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THE ROLE OF CONTINENTAL LITHOSPHERE IN THE GENERATION OF THE KAROO VOLCANIC ROCKS: EVIDENCE FROM COMBINED Nd- AND Sr-ISOTOPE STUDIES

by

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ABSTRACT

$^{143}Nd/^{144}Nd$, $^{87}Sr/^{86}Sr$, Sm and Nd analyses are reported on suites of Karoo volcanic rocks from the four sub-areas of Nuanetsi–north Lebombo, south Lebombo, the Central area, and north-west SWA/Namibia. Only seven (12 %) of the samples analysed have positive ε_{Nd} values similar to those found in the majority of recent mantle-derived rocks. Most of the rest have negative ε_{Nd} (−1.0 to −17.1) and positive ε_{Sr} (+3.0 to +240) and thus must contain at least a contribution from source areas which were both old, and had lower Sm/Nd and higher Rb/Sr ratios than the bulk earth. Such trace element ratios are typical of the continental crust, and it is envisaged that crustal contamination will tend either to generate some broad mixing relation between the original magma and a crustal component, and/or disrupt any pre-existing relationship between isotope and parent/daughter trace element ratios with the result that the two become "decoupled". Such decoupling is observed in some basalts from the south Lebombo which may have been contaminated with Archaean crust, but the majority of the Karoo volcanics studied have not been affected significantly by crustal contamination processes. Rather, different styles of trace element enrichment are recognized in both mantle xenoliths and Karoo basalts, and with time these result in different trends on ε_{Nd}-ε_{Sr} diagrams. The low $^{143}Nd/^{144}Nd$ and high $^{87}Sr/^{86}Sr$ ratios of many basalts and mantle xenoliths suggest that they at least are derived from within the continental lithosphere; since that is where variations in Sm/Nd and Rb/Sr ratios are likely to persist for long enough to generate the observed range in Nd- and Sr-isotopes. Finally, the evolution of the subcontinental lithosphere beneath southern Africa is provisionally described in terms of a two-stage model. Much of the lithosphere appears to have stabilized 1.4–1.0 b.y. ago, which is also the time of significant crustal growth within the Namaqua–Natal mobile belt. It is argued that the two are related, and that increasing the area of stable continental crust also increased the volume and perhaps even the thickness, of material incorporated into the subcontinental lithosphere. Karoo magmatism at ~190 m.y. was then followed by, and may have been responsible for, a second mantle enrichment event now observed in, for example, the modal metasomatism of K-richterite-bearing peridotite xenoliths.

CONTENTS

I. INTRODUCTION

The nature of the subcontinental mantle is arguably one of the more contentious issues currently confronting petrologists and geochemists. Most would accept that the uppermost mantle lies within the continental lithosphere, and some geophysical considerations suggest that as such it may have stabilized shortly after the last major thermal event in the overlying crust (Oxburgh and Parmentier, 1978). Much of this mantle is therefore likely to be old enough for trace element heterogeneities to be mirrored by variations in radiogenic isotopes. Moreover, since any old segments of the subcontinental mantle will be susceptible to the effects of later events, they may also represent a rare opportunity to investigate polyphase evolution within the upper mantle. Beneath the continental lithosphere the mantle is presumably part of the global convection system, and is therefore likely to be similar to that beneath oceanic areas.

The composition of the subcontinental mantle may be determined directly from mantle xenoliths (Menzies and Murthy, 1980; Erlank *et al.*, 1982) and inferred from the study of continental basalts (DePaolo and Wasserburg, 1976; Hawkesworth and Vollmer, 1979; Erlank *et al.*, 1980; Allègre *et al.*, 1981; Doe *et al.*, 1982). Yet both can be contaminated with crustal material *en route* to the surface (e.g. Carlson *et al.*, 1981; Mahoney *et al.*, 1982) and the irony remains that whereas its age and chemical variations make the subcontinental mantle highly suitable for isotopic investigation, its samples are obviously the only ones which can be affected by crustal contamination *sensu stricto*. This study reports $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ determinations on a wide range of Karoo magmatic rocks, and forms part of an integrated programme to compare evidence from magmatic rocks and both crustal and mantle xenoliths in southern Africa. The Karoo rocks crop out on a basement of Archaean cratonic nucleii (3.6–2.5 b.y.) surrounded by mobile belts ranging in age from 2.0–0.5 b.y. (Fig. 1). Moreover, they represent the first widespread magmatic event to take place after the last orogenic episode, and the subsequent stabilization of the crust, in southern Africa.

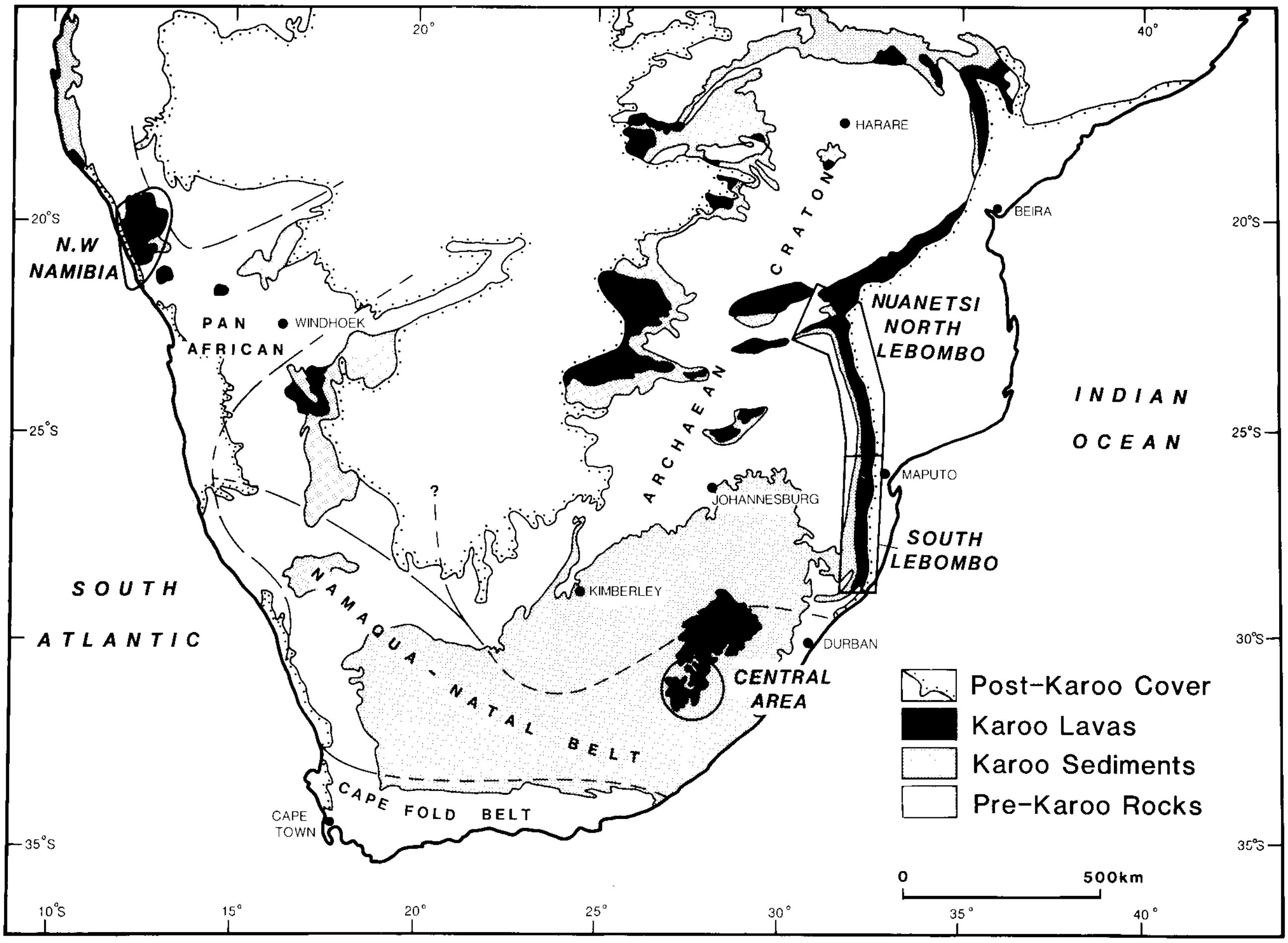

Figure 1
Geological sketch map of southern Africa illustrating the four areas from which samples of Karoo volcanic rocks were taken for isotope analysis.

II. GEOLOGICAL RELATIONSHIPS

The Karoo magmatic rocks form one of the classic flood basalt provinces (Walker and Poldervaart, 1949; Cox, 1980). Radiometric ages vary from early Jurassic ($\sim$190 m.y.) to early Cretaceous ($\sim$120 m.y.) (see Fitch and Miller, 1984; Allsopp *et al.*, 1984; Erlank *et al.*, 1984), and today remnants of lavas occur scattered across an area in excess of 3.5×10^6 km^2 in southern Africa (Fig. 1). In addition the underlying Karoo sedimentary sequences are host to an extensive intrusive suite of dykes and sills. Basaltic rock types of tholeiitic character are dominant throughout the Karoo province, but volumetrically important sequences of acid volcanics occur along both the eastern and western margins of the province.

Rocks for $^{143}Nd/^{144}Nd$ analysis were selected from four specific areas which had previously been the subject of detailed petrologic, geochemical, and in many cases, Sr-isotope studies: namely, the Central area, Nuanetsi–north Lebombo, south Lebombo and north-western SWA/Namibia (Fig. 1). Samples from within the intracratonic Central area (Marsh and Eales, 1984) come from the southern part of the Lesotho remnant where several geochemically distinct basalt types of limited thickness and distribution associated with trivial volumes of andesite–dacite occur beneath the voluminous Lesotho basalt type (Fig. 2a). The different basalt types exhibit narrow ranges in their major and trace element contents and distinctive sets of interelement ratios, and Marsh and Eales (1984) have shown that they are not related genetically by fractional crystallization or partial melting processes.

In the eastern marginal area Karoo volcanics crop out along the 700 km Lebombo monocline, a rift-related structure in which the basic lavas are overlain by thick sequences of rhyolite. In the Nuanetsi–north Lebombo area (Fig. 1) four major units have been recognized (Fig. 2b). However, moving south along the Lebombo monocline several important changes take place. First, the Mashikiri nephelinites and Letaba picrites pinch out so that in the south Lebombo the volcanic sequence consists simply of Sabie River low-MgO basalts, some thin interbedded intermediate to acid lavas (the Twin Ridge and Mkutshane volcanics), and an upper unit of up to 2 km of rhyolites—within which the Mbuluzi rhyolites are a particular quartz–phenocryst bearing facies. This south Lebombo succession was then intruded by the late but important 200 km long Rooi Rand dyke swarm. Second, the rocks of Nuanetsi–north Lebombo are substantially enriched in incompatible elements compared with those to the south. Thus since the Sabie River basalts are the one major unit which can be traced along the length of the Lebombo monocline, this change in incompatible element chemistry is observed *within* that stratigraphic unit, and it occurs at about 25°20′S (Cox and Bristow, 1984). Third, although the Mbuluzi and Nuanetsi rhyolites both succeed basic lavas in their respective areas they are chemically distinct and can also be discriminated on geochemical grounds from the lower interbedded, or Mkutshane, rhyolites within the south Lebombo Sabie River basalts. The acid rocks of the upper interbedded Twin Ridge Beds are probably related to the Mbuluzi rhyolites by fractional crystallization (Cleverly *et al.*, 1984).

