



REE mineralization at Gakara, Burundi: Evidence for anomalous upper mantle in the western Rift Valley

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Abstract—The 587 Ma-old hydrothermal bastnaesite mineralization of Gakara in the western branch of the East African Rift in Burundi has geological and chemical features typical of carbonatite-related REE ore deposits, but Nd, Ce, and Sr isotope data on the bastnaesite indicate a time-integrated LREE-enriched source with $\epsilon_{Nd}(T) = -11.9$, $\epsilon_{Ce}(T) = 1.6$, and $^{87}Sr/^{86}Sr \leq 0.7075$. The mid-Proterozoic Nd model age of this source coincides with the formation of the intracratonic Kibaran basin of central Africa and may indicate a mid-Proterozoic rift-related event of small-scale, but locally very effective, mantle metasomatism in this region. The formation of REE ore deposits in carbonatite environments is possibly linked to enriched mantle domains.

INTRODUCTION

THE MUCH LONGER LIFETIME of continental, compared to oceanic, lithosphere allows the preservation of chemical heterogeneities and their development into distinctive isotopic domains which may be tapped by continental volcanic or plutonic rocks of mantle origin. The interpretation of the isotope geochemistry of such rocks as a direct probe into the upper mantle is, however, severely hampered by uncertainties related to possible contamination by crustal material. Contamination can be expected to be of minor importance for elements which are enriched in mantle melt systems compared to the intruded crustal environment. Carbonatites contain the greatest REE contents of any rock type (average ΣREE ca. 2000 ppm) and have the largest LREE/HREE ratio (CULLERS and GRAF, 1984; WOOLLEY and KEMPE, 1989). Therefore, their Nd and Ce isotope systems are less sensitive to interaction with the crustal host environment than those of other mantle-derived rocks. This assumption is even more likely to be valid for such carbonatite systems in which REEs are so highly enriched that they form REE ore deposits. The quantitatively most important REE-bearing mineral phase of both magmatic and hydrothermal origin in such systems is bastnaesite [(LREE)(CO₃)F]. Bastnaesite can, therefore, be used as a petrogenetic tracer for intracontinental subcrustal reservoirs, provided that the commonly accepted assumption of the subcrustal origin of carbonatite magmatism is correct.

This paper is the outgrowth of exploration work on the bastnaesite-monazite ore deposits of Gakara in Burundi (in the literature also known as Karonge REE deposits) which turned out to have Nd isotope patterns highly unusual for carbonatite-related systems. This finding may have general importance as it provides insights concerning the scale of

mantle heterogeneity in rift-related environments, as well as the source rocks of REE-mineralized carbonatite systems.

GEOLOGIC SITUATION

The western Rift Valley in eastern Africa is host to numerous carbonatites and alkaline complexes. These rocks span a broad range in age from Late Proterozoic to Cenozoic (Fig. 1) and indicate repeated episodes of rifting along the same structural trend (TACK et al., 1984; VAN STRAATEN, 1989). The Gakara REE deposits in Burundi are thought to be related to a hidden carbonatite intrusion (THOREAU et al., 1958; VAN WAMBEKE, 1977; MARIANO, 1989a,b). This assumption is based on the tectonic setting of the ore deposits in the Lake Tanganyika rift zone, their mineral assemblage, the strongly alkaline character of the ore system, the lack of relationships to the regional pegmatite magmatism, and the extremely LREE-dominated pattern of the REE mineralization (VAN WAMBEKE, 1977; MARIANO, 1989a,b).

The hydrothermal REE mineralization consists of cm- to dm-thick, irregular veins and stockworks in a 20 × 20 km area near Gakara, 20 km SE of Bujumbura (Fig. 1) and is composed mainly of coarse-grained bastnaesite which is locally brecciated and metasomatically transformed into microcrystalline monazite (LREE-PO₄). Accompanying primary mineral phases are barite, quartz, microcline, biotite, pyrite, molybdenite, and galena. Supergene mineral phases are rhabdophane, crandallite-florencite, cerianite, goethite, and kaolinite (ADERCA and VAN TASSEL, 1971). In comparison with other REE deposits, the mineralization is characterized by the absence of simple carbonates. Potassic alteration haloes (biotite blastesis) are developed in the meta-granitoid wall rocks. Pseudoprimaries fluid inclusions in quartz consist of dense CO₂ and a cogenetic highly saline aqueous

