CHAPTER V

DISCUSSION AND RECOMMENDATIONS

5.1 Petrogenesis of Basalts

5.1.1 Characteristics of source region domain

In terms of source region identification of primitive magmas associated with the East African Rift system, two dominant melting models have been speculated. One is involved sublithospheric sources in the asthenoshere, or in mantle plumes to yield significant volumes of magma, while melting in the lithospheric mantle is too refractory to generate a large portion of lava (e.g. McKenzie and Bickle, 1988; White and McKenzie, 1989; Arndt and Christensen, 1992). The other considers a partial melting of a metasomatically enriched subcontinental lithospheric mantle (SCLM) source (e.g. Gallagher and Hawkesworth, 1992; Turner *et al.*, 1996; Spāth *et al.*, 2001). Several investigations have illustrated that the lithosphere underneath some parts of East Africa, including the Chyulu Hills Volcanic Province (CHPV) has undergone pervasive metasomatic alteration and enrichment (e.g. Rudnick *et al.*, 1993; Furman, 1995 and 2007; Paslick *et al.*, 1995; Spāth *et al.*, 2001).

In the study area, the overall OIB-like chemical characteristics of the basalts seem to imply a plume-related process. However, a K-depletion pattern observed on pyrolite mantle normalized incompatible element plots for all studied samples is more pronounce than the normal OIB. This suggests a diversified magma producing process from that of regular OIB. In a normal circumstance, potassium is expected to exhibit incompatibility in magma similar to other incompatible elements, e.g. Th, Nb, La, but this is not the case for the studied basalts. Comparable relative K depletions as observed have also been reported for mafic lavas from the other parts of the CHPV (e.g. Spāth *et al.*, 2001; Furman, 2007) as well as several other volcanic provinces associated with the Kenya Rift System, including the Huri Hills (Class *et al.*, 1994), the Laisamis-Merille area (Freerk-Parpatt, 1992 *cited in* Spāth *et al.*, 2001) and the

Rungwe region (Furman, 1995). The relative depletion in K reflecting an influence of a K-rich phase that leads to two possible explanations involving (1) the fractionation of a K-bearing phase, e.g. amphibole and/or phlogophite, or (2) partial melting of a source consisting of a residual K-bearing mineral. Nevertheless, the absence of amphibole or phlogopite phenocrysts and their remnants in all the studied basalt samples seems to rule out the first possibility. On the other hand, some findings of phlogophite-bearing mantle xenoliths in the CHVP and amphibole–phlogophite-bearing mantle xenoliths from other areas in Kenya and northern Tanzania (Henjes-Kunst and Altherr, 1992) favorably support the second possibility.

Since potassium (K) is an essential structural constituent of amphibole and phlogophite phases, it will be held in the source region until these minerals are consumed through progressive melting. By using the K/Th vs. Th plot, melting of mafic magma in the existing of either amphibole or phlogophite can, therefore, be simply explained (e.g. Class and Goldstein, 1997; Le Roex *et al.*, 2001; Späth *et al.*, 2001; Furman, 2007). According to Furman (2007), the silica-undersaturated lavas of the Chyulu Hills province have the highest Th (5-22 ppm) content and the lowest K/Th (<2000) ratio compared to those from the rest of the East Arican Rift system. The highest Th implies the lowest degree of melting while but the lowest K/Th ratio could be referred to amphibole-bearing source material, rather than phlogophite-bearing source domain, which usually holds a higher K/Th according to the virtue of the higher K content in the mineral, as for the Muhavura and Karisimbi lavas of the Weatern Rift (Furman, 2007). Correspondingly, the studied basalts have Th (6-15 ppm) and K/Th (~500-2,400) values well fitting within the overlap region between those of the Chyulu Hills and Rungwe province lavas (Figure 5.1) confirm an existence of K-bearing source domain underneath the study area. The differences in the ranges of Th contents additionally imply that the Nguu Hills and Kiboko lavas are derived from a relatively narrow range with larger degree of melting compared to most of the Ngulai Hills samples. The relatively low K/Th values suggest that amphibole is likely to be more influent than phlogophite in producing the lavas in the study area. Additionally, partial melting processes of spinel and garnet lherzolite, of which bulk partition coefficients for K and Th are generally similar, without a K-bearing phase are experimentally unable to generate the relative depletion in K observed in the mafic lavas (Späth *et al.*, 2001; Furman, 2007). Moreover, high chondrite-normallized Tb/Yb values of mafic lavas from the CHPV (2.7-5.6) are likely attributed to melting of an enriched source region rather than a garnet-bearing source (Späth *et al.*, 2001). These ranges of Tb/Yb_n values are also higher than those reported in other volcanic provinces (Furman, 2007)