The fourth area of detailed study is in north-western SWA/Namibia where remnants of the Etendeka Formation, comprising early Cretaceous lavas and

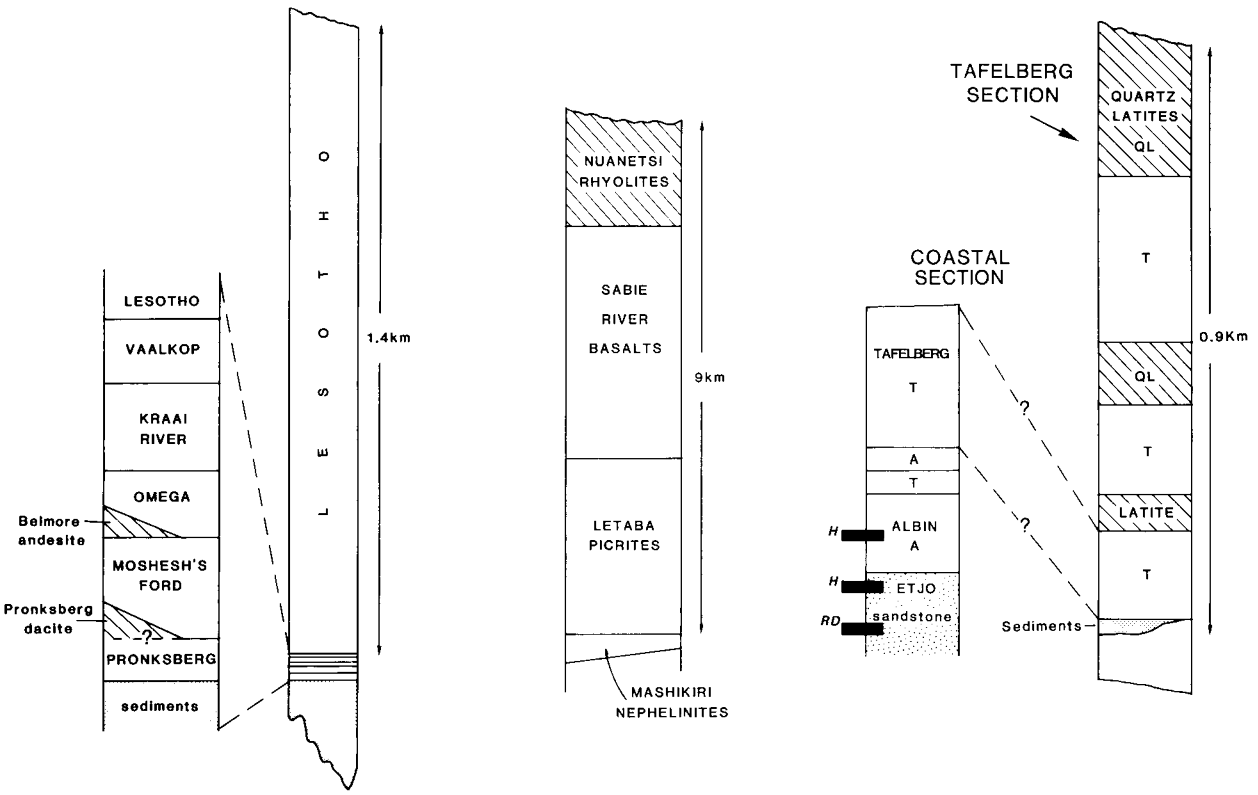

Figure 2

Diagrammatic sections of the main stratigraphic units recognized in (a) the Central area, (b) Nuanetsi–north Lebombo, and (c) north-west SWA/Namibia.

associated minor intrusives, and swarms of regional dolerite dykes, possibly of late Jurassic age, represent igneous activity related to the rifting of South America from Africa. The bulk of the lavas comprise a suite of aphyric basalts and evolved basalts (termed the Tafelberg type) interbedded with two important quartz latite units and a thin unit of latite of limited extent (Fig. 2c). This relationship is best observed at the locality of the Tafelberg beacon on the eastern edge of the Etendeka lava field, where the lava pile reaches a thickness of 900 m, and many of the samples analysed are from the vicinity of this locality. Along the coast plagioclase-phyric basalts (termed the Albin type) underlie and are partly interbedded with aphyric Tafelberg basalts, and although related to the Tafelberg rocks they tend to be less evolved. The Albin basalts are intruded by thin, aphyric dykes and sills, the Horingbaai dolerites, which exhibit a distinctive "primitive" chemistry in comparison to all other Karoo basic rocks. Dolerite dykes from the regional swarm which cuts basement and Karoo sediments but not the lavas are more evolved than the Horingbaai intrusives, but their precise geochemical relationship to the Albin and Tafelberg lavas (and their ages) is not clear at this stage (Erlank *et al.*, 1984).

III. SAMPLE SELECTION

In our sample selection we have sought the freshest representative material of the different rock types, although the Karoo igneous province is ~190 m.y. old and nearly all the extrusive rocks have experienced some degree of secondary alteration, zeolites being particularly common. Richardson (1984), however, has shown that between-sample variations due to secondary processes within a single Karoo sill were slight for $^{87}Sr/^{86}Sr$ (effective $(^{87}Sr/^{86}Sr)_{182m.y.}$ = 0.7061–0.7065) and Cs, Rb and Sr, and within analytical error for $^{143}Nd/^{144}Nd$ and other elements. Similar conclusions with respect to Rb, Sr and $^{87}Sr/^{86}Sr$ have also been reached regarding the thin undifferentiated Amherst sill and from measurements made on host basalt and separated zeolite and calcite (Bristow *et al.*, 1984). Moreover, Marsh and Eales (1984) considered the effects of alteration on samples of Lesotho basalts and dolerites and showed that although the Rb, Ba, Sr and K contents of individual samples may have been disturbed, the average of a number of samples from any basalt unit appears to provide a good estimate of the original trace element concentrations. In summary, secondary processes are probably locally responsible for small intra-sample differences (relative to the overall variations in Karoo rocks) in $^{87}Sr/^{86}Sr$ and the abundances of elements such as Rb, Cs, K, Ba and Sr, but they have had little noticeable affect on less mobile trace elements and on $^{143}Nd/^{144}Nd$ ratios.

IV. ANALYTICAL RESULTS

Nd was separated using a cation and then anion column procedure, and analysed as the metal species on a triple filament assembly in a VG 54E mass spectrometer. $^{143}Nd/^{144}Nd$ was normalized to $^{146}Nd/^{144}Nd = 0.7219$, and the average of ten analyses of BCR-1 = 0.51262 ± 2. $^{87}Sr/^{86}Sr$ ratios are reported relative to an average value of NBS 987 = 0.71015 ± 2 or Eimer and Amend = 0.70800 (see Bristow *et al.*, 1984, for further details and a compilation of all $^{87}Sr/^{86}Sr$ data available on Karoo rocks).

In the samples analysed present-day $^{87}Sr/^{86}Sr$ varies from 0.70305 to 0.72671, and $^{143}Nd/^{144}Nd$ from 0.51303 to 0.51168 (Table I). Note, however, that since previous work had shown that the volumetrically dominant magma types had

TABLE 1
Nd- and Sr-Isotope Results

Sample	Magma Type	SiO_2	MgO	Rb	Sr	Rb/Sr	$^{87}Sr/^{86}Sr$	Sm	Nd	Sm/Nd	$^{143}Nd/^{144}Nd$	ε_{Nd} (190 m.y.)	ε_{Sr} (190 m.y.)	T^{Nd}_{CHUR} (b.y.)
(a) Central Area														
JP 54	Lesotho basalt	49.40	6.83	11.0	194	0.057	0.70623 ± 4	3.4*	14.0*	0.243	0.51250 ± 2	− 1.53	18.7	0.43
JP 22	Lesotho basalt	47.95	7.39	8.7	196	0.044	0.70545 ± 4	3.1*	12.7*	0.244	0.51248 ± 2	− 1.93	9.0	0.50
JP 27	Lesotho basalt	49.87	7.54	8.0	192	0.042	0.70552 ± 4	2.9*	11.2*	0.259	0.51253 ± 2	− 1.18	10.3	0.42
PN 2101	Lesotho basalt	—	7.05	10.5	186	0.056	0.70641 ± 6	3.31	13.9	0.238	0.51249 ± 3	− 1.65	21.3	0.43
PN 2130	Lesotho basalt	—	7.02	7.0	145	0.048	0.70509 ± 4	2.49	9.48	0.263	0.51253 ± 2	− 1.23	3.5	0.45
CLA 01	Moshesh's Ford basalt	52.34	6.36	21.3	286	0.075	0.70613 ± 8	4.4*	19.0*	0.232	0.51244 ± 2	− 2.54	15.3	0.54
DBM 11	Moshesh's Ford basalt	52.27	6.41	19.6	303	0.065	0.70602 ± 4	4.1*	18.5*	0.222	0.51248 ± 1	− 1.61	15.7	0.39
AM 22	Omega basalt	50.12	7.33	4.0	198	0.020	0.70506 ± 4	2.68	9.89	0.271	0.51256 ± 1	− 0.77	6.1	0.37
KF 2	Kraai River basalt	51.24	6.33	6.3	201	0.031	0.70776 ± 4	3.7*	17.1*	0.216	0.51237 ± 2	− 3.67	43.2	0.62
KF 11	Kraai River basalt	52.05	8.22	26.3	176	0.149	0.70861 ± 4	3.0*	13.9*	0.216	0.51235 ± 1	− 4.06	42.2	0.67
AM 34	Vaalkop basalt	52.32	6.35	25.0	226	0.111	0.70750 ± 4	4.01	17.6	0.228	0.51251 ± 2	− 1.11	30.7	0.34
KRP 8	Pronksberg dacite	64.01	2.36	95.0	344	0.276	0.71512 ± 4	6.65*	31.3*	0.212	0.51235 ± 2	− 4.00	120.5	0.65
KRB 1	Belmore dacite	63.81	2.65	135	299	0.452	0.71325 ± 4	6.58	34.5	0.191	0.51229 ± 2	− 4.86	74.5	0.66
KRB 8	Belmore andesite	61.69	3.54	88.0	252	0.349	0.71216 ± 4	5.97	30.8	0.194	0.51229 ± 2	− 4.91	70.4	0.67
(b) Nuanetsi–Lebombo														
Nuanetsi														
NTS 12	Mashikiri nephelinite	41.30	5.84	63	1 663	0.038	0.70540 ± 6	9.4*	68*	0.138	0.51215 ± 2	− 6.82	9.0	0.66
N 133	Letaba picrite basalt	47.20	19.6	36	958	0.038	0.70505 ± 4	12.9*	71*	0.182	0.51211 ± 2	− 8.24	4.1	0.93
N 400	Letaba picrite basalt	47.80	18.1	42.3	998	0.042	0.70516 ± 4	12.0	68.8	0.174	0.51201 ± 1	−10.07	5.1	1.05
N 149	Letaba picrite basalt	48.40	15.3	21.5	604	0.036	0.70493 ± 4	10.0*	47*	0.213	0.51233 ± 1	− 4.40	2.68	0.70
N 386	Sabie River basalt	50.80	10.1	50	1 028	0.049	0.70621 ± 4	12.6*	80	0.158	0.51217 ± 2	− 6.72	19.3	0.71
N 345	Nuanetsi rhyolite	71.13	0.05	188	64.0	2.94	0.72952 ± 4	18.5	107	0.173	0.51190 ± 2	−12.21	28.2	1.22
N 347	Nuanetsi rhyolite	71.91	0.24	144	68.0	2.12	0.72354 ± 5	19.3	110	0.175	0.51194 ± 1	−11.46	35.0	1.17
Northern Lebombo														
KP 82	Mashikiri nephelinite	44.54	8.05	28.6	1 034	0.028	0.70696 ± 5	6.7*	37*	0.181	0.51170 ± 3	−16.22	32.3	1.64
KP 112	Letaba picrite basalt	45.17	23.0	61	795	0.077	0.70590 ± 5	123*	61*	0.202	0.51213 ± 2	− 8.15	11.8	1.04
KS 3	Letaba picrite basalt	49.77	10.6	58	842	0.069	0.70533 ± 4	12.6*	59*	0.214	0.51227 ± 2	− 5.59	4.6	0.84
CL 115	Sabie River basalt	49.58	4.45	24.4	696	0.035	0.70527 ± 6	13.2*	68*	0.194	0.51240 ± 1	− 2.76	7.5	0.46
CL 120	Sabie River basalt	51.24	5.65	60	1 162	0.052	0.70678 ± 4	13.2*	60*	0.220	0.51214 ± 2	− 8.21	27.0	1.20
Southern Lebombo														
A 117	Rooi Rand dolerite	51.1	4.2	26.8	268	0.100	0.70494 ± 6	9.27	39.1	0.237	0.51261 ± 1	+ 0.71	−4.4	0.09
A129	Rooi Rand dolerite	48.76	7.09	5.7	150	0.038	0.70415 ± 4	3.14	9.58	0.328	0.51283 ± 2	+ 3.67	−8.8	1.58
RC 110	Swaziland dolerite	51.7	4.61	13.3	298	0.045	0.70446 ± 4	7.47	34.1	0.219	0.51260 ± 1	+ 0.78	−5.1	0.10
RC 42	Mkutshane[1] rhyolite	66.87	0.58	95	158	0.601	0.71968 ± 4	7.8*	36.7*	0.213	0.51168 ± 1	−17.10	149.0	2.15
RC 36	Twin Ridge[2] rhyolite	67.13	0.64	127	193	0.658	0.70920 ± 4	23*	114*	0.202	0.51250 ± 2	− 0.92	−5.9	0.29
RC 128	Twin Ridge[2] rhyolite	61.36	1.3	88	245	0.359	0.70705 ± 4	22*	109*	0.202	0.51249 ± 1	− 1.12	−3.2	0.31
RC 74	Mbuluzi Fm. rhyolite	74.02	0.22	144	105	1.37	0.71460 ± 9	34*	166*	0.205	0.51250 ± 1	− 0.97	−8.6	0.29
RC 131	Mbuluzi Fm. rhyolite	69.54	0.49	144	124	1.16	0.71276 ± 8	24*	128*	0.188	0.51253 ± 1	− 0.14	−11.3	0.20
J 3	Sabie River basalt	46.85	5.66	8.82	235	0.038	0.70404 ± 4	6.08	22.7	0.268	0.51276 ± 1	+ 3.18	−10.3	—
L 285	Sabie River basalt	53.21	5.45	16.5	222	0.074	0.70513 ± 4	3.49	12.2	0.286	0.51268 ± 1	+ 1.36	1.1	—
L 12	Sabie River basalt	50.31	6.43	6.70	727	0.009	0.71043 ± 4	4.04	16.8	0.240	0.51195 ± 2	−12.2	83.6	2.04
L 18	Sabie River basalt	51.38	6.57	10.7	273	0.039	0.70891 ± 8	3.7*	16.0*	0.231	0.51188 ± 3	−13.5	58.9	2.03
L 29	Sabie River basalt	52.65	5.99	19.1	302	0.063	0.70865 ± 5	4.45	20.6	0.216	0.51202 ± 1	−10.5	52.3	1.43
L 36	Sabie River basalt	54.70	5.60	14.9	352	0.042	0.70947 ± 4	4.32	18.8	0.230	0.51202 ± 2	−10.7	66.3	1.64
L 348	Sabie River basalt	54.64	6.20	41	166	0.247	0.71536 ± 4	3.90	15.4	0.253	0.51160 ± 3	−19.2	127.1	3.60

