of the C1 lithospheric source as 588 discussed above (Fig. 9B). HREE fractionation points to low amount of garnet (Fig. 8B).

589 Indeed, the Tb_N/Yb_N ratio ranges from 1.41 to 1.85, the higher values corresponding to the

590 more alkali basalts. The source melted in upper level of the spinel-garnet transition zone.

591 Chemical variations along the chain can be explained by increasing of melting degree from

south (Tshibinda volcanoes) to the middle part (Tshibati volcanoes). However, in the northern

593 part of the TVC, the Leymera volcanoes, which are set after a volcanic gap of 8 km (Fig. 4),

show different chemical (Fig. 11) and isotopical features (Furman and Graham, 1999). The

595 Leymera lava has more Zr, less Th, and is isotopically depleted. This feature is close to the

by depleted end-member attributed to upwelling asthenosphere, which is absent in the rest of the

sources that resulted from mingling of asthenospheric blobs dispersed in the lithosphere.

597 TVC. This strong difference in a single magmatic event exemplifies heterogeneity of the

598

599

600 3.2. North-Idjwi lavas

601

602 To the northern tip of Idjwi Island, two decametre-sized outcrops of maftic lava are 603 situated on a hill above the Lake Kivu shore and in a small island, two miles from the 604 mainland. These outcrops are residues of an old volcanic cover. The rock, a nephelinite, 605 displays an intergranular texture with microphenocrysts of olivine and diopside in a 606 nepheline-rich groundmass. Compositionally, the rock is highly undersaturated and sodic-607 rich (Bellon and Pouclet, 1980; Marcelot et al., 1989; Table 1; Fig. 7). Similar nephelinitic 608 lava occurs on the upper western edge of the rift, in the Numbi area (Fig. 1) (Agassiz, 1954). 609 But, unfortunately, we were not able to sample these outcrops. The Primitive Mantle

610 normalized incompatible element pattern (**Fig. 12**) shows high incompatible element

abundances and strong fractionation (64<La/Yb<67) indicating low degree of melting of an

612 enriched source. This source is clearly related to the garnet-lherzolite mantle (Figs. 9, 11A)

613 complying with high values of the Tb_N/Yb_N ratio from 2.41 to 2.50. The partial melting

614 degree is calculated at 2%.

615 Structural position of these nephelinites is peculiar in the Kivu Rift, far north to the South-

616 Kivu volcanic area, and south to the Virunga area beyond the Lake Kivu. The nephelinites

617 have been K-Ar dated at 28 Ma (Bellon and Pouclet, 1980). A new K-Ar age shows that the

618 lavas are ca. 21 Ma (also see forward, geochronological section). Consequently, the first

619 volcanic activity related to the western branch of the rift was nephelinitic, and took place

620 somewhere between the South-Kivu and Virunga areas, a long time before the rifting and the

621 Lake Kivu formation.

622

623 3.3. Pre-Virunga lavas

624

625 The Middle Miocene Pre-Virunga lavas consist of dismembered flows roosted on the 626 western edge of the rift. Flows are cut by the Mushebele and Tongo faults (Fig. 6). First 627 petrographical and chemical data allocated these lavas to basaltic alkaline and sodic series 628 (Denaeyer, 1960; Pouclet, 1976). But, some other analyses were used to assume the presence 629 of olivine-tholeiites (Kampunzu et al., 1983, 1998b), which is not supported by petrographical 630 data. However, it is fitting to discard altered samples having high loss on ignition and 631 displaying a false tholeiitic norm composition. Using criteria given above in the South-Kivu 632 section, all the suspected lavas are olivine basalts and not tholeiites. We performed new 633 analyses in the Bishusha and Tongo sectors (Fig. 6; Table 1). All the lavas belong to a sodic-634 rich basanite series highly fractionated in the light rare earth elements (44<La/Yb<49), Nb, 635 Th, and Ba (Fig. 12). The convenient source must be garnet lherzolite (Fig. 9) taking into 636 account high value of the Tb_N/Yb_N ratio of 2.92. This source may be the same than the 637 lithospheric source of South-Kivu, but with smaller partial melting degrees of 4% to 2%. 638 In the Tongo sector, the new analyses confirm the presence of mugearite and benmore te 639 evolved lavas, and thus the occurrence of crustal reservoirs where differentiation processes 640 could have worked. This implies a focusing of a long-lasting source melting. 641 An intriguing question is the initial geographical distribution of Pre-Virunga lavas. 642 Present-day location of these lavas is limited to western upper step of the rift, west of Tongo 643 Fault. Similar old lavas are totally lacking in the eastern edge, namely in the Muhungwe area.

644 But one may assume that such lavas may have poured out above the lower steps of the rift, 645 presently overlain by the recent Virunga volcanoes. If it is the case, these lavas must have 646 been sampled by the numerous eruptions of Virunga, and may be collected as xenoliths, like 647 any basement rocks, in the Quaternary Virunga lavas. We have investigated the 107 flank and 648 parasitic cones of Nyamuragira, many flank cones of Nyiragongo, and the Nyamuragira and 649 Nyiragongo calderas. All our collected xenoliths (excluding the cognate xenoliths) only 650 consist of quartzites, shales, and micaschists in the Nyamuragira sector and of granite in the 651 Nyiragongo sector. No Pre-Virunga-like basalts were sampled. Only one sample of basaltic 652 lava has been found in 1959, as ejected block in the inner pit of Nyiragongo. Petrography of 653 this sample was done by Sahama (1978), but without any chemical analysis. The origin of this 654 "basalt" remains questionable. It is concluded that the Pre-Virunga magmatic activity was 655 restricted to the west part of the rift, between 13 and 9 Ma and before the rift valley 656 formation. Volcanic activity of the Virunga area along the rift axis only began in the late 657 Pliocene. 658 To the west of the rift, close to Pre-Virunga lavas, the Mweso lava flow has run along the 659 valley, from south-east to north-west (Figs. 1, 5, 6). This flow highly post-dated the Pre-

660 Virunga lavas that crop out at the hilltops. It is overlain by recent flows from Nyamuragira

parasitic events. Poor chemical data are available for this lava flow (Table 1). However, its

- alkaline content is close to that of the neighbouring Nyamuragira lavas that belong to a
- 663 potassic basanite series, and is very different to the sodic series of Pre-Virunga lavas.
- 664

665 3.4. Virunga lavas

666

667 Virunga lavas exhibit many outstanding compositions, such as high-potassium content 668 shared with lavas of north part of the Kivu Rift in the Toro-Ankole volcanic area, but 669 unmatched by any other lavas of the East African Rift, except some nephelinites and 670 melilitites of North Tanzania. In this section, the analyzed rocks are distributed according 671 their petrographical features in a simplified nomenclature. The geochemical groups are 672 defined and the question of their magma sources is discussed.

673

674 *3.4.1. Magma compositions*

675

676 Virunga lavas are characterized by a potassic magmatic signature, but range in two
 677 contrasting series: a leucite basanite series and a leucite-melilite nephelinite series, illustrated

678 by the two currently active volcanoes, Nyamuragira and Nyiragongo. Because the 679 nomenclature of potassic lavas was imprecise and confusing, we proposed a simplified 680 taxonomic system (Pouclet, 1980, b; Pouclet et al., 1981, 1983, 1984) that has been adopted 681 in most of the following studies of the Virunga lavas. We use the K-prefixed rock names of 682 the sodic series commonly known in the international community: K-basanite, K-hawaiite, K-683 mugearite, K-benmoreite, and K-trachyte. Limits of the terms are defined by the 684 differentiation index (DI) of Thornton and Tuttle (1960) values of 35, 50, 65, and 80. The 685 more mafic terms (DI < 25) enriched in phenocrystic olivine and/or pyroxene, are named K-686 limburgite and K-ankaratrite, respectively. The K-basanite and K-hawaiite correspond to local 687 terms of porphyritic kivite and kivite, respectively. The feldspathoid-rich lavas are named 688 after their main mineral contents: olivine melilitite, olivine nephelinite, nepheline melilitite, 689 melilite-leucite nephelinite, leucite nephelinite, and nepheline leucitite. 690 The leucite basanite series is located at Nyamuragira, Karisimbi, old Visoke, Sabinyo, 691 Gahinga, and Muhavura. It is suspected at Shaheru. The leucite-melilite nephelinite series is 692 located at Nyiragongo, Baruta, Mikeno, and young Visoke. Various compositions of these 693 volcanoes are depicted by the Primitive Mantle normalized trace element diagrams (Fig. 13). 694 Chemical data are given by Hertogen et al. (1985), De Mulder et al. (1986), Marcelot et al. 695 (1989), Toscani et al. (1990), Rogers et al. (1992), Rogers et al. (1998), Platz et al. (2004), 696 Chakrabarti et al. (2009a), and by new analyses (Table 1). 697 Nyamuragira lavas are characterized by moderate enrichment of large ion lithophile elements (LILE; La/Yb = 25-34), slight Sr-negative anomaly, and HREE depletion with 698 699 Tb/Yb_N ratios ranging from 1.95 to 2.24 (Fig. 13A). All the mobile LILE are equally 700 moderately enriched, including Rb. This last feature distinguishes the Nyamuragira-related 701 western lavas of Kamatembe (N46) and Mushari (N572) from the Pre-Virunga lavas (Table 1; 702 Figs. 5 and 6). These two successive magmatic activities (Pre-Virunga and W-Nyamuragira) 703 came from very different sources (Figs. 12 and 13A). Compared to Pre-Virunga lavas, the 704 Nyamuragira lavas are less enriched in LILEs with the noticeable exception of Rb. The 705 basanitic volcanoes Karisimbi, early Visoke, Sabinyo, Gahinga, and Muhavura share the same 706 trace-element patterns with Nyamuragira (Fig. 13B), though their evolved lavas are normally 707 more enriched in the whole incompatible elements. 708 Nyiragongo lavas are much more enriched in incompatible elements than Nyamuragira 709 lavas (Fig. 13C). Their La/Yb ratios range from 43 to 58 in the olivine nephelinites, 54 to 69

710 in the nephelinites and leucitites, and 63 to 73 in the melilitites. They are depleted in HREEs

711 with Tb/Yb_N ranging from 1.93 to 2.86. A peculiar feature is the prominent depletion in Hf.

