Monogenic and polygenic volcanoes in the area between the Nyiragongo summit crater and the Lake Kivu shoreline.

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MONOGENIC AND POLYGENIC VOLCANOES IN THE AREA BETWEEN THE NYIRAGONGO SUMMIT CRATER AND THE LAKE KIVU SHORELINE

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Abstract

This paper reports the preliminary results of a volcanological and geochemical investigation carried out on September 2002 in the area located between Nyiragongo Volcano and the northern shoreline of Lake Kivu (Democratic Republic of Congo). This area includes tens of mono- and polygenic cones mainly aligned along two preferential orientations: NE-SW and NS, although a few volcanic edifices also spread out radially from the central cone. The eccentric cones are grouped as follows: i) phreatic to hydromagmatic and ii) magmatic. Nevertheless some cones display a transition between type i) and ii). The former group is mainly located between the Lake Kivu and 1.5 km inland, whereas the magmatic cones are prevalently located from 1.5 -2 km northwards. As the result of different ratios of magma/water interaction, hydromagmatism has produced two types of deposits: 1) dry and wet surge deposits related to phreatomagmatic activities and 2) hydroclastic lithified sands ('peperite') derived by sub-lacustrine magma granulation and mingling with wet sediments. Moreover, the occurrence of at least three different polygenic and hydrothermally altered breccias of phreatic origin appears noteworthy. The magmatic activity, which usually ends with lateral effusions of degassed lavas, is characterised by both strombolian and hawaiian eruptive styles. Volcanic products, including the recent lavas from the 2002 eruption, are represented by foidites, tephrites and basanites. Rocks are generally porphyritic or subaphyric with a phenocryst modal mineralogy dominated by nepheline, melilite and/or leucite in the foidites and by clinopyroxene and olivine in the tephritic and basanitic rocks.

keywords: Nyiragongo volcano, Adventive cones, Hydromagmatic activity, Tuff cones, Phreatic activity.

1. Introduction

After the 2002 eruption from the Nyiragongo volcano the interest of the scientific community on this volcanic area suddenly increased (Komorowski *et alii* this volume). The occurrence of NE-SW and NS fracture feeding systems actually extending well beyond the present shore of Lake Kivu leads to focus our attention on the possible explosive interactions between the shallow and superficial waters and uprising magmas.

On September 2002 a field survey on the mono- and polygenic volcanoes, located within 2-3 km far from the shore of Lake Kivu was carried out, with the aim to assess the possible occurrence of explosive hydromagmatic activity close to or inside the most inhabited areas, including Goma centre. During this fieldwork, thirteen eruptive centres have been investigated and several rock samples were collected for petrographic and geochemical analyses.

2. Stratigraphy, morphology and classification

The area between the active Nyiragongo volcano and the Lake Kivu shoreline represents a large volcanic field where an intense eruptive activity has taken place, mostly producing small monogenic structures aligned along the main fracture systems. According to cone shapes and stratigraphic records, they were classified in terms of the prevailing eruptive mechanism (Table 1). Radiometric ages of this volcanic activity are not available in the literature and similar events in historical times are not reported.

About 50% of the eruptive vents in the investigated volcanic field are cinder and spatter cones, or a combination of both. Cinder cones are represented by mono- or polygenic volcanoes, 150-200 m high, showing a steep external slopes and bowl-shaped craters on top. The Kaboro cone, located in the area of Rushayo about 40 km NNW of Goma town (Fig. 1), belongs to this type of volcanoes, being composed of at least three different eruptive centres surrounded by scoria fall beds and minor tuff horizons. A final effusive activity is testified by the occurrence of a lava flow outpoured from the base of the edifice and frequently forming lava tunnels. The collapse of the lava tunnel roofs gave rise to elongated holes in the ground, such as those observed within the Rushayo village, or the 15-20 m wide elongated depressions with 4-5 m high vertical walls observed just SW of Kaboro cone.

