

Basalts from the deep ocean floor

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Summary. Basalts dredged from the floor of the deep ocean show general tholeiitic affinities. Some samples are rich in aluminium and of very similar composition to the Warner high-alumina basalt from California. Both olivine tholeiite and high-alumina basalt have been found in the form of glass in dredgings from the Mid-Atlantic Ridge, indicating that liquid magmas of both compositions have been erupted on to the sea bed in this area. In explanation of this association a tentative hypothesis of fractional melting of hydrated upper mantle material is proposed. It is suggested that under the mid-ocean ridges the 'basaltic fraction' of the mantle is locally in the form of an amphibole. Fractional incongruent melting of this amphibole appears to be a possible explanation of the range of composition encountered in dredged glass samples.

Introduction

INTERMITTENTLY during the last thirty years various petrologists (Powers, 1932; Anderson, 1941; Tilley, 1950; Kuno, 1960) have drawn attention to non-porphyrific varieties of basalt containing high contents of aluminium—the high-alumina basalts. Examples described by Powers and Anderson from the Modoc Lava-Bed quadrangle, California, especially the Warner basalt flow, have usually been taken as typical of this group. Basaltic rocks of similar composition have hitherto been recognized only from continental areas, though Kuno (1960) suggested that 'the absence, or at least scarcity, of the high-alumina basalt from the oceanic regions' is difficult to explain in the light of existing knowledge of the probable conditions in the upper mantle. Recently the general designation 'high-alumina' has been applied to lavas which, in their chemical compositions, differ considerably from the Californian examples though still displaying high aluminium contents and a non-porphyrific character, e.g. hawaiites (Yoder and Tilley, 1962, p. 417). Lavas of this type are found on other oceanic islands as well as Hawaii from which they were named, but high-alumina basalt of Warner characteristics does not appear to have been recognized on these islands.

Recent dredging of the deep ocean floor, especially that of the Atlantic, has yielded good hauls of solid rock fragments, mostly basalt. These

basalts are tholeiitic in their general affinities, usually extremely fine-grained and many of the fragments are rimmed with basaltic glass. Chemical analysis of these glassy basalts has shown that glass remarkably similar in composition to the Warner basalt is represented in these deep-sea hauls, though more normal tholeiitic material is present as well. If the existing collections of dredged fragments are at all representative, high-alumina basalt is not scarce on the deep ocean floor and Kuno's difficulty disappears.

Basalts from the deep ocean floor

A collection of basalt fragments obtained from a depth of 3566 metres (uncorrected) at 28° 53' N., 43° 20' W. and described by Nicholls, Nalwalk, and Hays (1964) contains both olivine tholeiite and high-alumina olivine tholeiite. The olivine tholeiite fragments from this locality are, for the most part, finely crystalline though some contain small amounts of glass in the groundmass. They are essentially non-porphyritic, only rare microphenocrysts of olivine having been observed. Olivine (Fo₉₀ to Fo₈₅), calcic labradorite, minute granules of augite and opaque iron ore, probably magnetite can be recognized in the groundmass. The chemical composition of a typical example is given in table I, col. 1. The high-alumina olivine tholeiite fragments have glassy margins enclosing cryptocrystalline centres. Phenocrysts are sparsely distributed in this type too, only a few crystals of olivine (Fo₉₀) and even fewer of bytownite having been observed. They tend to be more frequent in the centres of the fragments than in the glassy margins and in a few samples the glass rim is virtually devoid of crystalline material. In the cryptocrystalline centres of these fragments only olivine, calcic labradorite, and a translucent brown spinellid have so far been certainly identified. The compositions of an almost wholly glassy rim and the cryptocrystalline material it encloses are given in table II, cols. 1 and 2. These compositions are very similar to that of the Warner basalt (table II, col. 3) and, despite the presence of the rare microphenocrysts, the basalts to which they refer may safely be included in the high-alumina group.

Glass-rimmed fragments dredged from a depth of 3890 metres (uncorrected) at 50° 44' N., 29° 52' W. are of the olivine tholeiite type. The centres of these fragments are also cryptocrystalline with sparse microphenocrysts of olivine. Extremely small microlites of plagioclase, rare granules of brown spinel, and occasional crystals of olivine are the only minerals that have been distinguished in the groundmass. Analyses of

a glass rim and the cryptocrystalline centre it encloses are given in table I, cols. 2 and 3.

Both types of glass are remarkably free from alteration effects. In both types of fragment the differences between the analyses of the glassy margin and the cryptocrystalline centre are so slight that they cannot be regarded as significant and the compositions of the glasses may be taken as those of chilled basaltic liquids. Although, as shown below, dredged basalt fragments from elsewhere on the ocean floor have comparable compositions, particular weight is placed on these analyses of basaltic glass, indicating as they do that olivine tholeiite and high-alumina olivine tholeiite have existed on the floor of the Atlantic in a wholly liquid condition.