712 The other leucite nephelinite volcanoes, Baruta, Mikeno and young Visoke, share similar 713 composition (Fig. 13D). It is worth noting that melilitites are the most enriched in 714 incompatible elements. Leucite-rich leucitites show Rb (and K) enrichment and Ti (and Mg, 715 Fe) depletion, but also high Hf depletion. 716 In Virunga lavas, HREE depletion points to low degree of partial melting with residual 717 garnet in the source. By using similar approach than for the South-Kivu lavas, the magmatic 718 source of the Virunga lavas may be a garnet peridotite with low or no content of spinel (Fig. 719 14). The nephelinitic magma originated from lower degree of partial melting than the 720 basanitic magma. 721 Both K and Rb enrichments suggest the presence of phlogopite in the source (Furman, 722 2007), while low to moderate values of the K/Rb ratio (70-174 in K-basanite series and 117-723 202 in K-nephelinite series) preclude an amphibole-bearing source, as emphasized by 724 Chakrabarti et al. (2009a and b). In the Ba/Rb vs. Rb/Sr diagram of Furman et al. (2006), 725 elevated Rb/Sr ratios may indicate phlogopite or carbonatite metasomatism. High values are 726 recorded in the K-basanite series (Rb/Sr = 0.06-0.11), excluding the crustal contaminated 727 evolved lavas analyzed by De Mulder et al. (1986) and by Rogers et al. (1998), while the 728 values of the K-nephelinite series are moderate (Rb/Sr = 0.04-0.09). Zr/Hf ratios (41-47) of 729 the K-basanites are consistent with low partial melting of a garnet-clinopyroxene bearing 730 mantle source (Dupuy et al., 1992; Chakrabarti et al., 2009a) and do not indicate carbonate 731 contribution. A phlogopite contribution is retained for K-basanites. Very high Zr/Hf ratios in 732 the Nyiragongo leucite-nephelinites and leucitites (Zr/Hf = 47-94) may be a consequence of 733 carbonatite metasomatism (Dupuy et al., 1992). We show that high Zr/Hf values are due to Hf 734 depletion (Fig. 15). This implies contribution of a Hf-poor component in the Nyiragongo 735 source. According to analytical data of Andrade et al. (2002), Zr- and Hf-contents in 736 carbonatites display very large range of values and ratios. This is explained by heterogeneities 737 in the mantle source that are amplified by very low degrees of partial melting of the 738 carbonatite melt. Hf-poor carbonatites with super-chondritic Zr/Hf ratios occurred in Brazilian 739 and Namibian Cretaceous complexes, and in the Oldoinyo Lengai volcano of Tanzania (Fig. 740 15) (Andrade et al., 2002). In the Quaternary carbonatite lava of Fort-Portal in the Toro-741 Ankole volcanic area, northern end of Western Rift, the Zr/Hf ratio is 78 (Eby et al., 2009). In 742 the Namibian Kalkfeld Carbonatite Complex, associated nephelinites exhibit Zr and Hf 743 contents close to those of Nyiragongo nephelinites (Fig. 15). In this Complex, the carbonatite 744 melt contribution to nephelinitic magma has been demonstrated (Andrade et al., 2002). It is 745 concluded that the Nyiragongo nephelinitic magma is mixed with a carbonatite melt.

746 In summary, K-basanite layas originated from melting of a garnet- and phlogopite-bearing 747 source. According to both garnet and phlogopite stability fields in the mantle, the melt depth 748 must be between 80 and 150 km (Chakrabarti et al., 2009a). K-nephelinite series may be 749 derived from the same source, with lower partial melting degree. But, in the Nyiragongo area, 750 this magma has been contaminated by a carbonate component. The questions are: what is the 751 origin of this component, and why very neighbouring volcanoes, Nyamuragira and 752 Nyiragongo, may exhibit very different chemical composition, only one being contaminated? 753 Chakrabarti et al. (2009a) suggest two distinct melting of a very distant heterogeneous plume. 754 This model needs two different channelling in a very long distance for the spatially adjacent 755 volcanoes, and also for the other Virunga volcanoes. Thus, it seems to be an improbable 756 process. It is useful to re-examine the question of the Virunga heterogeneous source, because 757 until now, there is no convincing model.

758

759 *3.4.2. The carbonatite deal and the sources of Virunga volcanoes*

760

761 Carbonate metasomatism in Nyiragongo lavas is an old hypothesis for the Virunga magma 762 genesis to explain high alkali and lithophile element contents. Some authors also underline the 763 possible contribution of the crust, without or with carbonatite (Higazy, 1954; Holmes, 1965; 764 Bell and Powell, 1969). Others favour the role of a carbonatite melt (Dawson, 1964) or a 765 volatile transfer (Sahama, 1973). Petrological analyses ruled out the crust contribution 766 (Pouclet, 1973). The isotopic studies gave decisive data. Th isotope ratios are consistent with 767 carbonate metasomatism beneath Nyiragongo according to Williams and Gill (1992). Nd, Sr, 768 and Pb isotope systematics of Nyiragongo nephelinites imply that a previous fluid 769 contamination and LILE enrichment of the source has occurred around 500 Ma ago (Vollmer 770 and Norry, 1983; Vollmer et al., 1985) or between 750 and 850 Ma (Rogers et al., 1992). The 771 style of enrichment could be common metasomatism by mobile fluid or, more probably, melt 772 addition before and during magma genesis (Rogers et al., 1992; Williams and Gill, 1992). 773 Fluid and solid inclusions in Nyiragongo melilites shows that the lava was in equilibrium with 774 a carbonatitic liquid (Louaradi, 1994). The opportunity of carbonatitic enrichment is 775 supported by neighbouring occurrence of the nepheline syenite-carbonatite intrusive complex 776 of Lueshe dated at 619 ± 42 Ma by Van Overbeke et al. (1996) and at 558 ± 11 by Kramm et 777 al. (1997). We discard the 822 ± 120 Ma date of Kampunzu et al. (1998a) having a bad mean 778 square of weighted deviates (MSWD). Coincidently, large flakes of biotite developed close to 779 cancrinite-bearing syenite, in the Lueshe pyrochlore-rich sövite, display a K-Ar age of $516 \pm$

780 26 Ma (Bellon and Pouclet, 1980). The Lueshe complex is associated with, at least, four 781 alkaline syenitic intrusions of similar Late Neoproterozoic ages, in the neighbouring west-782 Virunga area (Kirumba, Bishusha, Fumbwe, Numbi, Fig. 16). The cancrinite- and sodalite-783 bearing syenite of Kirumba is partly rimed with a thin fringe of ankeritic carbonatite. 784 Occurrence of pyrochlore in the alkaline syenite of Numbi suggests a close association with a 785 carbonatite body. Hence, alkaline fluids have contaminated many parts of the sub-continental 786 mantle in the Virunga area at the time of the carbonatite-syenite magmatic activities. 787 We tentatively locate the potassium-enriched mantle beneath the Virunga volcanic system 788 as a function of magma fingerprints of the different volcanic activities. This mantle extends 789 WSW-ENE from the south-western and western small volcanoes: Nahimbi, Rumoka, 790 Rushayo, Suri-Turunga and Muvo (Nh, Rm, Rs, St, Mv) which are the sites of the most 791 primitive magmas (K-limburgites and olivine-melilitites or "rushayites") fed by independent 792 tectonic drains unrelated to the tectonic system of the great volcanoes, to the north-east 793 Bufumbiro Bay (Bf) small volcanoes of primitive lavas (K-limburgites or "ugandites" and K-794 ankaratrites or "murambites"), which were directly fed by their own drains with no magmatic 795 relationships to the neighbouring Muhavura (Fig. 16). This mantle source area includes the 796 more enriched carbonate core extending from Nyiragongo-Baruta to Mikeno and Visoke. The 797 Virunga volcanism began after the uplift of the west (Tongo) and east (Muhungwe) borders, 798 and the sinking of the Kivu and Edward basins dated around 5 Ma. We assume that the early 799 activity took place along the SW-NE oblique zone of the anomalous mantle underlining the 800 offset of rift axis, because the Mikeno emplaced in the middle part of this zone ca. 2 Ma. 801 The melting depth increased from the western uplifted rift edges (1) to the upper-middle 802 steps (2) and the lower step (3) of the rift valley with the following magma genesis: 1) pre-803 Virunga sodic basalt, 2) potassic basanite of Nyamuragira and eastern volcanoes, and 3) 804 potassic nephenilite of Nyiragongo, Mikeno and Visoke. Hence the metasomatised mantle 805 was melted at the deepest level of magma genesis of the Virunga area. Similar melting is 806 exhibited in the northern part of the Kivu rift, in the Toro-Ankole volcanic area characterised 807 by highly alkaline, potassic and carbonated lavas defining the kamafungite series. The 808 kamafungite magma genesis implied important contribution of the potassium-rich and 809 carbonatitic component from very deep metasomatised source (Rosenthal et al., 2009). 810 In the eastern rift, the most K-enriched alkaline lavas are located in northern Tanzania 811 where the rift valley becomes poorly defined in a wide zone overlapping the boundary of the 812 Archaean Tanzanian craton and the Palaeo and Neoproterozoic Ungaran and Mozambique 813 belts. Volcanoes emplaced on the craton and the remobilized craton margin and exhibit K-

