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Isotopic and trace element evidence from lavas, bearing on mantle heterogeneity beneath Kenya

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Nd, Sr and Pb isotope data, together with new major and trace element data are presented for lavas from northern Kenya. A general trend towards silica saturation and decreasing incompatible element contents is observed from the Miocene to the present day. Significantly, the abundances of different incompatible elements decrease at different rates.

The Nd, Sr and Pb isotope compositions of the basic lavas are similar to those observed on the Atlantic ocean islands. Comparison of the Sm/Nd ratios required to produce the Nd isotope ratios with those observed in the rocks indicates that light rare earth elements (r.e.e.) have probably been added to the source region of the lavas comparatively recently. A model involving recent metasomatism of the subcontinental mantle beneath Kenya, which could account for the correlated silica undersaturation and incompatible element content of the lavas, is proposed.

The Kenya, or Gregory, Rift is part of the rift system of Eastern Africa extending from Ethiopia to Mozambique (King 1970). At its northern end, in Afar, the East African rift system joins the worldwide oceanic rift system, and it is this fact that has focused attention upon the East African rifts as possibly representing the site of active continental break-up. However, geological data (Baker & Wohlenberg 1971; King 1978) indicate that only about 10 km of dilation has occurred since the Miocene. Consequently, the observer is left with the impression that if this is indeed a continent caught in the act of break-up, then it is experiencing considerable difficulty in the process.

Various explanations for the limited crustal extension have been proposed. Many hinge upon uplift and consequent cracking and stretching of the crust. Such uplift is presumably a result of conditions within the underlying mantle and the lavas that have been erupted during the process may provide a means of investigating some aspects of mantle activity and chemistry before the time of volcanism. To further this end we have investigated the chemical variation of a large number of basic lavas ranging in age from Miocene to Recent from the rift between Lakes Barringo and Turkana in the northern half of Kenya (figure 1). In addition, the volcano of Kisingiri to the west of the rift and the Huri Hills to the east of the rift have also been investigated, but in less detail.

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PETROGRAPHY AND MAJOR ELEMENT CHEMISTRY

The basic lavas erupted in the northern part of the Kenya rift during the Miocene are alkaline basalts and basanites together with subordinate nephelinites. In addition, large amounts of phonolite were also extruded. Pliocene volcanism was characterized by the occurrence of less undersaturated lavas, with the level of silica undersaturation decreasing into the Pleistocene. More undersaturated melts occur toward the base of the Pliocene lava sequence, although nephelenites are not recorded. Petrographically these lavas have olivine followed by diopside or an aluminous augite as liquidus phases. Quaternary lavas are of a transitional nature in their level of silica saturation and display plagioclase following olivine as liquidus phases. Volcanism in the Quaternary was confined to a series of large bimodal basalt–trachyte volcanoes with a distinct lack of intermediate lavas. In summary, the level of silica saturation of lavas erupted within the northern part of the Kenya Rift rose steadily from the Miocene to the present (Lippard & Truckle 1978). However, as noted by these authors, the lavas erupted outside the rift, and particularly to the west, are more undersaturated than those within the rift at any single point in time. In fact volcanism in western Kenya and eastern Uganda was confined at all times to the production of nephelinitic magmas and their derivatives (M. J. Le Bas, personal communication). The volcano of Kisingiri in western Kenya, which has also been sampled in this study, erupted large quantities of olivine- and clinopyroxene-phyric nephelinites largely in the Miocene and bears witness to the above observation. The lava fields of the Huri Hills are located to the east of Lake Turkana and two Pleistocene lavas from this region have been included in the present study. As with the majority of Kenya lavas, these lavas have olivine and clinopyroxene phenocrysts.

TABLE 1. AVERAGE ANALYSES OF BASIC ROCKS ($MgO > 5\%$) FROM N KENYA RIFT

	Miocene ($n = 21$)	Pliocene ($n = 32$)	Pleistocene ($n = 12$)	Quaternary ($n = 10$)
	major elements (percentages)			
SiO_2	43.84	45.57	46.14	47.24
TiO_2	2.89	2.40	2.37	3.06
Al_2O_3	14.20	15.64	15.96	15.08
Fe_2O_3	13.28	12.57	12.81	13.94
MnO	0.21	0.21	0.19	0.22
MgO	7.28	6.87	7.12	5.65
CaO	10.91	10.37	10.65	10.22
Ma_2O	3.87	3.22	2.97	3.78
K_2O	1.48	1.26	0.78	0.96
P_2O_5	0.57	0.55	0.44	0.71
	trace elements (micrograms per gram)			
Rb	33	27	12	19
Sr	924	834	617	475
Zr	189	138	117	123
Nb	70	46	24	34
Y	27	23	28	35

Major elements determined on fused disks and trace elements on pressed powder pellets using a Philips P.W. 1212 X-ray spectrometer at Bedford College, London. n, Number of analyses.

