The Evolution of Volcanism in the Junction area of the Red Sea, Gulf of Aden and Ethiopian Rifts

I. G. Gass

Phil. Trans. R. Soc. Lond. A 1970 **267**, 369-381
doi: 10.1098/rsta.1970.0042

Phil. Trans. Roy. Soc. Lond. A. **267**, 369–381 (1970) [369]
Printed in Great Britain

The evolution of volcanism in the junction area of the Red Sea, Gulf of Aden and Ethiopian rifts

By I. G. GASS†
Department of Earth Sciences, The University, Leeds 2

Some 70 Ma ago this region became the site of intense magmatic and tectonic activity. The variety of magmatic products and the style of deformation have altered radically during the period and it appears that they are related on a regional scale for: (1) alkali basalts were erupted during the early period when vertical uplift was dominant, (2) zones where the sialic crust is, or has been, attenuated are the sites of peralkali volcanism, whereas (3) the 'oceanic' crust in the Red Sea and Gulf of Aden, and possibly the Afar depression, formed during the lateral movement of sialic blocks in the late Tertiary, is of tholeiitic character.

It is suggested that both the tectonic history and the volcanic evolution are the result of an isolated 'lithothermal' event in the upper mantle; the theoretical thermodynamic evolution of such a system is compared with the tectono-magmatic development of the junction area.

INTRODUCTION

In Lower Tertiary times, after a long period of tectonic stability and magmatic quiescence extending from late Precambrian times, this 'junction' area became the site of intense magmatic and tectonic activity that has continued, virtually without interruption, to the present day. However, throughout the last 70 Ma, the type of magmatic activity and the style of deformation have changed radically. It is the purpose of this article to review the sequence of magmatic and tectonic events to see if they are related in time and space, and if so, to establish the nature of the relation.

The dominant magmatic activity has been the extrusion of basic lavas; silicic eruptives, although abundant, can usually be recognized as differentiation products of a basaltic parent. As well as the alkaline and tholeiitic associations, originally recognized by Kennedy (1933), a third, intermediate in composition between true tholeiites and true alkali basalts, which produced peralkali differentiates on fractionation (Coombs 1963), is also present.

Regional crustal deformation seems to have started in the early Tertiary and, until the end of the Eocene, the region was the site of vertical uplift that has produced the major topographic feature of the Afro-Arabian dome (Dainelli 1943; Beydoun 1964; Mohr 1963). Attenuation of the sialic crust across the dome, in response to this vertical uplift, caused it to be split into three distinct crustal segments: (1) the Arabian segment; (2) Egypt–Sudan–Ethiopia (Nubian) segment; and (3) the Horn of Africa–Somaliland (Somalia) segment by zones of weakness (Cloos 1939) (see figure 1). Each of the zones of weakness, the 'proto' Red Sea, Gulf of Aden and Ethiopian rift, became the site of further tectonic activity in the Miocene when the style of deformation changed to one of predominantly lateral movement.

Since that time some 50 km of new oceanic crust have been formed in the southern Red Sea (Girdler 1958; Drake & Girdler 1964), although Davies & Tramontini (this volume, p. 181) suggest that oceanic basalts may underlie most of the Red Sea and not be confined solely to

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† Present address: Department of Earth Sciences, The Open University, Walton Hall, near Bletchley, Buckinghamshire.

