

# Geochemical Investigations of Basalts and Associated Rocks from the Ocean Floor and their Implications

G. D. Nicholls and M. R. Islam

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## Geochemical investigations of basalts and associated rocks from the ocean floor and their implications

BY G. D. NICHOLLS AND M. R. ISLAM

*Department of Geology, University of Manchester*

Variations in trace element contents and inter-element ratios of deep-sea basalts are much more marked than variations in major element contents. This paper explores possible reasons for the variations which have been discovered.

Inadequacy of sampling techniques may be responsible for some reported differences, but variations due to this cause are unlikely to approach the magnitude of reported variations. Some variation in samples from restricted areas of the ocean floor can be correlated with variation in the degree of silica saturation of the basalts. Submarine alteration of lavas by reaction with sea water is another possible cause of variation. Studies of metamorphosed deep-sea basalts suggest that very low-grade metamorphism may cause some, though slight, elemental migration. Studies on ultrabasic rocks show variations in trace element contents which, to some degree, appear to complement the variations encountered in basalts, suggesting that the extent of partial melting in the mantle during basaltic genesis influences the trace element contents of the products of melting.

However, when such possible explanations have been considered, there remain variations in trace element contents of otherwise comparable basalts from different parts of the ocean floor, which appear to represent real variations in the trace element contents of the erupted basaltic magmas. In view of the difficulty of explaining such differences by contamination of magmas on their way to the surface, it is suggested that variations exist in the trace element contents of mantle material at the levels of basaltic genesis. Geochemical provinces exist in oceanic areas just as they do in continental regions.

### INTRODUCTION

In one of the earlier papers to present data on trace element contents in deep-sea basalts (Engel, Engel & Haven 1965) the similarities between the trace element contents of ten 'oceanic tholeiitic' basalts prompted the calculation of an average trace element content for rocks of this type. Though more variation was encountered in the trace element contents of 'oceanic alkali basalts' an average trace element content for these rocks showed significant differences from that for the 'oceanic tholeiites' (see table 2, columns 1 and 2). During the past five years many more data on the geochemistry of deep-sea basalts have been accumulated and the trace element geochemistry of these rocks no longer appears so simple and straightforward. Variations in the magnitude of trace element contents and in inter-element ratios have been discovered, thus opening the question of the utility of trace element studies in petrogenetical discussions of basalts and associated rocks from the ocean floor. There has been a tendency for authors to present the results of trace element determinations with little or no discussion of their significance, no doubt reflecting uncertainty about their value in elucidating rock origins. Reported trace element contents of igneous rocks depend on a variety of factors, such as the trace element contents of the original magmas from which the rocks were derived, modification by processes of differentiation or assimilation before eventual solidification of the rocks, postsolidification processes such as alteration and metamorphism, adequacy of sampling and, not least, the accuracy of the analytical determinations. No doubt some of the variation in reported trace element contents of deep-sea basalts and associated rocks stems from inter-laboratory inconsistency, but if reported results on geochemical standards such as G.1 and W. 1 are indicative of the magnitude of variation due to this cause, the variation in the reported elemental contents of similar deep-sea basalts from the ocean floor cannot be wholly attributed to this cause.

## ADEQUACY OF SAMPLING

Sampling of rocks outcropping on the deep ocean floor presents considerable problems and the care normally exercised in the selection of samples from continental areas can hardly, in the present state of deep-sea technology, be applied to sample selection from the ocean floor. There is, as yet, no published work on how far collected samples from a particular dredge station are truly representative of the rocks outcropping on the ocean floor at that station, nor on the minimum size of sample from the ocean floor that can be considered representative of the larger

TABLE 1. TRACE ELEMENT CONTENTS (IN PARTS PER MILLION BY MASS) IN TWO BASALTIC SAMPLES OF CONTRASTING GRAIN SIZE FROM THE SAME DREDGE HAUL

	(1)	(2)		(1)	(2)
Ba	100	100	Rb	12	7
Co	55	32	Sc	10	22
Cr	700	450	Sr	250	250
Cu	45	55	V	250	320
Ga	16	10	Y	18	22
Li	2	3	Zr	45	45
Ni	1000	150			

(1) Olivine enriched dolerite 4519-11 (Muir & Tilley 1964, Table 8, col. 1).

(2) Basalt 4519-55 (Muir & Tilley 1964, Table 8, col. 7).

Both samples from the M.A.R., 45° 44' N, 27° 43' W, depth 3370 m.

rock body, e.g. a lava flow, of which it once formed part. When a dredge haul contains both coarse-grained basaltic material (dolerite) and very fine-grained or tachylytic basalt it is not generally known whether different samples come from different parts of a single rock body or from different bodies, e.g. sills and lava flows. For example, the collection of samples from 'Discovery' station 4519 studied by Muir & Tilley (1964) contains dolerites as well as basalts. One analysed olivine enriched dolerite (4519-11) and an analysed basalt (4519-55) appear to be of similar (possibly the same) age. They could represent a sill (or dyke) and a lava flow or they could conceivably represent different parts of the same flow or series of flows, the dolerite being derived from the coarser interior of the flow. The trace element contents of these two samples, reproduced here in table 1, show some differences greater than those which could be attributed to determinative error, e.g. for Co, Cr, Cu, Ga, Ni, Sc, V and Rb. The high Cr and Ni contents in 4519-11 are probably to be attributed to the presence in this rock of xenocrystal olivine containing chrome spinel inclusions, but the differences in the contents of Ga and Rb and probably some of the other elements can hardly be attributed to this cause. Thus the data pose the question whether such differences in trace element contents are sufficient to permit a conclusion that the two samples must have come from different rock bodies, or whether differences of the order of  $\pm 25\%$  about a mean value are such as might be encountered in different parts of the same rock body in consequence of magma heterogeneity or near-surface trace element fractionation processes. At the present state of knowledge we can offer no answer, but merely desire to draw attention to the existence of a problem which has hitherto escaped published comment. It has considerable bearing on the magnitude of differences in trace element contents that should be considered significant and the extent to which determined trace element contents of a deep-sea basalt sample can be regarded as representative of the trace element contents of a magma from which the basalt was derived. Until evidence to the contrary

is forthcoming it is probably wiser to refrain from attributing real significance to differences in trace element contents less than  $\pm 20\%$  of a mean value, interpreting such differences as probably due to inadequate sampling technique and analytical error.

VARIATION OF TRACE ELEMENT CONTENTS WITH THE  
PETROGRAPHICAL CHARACTER OF OCEANIC ROCKS

Some variation in the trace element contents of deep-sea basalts from geographically restricted areas of the ocean floor can be correlated with the degree of silica saturation of the rocks. Of the samples so far studied, relatively few deep-sea basalts are silica oversaturated (i.e. carry normative quartz) or so markedly undersaturated as to carry normative nepheline. Most fall between these extremes and carry both normative olivine and normative hypersthene. Some measure of the degree of silica undersaturation in these rocks is afforded by the value of the normative olivine/normative hypersthene ratio, this ratio increasing with increasing undersaturation. Unfortunately, this ratio is affected by the  $\text{Fe}_2\text{O}_3/\text{FeO}$  ratio in the rock and is not as reliable a monitor of degree of silica undersaturation as could be desired. As the  $\text{Fe}_2\text{O}_3/\text{FeO}$  ratio rises the calculated degree of silica undersaturation falls, other compositional features remaining constant, and this effect must be taken into account when using the normative olivine/normative hypersthene ratio as an indicator of the degree of silica undersaturation. However, if deep-sea basalts are arranged in sequence of increasing degree of silica undersaturation certain features of their geochemistry do appear to vary systematically.

