Petrological and Geochemical Evidence for Convection in the Earth's Mantle

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XIV. Petrological and geochemical evidence for convection in the Earth's mantle

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Various lines of evidence suggest that layer 3 of the oceanic material is partially serpentinized peridotite. Hess (1962) suggested that this layer originated by serpentinization of the upper part of the mantle, the necessary water being derived from the degassing of rising columns of mantle convection cells beneath the mid-ocean ridges. In this paper it is shown that support for this hypothesis can be derived from two entirely different lines of evidence.

The first concerns the characters of volcanic lavas extruded in oceanic areas. Although these are, in general terms, basaltic, significant minor differences exist between basalts dredged from different parts of the ocean floor and between many dredged basalts and the lavas of oceanic islands. In particular high-alumina tholeiitic basalt of Warner type has been obtained from the more deeply submerged parts of the Mid-Atlantic Ridge. Experimental work has shown that, although alkali basalts and normal tholeiitic basalt could be derived by partial fusion of a dry mantle, the presence of water in the upper mantle is probably necessary for the genesis of Warner type basalts. The apparent restriction of Warner type basalts to the mid-ocean ridge areas suggests a similar restriction of the presence of water in the upper mantle and thus the restriction of the serpentinization process to these localized areas as suggested by Hess. The wide distribution of layer 3 in the oceanic crust must then imply some mechanism such as mantle convection currents for its dispersal from the areas of origin.

The second concerns the contrast in composition between the total volatiles that have emerged from the Earth's interior throughout geological time and the gases emerging from oceanic volcanoes at the present time. The state of oxidation of modern oceanic volcanic gases is very close to that predicted for gases in equilibrium with a Mg–Fe–silicate upper mantle, which suggests they have suffered no appreciable contamination on their way to the surface. They are, however, on a percentage basis, much richer in compounds of C, S and N and poorer in those of Cl and H_2O than the total emergent volatiles. The amount of water which must have emerged from some other source than oceanic volcanoes in order to explain the total volatiles composition can be calculated to be 8500 to 12600×10^{20} g. On the basis of the Hess hypothesis the amount of water liberated by dehydration of serpentinized peridotite in convective down currents can also be calculated. It is 13000×10^{20} g for a convective system moving at a rate of 1 cm/y. Two-channel escape of volatiles from the Earth's interior should result in minor changes in the partial pressure of carbon dioxide in the atmosphere. These should be reflected in the geochemistry of sedimentary rocks. The agreement between deduced and observed effects is surprisingly good in view of the uncertainties in the data and supports the hypothesis of transfer of the serpentinized perioditite layer from areas of convective up-current in the ocean basins to those of down-currents under the continents or continental margins.

INTRODUCTION

Seismic investigations at sea by a number of workers have established that the outer part of the lithosphere now covered by the deep oceans differs significantly from that under the continents. The seismic discontinuity separating material above with a P-wave velocity less than 7·8 km/s from material below with a P-wave velocity greater than this lies much nearer the surface of the lithosphere in these areas. This discontinuity, generally known as the Mohorovičic discontinuity (though not necessarily the same as, or even continuous with, the discontinuity known by that name under the continents), is only about 6·5 km below the ocean floor under the deep ocean basins. Following the normal practice of designating the material outside this discontinuity as 'crust' and that below as 'mantle' the oceanic crust is much thinner than the continental one. Throughout most of the oceanic areas three layers can be recognized within this crust; they are numbered 1, 2 and 3 in descending sequence. Layer 1 is of variable thickness and can be safely attributed to sediments which have accumulated on the ocean floor. Opinions vary about the probable nature of layers 2 and 3. Hamilton (1959, 1960) has suggested that layer 2 is consolidated sediment, but the frequency with which basalt occurs in dredge hauls of solid rock from the ocean floor suggests that basalt occurs and is possibly abundant in this layer. Until recently layer 3 was generally regarded as basalt, but Hess (1962) has suggested that it is serpentine or partially serpentinized peridotite. Various lines of evidence support this suggestion. The thickness of layer 3 is strikingly uniform in view of its presence throughout all oceanic regions. In view of the probable error of thickness determination from seismic data, reported thicknesses of $4\cdot8 \pm 1\cdot4$ km for 75% of the determinations make it unlikely that this layer is an accumulation of basaltic lava flows. It is much more likely that the base of it is determined by some change in material occurring under a restricted range of pressure–temperature conditions, such as the hydration of mantle peridotite to serpentine. The P-wave velocity of layer 3 ($6\cdot69 \pm 0\cdot26$ km/s; Raitt 1963) could correspond to 70% serpentinized peridotite (Hess 1962, figure 3) and the reported velocity range (6·0 to 7·2 km/s) would be embraced by serpentinized peridotite of 40–90% hydration. The best evidence that serpentine is present in part of the oceanic crust is the dredging of this rock type from the deep ocean floor at widely spaced localities. Published reports of such dredging from the central valley of the Mid-Atlantic Ridge at about 30° N (Shand 1949; Nicholls, Nalwalk & Hays 1964) and from the north wall of the Puerto Rico trench (Hersey 1962) are supplemented by further dredgings in the western equatorial Atlantic taken on the 35th cruise of R.V. *Chain* (1° 24·55′ S, 29° 12′ W).