Sample	Magma Type	SiO_2	MgO	Rb	Sr	Rb/Sr	$^{87}Sr/^{86}Sr$	Sm	Nd	Sm/Nd	$^{143}Nd/^{144}Nd$	ε_{Nd} (121 m.y.)	ε_{Sr} (121 m.y.)	T^{Nd}_{CHUR} (b.y.)
(c) Etendeka–Northern Namibia														
KLS 43	Regional dolerite	48.31	8.76	10.2	274	0.037	0.70673 ± 4	3.45*	14.9*	0.232	0.51239 ± 3	− 4.01	28.2	0.68
KLS 122	Horingbaai dolerite	45.58	9.09	4.30	186	0.023	0.70334 ± 4	2.13*	7.19*	0.296	0.51294 ± 2	6.13	−18.6	—
KLS 145	Horingbaai dolerite	46.16	8.50	2.20	192	0.012	0.70305 ± 3	2.86*	9.9*	0.289	0.51303 ± 3	7.95	−22.1	—
KLS 66	Tafelberg basalt	48.22	6.10	18.3	189	0.097	0.71208 ± 6	4.66	21.4	0.218	0.51233 ± 2	− 5.05	100.0	0.73
KLS 100	Tafelberg dolerite	49.22	7.14	20.0	241	0.083	0.71072 ± 4	4.09	16.5	0.248	0.51241 ± 1	− 3.77	81.7	0.75
KLS 38	Tafelberg dolerite	49.29	6.69	43.0	349	0.123	0.71039 ± 6	6.22	30.0	0.207	0.51232 ± 2	− 5.14	74.2	0.68
KLS 48	Tafelberg dolerite	49.69	10.39	16.1	313	0.051	0.70805 ± 4	4.25	21.0	0.202	0.51196 ± 1	−12.1	46.0	1.39
KLS 24	Tafelberg basalt	51.28	6.71	18.7	214	0.087	0.70990 ± 6	4.4*	18.6*	0.237	0.51238 ± 2	− 4.25	69.8	0.74
KLS 58	Tafelberg basalt	52.15	6.33	32.0	275	0.116	0.71257 ± 4	3.60	15.6	0.231	0.51228 ± 1	− 6.14	105.6	0.96
KLS 46	Tafelberg basalt	52.27	6.59	32.9	281	0.117	0.70867 ± 4	4.11	18.0	0.228	0.51233 ± 2	− 5.14	50.2	0.80
KLS 16	Tafelberg basalt	52.87	4.06	51.9	293	0.177	0.70895 ± 4	6.81	32.3	0.211	0.51224 ± 1	− 6.74	49.9	0.88
KLS 144	Albin basalt	53.17	4.45	41.0	234	0.175	0.71388 ± 4	5.70*	29.7*	0.192	0.51226 ± 1	− 6.17	120.0	0.72
KLS 53	Tafelberg basalt	54.47	5.56	52.0	214	0.243	0.71206 ± 7	4.53	21.2	0.214	0.51227 ± 3	− 6.18	89.4	0.84
KLS 40	Tafelberg basalt	55.83	3.67	70.9	213	0.333	0.71445 ± 4	6.18	28.7	0.215	0.51224 ± 2	− 6.78	117.0	0.92
KLS 54	Tafelberg basalt	57.01	3.25	83.0	186	0.446	0.71445 ± 8	6.43	29.6	0.217	0.51224 ± 1	− 6.79	108.9	0.93
KLS 42	Tafelberg basalt	57.55	2.29	96.0	187	0.513	0.71605 ± 5	8.3	38.5	0.216	0.51221 ± 2	− 7.37	126.9	0.99
KLS 69	Tafelberg latite	58.05	1.66	142	215	0.660	0.71866 ± 5	12.5*	71*	0.176	0.51211 ± 2	− 8.95	153.5	0.90
KLS 51	Tafelberg qtz. latite	66.3	1.08	162	158	1.03	0.72653 ± 8	8.5*	40.3*	0.211	0.51219 ± 1	− 7.71	239.3	0.99
KLS 36	Tafelberg qtz. latite	66.42	1.09	138	163	0.853	0.72320 ± 8	8.8*	46.2*	0.190	0.51219 ± 2	− 7.52	204.3	0.84
KL 20	Tafelberg qtz. latite	67.12	1.39	161	139	1.16	0.72472 ± 14	7.3*	34.5*	0.212	0.51215 ± 2	− 8.50	204.2	1.09

Sm and Nd determinations by isotope dilution, except for those marked* which are by spark source mass spectrometry.
1. Lower part of the Sabie River Formation. 2. Upper part of the Sabie River Formation.
All analytical data are measured concentrations, not corrected for volatile-loss.

relatively restricted ranges in isotope and trace element ratios (see summaries by Bristow *et al.*, 1984; Duncan *et al.*, 1984), there is an inherent sampling bias towards the more unusual and volumetrically less significant rock types. Initial $^{143}Nd/^{144}Nd$ ratios have been calculated at 190 m.y. for the rocks of the Central area, Nuanetsi and Lebombo, and at 121 m.y. for those of northern SWA/Namibia, and are presented as ε_{Nd} in histogram form in Fig. 3.

Only seven (i.e. ~12 %) of the samples analysed have positive ε_{Nd} values similar to those found in the majority of recent mantle-derived rocks. The rest have negative ε_{Nd} and thus must contain at least a contribution from an older, low

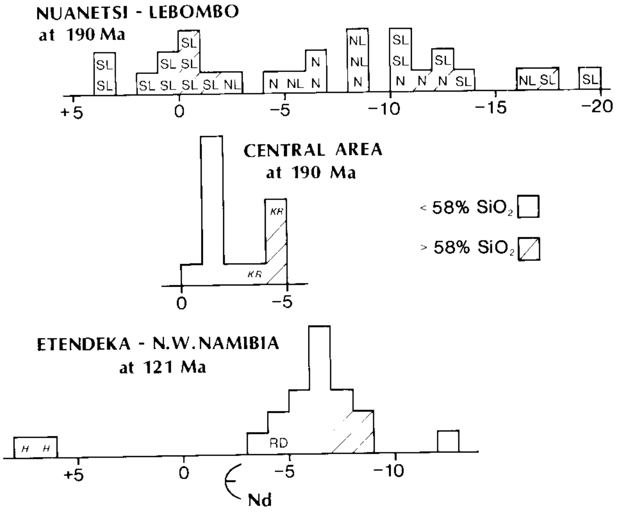

Figure 3

Histograms of the initial ε_{Nd} values of the Karoo volcanic rocks. N—Nuanetsi, NL—north Lebombo, SL—south Lebombo, KR—Kraai River, H—Horingbaai dolerites, RD—Regional dolerites.

$$\varepsilon_{Nd} = \left(\frac{^{143}Nd/^{144}Nd_I}{^{143}Nd/^{144}Nd_{BE}} - 1\right) \times 10^4, \text{ where}$$

$^{143}Nd/^{144}Nd_I$ = initial Nd isotope ratio of the sample

$^{143}Nd/^{144}Nd_{BE}$ = contemporaneous Nd isotope ratio of the bulk earth relative to a present-day bulk earth value of 0.51264.

Sm/Nd (and hence LREE enriched) source, be that in the crust or the upper mantle. Particularly for the more basic rock types it is therefore important to consider whether their isotope and trace element ratios have been modified significantly by the processes of partial melting, contamination and fractional crystallization; or whether they are still similar to those in their source regions—before contemplating the nature of those sources. The isotope results are therefore discussed initially in the light of the co-existing variations in parent/daughter element ratios, in an attempt to identify areas (or magma types) where both behave coherently and others where the trace elements and isotopes appear to be "decoupled".

The stratigraphy of the sampled portion of the Central area (Fig. 1) is dominated by some 1300 m of extremely uniform Lesotho type basalts, locally underlain by small volumes of various other basaltic magma types (Fig. 2). The exceptions are the high-K andesites and dacites of the Pronksberg and Belmore, and they are generally thought to have been derived from within the crust (Marsh and Eales, 1984). In general the rocks of the Central area are among the least trace element enriched of the Karoo lavas, they have Sm/Nd ratios in the range 0.22 to 0.26 (Table I), and most of their initial Nd-isotope ratios are only slightly lower than that of the chondritic reservoir or bulk earth, at 190 m.y. ($\varepsilon_{Nd} = -0.8$ to -2.5). Lower ε_{Nd} values are observed in both the more light REE enriched basalts of the Kraai River (-3.7, -4.1) and in the basal andesites and dacites (-4.0 to -4.9, Table I, Fig. 3).