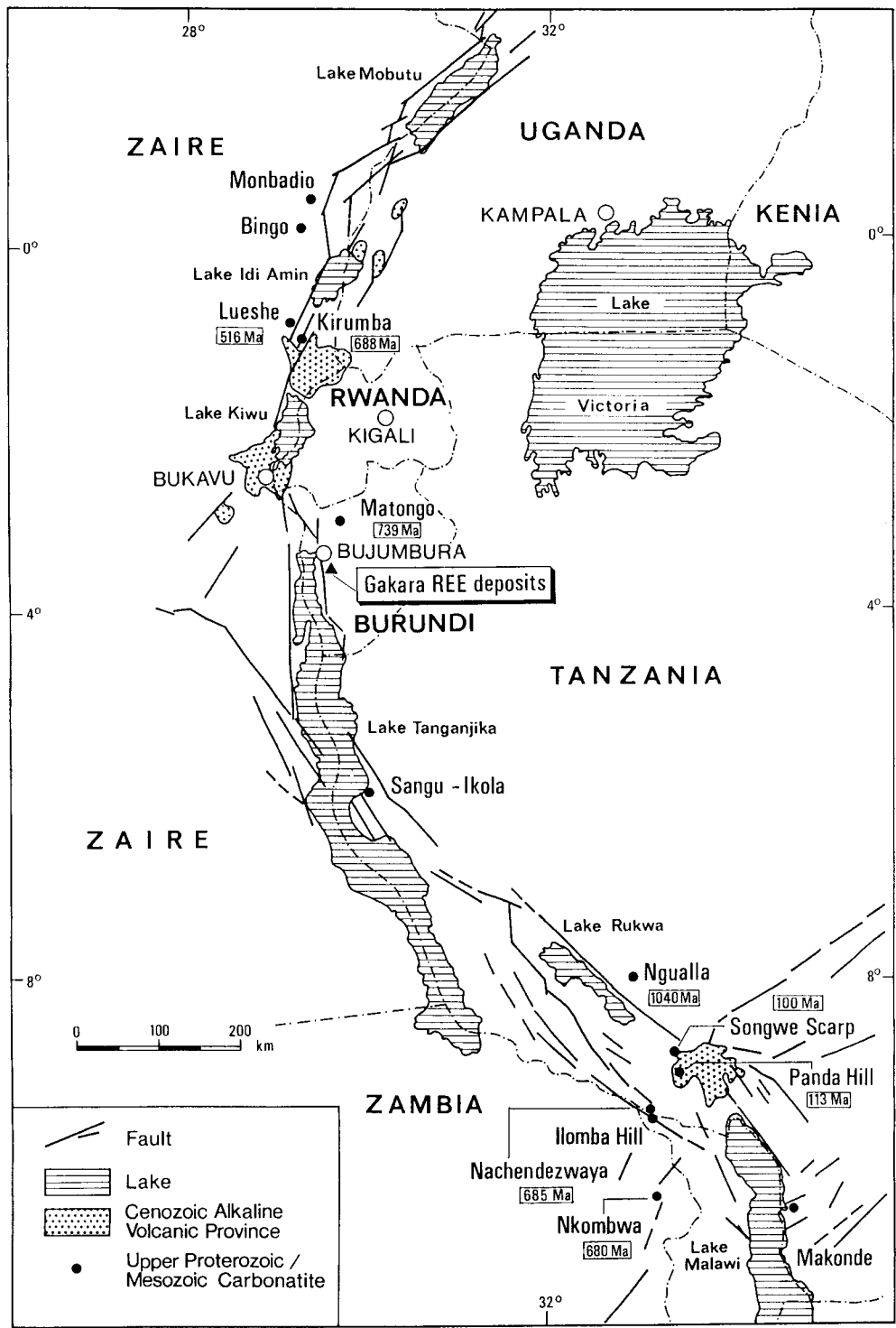


FIG. 1. Location of the Gakara REE deposits in Burundi, and of Proterozoic and Phanerozoic alkaline intrusions with associated carbonatites, and Cenozoic alkaline volcanic fields in part of the western branch of the East African rift system (TACK et al., 1984; VAN STRAATEN, 1989).

fluid phase with daughter crystals of NaCl, KCl, K₂SO₄ (arcanite), and homogenization temperatures of $\geq 420^{\circ}\text{C}$. The bastnaesite has yielded a high-precision La-Ba isochron age of $587 \pm 4 \text{ Ma}$ (NAKAI et al., 1988).