Mean analyses of lavas with more than 5% MgO from localities within the Kenya rift are given in table 1 grouped according to age. Although each group contains a range of MgO concentrations, the mean values of each group are similar, with the exception of the Quaternary lavas which have slightly lower MgO contents. For lavas precipitating olivine and clinopyroxene, MgO drops sharply with fractionation. Hence the level of fractionation displayed by the Miocene, Pliocene and Pleistocene groups appears to be similar, whereas that of the Quaternary group is slightly greater. Levels of SiO_2 are seen to rise with time while Na_2O falls.

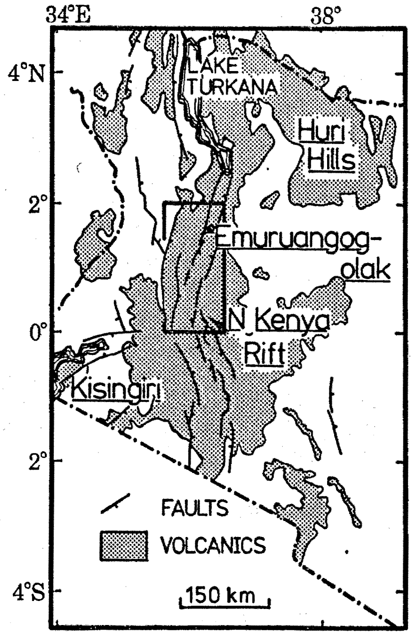

Figure 1. Locality map, showing the distribution of Kenyan lavas.

Continental crustal contamination

Unlike volcanoes from oceanic regions, those located upon continental crust may have their magmas contaminated by material of grossly different trace element and isotopic composition to themselves. Investigation of the source regions of such magmas are hampered by this uncertainty, and before progress can be made the magnitude of effects brought about by contamination must be assessed. Isotopic ratios are potentially one of the most sensitive indicators of crustal contamination. We have therefore chosen one volcano for a detailed isotopic study.

The Quaternary volcano Emuruangogolak is located in the northern part of the rift sector used in the present study (figure 1), and has been described by Weaver (1978). The occurrence of repeated caldera collapse is a feature of this volcano and almost certainly indicates the presence of large near-surface magma chambers. Major and trace element studies carried out by Weaver (1978) show that the trachytes were probably produced by low pressure crystal settling from the basalts, presumably in the magma chambers into which the calderas collapsed. Residence of the magmas within these chambers during fractionation would seem to present a favourable situation in which contamination might occur.

Isotopic data from a selection of rocks chosen to span the life of the volcano are presented in table 2. The Sr isotope ratios of the basalts are largely within analytical error of one another. However, all of the Sr isotope ratios of the trachytes are higher than those of the basalts, a fact that requires either the introduction of a contaminant or derivation from a different source. On the other hand, no consistent difference in Pb or Nd isotopes exists between the basalts and trachytes. Variations of Sr isotope ratios observed in fresh oceanic basalts are almost always accompanied by a sympathetic variation in Nd isotope ratios, a fact that is thought to represent variations in the composition of the magmas' source regions. Hence it would seem very probable that the Sr isotope variation within the Emuruangogolak trachytes is indeed due to contamination by continental crust. The fractionation trend observed within the lavas displays increasing Nd and Pb concentrations accompanied by decreasing Sr (Weaver, unpublished data). Thus, with increasing fractionation, Sr isotope ratios become more susceptible to change by contamination whereas Nd and Pb isotopes become increasingly resistant. This fact may explain the pattern of isotope variations observed.