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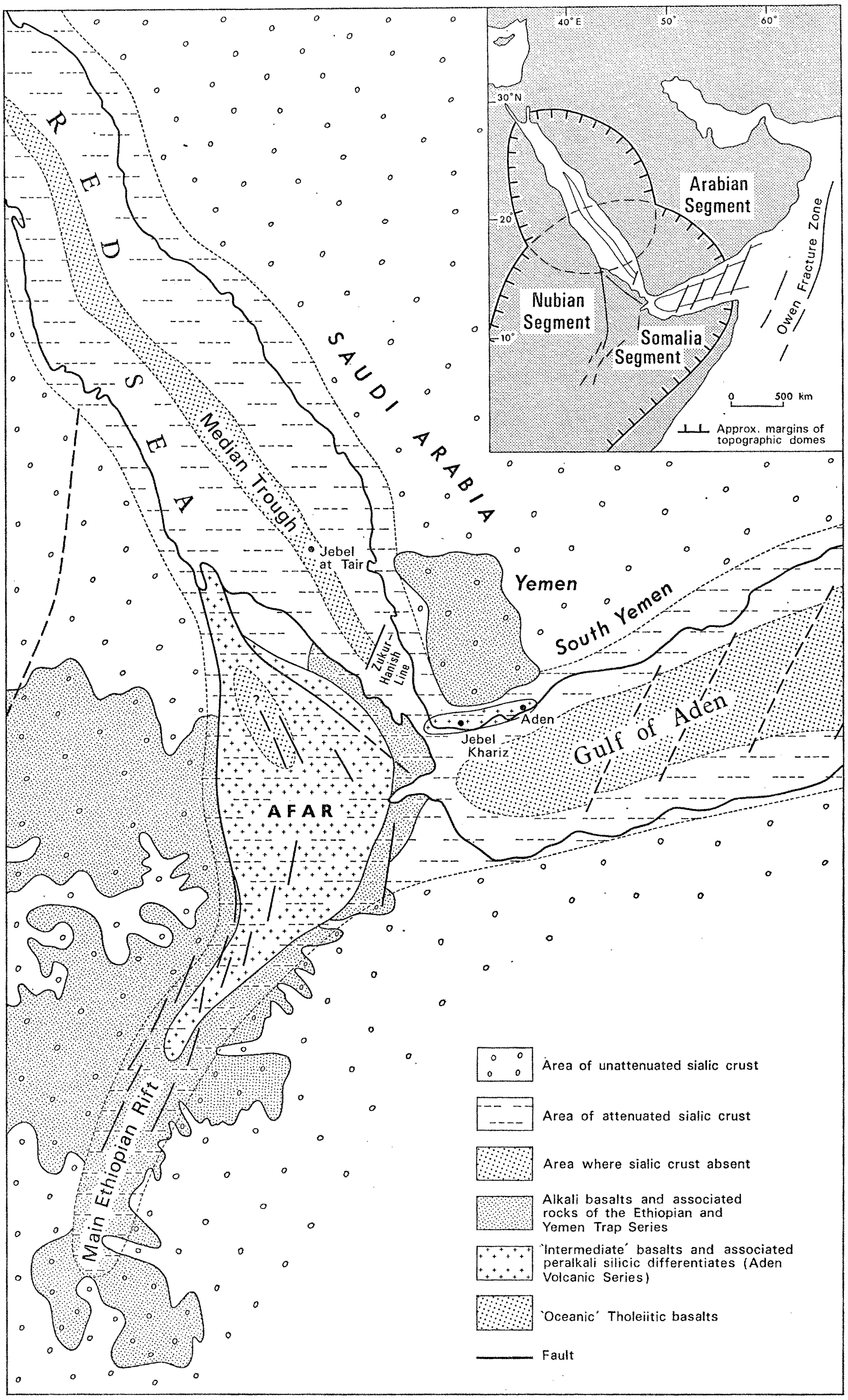

FIGURE 1. Distribution of basalt types and major structural elements.

the median trough. The width of oceanic crust in the Gulf of Aden formed during this period is as much as 200 km (Laughton 1966). These data mean that the Arabian peninsula must have moved horizontally away from the Nubian and Somalia segments. Although no obvious oceanic crust is present in the Ethiopian rift, there is evidence (Gibson, in press; Gass & Gibson 1969) that the Somalia segment is moving northeastwards with respect to the Nubian segment which seems to have remained relatively stationary with respect to Eurasia since the Middle Miocene.

Regionally, it would appear that the type of magmatic product can be correlated with the style of deformation: first, preceding and concurrent with vertical uplift alkali basalts were erupted; secondly, the zones of crustal attenuation are the site of volcanic activity that is characterized by the abundance of peralkali silicic differentiates; and thirdly, areas of new ocean crust in the Red Sea, the Gulf of Aden, and possibly in the northern Afar depression, are of low potassium tholeiitic basalts of oceanic character. There are several exceptions to this regional correlation, notably alkali basalts of very recent age occur in the attenuated zones and on the flanks of the dome. The spatial extent of these volcanic and structural provinces is shown in figure 1 and the temporal relations are given in table 1.

The alkali suite associated with vertical uplift

The term 'Trap Series' has been applied and is here used, for the dominantly basaltic, Lower Tertiary flood basalt sequences which cover some 750 000 km^2 in Ethiopia and some 30 000 km^2 in the Yemen and southwest Saudi Arabia. The data presented hereunder are taken mainly from the works of Mohr (1962, 1963) who in turn has drawn upon earlier works, notably Blanford (1869), Comucci (1928, 1932, 1933*a*, *b*, 1948, 1950), Dainelli (1943), Duparc (1930) and Hieke-Merlin (1950, 1953). Information on the Yemen traps is taken from Roman (1926), Lamare (1930), Lipparini (1954), Shukri & Basta (1954) and Gass & Mallick (1968).

Before the volcanic activity, the area was a peneplaned surface cut into Mesozoic sediments (Mohr 1963; Brown, this volume, p. 75) and it was onto this regionally flat surface that the Trap Series, amounting to some 3500 m in Ethiopia and 2000 m in the Yemen, was extruded. The areas now occupied by the Red Sea, the Gulf of Aden and the Ethiopian rift were originally covered by rocks of this series, and although extensively fractured by subsequent faulting, particularly in the south Yemen (Gass & Mallick 1968), and downwarped along the margins of the rift zones, the original regional disposition of the Trap Series was approximately horizontal.