The mineralization is located in, and cuts through, a Proterozoic metagranitic biotite and biotite-muscovite gneiss se-

quence containing minor pegmatite bands. The age of the granite gneiss is constrained by a six-point Rb-Sr isotope scatterchron of $948 \pm 171 \text{ Ma}$ with an initial $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.7387 ± 85 (recalculated from LIÉGEOIS et al., 1982). The granite pegmatites have a four-point Rb-Sr isochron age of $969 \pm 17 \text{ Ma}$ with an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7303 ± 15

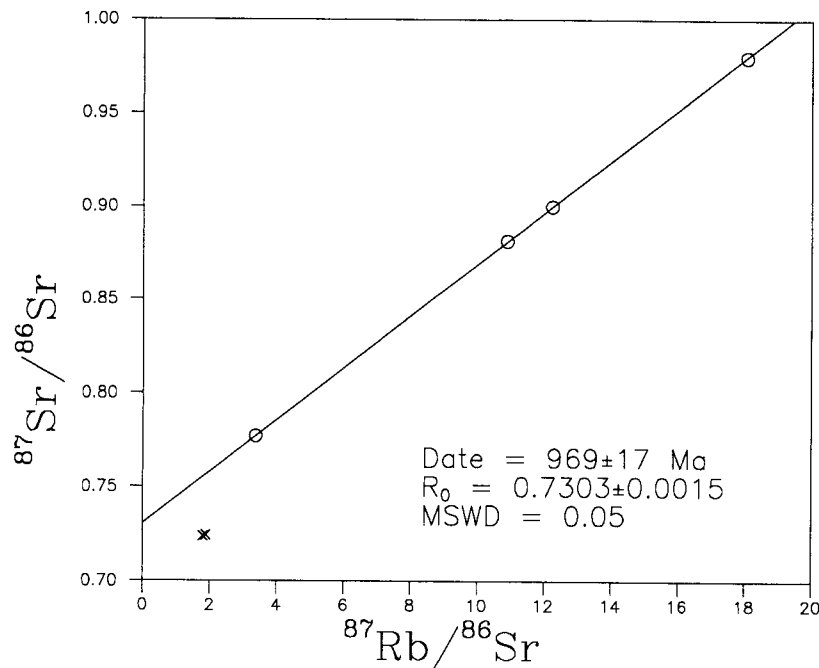


FIG. 2. Rb-Sr isochron diagram for six pegmatite samples from Gakara (coarse-grained quartz-alkalifeldspar \pm biotite \pm muscovite rocks). Four samples (open circles) define an isochron; the two samples Peg 1 and Peg 2 (crosses) have a disturbed Sr isotopic systematics and modified REE patterns (see Fig. 5).

(Fig. 2; Table 1). Two of the six analyzed pegmatite samples are from an area with small bastnaesite-monazite veinlets and have a disturbed Rb-Sr isotope system (Fig. 2) and will be discussed below.

BASTNAESITE COMPOSITION

There are very few chemical data on bastnaesite available. The reviews by MURATA et al. (1957), FLEISCHER (1965), and MARIANO (1989a) point to the fact that REE patterns of bastnaesite and monazite reflect their geologic environment of formation, i.e., relatively high HREE contents in granitic environments and a shift towards LREE enrichment in alkaline rocks and carbonatites. Our data on bastnaesite from Gakara and on reference samples from Mountain Pass, California, USA (carbonatite system) and from the Pikes Peak area, Colorado, USA (granitic system) are compiled in Table 2. The chondrite-normalized REE pattern of the Gakara bastnaesite plots close to a straight line with extreme La/Lu fractionation (Fig. 3). This pattern is similar to that of bastnaesite from the Mountain Pass carbonatite environment and distinctly different to that of the bastnaesite samples of crustal derivation from the Pikes Peak area, which have negative Eu anomalies and less pronounced LREE/HREE fractionation (Fig. 3).

