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Major Element Variations in Ocean-Floor Basalts

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Major element variations in ocean-floor basalts

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Although ocean-floor basalts form a very convergent group from the point of view of their major element compositions, the variation that they do show can be interpreted in geological terms to a certain extent, though analytical variation must contribute substantially to that observed. Multivariate statistical methods demonstrate a high-level fractional crystallization trend in 94 selected ocean-floor basalts caused by precipitation of calcic plagioclase, forsteritic olivine and augite. After this effect is subtracted, a moderate amount of variation remains which can be interpreted as caused by crystal–liquid processes involving amphibole, though this is less certain. A new average of ocean-floor basalt compositions is presented, and it is suggested that the term 'oceanic tholeiite' should not be retained.

Introduction

That basalts from the deep ocean floor show chemical peculiarities that distinguish them from most other basalts has been recognized for a number of years now, and has been mostly set out by Engel, Engel & Havens (1965). In the last few years an increasing number of chemical analyses of deep ocean-floor basalts has become available, and this study is an attempt to define the range of chemical composition of these rocks more closely, using all obtainable data, and to make deductions about the genesis of this basalt type from the variation seen in its major element composition.

Selection of analyses

Over 200 major element chemical analyses of ocean-floor rocks are at present available, but many are unsuitable for this study, and so a selection procedure was devised to sort out the appropriate samples.

First, because this study is concerned essentially with liquids and relations between liquids, a set of criteria were designed to remove rocks whose compositions are likely not to represent original liquids. Thus basalts and dolerites only were used because coarser grained rocks are always liable to have undergone accumulation. Then basalts carrying more than a small amount of the calcic plagioclase and/or forsteritic olivine phenocrysts (or xenocrysts, Muir & Tilley 1964) were removed, again because of the likelihood of accumulation. Then basalts that had become weathered through prolonged contact with sea water (defined as H_2O greater than 2 %, and/or $Fe_2O_3/FeO + Fe_2O_3$ greater than 0.4) were omitted because chemical studies (see Matthews 1970; Hart & Nalwark 1970) have shown that such weathering introduces profound changes in the major (and trace) element contents, which clearly makes weathered basalts unsuitable for this kind of work. Finally, metamorphism can introduce chemical changes too (Cann 1969; Melson, Thompson & van Andel 1968), so rocks in which the original igneous mineralogy had been modified by re-heating were also omitted.

Secondly, Engel *et al.* (1965) demonstrated a considerable and fundamental difference between the compositions of basalts from oceanic islands, their underwater slopes and large isolated seamounts, and basalts from the deep ocean floor proper. This suggests that a different mechanism of formation is operating in the two cases, so basalts from islands and large seamounts were not considered here.

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Thirdly is the question of analytical accuracy. This is a very difficult question to deal with. One expects a certain degree of analytical inaccuracy or lack of precision, and this is discussed later. However, some of the available analyses gave signs of suffering from more gross analytical errors, and an attempt was made to recognize and discard these. In particular the analyses in Poldervaart & Green (1965) are suspect, especially when compared with analyses of other rocks from the same dredge hauls by Muir & Tilley (1966) and Miyashiro, Shido & Ewing (1969). Two other analyses were omitted for this reason, that in Korzhinskii (1962) and that in Yagi (1960).