Other basalt fragments dredged from the Atlantic floor show signs of alteration from contact with sea water. Nicholls (1963) presented data indicating that the alteration of basaltic glass by sea water on the ocean bed results in a marked increase in the ferric iron-ferrous iron ratio and in the H₂O content, an increase in total iron percentage, a slight increase in alumina percentage, marked decreases in the percentages of lime and magnesia, and a lesser decrease in silica percentage. Further unpublished studies suggest that where the original material was partly crystalline (e.g. porphyritic) the crystalline material is altered less rapidly than the glass. Elements held in silicate mineral structures may be retained in the altered material although they are leached from glass. These effects of sea-water alteration must be taken into account when analyses of altered dredged basalt fragments are considered.

Basalt dredged from a depth of *c.* 3125 metres at 22° 56' N., 46° 35' W. was porphyritic with 10 % phenocrysts of bytownite (An₈₂) distributed through a dark red-brown, almost opaque, groundmass. Rare microlites of olivine and more frequent ones of plagioclase are the only crystalline components distinguishable in this groundmass. While this groundmass appears to be strongly altered the feldspar phenocrysts are virtually free from such effect. The analysis of this basalt displays a very high content of aluminium (table II, col. 4). In col. 5 of the same table a calculated composition of the altered groundmass of this rock is given, obtained by subtracting 10 % plagioclase An₈₂ from the total rock composition. This still shows a high content of aluminium. It differs from the high-alumina olivine tholeiite along the lines that would be expected since it has suffered sea-water alteration. The original magnesium content may not have been as high as that of the high-alumina olivine tholeiite glass, but there can be little doubt that magma

TABLE I. Tholeiitic basalts and related rocks from the deep ocean floor

	1	2	3	4	5	6	7	8
Chemical data (wt. %)								
SiO ₂	49.27	50.47	50.58	49.54	47.58	49.43	52.24	49.97
TiO ₂	1.26	1.04	1.12	0.78	2.10	1.94	1.83	—
Al ₂ O ₃	15.91	15.93	15.91	16.47	15.05	15.04	15.02	11.68
Fe ₂ O ₃	2.76	0.95	1.03	2.30	6.74	2.21	2.93	2.45
FeO	7.60	7.88	7.91	7.55	4.42	7.39	6.31	10.60
MnO	0.13	0.13	0.13	0.19	0.14	0.23	0.14	trace
MgO	8.49	8.75	8.78	7.91	5.71	8.40	6.01	12.84
CaO	11.26	11.38	11.26	11.43	10.97	6.69	8.73	11.20
Na ₂ O	2.58	2.60	2.70	2.62	3.19	4.45	4.02	1.60
K ₂ O	0.19	0.10	0.10	0.30	0.04	0.11	0.21	0.25
H ₂ O ⁺	0.35	0.53	0.24	0.95	0.99	3.16	2.25	—
H ₂ O ⁻	0.51	0.06	0.31	0.27	2.46	0.86	0.50	—
P ₂ O ₅	0.13	0.11	0.13	0.08	0.23	0.19	0.20	0.33
Total	100.44	99.93	100.21	100.60*	99.62	100.10	100.39	100.92

* Includes 0.17 % BaO and 0.04 % Cr₂O₃.

C.I.P.W. norms

Qz	—	—	—	—	3.2	—	2.3	—
Or	1.1	0.6	0.6	1.8	0.2	0.7	1.2	1.5
Ab	21.8	22.0	22.8	22.2	26.5	37.6	34.0	13.5
An	31.2	31.5	31.0	32.3	26.6	20.7	22.3	21.2
Di	19.2	19.7	19.5	19.4	20.5	9.1	15.9	26.1
Hyp	13.6	15.4	14.7	11.1	4.8	8.0	13.8	25.0
Ol	5.9	6.6	7.1	7.4	—	12.7	—	7.4
Mt	4.0	1.4	1.5	3.3	8.6	3.2	4.3	3.6
Ilm	2.4	2.0	2.1	1.5	4.0	3.7	3.5	1.9
Ap	0.3	0.3	0.3	0.2	0.5	0.5	0.5	0.8
Rest	0.9	0.6	0.6	1.2	4.3	4.0	2.8	—

Norm plag.
composition
mol % An

57 57 56 58 48 34 38 60

1. Fine-grained olivine tholeiite, dredged fragment from 28° 53' N., 43° 20' W.; depth 3566 metres, anal. G. D. Nicholls.
2. Glass rim of dredged basaltic fragment from 50° 44' N., 29° 52' W.; depth 3890 metres, anal. G. D. Nicholls.
3. Cryptocrystalline centre of same dredged fragment as analysis 2, anal. G. D. Nicholls.
4. Dredged basalt fragment from 1° 56' S., 12° 40.7' W.; depth 2000 metres (Correns, 1930, p. 80).
5. Variolitic 'basalt', dredged fragment from *Mabahiss* station 133; approximately 1° 23' S., 66° 35' E.; depth c. 3385 metres—for details of this location see text. (Wiseman, 1937, table III, no. 1.)
6. Variolitic augite 'basalt', dredged fragment from '*Mabahiss*' station 133. (Wiseman, 1937, table V, no. 1.)
7. Augite 'basalt', dredged fragment from *Mabahiss* station 133. (Wiseman, 1937, table I, no. 1.)
8. Basic volcanic glass, dredged from *Challenger* station 285; 32° 36' S., 137° 43' W.; depth 4344 metres. (Murray and Renard, 1891, p. 456, anal. 82.)