In Ethiopia, Mohr (1963) supports the subdivision made by earlier workers and divides the Trap Series into two units: a lower unit between 200 and 1200 m thick, consisting of a few thick, extensive, and petrographically uniform flows of aphyric alkali basalt erupted from north–south fissures; and an upper unit, up to 2600 m thick, of more widely varying, generally porphyritic types that were erupted from north–south alined central vent volcanoes which, although containing abundant silicic and ultramafic varieties, are of alkaline affinity throughout. According to Mohr (1963) the period of Trap volcanism ranged from the Oligocene to the lowest Miocene; the uplift that formed the Afro–Arabian dome did not continue after Upper Eocene times, and the central vent volcanism did not become generally active until the period of uplift was over. This is disputed by other workers (I. L. Gibson and A. Azzaroli, personal communications) but a Lower Tertiary age for the volcanic activity is generally accepted. The Trap Series of the Yemen is considered to be of Eocene age (Lipparini 1954). All who have

TABLE 1. TIME CORRELATION BETWEEN MAGMATIC AND STRUCTURAL EVENTS

TIME SCALE	Ma	REGIONAL TECTONICS	REGIONAL MAGMATISM	CRUSTAL SEGMENTS			RIFT ZONES		
				NUBIAN	SOMALIA	ARABIAN	GULF OF ADEN	RED SEA	ETHIOPIAN RIFT
RECENT	0.5		"OCEANIC" THOLEIITIC VOLCANISM			basaltic volcanism in Saudi Arabia	basaltic volcanism in south Arabia		tholeiitic volcanism in N. Afar, incipient crustal separation
PLEISTOCENE	1.5	HORIZONTAL NORTHWARD MOVEMENT OF CRUSTAL SEGMENTS AT VARIOUS RATES		continuing uplift greatest at margins	continuing uplift greatest at margins	continuing uplift greatest at margins	widening of 'oceanic' zone concomitant with tholeiitic volcanism	widening of median trough concomitant with injection & extrusion of tholeiitic basalt	peralkali volcanism within rift zone
PLIOCENE	7.0		'PERALKALI' VOLCANISM	alkali shield volcanism	alkali shield volcanism		peralkali volcanism on S. Arabia coast	separation of sialic crust	rift widening by downwarp associated with normal faulting
MIOCENE	25			marginal alkali volcanism in Sudan		block faulting near margins	separation of sialic crust		
OLIGOCENE	37	VERTICAL UPLIFT; FORMATION OF AFRO-ARABIAN DOME & PROTO RIFT ZONES	ALKALINE TRAP SERIES VOLCANISM	trap volcanism in Ethiopia & Sudan; younging southwards	trap volcanism in Somalia	trap volcanism in SW Arabia	attenuation of sialic crust by downwarp & normal faulting	attenuation of sialic crust by downwarp & normal faulting	
EOCENE	54								
PALAEOCENE	65	NORTHWARD MOVEMENT OF UNIFIED AFRO-ARABIAN PLATE							
UPPER CRETACEOUS	100				folding of Mesozoic sediments	folding of Mesozoic sediments			
PRE-UPPER CRETACEOUS	600	EPEIROGENIC MOVEMENTS							
PRECAMBRIAN									

studied it, Roman (1926), Lamare (1930), Shukri & Basta (1954) and El-Hannawi (1964) have emphasized the alkaline character and the pronounced similarity of the series to the coeval volcanics of Ethiopia. There is such a clear correlation, in time and composition, between the Yemen and the Ethiopian Trap Series that the chemistry of the sequence can be considered as a whole.

It is clear that in both Ethiopia and the Yemen the series is alkaline on the normative classification of Yoder & Tilley (1962) provided that the effect of excessive oxidation is taken into account. Mohr (1963) has noted that the average for Ethiopian basalts is closely comparable to Nockold's (1964) average for world alkali basalts, and emphasized that the series has such typical alkali association traits as low TiO_2, high H_2O and, particularly, high Na/Si and ferric/ferrous ratios. In Ethiopia, the aphyric alkali basalts which form the lower part of the Trap Series are low in MgO in keeping with the absence of modal olivine (see table 2). The upper part of the sequence, on average richer in MgO, is more typically alkaline. However, as a wider variety of generally porphyritic rock types is present, it is clear that these are the products of more extensive, high-level fractionation probably in a magma chamber under a central vent volcano. Analyses from the Yemen Trap Series often lack accompanying field and petrographic data and are, in many cases, of an obviously less reliable nature. However, the better analyses are averaged in table 2 and show the alkali nature of the series and further emphasize the similarity of the Yemen Traps to those of Ethiopia.

Volcanism in the zones of crustal attenuation

In places, a phase of volcanic quiescence followed the eruption of the Trap Series in both Ethiopia and in Arabia (Dainelli 1943; Gass & Mallick 1968), although vertical uplift, and the crustal attenuation that formed the 'proto' Red Sea, the Gulf of Aden and the Ethiopian rift seems to have been continuous. When volcanic activity recommenced it was of two types which, although broadly contemporaneous, differed markedly from each other in the composition of their products and their eruptive mechanisms.

Along the central lines of the Red Sea and the Gulf of Aden, separation of the sialic crust took place and new ocean floor of tholeiitic basalt was formed. Elsewhere, in the zones where the sialic crust was attenuated, the volcanism was of the 'intermediate' type that leads on fractionation to peralkali differentiates. In volume this latter association, often termed the Aden Volcanic Series, constitutes about $\frac{1}{500}$ of the Trap Series and must be considered as essentially a transitional stage between the voluminous Trap volcanics and the undoubtedly abundant tholeiitic basalts of the central Gulf of Aden and the Red Sea; it is this 'intermediate' association that is now discussed.

