

PETROGRAPHY, GEOCHEMISTRY AND Sr-Pb ISOTOPIC COMPOSITION OF BASALTS FROM THE WESTERN INDIAN OCEAN (DSDP - SITES 235, 236, 239, 240)¹

by

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(10 figures and 7 tables)

RESUME.- Les Legs 24 (sites 235 et 236) et 25 (sites 239 et 240) du DSDP ont échantillonné des basaltes anciens (60-75Ma) sur le fond de la partie ouest de l'Océan Indien.

La plupart des échantillons étudiés sont des tholéiites altérées, à structure porphyrique. Le plagioclase, le clinopyroxène augitique et l'olivine serpentinisée sont les principaux phénocristaux. La chromite n'apparaît que localement, en microphénocristaux. L'orthopyroxène n'a été trouvé que dans un seul échantillon du site 236.

Géochimiquement, les basaltes des différents sites sont variables : les variations observées des rapports FeOtot/MgO et du contenu de certains éléments en trace (éléments de transition, terres rares) ne peuvent pas être expliquées par un simple processus de cristallisation fractionnée. Par ailleurs, les variations de composition isotopique en Sr et en Pb impliquent des hétérogénéités géochimiques dans le manteau supérieur, région-source des basaltes.

Nos données, couplées à celles publiées pour d'autres échantillons de l'Océan Indien, montrent le caractère plus radiogénique (en Sr et en Pb) des roches de l'Océan Indien par rapport à celles du Pacifique et de l'Atlantique, ce qui confirme l'existence d'une anomalie isotopique à grande échelle dans le manteau de l'hémisphère Sud (l'anomalie Dupal de Hart, 1984).

ABSTRACT.- DSDP Legs 24 (Sites 235 and 236) and 25 (Sites 239 and 240) sampled basalts from old (60-75 MA) ocean floor in the Western Indian Ocean. Most of the samples are altered porphyritic quartz tholeiites. The main phenocryst phases are : plagioclase, augitic clinopyroxene and serpentinized olivine. Chromite occurs only locally; orthopyroxene has been found in only one sample of Site 236.

The different sites appear geochemically quite variable; they show differences in the FeOtot/MgO ratios, in transition element contents and in REE patterns which cannot reasonably be explained by fractionnal crystallization processes. Moreover, variations in both Sr and Pb isotopic compositions suggest heterogeneities in the mantle source-region.

Our data, together with those reported in the literature for other Indian Ocean rocks show more radiogenic Pb and Sr isotopic compositions than Atlantic and Pacific oceanic rocks which confirms the existence of a large scale isotopic anomaly in the southern hemisphere mantle (Dupal anomaly of Hart, 1984).

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INTRODUCTION

Basalt samples were obtained on Legs 24 (Sites 235 and 236) and 25 (Sites 239 and 240) of the Deep Sea Drilling Project (DSDP) in the Western Indian Ocean (fig. 1). Table 1 gives some information on these sites. The Sites 235 and 236 are located in the Somali Basin to the North of the Mascarene plateau, while Site 240 lies between the Seychelles bank and the African coast. Site 239 is situated further south, between Reunion Island and Madagascar.

In each case, the age of the basalt was estimated from the chronology of the magnetic anomalies - scale of Heirtzler *et al.* (1968) and McKenzie & Sclater (1971), revised by Schlich (1974) - and/or from the biostratigraphic age of the superimposed sediments (Initial Reports of DSDP). The basalt ages range from Upper Cretaceous (75 Ma) for Sites 235 and 239 to Upper Paleocene (58 Ma) for Site 236.

The aim of this paper is to define the petrological and geochemical character of these basalts as well as their Sr and Pb isotopic composition and to compare these data with mid-ocean ridge basalts (MORB) in general and with other Indian Ocean rocks in particular.

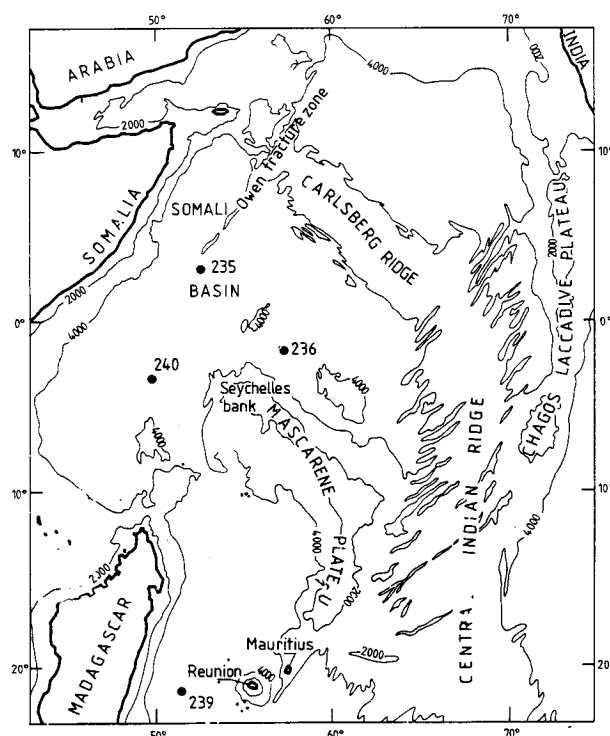


Figure 1.- Schematic map of the Western Indian Ocean with location of the studied sites.

Table 1.- Location of the studied sites

Leg	Site	Latitude	Longitude	Total Penetration (m)	Penetration in basalt (m)
24	235	03°14.06'N	52°41.64'E	684.0	32.5
	236	01°40.62'S	57°38.85'E	327.5	21.5
25	239	21°17.67'S	51°40.73'E	326.0	6.0
	240	03°29.28'S	50°02.42'E	195.0	3.0

ANALYTICAL METHODS

The major element composition and the concentrations of trace elements Rb, Sr, Y and Zr have been determined by X-ray fluorescence (M. Delvigne and F. Durez, Museum of Central Africa, Tervuren). Rare Earth Elements (REE) and other trace elements (except Ni which was measured by atomic absorption) were determined by instrumental neutron activation analysis. After a 7 hr irradiation at a neutron flux of $2.10^{12} \text{ n.cm}^{-2} \text{ s}^{-1}$ in the Thetis reactor of the Institute of Nuclear Sciences, Gent University, the induced gamma-ray activities were measured with large volume

coaxial Ge(Li) detectors and a planar 0.4 cm³ extra high resolution low energy Ge(Li) detector (Hertogen & Gijbels, 1971). USGS AGV-1 reference rock and secondary in-house reference rocks were used as standards.