Lanthanide rare earth enrichment in the more markedly undersaturated deep-sea basalts and, more particularly, relative enrichment of the lighter lanthanides has been established (Graham & Nicholls 1969). Variations greater than can be attributed to inadequacy of sampling or analytical error also exist for other elements. In table 2 the average trace element contents in 'oceanic tholeiitic basalts' (undersaturated deep-sea basalts carrying normative olivine and normative hypersthene) and in 'alkali basalts' (more undersaturated deep-sea basalts) given by Engel *et al.* (1965) are reproduced, together with data for two pairs of basalts, each pair from a relatively restricted area of the ocean floor. Major element chemistry and lanthanide rare earth contents for the first pair (CH 35-4-1-5A and CH 35-2-1-1) have already been published by Graham & Nicholls (1969). Major and trace element data for the second pair (4519-46 and 4519-34) are given by Muir & Tilley (1964).

In each pair the more undersaturated member carries the higher content of Ba, Cu, Rb, Sr and V. For Ba, Cu, Rb and Sr the differences are more pronounced in the first pair (for which the range of silica undersaturation is greater) than in the second. The averages of Engel *et al.* similarly show higher contents of Ba, Rb and Sr in the more undersaturated rocks, but in the rocks studied by these authors Cu and V are more abundant in the less undersaturated rocks. Where data are available Nb is also considerably more abundant in the more undersaturated rocks. The analytical figures consistently indicate higher contents of Ga in the more undersaturated representatives, but the differences are hardly large enough for sampling inadequacy to be eliminated as a cause. For Co, Li and Y the behaviour is inconsistent and, in any case, the differences are generally so small that they could be due to sampling inadequacy and analytical error. Further work has failed to substantiate the lower contents of Cr, Ni and Sc in the more undersaturated rocks reported by Engel *et al.* In the pair of samples from the equatorial Atlantic (CH 35 pair) the analytical figures do show lower contents of these elements in the more

undersaturated rock, but the differences are doubtfully significant. In contrast, Muir & Tilley report higher contents of these elements in the more undersaturated basalt from 45° 44' N, especially so in the case of Cr. Zr is significantly more abundant in the more undersaturated rocks in the data of Engel *et al.* and in the normative nepheline basalt from the equatorial Atlantic, but this behaviour is not exhibited by the pair of basalts from 45° 44' N. Data on Zn are sparse; such as exist suggests that the content of this element may be higher in the more undersaturated rocks.

It appears still true that the more undersaturated deep-sea basalts are relatively enriched in Ba, Nb, Rb and Sr, and that the processes responsible for the formation of different kinds of deep-sea basalt in some way influence the contents of these elements, but some of the differences in trace element contents of different kinds of deep-sea basalt reported earlier have not been substantiated as more data have become available. Contents of other elements listed in table 2 cannot be consistently related to the nature of the process of magma genesis.

TABLE 2. TRACE ELEMENT CONTENTS (IN PARTS PER MILLION BY MASS) IN DEEP SEA BASALTS OF VARYING DEGREES OF SILICA SATURATION

	(1)	(2)	(3)	(4)	(5)	(6)
Ba	14	498	35	530	100	160
Co	32	25	42	36	26	38
Cr	297	67	310	240	380	700
Cu	77	36	30	110	45	100
Ga	17	22	7	10	10	16
Li	9	11	—	—	2	2
Nb	< 30	72	5.2	65	—	—
Ni	97	51	160	145	100	220
Rb	< 10	33	1.0(5)	20	12	22
Sc	61	26	43	33	15	22
Sr	130	815	130	680	220	320
V	292	252	290	390	220	350
Y	43	54	—	—	10	22
Zn	—	—	35	60	—	—
Zr	95	333	85	210	45	45

(1) Average trace element contents in 'oceanic tholeiitic basalts' (Engel *et al.* 1965, Table 2).

(2) Average trace element contents in 'alkali basalts' (Engel *et al.* 1965, Table 2).

(3) Deep-sea basalt CH35-4-1-5A; oversaturated (normative quartz 2.67%); 00° 52.5' S, 30° 07' W, depth 3559 m; new data—major element composition and rock description given by Graham & Nicholls (1969, Table 1, col. 1).

(4) Deep-sea basalt CH35-2-1-1; normative nepheline 2.46%; 00° 36' N, 32° 50' W, depth 3449 m; new data—major element composition and rock description given by Graham & Nicholls (1969, Table 1, col. 6).

(5) Deep-sea basalt 4519-46; undersaturated (normative olivine/normative hypersthene = 1.13,  $Fe_2O_3/FeO = 0.212$ ) (Muir & Tilley 1964, Table 8, col. 6); M.A.R., 45° 44' N, 27° 43' W, depth 3370 m.

(6) Deep-sea basalt 4519-34; strongly undersaturated (normative olivine/normative hypersthene = 11.6,  $Fe_2O_3/FeO = 0.352$ ) (Muir & Tilley 1964, Table 8, col. 5); M.A.R., 45° 44' N, 27° 43' W, depth 3370 m.

In this context it is of interest to examine trace element contents in some ultrabasic rocks from the oceanic environment. The peridotites of St Paul's Rocks emerge above the waves but provide an opportunity of collecting peridotites in a part of the ocean where deep-sea basalts of varying degrees of silica saturation are known to exist. In these peridotites the lanthanide rare earth distribution pattern appears to be dependent on the total content of lanthanide rare earths. The patterns for three samples are shown in figure 1. With between 25 and 45 parts/ $10^6$  total lanthanide rare earths, light lanthanide enrichment relative to chondrites is more marked than heavy lanthanide enrichment (pattern 1 of figure 1). At the other extreme, with < 1 part/ $10^6$  total lanthanide rare earths, depletion in light lanthanides relative to chondrites is greater than

that in the heavy lanthanides (pattern 3 of figure 1). At intermediate total lanthanide contents intermediate conditions exist (pattern 2 of figure 1). Such data accord with the suggestion, already advanced by others, that the St Paul's peridotites represent a residual mantle fraction from which basaltic material has been removed by partial fusion, provided that the removed basaltic material was markedly undersaturated with respect to silica (normative nepheline type of basalt). Increasing extraction of lanthanide rare earths has involved relatively more marked