The homogeneity of Sr isotope ratios within the population of basalts sampled, together with the positioning of the Emuruangogolak basalt analysed for both Sr and Nd isotope ratios within the field previously defined for Iceland (O'Nions *et al.* 1977), suggest that contamination

TABLE 2. STRONTIUM ISOTOPE RATIOS OF KENYAN LAVAS

	^{87}Sr/^{86}Sr			^{87}Sr/^{86}Sr	
		Main Rift			
3/23	0.70365 ± 4	Pliocene basalt	5/81	0.70332 ± 4	Pleistocene basalt
3/33	0.70359 ± 5	Pliocene basalt	5/421	0.70366 ± 5	Miocene basalt
3/153	0.70351 ± 6	Pliocene basalt	10/322	0.70337 ± 5	Pleistocene basalt
5/50	0.70355 ± 4	Pliocene basalt	13/515	0.70449 ± 4	Pleistocene basalt
5/70	0.70340 ± 3	Pleistocene basalt	13/706	0.70373 ± 5	Pleistocene basalt
13/1475E	0.70456 ± 4	Pleistocene basalt	10/749	0.70376 ± 4	Miocene basalt
11/100	0.70333 ± 3	Miocene basalt	1/609E	0.70402 ± 5	Miocene basalt
14/65	0.70476 ± 4	Pliocene basalt	1/567A	0.70359 ± 5	Miocene basalt
14/276	0.70458 ± 5	Pliocene basalt	1/515	0.70378 ± 3	Miocene basalt
		Kisingiri			
U 904	0.70323 ± 5	Miocene nephelinite	N 595	0.70429 ± 4	Miocene nephelinite
U 1143	0.70382 ± 4	Miocene nephelinite	K 93	0.70319 ± 3	Miocene nephelinite
K 61	0.70387 ± 4	Miocene nephelinite	K 91	0.70360 ± 4	Miocene nephelinite
K 2	0.70332 ± 4	Miocene nephelinite	K 38	0.70362 ± 3	Miocene nephelinite
		Huri Hills			
SKTC/A	0.70311 ± 4	Pleistocene basalt	635	0.70366 ± 4	Pleistocene basalt
SKTC/B	0.70310 ± 5	Pleistocene basalt			
		Emuruangogolak			
S 20	0.70342 ± 4	basalt	550	0.70341 ± 5	basalt
S 88b	0.70343 ± 6	basalt	554	0.70372 ± 4	trachyte
S 19	0.70338 ± 6	basalt	572	0.70578 ± 3	trachyte
S 97	0.70342 ± 4	basalt	559	0.70496 ± 5	trachyte
S 5	0.70342 ± 5	basalt	580	0.70535 ± 4	trachyte
G 55	0.70342 ± 5	basalt	563	0.70403 ± 4	trachyte
S 6	0.70341 ± 6	basalt			

Isotope ratios were measured on a VG-Micromass mass spectrometer at Leeds University and quoted relative to an Elmer–Amend standard value of 0.70800. Errors quoted at 2σ level.

of the basalts by continental crust was unimportant. Concentrations of Sr in the Emuruangogolak basalts (300–400 μg/g) are among the lowest in basic rocks sampled in this study. Since concentrations of 1000–2000 μg/g are quite common in the more undersaturated lavas, we would expect that most of the other basic lavas studied would be even more resistant to contamination while passing through the crust.

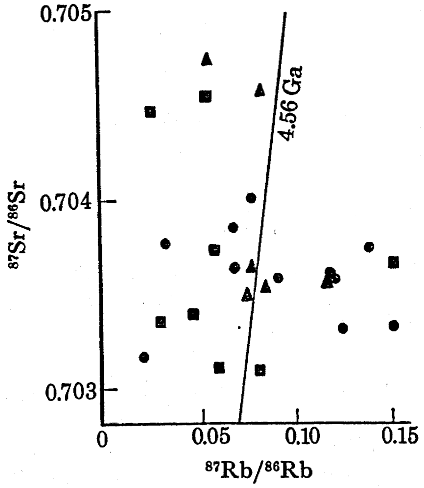

FIGURE 2. $^{87}Sr/^{86}Sr$–$^{87}Rb/^{86}Sr$ plot, with geochron shown. ●, Miocene lavas; ▲, Pliocene lavas; ■, Pleistocene lavas.

ISOTOPE VARIATIONS

If contamination by crustal materials is insignificant, variations in Nd, Sr and Pb isotope ratios give the most direct evidence of heterogeneity within the source of the lavas. With knowledge of the isotope ratios present in the Earth at the time of its formation, the time-integrated parent:daughter elemental ratios that existed in the source regions of analysed lavas, over the age of the Earth, may be calculated for the appropriate decay schemes. These calculated parent:daughter ratios may then be compared with the values actually measured in the rocks.