The isotopic composition of Sr separated on ion exchange columns has been measured by thermoionisation on double Re filament with a FINNIGAN MAT 260 mass spectrometer from the «Centre Belge de Géochronologie». Values are normalized to ⁸⁶Sr/⁸⁸Sr ratios of 0.1194. The NBS 987 Sr Standard gives as a mean ⁸⁷Sr/⁸⁶Sr = $0.710237 \pm 12(2\sigma_M)$ for 17 measurements.

After dissolution of 200 mg of whole rock sample by a HF-HClO₄ mixture in a teflon bomb, Pb is extracted on anion exchange column in 1M HBr/0.1 M HCl medium. The Pb isotopic composition is analyzed on single zone - refined Re filament on a FINNIGAN MAT 260 mass spectrometer by the silica gel - H₃PO₄ method. Repeated analyses of the NBS 981 standard give a mean mass discrimination factor of -0.84 ± 0.34 % per a.m.u. for a T° range between 1090° and 1200° C. Error limits are assumed to be less than 0.1 % for the ²⁰⁷Pb/²⁰⁴Pb and ²⁰⁶Pb/²⁰⁴Pb ratios and less than 0.15 % for the ²⁰⁸Pb/²⁰⁴Pb ratio. Pb blank for the whole procedure is less than 2.3 ng. The procedure is described in detail in Weis (1981).

PETROGRAPHY

At Site 235, the basaltic basement was penetrated to a depth of 32.5 m but only 12.9 m of basalt were recovered (Dmitriev & Fisher, 1974). Most of the samples appear as greenish-grey rocks with a porphyritic texture; plagioclase phenocrysts are abundant. Seventeen thin sections were examined. At Site 236, 11 m of basalt were recovered on the 21.5 m cored. In the 20 thin sections studied, augite is the dominant phenocryst phase.

At the two other sites (239 and 240) only 2 m and 1.2 m of basalt have been sampled respectively, so that only three thin sections have been examined.

Most of the samples of all sites are severely altered. Fresh volcanic glass is completely lacking. The interstices between microphenocrysts are filled with greenish chlorite, smectite and calcite, which also occur as thin veinlets in the upper parts of most cores. The **groundmass** consists of plagioclase microlites and augite microphenocrysts, sometimes occurring in «ophitic» texture (= intersertal texture of Dmitriev & Fisher, 1974). The fine-grained mesostasis consists of very fine (20 to 50 μm) plagioclase needles. These needles are radially oriented or display fibrous aggregates in intergrowth with acicular clinopyroxene. Minute magnetite crystals are randomly distributed. The mesostasis also contains amygdales filled by either cryptocrystalline fibrous green smectite or calcite.

The **phenocryst content** varies from site to site: it is quite important - between 5 and 20% - in Sites 235, 236 and 240 but it is less than 2% in Site 239. **Plagioclase** is the common phenocryst in most of the samples; it occurs as isolated, prismatic and slightly zoned crystals (0.5 to 4 mm) or as glomeroporphyritic assemblages (synneusis; Vance, 1969). Microlites (0.2 mm) are also abundant. A large proportion of the plagioclase has been altered to fine grained cryptocrystalline green to brown smectite with some calcite; occasionally potassium feldspar may also crystallize as the result of Ca leaching and K introduction from seawater (Humphris *et al.*, 1980). The **olivine** crystals have been completely pseudomorphosed to serpentine and/or smectite-celadonite and calcite; only the habit of these crystals is still recognizable.

Augite appears as common phenocryst in most sites but is especially abundant in Site 236.

Red-brown **chromite** microphenocrysts (0.1 to 0.7 mm) are characteristic of Site 235 basalts. The chromite contains perfectly rounded inclusions interpreted as droplets of magma trapped during

crystal growth. Microprobe study (see later) reveals that these inclusions consist of plagioclase and clinopyroxene.

Orthopyroxene phenocryst (or xenocryst?) has been observed in one sample (236-37-1) of Site 236.

MINERALOGY

The main phenocryst phases and some minerals of the groundmass have been analyzed. Selected microprobe data are reported in Table 2.

The **plagioclases** are mostly slightly zoned. The cores of the phenocrysts have average An contents which differ from site to site: 83% An for Site 235, 86% for Site 236, 83% for Site 239 and 84% for Site 240. The corresponding An content of the border of the crystals is 73%, 74%, 65% and 76% respectively. These values are in the range of those reported for plagioclase of MORB (i.e. 91 to 65% An for Leg 82 basalts in Central North Atlantic, Weaver *et al.*, 1985). The microlitic plagioclases have slightly more albitic compositions: 70% An (Site 235), 72% (Site 236), 60% (Site 239) and 74% (Site 240). The very fine plagioclase needles of the spherulitic textures are even more albitic: 60% An for Site 235 and 70% An for Site 236. These values are in good agreement with those reported by Frey *et al.* (1980) for the same Sites. The An content decreases in the sequence phenocryst-microlite-groundmass plagioclase which reflects the normal trend of fractional crystallization evolution with decreasing temperature (fig. 2).

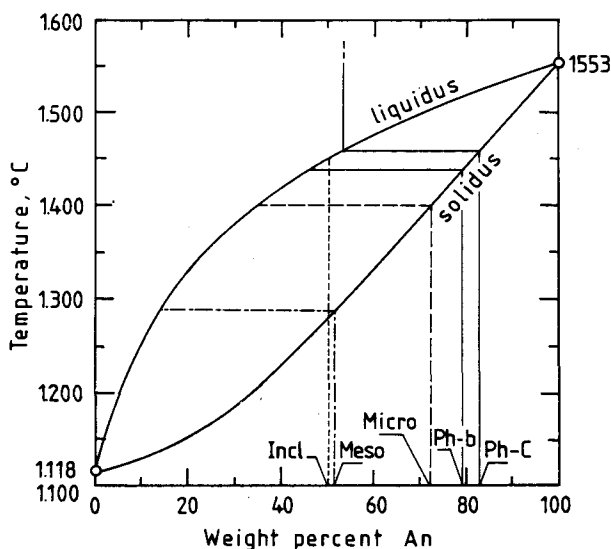


Figure 2.- Plagioclase composition in the sample 19/1/115-122 (Leg 24, Site 235).