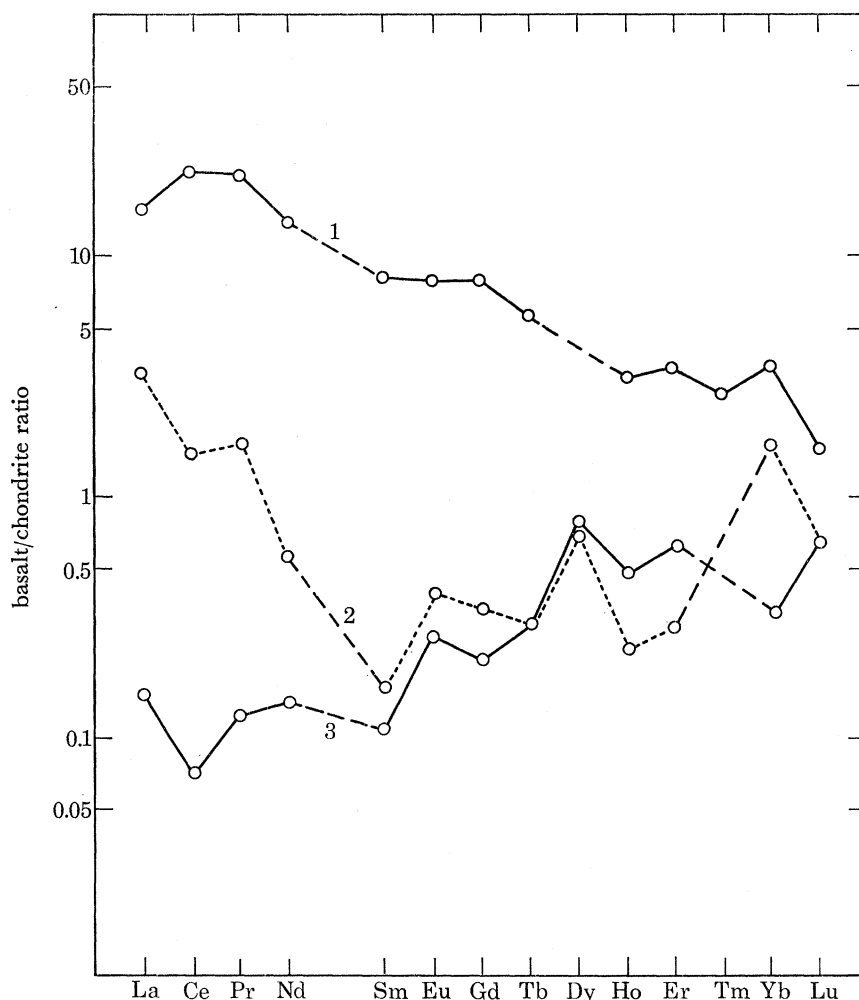


FIGURE 1. Lanthanide rare earth distribution patterns for peridotite samples from St Paul's Rocks. Pattern 1, sample no. Pl-i—total lanthanide rare earths excluding Dy—41 parts/ $10^6$ ; individual rare earth element abundance data from Haskin, Frey, Schmitt & Smith (1966, Table 13); pattern 2, spinel peridotite s.p.8—total lanthanide rare earths excluding Tm—3.5 parts/ $10^6$  (new data); pattern 3, spinel peridotite s.p.1—total lanthanide rare earths excluding Tm—0.8 parts/ $10^6$  (new data). Basalt/chondrite ratio obtained by dividing rare earth content in sample by average content of the same rare earth in chondritic meteorites given by Graham & Nicholls (1969, Table 5, col. A).

extraction of the lighter members, complementing the relative enrichment in lighter lanthanides of those deep-sea basalts in which total lanthanide rare earth contents are high (the normative nepheline type). Data on other trace elements (table 3) also accord with this interpretation. The sample with a very low total lanthanide rare earth content (s.p.1) also contains less Ba, Cu, Rb, Sr, V, Zn and Zr. With greater removal of the lighter lanthanides there appears to have been comparable removal of other trace elements in which the normative nepheline basalts of

the equatorial Atlantic are relatively enriched (table 2, compare columns 3 and 4). Nb does not show this effect despite its enrichment in the normative nepheline basalts.

In this area of the ocean floor it is not difficult to envisage the differences in trace element contents in the different sorts of deep-sea basalt as related to differences in a partial fusion mechanism of their generation rather than to any process of near-surface crystal fractionation. Elsewhere the controls *may* be different—in this region they appear to be related to magma genesis rather than magma fractionation.

TABLE 3. TRACE ELEMENT CONTENTS (IN PARTS PER MILLION BY MASS) IN TWO SPINEL PERIDOTITE SAMPLES FROM ST PAUL'S ROCKS, EQUATORIAL ATLANTIC

	(1)	(2)		(1)	(2)
Ba	1.3	4.1	Ni	75	120
Co	23	15	Rb	1.7	3.1
Cr	1150	1450	Sr	63	115
Cu	0.23	2.0	V	0.70	5.2
Ga	1.1	0.07	Zn	3.5	16
Nb	0.70	0.68	Zr	0.065	0.68

(1) Spinel peridotite s.p.1—low in lanthanides (total lanthanides excluding Tm—0.8 parts/10<sup>6</sup> by mass).

(2) Spinel peridotite s.p.8—rather richer in lanthanides (total lanthanides excluding Tm—3.5 parts/10<sup>6</sup> by mass)

THE EFFECT OF SUBMARINE ALTERATION OF OCEAN FLOOR ROCKS BY REACTION WITH SEA WATER ON THE GEOCHEMISTRY OF THOSE ROCKS

When samples dredged from the sea floor show obvious signs of alteration suspicion would naturally arise that their trace element contents might have been influenced by the alteration process. Modification of trace element contents might, however, occur before signs of major alteration by sea water became apparent and it is pertinent to inquire whether some of the variation in reported trace element contents in deep-sea basalts could be due to varying states of minor alteration. Studies of strongly altered basaltic glass from the ocean floor (Nicholls 1963) suggest that oxidation of iron to the ferric state, release of Mg, Ca and Na, increase of H<sub>2</sub>O content and increase of K content result from such alteration. Such changes, if they had affected a rock, would influence the reference of the rock to its proper degree of silica saturation and, in general, the norm of such an altered rock will show a higher degree of silica saturation than its parent material would have done. The magnitude of such possible reference error can be fairly closely estimated, though there is an obvious source of uncertainty regarding the original Fe<sup>3+</sup>/Fe<sup>2+</sup> ratio, Mg content, etc. The effect on trace element contents is less readily determined. Ideally it could be examined by comparing the altered exterior and unaltered interior of a single dredged fragment. In the absence of such fragments an empirical study may be attempted by comparing two almost identical samples from a single dredge haul, between which the slight differences in major element composition might be attributed to incipient sea-water attack. The Fe<sup>3+</sup>/Fe<sup>2+</sup> ratio alone is insufficient as an indicator of the extent of alteration by sea water, since the ratio may vary in unaltered samples and may well differ in basalts of different provenance. Several criteria must be simultaneously satisfied and the ones used for selecting rock pairs for this study have been: (i) increase in the Fe<sup>3+</sup>/total Fe ratio without significant change in the total Fe content, (ii) increase in the K content and (iii) decrease (usually slight) in the Ca and Mg contents. Only one pair of rocks available to us (5111.2 and 5111.5 collected by J. R. Cann from the northwestern Indian Ocean) met all these criteria.

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One other pair reported in the literature satisfies most of the chemical conditions, but the two rocks were taken in different dredge hauls though at approximately the same locality ( $22^{\circ}$  N on the Mid-Atlantic Ridge). Although the analytical data (table 4) do show differences between the two members of a pair there appears to be little consistency of trace element behaviour.

TABLE 4. DATA ON PAIRS OF DEEP-SEA BASALT SAMPLES TO ILLUSTRATE THE EFFECT OF ALTERATION BY SEA WATER ON THE GEOCHEMISTRY

	(1)	(2)	(3)	(4)
Total Fe as Fe	7.85%	7.74%	6.64%	6.14%
Fe <sup>3+</sup> /total Fe	0.246	0.291	0.234	0.530
Ba	96	14	3	7
Co	55	45	50	40
Cr	84	65	370	330
Cu	100	63	85	75
Ga	38	18	18	17
Ni	36	19	120	75
Nb	2.5	2.5	—	—
Rb	6.7	7.8	< 20	< 20
Sc	33	20	—	—
Sr	170	175	95	135
V	270	240	265	245
Zr	120	120	85	85

Trace element contents (Ba to Zr) given in parts per million by mass.

(1) Deep-sea basalt 5111.2;  $05^{\circ} 27' N$ ,  $61^{\circ} 50' E$ , depth 2500 m; further chemical data given by Cann (1969, Table 3, col. 3).

(2) Deep-sea basalt 5111.5;  $05^{\circ} 27' N$ ,  $61^{\circ} 50' E$ , depth 2500 m; further chemical data given by Cann (1969, Table 3, col. 4).

(3) Deep-sea basalt no. 2-18;  $22^{\circ} 31' N$ ,  $45^{\circ} 00' W$ , depth approximately 1900 m; data from Melson *et al.* (1968, Table 5).

(4) Deep-sea basalt no. 10-76;  $22^{\circ} 10' N$ ,  $45^{\circ} 15' W$ , depth approximately 3000 m; data from Melson *et al.* (1968, Table 5).