814	nephelinites and melilitites similar to the Virunga ones, and also carbonatites similar to the
815	Toro-Ankole ones (Le Bas, 1981, 1987). A carbonatite metasomatism has been evidenced
816	from mantle xenoliths originated from the lithospheric craton root (Rudnick et al., 1993).
817	Isotopic compositions suggest that the metasomatism occurred recently. The carbonatite was
818	generated either by melting lithosphere that had become carbonated by asthenosphere-derived
819	melts, or directly from the asthenosphere in relationship with the mantle plume heating.
820	In the Kivu rift, isotope data suggest an older carbonatitic event, may be Neoproterozoic
821	(Vollmer and Norry, 1983; Vollmer et al., 1985; Rogers et al., 1992). But, we cannot exclude
822	the contribution of a volatile-rich transfer from the hot upwelling asthenosphere. In the Toro-
823	Ankole field, Nd, Sr and Hf isotope arrays suggest two time-spaced enrichments of the
824	source: a potassic alkaline silicate metasomatism and later a carbonate-rich metasomatism
825	(Rosenthal et al., 2009).
826	To comply with these data, we conclude that the distribution of geochemical variations in
827	the Virunga area is explained by zoning of a lithosphere enrichment that has occurred during
828	a Neoproterozoic alkaline magmatic event and by the contribution of plume-related hot and
829	fluid-rich asthenospheric components.
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831	4. Geochronology and history of the rift
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 831 832 833 834 835 836 837 838 839 	 4. Geochronology and history of the rift <i>A.1. Previous data</i> Reliable K-Ar geochronological data are provided by Bagdasaryan et al. (1973), Guibert et al. (1975), Bellon and Pouclet (1980), Rançon and Demange (1983), De Mulder (1985), De Mulder and Pasteels (1986), Pasteels et al. (1989), and Kampunzu et al. (1998b). Some Ar/Ar ages of the Sabinyo and Muhavura volcanoes were obtained by Rogers et al. (1998). There is a consensus about a three stages volcanic story of the South-Kivu area. Activity
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 831 832 833 834 835 836 837 838 839 840 841 842 843 844 845 	 4. Geochronology and history of the rift <i>A.1. Previous data</i> Reliable K-Ar geochronological data are provided by Bagdasaryan et al. (1973), Guibert et al. (1975), Bellon and Pouclet (1980), Rançon and Demange (1983), De Mulder (1985), De Mulder and Pasteels (1986), Pasteels et al. (1989), and Kampunzu et al. (1998b). Some Ar/Ar ages of the Sabinyo and Muhavura volcanoes were obtained by Rogers et al. (1998). There is a consensus about a three stages volcanic story of the South-Kivu area. Activity began around 10 Ma with outpouring of tholeiites and olivine-tholeiites. While this tholeiitic production seems to decline, the magma evolves to an alkali basaltic composition, around 8 Ma. A new rising alkaline activity, the second stage, took place between 7 and 4 Ma. These Miocene to Pliocene activities supplied the main part of the basaltic pile of the South-Kivu area. The third stage consists of strombolian eruptions of the Tshibinda Chain, in the early Pleistocene. Around the Virunga area the Pre-Virunga activity is dated between 13 and 9 Ma.
 831 832 833 834 835 836 837 838 839 840 841 842 843 844 845 846 	 4. Geochronology and history of the rift 4.1. Previous data Reliable K-Ar geochronological data are provided by Bagdasaryan et al. (1973), Guibert et al. (1975), Bellon and Pouclet (1980), Rançon and Demange (1983), De Mulder (1985), De Mulder and Pasteels (1986), Pasteels et al. (1989), and Kampunzu et al. (1998b). Some Ar/Ar ages of the Sabinyo and Muhavura volcanoes were obtained by Rogers et al. (1998). There is a consensus about a three stages volcanic story of the South-Kivu area. Activity began around 10 Ma with outpouring of tholeiites and olivine-tholeiites. While this tholeiitic production seems to decline, the magma evolves to an alkali basaltic composition, around 8 Ma. A new rising alkaline activity, the second stage, took place between 7 and 4 Ma. These Miocene to Pliocene activities supplied the main part of the basaltic pile of the South-Kivu area. The third stage consists of strombolian eruptions of the Tshibinda Chain, in the early Pleistocene. Around the Virunga area the Pre-Virunga activity is dated between 13 and 9 Ma.

848 The northernmost volcanic area of Toro-Ankole, north-east of Lake Edward, is
849 approximately dated to the Late Quaternary, with some accurate ages between 50 and 10 ka

850

after Boven et al. (1998).

- 851
- 852 4.2. New K-Ar age data
- 853

We display a new set of 17 whole rock K-Ar determinations (Table 2). Samples locate from north and south of Idjwi Island, Bitare-Bugarama graben, Bukavu graben (Cyanguguupper Rusizi), and western upper edge of the rift (**Fig. 17**).

857 We paid a special attention to the Idjwi Island where we previously obtained very old ages

858 (Bellon and Pouclet, 1980) not supported by further studies (Pasteels and Boven, 1989;

859 Pasteels et al., 1989).

860 The small outcrops of nephelinite lava were sampled north of Idjwi Island. They are 861 residues of an old flow cover (see above). First dating yielded 28 ± 1.4 Ma, a rather old age 862 that has been declared "not reliable" by Kampunzu et al. (1998b). Enrichment of radiogenic 863 argon may be suspected. A new measurement (LKa4) indicates 19.98 ± 1.00 Ma. One another 864 sample (BK8) of the same lava gives a similar age of 20.97 ± 0.56 Ma. According these new 865 data, an early Miocene nephelinitic activity is proved. It took place between the South-Kivu 866 area and the Virunga area, before the birth of the Lake Kivu (dated ca. 5 Ma) that separates 867 the two areas.

868 The southern Idjwi Island is partly covered with tholeiitic and alkali basaltic flows

869 belonging to the South-Kivu volcanic area. Tholeiites poured out over the crystalline

870 basement and are overlain by alkali basalts. In two places, tholeiitic flows are linked to

871 accumulations of hyaloclastites that are remnants of under-water volcanic cones. They are

also few small outcrops of diatomite-rich lacustrine deposits that are dated to the early

873 Holocene by their diatom composition. These last deposits were produced when the Lake

Kivu has reached its highest level, between 10 and 8 ka B.P., before the digging of the Rusizi

875 canyon (Pouclet, 1975) and thus are not related to the hyaloclastites. New ages measurements

876 of tholeiite flows yield ages of 10.30 ± 0.35 , 9.56 ± 0.48 , 8.76 ± 0.44 , 7.73 ± 0.30 and 6.62 ± 0.44 .

- 877 0.66 Ma (BK14, 19, 15, 36 and 7, respectively). An alkali basalt (BK-18) overlying the
- tholeiites is dated at 7.07 ± 0.51 Ma.

Finally, what could be the true age for this tholeiitic activity? An analytical study of argon

880 behaviour in similar tholeiitic lavas from South-Idjwi has been conducted by Pasteels and

881 Boven (1989). Apparent ages were obtained from 16.9 to 3.9 Ma. The authors concluded to

882 the presence of excess argon and discarded the older ages. They dated to 4.1 Ma a sample of 883 alkali basalt overlying tholeiites, and suggested that tholeiite activity may be as young as 5 884 Ma. It is known that sample preparation for K-Ar analyses cannot totally eliminate 885 xenocrystic fragments of the substratum that cause argon gain leading to old apparent ages. 886 Conversely, alteration is responsible for potassium and radiogenic argon losses that likely 887 make the ages younger. Unfortunately, South-Kivu tholeiites are rich in vitreous groundmass 888 containing most of the potassium and radiogenic argon, and this groundmass is easily altered. 889 So, young ages are not more credible than the old ones. Taking up to 7.07 Ma the age of the 890 overlying (fresh and not vitreous) olivine basalt, the South-Idjwi tholeiites must be dated 891 between 10.3 and 7 Ma, owing to our new datings.

To document the question of initial tholeiitic activity of South-Kivu area, tholeiites from the on-land southern prolongation of South-Idjwi lavas (RW86, 87) have been analyzed by one of us (H.B.) and age results were listed in Marcelot et al., (1989). Respectively, the following results are obtained: 8.97 ± 0.45 , and 11.42 ± 0.57 . These results are consistent with previous age data of tholeiites from upper Rusizi (10.0 to 7.6 Ma; Pasteels et al., 1989), and from the western edges (8.2 to 6.9 Ma; Kampunzu et al., 1998b).

Additional alkali basalts were dated in the middle part of the rift (Fig. 17): Bugarama

graben (RW88, 83) 10.63 ± 0.53 and 7.75 ± 0.39 Ma, and upper Rusizi area (RW90, 89, 82,

900 81) 8.10 \pm 0.40, 7.68 \pm 0.38, 7.18 \pm 0.36, and 6.33 \pm 0.32 Ma. Of important are the lavas of

901 the Kahuzi fracture zone, which are cross-cut by the main faults of the western upper steps. A

902 dating (MM2) gives 8.19 ± 0.40 Ma (Figs. 1, 3).

903

904 4.3. Geodynamical history of the rift

905

Taking into account the revised and the new data, in addition to the previously published data (Bagdasaryan et al., 1973; Guibert et al., 1975; Bellon and Pouclet, 1980; Pasteels and Boven, 1989; Pasteels et al., 1989; Kampunzu et al., 1998b) there is a total of 67 K-Ar ages for South-Kivu, pre-Virunga, and Mikeno lavas (**Table 4**). We exclude the post-1 Ma young lavas. These ages are plotted on a histogram in **Figure 18**.

The earliest volcanic event happened around 21 Ma in the North-Idjwi, close to the future axis of the rift, and likely, to the western side (**Fig. 19**). It is assumed that most of the lavas of this first activity are hidden by the South-Kivu and Virunga lavas. These early Miocene lavas are strongly alkaline and nephelinitic and resulted from a very low partial melting of mantle source. At that time, the rift valley did not exist and no swell is evidenced. A large outcrop of

916 old nephelinites is located west of the Lake Kivu, close to an alkaline syenite intrusion 917 (Numbi, Fig. 16) belonging to the Neoproterozoic anorogenic alkaline activity already 918 checked in the Kahuzi area, and west of the Virunga. The alkaline intrusions are set along a 919 NNE-SSW striking line named "the Neoproterozoic Weakness Line" (Fig. 19A). It is 920 postulated that the initial volcanic activity of the Kivu Rift, as well as the Pre-Virunga early 921 activity was drained by such an inherited fracture zone. 922 We indicate that, in the Kivu Rift, volcanism began contemporaneously with that of the 923 Kenya Rift ca. 23 Ma (Hendrie et al., 1994) and of southern Ethiopia ca. 21 Ma (George and 924 Rogers, 2002), though the earliest magmatism of the eastern rift is dated at 45 Ma in the main

925 rift Ethiopia (George et al., 1998). Our data rectify common belief that the Western Rift

926 volcanism began 5-10 m.y. after the Kenya Rift volcanism.