Ph-c: Center of the phenocryst; Ph-b: border of the phenocryst; Micro: microlite; Meso: fine plagioclase needle in the spherulitic mesostasis; Incl.: plagioclase of the rounded inclusion in the chromite.

Table 2.- Selected microprobe analyses. 2a: Plagioclase; 2b: Pyroxenes and chromite.

Site	235					236				239				240		
Sample n°	19/1/115-122					35/3/55-65				21/1/70-79				7/1/90-101		
	Ph-c	Ph-b	Micro	Meso	Incl	Ph-c	Ph-b	Micro	Meso	Ph-c	Ph-b	Micro	Meso	Ph-c	Ph-b	Micro
SiO ₂	47.2	47.6	49.1	53.8	58.4	45.5	49.5	50.4	51.2	46.0	51.5	52.8	52.9	47.0	48.7	50.0
TiO ₂	.04	.06	.09	.16	.62	.06	.06	.07	.08	.04	.09	.10	.14	.23	.03	.07
Al ₂ O ₃	32.6	32.8	30.4	25.9	22.5	34.4	31.1	30.0	29.9	33.3	30.2	29.3	28.4	33.0	31.6	31.0
FeO _{tot}	.41	.32	.59	1.50	3.8	.45	.80	1.10	.88	.37	.58	.74	.93	.21	.56	.61
MgO	.24	.22	.51	.18	.68	.22	.33	.49	.46	.39	.30	.31	.44	.23	.47	.64
MnO	.01	-	-	-	.11	-	.06	.06	.01	.10	-	.02	.02	.03	.01	.23
CaO	15.9	15.8	14.6	9.5	6.4	17.6	14.7	13.9	13.6	16.5	13.3	12.4	11.8	16.5	15.2	14.6
Na ₂ O	1.77	2.25	2.92	4.8	3.4	1.30	2.57	2.93	3.14	1.87	3.92	4.47	4.74	1.75	2.73	2.81
K ₂ O	.04	.01	.03	.14	.24	-	.04	.10	.03	-	.05	.04	.01	-	.01	.04
Tot	98.21	99.06	98.24	95.98	96.15	99.53	99.16	99.05	99.30	98.57	99.94	100.18	99.38	98.95	99.31	100.00
Ab	16.8	20.4	26.5	47.3	47.8	11.8	34.3	27.5	29.3	17.0	34.7	39.3	42.0	16.1	24.4	25.7
An	83.0	79.5	73.3	52.0	50.0	88.2	65.3	72.0	70.5	83.0	65.0	60.5	57.9	83.9	75.5	74.1
Or	.2	.1	.2	.7	2.2	-	.4	.5	.2	-	.3	.2	.08	-	.08	.2

Ph-c : core of phenocryst ; Ph-b : border of phenocryst ; Micro : microlite ; Meso : plagioclase needle in the spherulitic mesostasis ; Incl : inclusion in the spinel

Site	CLINOPYROXENE						ORTHOP	CHROMITE	
	235		236		239	240	236	235	
	20/5/129-139		35/2/75-85		20/1/70-79	7/1/90-101	37/1/69-78	19/1/115-122	20/5/129-139
Sample n°	Meso	Incl	Pheno	Meso	Meso	Meso	Pheno		
SiO ₂	49.7	47.4	52.5	49.3	49.6	47.6	53.9	.09	.13
TiO ₂	.91	.96	.18	.64	1.29	1.18	.2	.40	.37
Al ₂ O ₃	3.7	11.5	1.8	3.3	4.6	5.2	1.30	31.0	30.6
FeO _{tot}	10.3	7.4	7.13	10.7	8.4	17.5	10.7	14.5	17.3
MgO	15.9	19.2	19.0	14.1	16.1	11.7	29.2	17.5	15.9
MnO	.22	.15	.23	.24	.27	.34	.18	.23	.20
CaO	17.8	13.0	17.9	20.4	18.6	15.8	2.4	.03	.01
Na ₂ O	.2	.1	.1	-	.25	.46	-	-	-
Cr ₂ O ₃	.29	.74	.20	-	-	.01	.3	37.6	36.9
Tot	99.02	100.45	99.04	98.68	99.11	99.79	98.18	101.35	101.41
Wo	37.1	28.5	35.7	42.0	38.9	34.3	4.7	-	-
En	45.9	58.6	52.8	40.4	46.9	35.4	79.0	-	-
Fs	15.0	12.9	11.5	17.6	14.2	30.3	16.3	-	-

The plagioclase found in the rounded inclusions of the chromite (Site 235) has about 50 % An. This plagioclase crystallized from a droplet of magmatic liquid trapped in the spinel, i.e. in a closed system. The composition of the plagioclase should thus be the same as that of the liquid from which it crystallized. This trapped liquid is comparable to the liquid in equilibrium with the plagioclase phenocrysts (see fig. 2). We can then conclude that the chromite crystallized rather early in the evolution of the basalt, simultaneously with the plagioclase phenocrysts.

All the analyzed plagioclases have very low K₂O contents, typically less than 0.1 wt%, which is characteristic of tholeiitic basalts. The FeO_{tot} and MgO contents are quite high and range from 0.2 to 1.5 wt% and from 0.05 to 0.70 wt% respectively. As shown by Bryan (1972, 1974), the total FeO_{tot}+MgO content of the plagioclase increases in the sequence phenocryst-microlite-groundmass crystal when the plagioclase is the only phase on the liquidus.

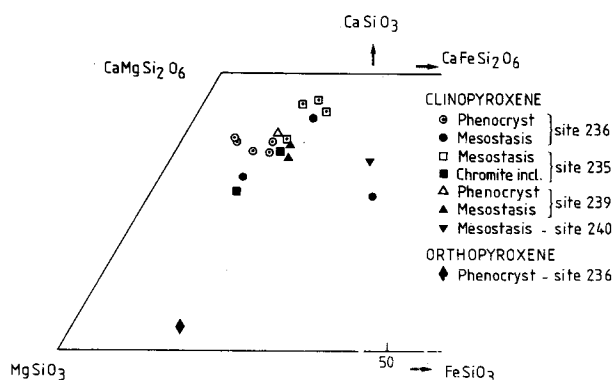


Figure 3.- Pyroxene analyses reported in the quadrilateral.