Spatter cones (few tens of meters high) are usually smaller than cinder cones with steeper-sided (sometime almost vertical) slopes (Fig. 2). These are certainly the most recurrent types of eccentric volcanoes in the area between the main edifice of Nyiragongo volcano and the northern shoreline of Lake Kivu. Closer to the lake shoreline, deposits from spatter cones are rare or absent. Kirunga is the only monogenic cone of magmatic origin recognised very close to the lake about 37 km NW of Goma (Fig. 1). It is a few tens meter high spatter cone with a well preserved pit-crater on its summit and small adventive vents and 'hornitos' on its NE flank. This occurrence seems to suggest a past low standing of the Lake Kivu level. Three small purely magmatic centres are located about 2 km E of the Buhymba-Nyabyunyu-Nyarutshiru volcanic alignment (Fig. 1). Two of them

Fig. 1. Simplified volcanological map of the investigated area.

are typical monogenic spatter cones (Kirunga and Turunga), the third one results from the coalescence of at least two cinder/spatter cones (Ndosho). A complete exposure is located in a quarry few tens of meters away from the main road. The sequence is composed by the piling up of 4-5 m of spatter scoriae followed by 2-3 m of typical strombolian scoria fall deposit, thus suggesting a local transition from hawaiian to strombolian eruptive style.

The remaining volcanic morphologies in the area can be referred to tuff-cones and tuff-rings. Tuff-cones are easily recognisable due to their typical height/rim diameter ratio and shape (Wohletz and Sheridan 1983). The height of the rims is in the range 100-200 m, while the crater floors are almost at the level of the pre-eruptive surface. Lac Vert is probably the most representative polygenic tuff-cone of the investigated area. The crater rim is about 150 m high, while the bottom appears permanently occupied by a crater-lake. As shown by some outcrops on the eastern flank, basal products from Lac Vert volcano consists of a whitish, coarse and unsorted tuff-breccia composed by no-juvenile hydrothermalized polygenic lithics up to 1 m in diameter set in a fine whitish matrix (FIG. 3). The basal breccia is overlaid by a sequence of 30-50 m of grey coloured, thinly laminated coarse ash. Thin beds of massive fine ash with accretionary lapilli are also common in the upper sequence. Diffuse, small scale folding and faulting at the top of the layered upper part of the sequence could represent gravity-driven, earthquake-induced (?) structures (FIG. 4). A small lava flow ends the depositional sequence. According to the stratigraphic records, the activity at Lac Vert started with pure steam explosions, followed by a sustained hydromagmatic activity, which emplaced dry and wet surge deposits, and small final lava flows. The deep alteration state of the components of the basal breccia as well as the absence of a juvenile fraction testifies the existence of a hydrothermal system, able to flash into steam and gas as the magma upraised towards the surface.

A similar eruptive sequence can be observed at the polygenic tuff cone of Buhymba (FIG. 1). The Buhymba tuff cone is the south-westernmost of three aligned and partially coalescent tuff cones (Buhymba-Nyabyunyu-Nyarutshiru), about 30 km WNW of Goma; it is the only tuff cone showing a relatively well exposure on its western flank. Two main sequences, separated by an angular unconformity, can be recognised. The lower sequence is represented by a massive block and lapilli tuff, composed by polygenic blocks and lapilli similar to the Lac Vert basal breccia but containing a significant juvenile component. The upper and final sequence consists of faintly laminated ash and lapilli tuff about two meters thick. Nyabyunyu and Nyarutshiro cones also appear as typical tuff cones, the former having the crater breached on its NE flank.

Mt. Goma is a 200 m high polygenic tuff cone located well inside the urban area of Goma (FIG. 1). It consists of at least three coalescent cones; two of them are breached southwards. The Goma harbour is located on this breach. The activity in the area started with the emplacement of thick sandstones (> 2 m thick) (FIG. 5), made of decimetric lumps of black glassy lavas supported in a coarse sandy matrix and interbedded with

FIG. 2. Spatter cone of the 2002 eruption close to Monigi area.

FIG. 3. Hydrothermalized, polygenic breccia at the base of the Lac Vert pyroclastic sequence.

TABLE 1. Prevailing eruptive mechanism and major element (wt. %) composition of representative adventive cones from Nyiragongo area.