However, since the hydration of Mg-rich olivine and talc to serpentine proceeds at temperatures of *ca.* 500° (Bowen & Tuttle 1949) the base of layer 3 cannot reasonably be attributed to the serpentinization of peridotite proceeding *in situ*. Temperatures 6 to 7 km below most of the deep ocean floor are unlikely to exceed 200° C and are probably not more than 150° C. This led Hess (1962) to suggest that the serpentinization process proceeds only under localized parts of the ocean floor, namely the mid-ocean rises, where the greater heat flow and thermal gradient suggest that temperatures of the order of 500° C may exist at approximately 5 km below the ocean floor. On this hypothesis the necessary water for hydration is derived from degassing of rising columns of mantle convection cells, these columns being located beneath the mid-ocean ridges. If this is so, differences should exist between the condition of the upper mantle in these areas and that of the upper mantle away from the zones of convective up-welling. Under the mid-ocean ridges the mineralogical assemblage in the upper mantle should be one which is stable in the presence of water at the appropriate temperature and pressure, whereas away from these areas the upper mantle assemblage should be one stable at much lower vapour pressures of water, or even under almost dry conditions.

Some schools of petrological thought have long believed that basaltic magmas must be generated in the mantle of the Earth and this view is rapidly gaining general acceptance.

Variation in mantle conditions might therefore be reflected in the nature of magmas generated in, and extruded from, different parts of the mantle and thus it becomes possible to test the Hess hypothesis against petrological facts.

It is now well established that the Mid-Atlantic Ridge has been the location of considerable submarine activity and in localized areas continuing vulcanicity has constructed volcanic piles of such magnitude that they emerge through the waves as oceanic islands, e.g. Iceland, Ascension, Tristan da Cunha. Topographic profiles across other mid-ocean ridges suggest that they, too, have been the site of considerable vulcanicity. In such areas, remote from the continental crust, the possibility of contamination of the products of volcanic activity during their passage upwards to the surface is minimal and it is generally accepted that such products have, in consequence, especial petrogenetical significance. Volcanic activity usually results in the extrusion of both lava and volcanic gases and consideration will be given to both in exploring how far the nature of the products of oceanic vulcanicity support the Hess hypothesis of mantle convection currents.

Volcanic lavas from the ocean basins

Samples of volcanic lavas from oceanic areas may be obtained either from the oceanic islands or by dredging rock outcrops on the deep ocean floor. Those from oceanic islands have attracted the attention of many petrologists and an extensive literature on them exists. Basaltic rocks are abundant, though other types, e.g. trachyte, occur in subordinate amount. Both tholeiitic basalt and alkali olivine basalt (normative nepheline) are common on the oceanic volcanic islands. These islands represent only those parts of the volcanic piles above present sea level and, in the majority of cases, only a small fraction of the total volcanic accumulation is exposed. The lavas of the deep ocean floor are not so well known. The overwhelming majority of dredged samples are basaltic in general character. Many are very fine grained and require chemical analysis before reference to basaltic type. Some thirty chemical analyses of dredged basalt samples now exist, though some are from the tops and upper flanks of sea-mounts (Engel & Engel 1963). All of the twenty-four analysed samples from depths greater than 1000 m are tholeiitic following the definitions of Yoder & Tilley (1962). There appears to be no published analysis or description of an alkali olivine basalt (normative nepheline) taken from a depth greater than 1000 m, despite the frequency of this basalt type on oceanic islands and the continents. Basalts dredged from submerged parts of the mid-ocean ridges at depths greater than 1000 m show a range of composition from tholeiite rich in both aluminium and magnesium (high-alumina basalt of Warner type—table 1, col. 1) to more normal tholeiite (table 1, col. 2). Basalts so far reported from dredged locations on the deep ocean floor not obviously connected with the mid-ocean ridges are of the more normal tholeiitic composition, and there appears, at present, to be a correlation between the distribution of Warner-type high alumina basalt on the deep ocean floor and the location of the mid-ocean ridges (Nicholls 1965).

Some samples dredged from the Mid-Atlantic Ridge assume critical importance in this context. They are glassy and the magma from which they solidified must have congealed before any significant crystallization occurred. Both the Warner type high alumina tholeiite and the more normal tholeiite are represented among these glasses and the analyses of Mid-Atlantic Ridge rocks in table 1 actually refer to two such glassy samples. These samples testify to the extrusion of liquid lava of these compositions within the Mid-Atlantic Ridge area and, almost certainly, represent liquid products of fractional remelting of mantle material under the ridge.