In calculating the norm of this rock the TiO₂ % has been arbitrarily assigned a value of 1.00 % and the Al₂O₃ % accordingly modified to 10.68 %.

from which this rock crystallized also possessed high-alumina characteristics.

A basalt fragment dredged from a depth of 2000 metres at $1^{\circ} 56' S.$, $12^{\circ} 40.7' W.$ contained phenocrysts of plagioclase (bytownite), olivine, and augite (Correns, 1930). The analysis of this rock, reproduced in table I, col. 4, shows a rather high aluminium content, though lower than in the high-alumina olivine tholeiites from farther north. The porphyritic character of this rock raises doubts about referring it to the high-alumina group, but the marked chemical resemblances between it and the analysed glasses strongly suggest that it is petrogenetically related to them.

Rocks described as basalt have been dredged from the Carlsberg Ridge in the Indian Ocean (Wiseman, 1937). They were moderately fresh and were obtained from a depth of *c* 3385 metres at station 133 of the *Mabahiss* cruise ($1^{\circ} 25' 54'' S.$ to $1^{\circ} 19' 42'' S.$, $66^{\circ} 34' 12'' E.$ to $66^{\circ} 35' 18'' E.$). These rocks differ from those obtained in the Atlantic both in their mineralogy and chemistry, though they are of broad and general tholeiitic affinities. Olivine has not been observed in the Carlsberg rocks, augite is much more prominent than in the Atlantic rocks and the plagioclase present is distinctly more sodic than the labradorite-bytownite encountered in the rocks described above. Chemically they are richer in sodium than the Atlantic samples, though they show the same low potassium contents (table I, cols. 5, 6, and 7). The aluminium contents are not high and the magnesium contents generally lower than those of the Atlantic basalts, though the extent of chemical change by sea-water alteration of these rocks is difficult to evaluate. The two examples of low magnesium content both show rather high ferric iron-ferrous iron ratios when compared with the fresh Atlantic rocks and all three are richer in H_2O , effects that often result from such alteration. It is unfortunate that these intriguing rocks are altered, and highly desirable that really fresh material should be obtained from this area of the ocean floor.

Fragments of basaltic glass were dredged from the deep Pacific by the *Challenger* expedition and have been described by Murray and Renard (1891). Olivine and plagioclase (between labradorite and bytownite) were reported to be present in these glasses, but augite was much less frequently seen. Chemical data were given for three samples of these dredged glass fragments and are reproduced here in table I, col. 8, and table II, cols. 6 and 7. In these analyses, now over seventy years old, TiO_2 contents were not reported and P_2O_5 was reported in only one case.

TABLE II. High-alumina basalts from the deep ocean floor and related rocks

	1	2	3	4	5	6	7
Chemical data (wt. %)							
SiO ₂	48.13	47.94	47.77	46.39	46.24	46.76	46.84
TiO ₂	0.72	0.75	0.71	1.46	1.62	—	—
Al ₂ O ₃	17.07	17.45	18.52	20.19	18.70	17.71	17.78
Fe ₂ O ₃	1.17	1.21	1.49	7.31	8.12	1.73	1.64
FeO	8.65	8.47	7.31	2.87	3.19	10.92	10.79
MnO	0.13	0.13	0.14	0.12	0.13	0.44	0.34
MgO	10.29	10.19	9.88	4.59	5.10	10.37	9.24
CaO	11.26	11.26	11.32	11.48	10.92	11.56	11.87
Na ₂ O	2.39	2.37	2.55	2.82	2.89	1.83	2.02
K ₂ O	0.09	0.09	0.12	0.13	0.14	0.17	0.28
H ₂ O ⁺	0.27	0.23	0.31	1.15	1.28	—	—
H ₂ O ⁻	0.02	0.15	0.11	1.41	1.57	—	—
P ₂ O ₅	0.10	0.08	0.07	0.06	0.07	—	—
Cl	—	—	—	0.26	0.29	—	—
Total	100.29	100.32	100.30	100.38*	100.18*	101.49	100.80

* Totals corrected for O equivalent of Cl.