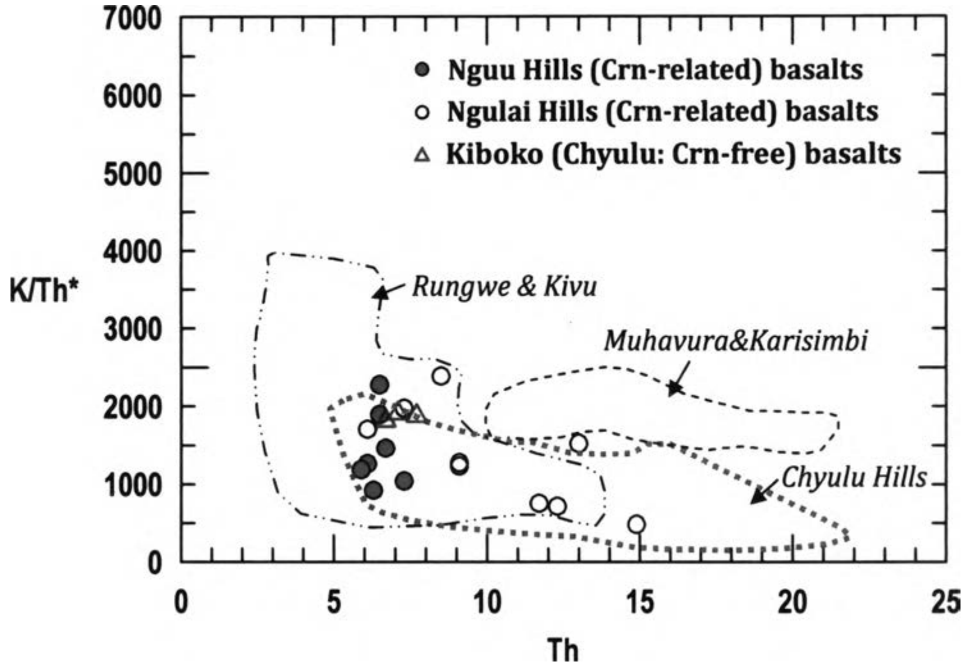

Figure 5.1 Covariation plot of K/Th* (= K_2O*10,000/Th) versus Th (ppm) for the basaltic rocks from the Nguu Hills, Ngulai Hills, and Kiboko (Chyulu) lavas in comparison with the published data ranges from the Chyulu Hills and the Western Rift of Rungwe and Muhavura volcanic provinces. Dotted and dashed borders are from Furman (2007).

According to isotropic characteristics, based on data compilation on available published works (e.g. Davies and MacDonald, 1987; Class *et al.*, 1994; Furman 1995, 2007; Black *et al.*, 1998; le Roex *et al.*, 2001; MacDonald *et al.*, 2001; Späth *et al.*, 2001; and references here in), a defined negative correlation between $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ (Figure 5.2) of East African Rift mafic lavas reflect mixing of melts from lithospheric and sub-lithospheric sources, with or without direct contributions from a mantle plume (Furman 2007). The Sr-Nd isotopic compositions from Eastern Kenya Rift lavas fall within a triangle region defined by three isotopic end members including DMM (the shallow convective asthenosphere which is the source region for depleted mid-oceanic ridge basalts), HIMU (a reservoir with a high time-integrated U/Pb ratio) and BSE (the bulk silicate earth). The values from the off-rift Chyulu Hills lavas overlap the higher radiogenic part of the northern section of the Eastern Kenya Rift lavas (NKR) while those from the within-rift volcanoes of the southern section (SKR) overlap part of the Kivu volcanic region of the Western Kenya Rift, which are slightly away from HIMU and more towards BSE. The $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ values from the Chyulu Hills region range from 0.51276-0.51284 and 0.70330-0.70359 for northern Chyulu Hills lavas, and 0.51278-0.51280 and 0.70355-0.70372 for southern lavas, excluding transitional basalts of Mzima-type (Späth *et al.*, 2001). Among these, two samples from the Nguu Hills lavas yield the values from 0.51279-0.51281 and 0.70352-0.70359 (Späth *et al.*, 2001). The Sr-Nd isotopic values obtained from these primitive lavas form a moderately tight cluster in the depleted quadrant of the isotope correlation diagram. This is an indicative of deriviation from a common source with time-integrated depletion in incompatible trace elements (Späth *et al.*, 2001). The low Sr-isotope values and the existence of these compositions in oceanic island basalts worldwide (~0.512312-0.513095 and ~0.702720-0.70651 (Rollingson, 1993)) suggest a sublithospheric source (Furman, 2007) since the low Sr-isotope values are not an usual composition for the lithospheric domain. This implies that the basalts exposed in the vicinity of the study areas: Nguu Hills, Ngulai Hills and Kiboko, bear a generatic signature of sublithospheric source domained as well.

The Pb isotopic signatures of Eastern Kenya Rift lavas define source domains which are corresponding to those inferred from the Sr-Nd isotopic evidence. They show that southern Kenya Rift lavas bear the Pb isotopic compositions overlapping the values of northern Kenya Rift lavas which extend from low radiogenic values of the Ajar plume towards more highly radiogenic values approaching the HIMU lavas of St. Helena (Hanan *et al.*, 1986 and Chaffey *et al.*, 1989 *cited in* Furman, 2007) (Figure

5.3). The Pb isopic, $^{208}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$, values from the Chyulu Hills region range from 19.743-20.003, 15.589-15.643 and 39.592-39.916 for northern Chyulu Hills lavas, and 19.288-19.353, 15.585-15.613 and 39.168-39.354 for southern lavas, excluding transitional basalts of Mzima-type (Späth *et al.*, 2001). Among these, a sample from the Nguu Hills lavas provides the Pb radiogenic values of 19.829, 15.607 and 39.719 (Späth *et al.*, 2001). These values also fall within the compositional ranges of oceanic island basalts, which are 17.54-21.69, 15.44-15.84 and 37.69-40.69 (Rollingson, 1993). The southern Chyulu Hills basanites, akali basalts and hawaiites have, however, lower $^{208}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ ratios than the northern units. These ratios ranges overlap those of northern Kenya Rift and approach those of high-μ oceanic island basalts.