Sample	NY1	NY2	NY23	NY4	NY5	NY6	NY7	NY11	NY12	NY13	NY15	NY16	NY17	NY19	NY20	NY22	NY25	NY26	NY27	NY28	NY29	NY30	NY32
Local name	*Nyibusta*	*Lac-Vert*	*Lac Vert*	*Kashaka*	*Kashaka*	*Shaheru*	*Shaheru*	*Mt. Goma*	*Nakongo (Mt. Goma)*	*Nakongo (Mt. Goma)*	*Mt. Goma*	*Mt. Goma*	*Mt. Goma*	*Monigi*	*Monigi*	*Kaputembo*	*Buymba*	*Buymba*	*Kirunga*	*Ndosho 1*	*Ndosho 2*	*Nengo*	*Nengo*
Description	*spater cone with lava*	*polygenetic tuff come*		*polygenetic tuff come*		*spatter come and lava effusion*		*coalescent polygenetic tuff cones with lava effusion and dikes*						*spatter comes*		*tuff ring*	*tuff cone*		*spatter cone*	*spatter and cinder cones*		*cinder cone*	
Sample description	*juv. scoria*	*acc. lithics*		*juv. scoriae*		*juv. scoria*		*juv. lithic*	*lava*	*dike*	*bomb*	*juv. scoria*	*lava*	*lava*	*juv. scoria*	*juv. scoria*	*bomb*	*lava*	*juv. scoria*	*juv. scoria*	*lava*	*juv. scoriae*	
Coordinate	*01°35'39.5" 29°09'49.8"*	*01°36'56.9" 29°08'15.3"*		*01°36'10.0" 29°08'12.3"*						*01°41'02.3" 29°13'27.2"*					*01°37'16.5" 29°08'15.1"*		*01°37'56.9" 29°08'56.1"*		*01°38'09.0" 29°08'19.7"*	*01°38'08.8" 29°10'36.2"*	*01°38'24.6" 29°10'51.4"*		
Prevailing eruptive mechanism	*magmatic*	*phreatic/ hydromagmatic*		*magmatic/ hydromagmatic*		*magmatic*		*hydromagmatic/magmatic/sub-lacustrine*						*magmatic*		*hydro-magmatic*	*hydromagmatic*		*magmatic*	*magmatic*		*magmatic*	
SiO_2	39,2	39,2	39,0	40,1	40,6	39,3	38,7	37,9	39,5	38,8	38,6	38,8	39,1	39,5	39,8	44,0	43,7	39,4	37,8	39,8	39,1	44,6	45,2
Al_2O_3	14,8	10,6	10,5	10,6	10,7	14,6	14,4	14,2	14,9	14,6	14,6	15,0	15,1	14,6	14,6	16,3	14,6	15,3	14,2	15,1	15,1	13,4	13,4
Fe_2O_3	13,7	12,6	12,5	12,2	12,3	13,2	13,2	13,4	13,9	13,6	13,9	14,2	13,4	13,3	13,2	12,6	11,6	13,4	13,0	13,5	13,3	12,4	12,4
MgO	4,5	10,4	10,4	13,1	13,2	4,1	4,1	4,4	4,5	4,4	4,6	4,2	4,1	4,1	4,1	4,3	5,7	4,3	4,4	4,5	4,1	8,1	8,0
CaO	12,3	16,5	16,3	13,6	13,6	12,2	12,2	12,3	12,8	12,5	12,5	12,0	12,3	12,3	12,1	9,5	11,5	12,1	12,0	11,8	12,0	11,7	11,9
Na_2O	4,9	2,6	2,6	2,7	2,1	5,6	5,8	4,3	4,4	4,5	5,6	5,1	5,0	5,8	5,7	4,4	4,1	4,8	4,3	4,6	4,9	2,8	2,8
K_2O	5,4	2,6	2,4	2,2	2,4	5,1	5,4	3,8	4,4	4,3	2,5	4,6	5,3	5,4	5,3	4,3	3,7	4,6	4,8	4,5	4,9	2,6	3,0
TiO_2	3,0	3,2	3,1	2,9	2,9	2,7	2,7	3,1	3,2	3,1	3,2	3,1	3,0	2,8	2,7	3,1	2,9	3,1	2,9	3,1	3,0	3,3	3,3
MnO	0,29	0,22	0,22	0,20	0,20	0,29	0,29	0,27	0,28	0,28	0,28	0,29	0,29	0,29	0,29	0,22	0,21	0,27	0,27	0,27	0,29	0,19	0,19
P_2O_5	1,71	1,31	1,34	0,81	0,82	1,47	1,47	1,63	1,69	1,64	1,69	1,71	1,68	1,48	1,47	1,09	0,89	1,68	1,61	1,66	1,58	0,53	0,56
Total	99,6	99,8	98,9	98,0	98,9	98,0	97,1	98,6	99,5	98,6	98,8	99,3	99,2	98,5	98,5	99,6	98,4	99,1	96,1	98,9	98,2	99,4	100,2
Mg#	39,4	62,0	62,3	68,0	68,1	37,9	37,9	39,6	39,1	39,3	39,8	36,9	37,7	37,8	38,0	40,4	49,2	39,1	39,9	39,7	37,8	56,4	56,2