The composition of most of the pyroxenes corresponds to **augitic clinopyroxene** (fig. 3). They occur as microphenocrysts in most samples, especially in Site 236 basalts, and as fine intergrowths with plagioclase in the spherulitic textures. In general, the augite phenocrysts of Site 236 are the most magnesian rich (Mg : 50-54), while the augites from the mesostasis have a more variable composition, down to Mg : 40. At Site 235, the augites are more calcium rich (Ca : 45) than in the other sites (Ca : 35-40). The clinopyroxene in the rounded inclusions of the spinel-chromite is more Mg rich (Mg : 59) than the augite of the mesostasis of the same thin section (Mg : 46). This is likely due to subsolidus equilibration of the pyroxene with the host spinel. Irvine (1967) has indeed shown that the K_{Mg-Fe} between pyroxene and spinel increases with decreasing temperature.

GEOCHEMISTRY

MAJOR ELEMENTS

The major element compositions are reported in Table 3. As shown in the Petrography section, most of the samples are severely altered. This is also obvious in the chemistry : Fe_2O_3/FeO ratios are usually greater than unity and the H_2O content is also high (2 to 5 wt %).

The normative composition of most samples corresponds to quartz tholeiites (fig. 4). If the Fe_2O_3

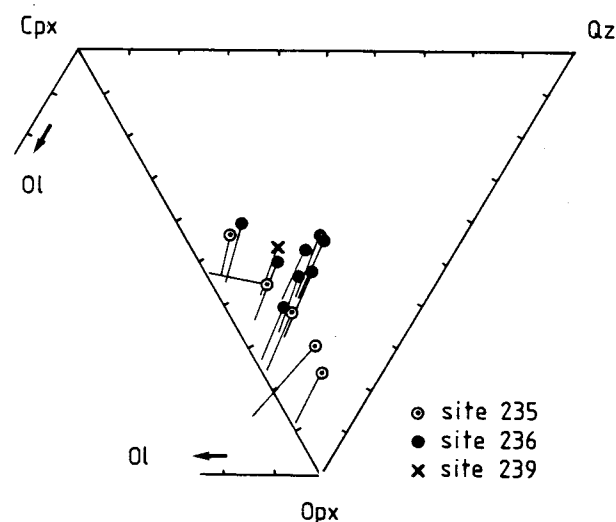


Figure 4.- Normative plot of the basaltic rocks from the Somali Basin. The straight lines show the normative composition recalculated assuming $Fe_2O_3 = 1.5\%$ to take into account the iron oxidation during alteration.

Table 3.- Major element compositions of the Somali Basin basalts.

Leg	24-site 235					24-site 236								25-site 239
	19/1/115-122	19/2/96-105	19/3/90-101	20/3/111-122	20/5/129-139	33/1/82-91	34/1/125-134	34/2/140-150	35/1/143-150	35/2/121-131	35/3/132-142	36/1/116-130	36/2/125-133	21/1/70-79
SiO ₂	47.16	47.08	48.48	47.30	48.49	50.87	50.85	48.11	50.06	49.01	49.78	50.48	49.30	52.42
TiO ₂	1.01	.82	.80	.87	.79	.61	.63	.50	.60	.63	.60	.65	.64	1.35
Al ₂ O ₃	18.13	18.25	17.51	18.23	17.19	15.96	16.54	13.75	16.16	16.53	16.10	16.54	16.17	15.25
Fe ₂ O ₃	6.28	4.75	3.96	4.46	3.29	4.90	4.72	4.69	4.73	5.17	4.90	4.77	4.69	3.77
FeO	2.76	3.49	4.03	3.78	4.56	3.99	5.14	4.82	4.66	4.06	4.19	5.12	4.81	5.69
MnO	.15	.13	.16	.16	.15	.15	.13	.17	.14	.17	.12	.19	.21	.17
MgO	8.41	9.67	8.75	8.23	7.36	7.44	7.80	8.01	8.59	8.24	7.40	8.80	8.86	7.84
CaO	9.41	9.92	11.43	10.85	11.99	10.03	10.95	10.54	10.78	10.31	10.44	10.87	9.83	9.96
Na ₂ O	1.44	1.28	1.54	1.44	1.92	1.49	1.28	1.81	1.65	1.44	1.88	1.28	1.63	2.34
K ₂ O	.97	.18	-	.21	-	.28	.07	.14	.13	.11	.09	.06	.39	.19
P ₂ O ₅	.10	.10	.11	.12	.04	.07	.03	.05	.05	.12	.06	.09	.09	.14
H ₂ O	4.46	5.52	4.42	4.93	2.46	4.60	2.65	5.64	2.95	3.20	4.20	2.51	3.05	2.14
Total	100.28	101.24	101.19	100.58	98.14	100.39	100.79	98.23	100.49	99.59	99.16	101.36	99.69	101.26

content is fixed at 1.5 % to account for oxidation during weathering (Coombs, 1963), the recalculated norms are clearly less rich in normative quartz. These data are comparable to those reported by Subbarao *et al.* (1979, fig. 3) for Indian Ocean rocks.

Basalts from Site 236 are distinctly SiO₂ rich (50 %) and TiO₂- and Al₂O₃- poor relative to Site 235. The FeO_{tot}/MgO ratio varies from 0.8 to 1 in Site 235 while it is higher than unity (up to 1.2) in Site 236, which could point to the more fractionated nature of the latter rocks. When the data of Frey *et al.* (1980) for the same sites are included, there is some overlap between the two sites (fig. 5) although, in a broad sense, the same conclusion can be drawn.

For primitive basaltic magmas, the amount of TiO₂ (considered as an incompatible element) may be used to estimate the degree of partial melting (Sun *et al.*, 1979; Subbarao & Reddy, 1981; Hertogen *et al.*, 1985). As the degree of melting increases, the TiO₂ content of the basalt decreases and the CaO/TiO₂ and Al₂O₃/TiO₂ ratios increase up to limiting values of about 17 and 20 respectively corresponding to chondritic values. In fact, most of the studied basalts, especially those of Site 236 have so low TiO₂ content and consequently so high Al₂O₃/TiO₂ and CaO/TiO₂ ratios, even higher than chondritic ratios, that their source should have peculiar geochemical characteristics, namely depletion in TiO₂.