Pre-Virunga volcanic activity took place between 13 and 9 Ma. It is located in the
Neoproterozoic Weakness Line, and controlled by NW-SE faults oblique to the rift axis
(Fig.19A). The Tongo Fault was not yet active. The existence of a crustal magma chamber
beneath this volcanic field is attested by the output of evolved lavas. The composition is

alkaline sodic and indicates a low degree of melting of the source.

At ca. 11 Ma, tholeiitic volcanism was emplaced in the South-Kivu, along the South-Idjwi — Bitare-Bugarama structure, parallel to the rift axis (Fig. 19). Flows poured out along a north-south fracture system. Besides, the 8.2 Ma Kahuzi flow (MM2) to the edge of the upper step ran down to the west. This flow direction complies with the existence of a swell and with the absence of a rift graben. However, the tholeiitic underwater hyaloclastites and flows of South-Idjwi, which are dated around 8 Ma, involve the existence of a lacustrine basin. It must be assumed that a first, though limited graben was formed along the rift axis, at ca. 8 Ma.

Afterwards, the tholeiite magma contribution decreased until 5 Ma, but was no longer restricted to the rift axis. Last tholeiitic lavas poured out on the western upper Kahuzi step and on the Mwenga area where they are overlain by 5.8 to 2.6 Ma alkaline lavas (Fig. 19). In the same time, since 10.6 Ma or 8.5 Ma, an alkaline magma production resulted from less partial

943 melting of a heterogeneous source. The activity was located along the Bugarama north-south

944 tectonic axis, and then, along the N-S and NNE-SSW trending faults of the whole area. The

945 most significant basaltic supply is dated between 8 and 7 Ma. The alkali basalt lava flew

946 down above the western steps of the rift. Their local unconformity above the tholeiites in the

947 Bugarama graben confirm that the rift valley was initiated around 8 Ma. Subsidence of the

948 northern basin of Lake Kivu began ca. 5 Ma. Between 6 and 5 Ma, extrusion of evolved lavas

949 (trachyte-phonolite), into and close to the Bukavu graben, pointed to the ponding of alkaline

950 magma into crustal reservoirs in a limited area. After 5 Ma, volcanic activity decreased and 951 migrated to the south-west tectonic zone of Mwenga until 2.6 Ma, in correlation with the 952 decreasing of the partial melting degree of the source which produced Mg-basanites. Such a 953 timing and the magmatic feature are consistent with a rift propagation in the Mwenga branch. 954 The last activity, around 1.7 Ma, has built the Tshibinda Chain at the edge of Mount Kahuzi. 955 Its alkaline lavas imply a new and moderate degree of melting of a similar source. 956 Consequently, a thermal anomaly was persisting below the higher western part of the rift in 957 the Lake Kivu area. More recent eruptions (possibly late Pleistocene) in the Tshibinda Chain 958 and Rwandese shore lake have been assumed by Pasteels et al. (1989) and by Ebinger 959 (1989a). However, new accurate chronological data are needed to improve the temporal 960 constraints of these latest eruptions. 961 In the Virunga area above the shelf between lakes Kivu and Edward, volcanic activity was 962 initiated along a SW-NE fracture zone at the Mikeno area, ca. 2.6 Ma (Guibert et al., 1975), 963 and then propagated to the SW at the Shaheru, and to the NE at the early-Visoke, early-964 Karisimbi, Sabinyo, Gahinga and Muhavura until to 0.1 Ma (Bagdasaryan et al., 1973; 965 Rançon and Demange, 1983; Rogers et al., 1998). In recent time, volcanism occurred 966 simultaneously in the eastern side at young-Visoke, Karisimbi and Muhavura (Rançon and 967 Demange, 1983; De Mulder, 1985; Rogers et al., 1998), and in the middle area, at Baruta. 968 Lastly, eruptions were focused in the middle Virunga at Nyiragongo, and to the west at 969 Nyamuragira.

970

971 7. Conclusions

972

This study addresses the tectonic pattern, volcanic rock compositions, and age dating of the Kivu Rift in the western branch of the East African Rift system, with the aim of improving the history of the rift and deciphering the relationships between the volcano-tectonic pattern and the conditions of magma genesis.

977 The rift resulted from stretching of the continental lithosphere that produced thinning and 978 passive upwelling of hot asthenosphere. The tectonic framework evolved with linking of fault 979 segments inherited from weakness zones of the basement, and with development of isolated 980 basins in the rift axis. Rising of the top of the asthenosphere with thinning of the lithospheric 981 mantle initiated the decompressional driven partial melting of the lithosphere and 982 asthenosphere, successively. This first pre-rift doming stage is portrayed with the 21 Ma 983 nephelinites of North-Idjwi, the 13-9 Ma alkaline basalts of West-Virunga, and the 11-8 Ma

tholeiites of South-Kivu. At that time, no fault scarps were developed and the rift valley was
not yet created, though a small lacustrine basin existed in the South Idjwi area owing to the
occurrence of hyaloclastites. The magma composition logically evolved from highly alkaline
to moderately alkaline and to sub-alkaline with increasing amount of lavas, in relationships
with increasing degree of partial melting and more important contribution of the
asthenospheric component. The N-S and NNW-SSE trend of the fertile fractures suggests an
E-W strain field direction.

991 But, in the following stage, the magma production stopped in the Virunga area and 992 completely changed in South Kivu with the outpouring of alkaline basalts, as soon as 8.5 Ma. 993 The partial melting decreased and was limited to lithospheric mantle. One may note the lack 994 of voluminous flood basalts, a salient component of the extensional rifting evolution in the 995 Ethiopian-Somalian branch of the East African rift. Then, the rift valley was created and the 996 lake basins subsided, namely around 5 Ma for the Lake Kivu. This indicates the cessation of 997 the extensional process and the cooling of the underlying mantle, as proved by the decreasing 998 degree of partial melting of the late Pliocene Mg-basanites of the Mwenga branch. The 999 extrusion of differentiated lavas between 6 and 5 Ma in the Bukavu graben, points to magma 1000 storage into crustal reservoir, and to the non-existence of an opened fissural system.

1001 Again, the Kivu rift evolution completely changed when a new highly alkaline and potassic 1002 volcanism appeared in the Virunga site around 2.6 Ma. From that time until now, this event is 1003 controlled by a transtensional constraint and the opening of a tension gash with an ENE-1004 WSW extensional displacement. This constraint affected the South-Kivu and induced a 1005 moderate melting of the lithosphere in the Tshibinda Volcanic Chain during the Pleistocene. 1006 In the Virunga area, the magmas tapped a deep mantle source previously enriched by 1007 carbonated metasomatism. The success of the melt production is explained by the high 1008 volatile content of the mantle source which facilitated the melting. In the same structural context, a normal mantle would not melt. In return, the presence of a metasomatized mantle is 1009 1010

1010 the effect of a former Proterozoic magmato-tectonic event which created the structural

1011 weakness zone reactivated and used by the Kivu rift. Thereby, the existence of the

1012 outstanding Virunga volcanic province is not really fortuitous.

1013 The history of the Kivu rift is not a smooth running of a standard rift development. It is 1014 strongly dependent on space and time distribution and changing of the surrounding driving 1015 forces in the African plate. Meanwhile, no accurate correlations can be evidenced with the 1016 eastern branch of East African Rift. Further studies and age datings are needed to attempt a 1017 more comprehensive model of the East African magmato-tectonic evolving constraints.

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1352	
1353	Caption
1354	
1355	Fig. 1 - Tectonic pattern of the western branch of the Eastern Africa rift system in the Lake
1356	Kivu region, after Pouclet (1976) slightly modified. Map of the South-Kivu and Virunga
1357	volcanic areas. Volcanoes of Virunga: Nyamuragira (N), Nyiragongo (Ny), Mikeno (M),
1358	Karisimbi (K), Visoke (V), Sabinyo (S), Gahinga (G), and Muhavura (Mh).
1359	
1360	Fig. 2 - Tectonic map of the Lake Kivu and altitude of rift steps in metres. This new map is
1361	drawn after the bathymetric map and the geophysical data of Degens et al. (1973) and
1362	Wong and Von Herzen (1974), which were acquired during two cruises of the Woods Hole
1363	Oceanographic Institution in 1971 and 1972. The sub-water volcanoes were discovered
1364	using echo sounder and magnetometer records. A-B and C-C, interpreted cross-sections in
1365	the northern and southern basins, respectively. Sub-lacustrine volcanoes of the northern
1366	lake side are linked to the Late Pleistocene activity of Virunga during the high level stage
1367	(Pouclet, 1975). The South-Idjwi sub-lacustrine volcanoes are much older (Miocene), see
1368	section 4.2. Mineral hot springs deposited thick travertine terraces or sinters in the
1369	Holocene. The up-lifting points are localized using topographical data. They mark the
1370	westward and eastward tilting of the horst steps, in the west side and the east side,
1371	respectively.
1372	
1373	Fig. 3 - Geological sketch map of the Mount Kahuzi area showing the birth of tholeiitic
1374	Lugulu flows (new map). The MM2 basaltic lava is dated at 8.19 ± 0.40 Ma (new dating,
1375	Table 2). This lava flow westward poured out during the doming stage of the Kivu Rift,
1376	before the rift valley formation. Igneous intrusions are dated to Neoproterozoic and consist
1377	of quartz-porphyry microgranite in Mount Kahuzi and of acmite-riebeckite-bearing
1378	granites and syenites in the other areas (ref. in the text).
1379	
1380	Fig. 4 - Map of strombolian cones of the Tchibinda Volcanic Chain (new map) and location
1381	of the analysed lavas. The CRSN "Centre de Recherches en Sciences Naturelles", formerly