Although seismic evidence (Knott, Bunce & Chase 1967; Gouin, in Mohr 1963; Laughton 1967) indicates that the sialic crust is attenuated along the margins of the Red Sea and the Gulf of Aden and also within the Ethiopian rift, only two areas of peralkali volcanism have been convincingly identified and studied in any detail. These are the line of Miocene–Pliocene central vent volcanoes along the South Arabian coast between the entrance of the Red Sea and Aden (Gass, Mallick & Cox 1965; Gass & Mallick 1968; Cox, Gass & Mallick 1970); and the Pliocene to Recent volcanoes within the Ethiopian rift (Mohr 1963; Gibson 1969). In both of these regions the volcanic centres lie along lines of structural significance; the Arabian centres are on an east–west line parallel to the northern margin of the Gulf of Aden, those in Ethiopia are within the seismically active Wonji Fault Belt or along the northern margin of the Somaliland horst (Gouin, in Mohr 1963) (see figure 1). However, in both African and Arabia the silicic volcanics occurring towards the top of the Trap Series also have marked peralkaline affinities and although they are in many ways petrochemically similar to the Aden Volcanic Series, they are separate from it in both time and space (see p. 373).

Dickinson, Dodson, Gass & Rex (1969) have shown that specimens from the South Arabian centres of the Aden Volcanic Series, including the most silicic varieties, have $^{87}Sr/^{86}Sr$ ratios of 0.704 to 0.707, which strongly suggests a mantle origin. Similar ratios have been obtained for Recent volcanic rocks from the north-central zone of the Afar depression (Barberi *et al.*, this volume, p. 293). Theoretically, it may be assumed that the original melt, produced by partial fusion of the Upper Mantle, was basaltic and therefore that the least evolved surface rocks would be aphyric basalts. Average compositions of aphyric basalts from the Aden Volcanic Series in Ethiopia and from Jebel Khariz in the south coast of Arabia are presented in table 2 together with basalt averages for north-central Afar. Once the effect of excessive oxidation is removed the aphyric basalt average, considered to represent the most primitive magmatic liquid, is mildly nepheline normative in Arabia and mildly hypersthene normative in Ethiopia (table 2; analyses 5*a* and 4*a*). Although deductions concerning the composition of the parental magma for this 'intermediate' association are basalto-centric, it must be emphasized that silicic rocks are abundant in the Aden Volcanic Series of Arabia, although types ranging from olivine basalt through intermediate varieties to peralkali rhyolite are present. In the Ethiopian rift, silicic rocks are abundant and basalts occur, but rocks of intermediate composition are rare or absent.

The oceanic association of the Red Sea and Gulf of Aden

Geophysical studies have indicated that sialic crust is absent under most of the Gulf of Aden (Laughton 1966, 1967; Laughton *et al.*, this volume, p. 227) and under the southern part of the Red Sea median trough (Drake & Girdler 1964) or under most of the Red Sea (Davies & Tramontini, this volume, p. 181). The most acceptable explanation is that concomitant with the separation of Arabia from Africa, new oceanic crust was generated in the axial zone of both rifts. This process is considered to have operated since the early Miocene in the Gulf of Aden (Laughton 1967), but only during the last 5 Ma in the Red Sea (Vine 1966) if oceanic crust is only present in the median trough. To explain the creation of new oceanic crust and the presence of magnetic strip anomalies in these areas and elsewhere, it has been suggested (Hess 1962; Vine & Matthews 1963) that basaltic material was injected along the axial zone of mid-ocean rises, probably as dyke-like feeders leading to submarine lava flows. Logically, with time, the older intrusions will move aside to make way for subsequent injections in the axial zone; the once adjacent continental masses would thus be moved farther apart as more ocean floor was created.

There is increasing evidence (see, for example, Engel, Engel & Havens 1965; Cann & Vine 1966) that the volcanic rocks of the deep ocean floors, the abyssal basalts, intruded and extruded by the mechanism just described, have characteristic major oxide and trace element compositions. On the classification of Yoder & Tilley (1962) they are dominantly over-saturated tholeiites, carrying abundant normative hypersthene and often normative quartz. In the major oxides, abyssal basalts are high in SiO_2 and CaO, low in TiO_2 and particularly low in K_2O;

in trace elements they are impoverished in the large ion elements such as rubidium, thorium, uranium, barium (Gast 1968).

Dredge hauls from the Gulf of Aden have brought up a variety of mafic and ultramafic rocks in various stages of alteration, but also unaltered aphyric basalts. Eight of these basalts have been analysed by Cann, and the average (table 2, analysis 7) is typical for abyssal basalts elsewhere (J. R. Cann, personal communication); petrochemical data thus substantiates the oceanic nature of the crust within the Gulf of Aden. In the Red Sea, specimens of volcanic glass recovered from depressions in the median trough (Chase 1969) have major oxide compositions close to those of abyssal basalts (table 2, analysis 8). Furthermore, the volcanic island of Jebel At Tair, which lies within the median trough, is formed of distinctly tholeiitic lavas (Gass, Mallick & Cox, in preparation) (table 2, analysis 9) and, although these are considerably more evolved than the abyssal basalts, they are nevertheless of 'oceanic' character and are comparable in their major oxide chemistry to oceanic island theoleiites. Confirmatory evidence has recently been provided by Schilling (in Press), who notes that the chondritic relative rare earth element abundance pattern of the dredge samples from the median trough is strictly analogous to that of abyssal basalts elsewhere, while the pattern for Jebel At Tair basalts is closely comparable to those of mid-ocean islands. There is therefore little doubt that the floor of most of the Gulf of Aden and the southern part of the Red Sea median trough is formed of abyssal basalts belonging to a tholeiitic association that is significantly different in its chemistry from the alkali and 'intermediate' suites of the Trap Series and the Aden Volcanic Series.