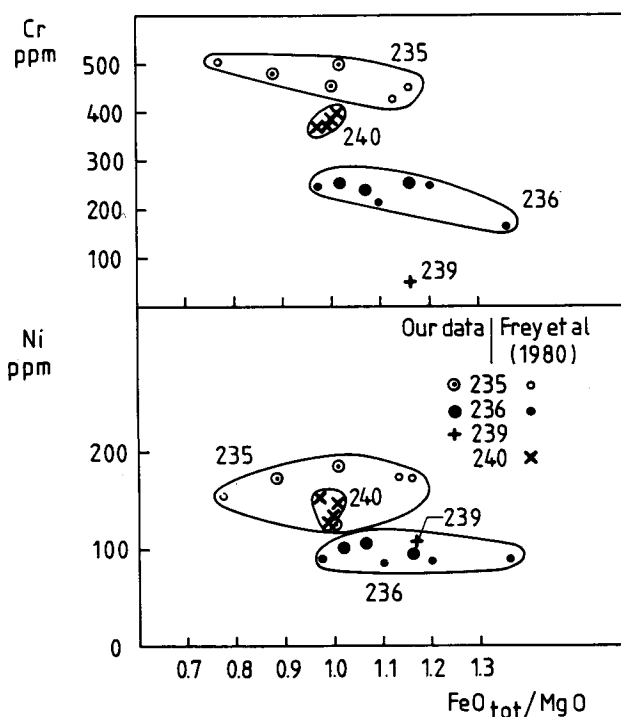


Figure 5.- Ni and Cr versus FeO_{tot}/MgO diagrams for the Somali Basin basalts. including the data of Frey *et al.* (1980).

TRACE ELEMENTS

Trace element concentrations are reported in Table 4.

Large Ion Lithophile (LIL) elements

Tholeiitic basalts from the Somali basin tend to be less depleted in LIL elements than the tholeiites from Atlantic and Pacific Oceans (Kay & Hubbard, 1978; Sun *et al.*, 1979; Hertogen *et al.*, 1985). This appears to be a general feature of the Indian Ocean rocks (Subbarao & Reddy, 1981).

In Sites 235 and 236, the analyzed samples have indeed a higher Rb content, between 2 and 8 ppm, than in normal MORB (0.2 to 3 ppm) but these high values could result from the extensive alteration (seawater interactions). The K/Rb ratio is between 300 and 1300. The Sr content is between 100 and 120 ppm for Sites 235 and 239 but distinctly lower, about 80 ppm for Site 236.

The same kind of differences is observed for Zr and Hf; their concentrations are respectively between 50 and 65 ppm and 1.2 to 2 ppm for Sites 235 and between 30 to 40 ppm and less than 1 ppm for Site 236. Nevertheless, the Zr/Hf ratio

Table 4.- Trace elements analyses of basalts from the Somali Basin.

Site	235			236		239	
Sample n°	19/1/115-122	19/3/90-101	20/5/129-139	35/3/132-142	36/1/116-130	36/2/125-133	21/1/70-79
L.I.L. elements							
K/Z	1.2	-	-	0.1	0.1	0.5	0.2
Rb	6.7	2.0	1.4	3.7	3	7.3	5.6
Sr	121	106	108	83	88	122	116
Zr	64	50	51	37	41	32	81
Hf	1.57	1.19	1.22	0.84	0.81	0.81	2.1
Th	0.22	0.13	0.11	0.24	0.24	0.25	0.11
U*	<0.15	0.07	0.05	0.11	0.06	0.04	0.13
Transition elements							
Sc	39.6	31.2	32.0	47.8	47.9	47.4	42.3
V	246	184	182	263	263	258	306
Cr	440	475	501	264	238	240	48
Co	37.4	42.3	43.2	48.2	57.1	52.4	47.9
Ni	127	177	188	96	114	100	108
Rare Earth elements							
La	2.7	1.74	1.65	1.54	1.72	1.63	2.4
Ce	8.3	5.4	5.2	4.0	4.5	4.0	8.3
Nd	6.5	5.0	4.8	3.1	3.2	2.8	7.7
Sm	2.28	1.81	1.83	1.26	1.34	1.23	3.04
Eu	0.92	0.75	0.75	0.54	0.55	0.52	1.18
Tb	0.58	0.46	0.47	0.34	0.37	0.36	0.81
Yb	2.34	1.92	2.01	1.54	1.77	1.66	3.34
Lu	0.37	0.29	0.31	0.25	0.29	0.27	0.49
Y	33	28	27	21	22	21	49
(La/Yb) _N	0.68	0.53	0.48	0.59	0.57	0.58	0.42

* Concentrations measured by isotope dilution

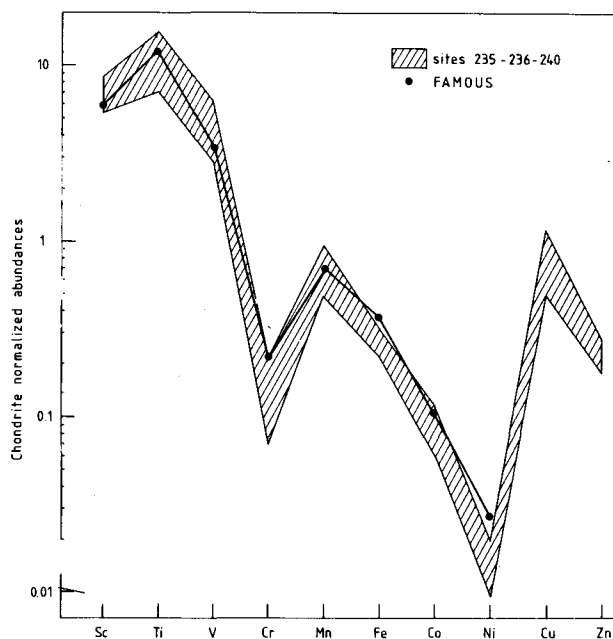


Figure 6.- Chondrite-normalized transition metal distribution in the Somali Basin basalts; the data of Frey *et al.* (1980) for the same Sites have been included. The FAMOUS data are from Langmuir *et al.* (1977).

remains roughly constant, between 37 and 45 which is comparable to the values reported for normal MORB (39 ± 5 ; Bougault *et al.*, 1979) and for the FAMOUS rocks (38.8; Langmuir *et al.*, 1977).

