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Proposals concerning the Variation of Volcanic Products and Processes within the Oceanic Environment [and Discussion]

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Proposals concerning the variation of volcanic products and processes within the oceanic environment

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An attempt is made to fit available petrochemical data on oceanic volcanic rocks into the structural model for the ocean basins presented by the plate tectonic theory. It is suggested that there are three major volcanic régimes: (i) the low-potassic olivine tholeiite association of the axial zones of the oceanic ridges where magmatic liquids are generated at low pressures high in the mantle, (ii) the alkalic (Na > K) associations along linear fractures where liquids generated at greater depth gain easy egress to the surface, (iii) those alkalic associations, rich in incompatible elements, of island groups, remote from fracture zones, where magmas created at depth proceed slowly to the surface and in consequence suffer intense fractionation.

There are certain discrepancies in this pattern, notably that there is no apparent relation between rate of sea-floor spreading and degree of over-saturation of the axial zone basalts and that certain areas, such as Iceland, are characterized by excess volcanism. Explanation of these anomalies is sought by examining an oceanic area in an early stage of development—the Red Sea. It is tentatively suggested that the initial split of a contiguous continent might be brought about by the linking of profound fractures, caused by domal uplift related to rising isolated lithothermal systems, and that the present anomalies in oceanic volcanism may reflect the variation in rate of thermal convection within the original isolated lithothermal plumes.

In this attempt to appraise the variation in volcanic products within the oceanic environment, the spatial parameters taken are the oceanic side of the continental slope or, where this does not exist, the oceanic side of ocean trench system. Examples quoted are mainly from the Atlantic Basin but reference will be made to the Red Sea which serves in the office of a 'proto' ocean.

The state of petrochemical knowledge in this field is not high. Data from the oceanic islands may well be atypical and ocean floor dredges, although increasingly abundant, do not give anything like complete coverage. It is intended to discuss first the gross structural configuration of the ocean basins and to see if the petrochemical data available fits, in any way, into this model. In many ways the model proposed as a basic tenet is itself controversial and one in which the line between a legitimate inference and unwarranted speculation is blurred and difficult to define.

The basic tenet (of plate tectonics) is so well supported by a wide variety of geophysical and geological data that it is, if not a fact, by far the most acceptable theory now available. Also basic to the arguments here presented is the acceptance, albeit tentative, that the mantle is in a state of unstable thermal convection and that beneath oceanic ridges there is a zone of ascending flow, rising at a rate high by comparison with the rate at which heat can be lost by conduction. This upward flow has no recognizable base and may commence at depths as great as 300 to 400 km. On reaching the surface, the hot material diverges to give surface flow to depths of 200 km. The uppermost 100 km of this surface flow has a steep thermal gradient and is part of the newly created oceanic lithosphere. Between 100 and 200 km, loss of heat by conduction is low and a liquid fraction due to partial melting allows the layer to act as a viscous fluid. This schematic mechanism is that recently described by Oxburgh (1971, Fig. 19.19 (*b*),

p. 278), although calculations concerning the width of the ascending column under the oceanic rises vary (Oxburgh & Turcotte 1968; Cann 1970; Matthews & Bath 1967). Furthermore, as the oceanic lithosphere increases in age away from the ridge axis, it has had increasingly longer time to lose heat by conduction and so become thicker (Oxburgh 1971).

This, the framework of oceanic volcanism, is not only the most acceptable theory but has recently been 'proven' beyond reasonable doubt by the J.O.I.D.E.S. drilling programme (see Vine 1971, Fig. 16.11, p. 244). The basic picture is that, under a thin veneer of late Mesozoic and Cenozoic sediments, the majority of the ocean floor is formed of volcanic rocks—primarily created at the axes of the oceanic ridges—which have spread, diverging sideways with time.

