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Age progressive volcanism in the Comores Archipelago, western Indian Ocean and implications for Somali plate tectonics

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The Comores Islands together with the Tertiary volcanic province of northern Madagascar form a sublinear trend of alkali olivine basalt shield volcanoes across the northern entrance of the Mozambique Channel. Potassium-argon dating of shield-building lavas confirms an eastward increase in age of volcanism along the chain, consistent with a hotspot origin for the lineament. The velocity of the Somali plate over the mantle magma source is 50 mm/yr.

We use the distribution of ages along the Comores-Madagascar chain in conjunction with existing age data for the Reunion-Mascarene Plateau hotspot track to model the absolute motion of the Somali plate for the last 10 m.y. We calculate the relative motion across the East African Rift by subtracting the Somali plate absolute motion from African plate absolute motion during this period. The model predicts 320 km of total separation across the East African Rift during the past 10 m.y. which is greater than has been estimated from surface geological evidence

The geometry of older portions of the Comores and Reunion trends indicates that there was no significant relative motion between the African and Somali plates prior to about 10 m.y. ago.

1. Introduction

Recent modeling of worldwide sets of hotspots has shown that these point sources of volcanism are fixed (in the mantle) with respect to one another over long periods of time, and thus constitute a frame of reference for measuring lithospheric plate motions [1-3]. In particular, the azimuth and age distribution of volcanism along chains of islands and seamounts emanating from these sublithospheric melting anomalies directly determines past plate positions. The usefulness of this reference frame depends on accurate knowledge of geometry and chronology, as has been demonstrated by the younger island chains on the Pacific plate.

The volcanic lineaments seen in the western Indian Ocean, however, have not yet been reconciled with the global pattern of hotspot tracks. Specifically, the trends of volcanoes trailing from hotspots near Grande Comore and Reunion (Fig. 1) diverge significantly from those expected from examination of African plate motion with respect to hotspots in the Atlantic [3]. Relative motion between the Somali plate *, which overlies the western Indian Ocean hotspots, and the African plate could account for the differences.

We present K-Ar determinations from the four volcanic islands in the Comores Archipelago and from late Tertiary central volcanoes in northern Madagascar to show that volcanism along this lineament is age progressive and can be attributed to hotspot activity during the past 10 m.y. Earlier difficulties in explaining these trends as hotspot features may disappear when plate separation across the East African Rift is taken into account. We propose that the earliest manifestation of the Grande Comore hotspot is to be found on the

* The Somali plate is bounded on the south and east by the Southwest Indian, Central Indian, and Carlsberg Ridges; on the north by the Sheba Ridge within the Gulf of Aden, and on the west by the East African Rift System.

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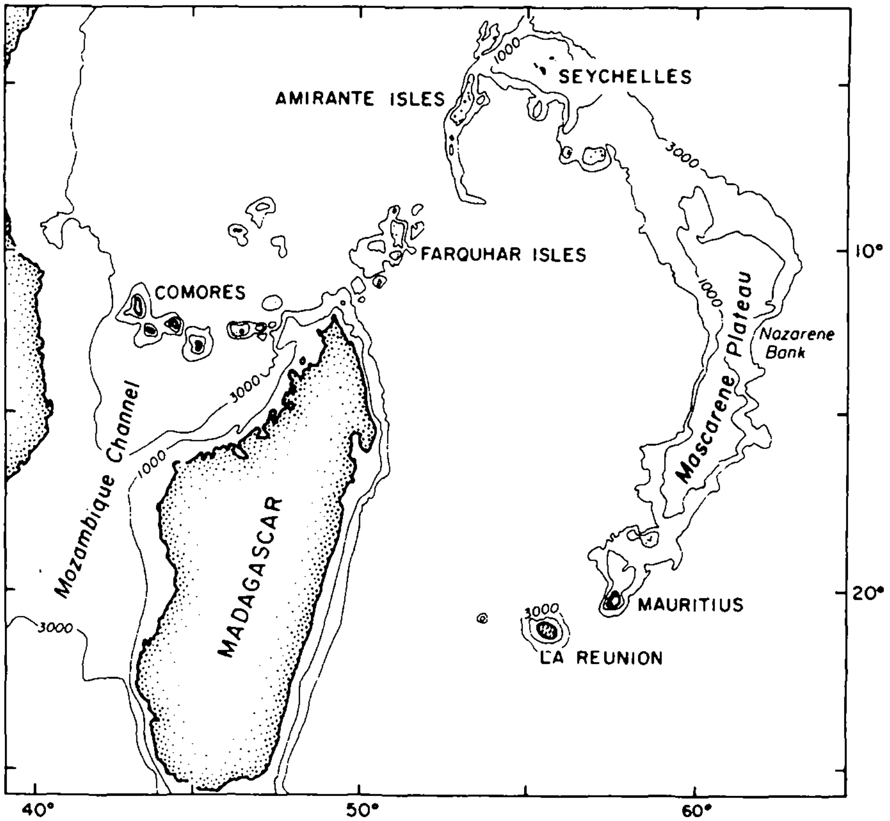

Fig. 1. The Comores Islands are the youngest expression of hotspot activity which may earlier have produced volcanism in northern Madagascar, the Farquhar and Amirante Islands (now coral atolls), and Tertiary basalt and syenite outcrops in the Seychelles Islands. This volcanic lineament is subparallel to the Reunion-Mauritius-Mascarene Plateau trend. Seamount volcanism to the west of Reunion may mark the present hotspot position. Bathymetry is indicated in 1000 and 3000 m contours (4).

