Geochemistry and Mantle Source(s) for Carbonatitic and Potassic Lavas, Western Branch of the East-African Rift System, SW Uganda

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ABSTRACT: Samples from the various volcanic fields in the Uganda portion of the western branch of the East African rift system were analyzed for major and trace elements. The northernmost Fort Portal field consists of extrusive carbonatite tuffs and lavas. All these samples are mixtures of carbonatite, basement rock fragments and peridotite xenoliths. The central fields, Katwe-Kikorongo and Bunyaraguru, and Kasenyi Crater, are ultrapotassic, but detailed sampling indicates that the degree of K enrichment, with respect to Na, varies geographically with Bunyaraguru and Kasenyi Crater showing the greatest enrichment. The southern field, Bufumbira, while also potassic shows a much lower degree of K enrichment. In terms of a variety of trace elements, and trace element ratios, various mantle domains can be identified that gave rise to the magmas in each of the volcanic areas. The data indicate that the subcontinental mantle under this portion of Uganda has undergone variable degrees of metasomatism. A complete description of the character of the primary magmas requires a consideration of both the degree of metasomatism and the degree of melting of the garnet-bearing source.

KEY WORDS: western rift, potassic magmatism, carbonatite, trace elements, mantle source.

Introduction

The western branch, in SW Uganda, of the East African rift system is one of the classic localities for potassic alkaline magmatism. A significant variety of igneous lithologies are found in the Uganda segment of the rift: extrusive carbonatites to the north (Fort Portal), ultrapotassic volcanics in the central portion (Katwe-Kikorongo, Bunyaraguru and Kasenyi Crater) and potassic mafic and felsic volcanics to the south (Bufumbira) (see Fig 1 for locations of the various volcanic fields). A summary of the geology, mineralogy and chemistry of these fields can be found in Lloyd et al. (1991). The purpose of this paper is to present preliminary results and conclusions concerning the origin and evolution of the carbonatites and potassic volcanics based on new geochemical data obtained for samples from the various volcanic fields.

General geology

Fort Portal

The Fort Portal volcanic field was initially described by Holmes and Harwood (1932). Subsequent studies were carried out by von Knorring and DuBois (1961), Bell and Powell (1969), Nixon and Hornung (1973) and Barker and Nixon (1989), among others. Volcanic activity at Fort Portal occurred 6000 to 4000 years ago (Vinogradov et al. 1980) and resulted in the formation of approximately 50 monogenetic cones, comprised of lapilli tuff, that form two ENE-trending belts. The cones and surrounding area are covered with massive to planar-bedded "flaggy tuffs" that vary from 0.5 m to 2 m in thickness. Barker and Nixon (1989) interpreted these tuffs to be wet-surge deposits. Lava flows, up to 5 m thick and 0.3 km^2 in areal extent, are found in the northwest corner of the field. Basement rock fragments and peridotite xenoliths are ubiquitous in the tuffs and lavas. Barker and Nixon (1989) concluded that the chemistry of individual tuff and lava samples could be largely explained by mixing between carbonatitic magma and country rock fragments. Many elements formed linear trends when plotted versus alumina (an element that was assumed to have only a country-rock source), but others showed more erratic behavior.

Katwe-Kikorongo, Bunyaraguru and Kasenyi crater

The lavas and tuffs of these fields are strongly silica-undersaturated and potassic to ultrapotassic in composition (kamafugitic affinity of Sahama 1974). These fields are the type area for the three primary magmas of Holmes (1965) that comprise the kamafugitic affinity: ugandite (primary minerals are olivine, pyroxene, leucite), mafurite (primary minerals are olivine, pyroxene, kalsilite) and katungite (primary minerals are olivine, melilite, kalsilite, leucite). The fields largely consist of pyroclastic ring-craters, lavas are rare. Lloyd et al. (1991) estimate that the fields consist of 0.07 km^3 of small lava flows and lava piles and 63 km^3 of ash. Stoppa et al. (2000) have recently reported the occurrence of carbonatite lapilli and a carbonatite bomb from Murumuli crater (Katwe-Kikorongo field), indicating that carbonatite magmas were also present.

