GEOCHEMISTRY OF THE POTASSIC BASALTS FROM THE BUFUMBIRA VOLCANIC FIELD IN SOUTHWESTERN UGANDA

E Barifaijo, A Muwanga and A Schumann
Makerere University, Department of Geology
P.O. Box 7062 Kampala, UGANDA
Tel. +256-41-541258, Fax. + 256-41-531061,
E-mail: ebarifaijo@sci.mak.ac.ug, geology@sci.mak.ac.ug

ABSTRACT

Bufumbira volcanic field is the southernmost of the four Ugandan small Pleistocene to Recent volcanic fields within the western branch of the East African rift system. The rocks consist of silica undersaturated and vesicular basalts with numerous primary structures. The rocks consist of basanites, leucitites, olivine basalts, trachytes, tephrites, trachyandesites and andesites. The basalts are picritic in the northern part of the field where they are dominated by olivine and are clinopyroxene rich in the southern part of the field. Leucite and plagioclase are common in the groundmass in varying proportions by volume for the entire field. Type 1 dunite and wehrlite upper mantle xenoliths characterize the northern part of the field whereas type II clinopyroxenite xenoliths are common in the southern part of the field. The various basalts are low in SiO_2 *wt %,* Al_2O_3 *wt % and* Na_2O *wt % but high in MgO wt %,* TiO_2 *wt %, CaO wt %,* K_2O *wt % with* K_2O/Na_2O *= 1.08 to 2.07. These are potassic belonging to the kamafugite series. Plots discriminate two geochemical trends corresponding to the picritic and clinopyroxene rich basalts. The diagram of* $Na_2O + K_2O$ *wt. % against* SiO_2 *wt. % enables various rocks to plot in the designated fields for the different alkaline basalts. The field is enriched in trace, light rare earth (LREE) and high field trace elements (HFSE) where La/Yb = 31 – 55. The petrographic and geochemical studies elucidate enrichment of the upper mantle by both mineralogical (modal) and cryptic (geochemical) metasomatism.*

Key Words: Basalts, Enrichment, Mantle, Metasomatism, Potassic,

INTRODUCTION

The Bufumbira volcanic field (320 km^2) is the southernmost of the three small fields in Uganda that are associated with the western branch of the East African rift system (Fig. 1). It is the northeastern portion of the bigger Birunga field (2600km^2) which extends southwards into Rwanda and westwards into the Democratic Republic of Congo. It is enclosed between longitudes 29^o 30'E and 29^o 50'E and latitudes 1^o 30'S and 1^o 10'S.

The field consists of many volcanic centres with spectacular craters on top of most of the conical hills. These craters give the entire field a hilly panoramic appearance. The highest mountains of Muhavura (4,127 metres), Mgahinga (3,420 metres) and Sabinyo (3,588 metres) are aligned in an E-W direction along the boundary between Uganda and Rwanda. Sabinyo sits atop the boundary of the three countries. The volcanic centres of Nyiragongo and Nyamulagira (most recent eruption was January and November, 2002 for Nyiragongo and November, 2006 for Nyamulagira in the Democratic Republic of Congo) are still active and the rest are dormant (Kervyn *et al.* 2007; Kasereka *et al*. 2007, Wafula *et al.* 2007).

The volcanic fields in the central western part of Uganda (e.g. Lloyd 1972, Lloyd and Bailey 1975, Lloyd 1981, Lloyd 1987, Lloyd *et al.* 1987, Thomas and Nixon 1987, Foley *et al*. 1987, Link *et al.* 2010) and part of Birunga field in Rwanda and the Democratic Republic of Congo (Vollmer and Norry 1983 a, b; Demant *et al*. 1994, Rogers *et al*. 1998, Platz *et al*. 2004, Rosenthal *et al*. 2009) have been thoroughly investigated for upper mantle metasomatism as the responsible process for producing the unique ultrapotassic to potassic rocks of those fields with their associated upper mantle xenoliths. The Bufumbira volcanic field was therefore investigated in this study for upper mantle metasomatism to have a full set of results for all these volcanic fields.

GEOLOGY

The volcanic rocks overlie the Karagwe-Ankolean (1000 - 1400 Ma) arenaceous and argillaceous sedimentary rocks. The rocks are mostly silica undersaturated basalts which are Pleistocene to Recent in age. The magmas were laden with volatiles which is envisaged in the numerous vesicles in the lavas and a few pyroclastic rocks. The primary structures in the lavas include pahoehoe, clinker and agglutinate that resemble graded bedding. The Karagwe-Ankolean is the northernmost extension of the Kibaran belt that covers most of south western Uganda. Inliers for the rocks of this system are sometimes found outcropping on some hills (e.g. Mutolere) and also as accidental xenoliths in the basalts.

The magmas brought with them upper mantle fragments which occur as xenoliths in the various basaltic rocks. The upper mantle xenoliths are both type I, subtype Ib where LREE/HREE >1. This type consists of olivine, phlogopite and clinopyroxene and the xenoliths are either dunites or wehrlites. The xenoliths also consist of type II, subtype II (i) which have rare olivine most of it being replaced by clinopyroxene and phlogopite and subtype II (ii) with isolated and rare olivine, plenty of clinopyroxene followed by phlogopite and apatite (Table 1).

Table 1: Xenolith types and subtypes in the three volcanic fields

Volcanic field	Xenolith type	Xenolith subtype	Characteristics
Katwe-Kikorongo and Bunyaruguru After Lloyd 1972; 1981; 1987 and Lloyd and Bailey 1975; Lloyd et al. 1987	II	II(i), II(ii), II(iiia + iiib)	II(i) Olivine replaced by clinopyroxene and phlogopite. Diopside replaced by drark mica and augite. Diopside, augite and phlogopite replaced by titanomagnetite, sphene, apatite and feldspar. II(ii) Rare isolated olivine, clinopyroxene, phlogopite and apatite. Appearance of sphene, calcite and feldspar. II(iia+iiib) Magmatic crystallisation of clinopyroxene (iiia) overprinted by metasomatic features in (iiib) of apatite occurring together with clinopyroxene, titanomagnetite, co-existing with apatite and clinopyroxene. Occurrence of phlogopite with sphene, calcite and feldspar.
Fort Portal After Thomas and Nixon 1987 and Nixon and Hornung, 1973	Lower crust accidental xenoliths		Garnet granulite and eclogite.
Bufumbira After Barifaijo 2000	I and II	Ib, II(i) and II(ii)	I (b) Olivine, phlogopite, clinopyroxene where LREE/HREE > 1. II (i) Olivine (rarely present) replaced by clinopyroxene followed by phlogopite. II (ii) Rare loose and isolated islands of olivine with clinopyroxene followed by phlogopite and apatite co-

existing with clinopyroxene.