C.I.P.W. norms

Qz	—	—	—	2.4	2.8	—	—
Or	0.6	0.6	0.7	0.8	0.8	1.0	1.7
Ab	20.2	20.0	21.5	22.0	22.3	15.0	16.7
An	35.6	36.7	38.6	43.0	38.7	36.7	35.5
Di	16.0	15.2	13.8	10.9	11.7	16.2	18.7
Hyp	4.7	4.5	1.7	6.5	7.3	6.4	2.9
Ol	19.7	19.7	19.9	—	—	21.4	20.8
Mt	1.7	1.8	2.1	5.1	6.1	2.5	2.4
Ilm	1.4	1.4	1.4	2.8	3.0	1.9	1.9
Ap	0.2	0.2	0.2	0.1	0.2	0.3	0.3
Rest	0.3	0.4	0.4	7.2	7.3	—	—

Norm plagi.

composition

mol. % An	62	63	63	65	62	70	67
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1. Glass rim of dredged basalt fragment from 28° 53' N., 43° 20' W.; depth 3566 metres, anal. G. D. Nicholls.
2. Cryptocrystalline centre of same dredged basalt fragment as 1, anal. G. D. Nicholls.
3. High-alumina basalt, Warner flow, Medicine Lake Highlands, California (Yoder and Tilley, 1962, table 2, no. 17).
4. Porphyritic altered basalt fragment from 22° 56' N., 46° 35' W.; depth 3125 metres, anal. G. D. Nicholls. Chlorine was recast as NaCl in the normative calculations.
5. Calculated groundmass composition of same porphyritic altered basalt, derived from analysis 4 by subtracting 10 % phenocrysts of bytownite (An₈₂). Chlorine was recast as NaCl in the normative calculations.
6. Basic volcanic glass, dredged from *Challenger* station 276; 13° 28' S., 149° 30' W.; depth 4298 metres. (Murray and Renard, 1891, p. 463, analysis 94.) In calculating the norm the TiO₂ % has been arbitrarily assigned a value of 1.00 %, P₂O₅ 0.13 %, and the Al₂O₃ % accordingly modified to 16.58 %.
7. Basic volcanic glass, dredged from *Challenger* station 302; 42° 43' S., 82° 11' W.; depth 2652 metres. (Murray and Renard, 1891, p. 464, analysis 95.) In calculating the norm the TiO₂ % has been arbitrarily assigned a value of 1.00 %, P₂O₅ 0.13 %, and the Al₂O₃ % accordingly modified to 16.65 %.

The Al_2O_3 figures are, therefore, almost certainly too high. In calculating norms for comparison with the other analyses in these tables TiO_2 contents of 1.00 % were assumed and in the two cases where P_2O_5 was not reported 0.13 % was assigned to this constituent, the Al_2O_3 figures being modified accordingly. Such 'assumed' norms have only very limited value, though they serve to point up the essential similarities between these Pacific glasses and those from the Atlantic. The two Pacific samples for which analytical data are reproduced in table II may be safely referred to the high-alumina group even on the present available information, though new analyses are clearly desirable. The third Pacific glass is low in aluminium and, for this reason, is included in the other table. Its general tholeiitic character is apparent and it is clear from the norm that the low aluminium content is due to abnormally low normative plagioclase content. The molecular An % in this normative plagioclase cannot be very different from that in the other dredged basaltic glasses and some genetic affinity between these Pacific glasses appears probable. Despite this earlier analytical work being incomplete it indicates that there exists on the floor of the Pacific basaltic material remarkably similar to that recently dredged from the Atlantic.

Although there are very few published analyses of basalts from the deep ocean floor those that are available show relatively little variation and this is particularly so if only those from the Atlantic and Pacific are considered. In this paper they are listed in two tables for convenience, but this is not intended to imply that there are two distinct types—rather, a range between, and possibly beyond, the two compositions represented by the glasses from the Atlantic. The only representatives from the Indian Ocean are distinguished by high sodium contents, but all came from one locality and it would be unwise to read too much significance into these sodium figures at present. Two features emerge from a study of the analyses of deep-sea basalts presented in this paper.

First, all the analysed basalts have tholeiitic affinities. Typical alkaline olivine basalts and basalts bearing modal or normative nepheline have not yet been reported from the *deep* ocean floor, despite their frequent occurrence on oceanic islands. High-alumina basalt is present on the floor of the deep ocean and its occurrence there in the form of glass indicates that basaltic magma of such composition has been erupted in a completely liquid condition in oceanic areas. In these deep-sea high-alumina basalts the high aluminium contents are not accompanied by relatively low contents of magnesium, as is often the case in high-

alumina basalts from islands and continental areas. In this respect they resemble the Warner basalt.

Second, all the analyses show relatively low potassium contents. The highest value (0.30 % K_2O) is exceeded by all the representative basalts studied by Yoder and Tilley (1962) with the exception of the Warner basalt. The basalts of the oceanic islands do not show such low K_2O contents and it would be unwise to assume that all deep-sea basalt is similarly low in potassium. However, these early data suggest that, in any future analyses of deep-sea basalts, the potassium contents merit particular attention.