The theory of plate tectonics, as expounded by Morgan (1968), called for the movement of rigid segments of lithosphere around axes of rotation, movement of these plates being least in high, and greatest in low rotational latitudes. This coincides with variations in the spreading rate from 1 to 9 cm/year per ridge flank. Within the Atlantic, with the pole of rotation at 62° N, 36° W, spreading in the North Atlantic should be slower than in the south Atlantic (Oxburgh 1971, Fig. 19.5). Furthermore, there is evidence that in the recent geological past the rate of spreading has varied with time, periods of rapid spreading being interspersed by intervals when this was markedly slower. The guide to spreading direction is given by the transform faults which, if Morgan's concept is correct, should, in all cases, be small circles to the pole of rotation.

An attempt to correlate this tectonic picture with the products of volcanic activity must define, as far as possible, the parameters which control the type of magma produced within this mechanism. It is here proposed to accept the experimental evidence of Kushiro (1965), and others, that the composition of the magmatic liquids produced by partial fusion of a pyrolite mantle is related to the lithostatic pressure at which the fusion takes place. Kushiro (1965) suggests that with decreasing pressure the resulting melt will be progressively oversaturated. It is fully realized that this is by no means the only possibility and that with a hydrous mantle it is possible to reverse this sequence at greater pressures (O'Hara 1968). Nevertheless, it is felt to be a broad parameter acceptable in the pressure ranges here considered (5 to 60 kbar; 0.5 to 6 GPa) and in the relatively simple-minded manner in which it is intended to approach this problem.

Within the framework of mantle convection, sea-floor spreading and global tectonics, there seem to be three major oceanic volcanic régimes. By far the most important, quantitatively, is the axial zone of the oceanic rises, for it is here, at the constructive trailing edges of the moving plates, that new oceanic crust, dominantly of low-potassic olivine tholeiite composition, is created. Wright (1971) has recently calculated that 3.4 km^3 of volcanic products are produced at these sites each year, whereas G. P. L. Walker (unpublished) puts the figure as high as 10 km^3. Elsewhere in the ocean basins there seem to be two distinct tectonic settings at which volcanism can occur. These are volumetrically minor compared with the axial zone activity and it is not possible, on the amount of data available, to decide which is quantitatively the most significant. However, they appear, at least to some workers, to be petrochemically distinct. Along linear fractures within the ocean basins, particularly along the transform faults which separate the spreading axes and their 'inactive' continuation down the flanks of the rise, alkalic basalts, with soda in excess of potassium, seem to be the dominant eruptive type (Menard 1967; Melson, Thompson & Van Andel 1968; Oxburgh 1971). It is now left to explain those basaltic associations, still alkaline, but much richer in the incompatible elements such as K, Rb, Ti, Ba, Sr, U and Th. These are known from such islands as the Tristan da Cunha group (Baker, Gass, Harris & Le Maitre 1964) and Gough Island (Le Maitre 1962) in the Atlantic and the Marquesas (Lacroix 1931) in the Pacific and possibly Kuguelan in the Indian Ocean. These potassic islands rise from ocean floor away from the axial rift zones and seemingly also isolated from any linear fractures.

It is now intended to examine each of these structural settings and their volcanic products.

For oceanic ridge volcanism, the model of Cann (1970, Fig. 2, p. 929) is accepted. This model is compatible with the magnetic, heat flow and petrographic data and is also entirely acceptable in the light of structural and field evidence presented by the rare terrestrial analogues of deep ocean floor such as the Troodos Massif of Cyprus (Gass 1968) and the south Oman complex in south-east Arabia (Reinhardt 1969). Cann (1970) envisages the mobile mantle material as being injected along a narrow fracture between the separating crustal plates. This fracture, he maintains, on magnetic and petrographic evidence, is less than 25 km wide and this is supported by the evidence of Aumento (1967) and Kay, Hubbard & Gast (1970) that ocean tholeiites, whose chemistry is entirely consistent with a derivation by extensive partial melting at low pressures, are erupted only within the median valley of the oceanic ridges. These olivine-bearing tholeiites are usually impoverished in the incompatible elements and this, in turn, supports the suggestion that they are the products of high-level fusion and have not undergone any extensive fractionation which would have enriched the residual melts in K, Rb, Ti, etc. Although seemingly erupted only along a narrow zone at the spreading axis, it is these volcanic products which adhere to the trailing edge of the spreading plates and with time form the 'basement' (layer 2) of the oceans.