TABLE 1. SOURCES OF THE 94 ANALYSES USED

Source	analyses selected
Aumento (1968)	9–4*; 9–7*; 9–18*; 56–2*
Bezrukov, Krylov & Chernysheva (1966)	basalt from 36° 02′ S, 71° 17′ E*
Cann (1969)	5106.21; 5111.2, 5, 7*
Cann (1970)	6231*; 6243.2*; 6224.2*; 6244*
Cann (unpublished)	glass from 2° 48′ N, 59° 52′ E
	basalt from 13° 54′ N, 51° 45′ E*
	basalt from 14° 20′ N, 51° 59′ E*
Chernysheva & Bezrukov (1966)	basalt from 5° 24′ N, 62° 08′ E*
Correns (1930)	basalt from 1° 56′ S, 12° 41′ W*
Engel & Engel (1963)	EM; PV 17
Engel & Engel (1964a)	D2–1; D3*; D5–5*
Engle & Engel (1964b)	D3; D4*; D5*
Engel, Fisher & Engel (1965)	D113A$_1$; D114D; D115*; D143A*; D143B*
Fisher, Engel & Hilde (1968)	DODO 128B*, DODO 128C*
McBirney & Aoki (1966)	glass from Amph RD3
Melson, Bowen, van Andel & Siever (1966)	Ch44DR2 fresh basalt
Melson, Thompson & van Andel (1968)	Ch44DR2-1*;
	Ch44DR2-18*;
	THV18 10–76*
Miyashiro, Shido & Ewing (1969)	A150–7–AM 1, 2, 4, 5, 7, 9, 15A, 16B;
	V25–1–T1A, 3, 9, 11, 87, 89*, 91*;
	92*, 94*, 96*, 97*, 99*, 102*, 103*;
	V25–RD3–T1E; V25–6–T20*; V25–8–T2*;
	A150–RD20–AM3, 4, 27, 28
Muir & Tilley (1964)	4519.25, 65, 34*, 46, 55, 56*
Muir & Tilley (1966)	73519*; 73521; 79487; 92541; 92542; 92543;
	92544; 92545; 4519.45*; 4520.1*, 4*
Nicholls, Nalwalk & Hays (1964)	pillow rim from 50° 44′ N, 29° 52′ W*
	pillow rim from 28° 53′ N, 43° 20′ W*
Petelin (1964)	pillow from 5° 45′ S, 152° 43′ E*
Wiseman & Sewell (1937)	basalt from 8° 32′ N, 94° 10′ E*

* Basalts included in the 'primitive' group (see section on residual variation).

After this procedure, chemical analyses of 94 basalt specimens were left. Where two or more analyses had been made of the same specimen, the analysis was chosen which was of the glassy crust of the rock, or the nearest equivalent if this was not available, because experience shows this to be likely to have been least affected by weathering or deuteric processes. The 94 analyses remaining are listed by source in table 1, and are the basis of the calculations in the rest of this paper.

Most of the analyses accepted are of samples from the crests of mid-ocean ridges, because basalts from the flanks of the ridges and the deep ocean floor away from ridges are almost always too weathered. Some of the samples, though, come from fracture zones or deep ocean trenches.

GENERAL COMPOSITIONAL CHARACTERISTICS

Engel *et al.* (1965), and several other authors, have noticed that deep ocean-floor basalts are highly convergent in major element composition, as well as having a characteristic composition different from other basalts.

Table 2 shows the means of the major element oxides for the 94 selected basalts. They show the same kinds of features that were commented on by Engel *et al.* (1965) in their earlier compilation, though brought into clearer perspective by the omission of the kinds of analyses referred to above. Particularly notable are the low K_2O, TiO_2 and P_2O_5, the rather high Al_2O_3 (especially as these analyses are of virtually aphyric rocks), the high CaO and the very high Na/K ratio.

TABLE 2. MEANS, STANDARD DEVIATIONS AND STANDARD ERRORS OF MEANS OF MAJOR ELEMENT OXIDES IN 94 SELECTED OCEAN FLOOR BASALT ANALYSES

	means	standard deviations	standard errors of means
SiO_2	49.61	0.72	0.074
Al_2O_3	16.01	0.85	0.087
FeO†	11.49	1.27	0.131
MnO	0.18	0.04	0.004
MgO	7.84	0.90	0.092
CaO	11.32	0.64	0.066
Na_2O	2.76	0.25	0.026
K_2O	0.22	0.12	0.012
TiO_2	1.43	0.29	0.030
P_2O_5	0.14	0.07	0.007

† All iron calculated as FeO.