High-alumina basalt

As hitherto defined this term embraces all aphyric basaltic rocks of relatively high aluminium content (17 % Al_2O_3 or more) and it is in this sense that it has been applied to such rocks as hawaiiite. Such an extremely broad definition encompasses considerable variation. Comparison of analyses of the Warner basalt and typical hawaiiites shows major differences in the contents of MgO , CaO , Na_2O , K_2O , and TiO_2 . Large differences in the MgO content may be particularly significant. Where high aluminium contents are due to effective concentration of plagioclase in a basaltic magma, whether by resorption of locally accumulated crystals, extraction of non-felspathic components or delayed crystallization of the feldspar in water-rich magma (Yoder, 1954), the resulting composition of the product should be depleted in those elements not involved in the feldspar lattice, notably magnesium. Examination of analyses of various basalts referred to the high-alumina group, e.g. by Kuno (1960), shows that this is often so. However, there are other basalts rich in aluminium which contain normal to high contents of magnesium, as does the Warner basalt to which the name high-alumina basalt was first applied. As pointed out above the deep-sea aluminium rich basalts are good examples of these. Such rocks show high contents not only of normative plagioclase but also of normative olivine, as recognized by Tilley (1950, p. 55). If their compositions are to be attributed to the resorption of accumulated crystals in a basaltic magma both plagioclase and olivine would have to be involved. Yoder and Tilley (1962, p. 419) have shown that if 22 % plagioclase (An_{64}) is extracted from an analysis of the Warner basalt a composition similar to that of an olivine basalt from Hualalai is produced. The presence of 26 % normative olivine (mol. Fa % 20) in this Hualalai rock suggests that its final composition has been influenced by some concentration of

olivine. The effect of this treatment of the Warner basalt composition is then merely one of breaking down the accumulative and resorption processes into two separate stages. The need to accumulate and resorb both plagioclase and olivine if the Warner type high-alumina basalts are to be explained by such a process still remains. Quite apart from the difficulty of accounting for an adequate energy source for the resorption of the accumulated crystals, the problem of explaining the considerable excess of plagioclase and olivine over pyroxene in the resorbed fraction is a major obstacle to accepting such an interpretation of Warner type high-alumina basalts.

This can be further illustrated by considering the basalts dredged from the floor of the Atlantic. At $28^{\circ} 53' N.$, $43^{\circ} 20' W.$ the dredge haul included both high-alumina basalt glass and olivine tholeiite of lower aluminium content. If the composition of this high-alumina basalt is to be attributed to resorption of accumulated crystals in a basaltic magma it is reasonable to take the composition of the olivine tholeiite, or, better, that of the glass of very similar composition from farther north, as that of the basaltic magma. From the analytical data (table I, col. 2, and table II, col. 1) the resorbed accumulated fraction would have to have a SiO_2 content less than 48.1%. However, a graphical subtraction shows that if this is less than 46.2 the overall composition of this fraction would be such that nepheline would have to be represented amongst the resorbed accumulated crystals. Dismissing this as most improbable, the composition of the least siliceous accumulated fraction would correspond to approximately 57% plagioclase (An_{68}), 27% olivine (Fe_{72}), 13% pyroxene, and 3% iron ore. Mineralogically this is not too unreasonable, though the excess of plagioclase and olivine over pyroxene may be noted. But the amount of such a fraction that would have to be resorbed makes this explanation most improbable. The olivine tholeiite magma would have to assimilate one and one-quarter times its own weight of this accumulated fraction. Thus it does not appear that the composition of the high-alumina basaltic glass can be satisfactorily explained by resorption of accumulated crystals in this tholeiitic magma. The same graphical solution can, of course, be used to evaluate the possibility that the tholeiitic glass composition is derived from the high-alumina magma by partial crystallization of the latter. In this case approximately 45% of the magma would have to crystallize, the separated crystal fraction having the composition given above. There is no energy difficulty here, but such an explanation of a relationship between the two glass compositions is hardly in accord with the nature

of the rare microphenocrysts in the two types. In those high-alumina basalt fragments which carry rare microphenocrysts both olivine and plagioclase occur, whereas in the tholeiite fragments only olivine microphenocrysts are present. Near-surface fractional crystallization appears inadequate as a satisfactory explanation of the occurrence of both compositions in a relatively localized part of the Atlantic floor.

Possible mantle conditions and their influence on magma genesis

Petrological opinion is rapidly moving towards agreement that basaltic magmas must be generated in the mantle of the Earth. Defining mantle material as that possessing a compressional wave velocity greater than 8 km/sec the upper surface of the mantle lies at approximately 6 km below the sea bed under much of the ocean. The seismic discontinuity separating the overlying crust from the mantle (often called the Mohorovicic discontinuity although not necessarily the same, or even continuous with, the seismic discontinuity under continental areas originally called by that name) can be readily detected under many areas. Under others, notably the mid-ocean ridges, it is less apparent. Then material of compressional wave velocity 7.3–7.5 km/sec is present about 3 km below the sea floor and continues to depths of more than 20 km below the floor (Heezen and Ewing, 1963, p. 406). Hess (1962) suggests that this also is mantle material and that the lower wave velocity is to be attributed partly to intense fracturing and dilation and partly to abnormally high temperatures in the upper mantle under these areas. Whatever the true explanation may be, the seismic evidence leaves little doubt that the upper mantle beneath the mid-ocean ridges must differ in some respects from that under the deep abyssal plains of the ocean floor.