In the northern area of Nuanetsi and north Lebombo (Fig. 1) the Karoo igneous rocks are characterized by unusually high incompatible element contents; viz. ~900 ppm Sr, ~350 ppm Zr, ~65 ppm Nd compared with ~200 ppm, ~90 ppm and ~14 ppm respectively in, for example, the Lesotho basalts of the Central area (Table I, and Duncan *et al.*, 1984). They are relatively enriched in LREE, their Sm/Nd ratios are low (0.14–0.21), and so too are their initial Nd-isotope ratios ($\varepsilon_{Nd} = -2.8$ to -10.1). No systematic differences in initial $^{143}Nd/^{144}Nd$ were observed between the rocks of the Sabie River, Letaba, or Mashikiri formations; although one Mashikiri nephelinite has unusually low Rb (29 ppm), Nd (37 ppm) and ε_{Nd} (-16.2) values. The two samples of Nuanetsi rhyolite have $\varepsilon_{Nd} = -12.2$ and -11.5, lower than those in any of the underlying basalts or picrites.

Southwards along the Lebombo monocline (Fig. 1) the Mashikiri and then the Letaba formations pinch out (Fig. 2), and at about 25°20′S there is a sharp change in the trace element characteristics of the Sabie River basalts (Cox and Bristow, 1984). They become much less enriched in incompatible elements and have higher Sm/Nd ratios, but these are not accompanied by a consistent change in $^{143}Nd/^{144}Nd$ ratios.

In detail, the initial ε_{Nd} values of the south Lebombo rocks fall into two groups (Fig. 3). The first includes the late dolerites of Swaziland and the Rooi Rand dyke swarm, and two basalts of the Sabie River Formation (J 3 and L 285), which all have slightly positive ε_{Nd} values; together with the main (upper) rhyolites whose $\varepsilon_{Nd} = -0.1$ to -1.1. The second group consists of five Sabie River basalts with very enriched isotope ratios ($\varepsilon_{Nd} = -10.5$ to -19.2) and a sample of the lower interbedded Mkutshane rhyolite ($\varepsilon_{Nd} = -17.1$), which had previously been shown to contain a large component of Archaean crustal Pb (Betton, 1979). The more basic rocks of the first group appear to have been derived from upper mantle source regions which were slightly enriched in incompatible elements, and then not to have interacted with the overlying continental crust. By contrast, the basalts of the second group have similar trace element compositions but much lower ε_{Nd} values, and thus their radiogenic isotope and trace element ratios are strongly decoupled. This "decoupling" might reflect crustal contamination *en route* to the surface, and/or mixing processes during magma generation in the upper mantle.

In north-western SWA/Namibia the volumetrically dominant aphyric Tafelberg basalts and dolerites, together with the plagioclase-phyric Albin basalts, exhibit a range in composition (SiO_2: 48.2–57.5%; MgO: 10.4–2.3%; Zr: 101–237 ppm) within which most major and trace elements exhibit rational trends. These trends can be modelled in terms of fractional crystallization of a number of parental magmas with a range of interelement and isotopic ratios. Erlank *et al.* (1984) have also shown that the basic suite is not related to the more SiO_2-rich latite (Fig. 2) which is highly enriched in incompatible elements (Zr: 460 ppm; Ba: 1110 ppm), nor to the interbedded quartz latites which exhibit a small range in most major and trace elements contents and whose incompatible element contents (e.g. Zr: 258–298 ppm) are only slightly greater than those in the most evolved basalts. The basaltic suite exhibits a range in relative LREE enrichment (Sm/Nd = 0.25–0.19) and corresponding variable Nd isotope ratios which are lower than the bulk earth ($\varepsilon_{Nd} = -3.8$ to -7.4, with one sample KLS 48 = -12.1). The quartz latites have slightly lower ε_{Nd} values (-7.5 to -8.5), although their Sm/Nd ratios overlap with the lower end of the range for the basalts, whereas the latite has the most fractionated Sm/Nd ratio (0.176) and a low $\varepsilon_{Nd} = -8.95$.

The single regional dolerite analysed (KLS 43) is similar geochemically to the less evolved members of the Tafelberg and Albin basic suites, but with slightly lower incompatible element contents (e.g. Zr = 82 ppm). Its age is not known, but KLS 43 has Sm/Nd = 0.232, and $\varepsilon_{Nd} = -4.01$ at 121 m.y. and -3.51 at 190 m.y.

In contrast to the other Karoo rocks analysed from north-western SWA/Namibia, the two Horingbaai dolerites from the coastal area have primitive major element compositions and low incompatible element contents (e.g. Zr = 52–67 ppm). Their REE are relatively unfractionated (Sm/Nd = 0.296 and 0.289) and their $^{143}Nd/^{144}Nd$ ratios are correspondingly radiogenic ($\varepsilon_{Nd} = +6.13$ and $+7.95$, Fig. 3).

V. $^{143}Nd/^{144}Nd$–$^{87}Sr/^{86}Sr$ AND Sm/Nd–Rb/Sr VARIATIONS

The co-variation between initial Nd- and Sr-isotopes is illustrated in Fig. 4; although note that whereas the ε values for most of the Karoo rocks are calculated for 190 m.y., those for the Etendeka samples are for 121 m.y. The dolerites of Horingbaai and the south Lebombo (Rooi Rand), together with two south Lebombo basalts, plot in the so-called "mantle array" (e.g. DePaolo and Wasserburg, 1976), but the vast majority of lavas have positive ε_{Sr} and negative ε_{Nd} values and so fall in the isotopically "enriched" bottom right quadrant. Moreover, it is significant that all the silica-rich rock types have Nd- and Sr-isotope ratios outside the fields defined by the basalts in their particular areas.

The $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ results on the isotopically enriched Karoo lavas in particular appear to describe two distinct trends (Fig. 4). Those from the Central area and north-west SWA/Namibia show large variations in ε_{Sr} with relatively little change in ε_{Nd} resulting in flat lying arrays which are in sharp contrast to the near vertical trend exhibited by the lavas of Nuanetsi and north Lebombo. The higher ε_{Sr}, lower ε_{Nd} samples from the south Lebombo would appear to have intermediate characteristics but, as discussed below, they may reflect late-stage processes during magma genesis. However, a striking aspect of the Karoo rocks is how many of the variations in $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ ratios are mirrored by similar trends between Sm/Nd and Rb/Sr ratios (Fig. 5).

It has been recognized for several years that while trace element enriched basalts tend to have high Rb, Sr and LREE contents and low Sm/Nd ratios, their Rb/Sr ratios vary—presumably depending on the nature of the enrichment processes (Hawkesworth *et al.*, 1979). Similar variations are also observed in the Karoo; samples from the Central area and north-west SWA/Namibia exhibit a range in Rb/Sr but little change in Sm/Nd, whereas the Nuanetsi–North Lebombo rocks which have higher incompatible element contents, and hence lower Sm/Nd ratios, also have relatively low Rb/Sr ratios (Fig. 5). In detail the trace element variations in the Karoo rocks are complicated and in particular it is difficult to assess the effects of alteration on individual samples. However, since the fields on Fig. 5

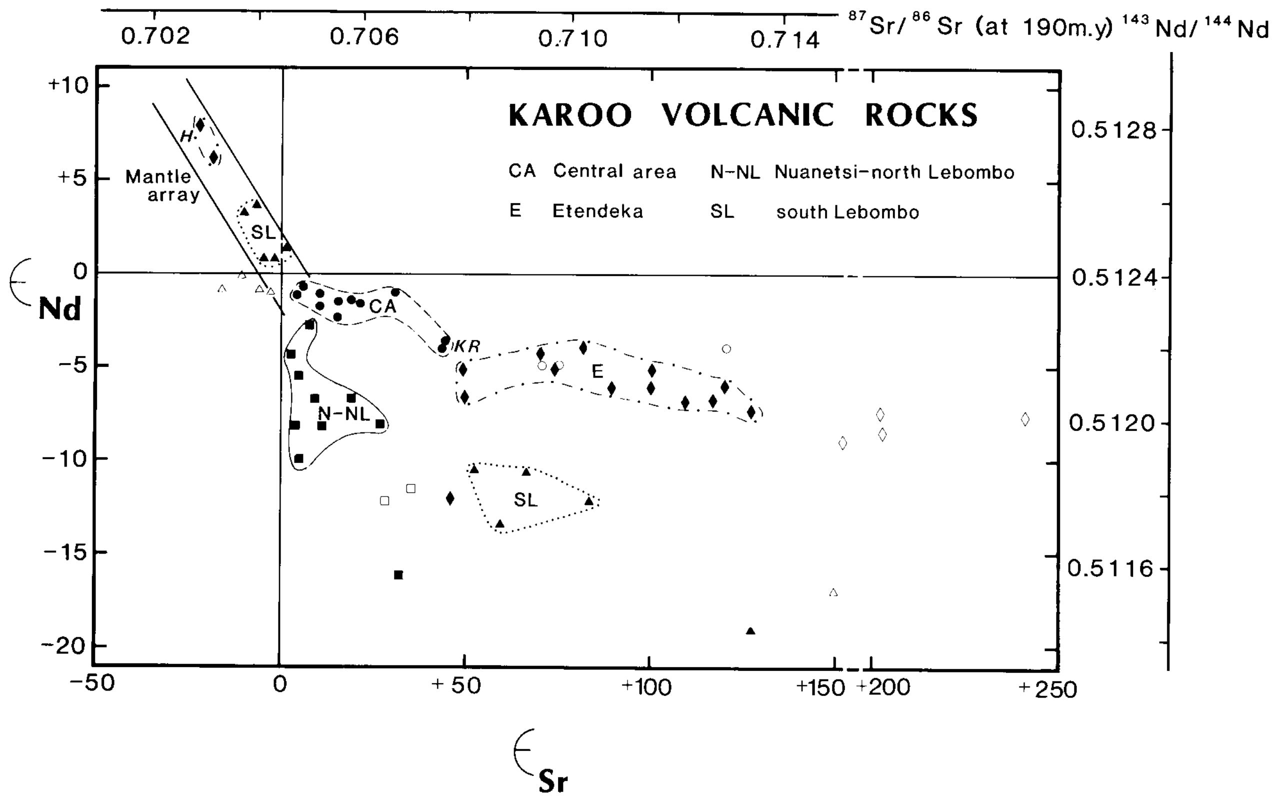

Figure 4

Initial ε_{Nd} and ε_{Sr} values. Circles—Central area, squares—Nuanetsi-north Lebombo, triangles—south Lebombo, diamonds—north-west SWA/Namibia. Filled symbols signify less than 58 % SiO_2, and open symbols greater than 58 % SiO_2. H—Horingbaai dolerites, KR—Kraai River basalts. All initial ratios calculated at 190 m.y., except for the rocks from north-west Namibia for which 121 m.y. was used (Table I). Note that the regional dolerite KLS 43 is not plotted because its age is not known, and that the available Sr-isotope data (Bristow *et al.*, 1984) suggests that there may be a continuum of compositions between the two fields of south Lebombo basalts.

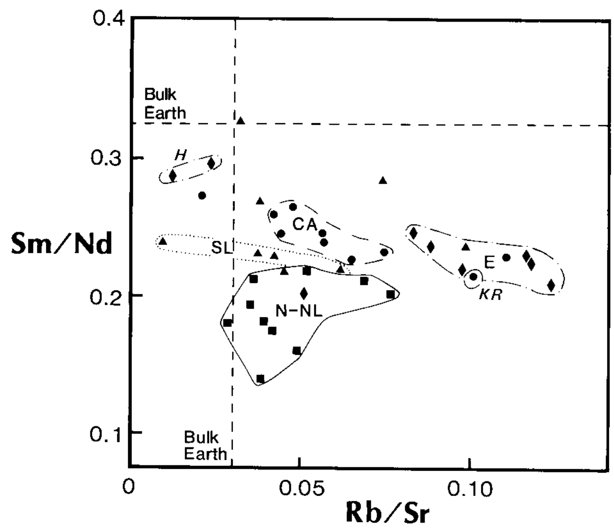

Figure 5

Sm/Nd and Rb/Sr variations in selected Karoo basalts for which Nd- and Sr-isotope results are available. Key as for Fig. 4. Note that average ratios have been used for the Kraai River basalts (see discussion in text), and that the four encircled south Lebombo basalts are those with positive ε_{Nd} values in Fig. 4. L 348 has an Rb/Sr ratio of 0.25 and so plots outside the diagram.

are consistent with the average Rb/Sr ratios of all the basalts analysed from each of the different areas (see Duncan *et al.*, 1984) most of the samples chosen for isotopic study appear not to have been affected significantly by alteration. Two important exceptions are the two Kraai River basalts which have Rb/Sr ratios that vary by an order of magnitude (Table I), so that the average Rb/Sr ratio for Kraai River basalts (0.10, n = 24) has been used in Fig. 5.