Transition elements

The chondrite normalized transition element abundances are reported in fig. 6, together with the data of Frey *et al.* (1980). The curves have a typical W shape (Allègre *et al.*, 1968) with minima corresponding to Cr and Ni. All the samples are roughly similar and appear slightly more depleted in Fe, Cr and Ni relatively to the FAMOUS samples (Langmuir *et al.*, 1977). In detail however, there are some differences between sites. In particular, it appears that the transition element abundances reflect the nature of the main phenocrysts. The significantly higher Cr content in Site 235 (450-500 ppm compared to 250 ppm in Site 236) is due to the presence of chromite microphenocrysts while the high Sc (48 ppm) and Co (45-55 ppm) in Site 236 may be explained by the high augite content. In the Ni-FeO_{tot}-MgO and Cr-FeO_{tot}-MgO diagrams (fig. 5), the two Sites are clearly distinct.

Rare Earth Elements

The chondrite normalized REE patterns are plotted on figure 7 with the data of Frey *et al.* (1980). All the samples are depleted in LREE and are characterized by $(La/Sm)_{e.f.}$ between 0.4 and 0.8. The Somali basin tholeiitic basalts can be classified as normal-type light REE depleted

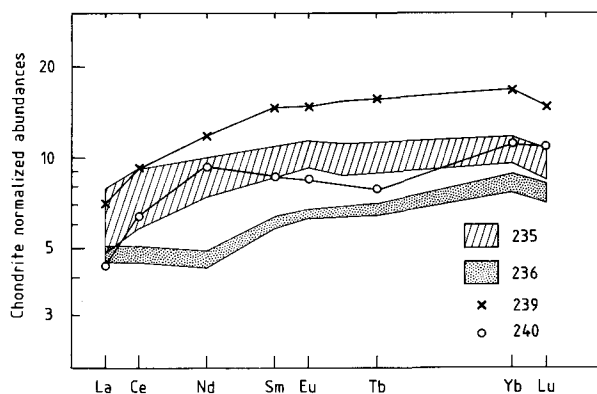


Figure 7.- Chondrite-normalized REE abundances. Site 240 data are from Frey *et al.* 1980).

tholeiites (N-MORB) following Schilling (1973, 1975) while plume-type and aseismic ridge basalt (i.e. Ninetyeast ridge, Subbarao & Reddy, 1981) have $(La/Sm)_{e.f.} < 1$.

Only one sample of Site 239 has been analyzed; it has the highest REE content but is nevertheless depleted in LREE. In general, Site 235 basalts are more rich in REE than those from Site 236. In Site 235, two samples display a slight positive europium anomaly ($Eu/Eu^* \approx 1.1$) which may be due to the rather large amount of plagioclase phenocryst. One sample from Site 240 has been analyzed by Frey *et al.* (1980); its REE distribution trend is in the range of values for Site 235. For Site 236, the chondrite normalized patterns display slight enrichment in La and Ce which is most likely due to weathering. Similar results have been obtained by Frey *et al.* (1974) for weathered basalts from the Mid-Atlantic ridge (Legs 2 and 3): they observed that La abundance increases by a factor of two in weathered samples relatively to fresh samples.

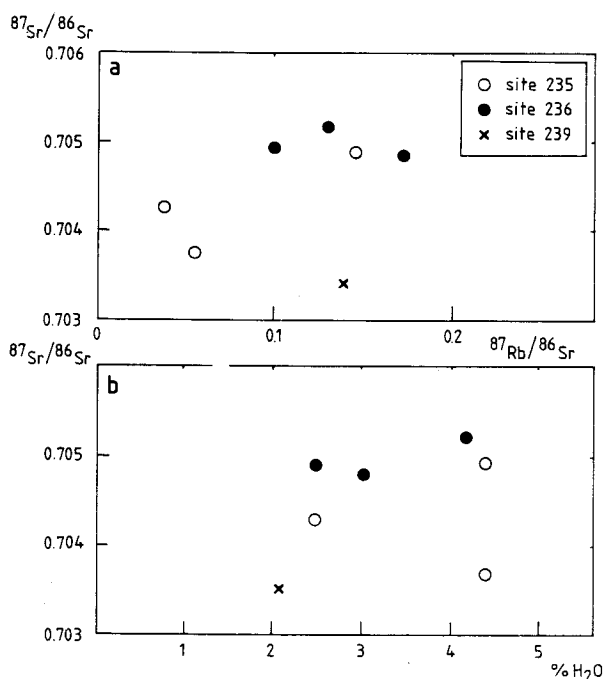
ISOTOPIC DATA

Sr isotopic composition

The Rb and Sr contents together with the $^{87}Sr/^{86}Sr$ isotopic ratios are reported in Table 5. As said previously, the Sr contents (83-135 ppm) are comparable to those of normal MORB while the Rb contents tend to be higher (1.4 to 7.3 ppm). The measured $^{87}Sr/^{86}Sr$ ratios are relatively high: 0.70344-0.7520. The Sr isotopic ratios reported for Indian ocean rocks are usually higher (0.7028-0.7043; see compilation in Subbarao & Reddy, 1981 and also Dupré & Allègre, 1983 and Ito *et al.*, 1987) than those obtained for Atlantic and Pacific Oceans (average : 0.7028; i.e. Hofmann & Hart, 1978). To check if these high values could be due to seawater contamination (Hart, 1971; Spooner, 1976; Staudigel *et al.*, 1980) leaching experiments have been performed. It is well known that

Table 5.- Rb and Sr contents and $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic ratios of the Somali Basin basalts.

	235			236			239
	19/1/115-122	19/3/90-101	20/5/129-139	35/3/132-142	36/1/116-130	36/2/125-133	21/1/70-79
Rb ppm	6.7	2.0	1.4	3.7	3.0	7.3	5.6
Sr ppm	134	106	108	83	88	122	116
$^{87}\text{Rb}/^{86}\text{Sr}$.145	.0546	.0375	.129	.0987	.173	.139
$^{87}\text{Sr}/^{86}\text{Sr} \pm 2\sigma$.70493 \pm .00007	.70376 \pm .00007	.70427 \pm .00009	.70520 \pm .00008	.70493 \pm .00014	.70486 \pm .00004	.70344 \pm .00012

Figure 8.- $^{87}\text{Sr}/^{86}\text{Sr}$ versus $^{87}\text{Rb}/^{86}\text{Sr}$ (8a) and $^{87}\text{Sr}/^{86}\text{Sr}$ versus H_2O content (8b).

seawater may interact with basaltic ocean floor to a depth of several hundred meters while in the studied sites, the cores have penetrated only 30 m in the basaltic basement and our samples are indeed petrographically severely altered. Moreover there is a rough positive correlation between the measured $^{87}\text{Sr}/^{86}\text{Sr}$ ratio and the H_2O and Rb contents (fig. 8). We have tried to remove the altered fraction of 3 samples by leaching with hot HCl 6M following the procedure described by O'Nions & Pankhurst (1976). In only one case (sample 24/236/36/116-130), the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the leached rock was slightly lower (0.70503 ± 0.00008) while the leachate was indeed more radiogenic (0.70577 ± 0.00006). In the two other leached rocks, there was no difference between the leached and unleached samples. The same results have been obtained by Whitford & Duncan (1978) on samples which have also suffered extensive low-T alteration. The variable Sr isotopic compositions could reflect either a low-T alteration by seawater (in that case,

the leaching treatment would not have been strong enough to remove the altered fractions) or heterogeneities in the mantle source regions of the tholeiitic basalts (see discussion below).