1382 IRSAC "Institut pour la Recherche Scientifique en Afrique Centrale" is located at Lwiro.

1383	Sample numbers refer to analysed rocks (Table 1). Full dots are dated samples: $TB4 = 1.9$
1384	Ma ; MM1 = 1.7 Ma ; KT1 = 1.6 Ma (Table 4); MM2 = 8.19 Ma (Table 2).
1385	
1386	Fig. 5 - Map of the Virunga Volcanic area locating the Plio-Quaternary volcanic activities
1387	after Pouclet (1977) completed with the recent volcanic centres. Main edifices:
1388	Nyamuragira (N), Nyiragongo (Ny) and its two "elder brothers" Shaheru (Sh) and Baruta
1389	(B), Mikeno (M), Karisimbi (K) and its older craters Branca (Br) and Muntango (Mt),
1390	Visoke (V), Sabinyo (S), Gahinga (G), and Muhavura (Mh). Lithology of the surrounding
1391	substratum is specified. Red dots, flank or parasitic cones; red diamonds, historical
1392	parasitic activities.
1393	
1394	Fig. 6 - Map of the Bishusha-Tongo area (new map). Outcrops of the Miocene lavas.
1395	Altitudes of the Tongo uplifted Pleistocene terraces in metres.
1396	
1397	Fig. 7 - Qtz-Ab+Or-Hy-Ol-Ne combined ternary diagrams of the Kivu basaltic lavas. Data
1398	after Meyer (1953), Meyer and Burette (1957), Denaeyer et al. (1965), Denaeyer (1972),
1399	Pouclet (1976), Guibert (1977), Villeneuve (1978), Kampunzu et al. (1979, 1983, 1998b),
1400	Bellon and Pouclet (1980), De Paepe and Fernandez-Alonso (1981), Kanika et al. (1981),
1401	Lubala (1981), Lubala et al. (1982, 1984, 1987), Tack and De Paepe (1983), Auchapt
1402	(1987), Auchapt et al. (1987), Marcelot et al. (1989), Pasteels et al. (1989), Furman and
1403	Graham (1999), and new analyses (Table 1). Normative nomenclature: T, tholeiite (Qtz);
1404	Ol-T, olivine-tholeiite (Ol and > 15% Hy); Ol-B, olivine basalt (Ol and < 15% Hy); Alk-B,
1405	alkali basalt (0.01% < Ne < 5%); Bs, basanite (5% < Ne < 15%); Neph, nephelinite (Ne >
1406	15%).
1407	
1408	Fig. 8 - Primitive Mantle normalized incompatible element diagram of the South-Kivu
1409	tholeiitic and alkali basaltic lavas. Tholeiitic and basaltic areas drawn after the analytical
1410	data set. New analyses of (A) Miocene lavas, and (B) Pleistocene lavas of the Tchibinda
1411	Volcanic Chain from Table 1. Normalizing values after Sun and McDonough (1989).
1412	
1413	Fig. 9 - Yb vs. La/Yb and La/Sm vs. Sm/Yb diagrams for determining the enrichment of the
1414	source and the partial melting degrees of mantle source. (A) The Yb vs. La/Yb diagram
1415	indicates an increase of partial melting, from basanites to tholeiites, and/or varying
1416	enrichment of sources compared with the average OIB-type source. (B) Batch melting of

1417	the enriched source C1 and of the less enriched source C2. Melt curves are drawn for
1418	spinel-lherzolite, garnet-lherzolite and a 50:50 mixture of spinel- and garnet-lherzolite.
1419	Modal compositions of spinel-lherzolite (olivine 53%, OPX 27%, CPX 17%, spinel 3%)
1420	and garnet-lherzolite (olivine 60%, OPX 20%, CPX 10%, garnet 10%) are after Kinzler
1421	(1997) and Walter (1998). Mineral/melt partition coefficients for basaltic liquids are after
1422	compilation of Rollinson (1993). Tholeiites may have resulted from ca. 10% of partial
1423	melting of spinel-lherzolite from a moderately enriched source. Basaltic and alkaline lavas
1424	resulted from lower degrees of partial melting (10% to 2%) of a spinel- and garnet-
1425	Iherzolite mixture of varying amount of spinel and garnet.
1426	OIB, Primitive Mantle, N-MORB, and E-MORB compositions are from Sun and
1427	McDonough (1989).
1428	
1429	Fig. 10 - Nb/Yb vs. Th/Yb diagram to test crustal contamination. Same symbols as for Figure
1430	9. OIB, Primitive Mantle, and N-MORB compositions are from Sun and McDonough
1431	(1989). All the lavas plot in the mantle array, precluding any perceptible crustal
1432	contamination.
1433	
1434	Fig. 11 - (A) La vs. Yb, (B) Ba vs. La, and (C) Nb vs. Zr covariation diagrams. Same symbols
1435	as for Figure 9. Tsh, Tshibinda Volcanic Chain; Lem, Leymera; PM, partial melting
1436	curves; FC, fractional crystallization; trend #1, low-Yb, high-La, high-Ba, and low-Zr
1437	curves evolving from basanites to olivine basalts (enriched source); trend # 2, low-La, low-
1438	Ba, and high-Zr curves characterizing the tholeiites and some olivine basalts (less enriched
1438 1439	Ba, and high-Zr curves characterizing the tholeiites and some olivine basalts (less enriched source); trend # 3, intermediate high-Ba and high-La pattern, and intermediate Nb and Zr
1438 1439 1440	Ba, and high-Zr curves characterizing the tholeiites and some olivine basalts (less enriched source); trend # 3, intermediate high-Ba and high-La pattern, and intermediate Nb and Zr feature (intermediate or mixed source). The pattern of these trends attests for the
1438 1439 1440 1441	Ba, and high-Zr curves characterizing the tholeiites and some olivine basalts (less enriched source); trend # 3, intermediate high-Ba and high-La pattern, and intermediate Nb and Zr feature (intermediate or mixed source). The pattern of these trends attests for the contribution of two sources. The trend # 1, best exposed by the Tshibinda Chain lavas,
1438 1439 1440 1441 1442	 Ba, and high-Zr curves characterizing the tholeiites and some olivine basalts (less enriched source); trend # 3, intermediate high-Ba and high-La pattern, and intermediate Nb and Zr feature (intermediate or mixed source). The pattern of these trends attests for the contribution of two sources. The trend # 1, best exposed by the Tshibinda Chain lavas, derived from an enriched source. The trend # 2 derived from a less enriched source. These
1438 1439 1440 1441 1442 1443	 Ba, and high-Zr curves characterizing the tholeiites and some olivine basalts (less enriched source); trend # 3, intermediate high-Ba and high-La pattern, and intermediate Nb and Zr feature (intermediate or mixed source). The pattern of these trends attests for the contribution of two sources. The trend # 1, best exposed by the Tshibinda Chain lavas, derived from an enriched source. The trend # 2 derived from a less enriched source. These two sources are documented by isotopic studies (see text). The enriched source is
1438 1439 1440 1441 1442 1443 1444	 Ba, and high-Zr curves characterizing the tholeiites and some olivine basalts (less enriched source); trend # 3, intermediate high-Ba and high-La pattern, and intermediate Nb and Zr feature (intermediate or mixed source). The pattern of these trends attests for the contribution of two sources. The trend # 1, best exposed by the Tshibinda Chain lavas, derived from an enriched source. The trend # 2 derived from a less enriched source. These two sources are documented by isotopic studies (see text). The enriched source is lithospheric, while the less enriched source can be mixed lithospheric and asthenospheric
1438 1439 1440 1441 1442 1443 1444 1445	 Ba, and high-Zr curves characterizing the tholeiites and some olivine basalts (less enriched source); trend # 3, intermediate high-Ba and high-La pattern, and intermediate Nb and Zr feature (intermediate or mixed source). The pattern of these trends attests for the contribution of two sources. The trend # 1, best exposed by the Tshibinda Chain lavas, derived from an enriched source. The trend # 2 derived from a less enriched source. These two sources are documented by isotopic studies (see text). The enriched source is lithospheric, while the less enriched source can be mixed lithospheric and asthenospheric materials.
1438 1439 1440 1441 1442 1443 1444 1445 1446	Ba, and high-Zr curves characterizing the tholeiites and some olivine basalts (less enriched source); trend # 3, intermediate high-Ba and high-La pattern, and intermediate Nb and Zr feature (intermediate or mixed source). The pattern of these trends attests for the contribution of two sources. The trend # 1, best exposed by the Tshibinda Chain lavas, derived from an enriched source. The trend # 2 derived from a less enriched source is lithospheric, while the less enriched source can be mixed lithospheric and asthenospheric materials.
1438 1439 1440 1441 1442 1443 1444 1445 1446 1447	 Ba, and high-Zr curves characterizing the tholeiites and some olivine basalts (less enriched source); trend # 3, intermediate high-Ba and high-La pattern, and intermediate Nb and Zr feature (intermediate or mixed source). The pattern of these trends attests for the contribution of two sources. The trend # 1, best exposed by the Tshibinda Chain lavas, derived from an enriched source. The trend # 2 derived from a less enriched source is lithospheric, while the less enriched source can be mixed lithospheric and asthenospheric materials. Fig. 12 - Primitive Mantle normalized incompatible element diagram of North-Idjwi and Pre-
1438 1439 1440 1441 1442 1443 1444 1445 1446 1447 1448	 Ba, and high-Zr curves characterizing the tholeiites and some olivine basalts (less enriched source); trend # 3, intermediate high-Ba and high-La pattern, and intermediate Nb and Zr feature (intermediate or mixed source). The pattern of these trends attests for the contribution of two sources. The trend # 1, best exposed by the Tshibinda Chain lavas, derived from an enriched source. The trend # 2 derived from a less enriched source. These two sources are documented by isotopic studies (see text). The enriched source is lithospheric, while the less enriched source can be mixed lithospheric and asthenospheric materials. Fig. 12 - Primitive Mantle normalized incompatible element diagram of North-Idjwi and Pre-Virunga lavas. These sodic-rich lavas are more fractionated than the basaltic lavas of
1438 1439 1440 1441 1442 1443 1444 1445 1446 1447 1448 1449	 Ba, and high-Zr curves characterizing the tholeiites and some olivine basalts (less enriched source); trend # 3, intermediate high-Ba and high-La pattern, and intermediate Nb and Zr feature (intermediate or mixed source). The pattern of these trends attests for the contribution of two sources. The trend # 1, best exposed by the Tshibinda Chain lavas, derived from an enriched source. The trend # 2 derived from a less enriched source. These two sources are documented by isotopic studies (see text). The enriched source is lithospheric, while the less enriched source can be mixed lithospheric and asthenospheric materials. Fig. 12 - Primitive Mantle normalized incompatible element diagram of North-Idjwi and Pre-Virunga lavas. These sodic-rich lavas are more fractionated than the basaltic lavas of South-Kivu. Normalizing values after Sun and McDonough (1989).