In summary we would emphasize the following aspects of the $^{143}Nd/^{144}Nd$–$^{87}Sr/^{86}Sr$ and Sm/Nd–Rb/Sr variations:

1. The *relative* positions of the Central area, Etendeka, Nuanetsi–north Lebombo, and even Horingbaai fields on the Sm/Nd–Rb/Sr diagram are similar to those on the ε_{Nd} *vs* ε_{Sr} diagram. At least in those areas the majority of isotope and parent/daughter trace element ratios appear to be mutually consistent; although it is noticeable that the Etendeka and Kraai River basalts have similar Rb/Sr but different initial $^{87}Sr/^{86}Sr$ ratios.
2. In contrast the isotopically enriched lavas from the south Lebombo do *not* plot in the same relative positions in Figs. 4 and 5: their isotope and trace element ratios are clearly "decoupled".
3. Although the relative positions of many of the fields in Figs. 4 and 5 are similar, their positions in relation to the estimated compositions of the bulk earth on each diagram are different. One explanation is that the Sm/Nd ratios in the source regions of the basalts were around 15 % higher than those now observed in the basalts themselves. The changes in the average ε_{Nd} and ε_{Sr} values of the Central area, Kraai River, Nuanetsi and north Lebombo rocks back in time to 1400 m.y. can be estimated using the average Sm/Nd and Rb/Sr ratios of the basalts. Such calculations indicate that if the mantle source regions beneath these areas ever had the same Nd- and Sr-isotope ratios then (a) those ratios would have been close to those of the bulk earth, and (b) the Sm/Nd ratios in the source regions would have to have been around 15 % higher than those in the basalts. Such a shift in Sm/Nd between basalts and their source rocks might simply reflect the processes of partial melting and fractionation of magmas *en route* to the surface (Cox 1980, 1983).

VI. ROLE OF CRUSTAL CONTAMINATION IN THE GENESIS OF THE KAROO LAVAS

Crustal contamination is used here simply to describe the contamination of magmas by crustal material as they migrate up through the continental crust. It does not apply to attempts to recognize the chemical effects of relict crustal material within the upper mantle (White and Hofmann, 1982) since they are essentially concerned with the origins of inferred isotope and trace element variations in upper mantle rocks, and that is a separate issue. Crustal contamination *sensu stricto* has been attributed to a variety of processes from selective chemical exchange to bulk assimilation (Francis *et al.*, 1980; Thompson *et al.*, 1982), and thus it may be that the debate between crustal contamination and enriched mantle will only be settled once a coherent picture of the trace element and isotope variations in oceanic and continental basalts, and mantle xenoliths, has been established. We return to that debate in the final section, but at this stage it is necessary to outline some of the arguments for and against crustal contamination in the Karoo volcanic rocks.

Crustal contamination acts to modify the composition of magmas *en route* to the surface, and hence it is likely either to generate some broad mixing relation between the original magma and a crustal component, and/or to disrupt any pre-existing relationship between isotope and parent/daughter trace element ratios with the result that the two become "decoupled". Note, however, that although such decoupling is a good indication that there has been a comparatively recent event (which affected the trace element ratios more than the isotope ratios, or *vice versa*), it can be due to different processes. Yet when decoupling is due to mantle processes the basalts and mantle xenoliths tend to be enriched in incompatible elements and have low Sm/Nd, and often slightly high Rb/Sr ratios, with high $^{143}Nd/^{144}Nd$ and low $^{87}Sr/^{86}Sr$ ratios (Hawkesworth *et al.*, 1979; Menzies, 1983; Norry and Fitton, 1983). By contrast, if the decoupling reflects crustal contamination $^{87}Sr/^{86}Sr$

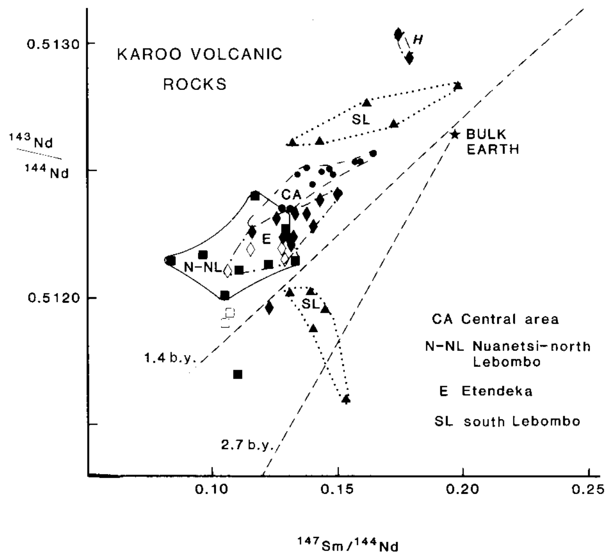

Figure 6

$^{143}Nd/^{144}Nd$ *vs* $^{147}Sm/^{144}Nd$ for the Karoo volcanic rocks; the 1.4 and 2.7 b.y. reference lines are from the crustal xenolith data in Fig. 7. Symbols as in Fig. 4.

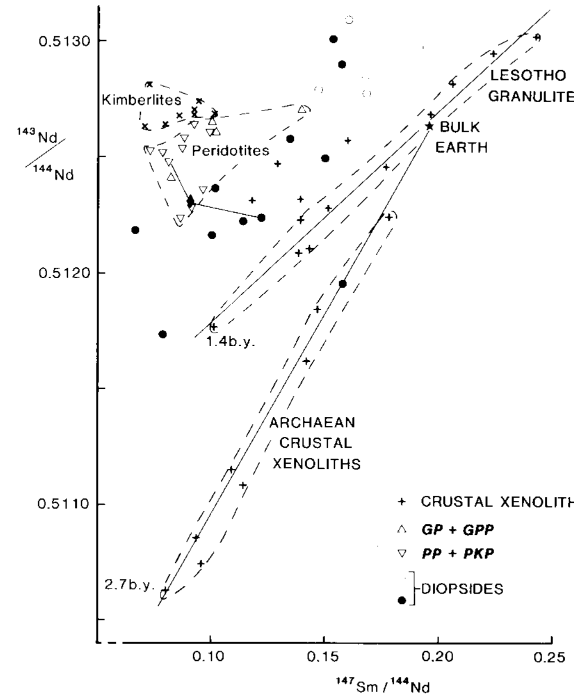

Figure 7

$^{143}Nd/^{144}Nd$ and $^{147}Sm/^{144}Nd$ variations in crustal and mantle xenoliths from southern Africa, after Hawkesworth *et al.* (1983). Data from Basu and Tatsumoto (1980), Menzies and Murthy (1980), Kramers *et al.* (1981), Erlank *et al.* (1982), Rogers and Hawkesworth (1982), and Hawkesworth, Menzies and Erlank (unpubl.). The solid line links co-existing diopside, K-richterite and their whole rock peridotite. Filled circles—diopsides from mantle peridotites, open circles—diopside megacrysts, filled diamond—K-richterite. GP—garnet peridotite, GPP—garnet phlogopite peridotite, PKP—phlogopite K-richterite peridotite, PP—phlogopite peridotite.

may typically be higher, and $^{143}Nd/^{144}Nd$ lower, than would be expected from the relevant trace element ratios in the rocks themselves.

The $^{143}Nd/^{144}Nd$ and $^{147}Sm/^{144}Nd$ ratios of Karoo rocks are presented in Fig. 6, and Fig. 7 summarizes comparable data on crustal and mantle xenoliths from South African kimberlite pipes (Basu and Tatsumoto, 1980; Menzies and Murthy, 1980; Erlank *et al.*, 1982; Rogers and Hawkesworth, 1982; Hawkesworth *et al.*, 1983). Both figures are isochron diagrams and positive straight lines between individual data points and the bulk earth have slopes which correspond to their model Nd, or T^{Nd}_{CHUR} ages (De Paolo and Wasserburg, 1976). In addition, simple two component mixing will also produce linear trends on such diagrams, with either a positive or negative slope (Langmuir *et al.*, 1978).

The majority of Karoo rocks plot in a broad linear array in Fig. 6, with the most obvious exceptions being the five high ε_{Sr}, low ε_{Nd} (or $^{143}Nd/^{144}Nd$) basalts from the south Lebombo. Significantly they comprise the group whose isotope and trace element ratios were most strongly decoupled (Figs. 4 and 5) and, since the sample with the lowest $^{143}Nd/^{144}Nd$ ratio (L348) contains small fragments of what appears to be partially digested granitic material (Cox and Bristow, 1984) and has a model Nd age of 3.6 b.y. it seems reasonable to conclude that this group of basalts has been contaminated with Archaean crust.

The rest of the Karoo lavas tend to have broadly coherent isotope and trace element ratios, and they have similar $^{143}Nd/^{144}Nd$ and $^{147}Sm/^{144}Nd$ compositions to many of the diopsides separated from peridotite xenoliths (Figs. 6 and 7). Nonetheless most of their initial ε_{Sr} and ε_{Nd} values are respectively higher and lower than those of the bulk earth (see Fig. 4) and since these are often regarded as indicative of a crustal origin, considerable efforts have been made to reproduce the chemical and isotopic variations observed within the different Karoo study areas (Fig. 1) by crustal contamination processes (see Marsh and Eales, 1984; Bristow *et al.*, 1984; Erlank *et al.*, 1984). However, with the exception of the high ε_{Sr} south Lebombo rocks discussed above, these efforts have so far met with little success and the present consensus is that crustal contamination has had little significant effect on the chemistry of the vast majority of Karoo volcanic rocks. The key word is "significant", and how that is defined can vary depending on the objectives of the particular project. Here we are concerned primarily with the nature of the source of the Karoo basalts, and how it compares with samples of upper mantle available as xenoliths in kimberlite pipes, and with the relation between basic and more evolved rock types in particular areas. Thus crustal contamination only becomes significant when it has more effect than, for example, local intra-area source heterogeneity and late-stage alteration. Specifically, it would become significant if it were even partially responsible for the *position* of the isotope and trace element fields for the different magma types on Figs. 4, 5 and 6, rather than just for some of the scatter *within* those fields—which might well be due to interaction with crustal material.

In many ways the crux of the argument is that the Karoo basalts include a number of different magma types with different isotope and trace element characteristics. Within the Central area, for example, several magma types are recognized on the basis of trace element ratios such as Ti/Zr and Zr/Nb, and it has been shown that the observed variations in these ratios are extremely unlikely to be due to crustal contamination processes (Marsh and Eales, 1984). On a regional scale, that is, between the different sub-areas in Fig. 1, there are consistent differences in a range of trace elements (Duncan *et al.*, 1984) and these are reflected in the separate Sm/Nd-Rb/Sr fields in Fig. 5, and apparently accompanied by coherent variations in Nd- and Sr-isotopes (Fig. 4). Thus if crustal contamination was responsible for the latter, it implies that it was also responsible for many of the trace element characteristics of the different magma types.