Table 1. Comparison of basalt compositions

	Mid-Atlantic Ridge basalts		Hawaiian Islands basalts	
	(1)	(2)	(3)	(4)
SiO_2	48·13	50·47	49·36	46·46
TiO_2	0·72	1·04	2·50	3·01
Al_2O_3	17·07	15·93	13·94	14·64
Fe_2O_3	1·17	0·95	3·03	3·37
FeO	8·65	7·88	8·53	9·11
MnO	0·13	0·13	0·16	0·14
MgO	10·29	8·75	8·44	8·19
CaO	11·26	11·38	10·30	10·33
Na_2O	2·39	2·60	2·13	2·92
K_2O	0·09	0·10	0·38	0·84
H_2O	0·27	0·53	—	—
H_2O	0·02	0·06	—	—
P_2O_5	0·10	0·11	0·26	0·37
total	100·27	99·93	—	—

(1) High alumina basalt (Warner type) glass; 28° 53′ N, 43° 20′ W, depth 3566 m. Analyst, G. D. Nicholls (quoted in Nicholls *et al.* 1964).

(2) Tholeiitic basalt glass; 50° 44′ N, 29° 52′ W, depth 3890 m. Analyst, G. D. Nicholls (quoted in Nicholls *et al.* 1964).

(3) Average tholeiitic basalt; Hawaiian islands (Macdonald & Katsura 1964).

(4) Average alkalic basalt, mostly olivine bearing; Hawaiian islands (Macdonald & Katsura 1964).

Analyses of basalt samples dredged from depths greater than 1000 m outside the mid-ocean ridge areas are scarce. Fortunately large numbers of analyses exist of the lavas from the Hawaiian islands, which lie off the mid-ocean ridge system but rise to such heights above sea level that erosion has dissected the whole volcanic pile to a greater extent than is usual on oceanic islands. High alumina basalt of Warner type has not been reported from the Hawaiian area. Average compositions of the tholeiites and alkali olivine basalts from the Hawaiian group (Macdonald & Katsura 1964) are given in table 1 for comparison with basalt types from the ridge areas. Significant differences exist between the two pairs of analyses. The ridge basalts are richer in Al and tend to be richer in Mg and Ca. They are poorer in Ti, total Fe and K. Such differences suggest some variation between the upper mantle of the ridge areas and that outside the ridge areas at the depths at which basaltic magmas are generated.

If basaltic magmas are generated by partial fusion of the upper mantle some fraction of such mantle material must be of basaltic composition (called hence-forward the basaltic fraction). The mineralogical composition of this basaltic fraction will depend on the conditions in the upper mantle (pressure, temperature, water vapour pressure, etc.) and any differences between different parts of the upper mantle are likely to be reflected in the mineralogical assemblages corresponding to the basaltic fraction. From the results of extensive experimental investigations Yoder & Tilley (1962) have produced a diagram delineating the pressure–temperature fields under dry conditions within which basaltic compositions would be represented by a 'basaltic' mineralogical assemblage (plagioclase, pyroxene, olivine) and by an 'eclogitic' mineralogical assemblage (garnet and jadeiitic pyroxene). The essential features of this diagram are shown in figure 1. In off-ridge areas