The Sr isotope results on the basic lavas are presented on an isochron diagram in figure 2. Many of the lavas plot to the left of the geochron and therefore contain insufficient Rb to support their radiogenic Sr. No 'pseudo' or 'erupted' isochron is apparent from the data. Miocene lavas exhibit a large range in Rb/Sr ratios but have many values higher than those in the Pliocene lavas which in turn are higher than those of the Pleistocene lavas. Little systematic variation in $^{87}Sr/^{86}Sr$ is observed between lavas of different ages. To produce the range in $^{87}Sr/^{86}Sr$ values observed in the lavas, Rb/Sr ratios of between 0.024 and 0.017 would have to be present in the lava source regions averaged over the age of the Earth. If a similar diagram is plotted for the Nd isotope data, all of the lavas fall to the left of the geochron and accordingly all lavas must, at some stage in their history, or the history of their source regions, have undergone a decrease in Sm/Nd; or, putting it another way, an increase in light r.e.e. relative to heavy r.e.e. Average Sm/Nd values of between 0.321 and 0.337 would produce the observed $^{143}Nd/^{144}Nd$ ratios during the age of the Earth (table 3).

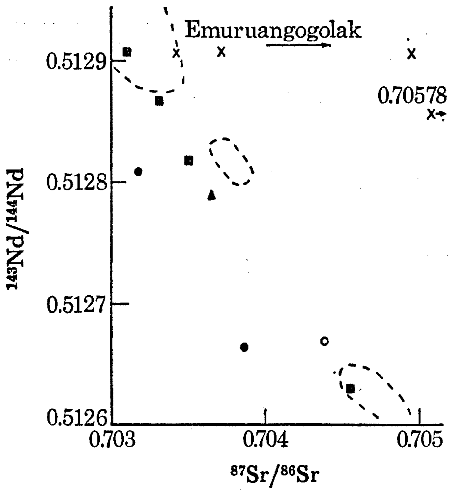

FIGURE 3. ^{87}Sr/^{86}Sr–^{143}Nd/^{144}Nd plot, with fields occupied by Atlantic Ocean Island data (O'Nions *et al.* 1977) outlined. Symbols as for figure 2 apart from recent lavas from Emuruangogolak (×) and Miocene phonolite (o).

TABLE 3. Nd ISOTOPE RATIOS IN KENYAN LAVAS

	^{143}Nd/^{144}Nd	
SKTC/B	0.51291 ± 3	Huri Hills Pleistocene basalt
3/23	0.51279 ± 4	Main Rift Pliocene basalt
3/153	0.51282 ± 3	Main Rift Pleistocene basalt
5/81	0.51287 ± 3	Main Rift Pleistocene basalt
13/1475E	0.51263 ± 3	Main Rift Pleistocene basalt
9/466	0.51267 ± 4	Phonolite Miocene basalt
		$({}^{87}Sr/{}^{86}Sr)_0 = 0.7045$
K 93	0.51281 ± 4	Kisingiri Miocene nephelinite
K 61	0.51267 ± 4	Kisingiri Miocene nephelinite
S 54	0.51291 ± 3	Emuruangogolak trachyte
S 97	0.51291 ± 3	Emuruangogolak basalt
S 72	0.51286 ± 3	Emuruangogolak trachyte
S 59	0.51291 ± 3	Emuruangogolak trachyte

Isotope ratios were measured on VG-Micromass 30 mass spectrometer at Leeds University by a method described by Hawkesworth *et al.* (1979) and quoted relative to a value for BCR-1 of 0.51262. Errors quoted at the 2σ level.

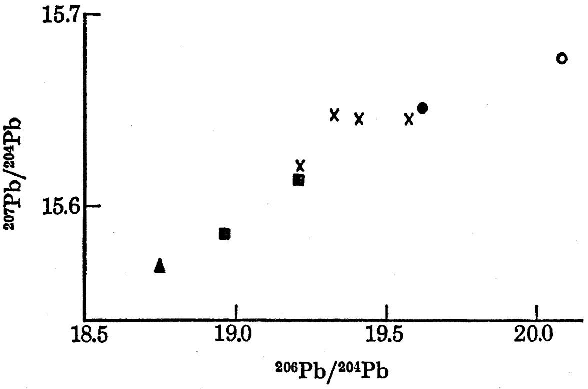

FIGURE 4. ^{207}Pb/^{204}Pb–^{206}Pb/^{294}Pb plot: symbols as for figure 3.

In figure 3, $^{87}Sr/^{86}Sr$ ratios are plotted against $^{143}Nd/^{144}Nd$. All of the basic rocks plot upon a negative trend which approximately overlies the trend previously established for Atlantic Ocean Island lavas (O'Nions *et al.* 1977). In fact the Kenyan data plot slightly to the left of that from the Atlantic, while the two lavas that have been analysed from Kisingiri plot slightly further to the left. One phonolite of Miocene age has also been analysed and, when corrected for the radiogenic decay of Rb over the 12 Ma since it was erupted, plots with the basic rocks. Hence, if this rock is typical, Kenyan phonolites may have been produced from sources similar to those for the basic lavas and have suffered little contamination during fractionation.