There are many objections to such an explanation for the different magma types in the Karoo, not least the sheer volume of contamination needed to influence so dramatically the composition of the estimated 1×10^6 km^3 of basalt. There would, for example, have to be a specific contaminant for each magma type, at least with respect to Rb/Sr and Sm/Nd ratios, and each batch of magma would have to be well homogenised, since even though different magma types are interbedded there is little or no compositional gradation between them. In both the Central area and north-west SWA/Namibia there are minute volumes of acid volcanics which represent the best evidence for contemporaneous crustal melting, yet in neither area can the isotope and trace element variations in the basalts (e.g. Figs. 4 and 5) be modelled by contamination with such acid material, even if the effects of fractional crystallization are allowed for (Marsh and Eales, 1984; Erlank *et al.*, 1984). Moreover, if, notwithstanding such specific models, the flat-lying and near vertical trends on the $\varepsilon_{Nd}-\varepsilon_{Sr}$ diagram (Fig. 4) are attributed to crustal contamination, the former would presumably reflect the incorporation of high Rb/Sr upper crustal rocks and the latter of low Rb/Sr lower crustal granulite facies rocks (e.g. Carter *et al.*, 1978). But granulites tend to have low U/Pb ratios, and hence with time unradiogenic Pb-isotope compositions; and this contrasts with the rocks of Nuanetsi–north Lebombo which, although they plot on the near vertical trend in Fig. 4, have comparatively radiogenic Pb-isotope ratios (Betton *et al.*, 1984) and are therefore unlikely to have been contaminated by crustal granulites.

Other difficulties with the widespread crustal contamination hypothesis can be illustrated with the results on Fig. 6. It has already been argued that the negative trend of the low $^{143}Nd/^{144}Nd$ south Lebombo basalts could be due to interaction with Archaean crust. However, if the positive trend defined by the majority of Karoo results on Fig. 6 was also due to crustal contamination, the slope of the trend implies that the contaminant was upper Proterozoic in age (that is, it would plot on or above the 1.4 b.y. reference isochron). Yet these basalts crop out on Archaean, Proterozoic, and Pan-African basement (Fig. 1), and there is no clear link between the age of the basement and the distribution of Karoo magma types. Moreover, it is particularly difficult to envisage why upper Proterozoic continental crust should be responsible for the isotope and trace element composition of lavas erupted onto an Archaean craton. In detail, if the isotope and trace element characteristics of the Nuanetsi–north Lebombo rocks were due to crustal contamination of, for example, the high $^{143}Nd/^{144}Nd$ south Lebombo lavas (see Figs. 4 and 6), then ~70–80% of their Nd and Sr contents would be of crustal origin. Yet these rocks include high-Mg picrites (Cox and Jamieson, 1974), and since the assimilation of that amount of crust would consume so much latent heat that the magmas would evolve to lower MgO compositions, such a model is most improbable (see also Cox, 1983).

In summary, the majority of Karoo basalts have higher ε_{Sr} and lower ε_{Nd} than the bulk earth (Fig. 4), and thus on the simplest isotopic arguments might be contaminated by continental crust. We envisage that such contamination will tend either to decouple any pre-existing coherent patterns between isotope and parent/daughter trace element ratios, and/or introduce broad mixing relations between the original magma(s) and any crustal components. In the case of the Karoo "decoupling" between isotope and trace element ratios has been observed in a group of south Lebombo basalts where it appears to be due to contamination with Archaean crust, but in most of the rocks analysed the Nd- and Sr-isotope ratios vary coherently from one magma type to another. Such coherent variations have proved extremely difficult to model satisfactorily by crustal contamination and they are presently believed to have been a feature of the subcontinental mantle in this area — a conclusion which is supported further by the available Nd- and Sr-isotope results on mantle xenoliths in kimberlite pipes (see Fig. 7 and the following discussion).

VII. TIMING OF EVENTS IN THE UPPER MANTLE BENEATH SOUTHERN AFRICA

Nd-isotope studies have been carried out on several suites of both crustal and mantle xenoliths from southern Africa, and the available $^{143}Nd/^{144}Nd$ and $^{147}Sm/^{144}Nd$ ratios are summarized in Fig. 7. Crustal xenoliths from kimberlite pipes on the Archaean craton yield model Nd ages of 2.9 – 2.4 b.y., as do two upper crustal xenoliths from northern Lesotho (Fig. 1). In contrast ten of 14 granulite xenoliths analysed from Lesotho scatter about an errorchron corresponding to an age of 1.4 ± 0.1 b.y. (MSWD = 28), with an initial Nd ratio only slightly higher than that of the bulk earth at that time (Rogers and Hawkesworth, 1982, and Fig. 7). Such results confirm that major crust-forming events took place in the late Archaean and in the upper Proterozoic (1.4–1.0 b.y., see also Barton *et al.*, 1981), and thus provide a framework in which to consider the data from mantle xenoliths in this area.

The relationship between separated mineral and whole rock analyses on mantle xenoliths is illustrated by the solid line joining co-existing diopside, K-richterite, and whole rock points in Fig. 7. In general the diopsides have much higher Nd concentrations and lower $^{143}Nd/^{144}Nd$ ratios than their host rocks (Menzies and Murthy, 1980; Erlank *et al.*, 1982) and they were clearly not in Nd-isotopic equilibrium at the time of their emplacement in the kimberlite (~90 m.y.). The simplest interpretation is that because of their low Nd contents (all but one have between 1–6 ppm Nd) the compositions of the whole rock samples have been more readily affected by interaction with material with high $^{143}Nd/^{144}Nd$ ratios, which in turn suggests that the compositions of the diopsides are the best available indication of the Nd-isotope ratios of these fragments of the upper mantle *before* their whole rock values were disturbed (Hawkesworth *et al.*, 1983).

The diopside with the lowest $^{143}Nd/^{144}Nd$ ratio in Fig. 7 is from an eclogite (Basu and Tatsumoto, 1980), but the remainder are from a variety of peridotite types including garnet phlogopite (GPP) and phlogopite K-richterite peridotites (PKP). Significantly, many of the diopsides plot within the main trend of the Karoo lavas in Fig. 6, and thus support the earlier conclusion that the trace element and Nd- and Sr-isotope ratios of the latter primarily reflect mantle processes, and have been little affected by crustal contamination. Most of the $^{143}Nd/^{144}Nd$ and $^{147}Sm/^{144}Nd$ ratios of the lavas and the diopsides from mantle peridotites are lower than those of the bulk earth indicating that both the xenoliths and the Karoo volcanics were derived from upper mantle source regions which had been variously enriched in LREE for considerable periods of time. Moreover, because most of the data plot above, and arguably with a slightly shallower slope, than the 1.4 b.y. reference lines in Figs. 6 and 7, 1.4 b.y. is a reasonable upper limit for the ages of these LREE enriched mantle source regions, which probably stabilized in the period 1.4–1.0 b.y. Notice, however, that one diopside on Fig. 7 has a 2.7 b.y. model Nd age and that coupled with some of the Pb-isotope data on inclusions in diamonds and on omphacites in eclogites (Kramers, 1979), indicates that at least patches of relict Archaean mantle also survived.

Most mantle peridotites have low Rb/Sr ratios (<0.07) with the result that $^{87}Sr/^{86}Sr$ ratios change slowly with time and it is often difficult to obtain useful age information from the Rb-Sr decay scheme. However, notable exceptions are the garnet-free, phlogopite (PP) and phlogopite K-richterite peridotites (PKP) from the Kimberley area, which have Rb/Sr ratios of 0.1–0.8 and thus could have generated the observed range in $^{87}Sr/^{86}Sr$ (0.7055–0.7104) in just 150 m.y. (Erlank *et al.*, 1982). The data are fairly scattered and their precise age significance is difficult to establish, but the preferred interpretation is that they primarily reflect a sharp increase in Rb/Sr brought about by metasomatism not long after the main Karoo event at ~190 m.y. (Erlank *et al.*, 1980). Such an event is too young to be dated by the Sm-Nd system, but Hawkesworth *et al.* (1983) speculated that it might have been responsible for the inferred displacement of whole rock compositions to higher $^{143}Nd/^{144}Nd$ (Fig. 7). That displacement could simply be due to contamination with the host kimberlite *en route* to the surface, but the fact that so-called "primary" phlogopites also tend to have higher $^{143}Nd/^{144}Nd$ ratios than co-existing diopsides (Basu and Tatsumoto, 1980; Menzies and Murthy, 1980) suggests that the observed Nd disequilibria probably reflect mantle processes.

There is evidence for at least three episodes of trace element enrichment in the upper mantle beneath southern Africa. A few relict fragments of Archaean mantle have been recognized (e.g. Kramers, 1979), but most of the Sm-Nd data on both mantle diopsides and Karoo lavas suggest that they were derived from LREE enriched portions of the upper mantle which stabilized at ~1.4–1.0 b.y. Many of these samples have Rb/Sr ratios which are too low to yield age information from the Rb/Sr system, but reassuringly the average model age of the only high Rb/Sr basalts from the Central area (the Kraai River, Fig. 5) is 1.2 b.y. In north-west SWA/ Namibia the picture is more complex because whereas the average model Nd age of the Etendeka rocks is 0.9 b.y., the average model Sr ages of the primitive samples is 2.0 b.y. (see Erlank *et al.*, 1984). The third trace element enrichment event then postdates Karoo magmatism at ~190 m.y. and was responsible for the metasomatism observed in at least the garnet-free, phlogopite and phlogopite K-richterite peridotites.

VIII. TRACE ELEMENT ENRICHMENT PROCESSES

Trace elements have been widely used, and with increasing success, to model processes of magmatic evolution and at least some aspects of partial melting (Gast, 1968; Allègre and Minster, 1978; Clague and Frey, 1982). However, comparatively little is understood about the processes which determine the inferred trace element variations in the mantle source rocks. Discriminant analysis has identified trends of trace element enrichment and depletion in the sources of basalts, and many studies have recognized that there are different styles of enrichment reflected by significant variations in the ratios between broadly "incompatible" elements (e.g. Pearce and Cann, 1973; Tarney *et al.*, 1980; Pearce, 1982). Moreover, when the variations in a range of trace elements are considered together, as on a mantle-normalized diagram (Fig. 11, and discussion), it is clear that the pattern of trace element enrichment can vary dramatically and is extremely complex. In southern Africa, xenoliths of upper mantle rocks are available from kimberlite pipes over much of the area of Karoo magmatism, and so this discussion concentrates on the extent to which the isotope and trace element compositions of particularly the peridotite xenoliths and the Karoo volcanics may reflect similar mantle processes.

Erlank *et al.* (1982) recently summarized much of the available data on xenoliths from the Bultfontein pipe near Kimberley (Fig. 1). They recognized four different types of peridotite: garnet peridotite (GP) which contains no texturally equilibrated or "primary" phlogopite, garnet phlogopite peridotite (GPP), phlogopite peridotite (PP), and phlogopite K-richterite peridotite (PKP). The latter two groups contain no garnet, while diopside may or may not be present in all four groups. All samples tend to be depleted in basaltic constituents such as Ca and Al, and enriched in incompatible trace elements, consistent with ideas that such xenoliths represent mantle which had undergone basaltic removal prior to trace element enrichment (Shimizu, 1975; Erlank and Rickard, 1977; Menzies and Murthy, 1980; Nixon *et al.*, 1981). However,

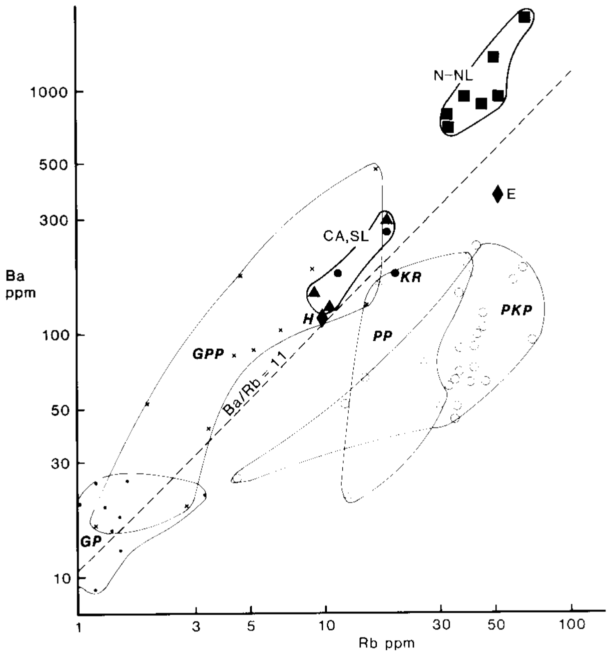

Figure 8
Ba *vs* Rb for peridotite xenoliths (after Erlank *et al.*, 1982) and Karoo volcanics. GP—garnet peridotite, GPP—garnet phlogopite peridotite, PP—phlogopite peridotite, PKP—garnet K-richterite peridotite. Values for the Karoo are average values for different rock units from sub areas within the four areas illustrated in Fig. 1 (compiled by Duncan *et al.*, 1984). Symbols as in Fig. 4.

in detail the *styles* of enrichment vary, since, for example, the GPP rocks have similar Ba but much lower Rb contents than the PP and PKP samples (Fig. 8). Interestingly, such differences cannot be due to original mineralogy (Erlank *et al.*, 1982) and although their origins remain obscure, they are pertinent to the present discussion since similar differences are also observed with the Karoo volcanics. The majority of Karoo magma types appear to follow the GPP style of enrichment, and just two, the Kraai River of the Central area and the Etendeka of north-west SWA/Namibia, have slightly high Rb/Ba ratios similar to those of the PP and PKP rocks (Fig. 8).