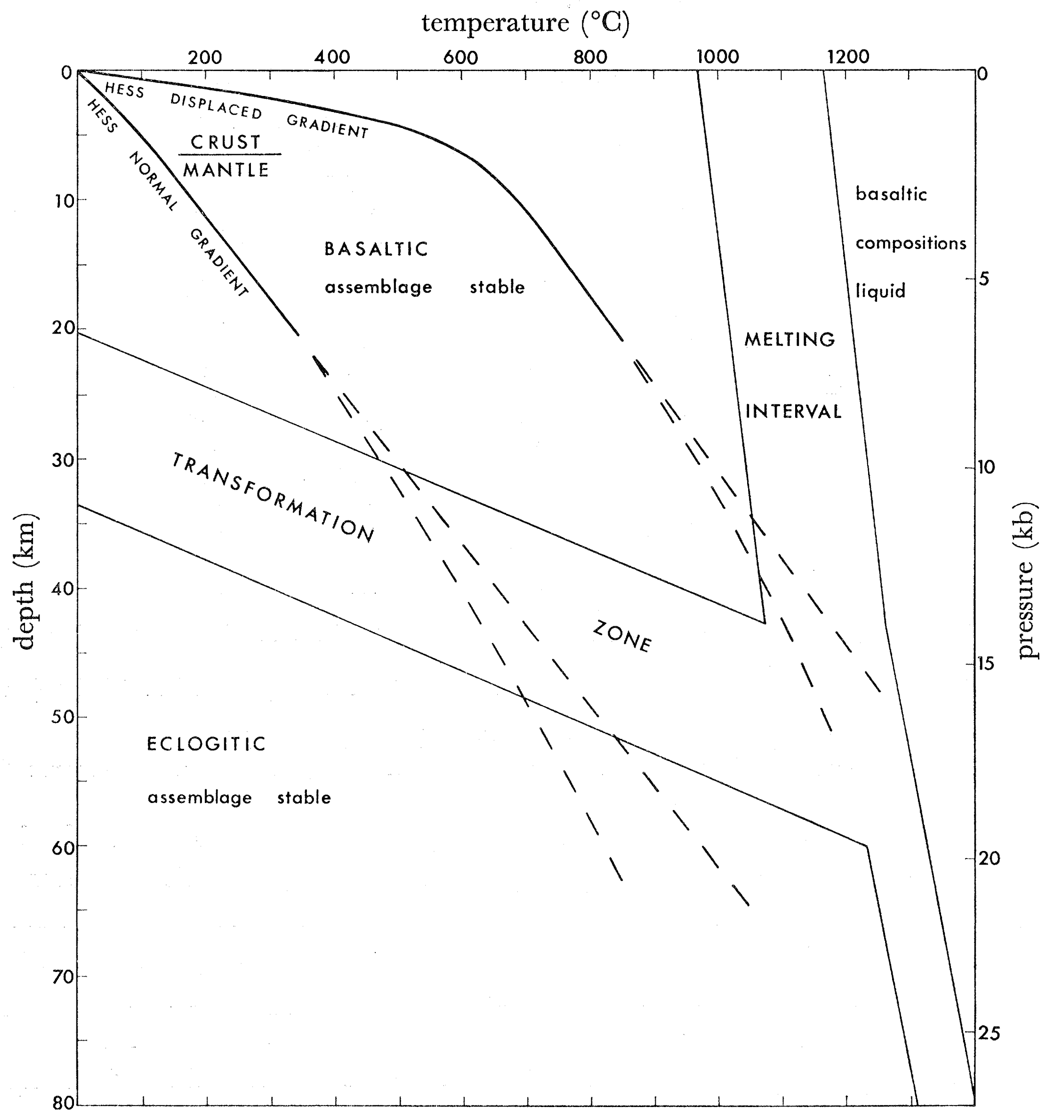

FIGURE 1. Pressure-temperature stability fields for basaltic and eclogitic mineralogical assemblages—based on Yoder & Tilley (1962, figure 43). The depth scale has been slightly modified to correspond to oceanic instead of continental conditions. The curves of temperature variation with depth, taken from Hess (1962) are increasingly less reliable with increasing depth. Below depths of 20 km they are shown as broad zones limited by dashed lines.

the thermal gradient is probably close to that shown as the 'Hess normal gradient' (taken from Hess 1962) and in the Hawaiian area basaltic magmas have probably arisen from depths of 60 km or more. For such regions basaltic magma generation by partial melting of an eclogitic mineralogical assemblage appears probable and Yoder & Tilley (1962) have presented a plausible hypothesis for the generation of either tholeiite or alkali olivine basalt by partial melting of such an assemblage. While further work, e.g. on the stability of aluminium bearing orthopyroxenes under appropriate pressure–temperature conditions (O'Hara 1963) may modify the details of this hypothesis, it is unlikely to prove it wrong in essential respects and basalt genesis in off-ridge oceanic areas appears to be adequately explained in terms of partial melting of upper mantle material of low water content.

In mid-ocean ridge areas the heat flow is significantly greater (Bullard 1963) and the thermal gradient probably closer to that shown in figure 1 as the 'Hess displaced gradient' (also from Hess 1962), though variation in the results of heat-flow measurements suggests that in these areas the thermal gradient is not everywhere the same and may, at any specific locality, be intermediate between the two gradients plotted in figure 1. Most of the earthquake foci along the seismically active mid-ocean ridges lie at comparatively shallow depths of about 30 km (Heezen 1960), so, if the depth of earthquake foci can be used as an indication of the depth of magma genesis, basalt magma generation may be occurring at these comparatively shallow depths under the mid-ocean ridges. Under dry conditions, the mantle basaltic fraction at this pressure and probable temperatures would be in the condition of the 'basaltic' mineralogical assemblage (figure 1). It is improbable that partial melting of such an assemblage of plagioclase, pyroxene and olivine could yield both glass compositions found in the Mid-Atlantic Ridge, dredge hauls. Relative to the tholeiitic composition that of the Warner type high alumina basalt is enriched in both normative plagioclase (the lowest melting component of the trio) and normative olivine (the highest melting component). It is very difficult to imagine any process of fractional melting that would enrich the liquid phase in both these components without the intermediate one, or, alternatively, in the intermediate pyroxene phase without either of the other two. Nor can the high alumina basalt be satisfactorily interpreted in terms of local accumulation and resorption of plagioclase and olivine in a tholeiitic magma, or the latter as a liquid differentiate of the former (see Nicholls 1965). Thus it appears extremely unlikely that this association of liquid high alumina basalt and liquid tholeiite could be satisfactorily explained in terms of partial fusion of water-poor upper mantle material beneath the ridge areas.