Mg# = 100 ($Mg^{2+}/Mg^{2+} + Fe^{2+}$)

thin to medium beds of scoriaceous coarse lapilli and blocks. In this respect it could be interpreted as 'peperites' (Skilling *et alii* 2002), produced by mingling of hyaloclastites with pre-existing wet sediments, during a high stand phase of Lake Kivu. Sub-aerial activity started with 8 to 10 m of parallel laminated lapilli tuffs containing ballistic blocks (FIG. 6) and interbedded with relatively thin beds of large lava spatters.

At least two typical tuff rings were recognised in the western sector of the investigated area. *Kabutembo* (FIG. 1) is a tuff ring consisting of a 0.8-1.0 km large and flat crater surrounded by an annular, relatively thin, rim of pyroclastic deposits, less than 50 m as maximum thickness. The overall shape of the edifice appears faintly dissected, open to SE and partially buried by younger lava flows which also fill the crater depression. The only accessible outcrops are located along the crater rim. They consist of a basal block and lapilli breccia, composed by both accessory (lithics) and juvenile (black scoriae and bread-crusted bombs) fragments, followed by roughly stratified and partially lithified ash and lapilli tuffs, draping over the crater rim and giving rise to quaquaversal dip structures. The lapilli fraction appears to be represented by black, highly vesiculated scoriae, also interpreted as juvenile in origin. No other significant stratigraphic horizon crops out. On the basis of these outcrops, the eruptive activity of the Kabutembo tuff ring was characterised, at least during its final stages, by alternating magmatic (strombolian) and hydromagmatic phases. Another unnamed tuff ring has been recognized between Lac Vert and Kashaka cones. It is highly dissected and its products are partially buried below those of Lac Vert and Kashaka volcanoes. The only deposit which can be referred to its activity is a polygenic, strongly hydrothermalized tuff breccia, very similar to that of the basal sequence of Lac Vert. Finally, the Kituko tuff cone is located very close to the present shoreline, and breached on its SE flank. A lithified roughly stratified coarse sandstone (probably hydroclastic deposit such as those pointed out at the base of Mt. Goma cone) can be identified. No other outcrops were observed.