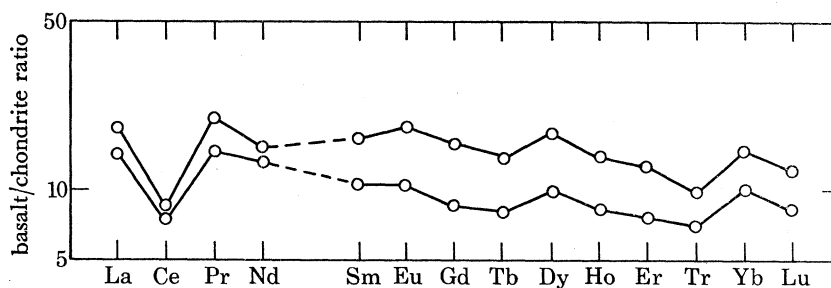


FIGURE 2. Lanthanide rare earth distribution patterns for two deep sea basalts (nos. 5111.2 and 5111.5) from the Carlsberg ridge in the Indian Ocean. Sample 5111.5 is the altered member of the pair chosen to illustrate possible effects of sea-water alteration on the geochemistry of deep-sea basalts. Basalt/chondrite ratio has the same meaning as in figure 1.

In the Indian Ocean pair the Ba content is less in the altered member but the reverse relation applies for the Atlantic Ocean pair. The reported contents of Co, Cr, Cu, Ga, Ni and V are lower in the altered member of each pair. For Cu and Ni this may be a real decrease, but for the other elements it is doubtful whether any real change is indicated in view of the problem of sampling inadequacy. Possibly Sr is slightly higher in the altered members, though again the evidence is doubtful. Total lanthanide rare earths are higher in the altered member of the Indian Ocean pair (45 as against 34 parts/ $10^6$ ). This increase is not uniformly distributed throughout the range of these elements (figure 2). The proportionate increase is less for La, Ce,



Pr and Nd than for Sm and the heavier rare earths. If the increase is to be attributed to sorption or some other method of uptake from sea water it is clear that the population of sorbed rare earths is weighted in favour of the heavy elements relative to the original population in the rock. Alteration would have some effect on rare earth distribution patterns in favour of enhancing the differences already noted between basalts of different degrees of silica saturation.

It appears from these data that the effect of slight alteration of a deep-sea basalt on its trace element contents is hardly significant for most elements. With much more intense alteration the effect would probably be much more marked, but the analyst would surely take account of such alteration in interpreting his results. While alteration effects certainly cannot be ignored in interpreting trace element contents in deep-sea basalts, at this stage of our knowledge it appears that variation due to this cause is much less than variation arising through the operation of other factors.

EFFECT OF CHANGES IN THE PHYSICAL OR PHYSICO-CHEMICAL ENVIRONMENT  
OF ROCKS FORMING PART OF THE OCEAN FLOOR

The possibility of modification of trace element contents by elemental migration occasioned by changes in the physical or physico-chemical environment such as would, at a more advanced stage, cause metamorphism of deep-sea basalts to greenstones will now be considered. To some extent, this presupposes a possibility that some of the trace elements are located in unstable positions in the basalts from which they can be readily leached by ambient fluid phases. Here, again, when the rock is demonstrably a greenstone its composition obviously will not be returned as that of a basalt and we are more concerned with possible effects of changes in the stress pattern, etc., insufficient to produce significant mineralogical transformation. In an attempt to assess the magnitude of possible changes in trace element contents under such conditions the products of more advanced transformation (greenstones) will be compared with basalts from the same areas of the ocean floor. There is an obvious difficulty about the nature of the basaltic parent of a particular greenstone and it is only possible to compare elemental ranges in groups of the two types of rock.

A collection of basalts and spilites (greenstones) from the Carlsberg ridge at  $5\frac{1}{2}^{\circ}$  N in the Indian Ocean was kindly made available to us by J. R. Cann. Major element compositions and petrographic descriptions of these rocks have been published by Cann (1969). The trace element data (table 5) do not disclose any clear trends of trace element compositional differences between the basalts and greenstones. If only the two spilites (columns 5 and 6) are compared with the basalts (columns 1 to 4) it might be suggested that Ba and Rb contents are lower in the metamorphosed rocks and possibly Ga, Sr and total lanthanide rare earths also, while Ni may be marginally higher in the spilites. However, taking all the data into account, there is no real indication of any systematic change in these trace element contents. Similarly, with individual lanthanide rare earth elements (table 6), there appear to be no systematic differences between the basalts and the metamorphosed rocks and the lanthanide distribution patterns for all eight rocks are remarkably similar.

Entirely comparable relationships exist among the basalts and greenstones dredged from the M.A.R. at  $22\frac{1}{2}^{\circ}$  N and described by Melson, Thompson & Van Andel (1968). Trace element determinations for twelve elements published by these authors show no significant differences between the two groups of rocks. Lanthanide rare earth element contents on a few samples from

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this collection have been determined and are given in table 7. The greenstones of this area carry lower contents of total lanthanide rare earths than the basalts and determined contents of Pr, Nd, Sm, Gd, Dy, Ho, Yb and Lu are lower in each greenstone than in either basalt. However, the lanthanide rare earth distribution patterns are very similar.

TABLE 5. TRACE ELEMENT CONTENTS (IN PARTS PER MILLION BY MASS) IN BASALTS AND ASSOCIATED ROCKS FROM THE CARLSBERG RIDGE AT  $5\frac{1}{2}^{\circ}$  N IN THE INDIAN OCEAN

	basalts				spilites		chlorite-rich rocks	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Ba	96	14	6	13	5.5	4	9	22
Co	55	45	67	110	74	77	65	280
Cr	84	65	250	420	340	270	270	380
Cu	100	63	110	100	130	100	63	115
Ga	38	18	19	33	18	18	17	44
Ni	170	90	85	165	230	165	65	195
Nb	2.5	2.5	2.2	6	3.8	3.4	4.5	9.3
Rb	6.7	7.8	3.4	8.8	2.8	1.6	4.1	7.6
Sc	33	20	66	80	58	45	26	135
Sr	170	175	85	140	100	36	23	32
V	270	240	300	440	440	290	200	470
Zr	120	120	125	165	145	100	95	205
total LaRE	34	45	26	59	31	31	31	57
norm. oliv.	8.1	6.4	2.4	3.1	—	—	—	—
norm. hyp.								

(1) Basalt no. 5111.2.

(5) Spilite no. 5106.2.

(2) Basalt no. 5111.5.

(6) Spilite no. 5106.7.

(3) Basalt no. 5106.18.

(7) Chlorite-rich spilite no. 5106.1.

(4) Basalt no. 5106.21.

(8) Chlorite-rich spilite no. 5106.12.

Major element compositions and descriptions of these rocks are given by Cann (1969).

TABLE 6. LANTHANIDE RARE EARTH CONTENTS (IN PARTS PER MILLION BY MASS) IN BASALTS AND ASSOCIATED ROCKS FROM THE CARLSBERG RIDGE AT  $5\frac{1}{2}^{\circ}$  N IN THE INDIAN OCEAN

	basalts				spilites		chlorite-rich rocks	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
La	4.2	5.3	3.5	7.0	2.7	3.2	3.3	6.7
Ce	6.2	7.0	5.1	10	5.0	4.1	4.7	11
Pr	1.7	2.4	1.2	3.4	1.4	1.4	1.5	3.1
Nd	7.6	8.5	4.8	11	5.9	6.1	6.8	9.5
Sm	2.2	3.4	1.5	3.4	2.2	1.9	1.8	3.3
Eu	0.79	1.3	0.67	1.5	1.0	0.92	0.84	1.6
Gd	2.7	4.8	2.5	5.6	3.8	3.4	3.2	5.3
Tb	0.67	0.77	0.39	0.95	0.56	0.55	0.51	0.91
Dy	3.1	5.2	2.8	6.3	3.6	3.7	4.1	6.5
Ho	0.59	0.98	0.52	1.2	0.70	0.73	0.70	1.4
Er	1.6	2.6	1.4	3.5	2.0	2.0	1.7	3.4
Tm	0.23	0.32	0.19	0.51	0.25	0.29	0.21	0.49
Yb	1.7	2.5	1.5	3.8	2.0	2.2	1.7	3.5
Lu	0.26	0.37	0.20	0.56	0.30	0.31	0.22	0.55

(1) Basalt no. 5111.2.