Neodymium and strontium isotope data for the bastnaesite from Gakara are presented in Table 3 and plotted in Fig. 4. The bastnaesite samples display an essentially constant $\epsilon_{Nd}(T)$ of -11.9 and a large spread in initial $^{87}\text{Sr}/^{86}\text{Sr}$ values. The range in Sr isotope values can be attributed to variable interaction of the hydrothermal system with its granitic wallrocks. The lowest Sr isotope ratio of 0.7075 defines an upper limit for the primary fluids. The highest $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7329 points to 20–80% Sr-exchange with the wallrocks for

most/least radiogenic wallrock compositions (Sr isotope data from LIÉGEOIS et al., 1982, for $T = 587$ Ma).

Neodymium or cerium contamination of the hydrothermal system by wall rocks is not likely for an initially LREE-rich fluid system in equilibrium with REE minerals. On the other hand, it is clear that REE-rich hydrothermal fluids will act on the REE patterns of their wallrocks. This is portrayed by two pegmatite samples from the vicinity of bastnaesite-monazite veinlets which have disturbed Sr isotope systematics (Fig. 2) and REE patterns (Fig. 5). The two samples display a REE pattern more similar to carbonatites, and distinctly different from those of the unaltered rocks of the granite gneiss-pegmatite sequence. Both pegmatite samples have an impossibly low calculated $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.698 for their emplacement age at 969 Ma. Their disturbed initial ratio can be understood as the result of younger overprint by a low $^{87}\text{Sr}/^{86}\text{Sr}$ fluid phase. Such a fluid phase can not have been derived from the metagranitic or pegmatitic rocks, because the Sr composition of these rocks is too radiogenic. The pegmatites had an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.730 at their time

Table 1. Rb-Sr isotope data for the Gakara pegmatites

Sample number	Rb (ppm)	Sr (ppm)	$^{87}\text{Rb}/^{86}\text{Sr}^*$	$^{87}\text{Sr}/^{86}\text{Sr}^{**}$ (measured)
Peg 1	125.6	192.7	1.892	0.72437
Peg 2	81.6	131.4	1.801	0.72388
Peg 3	407.1	67.04	18.06	0.97989
Peg 4	100.8	87.13	3.376	0.77708
Peg 5	397.2	107.5	10.89	0.88150
Peg 6	418.4	100.9	12.24	0.89996

* Analytical error is 2% (2s)

** Analytical error is 0.06% (2s)

Table 2. Chemical data for bastnaesites from Gakara and other localities in ppm. The accuracy of neutron activation and ICP-MS data is estimated at $\pm 10\%$, as deduced from analyzing bastnaesite standards IGS 40 and 41 and comparison with reference data in LISTER and COGGER (1986). The isotope dilution analysis followed the procedures described by MASUDA (1968). The isotopic ratios of spiked samples were measured more than five times for a sample.

Isotope dilution analysis (TIMS) ($\bar{x} \pm 2$ sigma; n=1):		
	Gakara K1	Mountain Pass
La	1.813 $\pm 0.007 \times 10^5$	1.537 $\pm 0.010 \times 10^5$
Ce	2.728 $\pm 0.006 \times 10^5$	2.289 $\pm 0.017 \times 10^5$
Nd	8.724 $\pm 0.046 \times 10^4$	5.801 $\pm 0.041 \times 10^4$
Sm	9.052 $\pm 0.046 \times 10^3$	4.042 $\pm 0.035 \times 10^3$
Eu	1.403 $\pm 0.022 \times 10^3$	6.241 $\pm 0.037 \times 10^2$
Gd	3.371 $\pm 0.024 \times 10^3$	1.137 $\pm 0.018 \times 10^3$
Dy	4.465 $\pm 0.122 \times 10^2$	2.022 $\pm 0.017 \times 10^2$
Er	4.433 $\pm 0.150 \times 10$	2.576 $\pm 0.042 \times 10$
Yb	6.655 ± 0.085	3.931 ± 0.048
Lu	6.447 $\pm 0.063 \times 10^{-1}$	3.411 $\pm 0.052 \times 10^{-1}$