However, there are other facets to this grandiose pattern. The spreading rate varies with the rotational latitude. There is certain, although not entirely unequivocal, evidence (Kennett & Watkins 1970) that volcanic activity is at a maximum when the geomagnetic polarity changes and certainly the rate of spreading seems to have varied in the geologically recent past (Vine 1971). Is it too much to suggest that where the spreading rate is fastest the heat flow will be greatest and the thermal gradients steepest? In such areas the zones of partial melting in the mantle beneath the axes of the oceanic ridges should be higher at lower pressure and therefore, in theory, the volcanic products progressively oversaturated. There is little evidence presented in the literature that this is the case. Indeed in the Atlantic, on the admittedly questionable evidence of the volcanic islands on the ridge axis, the area of greatest, and most oversaturated, volcanism is on Iceland where the spreading rate is less than 1 cm per year per ridge flank. Bouvet island is in a similar tectonic setting athwart the ridge axis but, in the south Atlantic where the spreading rate is almost 2 cm per year per ridge flank, is still oversaturated but not as much as Iceland (Oxburgh 1971, Fig. 19.5; McBirney & Gass 1967, Fig. 4). Although islands on the axes of the Mid-Atlantic Ridge are few, there is no spatial pattern whatsoever in terms of any saturation index (McBirney & Gass 1967). Furthermore, petrochemical studies on ocean floor basalts along ridge axes, such as those of Muir & Tilley (1966) indicate that there is significant but seemingly unsystematic petrochemical variation parallel to the ridge axes.

This evidence suggests, albeit tentatively, that there is little or no direct correlation between spreading rate and composition of the oceanic floor basalts, at least so far as the Atlantic is concerned. It seems therefore that the quantity of lavas extruded bears little relationship to the position of extrusion with respect to the pole of rotation. Where extrusion is in excess of spreading the obvious result is a vertical accumulation of volcanic rocks such as in Iceland.

Where the converse applies, the axial rift zone might be expected to be deeper and wider. The reason why certain parts of the oceanic rift are characterized by more voluminous volcanic activity is not discussed here but mechanisms will be postulated later (see p. 138).

Several authors, notably Menard (1967), Melson *et al.* (1968) and Oxburgh (1971) have commented on the occurrence of alkali basalts associated with the transform fractures and their inactive continuations. Oxburgh & Turcotte (1968) and more recently Sclater & Francheteau (1970, Fig. 6, p. 516) have shown that heat-flow diminishes with age of the ocean floor. This has been interpreted by Oxburgh (1971) as indicating a thickening of the oceanic lithosphere away from the ridge axis, the thickening being greatest in the first few hundred kilometres and thereafter becoming less rapid (see Oxburgh 1971, Fig. 19.19). If the liquids escape from these fractures, the 'leaky' transform faults of Menard (1967), then it seems reasonable to assume that such liquids originated within a partially melted asthenosphere and that their source would be progressively, though not systematically, deeper with increasing distance from the ridge. Assuming that the transform fractures in the lithosphere allow easy and rapid egress for these fluids, then fractionation on the way to the surface should be minimal and liquids erupted not necessarily markedly enriched in the incompatible elements and therefore, for instance, soda should always be well in excess of potassium. Such liquids, if generated within the asthenosphere, should be alkaline and they should also, if the mechanism envisaged is correct, become increasingly undersaturated with distance from the ridge axes. Other than the works of Aumento (1967), there is little evidence from the ocean floor basalts to suggest any relationship between distance from the ridge and degree of undersaturation. However, in this case, the composition of the oceanic islands provides a clue. Certainly, such islands as Trindade and Martim Vaz, Fernando de Noronha, the Cape Verde Islands and the Azores in the Atlantic and the islands in the Pacific to the south of the Tuamoto ridge, Pitcairn, Rapa and Tahiti, and those on the Clarion fracture zone, San Benedicto, Socorro and Clarion, show this distance/undersaturation relationship (McBirney & Gass 1967). Although the mechanism is far from proven, the evidence available suggests that it is at least worthy of hypothesis status.