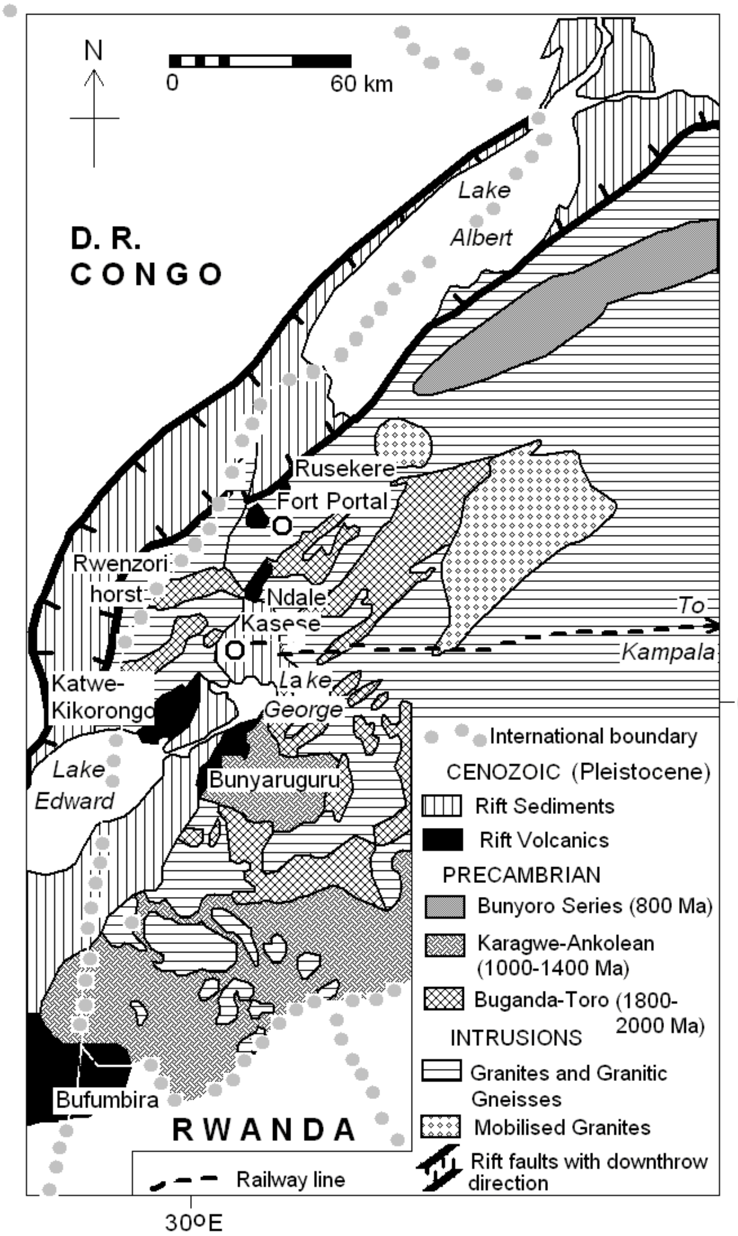


Figure 1 Geological map of Western Uganda (after Macdonald 1966) showing the small volcanic fields within the western branch of the East African rift system.

METHODS AND MATERIALS

The fieldwork involved mapping and samples collection. The petrographic studies were carried out at both Makerere University, Uganda and Kanazawa University, Japan using RPol, Zeiss (491726) research microscope. The same microscope was used for taking photomicrographs.

The microchemical studies to establish the chemistry of the various minerals were done at Kanazawa University, Japan using a Scanning Electron Microprobe (SEM), EMScope Model TB500. The results were processed with SORD M243 computer connected to the SEM.

Major and minor element geochemistry was achieved with Xray Fluorescence (XRF) spectrometer at both Kanazawa University, Japan (Model Rigoku) and University of Vienna, Austria (Model Phillips PW 2400) using bead pellets. The trace elements were analysed at both universities using powder pellets. The precision for both results was perfect. The rare earth elements (REE) were analysed on irradiated samples at the University of Vienna, Austria using a TRIGA Mark nuclear reactor.

PETROGRAPHY

The major mafic rocks which occur in the area consist of basanites, leucitites and olivine basalts. The intermediate rocks consist of trachytes, tephrites, trachybasanites and andesites (Fig.2). Olivine and clinopyroxene are ubiquitous both as phenocrysts, xenocrysts and fine grains in the groundmass (Barifaijo 2000). The xenocryst orthocumulates and mesocumulates would sometimes have internal voids or the voids would be filled with groundmass minerals. Olivine xenocrysts may possess strain lamellae and in some instances they may react with the alkaline magmas to produce clinopyroxene. The clinopyroxene xenocrysts may be both colour and chemically zoned. The cores consist of salite and rims are composed of titanaugite. The olivine phenocrysts have chromium-spinel inclusions and clinopyroxene has titanomagnetite inclusions. The clinopyroxene xenocrysts may also have apatite in the interstices. The groundmass consists of olivine, clinopyroxene, plagioclase flakes and microlites, round grains of leucite and opaque minerals which include both medium to finer-grained chromium-spinel and some titanomagnetite. The accessory minerals in the groundmass are sphene and apatite.

The intermediate rocks consist of clinopyroxene among the phenocrysts and groundmass, rarely olivine, biotite, plagioclase, sanidine, opaque and accessory minerals.

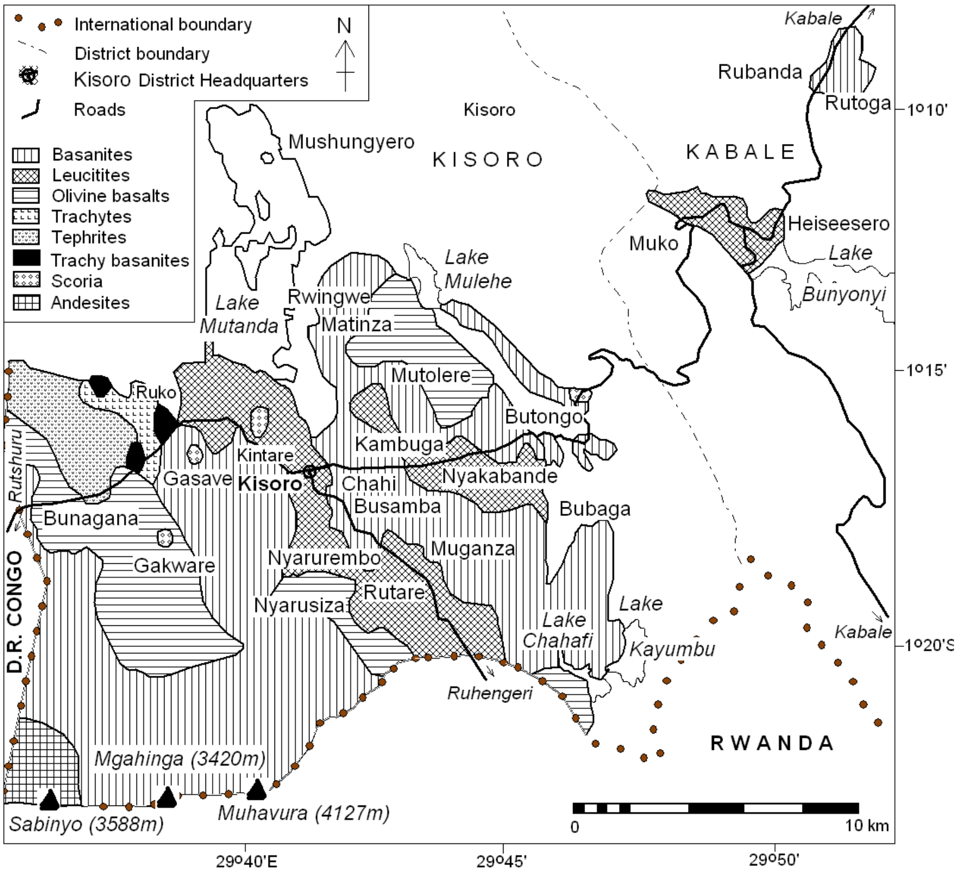


Figure 2 Geological map of the Bufumbira volcanic field (after Barifaijo 2000)

GEOCHEMISTRY

The rocks are generally low in SiO_2 wt% which ranges from 41.81 to 50.46 wt% in mafic rocks (Figs. 3&5) and 51.54 to 60.31 wt% in intermediate rocks and 39.86 to 50.81 wt% in mantle xenoliths. MgO wt% ranges from 8.00 to 17.16 wt% in the mafic rocks. It is 7.76 to 36.60 in the mantle xenoliths. Al_2O_3 (9.15 - 17.89) and Na_2O (1.61 - 3.00) wt% are generally low in concentration. The concentrations of CaO (4.27 - 13.35 wt%), TiO_2 (1.46 - 4.18 wt%) and K_2O (1.63 - 5.45wt%) are high for such mafic to intermediate rocks. The K_2O/Na_2O ratio ranges from 1.08 to 2.07.