In the presence of abundant water an additional mineralogical phase, hornblende, is stable at the pressures and temperatures under consideration. Figure 2, based on the work of Yoder & Tilley (1962), shows that if abundant water is present the melting relationships at depths of approximately 30 km would be quite different from those under dry conditions. Before the beginning of melting, the mantle basaltic fraction would be essentially a hornblende-plagioclase assemblage. On melting this would first produce liquid plus residual plagioclase and hornblende, then liquid and hornblende which would be melting incongruently. Eventually the incongruent melting of the hornblende would produce olivine and liquid, possibly with some pyroxene. This incongruent melting of the water-bearing phase, hornblende, could produce liquids of both the tholeiitic glass composition and high alumina basalt glass composition as successive stages in partial mantle melting (see Nicholls 1965), and appears the most likely way in which liquids of such compositions could be formed. The presence of glasses of both basaltic compositions in the ridge areas may be regarded as indirect evidence of hydration of the upper mantle beneath the ridges.

Oceanic islands situated on the mid-ocean ridges and the larger sea-mounts similarly located are the result of long continued vulcanicity at localized centres. The basalts exposed on the islands or forming the tops of the sea-mounts represent a late stage in this volcanic activity. Progressive partial melting of the mantle under localized parts of the ridges could, if continued over long periods, result in differential loss by escape of water and other volatiles and during the later stages of volcanic activity at these sites the upper mantle may be significantly less rich in water than in the earlier stages. In consequence, the types of lava extruded during these later stages would approach more closely those produced by partial melting of a water-poor upper mantle. Thus the occurrence of alkali olivine basalt (normative nepheline) on oceanic islands and the tops of larger sea-mounts, although more easily explained as a result of partial melting of water-poor mantle material, does not necessarily invalidate the hypothesis of general hydration of the upper mantle