Pb isotope results are shown in table 4 and plotted in figure 4; as with the Sr and Nd isotope data, they resemble those from oceanic islands. Again, the phonolite data point falls on the same trend as the basic lavas.

Table 4. Lead isotope ratios of Kenyan lavas

	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	
10/749	19.565	15.653	39.442	Miocene basalt
5/81	19.213	15.614	39.091	Pleistocene basalt
13/1475E	18.962	15.585	38.978	Pleistocene basalt
3/23	18.741	15.568	38.728	Pliocene basalt
9/466	20.097	15.679	39.883	Miocene phonolite
S 97	19.359	15.642	39.385	Emuruangogolak basalt
S 59	19.409	15.647	39.375	Emuruangogolak trachyte
S 54	19.587	15.642	39.443	Emuruangogolak trachyte
S 72	19.209	15.621	39.127	Emuruangogolak trachyte
S 80	19.338	15.648	39.256	Emuruangogolak trachyte

Measured on a VG-Micromass 30 mass spectrometer at Leeds University by the silica gel method. Mass fractionation correction of 0.15% per atomic mass unit. A precision of 0.1% is believed to have been obtained.

Incompatible element variation

Incompatible elements may also provide a means of investigating heterogeneity within the source of basic lavas. However, some fractionation between incompatible elements is to be expected if small degrees of partial melting occur. Thus rather more caution is required in the interpretation of the incompatible elements when applied to source heterogeneity.

Little fractionation between incompatible elements could be achieved by precipitation of the olivine–clinopyroxene–phenocryst assemblage present in the majority of the lavas without reducing the magnesia content of the residual liquid below 5% by mass.

Titanium values may rise less rapidly than those of other incompatible elements owing to the common partitioning of Ti into pyroxenes growing from undersaturated liquids, but the ratios between Rb, K, Nb, Sr, P and Zr are thought to reflect those of the parental magmas. The Quaternary lavas, however, precipitate plagioclase at an early stage and the Sr contents have been lowered as a consequence. These lavas are also more highly fractionated as evidenced by their lower MgO contents (table 1). For these reasons the Quaternary lavas will not be considered in the discussion of this paper. R.e.e. data (figure 5, table 5) show that the Miocene lavas exhibit enrichment of light r.e.e. relative to the younger lavas, as they also do in all other incompatible elements. No depletion in heavy r.e.e. is observed, indicating that garnet was not a residual phase during magma production. Small positive Eu anomalies are also

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observed in several of the lavas. These anomalies are not correlated with the appearance of plagioclase phenocrysts, which may imply that the original liquid had a positive Eu anomaly.

A similar normalized plot (figure 6) has been constructed for other incompatible elements by using the data of Wanke *et al.* (1974) together with isotope constraints. The abundances of the refractory elements Sr, Nb, Zr, and Ti have been adjusted to a value of 1.3 times C1 chondrite abundances to be consistent with the r.e.e. abundances of Nakamura (1974). K and Rb, being volatile elements, are depleted in the Earth relative to chondritic meteorites. An Rb/Sr value of 0.032 for the bulk Earth has been taken from O'Nions *et al.* (1977) and a K/Rb ratio of 350 from Ozima (1975). Chondritic phosphorus values indicate a deficiency of P in mantle-derived products relative to other incompatible elements (Nesbitt & Sun 1976). The presence of phosphide minerals in iron meteorites may indicate that P partitions partly into the Earth's core. A TiO_2/P_2O_5 value of 10 has been chosen as being typical of basic lavas with unenriched incompatible elements (Nesbitt & Sun 1976) and this value is used here.