(5) Spilite no. 5106.2.

(2) Basalt no. 5111.5.

(6) Spilite no. 5106.7.

(3) Basalt no. 5106.18.

(7) Chlorite-rich spilite no. 5106.1.

(4) Basalt no. 5106.21.

(8) Chlorite-rich spilite no. 5106.12.

All these rocks have been described by Cann (1969).

While local migration of trace elements in response to stress changes certainly cannot be eliminated there is no evidence, from these studies, that significant changes in content would result. Possibly small amounts of Ba, Ga, Rb, Sr and lanthanide rare earth elements might be lost from the rocks, though the available data do not definitely indicate this. It is clear that variation in trace element contents due to this cause is insignificant compared to changes produced by other factors.

TABLE 7. LANTHANIDE RARE EARTH CONTENTS (IN PARTS PER MILLION BY MASS) IN BASALTS AND ASSOCIATED ROCKS FROM THE MID-ATLANTIC RIDGE AT  $22\frac{1}{2}^{\circ}$  N

	basalts		greenstones		
	(1)	(2)	(3)	(4)	(5)
La	3.4	4.2	4.2	2.6	2.1
Ce	5.8	10	6.0	10	3.9
Pr	1.9	2.6	1.8	1.2	1.1
Nd	9.0	10	8.3	6.8	4.2
Sm	4.4	2.6	2.3	1.9	1.4
Eu	1.5	1.0	0.68	1.1	0.43
Gd	6.8	3.6	2.6	2.6	1.7
Tb	1.3	0.63	0.60	0.62	0.36
Dy	5.0	4.2	3.4	3.3	1.8
Ho	1.4	1.0	0.93	0.90	0.50
Er	4.8	2.6	3.0	2.0	1.4
Tm	0.62	0.35	0.38	0.28	0.22
Yb	3.0	1.9	1.7	1.2	0.80
Lu	0.57	0.40	0.28	0.22	0.20
total LaRE	49	45	36	35	20
norm. olivine	0.23	0.61	—	—	—
norm. hypersthene					

(1) Basalt; sample no. CH44-2-1.

(2) Basalt; sample no. CH44-2-2.

(3) Greenstone; sample no. CH44-2-5.

(4) Greenstone; sample no. CH44-3-2.

(5) Greenstone; sample no. CH44-3-6.

Descriptions, major element compositions and other trace element contents for these rocks are given by Melson *et al.* (1968).

#### VARIATION OF TRACE ELEMENT CONTENTS IN DEEP-SEA BASALTS FROM DIFFERENT GEOGRAPHICAL LOCATIONS

When deep-sea basalts from different parts of the ocean floor are compared, the contents of some trace elements are approximately constant, regardless of the locations from which the samples were taken, but other elements show considerable variation. As has been shown earlier the degree of silica saturation may influence the contents of Ba, Nb, Rb, Sr and the lanthanide rare earths. It is therefore desirable to compare basalts of similar degrees of silica saturation or attempt to take account of variation in this respect when comparing basalts from different parts of the ocean floor. The extremely undersaturated deep-sea basalts (normative nepheline basalts) have been excluded from the following discussion but, nevertheless, significant variations are still encountered in the contents of several elements. These variations will be indicated by discussing the distribution of trace elements in comparable basalts from different parts of the ocean floor.

*Barium*

Even when normative nepheline basalts are excluded barium contents in the remaining basalts of the M.A.R. vary by a factor of at least ten. In a collection of samples from approximately 45° N described by Aumento (1968) the barium contents range from 53 to 94 parts/10<sup>6</sup>. Samples from the same area described by Muir & Tilley (1964) showed barium contents in the range 55 to 220 parts/10<sup>6</sup>, but the three higher values are all in quite strongly undersaturated basalts (normative olivine/normative hypersthene greater than 2.0). For basalts with normative olivine/normative hypersthene ratios between 0.1 and 1.2 the range of barium contents is 55 to 100 parts/10<sup>6</sup>, in excellent agreement with Aumento's range. The basalts from approximately 22½° N described by Melson *et al.* (1968) have normative olivine/normative hypersthene ratios between 0.2 and 1.4, but their barium contents (3 to 9 parts/10<sup>6</sup>) are much lower than those of the basalts farther north. Basalts of similar degrees of silica undersaturation from 9° 39' N show similar low contents of barium—5 parts/10<sup>6</sup> (Engel *et al.* 1965). However, two samples from the equatorial zone (AD-3 of Engel *et al.* (1965) and CH35-4-1-5A, see table 2, column 3) show higher contents of barium (19 and 35 parts/10<sup>6</sup>) despite being marginally less undersaturated with respect to silica. A single sample from still further south (20° 40' S) shows the low level of barium content—5 parts/10<sup>6</sup> (AD-2 of Engel *et al.*). Thus, on the basis of existing data, there appears to be a general 'background' level of barium contents in deep-sea basalts of the M.A.R. of approximately 5 parts/10<sup>6</sup>, with an area around 45° N much enriched in barium and another around the equator less strongly enriched, but with barium contents 4 to 5 times greater than the general 'background' level. It will be apparent from the preceding sections of this paper that these differences are too pronounced to be attributed to inadequate sampling, analytical errors, alteration effects, changes in stress pattern, etc., and, since account has been taken of possible differences in the degree of silica undersaturation, they appear to represent real differences in the barium contents of magmas extruded at the different localities.

Barium contents in the basalts from the Carlsberg Ridge in the Indian Ocean range from 6 to 96 parts/10<sup>6</sup> (table 5). All are more undersaturated than the basalts from the Atlantic described above and the one carrying 96 parts/10<sup>6</sup> Ba is strongly undersaturated (normative olivine/normative hypersthene = 8.1). The other examples in which this normative ratio ranges from 2.4 to 6.4 carry 6 to 14 parts/10<sup>6</sup> Ba. Since these are appreciably more undersaturated than the Atlantic basalts it is possible that the 'background' level of barium contents for this part of the ocean floor is very similar to the Atlantic 'background' level and the slightly higher barium contents are to be attributed to the greater degree of undersaturation of these rocks. Basalts from further south in the Indian Ocean, described by Fisher, Engel & Hilde (1968) from the Amirante Ridge (6° 40' S, 52° 35' E) are more oxidized and probably older than the basalts of the Carlsberg Ridge. They contain 8 to 9 parts/10<sup>6</sup> Ba. The analyses as published, show one to carry normative quartz and the other to have a normative olivine/normative hypersthene ratio of 0.47, but the Fe<sup>3+</sup>/total Fe ratios are 0.45 and 0.31. If the oxidation ratios are modified to 0.1 the normative olivine/normative hypersthene ratios are changed to 0.4 and 1.4. They are then more comparable to the Atlantic basalts and their barium contents might then suggest a rather higher barium 'background' level in this part of the ocean. On the other hand, the barium contents may have been influenced by alteration processes—more data from this area are clearly required.

Engel *et al.* (1965) give some data on barium contents in Pacific deep-sea basalts. Two samples from north of the equator are both oversaturated and both somewhat oxidized (PV 17 and EM) they contain 12 and 17 parts/ $10^6$  Ba. Two samples from the East Pacific Rise at 7 and 13° S (PVD1 and PVD3) are slightly undersaturated (normative olivine/normative olivine ratios 0.29 and 0.84) but contain 21 and 25 parts/ $10^6$ . These barium contents are significantly higher than the Atlantic 'background' level, but a sample from 18½° S (PVD4C) has a barium content—6 parts/ $10^6$ —at this level, despite being more undersaturated than the basalts farther north (normative olivine/normative hypersthene ratio 1.6). Thus, despite the sparsity of data, there is some indication that variations in barium contents in the Pacific basalts may be comparable to those demonstrated for Atlantic deep-sea basalts.