The low values of SiO_2 and high values of MgO (Fig. 3) suggest a primitive upper mantle source for these rocks (e.g. Thompson 1985). The high concentration of MgO coupled with low concentrations of Al_2O_3 and Na_2O also point to a depleted upper mantle which was rendered refractory by earlier eruptions which extracted magmas of basaltic compositions (e.g. Mysen and Kushiro 1977). The high concentrations of Ni, Co and Cr especially for the picritic basalts from the northern part of the field (Mg_ = 88-90) accentuates the notion for the depletion of the upper mantle. The fact that K_2O/Na_2O > unity for all the mafic rocks at MgO ≥ 3.0 wt% (e.g. Foley et al.1987) suggests that the basaltic rocks are potassic. The intermediate rocks (MgO = 1.62 to 2.94 wt%) are non-potassic (e.g. Foley *et al.* 1987, Platz *et al.* 2004). The concentrations of alkalis in them could have been due to normal magmatic fractional crystallisation processes.

The variation diagrams, for example the plot of MgO wt% against SiO_2 wt% (Fig. 3) discriminate two distinct geochemical trends corresponding to the physico-chemical processes that operated in both the picritic and clinopyroxene basaltic parts of the field. The alkaline nature of the basalts is depicted on the various plots of total alkalis against silica. The Irvine and Baragar (1971) plot (Fig. 4) and Middlemost (1975) diagrams (Fig. 5) enable all the rock types of the field to plot in the alkaline field and the mantle xenoliths plot in the subalkaline field. The Cox *et al*. (1979) diagram (Fig. 6) places the various rocks in their appropriate fields. These exactly conform with petrographic studies. The Middlemost (1985) diagram (Fig. 7) clusters most of the mafic rocks between the basanite (6) and alkaline olivine basalts (8) field. The intermediate rocks stretch between the trachybasalt (9) to andesite (19) fields. The mantle xenoliths plot in the primitive field (16 – 18) of the diagram (picrite to tholeiite basalt field). The picrite field corresponds with the wehrlites and the tholeiite basalts correspond with the alkali clinopyroxenites.

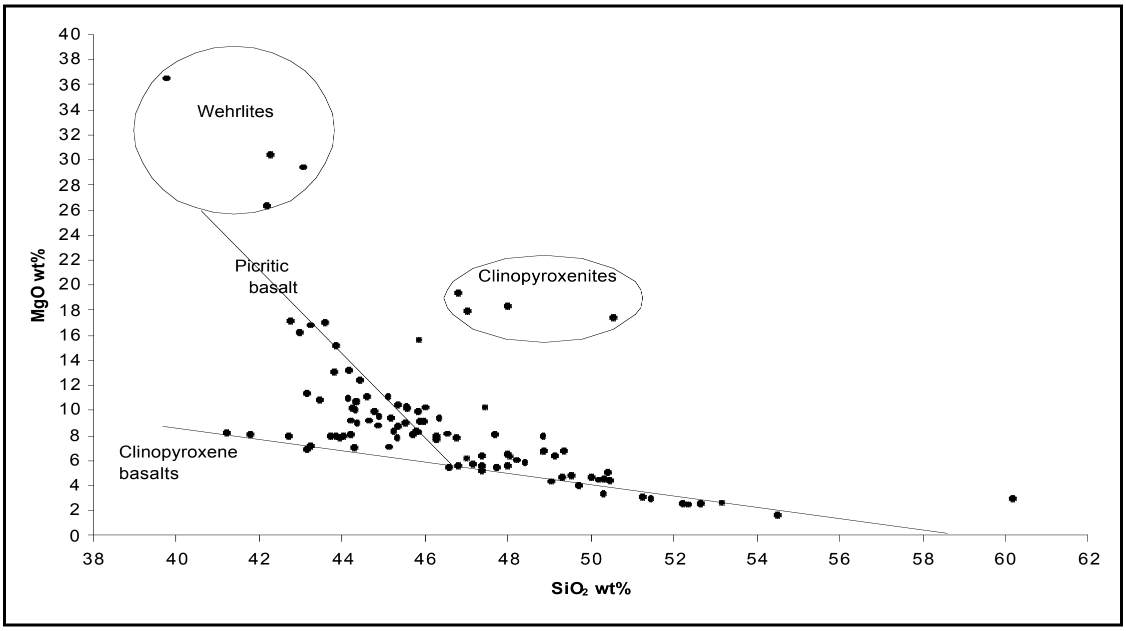


Figure 3 Variation plot of MgO wt% against SiO_2 wt% for the rocks from the Bufumbira volcanic field

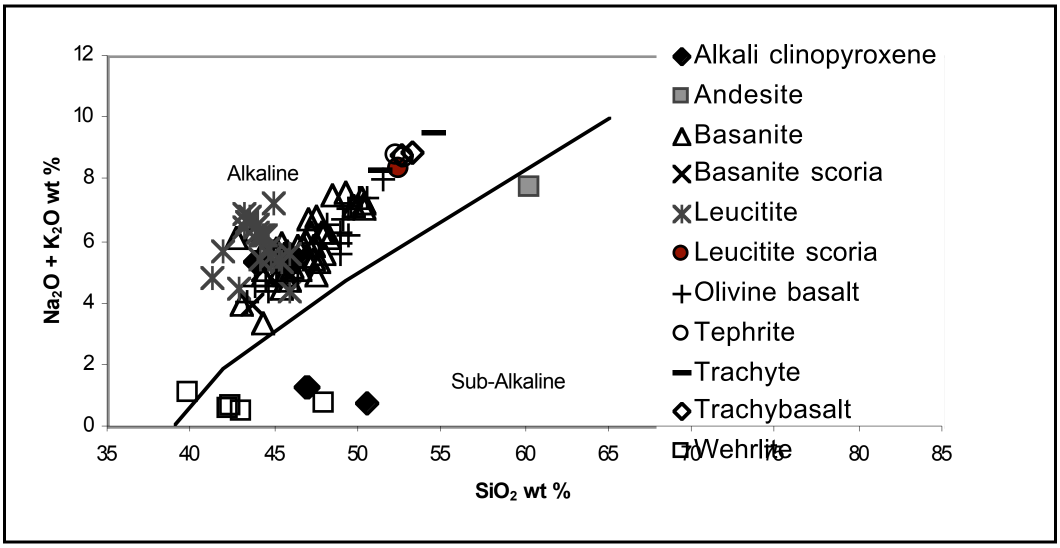


Figure 4: The plot of total alkalis (Na_2O + K_2O wt%) versus SiO_2 wt% (after Irvine and Baragar 1971)

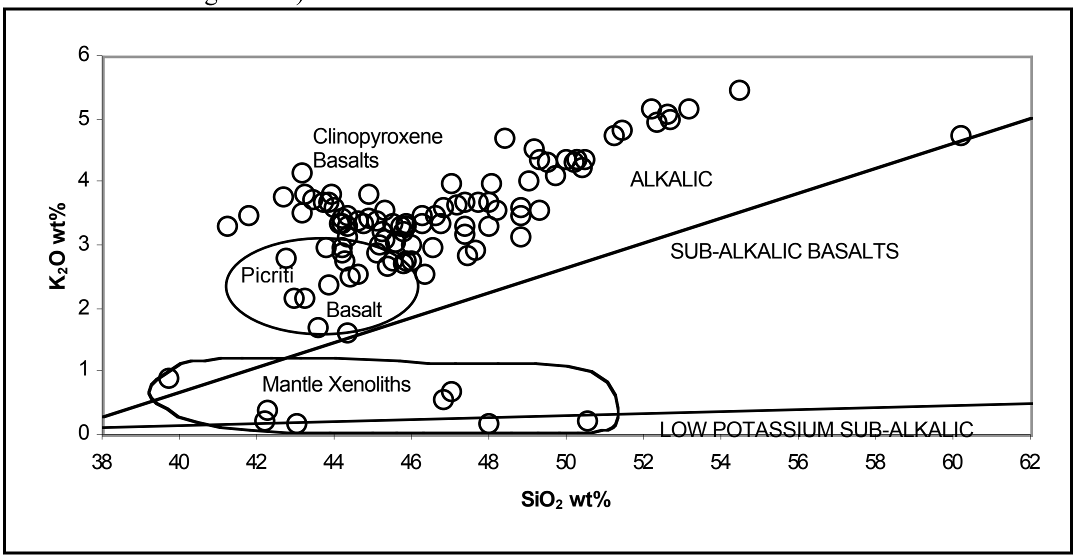


Figure 5: Binary diagram of K2O wt% against SiO2 wt% (after Middlemost 1975)