The second column in table 2 is a list of standard deviations of the oxides from their means. The values here are notably small, in some cases scarcely more than the standard deviation that would be expected for analyses of the same rock made by different analysts (Fleischer & Stevens 1962). This emphasizes the very high degree of homogeneity of major element composition of ocean-floor basalts, much greater than would be expected for, say, a collection of continental flood basalts made on a similarly worldwide basis. This feature must reflect very similar conditions of origin for all of these rocks, a worldwide homogeneity of the processes that give rise to ocean-floor basalts much greater than that of similarly restricted classes of basalts from other environments.

The third column in table 2 is a list of standard errors of the means of the different oxides. While the assumptions necessary for the strict interpretation of these values, normal distribution and random sampling, are not present, the very small values of the standard errors indicate that the value of the means is likely to change scarcely at all on further sampling, and that the means calculated here are as near the 'true' means as makes very little difference.

The results of this very simple analysis demonstrate both the high homogeneity and the characteristic major element features of ocean-floor basalts. These features are so distinctive that analyses of basalts can relatively easily be classified as similar to or different from the ocean-floor basalt class. Analyses of basalts outcropping above sea level can only rarely be classed as similar to ocean-floor basalts, and where they can, as for example, in Macquarie Island (Varne, Gee & Quilty 1969), they appear to form part of upthrust pieces of oceanic

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crust. The most useful diagnostic features are, given an appropriate SiO_2 content, that the Al_2O_3 and CaO contents should be suitably high and that the Na/K ratio should also be very high, while the TiO_2 content is low.
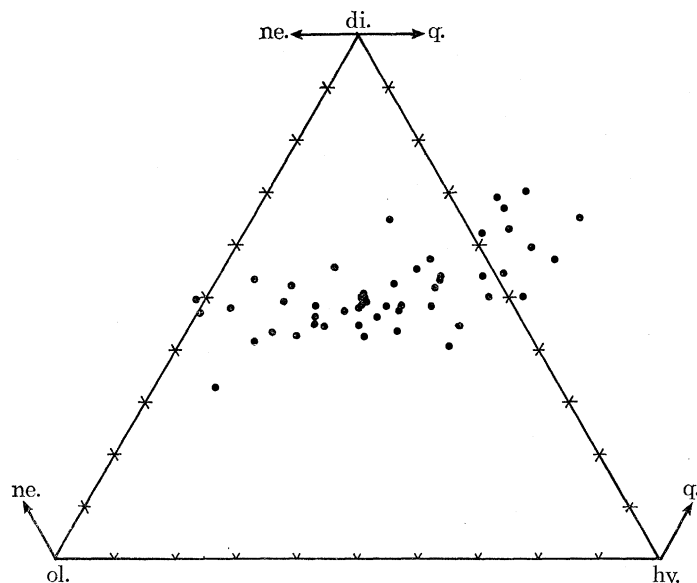

FIGURE 1. Triangular diagram of molecular proportions of $(Mg,Fe)_2SiO_4$, $Ca(Mg,Fe)Si_2O_6$ and $(Mg,Fe)_2Si_2O_6$ for 51 of the 94 selected analyses. This diagram is constructed using the raw data, i.e. the analytical data as given by the analyst.
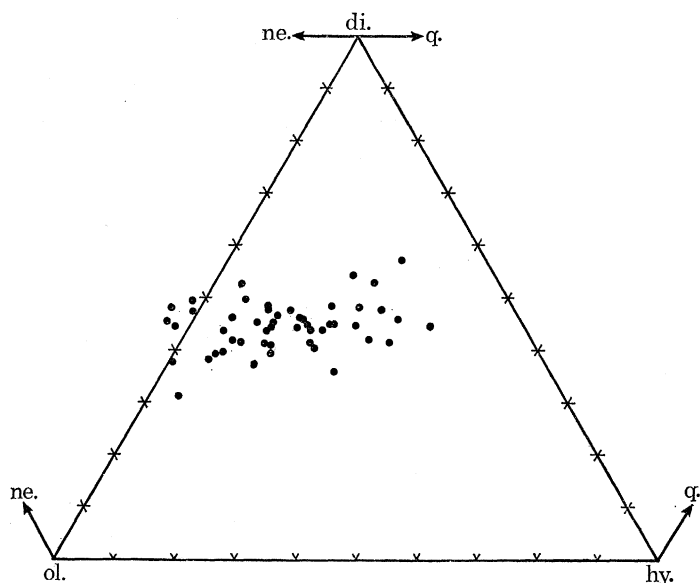