The suggestion that the lowest layer (layer 3) of the oceanic crust is serpentized peridotite (Hess, 1962) is supported by the dredging of such rock from several localities in the deep Atlantic (Shand, 1949; Hersey, 1962; Nicholls, Nalwalk, and Hays, 1964). Firm identification of layer 3 as serpentine would add weight to the prevailing view that oceanic mantle material is peridotitic in character. If basaltic magma is produced by partial melting of this material it cannot be a pure olivine rock. Instead, it may be regarded as a mixture of olivine with some proportion of the chemical constituents of basalt, the mineralogical location of these elements being dependent on prevailing conditions in different parts of the mantle. The transition from basalt to eclogite under high pressure and temperature has been experimentally studied,

e.g. Boyd and England (1959); Yoder and Tilley (1962), and the latter authors have produced a diagrammatic interpretation of the results obtained (*op. cit.*, p. 498). This diagram with some scale modification is reproduced in fig. 1 and shows the pressure-temperature conditions under which a water-free mantle fraction chemically equivalent to basalt would be present as a mixture of garnet and pyroxene, and those under which it would be represented by an assemblage of the minerals found in basaltic rocks.

The heat flow through those parts of the ocean floor away from the mid-ocean ridges averages $1.08 \pm 0.54 \mu\text{cal/cm}^2/\text{sec}$ (Bullard, 1963). From this it is apparent that the increase in temperature with depth under those areas of the ocean floor cannot be very different from that suggested by Hess (1962) and shown on fig. 1 as 'Hess normal gradient'. It is clear from the extrapolation to depths greater than 15 km that even if this gradient is maintained below this level the pressure-temperature conditions for eclogite stability would be encountered in a dry mantle at depths of *c.* 50 km below the sea floor. If the gradient falls off with depth as shown by the dotted extension of the 'Hess normal gradient' they will be encountered at somewhat shallower depths. Thus it is likely that at depths of 50+ km below the sea floor in areas away from the mid-ocean ridges the 'basaltic fraction' of the peridotite may well be in the form of pyroxene and garnet and the mantle material in the condition of a garnet peridotite. Discussions of basaltic magma genesis in terms of remelting of garnet peridotite (Yoder and Tilley, 1962; O'Hara and Mercy, 1963) are particularly applicable in such environments.

The heat flow through the ocean floor on the mid-ocean ridges is substantially higher than it is elsewhere (Bullard, 1963), values up to and even slightly above $8 \mu\text{cal/cm}^2/\text{sec}$ having been recorded. For these ridge areas the increase in temperature with depth under the sea floor is more likely to approach that suggested by Hess (1962) for the gradient displaced by convection and shown on fig. 1 as 'Hess displaced gradient'. Below 15 km depth considerable uncertainty exists as to the magnitude of the gradient, but as the figure shows, unless the average gradient between 15 km and 60 km falls to a value below $10.3^\circ\text{C}/\text{km}$ the pressure-temperature conditions for eclogite stability will not be encountered under the ridge areas at approximately 50 km depth.

The localities from which high-alumina basalt has been dredged in the Atlantic all lie on the Mid-Atlantic Ridge. Of the two Pacific examples one lies on the ridge running from Easter Island south-east