Bufumbira

The Bufumbira field lies in Uganda and forms the northern part of the much larger Virunga province which extends into

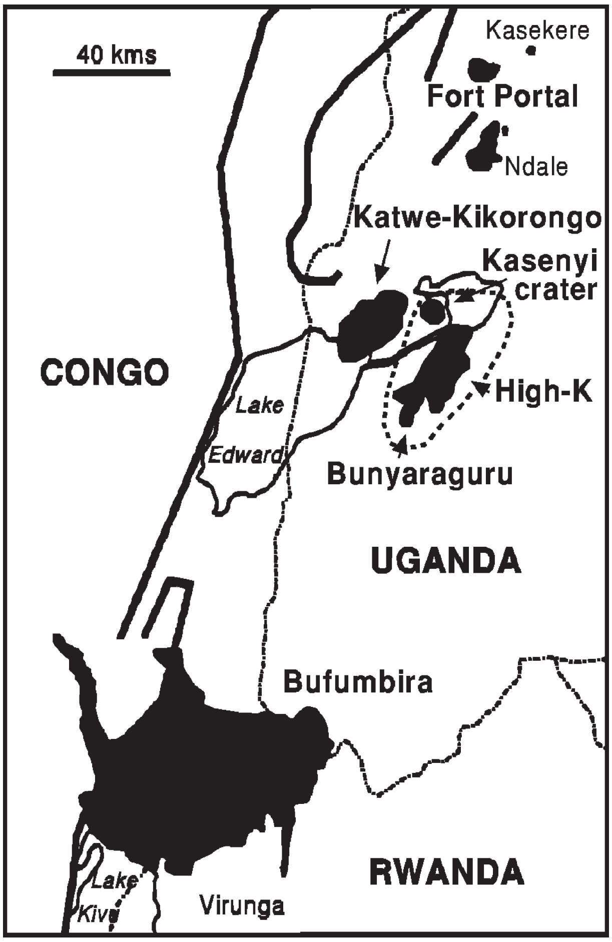

Fig. 1. Map showing the location of the various volcanic fields. Names in bold letters are the volcanic fields discussed in this paper. Area labeled "high-K" encompasses the region of ultrapotassic samples.

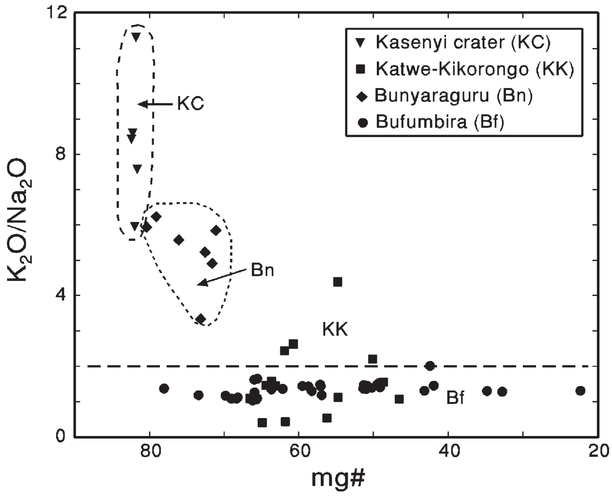

Fig. 2. Plot of K_2O/Na_2O versus mg#. Note the ultrapotassic character of the Kasenyi crater and Bunyaraguru samples.

the Democratic Republic of Congo and Rwanda. The province is dominated by an east-west chain of eight volcanic edifices. The Bufumbira volcanics were originally described by Combe and Simmons (1933) and a geochemical study was subsequently undertaken by Holmes and Harwood (1937). The Bufumbira field consists of three large volcanic structures with intercalated lavas and pyroclastics, 34 small cones mainly composed of pyroclastics and 11 pyroclastic domes and ridges (Lloyd et al. 1991). Lavas are much more abundant than pyroclastics. The most primitive mafic rocks are olivine basanites. Ferguson and Cundari (1975) identified two chemical series that diverged from the basanites, one through phonolitic-tephrite to trachyte and the other through leucitite to phonolite. In the mafic lavas olivine and titanaugite are the common phenocrysts. As the lavas evolve and olivine disappears either leucite (silica undersaturation trend) or leucite and plagioclase (silica saturation trend) appear as phenocryst phases.