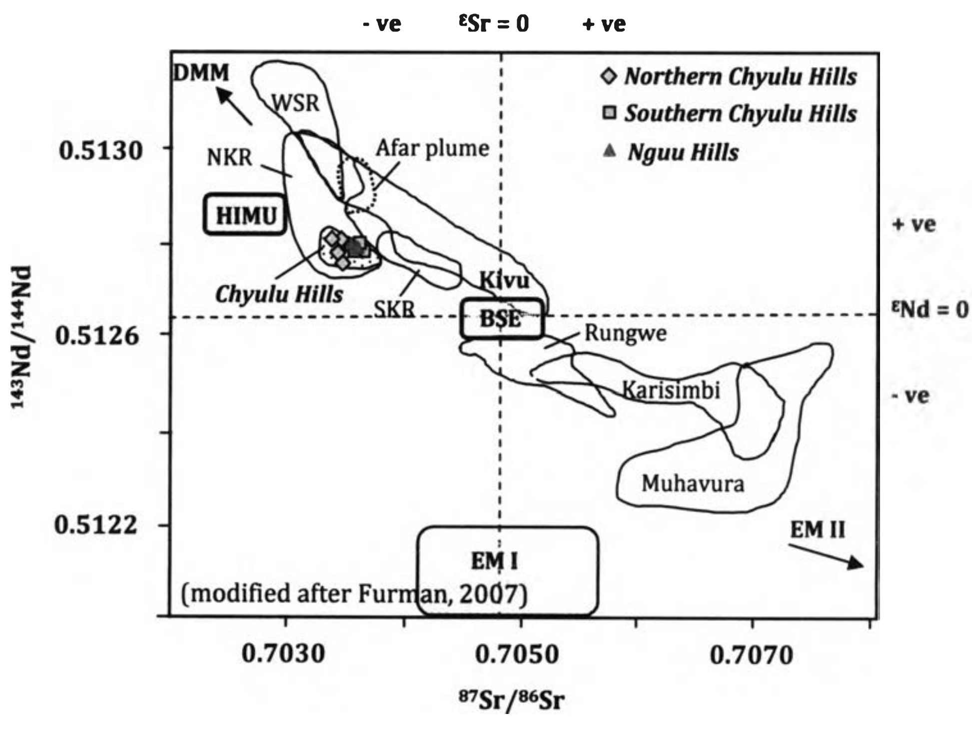

Figure 5.2 Covariation plot of $^{143}Nd/^{144}Nd$ vs. $^{87}Sr/^{86}Sr$ displaying a broad negative trend from less radiogenic values in northern section of the Eastern Kenya Rift (NRK) towards higher radiogenic compositions observed in the Western Kenya Rift of the Kivu, Rungwe, Karisimbi and Muhavura volcanic regions. The values from the Chyulu Hills are within the lower part of the NKR approaching towards the field of HIMU. Point data for Chyulu Hills and Nguu Hills lavas are from Späth *et al.* (2001).

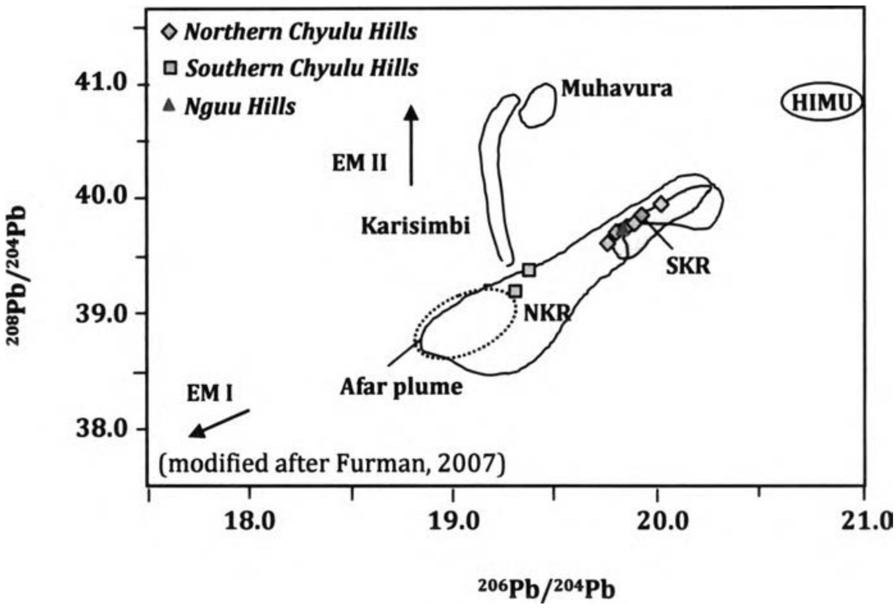

Figure 5.3 Covariation plot of $^{208}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ displaying a broad positive trend for northern Kenya Rift lavas (NKR) and southern Kenya Rift, both off-rift (Chyulu Hills) and within-rift (SKR), towards HIMU. Point data for Chyulu Hills and Nguu Hills lavas are from Spåth *et al.* (2001).