FIGURE 2. The result of calculating all iron as ferrous iron on the plot of 51 of the 94 selected analyses of figure 1. Note how the analyses cluster more closely together, and that there are now no quartz-normative examples.

Very many authors, and in particular the Engels and their co-workers (see references) have referred consistently to ocean-floor basalts as oceanic tholeiites. Some authors, however (Muir & Tilley 1964; Cann & Vine 1966) have described ocean-floor basalts with alkaline affinities, for example with no visible reaction relationship of olivine.

Figure 1 was plotted to look into this further. Fifty-one of the 94 selected analyses are shown here plotted on a normative ol–hy–di triangular diagram. There can be seen to be a complete range of basalts from some nepheline normative types to some quartz-normative ones, spanning the boundary between alkaline and tholeiitic basalts. Because the oxidation ratio of iron affects the position of points on this diagram, and because much of the oxidation seen is probably postmagmatic, a closer approach to the situation existing in the liquids is probably provided by figure 2, where, instead of using the raw data, the iron in the analyses was all calculated as ferrous iron before computing the norms. This probably errs somewhat on the other side. Analyses of fresh glasses suggest an oxidation ratio of about 10:1 ferrous to ferric iron in the liquids, but the procedure adopted here is much closer to the original state of affairs than if the raw data only were used.

In figure 2, the analyses have clustered much more closely together, and still span very effectively the boundary between alkali basalts and tholeiites. This boundary may be taken, to a first approximation, as the line di/di+hy = 0.8, near the limit of solid solution of hypersthene in magmatic augites. Taking this boundary, a minority, but a substantial minority, of these selected basalts lie on the alkaline side, while very many more cluster very close to the line.

Hence the use of the blanket term 'oceanic tholeiite' is of rather dubious value, particularly as there appears to be a continuous gradation from true tholeiitic types to definitely alkaline types in this very homogeneous group of basalts, and I believe that it should be abandoned.

Systematic variation in the major elements

Despite the high degree of convergence of the major element composition of ocean-floor basalts, much of the variation seen is in the form of systematic covariation of different oxides which cannot be the result of any plausible systematic analytical errors. This kind of variation must reflect the conditions of genesis of the basalts, and should be able to be interpreted in terms of one or more plausible mechanisms operating during their formation.

This kind of investigation is usually carried out with rock series by plotting them on one or more of a number of standard diagrams which spread them out in a convenient way. Unfotunately this approach does not work in the case of ocean-floor basalts. Diagrams of variation with SiO_2 content, with $Mg/Mg+Fe$ ratio and so on do not yield the usual clear-cut picture, and one is forced to use standard methods of multivariate statistical analysis to try to reach some conclusion.

The first step here is the calculation of a matrix of correlation coefficients between the oxides (table 3). The highest correlation coefficient is -0.62 between total iron and Al_2O_3, and this does not reflect a very high degree of correlation. However, because of the large number of analyses it is highly significant. With 94 analyses, a correlation coefficient of 0.26 is significant at the 1 % level, 0.33 at the 0.1 % level, and 0.39 at the 0.01% level. In addition, because the variation is close to that expected from analytical error, we would expect there to be a large amount of 'noise' in the variation, resulting from analytical variability, which will reduce the size of correlation coefficients accordingly. (To assist reading table 3, half the matrix has been filled with the actual values, while correlations greater than the 1 % significance level have been indicated in the other half.)