Geochemistry

Samples from the various fields were analyzed for 42 elements using standard X-ray fluorescence (University of Canterbury), instrumental neutron activation (University of Massachusetts Lowell) and wet chemical techniques (Natural History Museum). A listing of representative analyses can be obtained from the senior author.

Thirty-two tuff and five lava samples were analyzed from Fort Portal. As previously discussed by Barker and Nixon (1989), for many elements a plot of the element (or oxide) concentration versus Al_2O_3 gives a linear relationship. It was suggested that these linear trends represent simple mixing between crustal xenoliths and carbonatite magma. However, a number of elements do deviate from simple linear trends suggesting a more complicated mixing process. In all cases the lavas plot near or on the linear trends at the low alumina end of the trend. While these lavas do contain crustal material, the generally low silica content suggests that crustal contamination is limited and the lavas can be used to *approximate* the composition of the carbonatite magma, particularly in the case of trace element ratios. Besides Ca and CO_2, the other major components of the carbonatite lavas are Fe, Mg and P. In terms of minor and trace elements, the lavas are enriched in F, total REEs with extreme light REE enrichment [average $(Ce/Yb)_N = 61 \pm 2.9$], and Nb and Zr. Average Nb/Ta (21.6 ± 0.9) and Zr/Hf (74 ± 3) ratios are much greater than those of normal mantle. In contrast, the average Th/U ratio (4.4 ± 0.2) falls in the normal mantle range. The lava compositions are plotted on subsequent diagrams.

Twelve samples from Katwe-Kikorongo (tuffs, ashes, bombs and lava flows), five samples from Kasenyi crater (tuffs), seven samples from Bunyaraguru (tuffs, ash and lava flows) and 36 samples from Bufumbira (lava flows, tephra, scoria and bomb) were analyzed for major and trace elements.

The potassic character of the volcanic fields is shown by a plot of the K_2O/Na_2O ratio versus mg# [$mg\# = Mg/(Mg + Fe^{2+})$, in moles, calculated by setting $Fe^{2+} = 0.85$ total Fe] (Fig. 2). The various volcanic fields fall in discrete regions on this diagram. The samples from Bunyaraguru and the isolated Kasenyi crater, mid-way between the Bunyaruguru and Katwe-