In conclusion, the basaltic lavas of the study area exhibit a pronounce K-depletion pattern and other chemical characteristics corresponding to those observed from other primitive lavas of the Chyulu Hills Volcanic Province, which all bear similar isotope signatures of low Sr-Nd and Pb isotope ratios. These can be inferred that the mafic lavas from the study area are also derived from an amphibole-bearing spinel lherzolite source domain and the underlie lithospheric mantle has been affected by an enrichment process.

5.1.2 Melting models

In terms of melting models, Spåth *et al.* (2001) reconstruct REE compositions via a series of model melts using a theoretical source composition calculated from a foidrite sample, AS-101, which have REE compositions equivalent to samples *KKMb02* and *KKYd 03* of the Ngulai Hills lavas. An equilibrium batch melting model of a common spinel lherzolite source containing 5% amphibole modal contents can generate model REE patterns that correspond to the observed patterns of various lavas distributed within the CHVP, including the low-Ti nephelinite-basanite and basanite-alkali basalt subgroups of the Sultan Hamud-Emali-Simba lavas (SES: *Plb1*), the Ngatatema lavas (*Plb2*) and the southern Chyulu Hills basanites, a alkali basalts and hawaiite (*Rvb*) (Späth *et al.*, 2001) (Figures 5.4a-d). In addition, small amount garnet phase (1% modal) can be added into the source composition to produce REE patterns resembling to those of the high-T nephelinite group of the SES lavas which have distinctive REE patterns with steeper slopes in the MREE to HREE than those of the other CHPV lavas. Both fractional melting and continuous melting with a low residual source porosity of garnet-bearing as well as garnet-free lherzolitic sources cannot produce a series of melts with REE patterns comparable with those of CHVP lavas (Späth *et al.*, 2001).

In terms of degree of melting, the melting ranges of about 2-6% from the equilibrium batch melting model are able to cover the abundance ranges observed for both the LREE and the HREE of the studied samples. The REE patterns of the Nguu Hills and the Kiboko lavas are consistent with a narrow range of partial melting degrees of about 4-6% whereas those of the Ngulai Hills lavas are derived from a wider range of about 2-6%. These results correspond well to those implied by the range of Th contents observed.

5.1.3 Mechanism related to magmatism

In the aspects of mechanism driving melting processes associated the Kenya Rift System, particularly in the off-rift region, a plume-driven (active) mechanism (e.g. Karson and Curtis, 1989; Latin et al., 1993; Burke, 1996) has been debated against a plate-driven (passive) mechanism linked to tectonic and pre-existing structural controls (e.g. Bosworth 1987, 1989). The synthesis of these two mechanisms has recently been gained a favor to explain the volcanic activities beneath the CHVP, which involves the exploitation of pre-existing zones of lithospheric weakness by small diapirs of plume material derived from a larger plume appeared below the rift axis or the Tanzania Craton (e.g. Smith, 1994; Mechie *et al.*, 1997; Ritter and Kaspar, 1997). In addition, geophysical surveys have indicated the presence of a low seismic velocity anomaly, which was been interpreted as a partially molten body, located in the lithospheric mantle beneath the CHVP (e.g. Ritter *et al.*, 1995; Ritter and Kaspar, 1997; Novak *et al.*, 1997). However, due to the small size of this body together with the absence of a connection to the asthenosphere, it is unlikely originated as a direct melting of a rising mantle plume (Ritter *et al.*, 1995; Ritter and Kaspar, 1997).

