

## Preliminary note on the geochemistry of basalt samples from the Kudu boreholes

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Major and trace element concentrations, together with limited mineral and isotopic compositions, have been determined in 17 subaerial basalt samples recovered from the three Kudu wells (K9A1, K9A2 and K9A3) approximately 180 km west of Oranjemund. The primary purpose of this study is to characterise these basalts and their compositional variations, and to attempt to elucidate their oceanic or continental origin and tectonic setting. Full details of the stratigraphy of the boreholes are presented elsewhere in this volume by Wickens and McLachlan (1990), but it should be noted at the onset that the samples analysed are interbedded with what are considered to be dominantly aeolian sand-stones

of Barremian age which are presumed to be associated with the initial rifting of the South Atlantic.

The primary feature of these samples is that they are all, to varying degrees, altered by post-crystallisation low temperature sea-water alteration processes. This is immediately apparent macroscopically, with some sections of the core being highly amygdaloidal (zeolites, calcite, quartz, chlorite), and is confirmed by thin section observation. In some samples, the original mineralogy has been completely replaced by secondary minerals such as serpentine, chlorite, K-feldspar, calcite and haematite, with olivine pseudomorphs being present in several samples. Remnants of augite and calcic plagi-

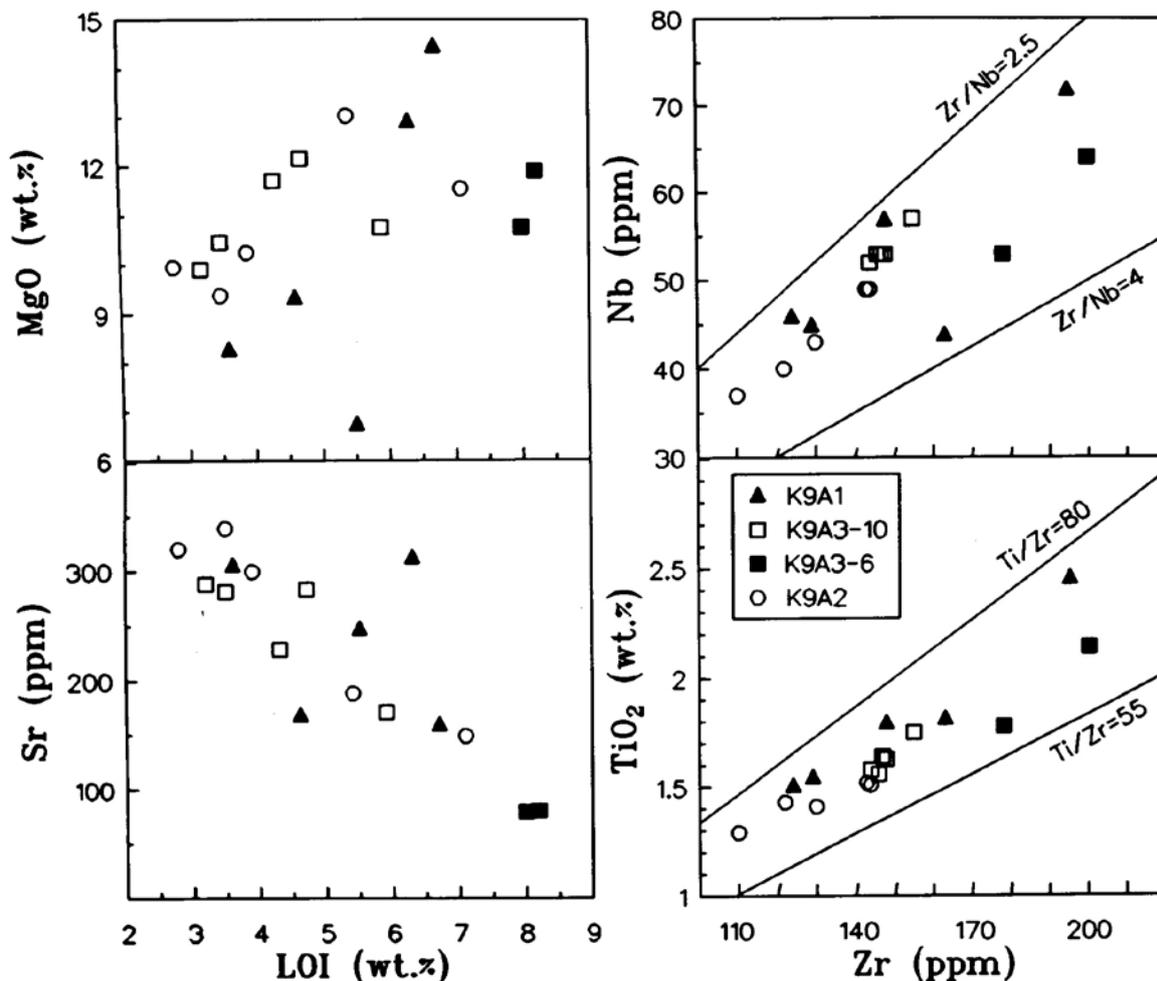


Fig. 1: Major and trace element variation diagrams for selected samples from the Kudu boreholes. LOI = Loss on Ignition.

oclase are still preserved in a few samples. Microprobe analyses indicate that the freshest plagioclase is An<sub>72</sub> while highly altered plagioclase laths reach Ab<sub>98</sub> (with 11 % Na<sub>2</sub>O and 0.34% CaO); some plagioclase rims have been converted to K-feldspar. This indicates that Na and K have been added, while Ca has been removed, during alteration. Augites are much less altered and average about Wo<sub>45</sub>En<sub>45</sub>Fs<sub>10</sub>. Unaltered augites have 0.8 - 1.4% TiO<sub>2</sub> and around 0.3% Na<sub>2</sub>O and thus do not clearly indicate the lineage of the basalts.