The resulting list of incompatible element abundances are thought to represent the relative abundances of these elements in unfractionated mantle material, although no such claim can be made for their absolute abundances. The mean incompatible element abundances (table 1)

TABLE 5. RARE-EARTH ELEMENT DATA (micrograms per gram) FOR SELECTED KENYAN LAVAS

	10/749	5/81	SK/635	11/100	13/1475E	11/354	SKTC/B	3/153	3/23	10/322
Ce	88.8	53.5	34.8	147.9	54.8	64.8	51.0	44.5	—	30.1
Nd	42.5	30.2	18.5	62.2	31.1	31.6	26.8	24.9	26.0	24.1
Sm	8.60	6.75	4.40	10.34	5.59	5.91	4.21	5.01	5.85	5.60
Eu	2.63	2.65	1.45	2.84	2.57	1.92	1.98	1.82	1.92	1.93
Gd	7.53	5.47	4.56	—	5.34	—	5.40	5.04	4.90	5.49
Tb	1.03	0.90	0.68	1.60	0.80	0.73	0.80	0.77	0.79	0.95
Tm	—	0.29	0.34	0.21	0.35	—	—	0.36	0.30	0.49
Yb	2.24	1.26	1.97	2.08	1.90	1.77	1.89	1.92	1.94	2.99
Lu	0.32	0.29	0.31	0.16	0.30	0.23	0.27	0.27	0.28	0.50

Measured by instrumental neutron activation analysis at Bedford College, London.

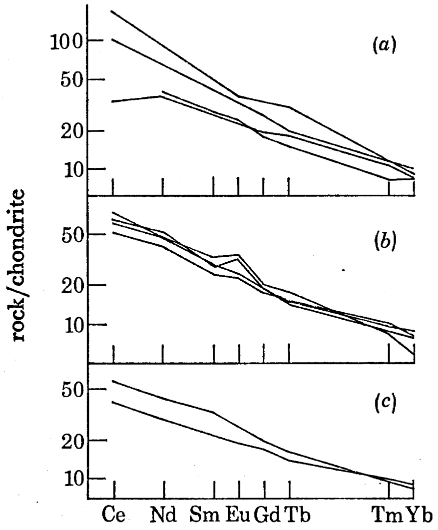

FIGURE 5. Logarithmic chondrite-normalized r.e.e. plot: (*a*) Miocene and Pliocene lavas; (*b*) Pleistocene lavas, Main Rift; (*c*) Pleistocene lavas, Huri Hills.

are plotted in figure 6. Abundances of incompatible elements clearly decrease from the Miocene to the Pleistocene, but each decreases at a different rate. This decrease in incompatible elements through time parallels the increase in silica undersaturation. In the Quaternary lavas, Sr is lower relative to the other incompatible elements, which probably reflects the plagioclase fractionation.

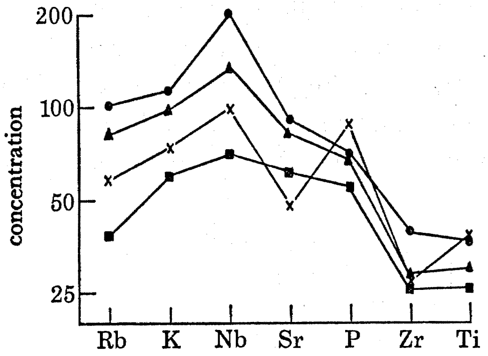

FIGURE 6. Mean incompatible element contents of lava groups from table 1, normalized as described in the text and plotted logarithmically. ●, Miocene; ▲, Pliocene; ■, Pleistocene; ×, Quaternary. Normalizing values: Rb 0.32 µg/g, K_2O 0.15% by mass, Nb 0.34 µg/g, Sr 10 µg/g, P_2O_5 0.08% by mass, Zr 4.76 µg/g, TiO_2 0.8% by mass.

DISCUSSION

The Nd isotope ratios of the Kenyan lavas indicate that they were derived from material that has had light r.e.e. depleted chondrite-normalized patterns for a large part of the Earth's history. Likewise their Sr isotope ratios could only have been produced from a source region characterized by low Rb/Sr ratios. When averaged over the age of the Earth, Sm/Nd and Rb/Sr ratios of between 0.321 and 0.337 and between 0.024 and 0.017 respectively would have produced the range in Nd and Sr isotope ratios of the basic lavas. (As mentioned in a previous section, the higher Sr isotope ratios from the volcano Emuruangogolak are believed to result from contamination by crustal material.) The actual Rb/Sr and Sm/Nd values measured in a selection of Kenyan lavas are plotted in figure 7 and are seen to be clearly different from the values deduced from the isotope ratios. This pattern of Rb/Sr ratios greatly in excess of Sr isotope time-integrated values and Sm/Nd ratios lower than the Nd isotope time-integrated values is frequently observed in both continental and ocean island basic lavas. The most obvious method of producing such a marked increase in Rb/Sr and decrease in Sm/Nd ratios is partial melting. Subsequent fractional crystallization has already been dismissed as a mechanism for inter-incompatible element fractionation in the Kenyan lavas. In this section, an attempt will be made to evaluate the efficiency of equilibrium partial melting for the fractionation of Sm/Nd and Rb/Sr ratios. If, however, this process proves a poor candidate for causing the fractionation we must look to other processes for which there is less direct evidence.