Finally we have those oceanic volcanic associations, so far only known as islands, such as the Tristan group and Gough in the south Atlantic and the Marquesas in the Pacific, associated neither with the axis of the ridges nor with linear fracture zones. These islands, although alkalic, are characterized by the abundant presence of the incompatible elements K, Rb, Ti, Ba, Sr, U and Th, which in turn suggests they are constructed of the end products of a long process of fractionation.

The absence of any easy line for intrusion and subsequent extrusion of these igneous liquids, taken in conjunction with their special petrochemistry, suggests that some process of gradual stoping through the lithosphere has taken place. During such a process, the mechanism of zone refining, as originally invoked by Harris (1957), seems particularly pertinent. In this process, the incompatible elements, mainly by virtue of their ionic radii, are unable to enter the lattices of the minerals forming by crystallization and they become concentrated in the liquid phase which subsequently erupts at the surface.

The assumption was made at the beginning of this article that the Earth's mantle is in a state of unstable thermal convection. It seems entirely possible and has indeed been shown experimentally by Elder (1970) that for a plate (the oceanic lithosphere) uniformly heated from below (the asthenosphere) the thermal plumes are likely to rise from the interface in an *ad hoc* fashion. These thermal plumes, which Elder (1970), Harris (1970) and Gass (1970) have envisaged as comparable in space-form to rising salt diapers, may be damped out or they may progress to the surface, depending essentially on whether the factors present at their point of origin encourage the penetrative convective mechanism or inhibit it. As the zone of convection penetrates through the lithosphere, a point will be reached when a discrete body of magma, probably plate-like in space-form (McBirney 1967; Gass 1970), will develop. As the body of magma rises through the pyrolite of the lithosphere, the process of zone refining will be in operation until, on nearing the surface of the lithosphere, the increase in volume, caused by the depression of the phase boundaries within the penetrative system, causes the brittle carapace to fracture. The hitherto slowly ascending magma will then escape rapidly to the surface.

These three associations are proposed for a well-established ocean basin, such as the Atlantic, in which spreading has been progressing for over 100 Ma. Some of the apparent volcanic anomalies, such as the excess volcanism in the Iceland area of the North Atlantic are, however, inexplicable in their present setting. They might become more easy to understand if the processes of continental fracture and the initial stages of sea-floor spreading were more clearly understood. It is therefore proposed to examine a 'proto' ocean, in this case the Red Sea. The reason for examining the Red Sea 'ocean' is that there may be preserved within it, and on the peripheral continental masses, evidence as to how and why it became an oceanic area—evidence no longer preserved or more difficult to interpret in 'mature' oceans. For instance, why did the Atlantic Basin develop where it did? Was there a primeval line of weakness? How and why did the contiguous continent split?

It is now generally accepted that the median trough of the Red Sea is floored by oceanic crust. Some, for instance Davies & Tramontini (1970), maintain that the entire marine area of the Red Sea is floored by oceanic basalts. In the former case it has been proposed that the spreading started some 5 Ma ago (Vine 1966), whereas for the latter case some 25 Ma of spreading must be entertained (Davies & Tramontini 1970).

Recently, the Red Sea and the Gulf of Aden, and particularly the structural evolution of the junction area, were the subject of a Royal Society discussion meeting (Falcon, Gass, Girdler & Laughton 1970). In an attempt to interpret the evolution of this junction area, Gass (1970) produced a tectono-magmatic timetable in which the salient points were:

(i) That before 50 Ma ago the area now trisected by the Red Sea, the Gulf of Aden and the Ethiopian rifts was peniplaned crystalline basement with a thin veneer of Jurassic sediments that had been unaffected by any major thermal event for over 500 Ma.

(ii) In the Eocene, vast quantities of volcanic lavas were erupted onto this peniplaned surface. These extensive eruptions, known as the Ethiopian and Yemen Trap Series, covered an area of almost 800000 km^2 to a maximum thickness of 3500 m.

(iii) While the volcanic activity was still in progress, differential uplift took place which created the area of uplift now known as the Afro–Arabian dome and the small dome farther to the north which is now bisected by the Red Sea and which has its maximum uplift at about 22° N.