3. PETROGRAPHY, GEOCHEMISTRY AND ROCK CLASSIFICATION

Major element composition (TABLE 1) of the volcanic material from the investigated eccentric cones was obtained by X-Ray Fluorescence at the Dept. of Geology, University of Edinburgh, UK, by means of a Philips PW 1400 XRF. Glass disks of rock samples were used. For comparison, two rock samples (namely Monigi and Shaheru) collected from the lava flows of January 2002 eruption, were also analysed and the corresponding composition is reported in Table 1. According to the chemical classification proposed by Le Bas *et alii* (1986), the studied rocks are mainly represented by foidites (melilite or leucite-bearing nephelinites), and by some tephrites and basanites (FIG. 7). Foidites include rocks (lavas and scoriae from Nyibusta, Kashaka, Kirunga, Shaheru, Monigi, Buhymba and Ndosho sites, lithics from Lac Vert, lavas and xenoliths from Mt. Goma) with variable characteristics. They generally exhibit porphyritic textures with variable phenocryst content (10-50 vol. %) and glassy or microcrystalline groundmass; phenocrysts are represented by abundant feldspathoids (nepheline and/or leucite), melilite, clinopyroxene ($Wo_{46-56}En_{28-44}Fs_{7-20}$)[1] ± olivine ($Fo_{73-89}$);

1. Phase composition on selected samples were determined by a JEOL JXA-8600 electron microprobe operating at 15 kV and 15 nA and equipped with a Series II Tracor Northern system. Correction for matrix effects were made according to Bence and Albee (1968).

kalsilite has been found in the lava samples from 2002 eruption; apatite and Fe-Ti oxides are the common accessory mineral phases. Calcite of probable magmatic origin (see Dermant *et alii* 1994) is locally present in the groundmass. Chromite has been observed as inclusion in the olivine crystals, in the Kashaka samples. In addition to melilite, in the Sheheru rook samples, kalsilite crystals have been found.

Tephrites (bomb from Buhymba tuff cone and scoria from Kaputembo tuff ring) display subaphyric textures with small quantities of clinopyroxene ($Wo_{46-50}En_{38-43}Fs_{9-12}$) and minor olivine ($Fo_{74-82}$) enclosed in a glassy matrix containing Fe-Ti oxides, plagiadase microlites and fine-grained aggregates of clinopyroxene, with cumulitic texture.

Basanites (scoriae from Nengo cinder cone) are porphyritic and contain euhedral and subhedral phenocrysts of clinopyroxene ($Wo_{48-50}En_{36-44}Fs_{8-14}$) and olivine ($Fo_{75-85}$) set in a groundmass composed by glass, leucite and Fe-Ti oxides.

In the rock samples, K_2O/Na_2O ratio is generally around 1. However, the different groups of rocks display some distinctive geochemical characteristics: in the diagram of Fig. 7, rock samples from Nengo, located east of Goma in the Rwandan territory, plot in the basanite field having olivine > 10% whereas a bomb from Buhymba tuff cone has a tephritic composition (olivine < 10%) (Fig. 7). Kaputembo tuff ring scoria and the glassy lava from Kashaka plot across the boundary between tephrites and foidites and basanites and foidites, respectively. All the remaining samples (including the 2002 products from the eruptive fissures at Shaheru and Monigi) plot in the foidite field even though lithics from Lac Vert and scoriae from Kashaka display low $Na_2O + K_2O$ (< 6 %). Variation diagrams of some major elements versus Al_2O_3, used as differentiation index, are given in Fig. 8. As in the alkali-silica diagram, the different rock samples plot in different areas of the diagrams. Foidites lie in a restricted area of major element diagrams even though a scattering of values is observed for TiO_2, Fe_2O_3, and $Na_2O + K_2O$. Noteworthy, in the foidites group, some differences exist between the recent (2002) products and the previously emplaced volcanics. In particular, products from Monigi and Shaheru display higher MnO and $Na_2O + K_2O$ and lower TiO_2 and P_2O_5 (Figs. 7 and 8) than the older volcanic products.

Among the studied rocks, rock samples from Lac Vert and Kashaka display the less evolved composition (Mg# 62-68).