Pb isotopic data

Seven samples have been analyzed for whole rock Pb isotopic compositions. The $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ diagrams are reported on figure 9 while the isotopic data together with Pb and U concentrations are given in Table 6. The range of values goes from 18.048 to 18.446 for the $^{206}\text{Pb}/^{204}\text{Pb}$ ratios, from 15.486 to 15.569 for the $^{207}\text{Pb}/^{204}\text{Pb}$ ratios and from 37.667 to 38.399 for the $^{208}\text{Pb}/^{204}\text{Pb}$ ratios. These ranges of values are roughly comparable to those observed for other MORB (Tatsumoto, 1978; Sun, 1980). The Pb concentrations vary from 0.42 to 1.08 ppm while the U concentrations from 0.04 to 0.13. These values are entirely comparable to those obtained by Tatsumoto (1978) in MORB from other oceans.

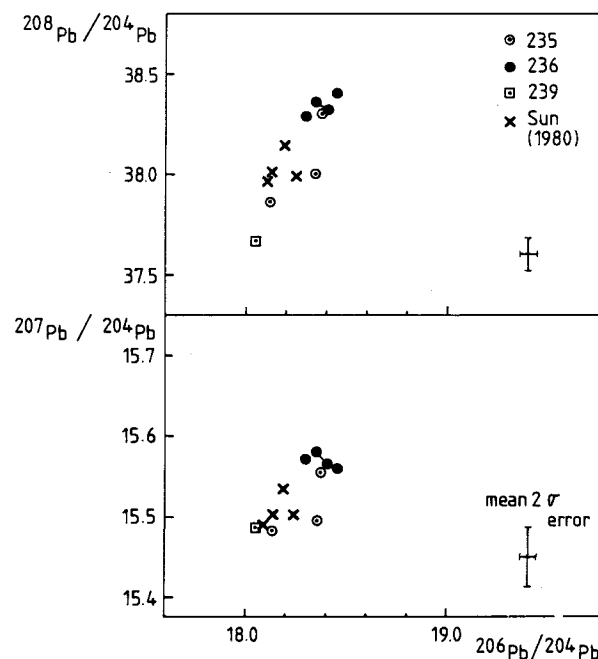


Figure 9.- Plot of $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ against $^{206}\text{Pb}/^{204}\text{Pb}$ for the Somali Basin basalts. The data of Sun (1980) for the Indian Ocean Ridge have been reported for comparison.

Table 6.- Pb isotopic data for the Somali Basin basalts.

Site	Leg	Sample	$^{206}\text{Pb}/^{204}\text{Pb} \pm 2\sigma_M$	$^{207}\text{Pb}/^{204}\text{Pb} \pm 2\sigma_M$	$^{208}\text{Pb}/^{204}\text{Pb} \pm 2\sigma_M$	Pb	U	$\frac{^{238}\text{U}}{^{204}\text{Pb}}$
235	24	19/1/115-122	18.376 0.013	15.556 0.008	38.307 0.029			
235	24	19/3/96-101	18.348 0.009	15.495 0.010	38.000 0.032	0.58	0.07	8.13
235	24	20/5/129-139	18.122 0.008	15.486 0.008	37.860 0.022	0.49	0.04	5.32
236	24	35/3/132-142	18.446 0.005	15.561 0.006	38.399 0.013	1.08	0.11	6.34
236	24	36/1/116-130	18.348 0.043	15.580 0.036	38.372 0.062	0.42	0.06	8.86
			18.388 0.005	15.566 0.005	38.306 0.011			
236	24	36/2/125-133	18.295 0.006	15.569 0.006	38.288 0.012	0.61	0.04	3.95
239	25	21/1/70-79	18.048 0.008	15.488 0.006	37.667 0.019	0.92	0.13	9.17

Site 235 basalts have Pb isotopic compositions in the same range as those of Indian ocean MORB studied by Sun (1980) (fig. 9). This seems to confirm that Indian ocean basalts have distinctly higher $^{207}\text{Pb}/^{204}\text{Pb}$ (and $^{208}\text{Pb}/^{204}\text{Pb}$) ratios than Atlantic and Pacific MORB's (see recent compilation by Hart (1984) and Hamelin & Allègre, 1985) and verifies the predictions of Tatsumoto (1978) based on the higher $^{87}\text{Sr}/^{86}\text{Sr}$ ratios. Site 239 basalt has Pb isotopic compositions in the lower part of the Site 235 range of values; this is especially true for $^{208}\text{Pb}/^{204}\text{Pb}$. For comparable $^{206}\text{Pb}/^{204}\text{Pb}$ ratios, Site 236 basalts have distinctly higher $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ ratios than the other sites.

The between site differences in Pb isotopic composition correspond most probably to heterogeneities in the mantle source regions of the different basalts, since Pb isotopes are not affected by seawater alteration because of the very low Pb content in seawater (< 1 ppb; Quinby-Hurt & Turekian, 1983).

DISCUSSION

Basalts cored in the Somali Basin (Western Indian Ocean) have geochemical characteristics (low L.I.L. element abundances, LREE depletion) comparable to normal, depleted tholeiitic basalts (N-MORB).

However, the data obtained in this study on three sites - 235, 236, 239 - and the additional data of Frey *et al.* (1980) for the same sites and for Site 240 display significant geochemical and isotopic differences from site to site which reflect different processes.

Three main mechanisms can a priori be invoked :

1. if the basalts belong to the same differentiation sequence, geochemical differences, especially in trace element contents, may result from variable degrees of fractionation;

2. if the samples are representative of primitive (= unfractionated) magmas, their differences may be due to the heterogeneities in the source-region or may result from different degrees of melting or different melting processes of the same source;
3. low-T alteration and/or basalt-seawater interaction may modify the primary geochemical and isotopic features of the basalt.