(iv) Tensional stresses produced by this updoming caused the fracturing of the upper continental lithosphere and the formation of the 'proto' Gulf of Aden, Red Sea and Ethiopian rifts.

The mechanism invoked to explain this sequence of events proposed the existence of a rising lithothermal system under the junction area and a smaller one farther to its north. The effect of such a system, progressively penetrating into lithosphere, would be to steepen the regional thermal gradient, cause extensive partial fusion at a high level in the lithosphere and also the depression of the main peridotite phase boundaries, thereby producing an increase in volume most easily relieved by uplift. The magmatic liquids escaped up pre-existing fractures before the uplift but, once the uplift had created profound fractures in the brittle carapace, the magmatic liquids preferentially, though not entirely, would escape through these routes; these would remain the major line of egress for magmatic liquids for it is here that the lithosphere is thinnest and weakest. With continued injection of hot mantle material, the formerly contiguous continental crust became entirely separated in the Gulf of Aden, at least in the central part of the Red Sea, and possibly also in the Afar depression (Barberi *et al.* 1970). The two former areas are generally accepted, in all but size, as truly oceanic.

Up to this point, the speculation concerning the mechanism responsible for the separation of the continental crust in one specific region is supported by several lines of evidence. From now on, the balance is heavily weighed on the side of speculation, but speculation which is not necessarily unwarranted as it at least keeps within the limited factual evidence available.

It is commonly, and not incorrectly, stated that the great African rift system extends from Jordan in the north southwards through the Red Sea and Ethiopian Rifts, into the rift systems of East Africa proper (see figure 1). Are these fractures all part of one major rift system? Commonly it is suggested that they are and arguments, still without resolution, rage as to whether movement along them is lateral or normal. But it is well to consider the following evidence before suggesting any solution:

(1) There is no single fracture from north to south; rather there is a pattern of fractures, at times overlapping and at others dying out and recurring again, the southern Ethiopian–northern Kenya region being an example in point (see figure 1).

(2) Topography along the rift is by no means uniform; from north to south it is possible to identify a Red Sea, Afro-Arabian, Kenyan and Tanzanian dome.

(3) Volcanicity, although apparently most intense within the rifts, is by no means confined to them and certain parts of the rift system, particularly the southern extremity in Malawi, are devoid of volcanism. Furthermore, the character of volcanism changes from one dome to another. For instance, in Ethiopia it is dominantly of alkali basalts whereas, in Kenya, flood phonolites, still alkalic, are abundant if not the dominant rock types (King 1970).

(4) Seismic and gravity data indicate that the continental crust becomes thinner towards the rift and also that the upper mantle is anomalous under these regions of uplift. This has been proposed on the existence of anomalously low P wave velocities (6.9 km s^{-1}) and on the absence of an isostatic gravity anomaly over the rise to the rift (Bullard 1936). Indeed, the structural model proposed by Sowerbutts (1969) on gravity data for the upper mantle structure under the Tanzanian rift is virtually identical to that proposed by Gass (1970) on petrochemical and structural evidence for the Afro-Arabian dome.

With these features in mind, it is tentatively postulated that the rift system could be the collective surface expression of separate lithothermal systems rising under the African continent. The limits of uplift and the pattern of fracture resulting from each penetrative diaper is depicted schematically in figure 1.

Having gone this far, it is proposed to take a further speculative step and to suggest that the split in contiguous continent that took place over 100 Ma ago to form the proto-Atlantic was by an amalgamation of lithothermal systems of the type here envisaged for the African Rift System. The similarities, in some ways, are striking. In both cases, continental rupture was