4. Volcanological characters of the investigated volcanic cones: general considerations and conclusions

The southern flank of the Nyiragongo volcano appears to be dominated by several tens of eccentric cones, whose distribution appears basically controlled by the NE-SW and NS main fracture systems (Fig. 1). Their nature, in terms of dominating eruptive mechanisms, appears strictly controlled by the distance of the present lake shoreline, other than by its possible temporal vari-

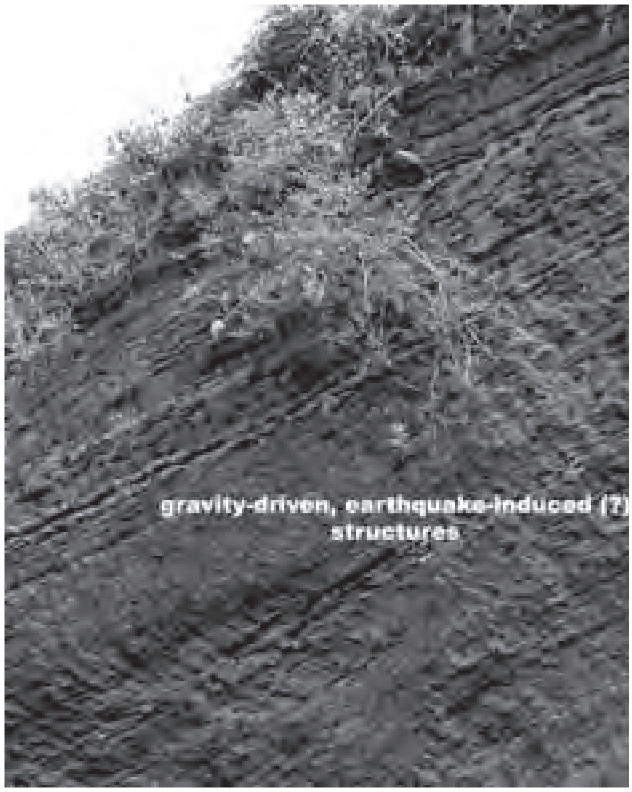

Fig. 4. Dry surge deposits at the top of Lac Vert pyroclastic sequence. Note the small scale folding possible related to earthquakes-induced, gravity movements.

Fig. 5. Strongly lithified deposit referred to subaqueous granulations of lavas ('peperite') at the base of the Goma tuff cone.

FIG. 6. Dry and wet surge deposits of the Goma tuff cone with asimmetric bomb sags.

ations, with only one documented exception (*Kirunga* spatter cone). According to the depositional records, among the hydrovolcanic cones, two different types of opening phases (that is *how the eruption starts*) can be recognised: 1) sub-aereal, mostly characterised by phreatic explosions (such as Lac Vert) producing hydrothermalized breccias; 2) subaqueous, with no-explosive or mildly explosive sub-aqueous effusions, giving rise to an intimate magma/sediment interaction and finally producing *hydroclastic rocks or peperite* deposits (such as at Mt. Goma and *Kituko* tuff cones). These latter seem to be related to high stand conditions of the Lake Kivu levels.

At distance roughly in excess of 2 km from the lake shoreline the adventive cones are cinder or spatter cones or effusive vents, while no tuff rings or tuff cones are documented. Therefore, phreatic/hydromagmatic activity dominates over the first 2 km from the lake shoreline, whereas pure magmatic activities are at distances > 2 km.

In order to have hydromagmatism on subaereal environment two essential conditions are needed: 1) presence of groundwater at relatively shallow depths; 2) variable degree of primary magmatic fragmentation before magma/water interaction. By contrast, in order to produce phreatic activity, the constraints are:

a) pervious water saturated horizons confined below unpervious layers;

b) heat source from below.

The lack of a documented relatively shallow aquifer at distance >2 km from the Lake Kivu shoreline seems to be the better explanation of this lateral zoning. At 2 km in the Lac Vert area the groundwater surface in equilibrium with the present lake level (the