In the Somali Basin, low-T alteration of the basalts is obvious (see Petrography section). As a consequence, the H_2O content and the $\text{Fe}_2\text{O}_3/\text{FeO}$ ratio are much higher than in fresh basaltic glasses. The Rb and K contents also increase (Hart, 1971). The relatively high $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic ratios could also point to important contamination by seawater Sr although leaching experiments do not always give convincing results.

Fortunately, immobile elements (middle and heavy REE, Zr, Hf, transition elements) are less, or not at all, affected by these low-T processes, they may be used to constrain the petrogenesis of these rocks.

If we suppose that the different basalts derive from the same primary magma, Site 236 basalts appear slightly more fractionated than Site 235 rocks : indeed they have higher SiO_2 content (> 50%) and $\text{FeO}_{\text{tot}}/\text{Mg}$ ratios (fig. 5).

Moreover, following the fractionation model of Shido *et al.* (1971) for ocean ridge basalt, the presence of abundant augite phenocrysts in Site 236 would imply that this mineral crystallized from a differentiated liquid with a high FeO/MgO ratio. However, more recent studies by Bender *et al.* (1978) show that a high volatile content may also induce the early appearance of pyroxene on the liquidus of tholeiitic basalt. Several lines of evidence suggest that the different basalts are not linked by a fractional crystallization process.

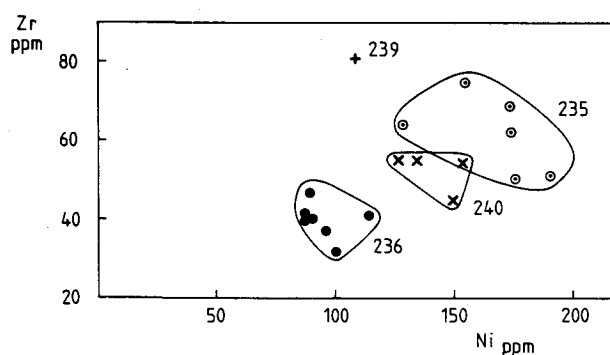


Figure 10.- Zr versus Ni diagram for the Somali Basin basalts, including the data of Frey *et al.* (1980). Symbols as in Fig. 9.

- the plagioclase phenocrysts of Site 236 are more An rich (86 % for the crystal's core) than those of site 235;
- the differences in Ni and Cr contents in the two sites are very important and for the same $\text{FeO}_{\text{tot}}/\text{MgO}$ ratio, the Cr content in Site 235 basalt is nearly twice as high as in Site 236 rocks (fig. 5);
- in a Zr-Ni diagram (fig. 10) where a compatible element (Ni) is plotted against an incompatible element, the rocks of the Somali Basin display a positive correlation which is opposite to what is observed in a fractional crystallization process;
- the phases which are on the liquidus of the basalt - plagioclase, olivine, augite - have solid/liquid partition coefficients for the REE smaller than unity (i.e. Schilling, 1971) and consequently, the more fractionated liquids must be enriched in REE relatively to the less fractionated ones. Site 236 basalts, with higher $\text{FeO}_{\text{tot}}/\text{MgO}$ ratios are poorer in REE ($\approx 8x$ chondrites) than Site 235 basalts (9 to 12x chondrites).

It is not possible then to relate the different basalts by a fractional crystallization process.

As a consequence, the geochemical differences between the basalts, especially in their immobile element contents and in their Pb isotopic compositions are considered to reflect differences in the composition of the source-regions and differences in degree of partial melting. The existence of large-scale mantle heterogeneities have already been suggested to explain the geochemical and isotopic peculiarities of tholeiitic basalts sampled in different oceans. At the scale of the Indian ocean, heterogeneities have also been proposed by Frey *et al.* (1980) to account for the differences in the trace element contents between the Arabian Sea and Somali Basin basalts. We propose here that, even at the more restricted scale of the Somali Basin the tholeiitic basalts of

Table 7.-Average Pb isotopic composition and $\Delta 7/4$, $\Delta 8/4$, ΔSr parameters for each site (see text and Hart (1984) for explanations)

Site	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$	$\Delta 7/4$	$\Delta 8/4$	ΔSr
235	18.282	15.512	38.056	+3.9	+32.9	+43.3
236	18.370	15.568	38.342	+8.6	+50.6	+50.0
239	18.048	15.488	37.667	+4.1	+22.0	+34.0

Sites 235, 236 and 240 seem to have evolved from compositionally different primary magmas.

Average Sr and Pb isotopic compositions for each analyzed Site are reported in Table 7 together with the ΔSr , $\Delta 7/4$ and $\Delta 8/4$ parameters calculated according to Hart (1984). (These values measure, for any given isotopic data set, the magnitudes of the isotopic anomaly of these data from a reference line defined by the oceanic basalts of the Northern Hemisphere). The measured $\Delta 7/4$ (+3.9 to +8.6) and $\Delta 8/4$ (+22 to +50.6) values fall in the large scale isotope anomaly («Dupal anomaly») defined by Hart for the Southern Hemisphere mantle which is characterized by higher $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ ratios, for a given $^{206}\text{Pb}/^{204}\text{Pb}$, than the North Atlantic mantle. Although relatively high, the ΔSr values for Sites 235 and 239 (+43.3 and +34 respectively) are also in agreement with the data reported for the Indian Ocean in general; consequently, they do not require contamination by seawater Sr. Only for Site 236 also showing enhancement of La and Ce concentrations, the ΔSr of 50 could require such a contamination process.

CONCLUSIONS

- The basalts sampled during Legs 24 (Sites 235 and 236) and 25 (Sites 239 and 240) in the Somali basin (Western Indian Ocean) have a porphyritic texture with plagioclase, olivine and augite phenocrysts.
- Most samples have suffered low-T alteration by interaction with seawater which increases both the K, Rb, ... contents and sometimes the $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic ratios and La, Ce contents.
- Between site geochemical differences in immobile elements (REE and transition elements) cannot be explained by different degrees of fractional crystallization; they probably reflect different degrees of partial melting and heterogeneities in the source-regions as also suggested by the variation of Pb isotopic compositions.
- The basalts have higher $^{207}\text{Pb}/^{204}\text{Pb}$, $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic ratios than Atlantic

MORB and fall within the large scale isotope anomaly of the Southern Hemisphere mantle, the so called «Dupal anomaly» (Hart, 1984).

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