Neutron activation spectrometry (INAA):		
	Gakara (n=4; $\bar{x} \pm 1$ sigma)	Mountain Pass (n=1)
La	1.71 $\pm 0.70 \times 10^5$	1.77 $\times 10^5$
Ce	2.35 $\pm 0.14 \times 10^5$	2.44 $\times 10^5$
Nd	8.08 $\pm 0.47 \times 10^4$	8.23 $\times 10^4$
Sm	9.15 $\pm 1.09 \times 10^3$	5.02 $\times 10^3$
Eu	1.33 $\pm 0.17 \times 10^3$	0.69 $\times 10^2$
Tb	1.61 $\pm 0.15 \times 10^2$	0.72 $\times 10^2$
Th	2.46 $\pm 2.62 \times 10^2$	1.12 $\times 10^3$

Inductively coupled-plasma mass spectrometry (ICP-MS):		
	Pikes Peak, CO (n=1)	Crystal Peak, CO (n=1)
La	1.44 $\times 10^5$	9.75 $\times 10^4$
Ce	2.16 $\times 10^5$	1.89 $\times 10^5$
Pr	2.96 $\times 10^4$	3.65 $\times 10^4$
Nd	8.41 $\times 10^4$	1.21 $\times 10^5$
Sm	7.47 $\times 10^3$	1.49 $\times 10^4$
Eu	2.19 $\times 10^2$	5.69 $\times 10^2$
Gd	2.75 $\times 10^3$	8.91 $\times 10^3$
Tb	2.48 $\times 10^2$	7.60 $\times 10^2$
Dy	5.46 $\times 10^2$	1.50 $\times 10^3$
Ho	63	122
Er	122	216
Tm	9	9
Yb	31	124

of emplacement which increased to 0.748–0.828 at 587 Ma; the metagranite samples had $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in the range of 0.748–0.788 at 587 Ma. The two disturbed pegmatite samples have a calculated $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.708 at 587 Ma. This value is close to the initial ratio of the least Sr-exchanged bastnaesite of 0.708 ± 4 . It, therefore, seems likely that the disturbed Sr system in the pegmatite samples was the result of hydrothermal overprinting during REE mineralization, in line with the observation of altered REE distribution patterns in these rocks.

The long suspected association of the Gakara REE mineralization with a hidden carbonatite system is consistent with the similarity of the REE pattern of the bastnaesite to those of carbonatites (extreme La/Lu fractionation with no Eu anomaly), and the range in Sr isotope ratios in bastnaesite down to $^{87}\text{Sr}/^{86}\text{Sr} \leq 0.708$ (far below that of any exposed rock unit). Additional features such as the fluid inclusion composition and wall-rock alteration style, the mineral assemblage with the major components CO_2 -LREE-F-P-Ba, and the regional structural and geochronological setting

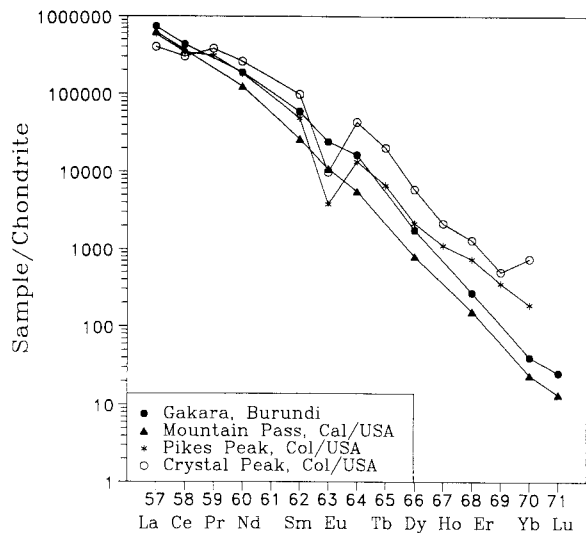


FIG. 3. REE patterns of bastnaesite samples from Gakara, Burundi, Mountain Pass, USA, and from the Pikes Peak Pluton, Colorado. The Pikes Peak and Crystal Peak bastnaesites are from a granitic environment, reflected in a negative Eu anomaly and a smaller degree of LREE/HREE fractionation compared to the Gakara and Mountain Pass bastnaesites from a carbonatitic environment. The same general patterns are valid for bastnaesite and monazite from other localities (MARIANO, 1989a).

substantiate this assumption. The nearly constant $\epsilon_{Nd}(T)$ value of -11.9 must be a feature of the assumed carbonatitic source rock of the Gakara REE mineralization. This $\epsilon_{Nd}(T)$ value is consistent with the corresponding positive $\epsilon_{Ce}(T)$ value of 1.6 determined for one bastnaesite sample (Table 3).