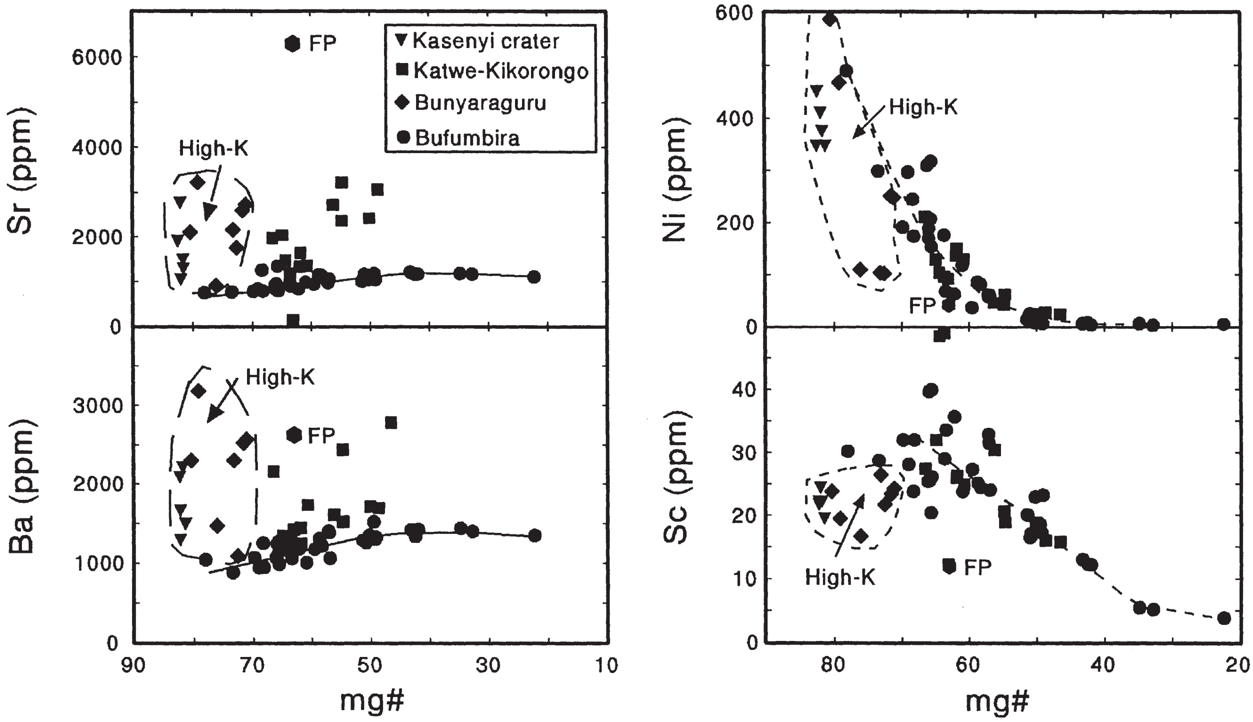

Fig. 3. Plot of Sr, Ba, Ni and Sc versus mg#. High-K samples plot in distinct fields. Field labeled FP encompasses lava samples from the Fort Portal carbonatite.

Kikorongo fields, show a strongly potassic character. On Figure 1, this region has been identified as the "high-K" region. A few of the other Katwe-Kikorongo samples also show some potassic enrichment, but most of the remaining samples have $K_2O/Na_2O<2$, as do the samples from the Bufumbira field. Thus we can distinguish between strongly potassic and mildly potassic volcanic regions.

The mg# can be used to determine the degree of evolution of a magma. Using the olivine-liquid distribution coefficient (K_D = 0.31) determined by Roeder and Emslie (1970) a magma in equilibrium with mantle olivine of composition Fo_{90} would have a mg#=74. A slightly more Mg-rich olivine, or a larger K_D value, would result in liquids of higher mg#. With reference to Figure 2, note that the samples from Kasenyi crater and the Bunyaraguru field all show a primitive character, as do several of the samples from the Bufumbira field. Petrographic examination reveals that some of the Kasenyi crater and Bunyaraguru samples contain biotite xenocrysts/phenocrysts. This would bias the data towards both higher mg# and K_2O. However, at this stage of our investigation there is no apparent pattern between the estimated amount of biotite and the rock chemistry. If we assume that samples with mg#s of 74 or greater represent primitive magma, then one conclusion is that the sources for the various fields were variably enriched in K_2O with respect to Na_2O. This enrichment was greatest for the source of the Kasenyi magmas and least for the source of the Bufumbira magmas. In a study of the pyroxene and mica chemistry of xenoliths from these fields, Lloyd et al. (1999) concluded that the xenoliths were derived from distinct sources, a conclusion in agreement with the whole-rock chemical data.

Variations in Sr, Ba, Ni and Sc concentrations, as a function of mg#, are shown on Figure 3. Given typical mantle mineralogies, during melting Sr and Ba would behave as incompatible elements while Ni and Sc would behave compatibly. Making the same assumption as above regarding the primitive character of the magmas, we note that the high-K magmas are richer in Sr and Ba than the Bufumbira and some of the Katwe-Kikorongo magmas. Ni contents of the primitive magmas are similar for all the volcanic fields. The Sc content of the primitive magmas from the high-K area are slightly less than for the other fields.

With fractionation of olivine and/or augite the mg# decreases. Thus, for magmas of mafic to intermediate composition the mg# can be used as a fractionation index. There is no regular variation of Sr or Ba with mg# for the samples from Katwe-Kikorongo, Bunyaruguru and Kasenyi crater (Fig. 3). For Bufumbira there is a regular increase in Sr and Ba with decreasing mg#, an expected result since both elements behave incompatibly with respect to the early crystallizing minerals (olivine and pyroxene). Both elements show a slight decrease at low mg#s which may indicate that the feldspar minerals (which have K_D values greater than 1 for both Sr and Ba) are becoming important fractionating phases. The declines in Ni and Sc concentrations (Fig. 3) with decreasing mg# are indicative of fractionation of olivine and pyroxene (Katwe-Kikorongo and Bufumbira), respectively.