The equation of Shaw (1970) describing equilibrium partial melting has been used together with measured mineral-melt distribution coefficients ($D^{\mathrm{m/liq.}}$) from the literature for two typical mantle assemblages: ol.–opx.–cpx.–gt.–liq., and ol.–opx.–cpx.–liq. The actual modes and sources of data are given in the caption to figure 7. A considerable spread in $D^{\mathrm{cpx./liq.}}_{\mathrm{r.e.e.}}$ values are found in the literature which, when plotted against the clinopyroxene's compositions, are seen to correlate negatively with Mg/Fe. This effect may be due to either temperature or composition. Consequently, lower values of $D^{\mathrm{cpx./liq.}}_{\mathrm{Sm}}$ and $D^{\mathrm{cpx./liq.}}_{\mathrm{Nd}}$ than are normally quoted have been used, corresponding to an Mg/(Mg + Fe) value of *ca.* 0.9, which is appropriate for mantle systems.

Melting curves for the two assemblages have been constructed and displayed in figure 7. As a starting composition, an Rb/Sr – Sm/Nd value related to the Sr and Nd isotope time-integrated values have been used. Figure 7 indicates that the garnet-free assemblage is incapable of creating sufficient fractionation of Sm/Nd. Even with garnet in the residue (a supposition that is not supported by the heavy r.e.e. abundances in the lavas themselves), only the extraction of liquids derived by extremely small amounts of melting can cause the required fractionation in Rb/Sr. Multi-stage processes, such that small proportions of melt are added to a segment of mantle which is in turn melted to a small degree, would be capable of producing the observed fractionation of Rb/Sr and Sm/Nd. However, pairs of elements such as Zr and Nb (with smaller but uncertain D values) would also be required to fractionate. Consequently, partial melting would seem to be an ineffectual method of creating the large fractionation of Sm/Nd and Rb/Sr required in the production of the Kenyan lavas. The fractionation observed between other pairs of incompatible elements would also seem to be unlikely to be caused by equilibrium partial melting.

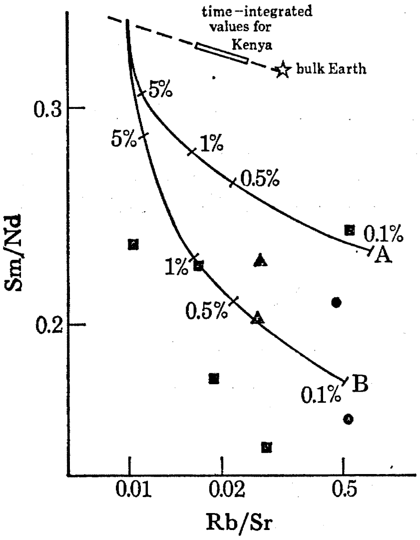

FIGURE 7. Logarithmic Sm/Nd–Rb/Sr plot. Lava symbols as for figure 2. Bulk Earth composition from O'Nions *et al.* (1977). Line A, melting of a source composed of olivine 65 %, orthopyroxene 25 % and clinopyroxene 10 %, with phases entering the melt in the proportions 10 %, 23 % and 67 %, respectively. Line B, melting of a source composed of olivine 50 %, orthopyroxene 25 %, clinopyroxene 10 % and garnet 15 % entering the melt in the proportions 6 %, 20 %, 30 % and 44 % respectively. Distribution coefficients from Schnetzler & Philpotts (1970) and Shimizu (1974). The source composition has been chosen arbitrarily, but as the plot is logarithmic the melting curves are still valid when their source composition is moved. The source composition chosen assumes that the mantle beneath Kenya was depleted within the first half of the Earth's history.

Petrographic descriptions and chemical analyses of ultramafic xenoliths (see, for example, Erlank 1976; Frey & Green 1974) leave little doubt that incompatible elements may be transported by fluid phases within the mantle, ultimately leading to mantle metasomatism. Melting of such metasomatized mantle would lead to lavas grossly enriched in incompatible elements. However, in the current state of our knowledge, little can be said about the fractionation *between* incompatible elements, i.e. which elements would have the greatest partition into the fluid and be transported in largest quantities. In fact, little is known about the composition of the mantle fluids other than that they contain H_2O, CO_2 and incompatible elements. Fluids of differing compositions, for instance differing $CO_2/(CO_2+H_2O)$ ratios, Cl and F contents, etc., equilibrating with mantle material of differing mineralogy and containing various accessory minerals under various P and T conditions may be expected to fractionate incompatible elements in a variety of patterns. While it is easy to voice an expectation that incompatible elements will be fractionated in a variety of patterns under differing circumstances, little is yet known from experiments as to what is possible. It is hoped that the following proposal for the correlated silica undersaturation and incompatible element contents and ratios of the Kenyan lavas will stimulate future experimentation.