The major and trace element chemistry, as shown by selected samples presented in Table 1, further demonstrates the nature of the alteration processes. Thus loss

on ignition (LOI), a measure of H<sub>2</sub>O<sup>+</sup> and CO<sub>2</sub> contents, is generally high, ranging from 2.8 to 8.2%. As indicated in Fig. 1, MgO shows a well-developed positive correlation with LOI, testifying to addition of Mg during serpentinisation and chloritisation of olivine and augite. Fig. 1 also shows that Sr is removed during alteration. This is also the case for Ca (not shown), in accord with the microprobe analyses discussed above. Other elements such as Na, K, Pb and Ba show erratic variations. These elemental changes in concentration during alteration are in accord with other studies concerned with sea-water alteration of ocean-floor basalt.

Definite evidence for alteration is provided by oxy-

TABLE 1: Selected analyses for Kudu and other basalts.

	K9A1 C-3	K9A2 7-10	K9A3 6-2	K9A3 10-2	Eten- deka	Walvis Ridge	Gough Island
SiO <sub>2</sub>	52.15	46.90	47.49	47.73	51.28	48.80	50.35
TiO <sub>2</sub>	1.47	1.24	1.60	1.52	0.99	1.27	3.08
Al <sub>2</sub> O <sub>3</sub>	14.54	14.84	14.68	14.93	14.67	16.04	14.31
Fe <sub>2</sub> O <sub>3</sub>	6.02	9.02	7.90	9.82	11.70	9.83	10.17
MnO	0.09	0.12	0.08	0.16	0.18	0.15	0.14
MgO	7.85	9.56	9.68	9.53	6.71	7.00	7.10
CaO	8.33	11.10	4.94	8.92	10.39	11.42	9.17
Na <sub>2</sub> O	2.48	2.06	1.85	1.80	2.09	2.80	3.24
K <sub>2</sub> O	1.39	0.90	1.69	1.44	0.82	0.48	2.11
P <sub>2</sub> O <sub>5</sub>	0.37	0.25	0.34	0.35	0.12	0.14	0.56
LOI	3.60	2.83	8.01	3.21	1.11	0.97	0.73
H <sub>2</sub> O-	0.65	1.53	1.00	1.21	0.28	1.86	
Total	98.94	100.36	99.27	100.62	100.34	100.76	100.96
Zr	122	106	161	139	112	81	275
Nb	43	36	48	50	7.4	11	46
Y	20	19	22	23	24	23	31
Rb	33	22	29	33	19	9.3	42
Ba	321	215	190	323	215	153	578
Sr	290	307	71	277	214	251	716
La		20	25	28	14		92
Ce		37	44	58	32		99
Nd		23	26	33	19		54
Co	39	50	47	53	54	49	43
Cr	482	717	528	558	72	48	187
Ni	154	285	188	224	62	50	149
Zr/Y	6.0	5.6	7.3	6.1	4.7	3.5	8.9
Zr/Nb	2.8	3.0	3.4	2.8	15	7.4	6.0
Y/Nb	0.47	0.53	0.46	0.45	3.2	2.1	0.67
Ba/Nb	7.5	6.0	4.0	6.5	29	13.9	12.6
Ti/Zr	72	70	60	66	54	94	67
Ti/P	5.5	6.8	6.5	6.0	11.3	12.5	7.5
Ce/Nd		1.6	1.7	1.8	1.7		1.8
Mg no.	75	70	74	69	57	63	60
δ <sup>18</sup> O (‰)		9.65	10.69	9.02			