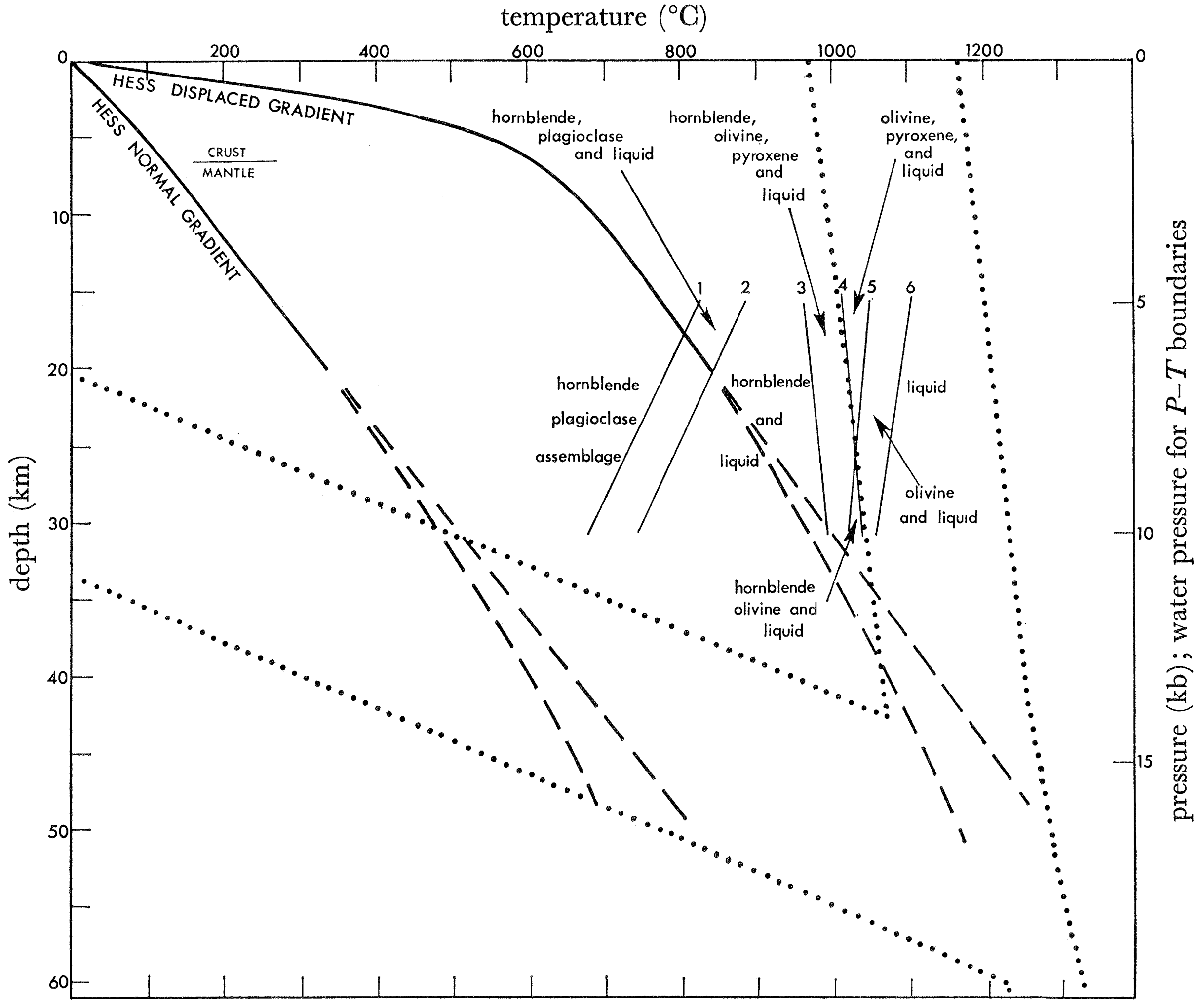

Figure 2. Stability relationships of assemblages of overall basaltic composition under wet conditions. The dotted boundaries are reproduced from figure 1 for comparison and the dashed continuations of the temperature-depth curves have the same significance as in figure 1. The positions of the P–T boundaries 1 to 6 are slightly dependent on the overall composition of the system and those plotted are means for the range of basaltic composition studied by Yoder & Tilley (1962). Significance of P–T boundaries plotted: 1, beginning of melting; 2, disappearance of plagioclase; 3, appearance of olivine and pyroxene by incongruent melting; 4, disappearance of hornblende; 5, disappearance of pyroxene; 6, disappearance of olivine, complete liquefaction.

under ridge areas. However, especial interest attaches to lavas dredged from the more deeply submerged parts of the ridges, which are more likely to be representative of early stage mantle melting in these areas, and it is in explaining the occurrence of these types that the hydration hypothesis has particular merit.

If the upper mantle under off-ridge areas of the deep ocean floor is comparably hydrated it is difficult to understand the apparent restriction in the distribution of Warner type high alumina basalt. On the petrological evidence currently available it appears much more likely that the upper mantle is more strongly hydrated under the ridges than under the off-ridge areas. Such variation in the degree of hydration of the upper mantle may help to account for the differences in seismic wave velocity encountered at depths of 15 to 25 km under different parts of the ocean (Heezen & Ewing 1963). Restriction of the water-rich parts of the upper mantle to areas beneath the mid-ocean ridges is in harmony with Hess's suggestion that rising columns of mantle convection cells are located beneath these ridges and suffer degassing to yield the water required for serpentinization of peridotite to produce crustal layer 3, implying a restriction of the serpentinization process to zones under the ridges (Hess 1962). Since layer 3 is a component of the oceanic crust beneath very wide areas of the ocean floor, restriction of the serpentinization process to the ridge areas implies some mechanism of dispersal of the serpentine from its areas of origin. Mantle convection currents dragging new formed oceanic crust laterally from the ridge areas to the regions of convective down-currents afford a probable dispersal mechanism.

Volcanic gases and their bearing on the problem

Thirteen years ago Rubey (1951) demonstrated that most of the water in the oceans and carbon dioxide now largely locked up in limestone could not be derived from the weathering of any pre-existing rocks. He computed quantities of what he called 'excess volatiles' now present on, or in, the outer parts of the lithosphere which must have been derived from some other source (table 2, col. 1), and went on to show that these 'excess volatiles' must have been liberated to the surface more or less continuously throughout geological time. More recent evaluations of the total amount of sediment and sedimentary rock in the lithosphere suggest that Rubey seriously underestimated the amount of 'excess' carbon dioxide and modified figures based on data given by Poldervaart (1955) are given in table 2, col. 2.