$^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ ratios have also been determined on selected examples of the different peridotite types (Fig. 9a). Whole rock analyses range from 0.7043–0.7104 and 0.51272–0.51227 for Sr- and Nd-isotopes respectively (Erlank *et al.*, 1982), while Menzies and Murthy (1980) report present-day $^{143}Nd/^{144}Nd$ ratios as low as 0.51195 on separated diopsides (see also Fig. 7). Particularly for whole rock samples there is a very real danger that their isotopic composition has been altered by interaction with the host kimberlite. However, because all but two of the samples analysed had *higher* $^{87}Sr/^{86}Sr$ ratios than the kimberlite at the time of emplacement (*ca.* 90 m.y.), any interaction with the kimberlite would serve only to *reduce* the $^{87}Sr/^{86}Sr$ of the peridotite xenoliths (Erlank *et al.*, 1982). Such interaction would also increase their $^{143}Nd/^{144}Nd$ ratios, and thus tend to reduce the range of data in Fig. 9. Conversely, the observed variations in Nd- and Sr-isotope ratios in these peridotite xenoliths presumably represents a minimum estimate of the actual range of isotope compositions present in the upper mantle beneath Kimberley today.

The striking aspect of the xenolith isotope data is that it also falls broadly into two groups. PKP and PP rocks have relatively high Rb/Sr and present-day $^{87}Sr/^{86}Sr$ ratios and thus are displaced to the right of the so-called "mantle array" (Fig. 9a), whereas the garnet-bearing peridotites (GP and GPP), which typically have lower Rb/Sr ratios, plot on or near the mantle array. The proximity of some whole rock results to those on kimberlites in Fig. 9a might simply reflect contamination *en route* to the surface, but seven of the nine diopsides plotted are from GPP rocks and

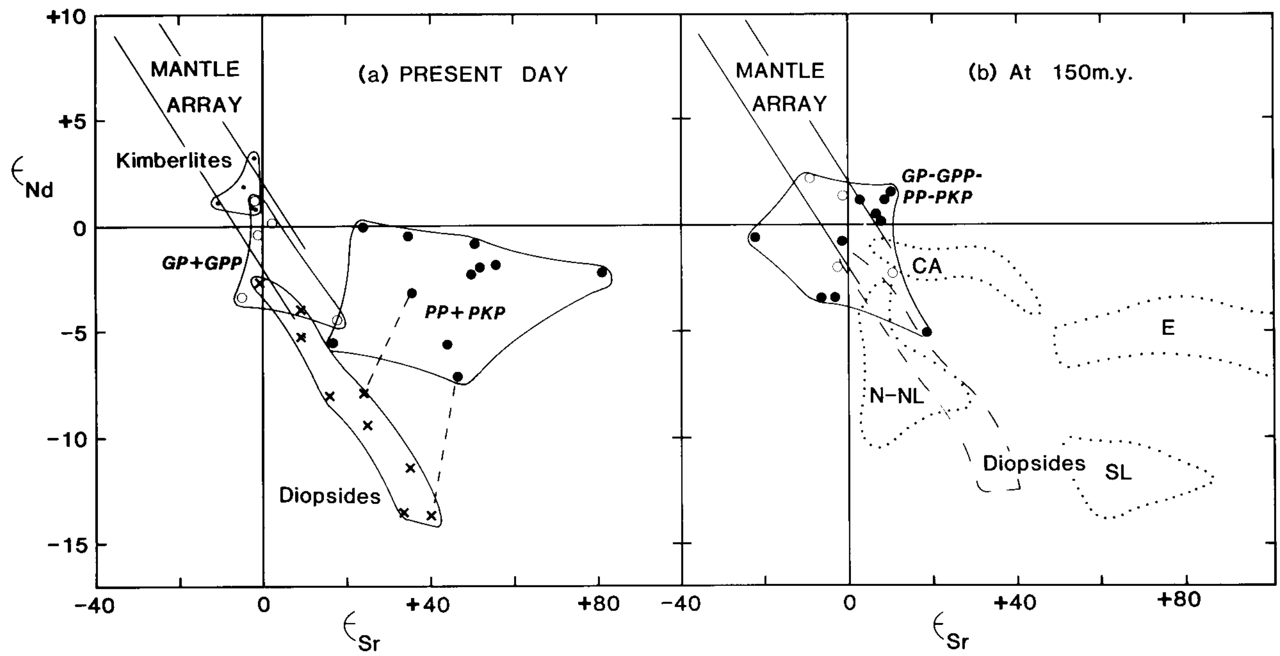

Figure 9
ε_{Nd} *vs* ε_{Sr} for kimberlites, mantle xenolith whole rocks and separated diopsides at the present day and 150 m.y. ago (data from Menzies and Murthy, 1980; Kramers *et al.*, 1981; and Erlank *et al.*, 1982). The dashed lines in Fig. 9a link co-existing diopsides and whole rock samples, and the dashed fields in Fig. 9b are for the Karoo basalts as in Fig. 4.

they clearly fall close to an extension of the mantle array. The two other diopsides are from PKP xenoliths (see tie-lines on Fig. 9a) and are a further indication that isotopic equilibrium did not occur during K-richterite metasomatism (see also Fig. 7 and discussion).

Overall, the present data suggest that there is a broad coherence between some aspects of the trace element variations (Rb, Sr, Ba, Sm, Nd) and Nd- and Sr-isotope ratios, and significantly *that coherence is observed in both* mantle xenoliths and Karoo volcanic rocks. One style of enrichment results in low Sm/Nd ($PKP_{ave.}$ = 0.16), high Rb/Sr ($PKP_{ave.}$ = 0.35), high Rb/Ba (Fig. 8) and consistently high $^{87}Sr/^{86}Sr$ ratios: and it is seen in PKP and PP mantle xenoliths and Kraai River and Etendeka Karoo volcanics. The second style also results in low Sm/Nd ratios, but it appears not to fractionate the Rb/Ba (Fig. 8) or Rb/Sr ratios to any marked extent and the Nd- and Sr-isotope ratios consequently tend to remain on or close to the mantle array (Fig. 9); for example, GP and GPP xenoliths and many of the Central area and Nuanetsi–north Lebombo Karoo rocks. Finally, although it is convenient to describe these data in terms of two styles of enrichment, it must be emphasized that they are likely to represent just two examples from a continuum of possible enrichment trends.

While such trace element and isotope similarities between lavas and peridotite xenoliths are encouraging, they have deliberately been termed enrichment "styles" particularly because the high Rb/Sr enrichments of the high $^{87}Sr/^{86}Sr$ Karoo rocks and the PP and PKP xenoliths are thought to have taken place at different times. The linear array of the Karoo data on Fig. 6, and the 1.2 b.y. average model Sr age of the Kraai River basalts, suggest that both the low Sm/Nd, high Rb/Sr rocks of the Kraai River were derived from source regions which had been enriched in trace elements for ~1.0 b.y. before the Karoo event. Similar ages may be inferred from the results on mantle diopsides (Fig. 7) and thus both the Karoo lavas and mantle xenoliths in kimberlite pipes appear to have sampled trace element enriched upper mantle material of upper Proterozoic age—which perhaps stabilized soon after the orogenic activity in the Namaqua–Natal belt (Fig. 1) (Rogers and Hawkesworth, 1982). The PP and PKP xenoliths by contrast have such high Rb/Sr ratios (average 0.43 and 0.35 respectively) that their relatively high $^{87}Sr/^{86}Sr$ ratios reflect a much younger enrichment event at around 150 m.y. (see section VII). This difference in the age particularly of the high Rb/Sr enrichments observed in these xenoliths and inferred in the source of some of the Karoo lavas is illustrated by recalculating the xenoliths isotope ratios at 150 m.y. (Fig. 9b). At that time the xenoliths had a much more restricted range in Nd- and Sr-isotopes than the Karoo volcanic rocks and so clearly reflect a different trace element enrichment event.

Finally in this section we consider briefly some general trace element characteristics of the Karoo lavas, and in particularly address the question of whether early subduction episodes influenced the inferred source compositions of the Karoo volcanics. Cox (1983) demonstrated that on a Ti–Y–Zr discriminant diagram (Pearce and Cann, 1973) the basalts of the south Lebombo and the Central area plot in the fields of calc-alkaline basalts, ocean floor basalts and low-K tholeiites. Similarly the Karoo, in common with some other continental flood basalt provinces, is characterized by relatively high SiO_2 and Al_2O_3 contents—features also shared by calc-alkaline basalt suites. Fig. 10 illustrates the variation in Nb/Ba and Rb/Ba ratios in the Karoo lavas and mantle xenoliths and compares them with data on basalts from both destructive plate margins and ocean islands. The Rb/Ba ratio discriminates between the two styles of enrichment already discussed (Fig. 8), and Nb/Ba may distinguish arc magmas from those generated in other tectonic settings. Gill (1981) argues that a Ba/Ta ratio greater than 450, which is arguably equivalent to Nb/Ba less than 0.04, is the single most diagnostic feature of an arc magma.

On Fig. 10 the majority of Karoo magma types plot in a broad linear trend anchored at one end in the field defined by subduction zone related magmas—in this case illustrated by the averages of circum-Pacific basalts and basaltic andesites compiled by Ewart (1982). Relative to estimates for the primitive mantle, or to typical trace element enriched ocean island volcanics from Hawaii and the Azores, all these Karoo lavas have low Nb/Ba ratios; and the more enriched rocks of Nuanetsi–north Lebombo in particular have Nb/Ba ratios low enough to be mistaken for arc-related magmas. The exceptions to the main trend of Karoo lavas are the nephelinites of the Mashikiri Formation, which are not shown in Fig. 10 but have slightly lower Rb/Ba ratios (~0.035), and the high Rb/Ba, high $^{87}Sr/^{86}Sr$ rocks of the Kraai River and the Etendeka.

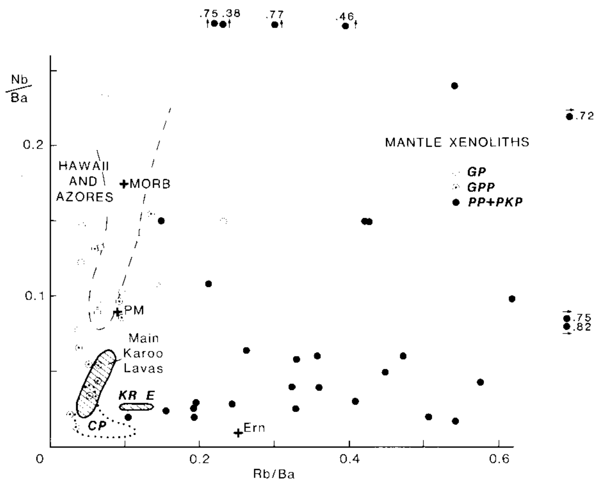

Figure 10

Nb/Ba *vs* Rb/Ba for mantle xenoliths compared with fields for basalts from Hawaii (Clague and Frey, 1982), the Azores (Norry, unpubl.) the Karoo, and circum-Pacific (CP) basalts and basaltic andesites (from averages compiled by Ewart, 1982). The field for the main Karoo lavas encompasses the average values for different rock types from different sub areas compiled by Duncan *et al.* (1984) and used in Fig. 8. PM—primordial mantle values, used for normalization in Fig. 11. Ern—Average of Ernici High-K volcanics, Italy (Civetta *et al.*, 1981). KR—Kraai River. E—Etendeka.