Mantle sources and melting models

The volcanic fields plot in different regions on a Y/Nb versus Nb/Zr plot (Fig. 4). The Nb/Zr ratio can be changed by metasomatic processes (Tiepolo et al. 2001), and should increase with increasing metasomatism. Note that this is the progression shown on Figure 4. Samples with the highest K_2O/Na_2O ratios also have

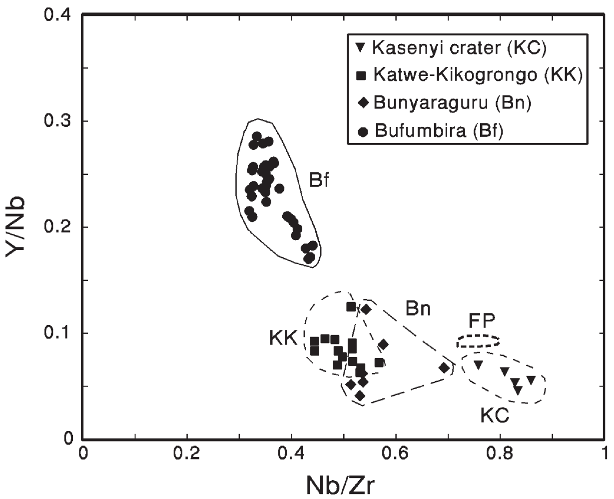

Fig. 4. Plot of Y/Nb ratio versus Nb/Zr ratio. Samples from the various volcanic fields plot in different areas suggesting different mantle sources. Field labeled FP encompasses lava samples from the Fort Portal carbonatite.

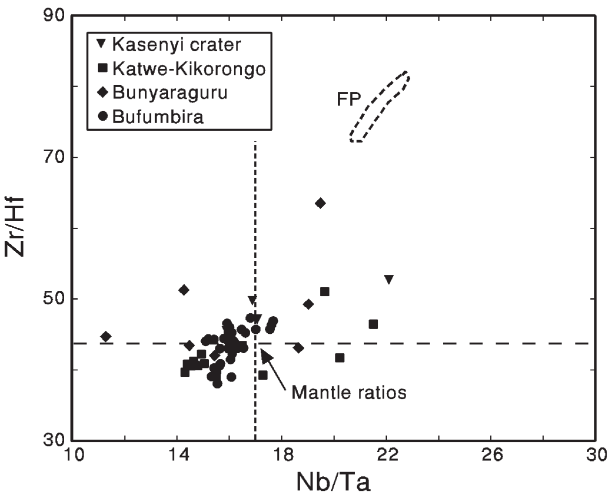

Fig. 5. Plot of Zr/Hf ratio versus Nb/Ta ratio. Most of the samples plot at lower Zr/Hf and Nb/Ta ratios than average mantle. Samples from Bunyaraguru, in particular, show a great deal of scatter. Field labeled FP encompasses lava samples from the Fort Portal carbonatite.

the highest Nb/Zr ratios. With decreasing metasomatism (as indicated by the relative concentration of K), the Nb/Zr ratio declines and the Y/Nb ratio increases. Thus we can identify discrete mantle domains that gave rise to each of the volcanic fields (or sub fields). On a Zr/Hf versus Nb/Ta diagram (Fig. 5), the bulk of the samples plot at slightly lower Zr/Hf and Nb/Ta ratios than average mantle (Zr/Hf = 44 and Nb/Ta = 17.5, Green 1995). Note that on a number of the diagrams (Figs. 3–6), the Fort Portal carbonatite lavas plot in a different location from the silicate rocks, suggesting a different source and magmatic history.