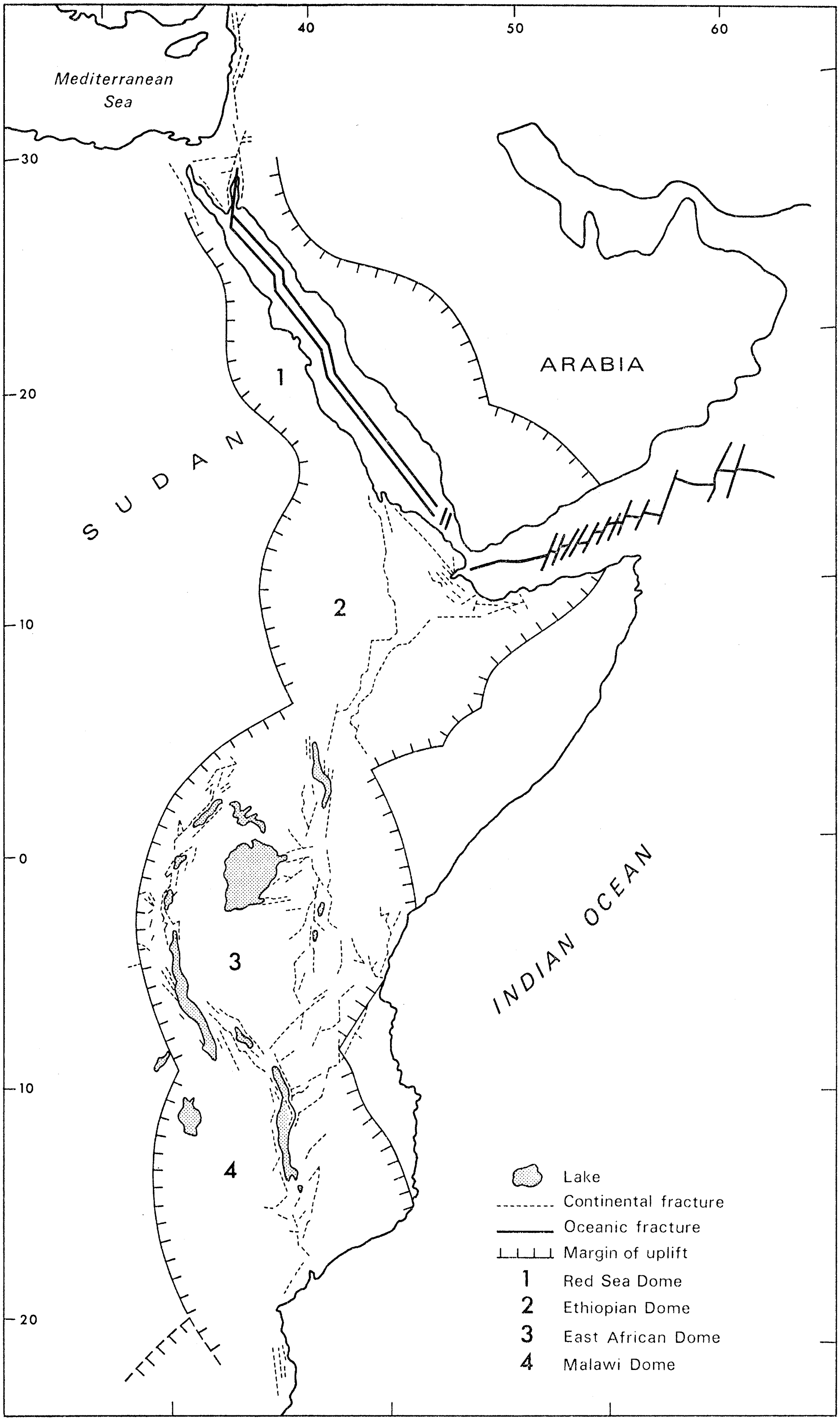
40
50
60
30
20
10
0
10
20
Mediterranean Sea
ARABIA
SUDAN
INDIAN OCEAN
1
2
3
4
Lake
Continental fracture
Oceanic fracture
Margin of uplift
1 Red Sea Dome
2 Ethiopian Dome
3 East African Dome
4 Malawi Dome

FIGURE 1

heralded by intense volcanic activity. The Karoo and Parana volcanics preceded the split at 170 Ma in the south Atlantic by about 20 Ma. The activity in the Thulian province at about 70 to 50 Ma was approximately coeval with the fracture that produced the north Atlantic. For the Gulf of Aden, Red Sea and Ethiopian Rift, the Ethiopian and Yemen Traps came about 20 Ma before the actual creation of oceanic crust in the centre of the Gulf of Aden.