1451	Fig. 13 - Primitive Mantle normalized incompatible element diagram of (A) Nyamuragira
1452	lavas compared with South-Kivu lavas, (B) the other basanitic volcanoes of Virunga, (C)
1453	Nyiragongo lavas compared with Nyamuragira lavas, and (D) the other leucite-nephelinitic
1454	volcanoes of Virunga.
1455	
1456	Fig. 14 - La/Sm vs. Sm/Yb diagram of Virunga mafic lavas. Batch melting of the enriched
1457	source C1. Melt curves as in Figure 9. The Virunga magma can be originated from a
1458	garnet- and a few spinel-bearing lherzolite source. The degree of partial melting is higher
1459	for the basanite magma than for the nephelinite magma. Same symbols as for Figure 13.
1460	
1461	Fig. 15 - Zr/Hf vs. Hf diagram of mafic lavas of Virunga. Hf and Zr/Hf chondritic values of
1462	K-basanites of Nyamuragira, Karisimbi, and eastern volcanoes are consistent with partial
1463	melting of common mantle. High Zr/Hf ratios in the Nyiragongo lavas imply the
1464	contribution of Hf-poor carbonatite component, as shown by the Namibian nephelinite-
1465	carbonatite association. Same symbols as for Figure 13.
1466	
1467	Fig. 16 - Inferred location of the metasomatized and carbonated mantle in the sub-lithospheric
1468	mantle of the Virunga area, after geochemical signatures of the Plio-Quaternary volcanoes.
1469	Normal mantle is suspected below the Miocene volcanic area.
1470	Small red stars are the eruptive centers of the most primitive lavas unrelated to the magma
1471	chambers of the large volcanoes (St, Suri-Turunga; Mv, Muvo; Nh, Nahimbi; Rm,
1472	Rumoka; Rs, Rushayo; Bf, Bufumbiro). Large star is the Lueshe carbonatite. Circled stars
1473	are Late Neoproterozoic intrusions of nephelinitic syenites (N, Numbi; F, Fumbwe; B,
1474	Bishusha; K, Kirumba).
1475	
1476	Fig. 17 - Location of the new geochronological data in the Lake Kivu and South-Kivu
1477	volcanic area. Data in Table 2.
1478	
1479	Fig. 18 - Histogram of all the geochronological data. Volcanic activity initiated south of the
1480	future Lake Kivu trough, at 21 Ma, with alkaline sodic nephelinite. It evolved to sodic
1481	basanite in the Pre-Virunga region, between 13 and 9 Ma. A distinct tholeiitic volcanism
1482	appeared in the South-Kivu region at 11 Ma, and is progressively replaced by alkaline
1483	activity until the last pulse in the Tshibinda Chain ca. 1.7 Ma. The oldest activity of the
1484	Virunga area is dated at 2.6 Ma in the Mikeno volcano.

44

1485	
1486	Fig. 19 - Geographical distribution of the volcanic activity
1487	(A) Data from 21 to 9 Ma. The initial activity is nephelinitic and is limited to the middle part
1488	of the future Lake Kivu. In the Virunga area, the rift valley did not exist during the Pre-
1489	Virunga activity. In the South-Kivu area, the activity is tholeiitic and located along N-S
1490	fractures of the future rift axis. Late Neoproterozoic alkaline intrusions: L, Lueshe; K,
1491	Kirumba; B, Bishusha; F, Fumbwe; N, Numbi; Kz, Kahuzi; Bg, Biega. The layout of these
1492	intrusions suggests a structural weakness line.
1493	(B) Data from 9 Ma to Present. In the Virunga area, activity began ca. 2.6 Ma in the middle of
1494	the oblique rift segment. In South-Kivu, activity extended to the whole area along N-S and
1495	NNE-SSW fractures and changed from tholeiitic to alkaline between 8.5 and 5.9 Ma.
1496	Activity occurred to the south-west along the NE-SW fractures of Mwenga, ca. 5.8 to 2.6
1497	Ma, and, finally, to the west, in the Tshibinda Chain, ca. 1.7 Ma.
1498	
1499	Table 1 - New analyses and analyses of dated samples from Marcelot et al. (1989). Alk-B,
1500	alkali basalt; Ol-B, olivine basalt; Bs, basanite; Na-Bs, sodic basanite; Benm, benmoreite;
1501	H, hawaiite; Mug, mugearite; Neph, nephelinite; T, tholeiite.
1502	Analytical method and laboratory: H = atomic absorption spectrometry (AA) for the major
1503	elements and instrumental neutron activation (INAA) and X-ray fluorescence (XRF) for
1504	the minor elements at the University of Halifax (Canada); O = inductively-coupled plasma
1505	spectrometry (ICP-OES) at the analytical laboratory of the University and CNRS of
1506	Orléans (France); P = atomic absorption spectrometry at the Department of Petrography-
1507	Volcanology of the University of Paris-Sud; T = XRF at the Musée Royal de l'Afrique
1508	Centrale of Tervuren (Belgique).
1509	Ages are from Tables 2 and 4.
1510	
1511	Table 2 - New K-Ar geochronological analyses. Most of potassium-argon ages were
1512	measured at the "Université de Bretagne Occidentale" in Brest (France) on grains of
1513	whole-rock, 0.3 to 0.15 mm in size, obtained after crushing and subsequent sieving of the
1514	solid samples. One aliquot of grains was powdered in an agate grinder for chemical attack
1515	of around 0.1 g of powder by 4 cc of hydrofluoric acid, before its analysis of K content by
1516	AAS (Atomic Absorption Spectrometry). A second aliquot of grains was reserved for
1517	argon analysis. About 0.7 g to 0.8 g of grains were heated and fused under vacuum in a

1518 molybdenum crucible, using a high frequency generator. Released gases during this step

1519	were cleaned successively on three quartz traps containing titanium sponge when their
1520	temperature was decreasing from 800°C to the ambient one, during 10 minutes; at the final
1521	step the remaining gas fraction was ultra-purified using a Al-Zr SAES getter. Isotopic
1522	compositions of argon and concentrations of radiogenic argon ${}^{40}\text{Ar}^*$ were measured in a
1523	stainless steel mass spectrometer with a 180° geometry and a permanent magnetic field.
1524	Isotopic dilution was realized during the fusion step, using precise concentrations of ³⁸ Ar
1525	buried as ions in aluminium targets (Bellon et al., 1981). Ages are calculated using Steiger
1526	and Jäger's (1977) constants and errors, following the equation of Mahood and Drake
1527	(1982).
1528	
1529	Table 3 - Trace element composition of the South-Kivu magma sources according to Auchapt
1530	(1987).
1531	
1532	Table 4 – K-Ar geochronological data for the Lake Kivu area lavas (Western Branch of the
1533	East African Rift) excluding the post-1 Ma lavas. References: 1, Bagdasaryan et al. (1973);
1534	2, Guibert et al. (1975); 3, Bellon and Pouclet (1980); 4, Pasteels and Boven (1989); 5,
1535	Pasteels et al. (1989); 6, Kampunzu et al. (1998b); 7, this work.