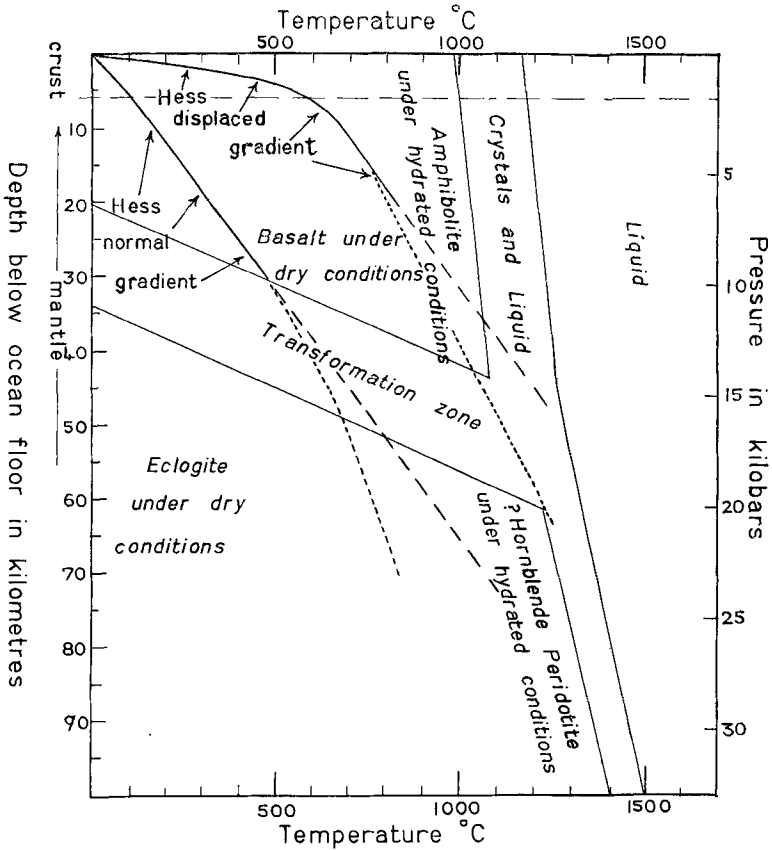


FIG. 1. Pressure-temperature diagram showing fields of stability of basalt and eclogite under dry conditions based upon a diagram given by Yoder and Tilley (1962, fig. 43). Under hydrated conditions amphibole rich assemblages are likely to be stable in the pressure-temperature fields shown. This diagram can be used to deduce the probable mineralogical character of the 'basaltic fraction' of the upper mantle under different conditions of temperature, pressure, and water content. Superimposed on the diagram are two curves showing the probable increase in temperature with depth below the ocean floor in two contrasting oceanic environments. That labelled 'Hess normal gradient' corresponds to conditions under the deep abyssal plains and that labelled 'Hess displaced gradient' to conditions under parts of the mid-ocean ridges. Both curves are based on Hess (1962). Increasing uncertainty with depth attaches to both curves below a depth of 15 km.

towards southern Chile and the other lies on the Mid-Pacific Mesozoic Ridge of Hess (1962, p. 605). The dredged tholeiite fragments from the Atlantic reported in this paper are also from the Mid-Atlantic Ridge, but the Pacific example does not appear to be associated with a ridge structure. Provisionally it appears that there may be some relationship between the unexpected occurrence of Warner type high-alumina basalt in the mid-ocean ridge areas and the conditions in the upper mantle under these areas.

Hess (1962) presented arguments in favour of interpreting the mid-ocean ridges as the sites of rising convection currents in the mantle, accompanied by degassing (dehydration) of mantle material. Under such areas of the sea floor the mantle material may be partially hydrated. The experimental work of Yoder and Tilley (1962) on the stability of amphibole in water-bearing basaltic compositions indicates that under these conditions the 'basaltic fraction' of the mantle material down to depths of approximately 30 km, or even more, may be largely in the structural state of an amphibole, i.e. the mantle material may be essentially a hornblende peridotite.

Most of the earthquake foci along the active mid-ocean ridges lie at the comparatively shallow depth of 30 km (Heezen, 1960). If the depth of earthquake foci can be used as an indication of the depth of magma genesis, this may be occurring at these comparatively shallow depths under the mid-ocean ridges, where the mantle material may well be a hornblende peridotite. Yoder and Tilley (*op. cit.*, p. 509) suggest that, in the absence of direct experimental evidence, it would be reasonable to suppose that the hydrous equivalent of eclogite may be pyroxene hornblendite. If so, at depths below 30 km the mantle material beneath the mid-ocean ridges may similarly be a form of hornblende peridotite, but one in which the mineralogical location of the chemical constituents differs from that at shallower depths. Thus it is not unrealistic to examine the possibility that the submerged basalts of the mid-ocean ridge areas have originated by partial melting of a hornblende peridotite.

The two basaltic glasses from the Atlantic both contain less water than the majority of amphiboles and a direct attempt to recalculate their compositions in terms of amphibole structures will display deficiencies in hydroxyl contents. There is no obvious means of establishing whether water has been lost from the magma during eruption and, thus, none of determining how much, if any, water should be added to the glass compositions before attempting to recast them as amphibole structures. To overcome this difficulty the amphibole structural formula may be

regarded as $X_{2-3}Y_5Z_8O_{23} + H_2O$ and the analyses recast on the basis of 23 oxygen atoms per formula unit, though this carries the implication that if the melting material was deficient in water this would reflect either an anion deficiency in the mantle amphibole or incomplete conversion of the 'basaltic fraction' to amphibole. The results of recasting the analyses are given in table III. The recast formula from the tholeiite

TABLE III. Compositions of the two Atlantic glasses recast to 23 oxygens and possible compositions of hornblendic fraction of the upper mantle on the same basis