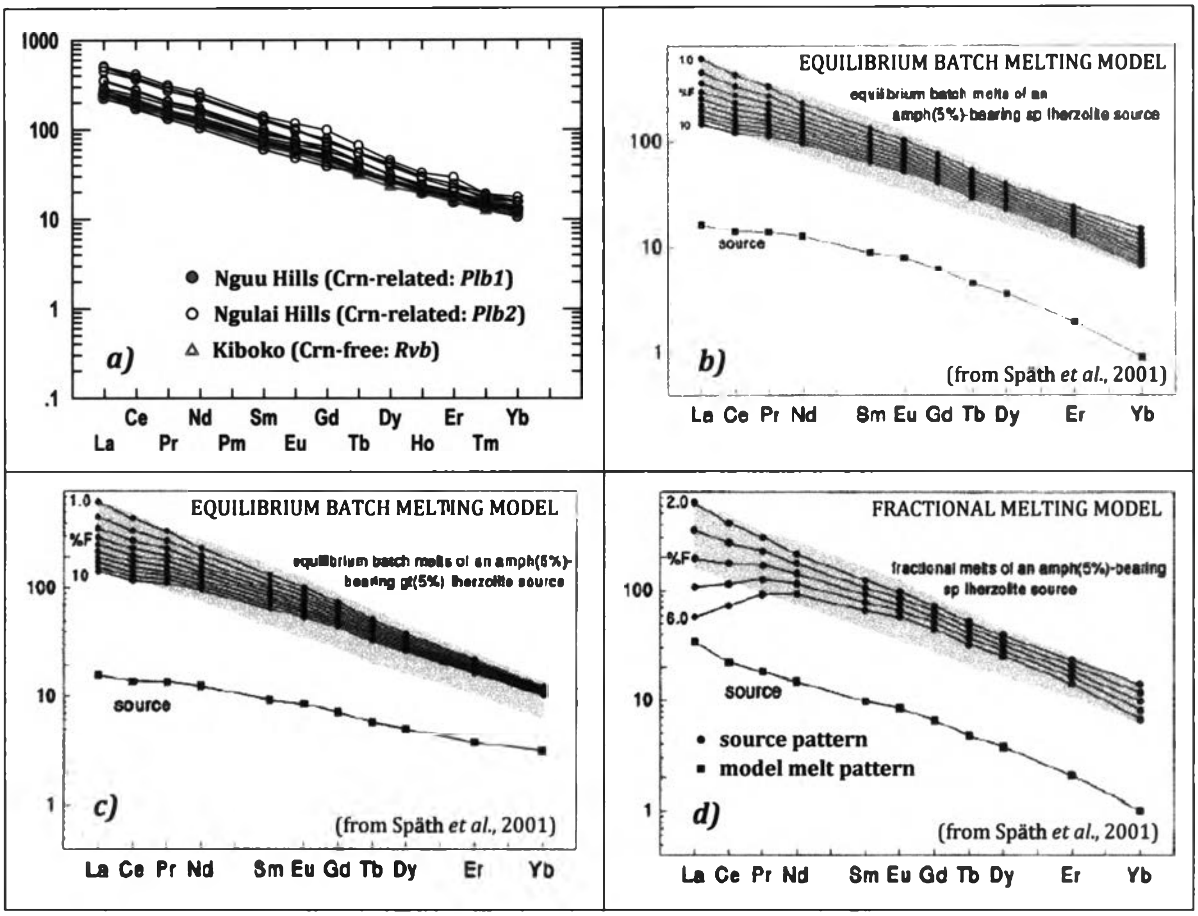

Figure 5.4 Showing Chondrite-normalized REE patterns for *a*) the cogenetic lavas from the Nguu Hills, Ngulai Hills, and Kiboka areas. *b*) equilibrium batch melts of an amphibole-bearing spinel lherzolite source. *c*) equilibrium batch melts of an amphibole-garnet-bearing spinel lherzolite source. *d*) fractional melts of an amphibole-bearing spinel lherzolite source. Normalizing values from Sun and McDonough (1989).

P-T estimations based on clinopyroxene-melt yield a high temperature but slightly low pressure in ranges of 1,200-1,450°C and 7-28 kb for both subterranes

(Figure 5.5). In addition, the olivine-melt thermometer gives slightly higher temperature range of about 1,300-1,500°C at equivalent given pressure up to 30 kb implying that the inferred depth of melting of the studied basalts is about 90 km. These results are consistent with the greatest melting pressures (>25-30 kbar) estimated for lavas from Chyulu Hills and Ol Esayeiti in southern Kenya on the basis of major and trace element data (Furman, 2007).