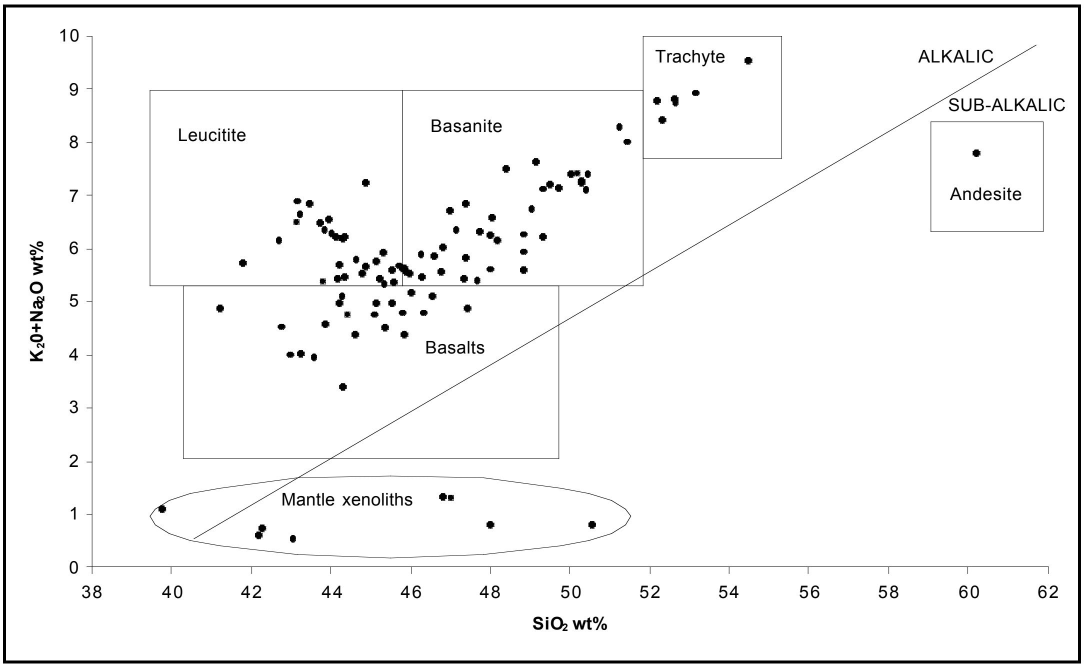


Figure 6: Plot of total alkalis (K_2O + N_2O wt%) versus SiO_2 wt% of the various rocks of the Bufumbira field (Cox *et al.* 1979)

The Le Maitre (1989) plot (Fig. 8) clusters most of the mafic rocks between the basanite (U1b) and trachybasalt (S1) fields followed by the leucitite (U1c) and basaltic trachyandesite (S2) fields. The intermediate rocks plot in the tephrite (U1a) and trachyandesite (S3) fields. The mantle xenoliths plot in the picrobasalt (PC) for wehrlites and basalt (B) fields for the clinopyroxenites. The Walker normative plot (Fig. 9) of olivine, diopside and plagioclase define a differentiation trend for the various rocks starting from the mantle xenoliths to the leucitites and olivine basalts of the picritic basalts followed by basanites and the intermediate rocks.

All the rock types have high concentrations of the incompatible trace elements Ba, Nb, Rb, Sr, Y, Zr, U, Th, Ta (Figs. 11&14). These are mafic rocks from the mantle. The enhancement in the concentrations of potassium and the incompatible trace elements suggests enrichment of these elements in the upper mantle before eruption. The variation diagrams between major elements and trace elements (e.g. Fig. 10) and trace elements versus trace elements (e.g. Fig. 11) still discriminate the two geochemical trends.

The rocks have also high concentrations of the light rare earth elements (Figs. 12a&b). The high concentrations could be attributed to enrichment of these elements in the upper mantle before eruption or garnet could have retained the heavy rare earth elements in the mantle. The absence of garnet in the mantle xenoliths negates the second possibility.

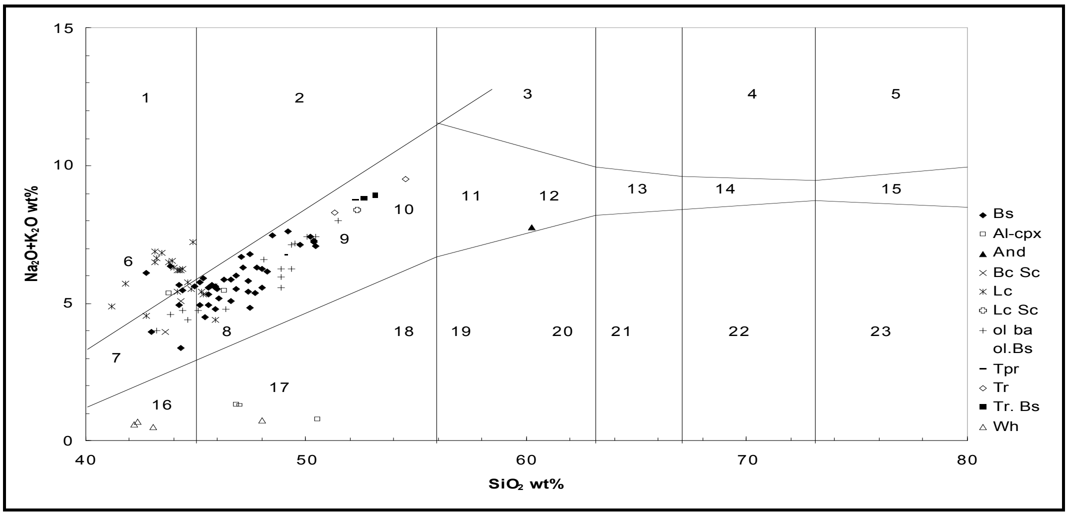


Figure 7: Variation diagram for total alkalis (Na_2O + K_2O wt%) against SiO_2 wt% (after Middlemost 1985)

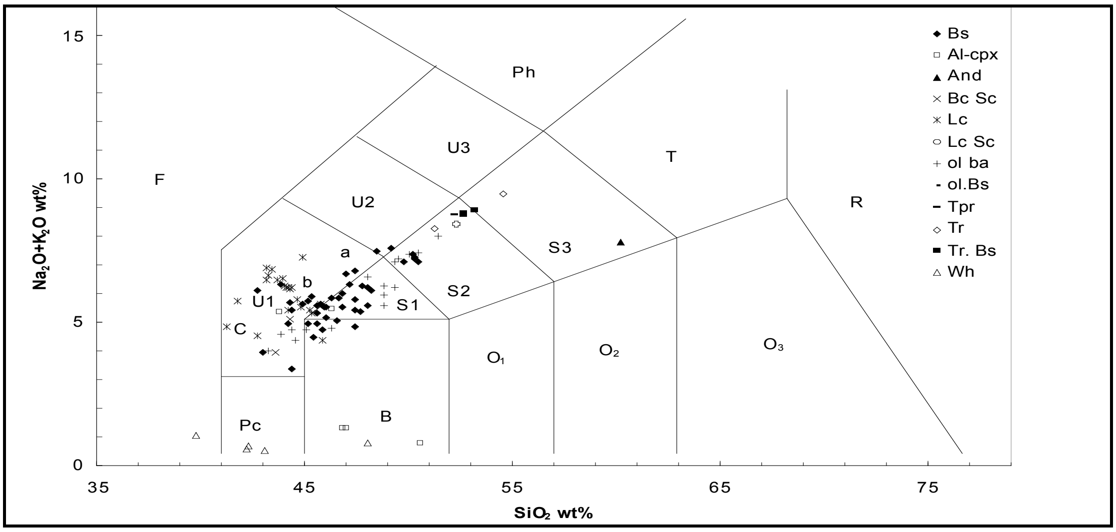


Figure 8 Diagram of total alkalis (Na_2O + K_2O wt%) against SiO_2 wt% of the Bufumbira basalts (after Le Maitre 1989)