NATURE AND AGE OF THE ISOTOPIC SOURCES

The Nd model age of the bastnaesites relative to CHUR (Chondritic Uniform Reservoir) is $1,250$ Ma. This calculation assumes a reservoir with a highly fractionated Sm/Nd ratio identical to the one measured in bastnaesite and typical of carbonatites (WOOLLEY and KEMPE, 1989), i.e., around 0.1 . This age value is, therefore, a minimum age. A less fractionated Sm/Nd ratio around 0.2 , more typical of a reservoir for less unusual alkaline rocks (FAURE, 1986), would give a model age of $1,750$ Ma. This time bracket of $1,250$ – $1,750$ Ma includes the early history of the intracratonic Kibaran basin of central Africa in which the more than 10 -km-thick mostly clastic sediments of the Burundi or Karagwe-Ankole supergroup were deposited. The sedimentation started around $1,400$ Ma and was initiated by rifting of the Archaean basement (KLERKX et al., 1987). The formation of the heterogeneous subcontinental lithosphere in Burundi was possibly initiated by this rifting event, either by segregation of small melt fractions during adiabatic decompression in the upper mantle or by delamination of lower crust into the mantle. The latter process seems less probable in view of the Archaean age of the lower crust in this region (with corresponding very low $^{143}\text{Nd}/^{144}\text{Nd}$ values) as deduced from metagranitic Archaean basement outcrops about 60 km south of Gakara (CAHEN and SNELLING, 1984).

Intracratonic rifting is likely to produce small-percentage partial melts from the convective mantle that are enriched in light REEs and other incompatible elements. Parts of a subcontinental lithosphere previously enriched or veined by such partial melts will have a lower solidus than the surrounding mantle material, and would provide small-degree partial melts during subsequent lithospheric thinning/decompression. Such melts would have light-REE enriched signatures, and their isotopic compositions would record the time-integrated response to element fractionation in the enriched mantle reservoir (cf. MENZIES and HAWKESWORTH, 1987).

PETROGENETIC CONCLUSIONS

The highly negative initial ϵ_{Nd} of the Gakara REE ore deposits is exceptional for carbonatite systems (NELSON et al., 1988; BELL and BLENKINSOP, 1989). The East African carbonatite trend shown in Fig. 4 is confined to compositions relatively close to CHUR with a general compositional range of negatively correlated ϵ_{Nd} values of $+5$ to -5 and ϵ_{Sr} values of -20 to $+10$. This variability has been attributed to mixing of a depleted and a little-constrained, enriched mantle reservoir. However, there are notable deviations from this general situation. The Proterozoic Phalaborwa carbonatite complex defines a trend with ϵ_{Nd} -3 to -7 and ϵ_{Sr} $+20$ to 120 (ERIKSSON, 1989). Young potassic rocks from the Western rift system in Zaire and Uganda have ϵ_{Nd} values around -10 and $^{87}\text{Sr}/^{86}\text{Sr}$ around 0.708 , and have been interpreted in terms of mixing of a depleted mantle fluid with a ca. 500 Ma-old ancient metasomatised lithospheric domain (VOLLMER and NORRY, 1983; DAVIES and LLOYD, 1989). On a global scale, potassic and ultrapotassic rocks of the lamproite