et al. (1989); 6, Kam_r

Table 1							Table	1 (continued 1)						Table	2 1 (continue	12)						Table 1 ((continued 3)						Table 1 (contin	ued 4)				Table 1 (continued 5)
Location	Kahuzi Bu	ikavu Bukavu	Upper-Ra	sizi South-	Idjwi	DU-C DU-C	Locati	on South-Idjwi	Bita	are	Bugarama	Tshibinda C	Thain (from sou	th to north) Locat	tion Tshib	nda Chain (is	an south to north	h)				Location	Tshibinda C	hain North-Id	ljwi	Bishusha		Tongo	Location Tor	ngo	Mweso West-	Nyamuragira	101-03 11-00-0	Location	Ny amuragira
# Method	T-0 1	T-O H	RW52 R	H O	0	T-0 P-0	P-0 Metho	ad 7-0 (18 KW 80	H H	UND RWINS	T-O	P-0 H	T-0 Meth	xod P-O	H	T-0 T-0	5 K125	T-0 T-0	0 T-0	T-0	T-0 Method	T-0 T	T-0 P-0	H 0	- P-O P	0 2-0	H P-0	Method B	I T-0 T-0	4) N337 N46 P P-0	P P	P P	P Method	P-0 H
Age (Ma)	8.19	Bs Bs 7	Bs A 7.18	IK-B 1 .68 6.62	10.30	8.76 9.56	i Rock	4a) 7.73 7.1	-в 1)7 8.97	11.42 7	rs Bs 75 10.63	Bs 1.7	Bs Na-Br 1.9	i Bi Rock Age (Ma) 1.6	OI-B	OI-B Na-E	IS OI-B	AIK-B AIK	-B Alk-B	Alk-B	Alk-B Rock Age (Ma	ык-в 0	JI-B Neph	Nepn Nep 19.98 20.9	pn Na-Bs Ni 97	-Bs Haw 12.6	Haw Na-Bs 8.9	KOCK B Age (Ma)	s Mug Benn	n OI-B K-Bs	K-BS K-BS	K-BS K-BS	K-BS ROCK Age (Ma	K-Bs K-Bs
SiO ₂ TiO ₂	44.09 45	5.43 46.45 2.07 2.04	45.65 4	7.62 50.22	50.03 1.69	49.41 50.9	1 51.44 SiO2 1.58 TiO2	52.64 46. 1.63 21	23 52.57	49.68 46	.60 43.90 12 2.87	46.58 4	5.67 46.84	48.50 SiO2	50.0	48.98 1.17	49.42 44.7	9 49.00 7 1.32	45.63 46.3	30 46.01 8 1.51	46.99 1.46	46.82 SiO2 1.48 TiO2	45.72 47	7.89 42.41	42.76 42.9	97 47.30 43 60 1.40 1	92 47.84 50 1.64	46.90 45.35 1.66 1.49	SiO2 44. TiO2 1.4	.13 53.16 57.84 53 1.04 1.13	6 48.93 46.24 2.38 2.75	45.42 45.93	46.01 46.55 3.16 2.71	44.54 SiO2 2.73 TiO2	45.88 44.90 3.10 3.37
Al ₂ O ₃	14.48 14	4.57 13.80	14.45 1	4.35 15.40	15.42	14.70 14.4	1 14.99 Al2O3	1.0.5 1.5	12 13.98	13.75 14	.10 14.94	15.08 1	4.04 13.56	12.76 AI20	13 13.5	13.55	14.92 15.2	5 15.36	14.40 16.5	50 15.60	15.08	15.41 Al2O3	15.67 15	5.66 11.98	11.68 12.	15 14.67 16	12 13.87	16.19 17.54	AI2O3 15.	72 16.98 19.10	0 15.17 15.53	15.06 12.73	14.94 13.95	10.78 AI2O3	14.53 13.55
Fe ₂ O ₃ t MnO	0.16 0	0.46 10.90).19 0.18	0.20 0	1.50 11.01 1.15 0.15	0.17	13.64 12.19 0.17 0.14	9 11.48 Fe2O3 4 0.15 MnO	0.11 0.1	55 10.86 10 0.14	0.30 0	095 12.88 21 0.18	0.22 (2.41 11.20 0.17 0.18	0.19 MnO	03 t 9.71 0 0.15	0.16	10.67 10.2 0.13 0.22	2 10.55 2 0.18	0.18 0.1	3 9.45 9 0.20	0.17	10.76 Fe2O3 t 0.19 MnO	0.20 0	0.78 10.50).19 0.16	10.47 9.8 0.17 0.1	17 11.36 11 6 0.04 0	56 17.27 10 0.03	11.62 10.93 0.21 0.03	Fe2O3 t 11. MnO 0.2	.08 8.27 4.41 22 0.17 0.06	12.51 11.12 0.04 0.20	0.03 0.03	12.58 11.25 0.03 0.03	12.71 Fe2O3 t 0.08 MnO	13.63 12.80 0.08 0.18
MgO CaO	10.19 8 10.83 10	8.66 8.61 0.93 10.90	7.17 (i.70 6.13 0.66 9.94	6.30 10.15	6.52 6.74 6.86 9.35	5.77 MgO 9.13 CaO	5.47 9.1 9.11 9.1	14 6.90 17 8.23	7.00 8 8.86 10	40 8.80 .70 9.85	10.23 9 9.38 1	9.08 8.87 2.12 11.59	9.56 MgO 10.90 CaO	9.98	10.68	9.23 9.63 10.36 10.0	8 9.00 8 9.38	11.11 6.9 9.91 9.3	6 9.20 3 10.60	10.18 10.01	9.36 MgO 10.27 CaO	10.36 9 9.84 9	9.80 12.41 9.75 13.55	12.11 12.4 12.90 13.3	44 5.97 6. 23 11.43 11	35 3.56 46 8.89	5.05 4.46 8.81 11.19	MgO 6.5 CaO 10.	52 3.36 1.36 92 5.44 4.27	7.24 7.76 8.29 10.12	5.62 9.89 10.77 11.13	6.37 8.54 10.08 10.97	11.15 MgO 11.85 CaO	6.79 7.50 10.44 10.70
Na ₂ O K ₂ O	2.53 3 0.91 1	1.56 3.67 1.24 1.55	3.63 3 1.56 1	.00 2.52 .35 0.28	2.65 0.30	3.20 2.77 0.55 0.45	2.68 Na2O 0.20 K2O	2.43 3.0 0.30 0.5	15 2.64 19 0.95	2.61 3 0.62 1	45 3.33 22 1.40	3.24 2 1.36 1	2.65 3.52 1.21 1.60	3.84 Na20 1.06 K2O	2.78	2.56 1.14	2.72 4.14 1.04 1.09	3.13 0.90	2.87 3.0 0.83 1.1	1 2.38 5 1.21	2.79 1.00	2.87 Na2O 1.12 K2O	2.61 2 0.97 0	2.75 3.57).90 0.69	3.64 3.4 0.97 1.0	19 4.44 4. 12 0.50 0.	27 4.07 97 0.96	3.66 4.21 1.45 1.49	Na2O 3.1 K2O 1.1	80 4.60 5.28 15 3.55 4.00	2.41 3.29	2.83 2.59 2.50 2.70	2.56 3.17 2.51 2.68	2.12 Na2O 1.97 K2O	2.86 2.80 2.82 2.90
P2O5	0.90 0	0.76 0.87	1.00 0	26 0.19	0.13	0.39 0.10	0.04 P2O5	0.21 0.3	4 0.24	0.24 0	89 0.96 \$1 0.98	0.54 0	0.40 0.70	0.55 P2O	5 0.53	0.44	0.43 0.60	0.47	0.56 0.9	4 0.64	0.36	0.46 P2O5	0.41 0	0.41 0.44	1.14 1.0	15 0.17 0	44 0.07	1.25 0.06	P2O5 1.1	12 0.57 0.56	0.06 0.00	0.06 0.06	0.08 0.07	0.32 P2O5	0.34 0.57
Total	101.45 10	0.38 100.12	99.14 9	9.88 100.2	0 100.21	100.58 100.9	7 100.43 Total	101.40 100	.91 99.22	99.45 95	.15 100.09	101.11 10	0.50 100.59	9 100.37 Total	1 101.0	7 99.66	100.61 98.8	7 100.53	100.15 102.	69 101.09	100.96	100.45 Total	100.69 10	01.36 99.74	99.61 100.	.10 101.30 99	88 101.66	99.10 99.76	Total 99.	03 99.89 100.7	6 100.18 100.3	6 100.17 99.86	99.09 100.19	99.44 Total	101.41 99.27
Rb Sr	21 733 1	31 35 178 1152	43 1107	30 390	8 255		Rb Sr	2	5 27 12 254	16 247 H	10 36 150 702	50 725	46 772	50 Rb 770 Sr	28 505	26 495	62 902			35 720		Rb Sr	6	32 682	32 33 1620 163	3 50 19	6 04	40 1400	Rb 4 Sr 18	9 90	104 940			Rb Sr	89 80 887 873
Y Zr	35 3 198 2	30 32 252 224	37 243	34 235	27 101		Y Zr	3	1	2	1 36 10 282	28 165	30 143	30 Y 145 Zr	24 116	22 104	29 172			30 157		Y Zr	:	25 166	30 28 192 19	8 : 9 2	4 50	36 273	Y 3 Zr 20	5 55	31 297			Y Zr	30 28 305 278
Nb Ba	99 1 857 5	120 125 998 10.38	170 1340	137 908	21 150		Nb Ba	6	2	1	09 67 96 614	88 1012	93 1123	90 Nb 1100 Ba	65 751	62 740	101 129	i D		95 802		Nb Ba	7	74 733	129 12 1311 125	0 1 99 17	74 70	190	Nb 23 Ba 17	37 10	124			Nb Ba	131 100 1106 1079
Hf Ta	4.1 5.0	5.5 4.3 6.1	4.9	4.9	2.5		Hf Ta	3.	7 3.0	2.7 4	.2 5.8	3.6 3.9	3.0	3.1 Hf 4.2 Ta	2.5	2.1	3.7			3.1 4.0		Hf Ta	3	3.6 4.0	3.2 3.	5 4 9 7	2	4.4	Hf 4. Ta	0	6.9 5.9			Hf Ta	6.3 6.0 6.1
Th	10.6	12 11.6	14.2	0.6	2		Th	6	6 6	3 5	.6 4.7	12	13	13 Th	9.8	9.8	14			12		Th	5	9.1	16.8 16	5 2	0	22.1	Th 17	.3	13			Th	12 10
La Ce	75.1 9 132 1	2.2 94.6 169 178	111 :	9.2 152	32.2		La Ce	45 85	.5 27.5 .2 50.4	20.3 8 38.1 1	1.2 45.4 51 94.3	70.8 110	72.3	72 La 121 Ce	48.1	45.6	81.1	,		62.2 119		La Ce	8	51 89.5	135 12 252 24	9 1 5 2	89	141 257	La 13 Ce 26	32 56	87.8 169			La Ce	70.3 66.8 147.2 138.0
Pr Nd	12.8 I 40.2 5	17.5 18.9 65.0	67.2	i0.9	3.9 15.5		Pr Nd	8.	7	17.2 9	9.1 46.8	12.6 40.1	40.6	12.5 Pr 40.2 Nd	9.1 25.8	24.9	14.3 46.5	5		12.6 40.2		Pr Nd	5	9.8 29.0	92.1 91.	.3 3 .3 10	1.2 2.0	84.2	Pr Nd 93	.0	16.6 54.5			Pr Nd	14.7 52.9 56.4
Sm Eu	8.6 9 2.4 2	9.8 10.4 1.99 3.04	3.31	0.3	3.9 1.4		Sm Eu	6.	4 4.53 1 1.48	4.11 9 1.46 2	64 10.20 89 3.27	7.2 2.0	7.39	7.3 Sm 2.1 Eu	4.6 1.5	4.43 1.45	7.3			7.0		Sm Eu	5	5.9 1.8	12.90 12. 3.77 3.0	.7 1. 6 3	9	11.60 3.32	Sm 12. Eu 3.1	.70 70	10.3 3.3			Sm Eu	10.0 9.47 3.1 2.72
Gd Tb	7.7 1	7.9 1.1 1.11	1.21	.20	4.6 0.8		Gd Tb	6.	2 15 0.79	0.75 1	05 1.35	5.4 0.87	0.88	5.4 Gd 0.87 Tb	5.2 0.7	0.62	6.3 1.1			5.5		Gd Tb	0	5.4).84	8.0 1.07 1.		8	1.05	Gd Tb 1.0	00	8.5			Gd Tb	8.4 1.1 0.95
Dy Yb	6.3 6 2.7 2	6.2 2.4 2.4	2.78		4.5 2.1		Dy Yb	5.	9 15 2.20	2.09 2	40 2.85	4.8 2.4	2.50	4.9 Dy 2.4 Yb	3.8	2.00	6.1 2.7			4.8 2.4		Dy Yb	4	4.0 2.2	2.02 2.0	6 5 0 2	8	3.07	Dy Yb 3.0	00	6.1 2.6			Dy Yb	5.9 2.3 2.22
Lu		0.37	0.44 (1.40			Lu		0.35	0.35 0	38 0.40		0.40	Lu		0.31						La			0.31			0.44	Lu 0.4	41				Lu	0.34
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Location	Sample #	Rock type	Fused mass (g)	K ₂ O (wt%)	$^{40}\text{Ar*}$ (10 ⁻⁷ cc/g)	40 Ar*/ 40 Ar _t	Age (Ma) $\pm 1 \sigma$	
North-Idjwi	BK8	Nephelinite	0.7137	1.46	9.82	42.6	20.74 ± 0.56	
			0.7094	1.46	10.04	57.9	21.21 ± 0.52	
						Mean age	20.97 ± 0.56	
North-Idjwi	LKA4	Nephelinite	1.0160	1.27	8.23	50.7	19.98 ± 1.00	
Bitare	RW87	Tholeiite	1.0108	0.55	2.03	27.0	11.42 ± 0.57	1
Bugarama	RW88	Basanite	1.0023	1.25	4.29	52.7	10.63 ± 0.53	
South-Idjwi	BK14	Tholeiite	0.7007	0.43	1.43	28.4	10.30 ± 0.35	
South-Idjwi	BK19	Tholeiite	1.0049	0.68	2.10	27.8	9.56 ± 0.48	
Bitare	RW86	Tholeiite	1.0009	0.90	2.61	37.3	8.97 ± 0.45	
South-Idjwi	BK15	Tholeiite	1.0145	0.66	1.87	19.3	8.76 ± 0.44	
Kahuzi	MM2	Alkaline basalt	1.0171	0.87	2.23	41.1	7.92 ± 0.21	
			0.7039	0.87	2.38	38.6	8.47 ± 0.24	
						Mean age	8.19 ± 0.40	
Upper Ruzizi	RW90	Olivine basalt	1.0130	0.76	1.99	26.6	8.10 ± 0.40	
Bugarama	RW83	Basanite	1.0115	1.15	2.88	39.8	7.75 ± 0.39	
South-Idjwi	BK36	Tholeiite	0.7154	0.38	0.95	16.5	7.73 ± 0.30	
Upper Ruzizi	RW89	Alkaline basalt	1.0022	1.20	2.98	32.7	7.68 ± 0.38	
Bukavu	RW82	Basanite	1.0072	1.56	3.62	44.3	7.18 ± 0.36	
South-Idjwi	BK18	Alkaline basalt	0.7101	1.00	2.28	10.8	7.07 ± 0.51	
South-Idjwi	BK7	Tholeiite	0.7007	0.43	0.92	9.7	6.62 ± 0.66	
Bukavu	RW81	Basanite	1.0086	1.45	2.96	43.0	6.33 ± 0.32	