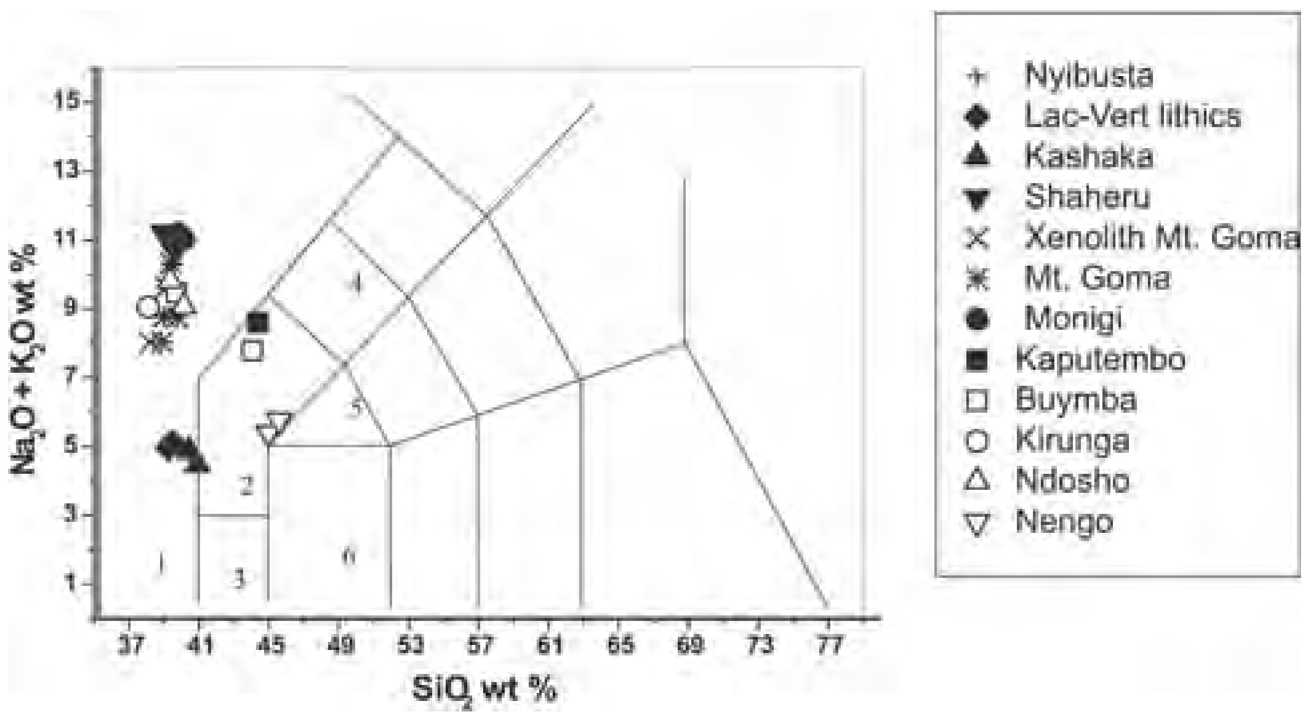

FIG. 7. Total alkali-silica classification diagram (after Le Bas *et alii* 1986).
Fields: 1 = foidite; 2 = tephrite and basanite; 3 = picro-basalt; 4 = phono-tephrite; 5 = trachybasalt; 6 = basalt.

local base level) should be located less than 50 m below the surface. Deeper ground waters should not give rise to efficient magma/water interaction because resting below the fragmentation level of the rising magma. Finally, the past occurrence of a diffuse hydrovolcanism in the area between Lac Vert and Buhymba appears well in coincidence with the highest concentration of sites with CO_2 accumulation at the land surface (*Mazukus*, Vaselli *et alii* this volume).

The chemical composition of the juvenile fraction displays a quite large variability, ranging from foidites at Kashaka cone to basanites at Nengo cinder cone. No clear relationship seems to exist between the composition of juvenile magmas and the eruptive style or between the magma composition and the eruptive position in respect to the rift (Figs. 1, 7 and 8).

Petrographic, mineralogical and geochemical data suggest a comagmatic origin between the studied foiditic rocks, the lavas from the 2002 eruption (Shaheru and Monigi) and the rock samples from Lac Vert and Kashaka, which represent the less evolved compositions. Magmas from Nengo cone display basanitic composition such as the basement of the Nyiragongo stratovolcano (Marcelot *et alii* 1989) and in several variation diagrams (Fig. 8) plot along a trend different from that of foidites, together with the volcanics from Kabutembo e Buhymba. However,