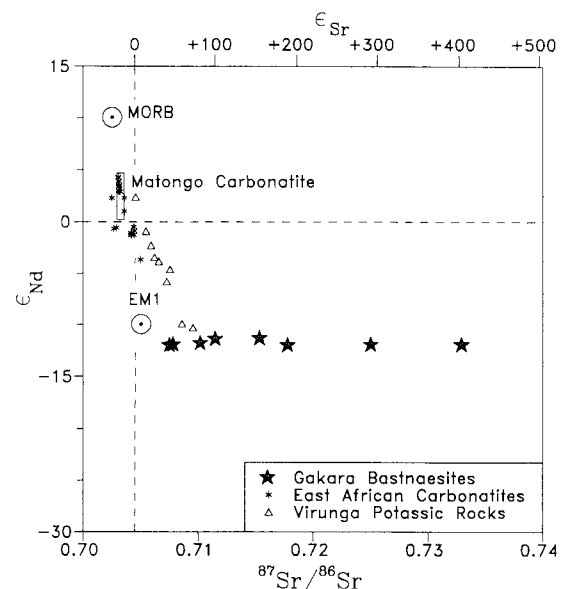


FIG. 4. Initial ϵ_{Sr} - ϵ_{Nd} variation diagram ($T = 587$ Ma) for bastnaesite samples from Gakara, Burundi. Reference data: Matongo carbonatite, Burundi (739 Ma) from DEMAIFFE et al. (1986); East African carbonatites from BELL and BLENKINSOP (1989); present-day depleted MORB mantle and enriched mantle (EM 1) reservoirs from ZINDLER and HART (1986).

Table 3. Isotope data for the Gakara bastnaesites

Sample number	Rb (ppm)	Sr (ppm)	$^{87}\text{Rb}/^{86}\text{Sr}^*$	$^{87}\text{Sr}/^{86}\text{Sr}^{**}$ (measured)	$\epsilon(T)$ T=587 Ma
M1a	0.0003	255	0.000003	0.71152	109
K2a	0.167	1,140	0.000416	0.71535	164
N1a	0.217	313	0.00198	0.71015	90
N2a	0.589	333	0.00504	0.71776	198
K1b	0.1768	162.6	0.00109	0.73294	414
N1b	0.10	110.9	0.0026	0.7078	57
N1c	n.a.	227.6	n.a.	0.70800	59
N2c	n.a.	99.9	n.a.	0.70754	53

* Analytical error is 2 % (2s)

** Analytical error is 0.06 % (2s)

Sample number	Sm (ppm)	Nd (ppm)	$^{147}\text{Sm}/^{144}\text{Nd}^*$	$^{143}\text{Nd}/^{144}\text{Nd}^{**}$	$\epsilon(T)$ T=587 Ma
M1a	7,340	83,190	0.0543	0.511507	-11.4
K2a	8,950	95,050	0.0579	0.511528	-11.3
N1a	6,470	73,290	0.0543	0.511488	-11.8
N2a	6,680	72,830	0.0564	0.511485	-12.0
K1b	9,052	87,240	0.0639	0.511515	-11.9
K2b	n.a.	n.a.	n.a.	0.511490	-11.9
N1b	n.a.	n.a.	n.a.	0.511512	-11.9

* Analytical error is 0.5 % (2s)

** Analytical error is 0.006 % (2s)

Sample number	La (ppm)	Ce (ppm)	$^{138}\text{La}/^{142}\text{Ce}^*$	$^{138}\text{Ce}/^{142}\text{Ce}^{**}$	$\epsilon(T)$ T=587 Ma
K1a	181,300	272,800	0.005432	0.0225797	1.6

* Analytical error is <0.3 % (2s)

** Analytical error is <0.006 % (2s)

$\epsilon(T)$ values refer to CHUR for Nd (FAURE, 1986) and Ce (SHIMIZU et al., 1988), and to UR for Sr (FAURE, 1986). Present parameters for CHUR (T=0) are $^{143}\text{Nd}/^{144}\text{Nd} = 0.512638$ and $^{147}\text{Sm}/^{144}\text{Nd} = 0.1967$, as well as $^{138}\text{Ce}/^{142}\text{Ce} = 0.0225722$ and $^{138}\text{La}/^{142}\text{Ce} = 0.003089$; normalization is to $^{143}\text{Nd}/^{144}\text{Nd} = 0.7219$ and $^{136}\text{Ce}/^{142}\text{Ce} = 0.01688$. Present-time UR parameters are $^{87}\text{Sr}/^{86}\text{Sr} = 0.7045$ and $^{87}\text{Rb}/^{86}\text{Sr} = 0.0816$. The decay constants $\lambda_{\beta-}^{138}\text{La} = 2.77 \times 10^{-12} \text{ a}^{-1}$ and $\lambda_{\text{EC}}^{138}\text{La} = 4.44 \times 10^{-12} \text{ a}^{-1}$ are used to calculate $\epsilon_{\text{Ce}}(T)$ following the technique of SHIMIZU et al. (1988).

clan as well as Group 2 kimberlites have Sr and Nd isotope signatures which indicate old subcontinental sources enriched in Rb and with low Sm/Nd, because these rocks due to their high REE and Sr contents—similar to carbonatites—are unlikely to have been subjected to significant crustal contamination (MITCHELL and BERGMAN, 1991).