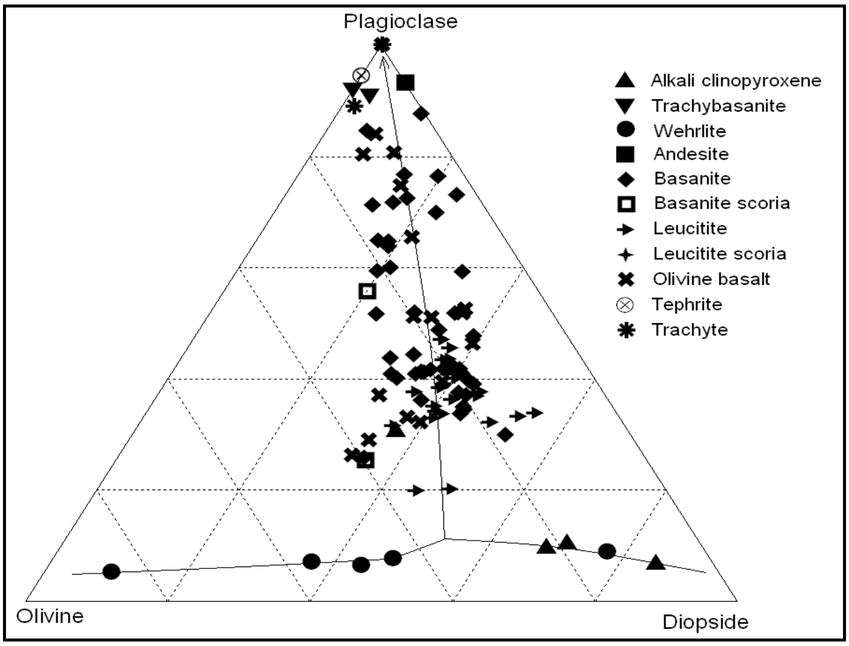


Figure 9 The Walker et al. (1989) normative ternary plot of plagioclase, olivine and diopside

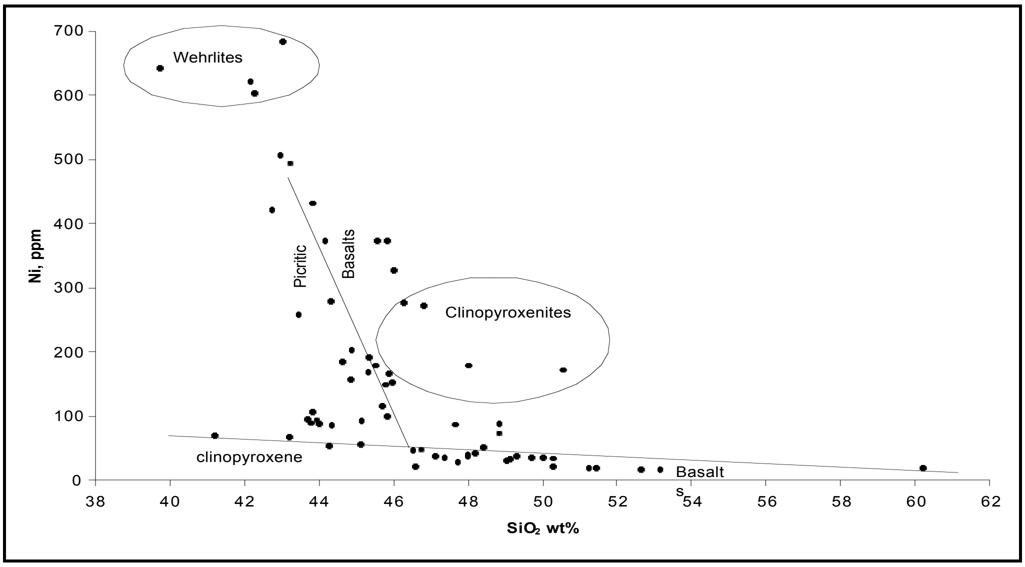


Figure 10 The variation plot of Ni ppm versus SiO_2 wt%

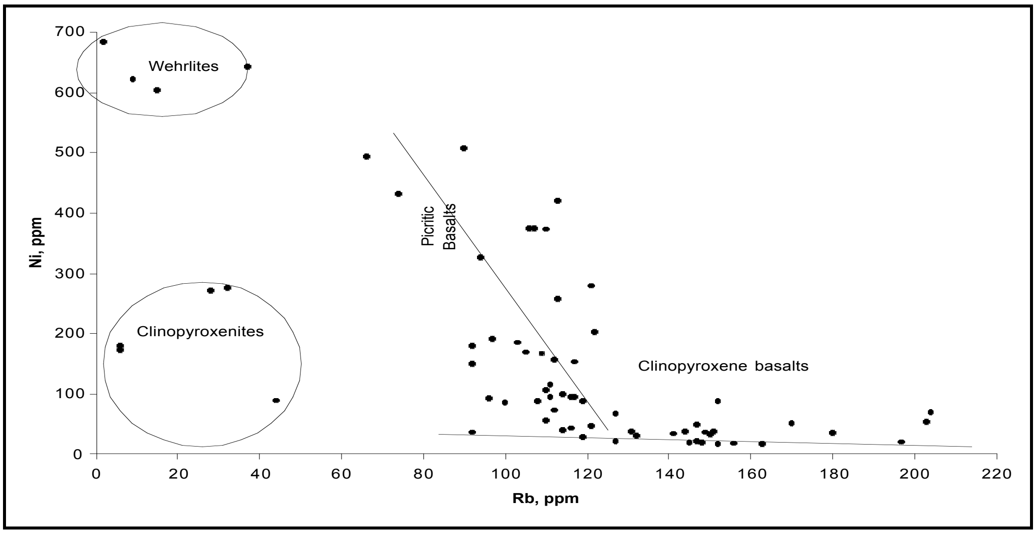
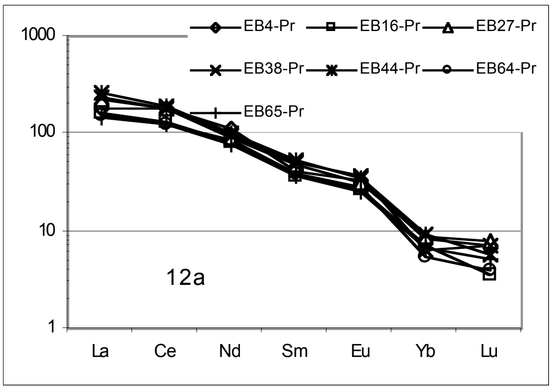


Figure 11: The binary diagram of Ni ppm versus Rb ppm



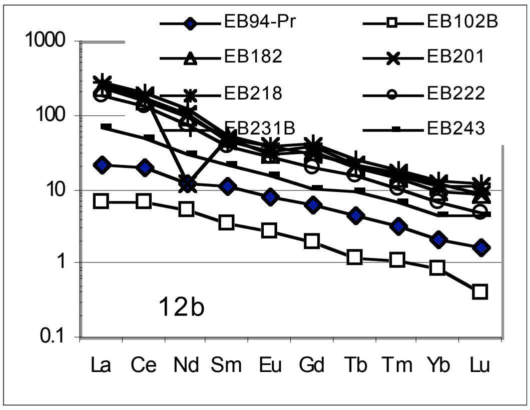


Figure 12a&b: CI – Chondrite normalised plots for rare earth elements of some rock samples from the Bufumbira volcanic field

The spiderdiagram plot (Fig. 13) shows the level of enrichment of the incompatible trace and light rare earth elements. The trough on Nb could be due to a refractory accessory phase like pyrochlore retaining it in the mantle. The trough on Cs could be attributed to its high mobility during upper mantle metasomatism. The Th/Yb versus Ta/Yb (Fig.14) diagram, concentrates the basaltic rocks in the group II ultrapotassic to potassic within plate basalts that were derived from an enriched mantle source (e.g. Pearce 1982; 1983). The mantle xenoliths also experienced moderate enrichment.