Major elements in wt%, trace elements as ppm. Total Fe as Fe<sub>2</sub>O<sub>3</sub>. Mg no. is Mg number or atomic ratio of Mg/(Mg + Fe<sup>2+</sup>) based on whole-rock Fe<sub>2</sub>O<sub>3</sub>/FeO = 0.20.

Sample C-3 is the third of four ditch cutting samples from a depth of 4340 - 4450 m. 7-10 is from core 7, 4436 m; 6-2 is from core 6, 4357 m; and 10-2 is from core 10, 4441 m.

Etendeka basalt is sample KLS 24 from Erlank *et al.* (1984); Walvis Ridge basalt is sample 528-39-1 from Richardson *et al.* (1984); and Gough Island basalt is sample ALR 259 from Le Roex (1985).

gen isotope analyses of 4 samples which yielded  $\delta^{18}\text{O}$  values of 9.0 - 10.7 ‰, with the sample with lowest LOI still having a high value (sample 7-10 in Table 1). These values should be compared with an expected upper mantle value of 5-6‰. CIPW norms, using a whole-rock  $\text{Fe}_2\text{O}_3/\text{FeO} = 0.20$ , reveal that the most altered samples have corundum instead of clinopyroxene in their norms. However, the “freshest” sample is olivine normative, consistent with pseudomorphs of pre-existing olivine phenocrysts. None of the samples are nepheline normative.

On face value the samples appear to be high-Mg tholeiitic basalts ( $\approx 10\%$  MgO), with primitive Mg-numbers around 70, and high Cr (560 - 810 ppm) and Ni (140 - 310 ppm) contents. However, this classification and the highest Cr and Ni concentration levels reached must remain suspect in view of the effects of alteration on MgO concentrations (Fig. 1). The immobile minor and trace elements (Ti, P, Zr, Nb, Y, La, Ce, Nd) show smaller variations and interelement ratios between any pair of these elements are remarkably constant (Table 1 and Fig. 1), suggesting that the basalts from all three boreholes are derived from a similar parent magma.

Apart from the constant interelement ratios referred to above, the most interesting aspect of the geochemistry of the Kudu basalts concerns the high Nb contents (34 - 52 ppm), reflected in relatively low Zr/Nb (2.8 - 3.4) and Y/Nb (0.32 - 0.56) ratios. These characteristics indicate that these basalts are somewhat unique in view of their inferred olivine-normative tholeiitic character, since high Nb contents and low Zr/Nb and Y/Nb ratios are typical of ocean island basalts or undersaturated varieties such as melilitites and nephelinites. Furthermore, these characteristics allow ready comparison with other basaltic types - see Table 1 for comparative analyses of a 130 Ma Tafelberg basalt from the Etendeka in north-west Namibia, an enriched plume-type basalt from the

Walvis Ridge, and a basalt from Gough Island. It is apparent that the Kudu basalts are not offshore equivalents of the Etendeka basalts, as might be suggested by the Barremian age (115 Ma) of the sediments hosting the Kudu basalts, nor for that matter do the Kudu basalts show any similarities to Karoo basalts (180 Ma) in southern Namibia (Erlank *et al.*, 1984). The Walvis Ridge sample has chemical characteristics which more closely match the Kudu samples, but the closest match in composition, especially considering Zr/Nb and Y / Nb ratios, is clearly the samples from Gough Island.

At this stage the Kudu basalts appear to be most similar to within-plate basalts of asthenospheric origin. Whether this is compatible with a subaerial origin in a coastal dune complex, as suggested by Wickens and McLachlan (1990), is not yet clear.

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