Recent volcanoes in the central part of the northern Afar depression (see figure 1) have been investigated and described by Tazieff, Marinelli, Barberi & Varet (in Press) and Barberi *et al.* (this volume, p. 293). Chemically, the products of these volcanoes are tholeiitic and compare most closely with the 'oceanic' basalts of the Red Sea and Gulf of Aden (table 2, analysis 6). As the area is one of active east–west dilatation, witnessed by the abundance of north–south tensional faults and basic dykes (Gibson & Tazieff, this volume, p. 331), it is possibly of embryonic oceanic character.

Magmagenetic and structural mechanisms

The spatial and temporal coincidence of the Trap volcanism with the vertical uplift that formed the Afro–Arabian dome can hardly be fortuitous, especially as coeval regional doming and extensive volcanism also occurred in East Africa (King 1970), Tibesti (Vincent 1970), the Hoggar (Black & Girod 1970) and the Bayuda area of the northern Sudan. That doming, rifting and magmatism are the expressions of the same major subcrustal process has been previously proposed by Shackleton (1953) and Bailey (1964, p. 1105) and the regional coincidence of doming and volcanism suggest that the primary mechanism could well be a localized thermal disturbance. This suggestion is in accord with the proposal of Sowerbutts (1969) to explain the presence of anomalously light mantle under the uplifted and rifted areas of East Africa.

In this regard, Elder (1966), using the term penetrative convection, has, on experimental evidence, postulated that there are within the Earth's mantle isolated lithothermal systems involving both heat and mass transfer. These systems are envisaged as discrete portions of the mantle, hotter than their surroundings, that can exist either as isolated, roughly equidimensional 'blobs' or as rising thermal plumes; in their space-form they have been compared to salt diapirs (Elder 1966; Harris 1970). The theoretical thermodynamic evolution of a rising

TABLE 2. AVERAGED ANALYSES, C.I.P.W. NORMS AND NIGGLI QUARTZ VALUES FOR BASALTS OF THE TRAP SERIES, THE ATTENUATED ZONES AND THE THOLEIITIC ASSOCIATIONS OF THE RED SEA AND GULF OF ADEN