In considering possible sources for the 'excess volatiles' Rubey compared the percentage composition (table 2, col. 1 A) with those of various naturally emitted gases and concluded that they may have reached the surface through fumaroles and hot springs (table 2, col. 4). If some allowance is made for recycling of water in continental hot springs and fumaroles (table 2, col. 5) an even better correspondence results than the one on which Rubey based his conclusion. But the average composition of fumarole and hot spring gases, whether corrected for recycling effects or not, does not agree well with the 'excess volatiles' composition based on Poldervaart's data (table 2, col. 2A). The least contaminated volatiles reaching the Earth's surface from the interior would be expected to be the volcanic gases emerging from oceanic volcanoes. The state of oxidation of Hawaiian volcanic gases is very close to that predicted for gases in equilibrium with a Mg–Fe–silicate upper mantle (Holland 1962), which suggests that they have suffered little or no contamination on their way to the surface. However the composition of these gases (table 2, col. 3) does not correspond to the 'excess volatiles' composition based on the data of either Rubey or Poldervaart. The Hawaiian gases are richer in carbon dioxide and poorer in water. They may be abnormally enriched in compounds of carbon and sulphur (Holland 1962, p. 451) but another explanation is also possible. The hypothesis of mantle degassing under ridge areas advanced by Hess (1962) involves the transport of water contained in serpentine from the areas of serpentine formation (the ridge areas) to the sites of convective down-currents at the margins of, or beneath, the continental crust. Although such water, together with other 'excess volatiles', may have risen from greater mantle depths in convective up-currents under the ridges, its geographical location of emission into the atmosphere would be quite different from that of volatiles not capable of entering the lattices of the mineral components of serpentine. Oceanic volcanic gas composition would then represent that of newly emergent volatiles less that water (and possibly chlorine) carried towards the convective down-currents in the serpentine layer. If one-ninth of the total 'excess volatiles' emerged during the first 500 My when conditions in the upper mantle may have been rather different than at present (see Holland 1962) approximately 14500 to 14750 × 10^{20} g of water have emerged in the subsequent 4000 My. Assuming that oceanic volcanic gases have not changed in composition appreciably during this time and that all carbon-bearing gases have emerged through oceanic volcanoes, the amounts of water reaching the atmosphere directly through oceanic volcanoes can be calculated; and, thus, the amounts of water transported in the serpentine layer and liberated through the continental crust and margins by de-serpentinization of this layer at the sites of the convective down-currents. Rubey's figures for 'excess volatiles' lead to a value of 12580 × 10^{20} g for the amount of water liberated by de-serpentinization of

TABLE 2. DATA RELEVANT TO THE NATURE AND SOURCE OF THE 'EXCESS VOLATILES'

Quantities of 'excess' volatiles in units of 10^{20} g

	(1)	(2)
H_2O	16600	16300
total C as CO_2	910	2490
S_2	22	24
N_2	42	44
Cl_2	300	335
A, F, H, B, Br, etc.	13	13

weight % composition of volatile phases

	(1A)	(2A)	(3)	(4)	(5)
H_2O	92·8	84·9	64·3	99·4	90·8
total C as CO_2	5·1	13·0	23·9	0·33	5·0
S_2	0·13	0·1	10·0	0·03	0·4
N_2	0·24	0·2	1·6	0·05	0·7
Cl_2	1·7	1·7	0·1	0·12	1·8
A	0·07	tr.	0·1	tr.	—
F_2			tr.	0·03	0·04
H, B, Br, etc.			tr.	0·05	0·7

(1) and (1A) Estimated 'excess' volatiles (Rubey 1951).
(2) and (2A) Estimated 'excess' volatiles using data given by Poldervaart (1955).
(3) Composition of Hawaiian volcanic gases (Eaton & Murata 1960).
(4) Composition of gases from fumaroles and hot springs (Rubey 1951).
(5) As for (4) but assuming 94% of the water is recycled.

layer 3—those of Poldervaart yield a value of 8500×10^{20} g. These figures may be compared with that of $1\cdot3 \times 10^9$ km^3 (13000×10^{20} g) deduced by Hess (1962) for the amount of water liberated in the de-serpentinization process. The agreement between the figure based on Rubey's data and that given by Hess is surprisingly good, but is probably fortuitous. In arriving at his figure Hess made certain assumptions, namely that only one-third of the present mid-ocean ridge system is active and that the velocity of the convection currents is 1 cm/y, corresponding to continental drift at the rate of 2 cm/y. A more general approach would be to use the data to calculate an average rate of movement away from the ridges and compare this with estimated rates for continental drift. Taking the length of the ridge system as 75000 km, the thickness of layer 3 as 4·8 km, the water content of the serpentinized peridotite of layer 3 to be 17·5 % and the total amount of water now in layer 3 to be 3000×10^{20} g, the figure of 12580×10^{20} g for water released on de-serpentinization (from Rubey's data) corresponds to an average rate of movement away from the ridges of 0·31 cm/y for the full length of the ridge systems throughout the period of 4000×10^6 y. The figure of 8500×10^{20} g (based on Poldervaart's data) yields an average rate of 0·23 cm/y. For comparison with estimated rates of continental drift these figures must be doubled but they still appear low by factors of 5 or more when compared with rates deduced, for example, from the separation of Africa and South America and the geological evidence for the period when these two continents began to separate. This may, of course, merely indicate that there are relatively short periods (of the order of 2 to 300 My) during which the rates are considerably higher than the long-term average and compensating periods when they are low.