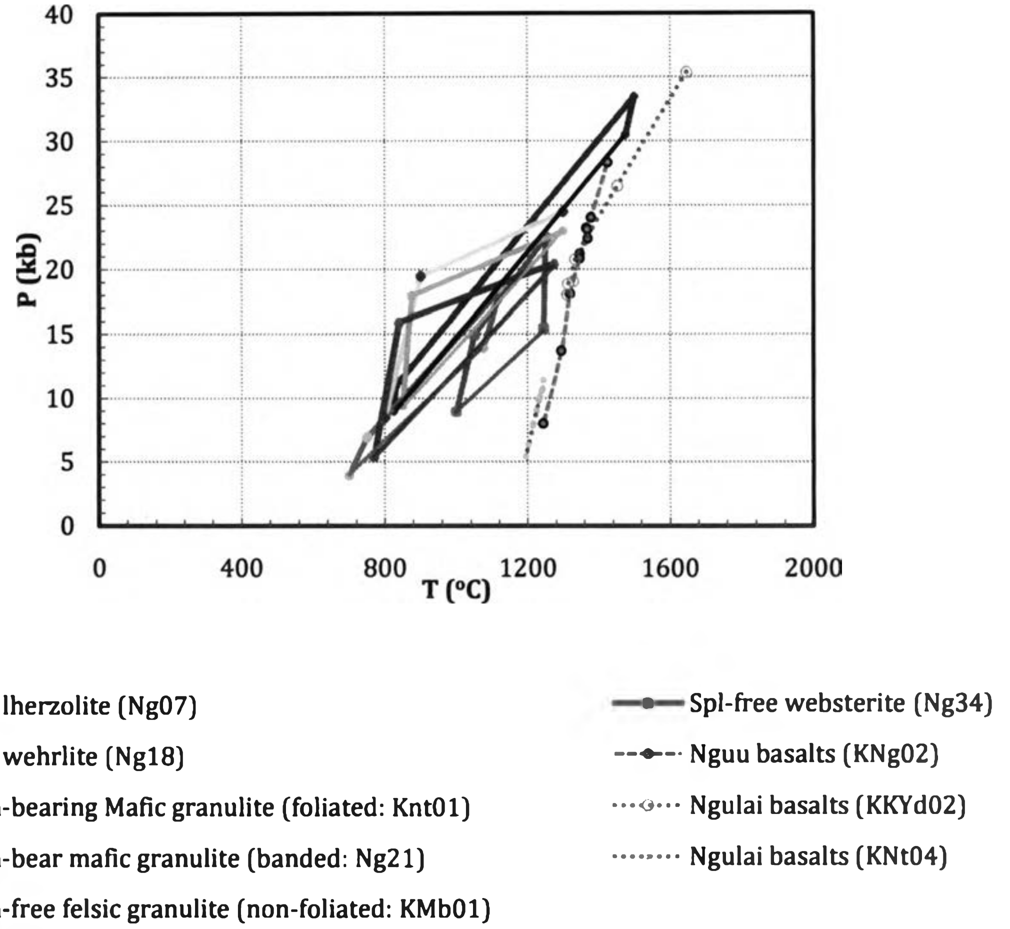

Figure 5.5 P-T constraint diagrams of the xenoliths compared to the host basalts.

On the basis of experimental work by Tsuruta and Takahashi (1998), primary melt of alkali basalt should occur at 60-70 kb (or depths of 200-230 km) during diabatic mantle upwelling, with a wide range of potential mantle temperatures exceeding 1,200°C. However, at shallower melting depth, the presence of garnet or phlogophite in the source region is required and experimental stability estimates for phlogophite-bearing assemblages suggest their stable pressure range is closed to 30-35 kbar (or depths of about 90-100 km) (e.g. Olafsson and Eggler, 1983 and Sato *et al.*, 1997 cited in Furman, 2007).

The high temperature range of the studied basalts obtained from the thermobarometer estimations, therefore, suggests that an elevated thermal influx has been induced underneath the area. A plausible explanation for a relatively low pressure range of partial melting observed could be involved the presence a hydrous K-bearing assemblage, e.g. phlogophite and/or amphibole, with or without garnet, in the source region as supported by chemical data.

5.2 Petrogenesis of Xenoliths

In the study area, several types of xenoliths derived from different parts of the Earth interior have been brought up to the surface via basaltic eruptions These xenoliths include ultramafics of various peridotite and pyroxenite varieties, exotic mafic granulite of both corundum-bearing and corundum-free types, and shallow level metamorphic complex basement of garnet-biotite gneiss, garnet-bearing granitiod and amphibolite. However, only deep-seated ultramafic and exotic granulite xenoliths have been focused in this study. Three main groups of these selected xenoliths, e.g. peridotite, pyroxenite, and granulites have been both petrographically and petrochemically investigated. The corundum-bearing granulite xenoliths have been more emphasized in this study because they can provide information on related gem ruby formation in addition to the characteristics of the predominant rock layers of the deep part underneath this area.

Peridotite xenoliths are represented by only two samples, spinel lherzolite and spinel wehrlite, in this study due to their scarcity and most of available specimens have been subjected to weathering. The chemical compositions of these xenoliths, e.g. corundum normative, accentuated Ba and Sr patterns, and Eu positive anormaly, suggest they were derived from mafic cumulates which had been dragged into a mantle zone and transformed into ultramafic assemblages rather than directly derived from primitive mantle.

Pyroxenite xenoliths are characterized by lack of olivine. Plagioclase may present in minor amount. The chemical compositions suggest that these xenoliths, particularly those of spinel-bearing websterites, are also cumulates and some are likely fragmented from a pyroxene-rich layer of composite banded mafic granulites.

Granulite xenoliths are emphasized in this study because they are more abundant than the other types of xenoliths observed in both the Nguu Hills and the Ngulai Hills areas. The corundum-bearing mafic granulite is the most common type of granulite xenoliths observed; however, corundum-free mafic and felsic types are also present in much lesser amounts. The chemical compositions, with good correlations between MgO and other oxides including some trace elements of the granulite xenoliths suggest that they are a suite of meta-igneous rocks, considered as a sequence of magmatic fractionation. However, they are not derived from the same source of the host magmas. The overall high whole-rock Mg#s (0.73 to 0.84) and low to very low concentrations of most incompatible trace elements including REE suggest that not only ultramafic xenoliths but also the granulites represent cumulates of a mafic magma source rather than residua melts (Ulianov *et al.*, 2006). Ba and Sr spikes on mantle-normalized patterns and positive Eu anomalies are consistent with nature of the specimens observed. These accentuated patterns suggest massive fractional crystallization of plagioclase (Bindeman *et al.*, 1998). Extreme fractionation of Eu in corundum-barren and some corundum-bearing granulite as well as in spinel lherzolite points to subsolidus crystallization via metamorphic reactions involving plagioclase which in good agreement with petrographic observation. The characteristic of these REE pattern is also corresponding to that of the granulite xenoliths from the Chyulu Hills (see Ulianov *et al.*, 2006). In contrast, smooth and rather flat with gentle HREE-enriched trends of the spl-crn-free websterite and the spl wehrlite xenoliths reflect a normal pyroxene accumulation without the influence of plagioclase fractionation.