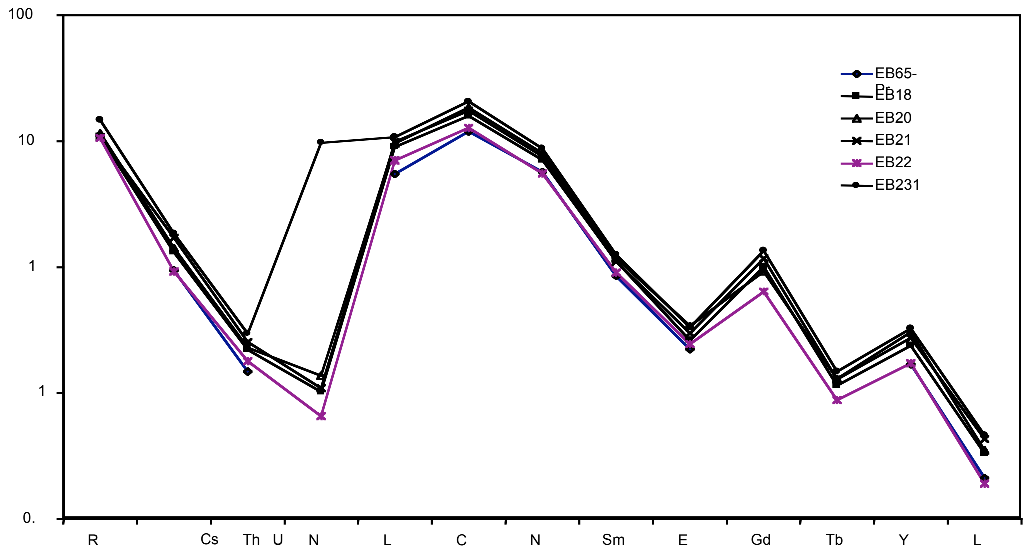


Figure 13: CI – Chondrite normalised spiderdiagram of some samples from the Bufumbira volcanic field

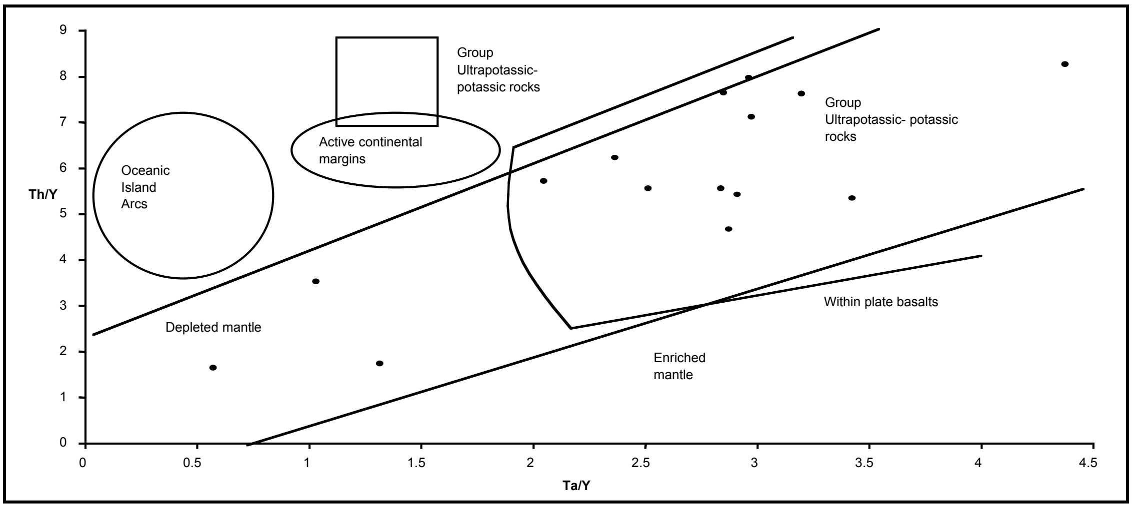


Figure 14: Plot of Th/Yb against Ta/Yb for samples of the Bufumbira volcanic rocks (after Pearce 1982, 1983)

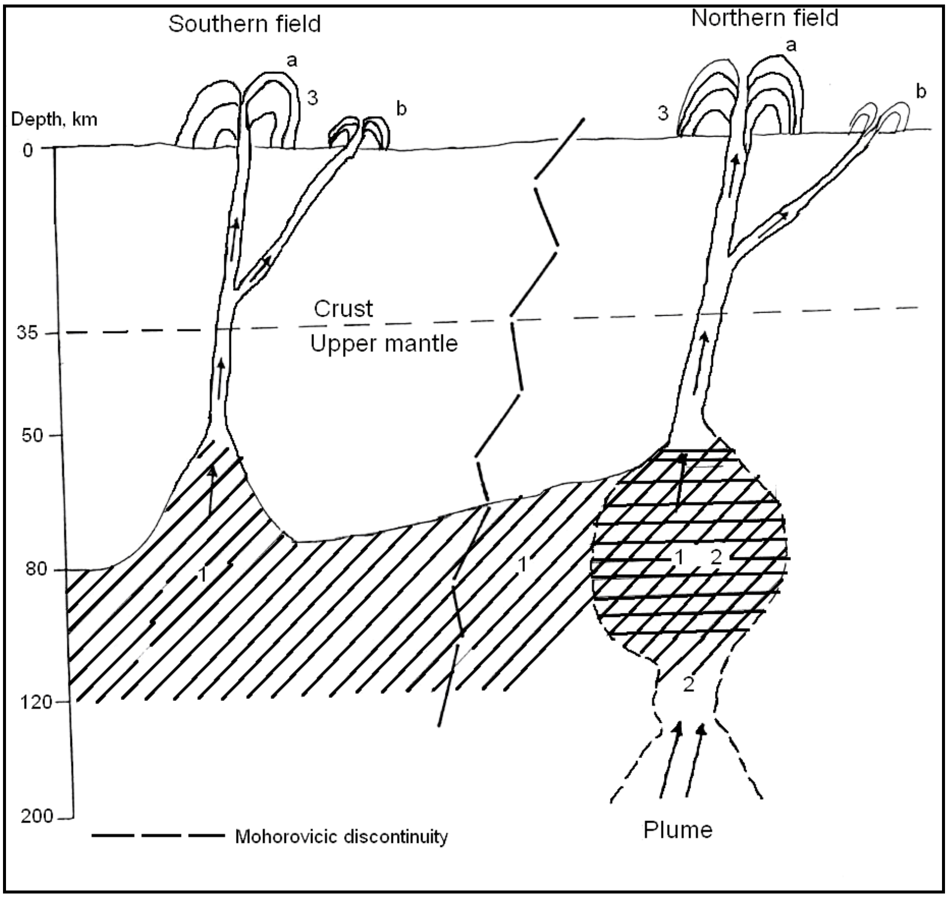
DISCUSSION

The low silica content, high magnesia and embayed mantle xenoliths suggest a mantle origin for the volcanic rocks of the Bufumbira field. The mantle was depleted by earlier extraction of basaltic melts which carried along the lithophile elements. Their replenishment in the upper mantle was a later event.

The proponents of the hypothesis involving crustal assimilation (e.g. Holmes 1950; Bell and Powell 1969; Cohen and 0' Nions 1982; Huppert and Sparks 1985; Prelevic et al. 2005) to explain the enrichment of the upper mantle were unable to account for the high isotopic variations in the rocks (e.g.Vollmer and Norry 1983a&b, Nelson *et al*. 1986, Vollmer 1989; Walker et al. 1989,, Reid 1995). Very large amounts of crustal material would be needed in order to significantly modify the radiogenic signature of potassic magma (e.g. Peccerillo 1992). The earlier suggested hypothesis of upper mantle metasomatism proposed by Lloyd (1972) was revived (e.g. Menzies and Murthy 1980; Peccerillo 1992; Widom et al. 1997, Rogers *et al*. 1998) to adequately explain upper mantle enrichment processes and isotope variations. It was found to be plausible in accounting for the enhancement in the concentrations of K_2O, CaO, TiO_2, incompatible trace and light rare earth elements (e.g. Furman 1995; Rosenthal *et al.* 2009, Link et al. 2010).