#### *Cobalt*

Differences in the cobalt contents of deep-sea basalts are small and doubtfully significant. The basalts from the M.A.R. at 45° N carry 31 to 60 parts/ $10^6$  Co (Aumento 1968) or 22 to 53 parts/ $10^6$  (Muir & Tilley 1964). In the equatorial zone they contain 34 to 42 parts/ $10^6$  Co and the sample from 20° 40' S contains 32 parts/ $10^6$  (table 2, column 3, and Engel *et al.* 1965). At 9° 39' N the M.A.R. basalts contain 26 to 28 parts/ $10^6$  Co, while reported Co contents in Pacific basalts range from 28 to 38 parts/ $10^6$  (Engel *et al.* 1965). The basalts of the Amirante Ridge in the Indian Ocean carry 33 to 34 parts/ $10^6$  Co (Fisher *et al.* 1968). In only two areas is there any evidence of different cobalt contents and even in those areas it is not strong. Reported cobalt contents in the M.A.R. basalts at 22½° N range from 40 to 75 parts/ $10^6$ , perhaps marginally higher than the general run of values elsewhere. In table 5 the cobalt contents of basalts from the Carlsberg Ridge are shown to range from 45 to 110 parts/ $10^6$ . Cann (1969) gives a range of 60 to 80 parts/ $10^6$ . Whichever set of values is preferred, the basalts of this Carlsberg Ridge area do appear to be marginally richer in cobalt than deep-sea basalts from other parts of the ocean floor.

#### *Chromium*

There is even less evidence of regional variation in the chromium contents of deep-sea basalts. Values tend to fall within the range 200 to 400 parts/ $10^6$  Cr with occasional examples above or below this range, but there is no regularity in the regional distribution of values falling outside the range. Chromium is a good example of an element, the content of which does not vary according to the geographical location of the collected samples.

#### *Copper*

In most deep-sea basalts the copper contents lie within the range 60 to 120 parts/ $10^6$  with the majority of values clustering between 70 and 90 parts/ $10^6$ . Occasional values above and below this range have been reported, as in the case of chromium, but the only area in which significantly different copper contents are recorded is the Amirante Ridge in the Indian Ocean. Here Fisher *et al.* (1968) report 160 to 170 parts/ $10^6$  Cu, much higher values than are found elsewhere. Possibly the Amirante Ridge is a relatively copper rich area.

#### *Gallium*

The gallium contents of deep-sea basalts have been frequently reported in the range 10 to 20 parts/ $10^6$  Aumento (1968) reports a range of 24 to > 50 parts/ $10^6$  Ga in the basalts of the M.A.R. at 45° N, though Muir & Tilley (1964) found only 10 to 16 parts/ $10^6$  Ga in basalts from this area. The M.A.R. basalts from 22½° N may be somewhat richer than usual in this element

as Melson *et al.* (1968) gave gallium values for these rocks between 17 and 32 parts/10<sup>6</sup>. The rocks of the Carlsberg Ridge also appear somewhat high in gallium. Values given in table 5 for these rocks range from 19 to 38 parts/10<sup>6</sup> Ga and Cann (1969) reports values of 20 to 25 parts/10<sup>6</sup>.

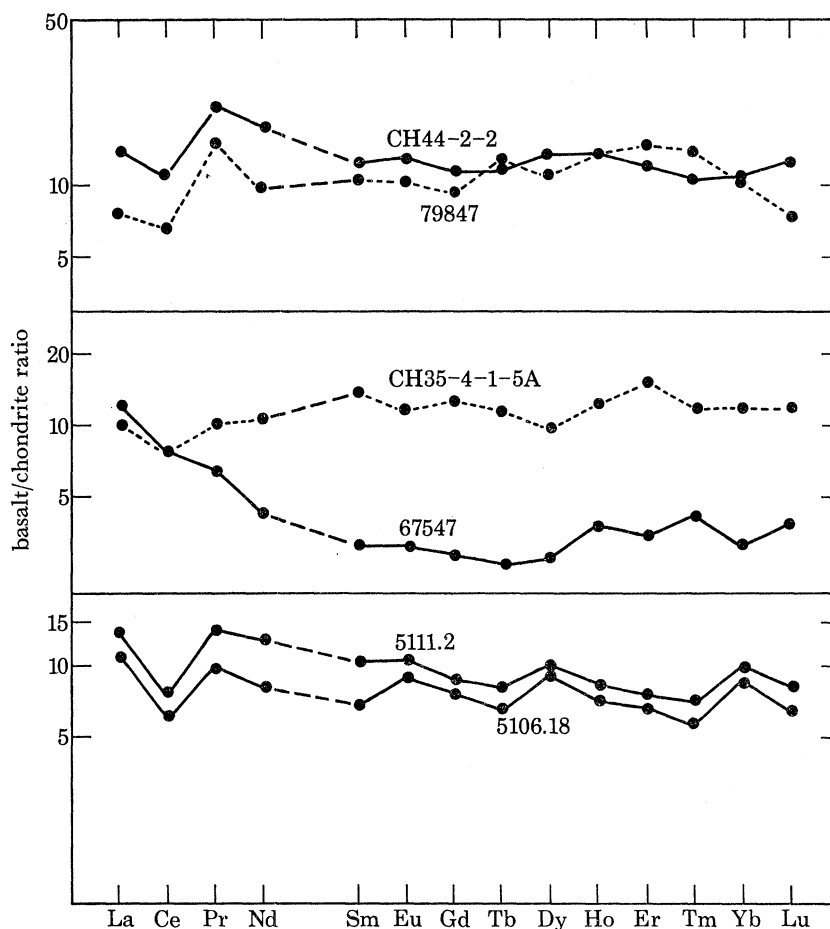


FIGURE 3. Lanthanide rare earth distribution patterns for several deep-sea basalts from the Atlantic and Indian Oceans. CH44-2-2, deep-sea basalt from the M.A.R. at 22½° N—plotted from data given by Graham & Nicholls (1969, Table 5, col. 6); 79847, deep-sea basalt from the M.A.R. at 30° N—plotted from data given by Graham & Nicholls (1969, Table 5, col. 2); CH35-4-1-5A, deep-sea basalt from the M.A.R. at 00° 52.5' S.—plotted from data given by Graham & Nicholls (1969, Table 5, col. 1); 67547, deep-sea basalt from the M.A.R. at 45° N—plotted from data given by Graham & Nicholls (1969, Table 5, col. 3); 5111.2, deep-sea basalt from the Carlsberg Ridge at 5½° N—plotted from data given in table 6, column 1 of this paper; 5106.18, deep-sea basalt from the Carlsberg Ridge at 5½° N—plotted from data given in table 6, column 3 of this paper. Basalt/chondrite ratio has the same meaning as in figure 1.

#### *Lanthanide rare earths*

Total lanthanide rare earth contents of comparable deep-sea basalts often show quite considerable variation even at one locality (table 5; Graham & Nicholls 1969) and, though variation in total lanthanide levels in basalts from different parts of the ocean floor exist, it is by no means certain that the differences exceed those encountered at one locality. Differences in lanthanide rare earth distribution patterns are probably more significant. Using data given by Graham & Nicholls (1969) lanthanide distribution patterns have been plotted for deep-sea basalts from four areas of the M.A.R. (figure 3). The patterns for the samples from the equatorial

zone,  $22\frac{1}{2}^{\circ}$  and  $30^{\circ}$  N are not significantly different, but that for the rock from  $45^{\circ}$  N shows a striking relative enrichment in the four lighter lanthanides, La, Ce, Pr and Nd, even though this rock has a normative olivine/normative hypersthene ratio of only 0.10. Data given by Frey, Haskin, Poetz & Haskin (1968) have been used to plot the lanthanide distribution patterns given in figure 4. Again the patterns for Atlantic basalts from  $30^{\circ}$  N and  $20^{\circ}$  S are similar, but the example from  $45^{\circ}$  N is relatively enriched in La, Ce, Pr and Nd. Frey *et al.* (1968) refer to this example as a 'transitional olivine tholeiite', but if the chemical data given by Muir & Tilley (1964) refer to the same sample, it is certainly not transitional, being only just undersaturated with respect to silica.