The increasingly undersaturated nature of the older Kenyan lavas in the area studied may be due to melting at increasing depth or at higher p_{CO_2}. The heavy r.e.e. of the lavas are not depleted and hence not suggestive of a significant amount of garnet remaining in the residue. Consequently melting probably took place at a comparatively low pressure. Melting under high p_{CO_2} conditions is known to produce highly undersaturated liquids (Eggler 1974). This implication of CO_2 in the Kenyan lavas is supported by the presence of carbonatites, although it must be added that they occur only to the west of the area studied. Recent work at the Carnegie Institution (W. Harrison, personal communication) has shown that CO_2 rich fluids within the mantle may therefore provide a mechanism for effective fractionation of light and heavy rare earths. Addition of an incompatible element enriched CO_2 fluid in various proportions to segments of the sub-Kenya mantle could give rise to the observed correlation between silica undersaturation and incompatible element abundances and ratios. Segments receiving most CO_2 could give rise to the low SiO_2, high incompatible element lavas erupted in the Miocene, while melting of mantle poorer in CO_2, or with a reduced flux of CO_2 into the mantle at the time of melting, could result in the higher SiO_2, lower incompatible element lavas erupted more recently.

The advantage of the CO_2 metasomatism model over the multi-stage low degree of partial melting model is now clearly visible. While the silica undersaturation – incompatible element correlation is readily explainable by CO_2 metasomatism, no such simple cause–effect relation exists for multiple partial melting.

Consideration of the rate at which each incompatible element increases may provide a mean of testing the above hypothesis. Average incompatible element abundances of the Miocene lavas if divided by those of the Pleistocene lavas give an order of enrichment: Nb 2.90, Rb 2.65, K 1.90, Zr 1.60, Sr 1.48, P 1.29 and Ti 1.20. A similar calculation may be carried out for the r.e.e. although our data are not sufficiently comprehensive to justify this. The fluid moving through the mantle must be able to extract and transport Nb much more efficiently than Ti. Thus the partitioning of the elements between the fluid and mantle material must be in the order set out above. Addition of some H_2O, Cl and F may be required to bring this about, although the fluid must remain dominantly composed of CO_2 to produce liquids of low SiO_2 contents upon final melting.

Conclusions

Despite the incompatible element enriched nature of the Kenyan lavas, their Sr, Nd and Pb isotopic compositions are reminiscent of those in lavas from oceanic regions, implying that their source regions have been impoverished in incompatible elements for much of their history. Partial melting would appear to be an ineffective way of creating the recent fractionation required to reconcile the isotope and trace element evidence. Thus a model has been proposed involving the recent metasomatism of the sub-Kenya mantle by variable amounts of a CO_2 and incompatible element-enriched fluid which resulted in the correlation of incompatible element abundance with the degree of silica undersaturation observed in the lavas.

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Discussion

D. K. Bailey (*Department of Geology, University of Reading, U.K.*). In support of the authors' suggestion of enhanced volatile activity and metasomatism through the Kenya Rift segment, I would point out that carbon dioxide is escaping from the ground in many places along the Rift, and that geologists working on the geothermal areas have proposed that the steam is derived from ground waters heated by hot, juvenile CO_2. Does Dr Norry envisage that the light rare earths and other elements had been added to the source just before the onset of melting, or would a longer period of more pervasive metasomatism be required?

M. J. Norry. I thank Professor Bailey for his comments. Although it is difficult to state quantitatively how long ago the metasomatism might have occurred, the high Rb/Sr and low Sm/Nd ratios present in many of the lavas would, if present in the mantle source material, evolve to higher $^{87}Sr/^{86}Sr$ and lower $^{143}Nd/^{144}Nd$ ratios than those of the main oceanic island correlation. Several examples of this type of behaviour are now known (Hawkesworth *et al.* 1979), and as the Kenyan samples still plot upon the Ocean Island correlation it would appear that metasomatism of the sub-Kenya mantle occurred only a short time ago, say less than 100 Ma.

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