Striking in table 3 is the chain of strong correlations between Al, Fe, Ti, Ca and Na. This

suggests strongly that there is some regular variation present in this cluster of analyses, but does not show what it is. To investigate this further, principal components analysis was used.

Principal components analysis can be broadly envisaged as follows. If we have measurements of variables for a set of rocks, the relations between the rocks can be completely visualized by plotting them as points in an n-dimensional graph. This is not usually possible, and we usually make use of projections from the n dimensions on to two or three dimensions. However, this assumes that we can identify the directions along which we can usefully make projections, something that is always difficult, and in this case impossible. Returning to the n-dimensional case, we can envisage the points as forming a cluster, in general terms like an n-dimensional ellipsoid. Principal components analysis is simply a mathematical manipulation which picks

TABLE 3. CORRELATION MATRIX FOR MAJOR ELEMENTS IN THE WHOLE GROUP
OF 94 SELECTED OCEAN-FLOOR BASALTS

The upper half of the matrix gives values for the correlation coefficients, and in the lower half those correlation coefficients significant at the 1 % level have been marked with + or − depending on whether they are positive or negative

	Si	Al	Fe	Mn	Mg	Ca	Na	K	Ti	P
Si	1	−0.23	−0.04	−0.17	−0.11	−0.26	+0.35	−0.23	+0.21	−0.27
Al	.	1	−0.62	−0.20	−0.24	+0.30	+0.10	+0.11	−0.53	−0.27
Fe	.	−	1	+0.29	−0.19	−0.35	−0.12	−0.23	+0.59	+0.17
Mn	.	.	+	1	−0.19	+0.23	−0.25	−0.09	+0.11	+0.28
Mg	.	.	.	.	1	−0.18	−0.20	+0.12	−0.25	−0.03
Ca	−	+	−	.	.	1	−0.57	+0.07	−0.50	+0.02
Na	+	.	.	.	.	−	1	+0.07	+0.32	−0.02
K	.	.	.	.	.	.	.	1	+0.01	+0.35
Ti	.	−	+	.	.	−	+	.	1	+0.19
P	−	−	.	+	.	.	.	+	.	1

out the major axis of this cluster, the one along which variance is greatest, and then picks out successively axes at right angles to this and all previous axes along which the variance is progressively less and less, finishing with the axis at right angles to the other axes along which variance is least. A computer will pick out these axes (principal components), will calculate the variance along each (the eigenvalues), will print out for each principal component the coefficients by which the values of the old variables must be multiplied to give the scores for each rock on each component (the eigenvectors) and will print out the scores calculated for each rock on each principal component. The advantages of this are twofold, first that a new set of orthogonal, i.e. independent, variables is produced, and secondly, that these new variables are arranged in decreasing order of variance. Table 4 gives part of the results of principal components analysis of all of the rocks included in this study. (Mn, K and P were omitted from this analysis as trace elements.)

Interpretation of principal components analysis is usually focused on the components with largest variance, partly because one is looking after all for a simple explanation, and partly because the smaller variance components are clouded by experimental error in determining the original variables and by other factors. The related procedure of factor analysis involves more subtle and difficult reasoning. Basically the difference between principal components analysis and factor analysis is that the former is purely a mathematical manipulation, while the latter involves making assumptions about the kind of answer you expect to get at the end, so that in factor analysis one is sometimes involved unwittingly in circular trains of argument. Neither kind of analysis has available any good test of significance, that normally used being

that if you get an answer that looks good, you accept it, while if it looks wrong you vary your parameters and repeat the analysis. Because of these difficulties, I have used principal components analysis not as an end in itself, but as a means for generating ideas which can be tested independently by using data not included in the analysis. Used in this way, it has been very successful.