	Alkaline Trap Series						'Intermediate' basalts of the attenuated zones						Tholeiitic associations of the Gulf of Aden and Red Sea						
number analyses ...	1	1a	2	2a	3	3a	4	4a	5	5a	6	6a	7	7a	8	8a	9	9a	
SiO_2	46.60	46.70	47.00	47.23	47.47	47.75	47.30	47.56	47.46	47.64	49.46	49.58	48.93	48.88	48.71	49.03	50.04	50.12	SiO_2
TiO_2	2.15	2.15	2.40	2.41	2.61	2.62	2.00	2.01	2.59	2.60	2.31	2.32	1.09	1.09	1.70	1.71	1.93	1.93	TiO_2
Al_2O_3	16.20	16.23	15.10	15.17	15.98	16.07	14.10	14.17	16.26	16.32	12.81	12.84	16.60	16.59	12.80	12.88	16.56	16.58	Al_2O_3
Fe_2O_3	3.80	1.50	6.00	1.50	7.07	1.50	6.70	1.50	5.23	1.50	4.14	1.50	2.09	1.50	7.80	1.50	3.31	1.50	Fe_2O_3
FeO	8.45	10.54	6.30	10.40	5.38	10.46	7.30	12.04	6.72	10.13	8.77	11.19	6.83	7.35	7.46	13.22	7.49	9.13	FeO
MnO	0.23	0.23	0.15	0.15	0.78	0.78	0.20	0.20	0.19	0.19	0.17	0.17	0.24	0.24	0.25	0.25	0.19	0.19	MnO
MgO	6.65	6.66	6.00	6.03	3.29	3.31	5.95	5.98	6.72	6.75	6.32	6.34	7.38	7.37	7.30	7.35	5.19	5.20	MgO
CaO	9.60	9.62	9.50	9.54	9.43	9.48	10.80	10.86	10.08	10.12	10.97	11.00	12.67	12.66	10.20	10.26	11.33	11.34	CaO
Na_2O	2.85	2.86	2.90	2.91	3.84	3.86	2.50	2.51	3.29	3.30	3.01	3.02	2.42	2.42	2.20	2.21	3.00	3.00	Na_2O
K_2O	1.25	1.25	1.90	1.91	1.67	1.68	1.30	1.31	0.84	0.84	0.71	0.71	0.19	0.19	0.19	0.19	0.36	0.36	K_2O
H_2O	1.80	1.80	2.40	2.41	2.03	2.04	1.45	1.46	—	—	0.98	0.98	1.56	1.56	0.88	0.89	0.65	0.65	H_2O
P_2O_5	0.44	0.44	0.34	0.34	0.45	0.45	0.40	0.40	0.61	0.61	0.35	0.35	0.15	0.15	0.45	0.45	—	—	P_2O_5
others	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.06	0.06	—	—	others
total	100.02	99.98	99.99	100.00	100.00	100.00	100.00	100.00	99.99	100.00	100.00	100.00	100.15	100.00	100.00	100.00	100.05	100.00	total
C.I.P.W. norms																			
q	—	—	—	—	—	—	0.60	—	—	—	0.19	—	—	—	6.48	—	—	—	*q*
or	7.39	7.39	11.23	11.23	9.87	9.93	7.69	7.74	4.97	4.97	4.20	4.20	1.12	1.12	1.12	1.12	2.13	2.13	*or*
ab	24.11	22.83	24.54	20.72	31.40	24.69	21.15	21.24	27.84	26.23	25.47	25.55	20.48	20.48	18.61	18.70	25.38	25.38	*ab*
an	27.72	27.76	22.58	22.69	21.44	21.57	23.42	23.53	27.12	27.24	19.35	19.39	33.88	33.85	24.49	24.67	30.66	30.72	*an*
ne	—	0.74	—	2.12	0.59	4.32	—	—	—	0.92	—	—	—	—	—	—	—	—	*ne*
di	13.83	14.10	17.71	18.51	17.69	19.02	22.08	23.09	15.05	15.59	26.67	27.22	22.69	22.77	18.49	19.35	20.83	21.12	*di*
hy	2.49	—	2.55	—	—	—	9.18	0.99	4.66	—	11.95	7.37	10.06	8.86	14.28	27.01	10.95	11.30	*hy*
ol	12.06	18.09	4.94	14.73	0.74	10.25	—	15.03	6.45	16.53	—	7.90	4.92	6.78	—	1.73	—	2.86	*ol*
mt	5.51	2.18	8.70	2.18	10.25	2.18	9.71	2.18	7.58	2.18	6.00	2.18	3.03	2.18	11.31	2.18	4.80	2.18	*mt*
il	4.08	4.08	4.56	4.58	4.95	4.97	3.79	3.82	4.92	4.94	4.39	4.41	2.07	2.07	3.23	3.25	3.67	3.67	*il*
hyap	1.04	1.04	0.80	0.80	1.06	1.06	0.94	0.94	1.44	1.44	0.83	0.83	0.35	0.35	1.06	1.06	—	—	*hyap*
H_2O	1.78	1.78	2.39	2.39	2.01	2.02	1.43	1.44	—	—	0.97	0.97	1.55	1.55	0.86	0.86	0.65	0.65	H_2O
Niggli quartz value																			
	−25.1		−26.4		−28.7		−20.8		−25.7		−15.1		−11.8		−9.1		−10.1		

Columns with the suffix (*a*) are the preceding analysis after the Fe_2O_3 content has been recalculated to 1.5 %. 1, Ethiopia, Lower unit (Ashangi) average of 16 analyses (Mohr 1963, p. 128, table 6); 2, Ethiopia, Upper unit (magdala) average of 17 analyses (Mohr 1963, p. 128, table 6); 3, Yemen, average of six analyses (Shukri & Basta 1955, p. 148, table 5); 4, Ethiopia, Aden Series, average of 25 analyses (Mohr 1963, p. 128, table 6); 5, Jebel Khariz, Aden Volcanic Series, South Arabia, average of five analyses (Gass & Mallick 1968, p. 78, table 3); 6, Central Chain of Afar depression. Average of nine analyses (Tazieff *et al.* in Press); 7, Gulf of Aden average of eight aphyric basalts (J. R. Cann, personal communication); 8, dredge specimen, Red Sea median trough 1920 m (1050 fathoms) (Chase, R. L., 1969); 9, Jebel At Tair; volcanic island within Red Sea Median trough. Average of six analyses (Gass, Cox & Mallick, in preparation).

lithothermal system is now compared with the magmatic and structural history of the junction area. Thermal activity of this type would cause partial melting in the Upper Mantle making basaltic magmas available and would increase the thermal gradient thereby necessitating the downward movement of the main phase boundaries in the mantle. The lowering of the phase boundaries would result in an increase in volume as low temperature, high-pressure minerals inverted to their less dense, high-temperature equivalents. The increase in volume would be most easily relieved by vertical uplift, in this case producing the Afro–Arabian dome, with the consequent attenuation of the sialic crust and the formation of the 'proto' rift zones of the Red Sea, Gulf of Aden and Ethiopia.

As partial melting occurred in response to the elevation of the thermal gradient, the first body of magma generated would probably have a roughly tabular space-form (see figure 2*a*) as more heat is required to extend the zone of melting vertically than to raise the temperature of the rock still below the melting range (Hess 1960, p. 18; McBirney 1963, p. 6351). Fracturing would occur in the overlying crust and mantle as this brittle carapace was updomed and these fractures would afford ready access to ascending magma. The first melts would be produced in a zone where the melting-point curve for peridotite or garnet peridotite intersected the thermal gradient. In the case of the Afro–Arabian dome this seems to have been at depths of about 60 km for the products of this first phase are alkaline (Kushiro 1965, 1968; Kushiro & Kuno 1963). The tendency for the upper part of the Trap Series to become less alkaline, noted by Mohr (1963) and implicit in the presence of abundant peralkali silicic differentiates, could be accounted for either by the upward movement of the primary magma-genetic zone or, more probably, by a pause in the upward movement of the magma and fractionation in a lower pressure regime on the way to the surface (O'Hara 1965).