The lateral and/or vertical extent of the assumed enriched mantle domain in the Gakara region seems to be small. The 739-Ma-old alkaline-carbonatite complex of Matongo, 55 km NNE of Gakara, has a depleted Nd and Sr isotope composition (Fig. 4) and, therefore, reflects a mantle domain unaffected by earlier incompatible-element enrichment. The REE-mineralization in Burundi, therefore, appears to mirror

a small-scale (≤ 50 km) Nd isotopic anomaly. This is the first time that such an extreme isotopic composition has been sampled in a LREE-rich hydrothermal-magmatic system of probable carbonatite affiliation, in which crustal Nd contamination during emplacement is less likely than in any other rock of mantle origin.

The possible relationship of REE enrichment in ancient mantle domains to REE ore deposits in association with carbonatite systems remains to be tested. Preliminary data on monazite and other REE minerals in the giant Bayan Obo REE deposit, China, point to a chondritic source composition for this system (NAKAI et al., 1989). Bastnaesite from the Mountain Pass deposit, USA, has an ϵ_{Nd} value of -3 and

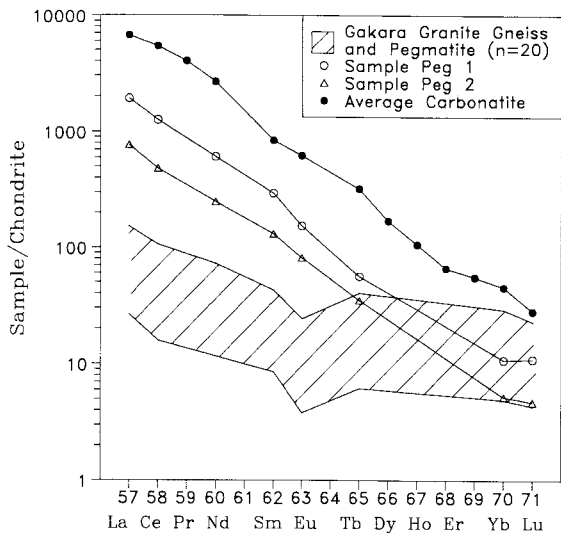


FIG. 5. REE compositional field for the Gakara granite gneiss-pegmatite sequence compared to hydrothermally altered REE patterns in samples Peg 1 and Peg 2 from wallrocks of bastnaesite-monazite mineralization. Reference data from average carbonatites from WOOLLEY and KEMPE (1989) and CULLERS and GRAF (1984). All data are normalized to C1 composition as compiled in McDONOUGH and FREY (1989).

$^{87}\text{Sr}/^{86}\text{Sr}$ of 0.705 ($T = 1,400$ Ma) (NAKAI, unpubl. data). This REE ore system is related to a carbonatite complex, in which Pb isotope data indicate an association with a lower crustal reservoir (MITCHELL, 1973).

Experimental evidence points to an origin of REE enriched carbonatite systems from metasomatized upper mantle sources where alkaline silicate melts are likely to be generated in the 75 km depth region (WYLLIE, 1989). During ascent and concomitant fractional crystallization, these silicate systems can yield immiscible carbonatite fractions with their own internal magmatic evolution in some crustal carbonatites towards late-stage REE-enriched carbonate melts (HEINRICH, 1966; JONES and WYLLIE, 1986). The exsolution of a $\text{H}_2\text{O}-\text{CO}_2$ vapour phase with high concentrations of alkalis and other solutes from a late-stage carbonatite is a necessary consequence of low-pressure crystallization and has its geological expression in the formation of hydro-carbo-thermal vein systems with bastnaesite, fluorite, barite, and quartz (WYLLIE et al., 1993). The REE enrichment process during the complex magmatic-hydrothermal evolution of such systems acts upon initially already high REE levels in the alkaline silicate parent. Therefore, the Sm-Nd isotope composition of the mantle source is not likely to be strongly influenced by interaction with crustal rocks. This assumption points for both the Gakara and Mountain Pass ore systems to an origin from anomalous subcontinental mantle.

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