TABLE 4. THE FOUR MOST IMPORTANT PRINCIPAL COMPONENTS DERIVED FROM THE
WHOLE GROUP OF 94 OCEAN-FLOOR BASALT ANALYSES

The principal components analysis was made using seven variables (K, Mn and P being omitted) which were first normalized to zero mean and unit standard deviation. Total variance thus equals the number of variables, and the eigenvalues give the variance explained by each principal component. This is also expressed as the percentage of the total variance explained by each principal component. The eigenvectors give the coefficients required to transform the original data, once normalized, by a linear transformation to the new principal components axes. Thus the scores on each principal component for any analysis may be calculated by normalizing it, multiplying the normalized values by the appropriate coefficients and taking an algebraic sum of the resulting figures.

| | Principal component number | | | |
	1	2	3	4
eigenvalue	2.64	1.59	1.22	0.85
variance explained as percentage of total variance	37.7	22.8	17.4	12.1
eigenvectors				
SiO_2	$+0.25$	$+0.37$	$+0.12$	$+0.82$
Al_2O_3	-0.43	$+0.42$	-0.18	-0.31
FeO†	$+0.43$	-0.42	-0.27	-0.12
MgO	-0.07	-0.24	$+0.84$	-0.07
CaO	-0.46	-0.21	-0.35	$+0.38$
Na_2O	$+0.27$	$+0.64$	$+0.06$	-0.25
TiO_2	$+0.53$	-0.03	-0.21	-0.10

† Total iron calculated as FeO.

To return to table 3, the first principal component accounts for 38 % of the total variance, and is thus clearly an important axis in our n dimensional array of data points. The eigenvector shows a strong positive loading for SiO_2, Na_2O, TiO_2 and total Fe and a negative loading for Al_2O_3 and CaO. This suggests a primary model to account for variation parallel to this vector of crystal fractionation where the material being precipitated is lower than the mean in SiO_2, Na_2O, TiO_2 and total Fe, and higher than the mean in Al_2O_3 and CaO. (The reverse is equally possible mathematically but chemically implausible.) To interpret this we return to the original data, and construct a subtraction diagram for the basalts which score high or low on this component and low on all other components. The composition where TiO_2 falls to zero can be read off (making the assumption that TiO_2 would be very low in any precipitate) and this calculated normatively to about 65 % An_{75}, 20 % Fo_{90} and 15 % augite. (An exact value may not be read off, because of uncertainties in drawing lines on the subtraction diagram. The composition quoted lies within the limits of error for an analysis of all of the basalts as well as for geographical groups taken separately, notably the basalts from 30° N on the Mid-Atlantic Ridge where this variation is particularly well developed.)

Confirmation that such a mechanism is the principal cause of variation in ocean floor basalts is given by (a) the fact that many ocean-floor basalts contain megacrysts (described by Muir & Tilley (1964) as xenocrysts) of calcic plagioclase (major) and forsteritic olivine (minor), and

(*b*) the common occurrence of anorthositic gabbros, presumably cumulates from such a crystallization process, in dredge hauls from the ocean floor. Because of (*b*), and because of the effect of pressure in suppressing the crystallization of plagioclase from a basaltic magma, this fractionation mechanism must operate at high levels either within, or just beneath, the oceanic crust. In fact it appears likely on geophysical grounds (Cann 1970) that this fractionation occurs within a magma chamber at the base of the ocean crust. That such a fractionation, involving principally olivine and calcic plagioclase, is important in the generation of ocean floor basalt compositional trends has been suggested on other grounds by Miyashiro, Shido & Ewing (1970) and by other authors.