As isostatic equilibrium appears to be maintained throughout doming (Bullard 1936), the volume changes in the mantle must be compensated by uplift (Sowerbutts 1969); linear zones of crustal attenuation must form to relieve the tensional stresses. It follows that these zones would be areas of mass deficiency and lines of structural weakness, both factors that would facilitate intense magmatic injection. This process would probably be accompanied by migration of volatiles from the mantle into the rift zones thereby causing adiabatic heating and acceleration of the rate of partial fusion (Bailey 1970).

Logically, the attenuated zones would be the sites of most intense injection and vulcanism and this is, in fact, the case at the present time in the Ethiopian rift and Afar depression where active fault belts are also the sites of the most active volcanism (Mohr 1963; Tazieff *et al.* in Press).

Injection of magma along the axial zones of weakness must distort the isothermal surfaces from their original, near-horizontal attitude, to give a region of high thermal gradient adjacent to and above the injection zone; the situation envisaged is similar to that demonstrated by the electric analogue experiments of McBirney (1963, p. 6328). With the increased thermal gradient, lowering of pressure and volatile flux in the injection zone, partial fusion under the areas of crustal attenuation would extend far higher into the mantle than elsewhere. Experimental evidence (Kushiro 1965) suggests that magma generated in such a low pressure régime would tend to be more silicic than that created by partial fusion of the same material at greater depth. It is suggested that the basaltic magma generated at this stage in the tectono-magmatic cycle would be intermediate between alkali and tholeiitic varieties and lead on fractionation to peralkali silicic differentiates (Coombs 1963). This stage is shown in figure 2*b*, and is envisaged

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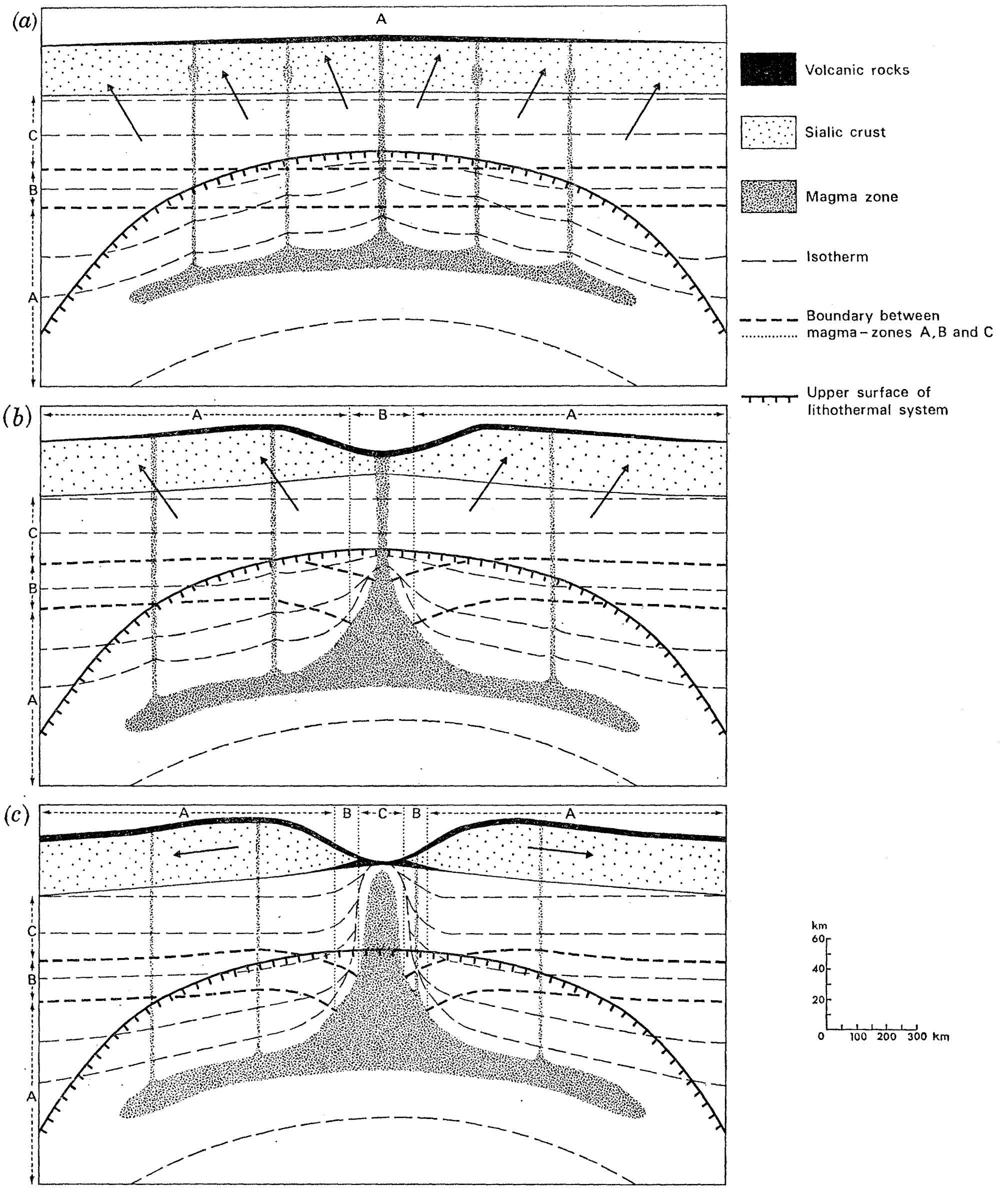