This hypothesis of two-channel escape of emergent volatiles, as hitherto expressed, cannot be regarded as other than highly speculative. But the possibility of variation in the rate of movement in the convecting systems and, thus, of rate of rise of volatiles from the mantle depths leads to a possible check of this hypothesis against geochemical data. Increase in the rate of rise of volatiles from mantle depths would be reflected almost immediately in an increased rate of emergence of carbon dioxide, sulphur-bearing gases, etc., into the atmosphere but only after some delay in that of water and possibly chlorine, since the greater part of the emergent water spends a considerable time in the serpentine layer. A fivefold increase in the rate of volatile rise from the mantle depths would cause the ratio of carbon dioxide to water in the emergent volatiles to change from the average value of 0·15:1 (table 2, col. 2A) to 0·29:1 (by weight). If the rate of rise subsequently returned to the average value, 100 to 150 My later this ratio would fall to 0·045:1, when increased amounts of water were liberated from the abnormally strongly hydrated serpentine being dehydrated in the convective down-currents. Since carbon dioxide has a comparatively short residence time in the atmosphere the atmospheric partial pressure of this gas should fluctuate in sympathy. As pointed out by Rubey (1951) any such fluctuation should be reflected in the contents of organic carbon in sedimentary rocks. From over 1000 analyses on composites from over 23000 samples Ronov (1959) has demonstrated significant variation in the organic carbon contents of Russian sedimentary rocks formed during the last 550 My and a very similar variation is found in American rocks. In sedimentary rocks which formed approximately 350 My ago the content of organic carbon is about 3 times greater than in those forming just before and after that time (figure 3). The two-channel escape hypothesis would imply a minimum organic carbon content in sedimentary rocks which formed 100 to 150 My later and, as shown in figure 3, this occurs. With such comprehensive sampling and correspondence between the results obtained on rocks from two continents it would be surprising if this variation was due to factors of only local significance. Periods of abnormally high partial pressure of carbon dioxide in the atmosphere should initiate periods of heavy carbonate deposition. Ronov's data on the amount of limestone forming at different periods of geological time, plotted in figure 3, show that a period of abundant limestone formation does stand in this temporal relation to the period of abnormally high partial pressure of carbon dioxide in the atmosphere. The time lag between the periods of maximum and minimum organic carbon contents in sedimentary rocks strongly supports the hypothesis of two-channel escape of volatiles. Since this, in turn, is dependent on the Hess hypothesis of serpentine formation and migration, the geochemical data can be regarded as indirectly supporting the hypothesis of convection currents within the mantle.

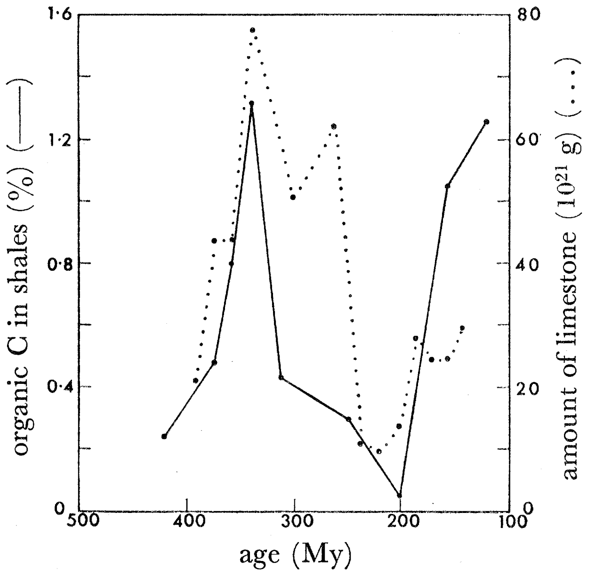

Figure 3. Variation in the content of organic carbon in sedimentary rocks and amounts of limestone forming in different periods of geological time. Based on data given by Ronov (1959).

Conclusions

Mantle convection associated with degassing in the rising limbs of the convection cells, as outlined by Hess (1962), should affect both the nature of the volcanic lavas extruded on different parts of the deep ocean floor and the mechanism of escape of volatiles emerging from the deeper parts of the mantle. While the number of rock samples dredged from the deep ocean floor is still below that which could be considered desirable, there does appear to be a restriction in the distribution of high alumina basalt of Warner type to the mid-ocean ridge areas. Such a restriction in distribution is explicable under the Hess hypothesis, but very difficult to account for under any other. Detailed geochemical data on sedimentary rocks supports the concept of two-channel escape of volatiles from the Earth's interior as required by the Hess hypothesis. Certain features, such as the time lag between periods of maximum and minimum organic carbon contents in sedimentary rocks can be accounted for under this hypothesis, but are difficult to explain under any other. While the existence of mantle convection currents cannot be proved on petrological and geochemical grounds, studies on the nature of deep sea lavas and probable mechanisms of volatile escape from the interior provide indirect evidence for them.

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