RESIDUAL VARIATION

The eigenvector associated with the fractionation of olivine, plagioclase and augite at high levels accounts for 38 % of the total variance of the original data; 62 % of this variance thus remains unaccounted for. Much of this must represent analytical variability, but it is possible that some is the result of other processes independent of the high-level fractionation already identified. The recognition of such a trend is, however, beset by many difficulties.
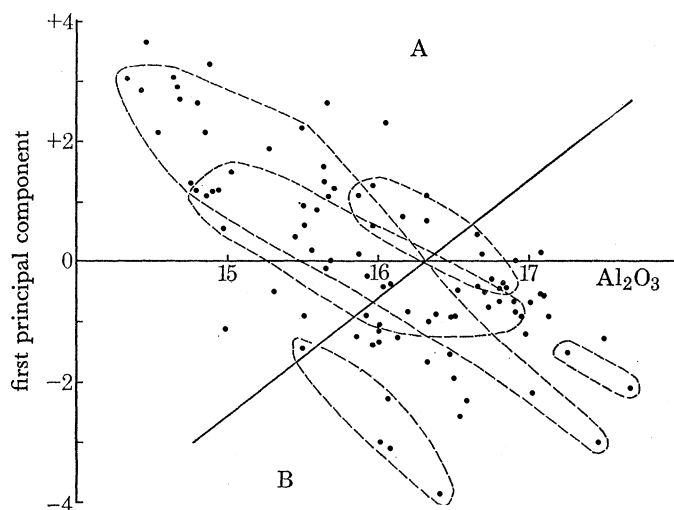

FIGURE 3. Plot of the first principal component derived from principal component analysis of the 94 selected analyses against Al_2O_3 for all 94 analyses. The fractionated basalts lie at the upper left, and the primitive basalts at the lower right. The diagonal line across the graph divides the 'primitive' group, lying in field B, from the rest. Dashed lines surround groups of analyses from restricted geographical areas, the largest such field covering the basalts from near 30° N on the Mid-Atlantic Ridge.

It would be possible to use the principal components of the original analysis which have lower variance, and try to associate them with some physico-chemical processes. However these components, as has been already mentioned, are mathematically independent of, i.e. orthogonal to, the first principal component, and it is unlikely that the other hypothetical processes would fulfil this condition. To overcome this, a form of factor analysis involving non-orthogonal factors could be used, but the objections to factor analysis have already been set out above.

Because of the conceptual difficulties of this approach, a different one seemed preferable. This involved selecting the basalt samples that did not appear to have been affected by the high-level fractionation (the 'primitive' basalts) and repeating the correlation and principal components analysis on them. In practice this was done by plotting a graph of the original

first principal component against Al_2O_3. This is shown as figure 3. On this diagram are outlined the fields covering basalts all from the same restricted geographical area. These fields are narrower than the total spread of analyses, suggesting that, superimposed on the trend caused by high-level fractionation, there is another trend which depends on factors varying from place to place in the oceans.

TABLE 5. CORRELATION MATRIX FOR MAJOR ELEMENTS IN THE GROUP OF
'PRIMITIVE' BASALTS

(See figure 3 and the text for an explanation of the selection of these analyses.) There are 48 analyses in this group. Correlation coefficients greater than 0.37 are significantly different from zero at the 1 % level. These have been marked with + or − in the lower half of the matrix.

	Si	Al	Fe	Mg	Ca	Na	Ti
Si	1	+0.04	−0.42	−0.10	−0.28	+0.41	+0.14
Al	.	1	−0.05	−0.42	−0.34	+0.39	+0.14
Fe	−	.	1	−0.21	+0.16	−0.46	−0.07
Mg	.	−	.	1	−0.12	−0.23	−0.21
Ca	.	.	.	.	1	−0.65	−0.25
Na	+	+	−	.	−	1	+0.30
Ti	.	.	.	.	.	.	1

TABLE 6. THE FOUR MOST IMPORTANT PRINCIPAL COMPONENTS DERIVED FROM
THE GROUP OF 'PRIMITIVE' BASALTS

See figure 3 and the text for an explanation of the selection of these analyses, and the legend to table 4 for an account of the meaning of the columns and rows of this table

	principal component number			
	1	2	3	4
eigenvalue	2.52	1.49	0.94	0.87
variance explained as percentage of total variance	36.0	21.3	13.4	12.6
eigenvectors				
SiO_2	+0.38	+0.27	+0.52	+0.04
Al_2O_3	+0.34	−0.46	−0.15	−0.45
FeO†	−0.32	−0.50	−0.31	+0.14
MgO	−0.17	+0.65	−0.49	+0.04
CaO	−0.45	−0.09	+0.61	+0.02
Na_2O	+0.56	−0.03	−0.06	−0.09
TiO_2	+0.29	−0.20	−0.05	+0.87

† Total iron calculated as FeO.