The peridotite xenolith data are highly variable, presumably reflecting the minute volumes of mantle they represent. Nonetheless many of the GPP samples again plot close to the main trend of the Karoo rocks (see also Figs. 8 and 9a). The PP and PKP xenoliths typically have high Rb/Ba ratios and those which do not contain complex Ba–Sr–Ca–Zr–Cr titanates also tend to have low Nb/Ba ratios. Moreover, for connoisseurs of the "Italian controversy" it is noticeable that recent Italian volcanics have low Nb/Ba and high Rb/Ba ratios similar to those of the PP and PKP rocks (data from Civetta *et al.*, 1981). Thus although much of this work is still very preliminary, there do appear to be some broad similarities in the isotope and trace element trends in these peridotite xenoliths and those in basalts. The $^{143}Nd/^{144}Nd$, $^{87}Sr/^{86}Sr$, Rb/Sr, Sm/Nd, Rb/Ba and Nb/Ba ratios are consistent with a model in which the majority of Karoo basalts were derived from upper mantle material that had undergone a similar style of trace element enrichment to that observed in GPP xenoliths, while the results on the Kraai River and Etendeka rocks suggest some affinity with the PP and PKP style of enrichment. In detail there are still difficulties. For example, it is not clear why the average Zr/Nb ratios in the xenoliths (3–5) are much less than those in the Karoo basalts which are typically >10

(Duncan *et al.*, 1984), and since in the oceanic environment Zr/Nb ratios of >15 are characteristic of derivation from a depleted source (Erlank and Kable, 1976).

An important feature of the xenolith data in Fig. 10 is that so many of the GPP, PP and PKP rocks have low Nb/Ba ratios, for relatively low Nb contents have recently been observed in several continental flood basalt provinces (e.g. Basaltic Volcanism Study Project, 1981, and discussions by Weaver and Tarney, 1983; and Thompson *et al.*, 1983). Fig. 11 illustrates mantle-normalized trace element patterns for four basalts from different areas within the Karoo, and compares them with selected basalts from within plate, destructive plate margin and MOR environments. The Karoo rocks exhibit variable relative abundances of Rb, Ba, Th and K, but all contain significant Nb anomalies which tend to be accompanied by low Sr and P contents relative to the REE, Zr and Hf in particular. Similar features are observed in BCR-1 (Columbia River) and to a lesser extent in the tholeiites from Hawaii and the Deccan (Fig. 11b). However, what is clear from both Figs. 11a and 10 is that relatively low Nb contents occur in rocks of very different Rb/Ba ratios (and Nd- and Sr-isotope trends), which suggests that the two features are not related and that the observed trace element patterns probably reflect a multi-stage history.

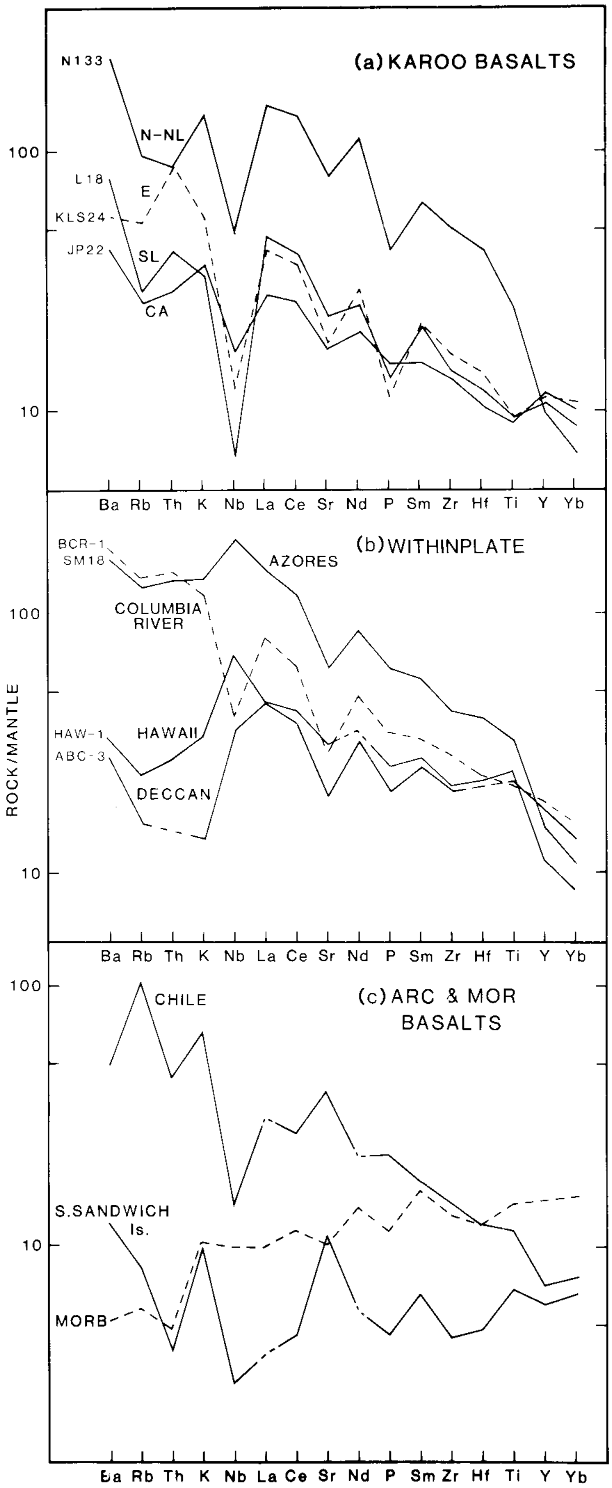

Figure 11

Mantle-normalized trace element patterns for (a) selected Karoo basalts, (b) within plate basalts from the Azores (alkali basalt), Hawaii, the Deccan and Columbia River (all tholeiites) and (c) MORB and two subduction zone related rocks. Normalization values after Thompson *et al.* (1982), with the exception of Ba = 3.85 ppm. Other data from Flanagan (1973), Basaltic Volcanism Study Project (1981), Pearce (1982), Norry (unpubl.) and Cox and Hawkesworth (unpubl.).

Low Nb abundances are a feature of subduction zone related magmas (Fig. 11c after Pearce, 1982) and thus the negative Nb anomalies in the Karoo rocks (Fig. 11a) could reflect the presence of the subduction zone component. The isotope evidence indicates that such a component would be upper Proterozoic in age, consistent with active subduction during the formation of the Namaqua–Natal belt (Fig. 1), and with ideas of a buoyant continental lithosphere formed by depleted (in major element terms) residual material rising from subducted oceanic lithosphere (Oxburgh and Parmentier, 1978). However, this hypothesis requires that the negative Nb anomalies in the Karoo rocks are unrelated to their relatively low Sr contents, since destructive plate margin rocks typically have high Sr/Nd and Sr/Ce ratios (see Fig. 11c, De Paolo and Johnson, 1979; Hawkesworth and Powell, 1980; Pearce, 1982). Thus an alternative and at present equally tenable interpretation is that the coherent variations in Nb, Sr and P in the Karoo rocks reflect the same process(es), and that their negative anomalies are due to scavenging by CO_2-rich fluids at some early stage in the evolution of their source rocks.

IX. CONCLUSIONS

Selected samples from four areas within the Karoo magmatic province have been analysed for Nd- and Sr-isotopes and, since the majority have negative initial ε_{Nd} and positive initial ε_{Sr} values (Fig. 4), they must contain at least a component from a source which was both old and had lower Sm/Nd and higher Rb/Sr ratios than the bulk earth. The basaltic rocks exhibit regional variations in trace element compositions, and apart from a suite of high ε_{Sr} rocks from the south Lebombo, broadly coherent trends are observed between Sm/Nd–Rb/Sr and $^{143}Nd/^{144}Nd$–$^{87}Sr/^{86}Sr$ ratios. The decoupling of isotope and trace element ratios in those south Lebombo rocks is most simply explained by contamination with Archaean crust *en route* to the surface, but elsewhere in the Karoo it appears that crustal contamination has not had a significant effect on the isotope and trace element composition of the various basaltic magma types. The dominant basalts of the Central area, the relatively low $^{143}Nd/^{144}Nd$ rocks of Nuanetsi–north Lebombo, and the relatively high $^{87}Sr/^{86}Sr$ rocks of the Kraai River could all have been derived from upper mantle source regions which had been variously enriched in incompatible elements *ca.* 1.0 b.y. before the Karoo event. The Etendeka volcanics of north-west SWA/Namibia are more problematical in that although their Nd-isotopes are consistent with such an interpretation, their Rb/Sr and $^{87}Sr/^{86}Sr$ ratios imply an older enrichment event. However, these lavas crop out on basement which was remobilized during the Pan-African (750–500 m.y.) and it may be that their discordant model Nd and Sr ages are an indication that their mantle source regions were disturbed by subduction in Pan-African times.

The existence of old (Upper Proterozoic) trace element enriched mantle beneath southern Africa is confirmed by the isotope and trace element results on peridotite xenoliths from kimberlite pipes in the Kimberley area (Menzies and Murthy, 1980; Erlank *et al.*, 1982). Significantly, however, it also appears that there are some similarities in the *styles of enrichment* observed in both the mantle xenoliths and the Karoo lavas. Garnet phlogopite peridotites (GPP) are enriched in incompatible elements and thus have low Sm/Nd ratios, but they tend to have relatively low Rb/Sr ratios so that with time they develop $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ ratios on or close to the extension of the "mantle array" (Fig. 9). In contrast, garnet-free peridotites containing primary phlogopite (PP), or both phlogopite and K-richterite (PKP), have similarly low Sm/Nd but high Rb/Sr ratios, and hence relatively high $^{87}Sr/^{86}Sr$ ratios. The majority of Karoo lavas in the Central area, Nuanetsi and north Lebombo share those features with the GPP style of enrichment, while the basalts of the Kraai River and the Etendeka are examples of volcanic rocks with similar trace element characteristics to the garnet-free peridotites. These variations are deliberately termed "styles of enrichment" because they do not necessarily reflect the same event and, for example, the high Rb/Sr enrichment in the PP and PKP xenoliths occurred ~1.0 b.y. after that inferred in the source of the basalts. Further comparisons between the trace element compositions of xenoliths and volcanics are still at a preliminary stage, and while similarities exist for ratios such as Rb/Ba and Nb/Ba (Figs. 8 and 10) the Karoo rocks tend to have unusually high Zr/Nb ratios which are 2–4 times higher than the average values for the peridotite xenoliths.

In the preferred model it is envisaged that considerable amounts of new continental crust were generated around the margins of the Archaean craton in the upper Proterozoic (1.4–1.9 b.y., Barton *et al.*, 1981; Rogers and Hawkesworth, 1982; Hawkesworth *et al.*, 1983) during the formation of the Namaqua–Natal belt (Fig. 1). That orogenic episode may have introduced subducted material into the subcontinental mantle, and on cooling it greatly increased the area of stable continental crust and the volume of upper mantle stabilized within the lithosphere. The result was segments of trace element enriched mantle of upper Proterozoic age which appear to have been present beneath both Archaean and Proterozoic crust, and whose inferred trace element characteristics are consistent with contributions from both subduction zone and intraplate enrichment processes. This enriched mantle was the principal source of the Karoo volcanics, and at least in the Kimberley area the Karoo magmatic event was followed by, and may well have initiated, the K-richterite metasomatism observed in peridotite xenoliths. Moreover, although in detail the temporal relationships across the Karoo province are still poorly understood, there is some evidence for a shift in source regions whereby most of the Karoo basalts were generated with the lithosphere, and the late dykes of the Rooi Rand and Horingbaai and the fluids involved in the post-Karoo metasomatism, were then derived from the underlying convecting upper mantle.

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