On the basis of immobility of Ti and V, which are not easily removed from rocks by either hydrothermal alteration or metamorphism at intermediate to high grades, the Ti-V plot can be used to distinguish between volcanic-arc tholeites, MORB and alkali basalts (Shervais, 1982). The plot shows that the majority of the studied xenoliths fall on or near Ti/V=10 line which suggests island arc tholeite type (Figure 5.2). This result corresponds to that for xenoliths studied elsewhere in the Chyulu Hills region as suggested by Ulianov *et al* (2006) to be related to arc magmatism, intraplate tholeite, or MORB. This is also partly supported by the REE patterns observed. Most arc cumulates are characterized by fairly low REE contents and by low to moderate fractionation of LREE over HREE (e.g. Himmelburg and Loney 1995; Cesare *et al.,* 2002; Spandler *et al.,* 2003; Claeson and Meurer, 2004). The tholeiitic cumulates related to MORB or continent intraplate magmatism may also have low concentration levels of most incompatible elements resembling to arc acumulates, but the characteristic of flat REE patterns or depletion in LREE is dominated (e.g. Kornprobst *et al.,* 1990; Benoit *et al.,* 1996; Morishita *et al.,* 2003). The studied xenoliths of spinel lherzolite, corundum-barren felsic granulite and some corundum-bearing granulites bear the characteristic comparable to those xenoliths from arc setting, whereas the most of the corundum-bearing mafic granulites, all the pyroxenites and the spinel wehrlite bear the characteristic closed to the xenoliths from MORB /intraplate setting. The LREE enrichment in some corundum-bearing xenoliths seem to involve late-stage overprints (Ulianov et al., 2006) as supported by an extensive kelyphitization observed in those specimens.

Therefore, the gabbroic protoliths of the corundum-bearing xenoliths may be derived from both arc and MORB/intraplate parental sources, which were incidentally adjoined underneath this region since the time of the Pan-African Orogeny and together underwent through granulitic transformation at different levels of depths for each group of the xenoliths, according to their attained equilibrium temperatures, prior be taken to the surface by basaltic magma.

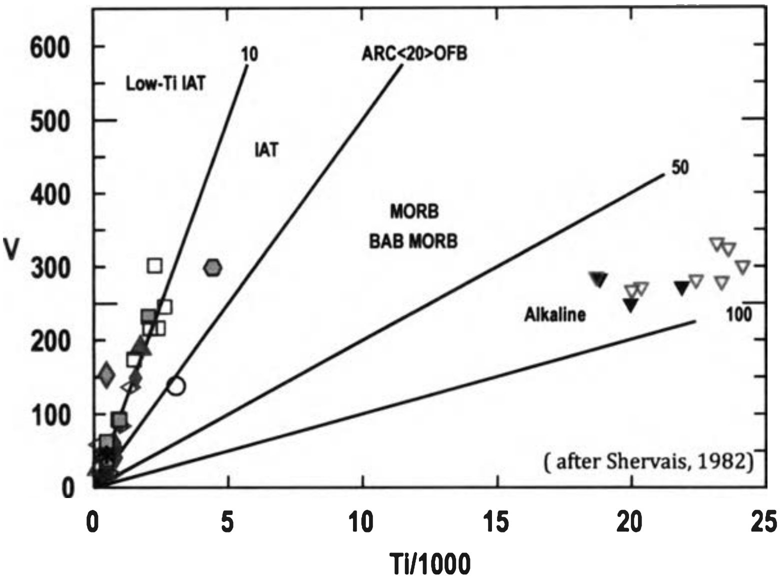

Figure 5.6 The Ti-V discrimination diagram for the xenoliths and their host basalts from the Nguu Hills and Ngulai Hills areas. IAT is standed for island arc tholeite and BAB is back arc basin. Lines represent Ti/V ratio.

5.3 Genesis Model of Ruby-bearing Xenoliths

Unlike other basalt-relted corundum deposits, actual corundum(ruby)-bearing source rocks can be easily seen around the Nguu Hills and the Ngulai Hills areas. Petrographic features, chemical properties as well as Ar-Ar ages of the host basalts, 0.9-2 Ma, all imply that the magma generating process is not related to ruby formation in the graulite xenoliths found in the areas. Without doubt, corundum has been formed under a regional metamorphic condition of granulite facies within a deep-seated mafic granulite formation and genetically unrelated to the host basalts.

Geochemical characteristics of the corundum-bearing mafic granulites have been metamorphosed from lithospheric mafic igneous protoliths equivalent to a gabbroic and anothositic suite originated both island arc and MORB/intraplate settings. The metamorphism have been occurred by plate collision event taken place during the Mozambique Belt Orogeny around 500-800 Ma. The plausible metamorphic reactions creating gem corundum are:

Pl + Spl = 2Crn + Di-cpx ----- (1)

3Pl + 3Spl = 4Crn + Pyrope + Grossular ----- (2)

The corundum-bearing formations and associated ultramafic statra were achieved their closure equilibria P-T constraints under a range of lower crust-upper mantle condition, in the range of 750-1500°C and 7-33.5 kb (~23-110 km). The peridotites were formed at deepest depth in the upper mantle region. The corundum-bearing granulites were also created within the upper mantle, but at a shallower level closer to the Moho. The pyroxenite (e.g. spinel-free websterite) xenoliths were formed near the Moho zone, whereas the corundum-free granulite xenolith was formed at shallowest level above the Moho.

A schematic model linking the paragenesis of ruby-bearing xenoliths and other associated types with basaltic activity is presented in Figure 5.7.