The chondrite-normalized Ce/Yb ratio is plotted versus mg# in Figure 6. This diagram reveals several significant relationships. First, the high-K fields plot in distinct regions on this diagram with the samples having the largest K_2O/Na_2O ratios also showing the largest $(Ce/Yb)_N$ ratios. Second, for Katwe-Kikorongo, Bunyaraguru and Kasenyi crater there is no regular variation in the $(Ce/Yb)_N$ ratio with mg#. In contrast, the Bufumbira suite starts with a significantly lower $(Ce/Yb)_N$ ratio and shows a regular increase with decreasing mg#, presumably in response to crystal fractionation. These observations can be interpreted to indicate that the source regions were variably enriched in light rare-earth elements (LREE), a response to metasomatism. However, a chondrite-normalized REE plot

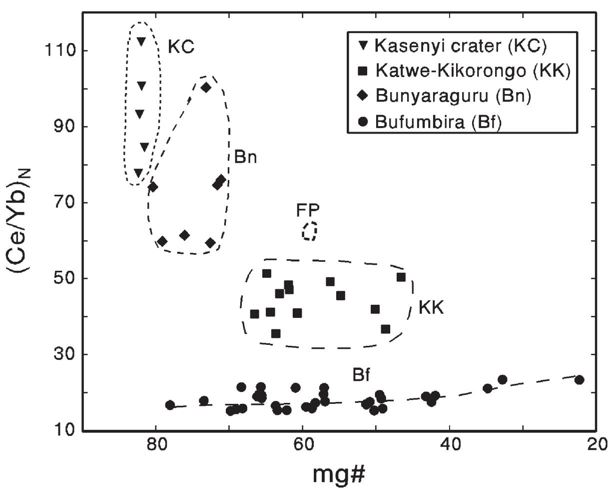

Fig. 6. Plot of chondrite-normalized Ce/Yb ratios versus mg#. Note that each volcanic field plots in a different area on this diagram. Field labeled FP encompasses lava samples from the Fort Portal carbonatite.

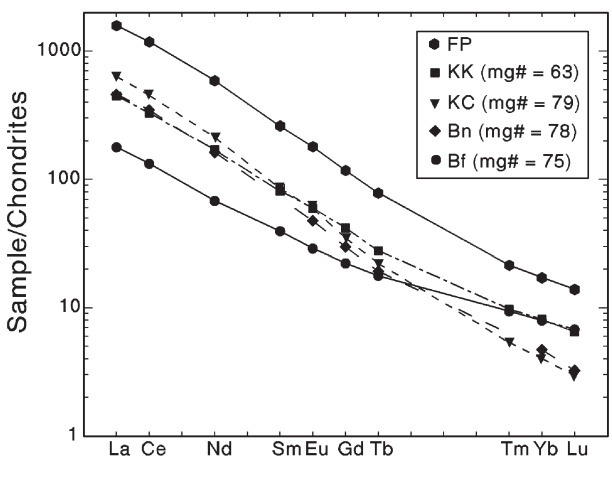

Fig. 7. Chondrite-normalized REE plots for the most primitive silicate-rock samples (as indicated by mg#) from each volcanic field. Note the crossing REE patterns that are often ascribed to variable degrees of melting of a garnet-bearing source. A representative REE plot for the Fort Portal lavas is also shown. Note the higher absolute REE abundances compared to the silicate rocks.

(Fig. 7) of the most primitive sample from each field shows the classic crossing patterns often attributed to variable degrees of melting of a garnet-bearing source. The $(Ce/Yb)_N$ ratio varies inversely as the degree of melting. The samples with the largest $(Ce/Yb)_N$ ratios also show the greatest enrichment in incompatible elements. Hence, some of the variations in incompatible element concentrations may be explainable by variable degrees of partial melting. However, the high K_2O/Na_2O ratios and other elemental variations do require the presence of metasomatized mantle. On the basis of xenolith data (Lloyd et al. 1999) and whole-rock chemistry we conclude that distinct mantle domains do exist under this part of Africa. For element ratios, such as Ce/Yb, which are sensitive to degrees of partial melting, initial mantle ratios are modified by the partial melting process. The relative significance of these two processes in determining the chemical composition of specific primary magmas awaits future quantitative modeling.

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