	1	2	3A	3B
Z	{ Si 6.972 } { P 0.013 } { Al 1.015 } 8.000	{ 6.660 } { 0.012 } { 1.328 } 8.000	6.272 0.011 1.717	6.272 0.011 1.717
Y	{ Al 1.575 } { Ti 0.108 } { Fe ⁺⁺⁺ 0.098 } { Fe ⁺⁺ 0.907 } { Mn 0.015 } { Mg 1.813 } 4.516	{ 1.451 } { 0.075 } { 0.121 } { 0.997 } { 0.015 } { 2.136 } 4.795	1.342 0.051 0.262 0.946 0.015 2.384	1.541 0.051 0.063 1.069 0.015 2.261
X	{ Ca 1.684 } { Na 0.694 } { K 0.018 } 2.396	{ 1.670 } { 0.639 } { 0.017 } 2.326	1.688 0.608 0.016	1.688 0.608 0.016

1. Result of recasting the composition of tholeiite glass (table I, col. 2) into an amphibole structural formula on the basis of 23 oxygen atoms per formula unit.
2. Result of recasting the composition of high-alumina basaltic glass (table II, col. 1) into an amphibole structural formula on the basis of 23 oxygen atoms per formula unit.
- 3A and 3B. Two possibilities for the structural formula (on basis of 23 oxygen atoms per formula unit) of the hornblendic fraction of hydrated mantle material based on the assumption that this fraction melts incongruently to liquid, olivine and amphibole of higher melting point.

glass has a higher $(Fe^{+++} + Fe^{++} + Mn)/(Fe^{+++} + Fe^{++} + Mn + Mg)$ ratio than that from the high-alumina basalt glass, a higher Na/Ca ratio and a lower (Al in 4-fold coordination)/Si ratio. Thus it would be expected to result from an earlier stage (lower temperature) of melting.

Neither composition conforms very closely to the structural formula of an amphibole. That derived from the tholeiite glass is nearly 10% deficient in Y group ions and that from the high-alumina basalt slightly more than 4% deficient in these ions. Yet the charge excess on the Y group almost exactly balances the charge deficiency on the Z group in both cases and the charge carried by the X group is, in both cases, very close to 4. If the liquids now represented by the glasses were, in fact, derived by melting of an amphibole bearing fraction of the mantle these

deficiencies could arise in either of two ways—(i) by the melting fraction being a mixture of an amphibole and silicate phase(s) of lower $X:(Y+Z)$ ratio, e.g. anorthite; or (ii) by the amphibole melting incongruently yielding a crystalline phase of higher $Y:Z$ ratio than that in the amphibole, e.g. olivine or a mixture of olivine and pyroxene. From the data at present available it does not appear possible to eliminate either of these alternatives. Calculations made to explore their feasibility show that in both cases the amphibole would have to melt incongruently along a continuous reaction series. The experimental data of Yoder and Tilley (1962, p. 448 et seq.) tend to favour the second possibility, which appears at present to be the more attractive. Under this interpretation, extrapolation of the compositional trends to the condition where there would be no deficiency in the Y group ions would give some idea of the composition of the amphibole phase melting. Uncertainty regarding the state of oxidation of iron prevents a close estimation of this composition and two possibilities are listed in table III, cols. 3A and 3B. No major obstacle to the hypothesis that the liquids corresponding to the dredged glasses originated by partial fusion of hydrated upper mantle material has emerged in the calculations that have been made. Consequently, it is tentatively suggested that some, at least, of the basaltic magma erupted along the mid-ocean ridges may have originated by the fractional melting of a hornblendic fraction of such hydrated upper mantle material.

Despite their uncertainty the figures in table III, cols. 3A and 3B, are adequate to show that complete fusion of such an amphibole fraction could produce basalt containing a small content of normative nepheline. However, magma originating in this way would also be rich in both aluminium and magnesium. Rocks of corresponding composition have not yet been reported from the sea bed, though samples transitional between olivine tholeiites and alkaline olivine basalts are known (Tilley, personal communication, 1963). Alkaline olivine basalts of normal aluminium content (11–15 %) are unlikely to result from a process of this nature. This is in accord with the developing opinion that such basalts originate at greater depths in the mantle than those considered here.

The basalts of oceanic islands now exposed above sea-level form the upper parts of considerable accumulations of lava in one localized area. In some cases, e.g. Hawaii, the sub-surface structure differs from that under the mid-ocean ridges and the processes of basalt genesis must be different from that discussed here. Other oceanic islands lie on the mid-

ocean ridges, though the basalts exposed on them frequently differ significantly from the dredged samples described in this paper. At present, when systematic investigation of basalts from the deep sea floor is in its very early stages, the relationships between basalts of the ocean bed and those of the oceanic islands are obscure and the present tentative hypothesis is not offered as a general explanation of all basalts of oceanic areas. It is no more than a working hypothesis on the origin of Warner type high-alumina basalt and related rocks found on the ocean floor, to be re-evaluated as more material becomes available for study. Should it prove to have any value it may form a means of estimating, eventually, the composition of the 'basaltic fraction' of the upper mantle.

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