In both cases, evaporites accumulated rapidly in low latitudes during the early stages when the continental crust was attenuated but not fractured (Kennedy 1965). The rise to the rift which is such a common feature of the African rift system is, of course, present in the oceanic setting, but the once uplifted continental areas bordering the Atlantic fracture have now moved so far apart that they have moved off the zone of anomalous mantle underlying the ridge and are therefore no longer reflecting any doming process.

The main theme of this article is variation of volcanism within the ocean basins. It is therefore pertinent to note that neither within the Red Sea nor in the Atlantic does there seem to be any direct regular spreading rate/petrochemical relationship. For the Arabian plate, the pole of rotation is plotted in various positions by different authorities; but all plot it towards the north end of the Red Sea either in Africa or North Arabia. With this in mind one might expect the most oversaturated volcanic rocks to occur at the southern end of the Red Sea. So far as volcanic islands are concerned this is not the case. The most oversaturated basalts occur in the northernmost island in the Red Sea and progressively these become more undersaturated to the south although the markedly alkali association of the Zukur–Hanish Line at the southern end of the Red Sea probably belongs to a north–east transform fracture zone and is itself an example of a 'leaky' transform fault (Gass, Mallick & Cox, in press). The suggestion here is that despite the linear nature of the Red Sea fracture, the chemical character of the rocks is still primarily controlled by the disposition of the original penetrative Red Sea diaper with the highest heat-flow and the most oversaturated rocks occurring near its centre. It is suggested that this might be the case in the Iceland area where not only is there the most prolific activity and most over-saturated products but where the adjacent continental areas were subjected to volcanic activity before Iceland itself became a site of volcanism. This again is analogous to the Red Sea–Gulf of Aden situation where the centres of diaparic uplift are also the regions of continental volcanism before separation (Gass 1970). Could it possibly be that Iceland was, and is, the centre of a penetrative convective system?

Finally, in making the tentative proposal that contiguous continent can be split by the linking of isolated lithothermal systems, I am not attempting to suggest that in all cases these convective penetrations develop further into major linear convective systems. It could, indeed as seems the case for the Red Sea, be that convective irregularities were produced in a moving plate riding on the back of a major convective conveyor belt originating elsewhere within the Earth's mantle. However, it is impossible to escape the conclusion that major continental plates are split and the segments produced continually separated by newly created ocean floor. This certainly seems to have been the case for the Pangaea super-continent 300 Ma ago. In this context, it is pertinent to note that the thermal régime below present-day continental masses is markedly more unstable than that under oceanic areas (Elder 1970). This, it has been suggested, is due to the concentration of radioactive elements in the continental lithosphere producing, in effect, a thermal 'blanket'. In this 'blanketing' situation, it seems thermodynamically more probable that initial continental separations were produced by a penetrative convection mechanism than by the spontaneous development of major linear systems.

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Discussion

Dr P. A. Sabine asked Professor Gass's views on origin of the alkaline islands of the Atlantic, especially Rockall. This island, which was extremely alkaline, appeared above a Bank, which both on the evidence of the fitting of the Continental margins (Bullard, Everett & Smith 1965) and on that of isotopic ratios (Moorbath & Welke 1968) suggested it was part of the continental crust. Yet an alkaline nature typified Atlantic islands. What was the explanation of this paradox?

Professor Gass: Rockall, as it is apparently part of the continental crust (Bullard *et al.* 1965), did not enter into my studies of the Atlantic volcanic islands (McBirney & Gass 1967, p. 272). However, strongly alkalic magmatism is not uncommon at the continental/oceanic junctions adjacent to constructive plate margins. This suggests that before the final rupture of the once contiguous continental plate, magmatic activity produced alkalic rather than tholeiitic assemblages.

References (Gass)

Bullard, E. C., Everett, J. E. & Smith, A. G. 1965 The fit of the continents around the Atlantic. *Phil. Trans. R. Soc. Lond.* A **258**, **41**.

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Moorbath, S. & Welke, H. 1968 Isotopic evidence for the continental affinity of the Rockall Bank, North Atlantic. *Earth Planet. Sci. Lett.* **5**, 211.

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