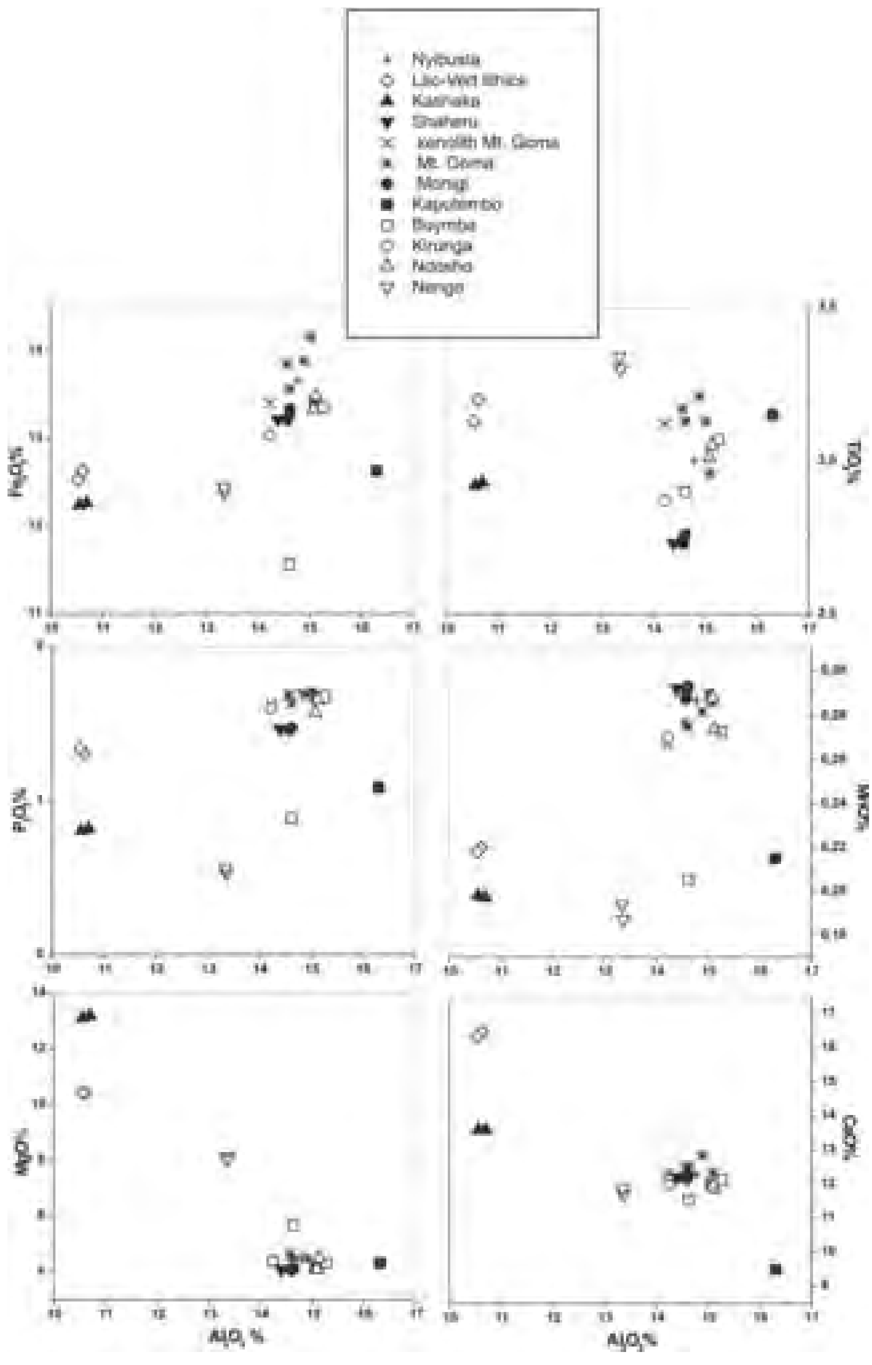

Fig. 8. Variation diagrams of major elements versus Al_2O_3 (in wt.%).

our inadequate knowledge of the basement and the lack of additional geochemical data make difficult at moment further inferences.

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