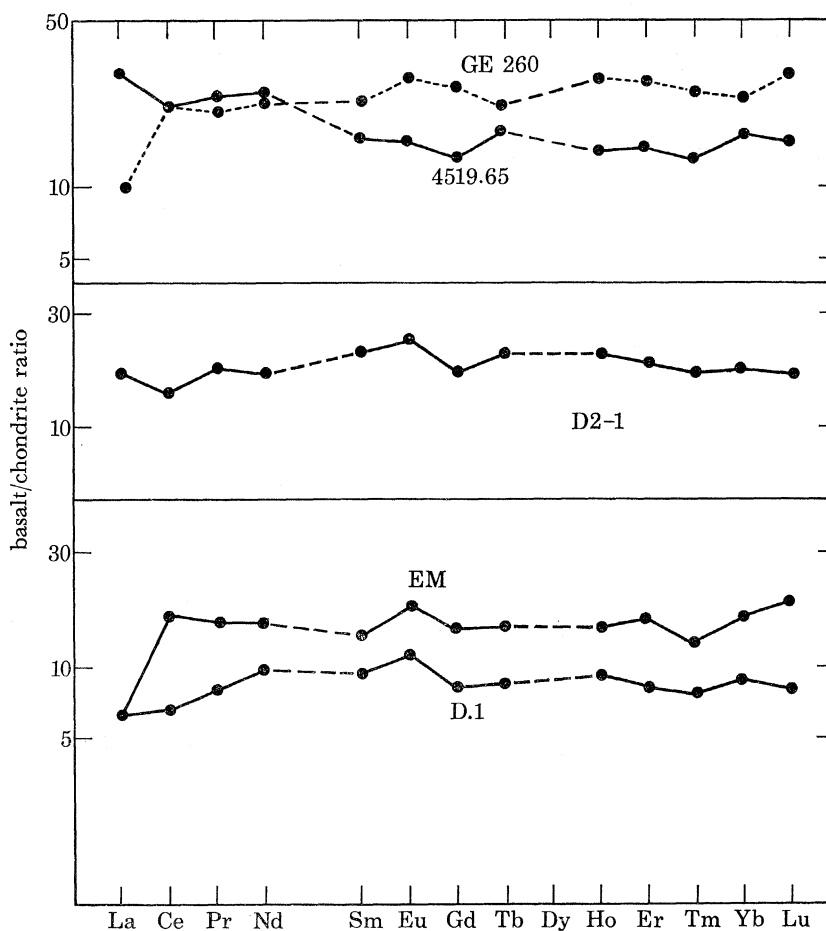


FIGURE 4. Lanthanide rare earth distribution patterns for deep-sea basalts from the Atlantic and Pacific Oceans, prepared from data given by Frey *et al.* (1968, Table 4). GE 260, deep-sea basalt from the M.A.R. at  $30^{\circ}$  N; 4519.65, deep-sea basalt from the M.A.R. at  $45^{\circ}$  N; D2-1, deep-sea basalt from the M.A.R. at  $20^{\circ} 40'$  S; EM, deep-sea basalt from the Pacific Ocean, encountered in the experimental Mohole; D. 1, deep-sea basalt from the East Pacific rise at  $7^{\circ}$  S. Basalt/chondrite ratio has the same meaning as in figure 1.

Compared with the Atlantic rocks from  $30^{\circ}$  N,  $22\frac{1}{2}^{\circ}$  N, the equatorial zone and  $30^{\circ}$  S, the Carlsberg Ridge basalts are less relatively enriched in La, Ce, Pr and Nd (figure 3) than might have been expected from their undersaturated character. This is especially true of sample 5111.2 which has a normative olivine/normative hypersthene ratio of 8.1. The basalts from this area only weakly display the trend for more undersaturated rocks to be relatively enriched in the lighter lanthanides. Basalts from the Pacific (figure 4) appear to possess similar lanthanide

distribution patterns to those from the Atlantic at  $30^\circ$  N,  $22\frac{1}{2}^\circ$  N, the equatorial zone and  $20^\circ$  S.

In two areas of the ocean floor, therefore, the basalts have distinctive lanthanide rare earth distribution patterns. At  $45^\circ$  N on the M.A.R. they are relatively enriched in the four lighter lanthanide elements and at  $5\frac{1}{2}^\circ$  N on the Carlsberg Ridge they are less strongly enriched in these elements than might have been expected.

#### *Nickel*

There is no real evidence of regional variation in the nickel contents of deep-sea basalts. Most reported values fall within the range 70 to 200 parts/ $10^6$  and values falling outside this range are sparse and show no systematic regional distribution. The values for nickel contents in the basalts from the Carlsberg Ridge given in table 5 (85 to 170 parts/ $10^6$ ) fall within this range, but Cann (1969) has reported values of 145 to 320 parts/ $10^6$  in the Carlsberg Ridge rocks. Two of the values reported by Cann are higher than most reported values, but the general level of his nickel determinations agree with other determinations of the content of this element in deep-sea basalts. At present it is questionable whether the basalts of the Carlsberg ridge area are marginally enriched in nickel.

#### *Rubidium*

Contents of this element in deep-sea basalts are often too low to permit determination by the methods used to determine other trace elements (Melson *et al.* 1968; Engel *et al.* 1965) and there are fewer published data to consider. Tatsumoto, Hedge & Engel (1965) give values ranging from 0.66 to 2.63 parts/ $10^6$  for deep-sea basalts from the M.A.R. between  $10^\circ$  N and  $21^\circ$  S and sample CH35-4-1-5A from the equatorial Atlantic contains 1.0 (5) parts/ $10^6$  Rb. The M.A.R. basalts from  $45^\circ$  N contain from 7 to 28 parts/ $10^6$  Rb according to Muir & Tilley (1964) or from 7 to 12 parts/ $10^6$  if the strongly undersaturated examples are omitted from consideration. Aumento (1968) gives a range of  $< 5$  to 5 parts/ $10^6$ , but, even so, there does appear to be a tendency for basalts from this area to be more enriched in rubidium than basalts farther south in the Atlantic. The basalts from the Carlsberg Ridge also appear to be slightly enriched in this element, contents ranging from 3.4 to 8.8 parts/ $10^6$  (table 5) or from 1 to 8 parts/ $10^6$  (Cann 1969). In view of the undersaturated character of these basalts, however, these values do not appear particularly high and it would be unwise to regard the Carlsberg Ridge as a rubidium enriched area on the present evidence.

#### *Scandium*

Basalts from the M.A.R. between  $10^\circ$  N and  $21^\circ$  S contain 38 to 44 parts/ $10^6$  Sc (Engel *et al.* 1965), but those from  $45^\circ$  N contain only 10 to 28 parts/ $10^6$  according to Muir & Tilley (1964). Reported scandium contents in Pacific basalts range from 30 to 56 parts/ $10^6$  (Engel *et al.* 1965) and the basalts of the Amirante Ridge contain 50 to 52 parts/ $10^6$  (Fisher *et al.* 1968). Possibly the Carlsberg Ridge basalts are somewhat enriched in this element. Cann (1969) gives values ranging from 55 to 70 parts/ $10^6$  and scandium contents given in table 5 range from 20 to 80 parts/ $10^6$ .