FIGURE 2. Schematic diagram illustrating the postulated distribution of magma-genetic zones and related eruptive rocks during the tectono-magmatic evolution of the area. (A) Zone of alkali basalt genesis and eruption; (B) zone of intermediate basalt genesis and eruption and (C) zone of tholeiitic basalt genesis and eruption.

for the Recent volcanics that lie along the active Wonji Fault Belt of the Ethiopian rift. Nevertheless, intermediate basaltic magmas of this type can be produced after crustal separation has occurred, for example, zone B in figure 2*c* and this is thought to apply to the Miocene–Pliocene (5 to 10 Ma) volcanoes that lie along the south coast of Arabia, between Aden and the Red Sea.

Repeated linear injections along the zones of crustal attenuation would result in the moving apart of the bordering sialic blocks and eventually the host rock for the injections would be the previously emplaced basaltic dykes. By this stage the sialic crystalline basement would be entirely separated by new basaltic crust. The effect of repeated injection would steepen, still further, the thermal gradient over the original attenuated belts so that the zone of partial melting might well extend to within 10 km of the surface (figure 2*c*); it is in this low-pressure environment that tholeiitic basalts appear to be generated (Kushiro 1965; Oxburgh & Turcotte 1968; Gast 1968; McBirney & Gass 1967). This phase started in the Miocene and has continued ever since so far as the Gulf of Aden is concerned. In the Red Sea, sialic separation may have taken place about 5 Ma ago (Vine 1966), whereas the strongly tholeiitic character of the basalts in the north central part of the Afar depression (Barberi *et al.*, this volume, p. 293) suggests that this stage has only just been reached. Once this stage has been reached (figure 2*c*) the process continues as long as a primary magma source is available because the high thermal gradient caused by the injections themselves ensures the production of magma high in the mantle.

The question now arises whether the sialic blocks, once they were fractured by the up-doming and separated by basaltic injection, continue to separate in response to the emplacement of basalt alone or must some other mechanism be envoked. It is therefore relevant to note that palaeomagnetic evidence suggests that from Cretaceous times onwards, Africa and Arabia have been moving northeastwards, possibly in response to the generation of new oceanic crust along the ridges of the south Atlantic and Indian oceans (McElhinney, Briden, Jones & Brock 1968). It is within this major 'conveyor belt' system, above the low-velocity layer, that the Afro–Arabian lithothermal event is thought to have occurred, and its effect has been to split the earlier single continental mass of Afro-Arabian into segments, and, by injection of basalts along the fracture lines, to generate ocean crust in the Gulf of Aden and the Red Sea, thus accentuating the northeasterly movement of the Arabian peninsula. Further, it should be noted that both before (Mohr 1963) and after the formation of oceanic crust on the Gulf of Aden and the Red Sea (Brown, this volume, p. 75; Kabbani, this volume, p. 89) that volcanism in sialic areas has been primarily along north–south lines suggesting that the same primary stress field has been operating throughout the entire period.

Throughout the foregoing discussion the upper surface of the lithothermal system has been treated as a uniform sphere. This is unlikely for there is distinct geomorphological evidence that a secondary topographic dome exists athwart the Red Sea with its major elevation at about 22° N (figure 1, inset). Furthermore, since coeval volcanism and rifting in East Africa are associated with major updoming, it is tentatively suggested that the African rift system may be the combined result of a number of lithothermal systems, each with its own regional updoming and resultant axial fracturing which coalesces or overlaps at the dome margins. The difference between the Afro-Arabian dome and others in Africa is that the former was succeeded by the formation of basaltic oceanic crust in the floor of the everwidening rifts. This process, in turn, could be related to the position of the dome near the margin of the Afro–Arabian continent, so that the lines of weakness were accentuated by ocean-floor spreading already operating from the Carlsberg ridge in the northwest Indian ocean (Le Pichon & Hertzier 1968).

I gratefully acknowledge the generosity of Dr J. R. Cann in making unpublished analytical data on the Gulf of Aden basalts available, and that of Professor H. Tazieff and his co-workers, Professor J. G. Schilling, Dr P. A. Mohr and Dr R. L. Chase for data in preprint form. My colleagues, Drs Dorothy H. Rayner and T. N. Clifford, are thanked for their constructive criticism of the text, and Mr R. C. Boud for cartographic assistance. Figures 1 and 2 were originally prepared for an earlier paper with a similar theme; I am most grateful to Messrs Oliver and Boyd for allowing them to be used in this article.

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