Table 2Whole rock K-Ar age dating

CEP CEP

Table 3Trace element composition of the South-Kivu magma sources

	C1	C2
Sr	51	45
Y	7.5	7.2
Zr	19	25
Nb	3.3	3.3
Ba	38	26
Hf	0.48	0.62
Th	0.52	0.26
La	3.80	2.33
Ce	7.10	5.05
Nd	3.10	2.90
Sm	0.84	0.80
Eu	0.30	0.30
Tb	0.16	0.16
Yb	0.67	0.66

Location	Sample #	Rock type	Age	Ref.	Location	Sample #	Rock type	Age	Ref.
North-Idjwi	BK8	Nephelinite	20.97 ± 0.56	7	Burundi	19	Tholeiite	7.6 ± 0.5	5
North-Idjwi	LKA4	Nephelinite	19.98 ± 1.00	7	South-Idjwi	18	Tholeiite	7.6 ± 0.3	5
Bishusha	N373	Hawaiite	12.6 ± 0.7	3	West-Bukavu	2	Basanite	7.3 ± 0.3	5
Tongo	TRK4	Benmoreite	11.8 ± 0.8	6	Upper-Rusizi	RW82	Basanite	7.18 ± 0.36	7
Bitare	RW87	Tholeiite	11.42 ± 0.57	7	South-Idjwi	BK18	Alk-Basalt	7.07 ± 0.51	7
Bishusha	TR44	Ol-Tholeiite	11.0 ± 0.5	6	Bukavu	BK24	Basanite	7.00 ± 0.35	3
Bishusha	TR50	Ol-Tholeiite	10.8 ± 1.7	6	Kahuzi	AK486	Ol-Tholeiite	6.90 ± 0.35	6
Bishusha	TR5	Ol-Basalt	10.7 ± 0.7	6	Upper-Rusizi	-11	Alk-Basalt	6.7 ± 0.5	5
Bugarama	RW88	Basanite	10.63 ± 0.53	7	South-Idjwi	BK7	Tholeiite	6.62 ± 0.66	7
South-Idjwi	BK14	Tholeiite	10.30 ± 0.35	7	Upper-Rusizi	12	Hawaiite	6.45 ± 0.90	5
Tongo	TRK2a	Benmoreite	10.2 ± 0.7	6	Upper-Rusizi	RW81	Basanite	6.33 ± 0.32	7
Lower-Rusizi	27	Tholeiite	10.0 ± 2.0	5	Upper-Rusizi	10	Hawaiite	6.2 ± 0.3	5
Bugarama	17	Tholeiite	10.0 ± 0.6	5	Upper-Rusizi	22	Benmoreite	6.14 ± 0.30	5
Bishusha	TR1b	Hawaiite	9.9 ± 1.2	6	West-Bugarama	9	Hawaiite	6.06 ± 0.27	5
Bishusha	TR12	Basanite	9.7 ± 1.3	6	Bugarama	13	Hawaiite	5.9 ± 0.5	5
South-Idjwi	BK19	Tholeiite	9.56 ± 0.48	7	Upper-Rusizi	5	Basanite	5.9 ± 0.4	5
Bishusha	TR24	Mugearite	9.2 ± 1.0	6	Kahuzi	RTL180	Ol-Tholeiite	5.9 ± 0.3	6
East-Cyangugu	14	Ol-Tholeiite	9.0 ± 0.6	5	Mwenga	K157	Ol-Basalt	5.8 ± 1.1	6
Bitare	RW86	Tholeiite	8.97 ± 0.45	7	Upper-Rusizi	25	Trachyte	5.74 ± 0.23	5
Tongo	N378	Basanite	8.9 ± 0.5	3	Upper-Rusizi	23	Trachyte	5.74 ± 0.09	5
South-Idjwi	BK15	Tholeiite	8.76 ± 0.44	7	Upper-Rusizi	4	Basanite	5.7 ± 0.4	5
W-Bukavu	1	Alk-Basalt	8.5 ± 0.5	5	Upper-Rusizi	21	Phonolite	5.7 ± 0.3	5
East-Cyangugu	20	Tholeiite	8.4 ± 0.3	5	North-Mushaka	7	Hawaiite	5.65 ± 0.23	5
Upper-Rusizi		Ol-Basalt	8.3 ± 1.1	1	Bugarama	15	Hawaiite	5.6 ± 0.3	5
Kahuzi	AK256	Alk-Basalt	8.2 ± 0.4	6	Upper-Rusizi	24	Trachyte	5.05 ± 0.4	5
Kahuzi	MM2	Alk-Basalt	8.19 ± 0.40	7	Mwenga	K40	Alk-Basalt	4.2 ± 1.1	6
Upper-Rusizi	RW90	Ol-basalt	8.10 ± 0.40	7	South-Idjwi	I-84-30	Ol-Basalt	4.1 ± 1	4
Upper-Rusizi	26	Tholeiite	8.0 ± 1.0	5	NW-Bukavu	6	Basanite	4.06 ± 0.21	5
Mushaka	3	Basanite	7.99 ± 0.24	5	Mwenga	K58	Basanite	2.6 ± 1.6	6
Bugarama	RW83	Basanite	7.75 ± 0.39	7	Mikeno		Trachyte	2.6 ± 0.4	2
South-Idjwi	BK36	Tholeiite	7.73 ± 0.30	7	Tshibinda	TB4	Basanite	1.9 ± 0.1	3
Upper-Rusizi	RW89	Alk-Basalt	7.68 ± 0.38	7	Tshibinda	MM1	Basanite	1.7 ± 0.2	3
Burundi	28	Tholeiite	7.6 ± 1.4	5	Tshibinda	KT1	Ol-Basalt	1.6 ± 0.3	3
Upper-Rusizi		Ol-Basalt	7.6 ± 0.5	1					

Table 4K-Ar geochronological data for the Lake Kivu area lavas























Fig. 8









Fig. 12















Fig. 16







Fig. 18


ACCEPTED MANUSCRIPT



Highlights

The pre-rift doming stage of the Kivu rift (East African Rift system) is dated at 21 Ma by nephelinites.

Tholeiite lavas initiate the extensional stage between 11 and 9 Ma.

In the Pliocene, alkali basalts indicate decreasing of the extensional process and cooling of the mantle.

Quaternary renewal of the activity in the Virunga is linked to a tension gash with an ENE-WSW extension.

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