Table 2 Chronological order of events for both the southern and northern parts of the Bufumbira volcanic field (after Barifaijo 2000)

Order	Southern	Northern
1	Pervasive modal metasomatism at an estimated shallow depth of 80-120 km. This was at low geothermal gradient.	Limited modal metasomatism at a depth of 80-120 km. Cryptic metasomatism is evident in the xenoliths.
2		Heat plume from greater than 200 km to trigger higher degree of partial melting.
3	Eruption of alkaline basalts for both mafic and intermediate rocks.	Eruption of picritic basalts. At Rutare centre these clearly pierce through the clinopyroxene rich basalts.
4	Formation of monogenetic mostly central volcanoes with rocks which are rich in clinopyroxene both among the phenocrysts and the groundmass with limited fissure eruption	Formation of central volcanoes rich in olivine among phenocrysts and groundmass with limited fissure eruption.



Event

1 Upper mantle metasomatised
2 Plume flow
1 + 2 Plume triggers higher degree of partial melting in already moderately metasomatised upper mantle
3 Eruption of volcanoes
3a Eruption of central volcano
3b Fissure eruption

Figure 15 Chronological orders of events in the mantle beneath the Bufumbira volcanic field up to eruption. These resulted in the different rock types for the northern and southern parts of the field (after Barifaijo 2000)

Potassic volcanism in low geothermal gradient rift regimes is always associated with volatitle activity. Large proportions of volatiles include CO_2, H_2O, F_2, Cl_2 (Eggler, 1987, Foley *et al.* 1987). The dominant gas for the Bufumbira field was CO_2 (Huntingdon 1973; Link *et al.* 2007) followed by H_2O and F_2. Bailey (1964, 1972, 1980, 1982, 1983, 1985) developed a hypothesis that bending and fissuring of the continental lithosphere during uplift and rifting localises mantle degassing, where the volatiles flow into the arches and tensional regions of the lithosphere locally metasomatising the mantle in those regions. Mckenzie (1989) suggested that silicate melt fractions smaller than 1% may be mobile within the upper mantle. The silicate melts together with the volatiles were derived from the fertile sublithospheric mantle and came laden with the incompatible trace elements which migrated upwards. Since they were small, they could not transfer much heat and they were able to freeze readily in the upper mantle with which they reacted (Peccerillo 1992). Melting of metasomatised veins which were rich in phlogopite or amphibole and some accessory phases yielded alkaline magmas. The Bufumbira mantle xenoliths show evidence of modal metasomatism where olivine was replaced by phlogopite and clinopyroxene. Lack of amphibole and preponderance of phlogopite means upper mantle metasomatism occurred between 80 - 120km under the normal geotherm (e.g. Lloyd and Bailey 1975; Demant et al. 1994).

The fact that the northern part of the Bufumbira field is dominated by picritic basalts (Mg_ = 80-90) plus dunite and wehrlite xenoliths and the southern part consists of clinopyroxene basalts (Mg_ = 69-86) and clinopyroxenite xenoliths means that upper mantle metasomatic reactions were more pervasive in the southern part than the northern part of the field (Table 2 and Fig. 15). The metasomatising fluids fluxing in the southern part of the field were more voluminous than those from the northern part (Barifaijo 2000). The picritic basalts originated from the deeper part of the mantle (120-200km).

CONCLUSION

The Bufumbira volcanic field is the southernmost of the three small volcanic fields found in the western branch of the East African rift system. The field is the northeastern portion of the Birunga field.

The rocks are silica undersaturated basalts which are vesicular. The mafic rocks consist of basanites, leucitites, olivine basalts and the intermediate rocks consist of trachytes, tephrites, trachybasanites and andesites. The various mafic rocks carry upper mantle xenoliths. The xenoliths are type I, subtype Ib and type II, subtypes II (i) and II (ii).

The rocks are low in SiO_2, Al_2O_3 and Na_2O wt%. They are high in MgO, CaO, TiO_2, K_2O wt%, Ni, Cr, Co, incompatible trace elements and the light rare earth elements. Variation diagrams discriminate the picritic and clinopyroxene basaltic trends. The plots for K_2O wt% against SiO_2 wt% and total alkalis against SiO_2 wt% enable the basaltic rocks to plot in the alkaline field and mantle xenoliths plot in the subalkaline field. The other variation diagrams for total alkalis versus SiO_2 wt% place the various rocks in the appropriate fields for which they were named. The names conform with those of other petrographic studies. The enhancement in the concentrations of certain elements was attributed to upper mantle metasomatism.

ACKNOWLEDGEMENTS

Greatly indebted to Japan International Cooperation Agency (JICA), Austrian Academic Exchange Service (ÖAD) and Makerere University (Mak) for the material support. Thanks very much to the Tanzania Journal of Science (TJS) for accepting to publish this work.

REFERENCES

Bailey DK 1964 Crustal warping - A possible tectonic control of alkaline magmatism. *J. Geophys. Res.* **69**: 1103 - 1111.

Bailey DK 1972 Uplift, rifting and magmatism in continental plates. *J. Earth Sci.* (Leeds) **8:** 225 - 239.

Bailey DK 1980 Volcanism, earth degassing and replenished lithosphere mantle. *Philos. Trans. Roy. Soc.*, A **297**: 309 - 322.

Bailey DK 1982 Mantle metasomatism - Continuing chemical change within the earth. *Nature* **296**: 525 - 530.

Bailey DK 1983 The chemical and thermal evolution of rifts. *Tectonophysics* **94**: 585 - 597.

Bailey DK 1985 Fluids, melts, flowage and styles of eruption in alkaline ultramafic magmatism. *Trans. Geol. Soc.* South Africa **88**: 449 - 457.

Barifaijo E 2000 *The geology and geochemistry of the Bufumbira alkaline volcanics in southwestern Uganda and the mantle characteristics that produced such rocks*. Ph.D Thesis, Department of Geology, Makerere University, Uganda.

Bell K and Powell JL 1969 Strontium isotopic studies of alkaline rocks: The potassium rich lavas of Birunga and Toro Ankole regions, East and Central Equatorial Africa. *J. Petrology* **10:** 536-572.

Cohen RS and O' Nions RK 1982 Identification of recycled continental material in the mantle from Sr, Nd and Pb isotope investigations. *Earth Planet. Sci. Lett.* **61**: 73-84.

Cox KG Bell JD and Pankhurst RJ 1979 The interpretation of igneous rocks. London, Allen and Unwin.

Demant A, Lestrade P, Lubala RT, Kampunzu AB and Durieux J 1994 Volcanological and petrological evolution of Nyiragongo volcano, Virunga volcanic field, Zaire. *B. Volcanology*, **56**: 47-61

Eggler DH 1987 Solubility of major and trace elements in mantle metasomatic fluids: Experimental constraints. In: Menzies MA and Hawkesworth CJ (Eds) *Mantle metasomatism* Academic Press, London.

Foley SF Venturelli G and Tosconi L 1987 The ultrapotassic rocks: Characteristics, classification and constraints for petrogenetic models. *Earth Sci. Rev.* **24:** 81 - 134.

Furman T 1995 Melting of metasomatised subcontinental lithosphere: Undersaturated mafic lavas from Rungwe, Tanzania. *Contr. Mineral. Petrol.* **122**: 97-115.

Holmes A 1950 Petrogenesis of katungite and its associates. *Am.. Mineral.* **35**: 772-792.

Huntingdon A T 1973 *An investigation of the volatile phase of igneous petrogenesis and its application to the Bufumbira volcanic field, SW Uganda*. Ph.D Thesis, University of Reading, UK.

Huppert HE and Sparks RSJ 1985 Cooling and contamination of mafic and ultramafic magmas during ascent through continental crust. *Earth Plan. Sci. Lett.* **74**: 371-386.

Irvine TN and Baragar WRA 1971 A guide to the chemical classification of the common volcanic rocks. *Can. J. Earth Sci.* **8:** 523 - 548.