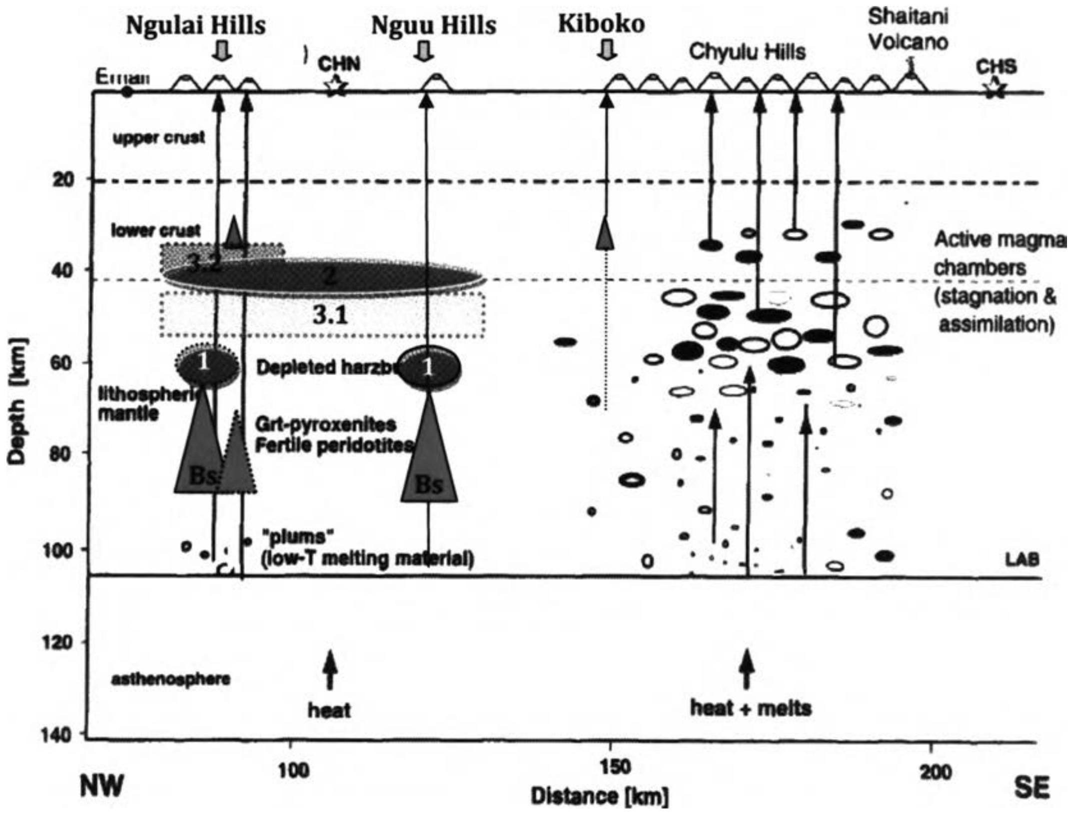

Figure 5.7 Cartoon summarizing the major features of deep structure underneath the study area and the Chyulu Volcanic Province (modified after Novak et al., 1997). Filled numbered ellipses represent ultramafic layers where 1 is peridotite and 2 is pyroxenite (plagioclase-free websterite). Filled numbered rectangles represent granulite layers where 3.1 is corundum-bearing mafic granulite and 3.2 is corundum-free felsic granulite. Filled triangles are basalt bodies.

5.4 Recommendations

Further work on the xenoliths and the host basalts should include the following:

1) More sampling of xenoliths should be carried out to look for other lithologies. With respect to obtain a full spectrum of deep-seated formations related to corundum as well as lithosheric signatures underneath the study area, more attention should be paid to mafic granulite xenoliths with less intense of reaction textures, fesic variety of garnulite xenoliths and peridotite xenoliths, especially amphibole- and phlogophite-bearing varieties. Analyses of alluvial corundum and some associated minerals, e.g. kyanite should be taken into account for futher interpretation.

2) EPMA should be set up for REE and trace element analyses of mineral assemblages in xenoliths and xenocrysts, particularly clinopyroxene, orthopyroxene, garnet, olivine, spinel, etc should be performed and compared with whole-rock analyses of xenoliths. These may lead to more detail interpretation of petrological processes, such as partial melting, fractionation, metasomatism and lithospheric contamination.

3) Isotopic studies of xenoliths should give more information on their petrogenesis. Radiogenic isotope, e.g. U/Pb, Rb/Sr and Sm/Nd, may yield both formation and metamorphic ages in addition to information on the metamorphic processes that affected the xenoliths.

4) P-T estimation should be done more on corundum-free xenoliths and basalts to compare to the corundum-related one to confirm the equivalent depths where both corundum-bearing and corundum-free formations located as well as to confirm the P-T conditions where the basalts originated.

5) Profiling analyses on olivine xenocrysts should be adopted to provide more insight on the aspect of a protential geospeedometer for the host basalts.

6) Together with detailed mapping on the exposure of basalt flows in the study area, Ar-Ar dating need to be carried out on more basaltic samples to ensure the preliminary age data obtained from this study and to fill in the gap on timing of

volcanism developed around the area in order to be linked with the East African Rifting evolution,