In order to separate off the primitive basalts, a line was drawn across this diagram, nearly at right angles to the high-level fractionation trend, so that all of the geographical areas for which a reasonable number of analyses was available had at least one member in the primitive group. The analyses of the basalts falling into this primitive group were then separately treated in the same way as the whole group of analyses had been earlier. Table 5 shows the correlation coefficients for the primitive basalts, and table 6 the principal components accounting for most of the variance in this set of analyses. (Mn, K and P were omitted again from this treatment as trace elements.)

Table 5 shows a number of significant correlation coefficients, which should be compared with those of table 3 for the analyses as a whole. They indicate some systematic variation in this group of analyses which is not caused by analytical variation and which presumably thus

has some petrogenetic control. The first principal component in table 6 accounts for 36 % of the total variance of the primitive basalt analyses. It is positively weighted by Si, Al and Na (with Ti subsidiary) and negatively weighted by Ca, Fe and, to a lesser extent, by Mg). Thus if we seek a crystal fractionation (or more generally crystal–liquid) explanation here, we are seeking a phase or combination of phases lower than the average in Si, Al and Na and higher in Ca, Fe and perhaps Mg (or vice versa, as before, with less petrological plausibility). Identification is more difficult here than in the previous case. The material would have a composition for example, near SiO_2, 44, Al_2O_3 14.5, Fe as FeO 11, MgO 9.5, CaO 15, Na_2O 1, TiO_2 1, depending on how much Na_2O it contained. It is difficult to envisage a combination of anhydrous silicates with the necessary composition, but such a composition could be matched by an amphibole. As this variation appears to be chiefly a regional variation, we might here be concerned with crystal–liquid relations in mantle material containing variable amounts of water at different points along the mid-ocean ridge system. But we are clearly here up against the difficulty of detecting a small amount of regional variation against a good deal of noise. In order to carry this further, more extensive studies of the chemistry of small regions of ridge crest must be made. At present we know well the region around 30° N on the Mid-Atlantic Ridge, thanks to the work of Muir & Tilley, Miyashiro *et al.* and other authors, but there is no other part of the ridge crest that we know nearly as well. Definite conclusions about this regional chemical variation in the basalts must await this further work.

Conclusions

This study of the major element composition of 94 ocean-floor basalts has drawn attention to the following points:

(1) These basalts form an extremely homogeneous group and show well-defined chemical criteria that distinguish them from other basalts, particularly their low K_2O, TiO_2 and P_2O_5, their rather high Al_2O_3, the high CaO and the very high Na/K ratio. (Conclusions similar to these were drawn on the basis of a smaller sample by Engel *et al.* 1965.)

(2) Within the group some systematic variation can be seen. In particular, the basalts range from definitely tholeiitic types to definitely alkaline types, with a wide zone of transitional basalts between the two extremes. The term 'oceanic tholeiite' as a blanket term for ocean-floor basalts should be dropped.

(3) Analysis of major element variation by multivariate statistical methods was attempted. A matrix of correlation coefficients showed several highly significant correlations that appeared not to have resulted from analytical variation. Principal components analysis gave a first principal component, accounting for 38 % of the total variance, interpretable in terms of fractional crystallization, involving precipitation of solid with composition 65 % plagioclase (An_{75}), 20 % olivine (Fo_{90}), and 15 % augite. This interpretation is supported by other lines of evidence, and appears to be a high-level, probably intra-crustal, fractionation.

(4) A further principal components analysis was carried out using basalts separated graphically as not having been affected to any great extent by this fractionation, the 'primitive' ocean-floor basalts. The first principal component here accounted for 36 % of the remaining variance, and could be interpreted as caused by crystal–liquid processes involving amphibole within the mantle, but with rather less certainty. Further study of these primitive basalts seems desirable.

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