Kasereka M, Wafula M, Kibuye M, Lukaya N, Ciraba M, Kavotha K, Yalire M, Kavule K, Rusangiza K, Mavonga T, Komorowski JK, Hamaguchi H, Durieux J, Newhall C and Dario T 2007 Volcanic, seismic activities and landslides risk reduction in the western branch of the East African Rift System. In: Muwanga A, Owor M, Schuman, A and Kawule W (Eds) *Abstracts volume of the international conference on the East African Rift System* EARS 07, 23-25 July, 2007, Kampala, Uganda: 67-68.

Kervyn F, d'Oreye , Cayol V, Wauthier C and Lukaya F 2007 Ground deformations associated with the Nyiragongo 2002 and the Nyamulagira 2006 eruptions (DRC) revealed by radar interferometry. In: Muwanga A, Owor M, Schumann A and Kawule W (Eds) *Abstracts volume of the international conference on the East African Rift System* EARS 07, 23-25 July, 2007, Kampala, Uganda: 66 - 66.

Le Maitre RW (ed) 1989 A classification of igneous rocks and glossary of terms. Blackwell Scientific Publications, London.

Link K, Rosenthal A, Pearson DG, Barifaijo E, Tiberindwa J, Nowell G and Foley SF 2007 Geochemical constraints on the origin of silica-poor alkaline volcanic rocks in the Toro-Ankole and Bufumbira region of western Uganda. *In: Abstracts* *volume of the conference on active volcanism and continental rifting with special focus on the Virunga, North Kivu, DRC*, November 19-21 in Luxembourg.

Link K, Koehn D, Barth MG, Tiberindwa JV, Barifaijo E, Aanyu K, Foley SF 2010 Continuous cratonic crust between the Congo and Tanzania blocks in western Uganda. *Int. J. Earth Sci.* **99**, No. 7:1559-1573, DOI:10.1007/s00531-010-0548-8.

Lloyd FE 1972 *The petrogenesis of strongly alkaline mafic lavas and nodules from southwest Uganda*. Ph.D Thesis, University of Reading, UK.

Lloyd FE and Bailey DK 1975 Light element metasomatism of the continental mantle: The evidence and consequences. *Phys. Chem. Earth* **9**: 389 – 416.

Lloyd FE 1981 Upper mantle metasomatism beneath a continental rift: Clinopyroxenes in alkali mafic lavas and nodules from southwest Uganda. *Mineral. Mag.* **44**: 315-323.

Lloyd FE 1987 Characterization of mantle metasomatic fluids in spinel lherzolites and alkali clinopyroxenites from the west Eifel and southwest Uganda. In: Menzies MA and Hawkesworth CJ (Eds) *Mantle Metasomatism* Academic Press, Geology Series, London.

Lloyd FE, Nixon PH, Hornung G and Condliffe E 1987 Regional K-metasomatism in the upper mantle beneath the west branch of the East African rift: Alkali clinopyroxenite xenoliths in highly potassic magma. In: Nixon PH (ed) *Mantle xenoliths* John Wiley and Sons Ltd, London.

Macdonald R 1966 Uganda Geology, Geochemical atlas of Uganda. *Department Geological Survey,* Uganda, plates **3**: 1 - 10.

Mckenzie DP 1989 some remarks on the movement of small melt fractions in the mantle. *Earth Planetary Science Letters* **95**: 53 - 72.

Menzies MA and Murthy VR 1980 Nd and Sr isotope geochemistry of hydrous mantle nodules and their host alkali basalts: Implications for local heterereogeneities in metasomatically veined mantle. *Earth Plan. Sci. Lett.* **46**: 323-364.

Middlemost EAK 1975 The basalt clan. *Earth Sci. Rev.* **11**: 337 - 364.

Middlemost EAK 1985 Magmas and magmatic rocks. Longman, London.

Mysen BO and Kushiro I 1977 Compositional variations of coexisting phases with degree of partial melting of peridotite in the upper mantle. *Am. Mineral.* **2**: 843 - 865.

Nelson DR, McCulloch MT and Sun SS 1986 The origin of ultrapotassic rocks as inferred from Sr, Nd and Pb isotopes. *Geochim.t Cosmochim. Acta* **50**: 231-245.

Nixon PH and Hornung G 1973 The carbonatite lavas and tuffs near Fort Portal, western Uganda. *Overseas Geology, Mineralogical Research Institute Geological Sciences* **41:** 168-179.

Pearce JA 1982 Trace element characteristics of lavas from destructive plate boundaries. In: Thorpe RS (Ed) *.Andesite: Orogenic andesites and related rocks* Wiley, Chichester, UK.

Pearce JA 1983 The role of sub-continental lithosphere in magma genesis at destructive plate margins. In: Hawkesworth CJ and Norry MJ (Eds) *Continental basalts and mantle xenoliths* Nantwich Shiva.

Peccerillo A 1992 Potassic and ultrapotassic rocks: Compositional characteristics, petrogenesis and geological significance. *Episodes* **15** No.4: 243-251.

Platz T, Foley SF and Andre_ L 2004 Low-pressure fractionation of the Nyiragongo volcanic rocks, Virunga Province, D.R.Congo. *J. volcanological and Geothermal Research* **136**: 269-295.

Prelevic D, Foley SF, Romer RL, Cvetkovic V and Downes H 2005 Tertiary ultrapotassic volcanism in Serbia: Constraints on petrogenesis and mantle processes. *J. Petrol.* **46**:1446-1487

Reid MR 1995 Processes of mantle enrichment and magmatic differentiation in the Eastern Snake plain: The isotopic evidence. *Earth Plan. Sci. Lett.* **131**: 239-254.

Rogers NW, James D, Kelley SP and De Mulder M 1998 The generation of potassic lavas from the Eastern Virunga Province, Rwanda. *J. Petrol.* **39** No.6: 1223-1247.

Rosenthal A, Foley SF, Pearson DG, Nowell GM, and Tappe S 2009 Magmatic evolution at the propagating tip of a continental rift – a geochemical study of primitive alkaline volcanic rocks of the western branch of the East African rift. *Earth Science Planetary Letters* **284**:236-248.

Thomas CW and Nixon PH 1987 Lower crustal granulite xenoliths in carbonate volcanoes of the western rift of East Africa. *Mineral. Mag.* **51**: 621-633.

Thompson RN 1985 Asthenospheric source of Uganda ultrapatassic magama? *J. Geology* **93**:603-608

Vollmer R and Norry MJ 1983a Unusual isotopic variations in Nyiragongo nephelinites. *Nature* **301**: 141-143.

Vollmer R and Norry MJ 1983b Possible origin of K-rich volcanic rocks from Virunga, East Africa by metasomatism of continental crust material: Pb, Nd and Sr isotopic evidence. *Earth Plan. Sci. Lett.* **64**: 374-386.

Vollmer R 1989 On the origin of the Italian potassic magmas, 1, a discussion contribution. *Chem. Geol.* **74:** 229-239.

Wafula MD, Kasereka M, Rusangiza K, Kavuke K, Mukambilwa K, Mavonga T, Lukaya N, Kavotha K, Yalire M and Ciraba M 2007 Some considerations on the Nyamulagira eruption of November, 27, 2006, Virunga region, D.R. Congo. In: Muwanga A, Owor M, Schumann A and Kawule W (Eds) *Abstracts volume of the international conference on the East African Rift System*, EARS 07, 23-25 July, 2007, Kampala, Uganda: 68-71.

Walker RJ, Carlson RW, Shirey SB and Boyd FR 1989 Os, Sr, Nd and Pb isotope systematics of southern African peridotite xenoliths: Implications for the chemical evolution of sub continental mantle. *Geochim. Cosmochim. Acta* **53**: 1583-1595.

Widom E, Carlson R W, Gill JB and Schmincke H - U 1997 Th-Sr-Nd-Pb isotope and trace element evidence for the origin of the Sao Miguel, Azores, enriched mantle source. *Chem. Geol.* **140:** 49-68.