#### *Strontium*

Strontium contents reported by Engel *et al.* (1965), Tatsumoto *et al.* (1965) and Melson *et al.* (1968) for deep-sea basalts from the M.A.R. between  $23^\circ$  N and  $21^\circ$  S and from the Pacific all lie within the range 90 to 190 parts/ $10^6$ . Most reported values for basalts from the Carlsberg Ridge also lie within this range (table 5; Cann 1969). Aumento (1968) reports values within the



same range for the basalts of the M.A.R. at 45° N, but Muir & Tilley (1964) give values of 220 to 450 parts/10<sup>6</sup> for basalts from this area. If the more undersaturated rocks described by these authors are omitted the range of strontium contents they report is restricted to 220 to 250 parts/10<sup>6</sup>.

Lower contents of strontium are reported from the basalts of one area of the ocean floor. The basalts from the Amirante Ridge contain only 40 to 43 parts/10<sup>6</sup> Sr (Fisher *et al.* 1968) and this may be a low-strontium area of the ocean floor.

Sr/Ba ratios, however, show considerable differences. In the basalts from the M.A.R. at 45° N the values of this ratio do not exceed 4, but in the basalts from the ridge at 22½° N they range from 13 to 34. At 9° 39' N the values are 18 and 32 but in the equatorial zone they are down to 3.7 and 8.4. The basalt from this ridge at 20° S has a Sr/Ba ratio of 38. With one exception the Pacific basalts have Sr/Ba ratios between 4.4 and 8 and those of the Amirante Ridge give values 4.4 and 5.4. Thus, despite differences in the absolute levels of barium and strontium contents in the deep-sea basalts of the equatorial Atlantic, the Pacific and the Amirante Ridge, all these basalts have Sr/Ba ratios within the range 3.7 to 8.4, whereas other deep-sea basalts show quite different values of this ratio. With one exception the Carlsberg Ridge basalts have Sr/Ba ratios in the range 11 to 14, which is lower than all but one of the ratio values for the basalts from the M.A.R. at 22½° N. Clearly, deep-sea basalts from different parts of the ocean floor tend to display characteristic Sr/Ba ratios.

#### *Vanadium*

As with chromium, there is no evidence of significant regional variation in the vanadium contents of deep-sea basalts. Almost all values recorded lie within the range 220 to 440 parts/10<sup>6</sup> V and the few that do not are not regularly distributed in definite regions. Vanadium is another example of an element, the content of which in deep-sea basalts does not depend on the geographical location from which samples are taken.

#### *Yttrium*

Yttrium contents in the basalts from the M.A.R. at 45° N range from 10 to 26 parts/10<sup>6</sup> (data from Muir & Tilley 1964; Frey *et al.* 1968). These values are significantly lower than the values (34 to 47 parts/10<sup>6</sup>) returned by Frey *et al.* (1968) on the basalts from the ridge at 30° N. Yttrium contents reported for M.A.R. basalts between 10° N and 21° S range from 30 to 60 parts/10<sup>6</sup> (Engel *et al.* 1965) and for basalts from the Carlsberg Ridge Cann (1969) reports values of 36 to 60 parts/10<sup>6</sup>. Our own determinations of yttrium contents of Carlsberg Ridge basalts (not reported in table 5) confirm Cann's figures, being within the range 38 to 55 parts/10<sup>6</sup>. The yttrium contents of the Amirante Ridge basalts are rather low—20 to 30 parts/10<sup>6</sup> (Fisher *et al.* 1968) and this area, like 45° N in the Atlantic, may be one of yttrium impoverishment in deep-sea basalts. Yttrium contents in the Pacific deep-sea basalts are mostly within the range 20 to 62 parts/10<sup>6</sup>, though there are too few data to establish any regional trends for the basalts from the floor of this ocean.

#### *Zirconium*

From the data at present available contents of zirconium in deep-sea basalts appear to be variable. For the basalts of the M.A.R. at 45° N Aumento (1968) reports contents of 84 to 160 parts/10<sup>6</sup>, but the values given by Muir & Tilley (1964) for basalts from the same area are,

with one exception, within the range 35 to 45 parts/ $10^6$ . For basalts from  $22\frac{1}{2}^\circ$  N Melson *et al.* (1968) return values ranging from 65 to 125 parts/ $10^6$ , but between  $10^\circ$  N and  $7^\circ$  S the range is only 62 to 88 parts/ $10^6$  (Engel *et al.* 1965 and table 2, column 3). In contrast, the basalt from  $20^\circ$  S contains 160 parts/ $10^6$  Zr. In the Carlsberg Ridge basalts zirconium contents range from 120 to 165 parts/ $10^6$  (table 5): Cann (1969) gives a range 96 to 220 parts/ $10^6$ , or 96 to 122 parts/ $10^6$  if one unusually high value is omitted. Zirconium contents of 40 parts/ $10^6$  have been reported for the basalts of the Amirante Ridge (Fisher *et al.* 1968). Values for Pacific basalts range from 44 to 150 parts/ $10^6$  (Engel *et al.* 1965), but too few data are available for the distinction of any regional trends in this ocean. Taking the range of zirconium contents in the basalts from the equatorial belt of the Atlantic as a basis for comparison, the Carlsberg Ridge basalts appear to be rather high in zirconium, those of the Amirante Ridge rather low and those of the M.A.R. at  $45^\circ$  N either high (if Aumento's data are preferred) or low (according to the data of Muir & Tilley).

#### *Areal variations*

From the foregoing discussion it is apparent that even when basalts of similar petrographic character are compared differences in trace element contents of deep-sea basalts are encountered which are too large to be attributed to inadequate sampling or analytical error. While many more data will be required to establish the reality of regional variation in trace element content levels in otherwise comparable basalts, those available at present do suggest that deep-sea basalts from different areas do possess distinctive trace element characteristics.

In the M.A.R. at  $45^\circ$  N the basalts contain abnormally high contents of Ba, are relatively enriched in La, Ce, Pr and Nd compared with the other lanthanide rare earths, show slight enrichment in Rb but have rather low contents of Sc and Y and display exceptionally low values of the Sr/Ba ratio.

In the same ridge at  $22\frac{1}{2}^\circ$  N the basalts are slightly enriched in Co and Ga and have high values of the Sr/Ba ratio.

The equatorial zone of the M.A.R. contains basalts with Ba contents four to seven times greater than those usually encountered in deep-sea basalts, but this feature is not accompanied by unusually low values of the Sr/Ba ratio.

The basalts of the Carlsberg Ridge contain rather high contents of Sc and Zr, are slightly enriched in Ga, have lower Ba contents than might be expected from their strongly undersaturated character and show less relative enrichment of La, Ce, Pr and Nd compared with the other lanthanides than could be expected in view of their petrographic characters.

Though sparsely sampled, the basalts of the Amirante Ridge appear to be rich in Cu, but contain rather low contents of Sr, Y and Zr.

Basalts from the Pacific north of  $13^\circ$  S have Ba contents several times greater than those usually found in deep-sea basalts, but have normal Sr/Ba ratios. Possibly more extensive studies would disclose other characteristics of these basalts and regional variation within this ocean.

#### CONCLUSIONS

The two main factors influencing the trace element contents of deep-sea basalts are the petrographical character of a rock and the location in the ocean floor from which it was obtained. Other factors such as inadequate sampling, analytical error, alteration effects and incipient metamorphism have much less influence on reported trace element contents.

Variation in trace element contents with changing petrographical character of the rock is probably related to the nature of the process of magma genesis along the lines discussed by Gast (1968). Regional variation of trace element contents in otherwise similar basalts requires some other explanation. Since most of the deep-sea basalts which have been studied have been obtained from different parts of the mid-oceanic ridge system it seems unlikely that contamination of ascending magmas by sedimentary materials could have materially affected magma compositions to produce the observed regional variations in trace element contents of these rocks. Such regional variations suggest regional variation in the trace element geochemistry of the source materials in the mantle from which the basalts were derived. If this is so, geochemical provinces probably exist in oceanic areas comparable to those long recognized in continental areas, but much more work is required before the existence of such provinces can be considered to be definitely established and their boundaries delineated.

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