Seychelles Plateau, and that hotspot activity records the entire Tertiary history of the western Indian Ocean.

2. Linear volcanism from the Comores Islands to northern Madagascar

The Comores Archipelago consists of four principal volcanic islands which lie across the northern entrance of the Mozambique Channel. The islands form a roughly linear chain 250 km in length, trending ESE from 11°30′S, 43°30′E. to 13°S, 45°15′E (Fig. 1). Extending from the eastern end of the Comores chain is a rather striking curvilinear trend of volcanic islands and atolls which intersects the northern tip of Madagascar, where it is manifest in numerous alkaline volcanic and subvolcanic bodies [5]. To the north, atolls built on volcanic foundations [6] seem to extend this geometrically continuous trend. The lineament possibly terminates at the Seychelles Plateau, where Tertiary dikes pierce the granitic Precambrian continental remnant at Mahe, Praslin and Silhouette Islands [7].

The Comores Islands (Fig. 2) exhibit the classical geomorphologic progression of oceanic island chains from the still active volcanism at Grande Comores on the western end of the line, through the more mature, dissected cones of Moheli and Anjouan, to the highly eroded island of Mayotte [8]. This age progression has been supported in a general way by a small number of K-Ar dates for Grande Comore (0.01 ± 0.01 m.y.), Anjouan (1.52

$\pm$ 0.10 m.y.), and Mayotte (3.65 $\pm$ 0.10 m.y.) [9].

The distinct sublinear geometry of the Comores trend, and the eastward increase in age suggested to Morgan [10] that the chain represents a hotspot trace produced as the Somali plate, on which it rides, moved over a mantle magma source. This is corroborated by the geochemical and petrologic characteristics of the Comores lavas [11–13] which are similar to the alkali olivine basalt-associated lavas of other proposed hotspot traces.

The Comores lavas are primarily silica-undersaturated alkali olivine basalts and their derivatives, rich in the incompatible elements. Three principal phases of volcanism are recognized at each of the two older islands: a shield-building stage of alkali olivine basalts, a post-erosional stage of alkali olivine basalts and nepheline-normative differentiated lavas, ranging to highly undersaturated phonolitic and nephelinitic compositions, and a rejuvenescent stage which produced small volumes of trachytic and phonolitic lavas. On Mayotte a final spurt of explosive volcanism produced tephrites and trachytic tuff cones which erupted very recently through the fringing reef to create the outboard islet of Pamanzi. Grande Comore is currently in the shield-building stage, having erupted only basaltic lavas, including basanites, ankaramites and oceanites.

To the east, the alkaline rocks in northern Madagascar have petrologic affinities to the Comores lavas [14], and exhibit a greater range in composition. Basaltic magmas have undergone extreme low-pressure fractionation toward both quartz-normative trachytes and rhyolites and nepheline-normative trachytes and phonolites [15]. This is consistent with segregation of a range of hypersthene to nepheline-normative melts at pressures greater than 10 kbar, or 30 km depth [16].

Upton [17] has suggested an alternative to the hotspot model for the Comores Archipelago, proposing that it represents a very slowly spreading ridge. He cites as an analogue the tholeiite and alkali olivine basalt islands at the southern end of the Red Sea. Several lines of evidence oppose this concept. First, the Comores volcanism is not accompanied by any significant zone of seismicity or young magnetic anomalies, and is thus not likely to represent a divergent plate boundary. Second, the rocks exposed in the Comores Islands are wholly alkali olivine basalts rather than the tholeiites typical of spreading centers. Third, one would expect to see simultaneous volcanism along a spreading axis rather than a regular age progression of the magnitude seen in the Comores. Speculation of an age progression within the Red Sea islands was based on the relative sizes of the volcanoes, the larger ones in the south being considered the oldest and the smaller ones in the north the youngest. No radiometric age data substantiate this inference and Gass et al. [18] state that all the islands appear to be equally young.

Another possible origin for the Comores Islands is by volcanic activity along a "leaky" transform fault, although we know of no other such fault producing oceanic islands. In fact, known transform faults in the vicinity, such as the reactivated Davie Fracture zone ([19], and Fig. 6), are oblique to the Comores trend. Again, a plate boundary is not indicated seismically.

3. Sample collection and coverage

During a 3-week sampling session in the Comores we focussed our attention on Mayotte, the oldest and least studied of the Comores Islands. Our collection includes lavas from each of the three principal phases of volcanism. Since the age of initial volcanism at each island is of primary concern in this study, care was taken to collect fresh, datable samples of the shield-building lavas, of which few remnants have survived deep erosion and laterization. The stratigraphically oldest lavas were exposed at the northwest corner of this island.

Collections were also made of lavas from each of three younger islands, although the coverage of the major phases of volcanism is not as complete as for Mayotte. Additional samples from these islands have been donated by Dr. B.G.J. Upton (Grant Institute of Geology, University of Edinburgh), and Dr. A. Hajash (Department of Geology, Texas A&M University). Samples from northern Madagascar were made available by Dr. J.-P. Lorreau (Laboratoire de Géologie du Museum

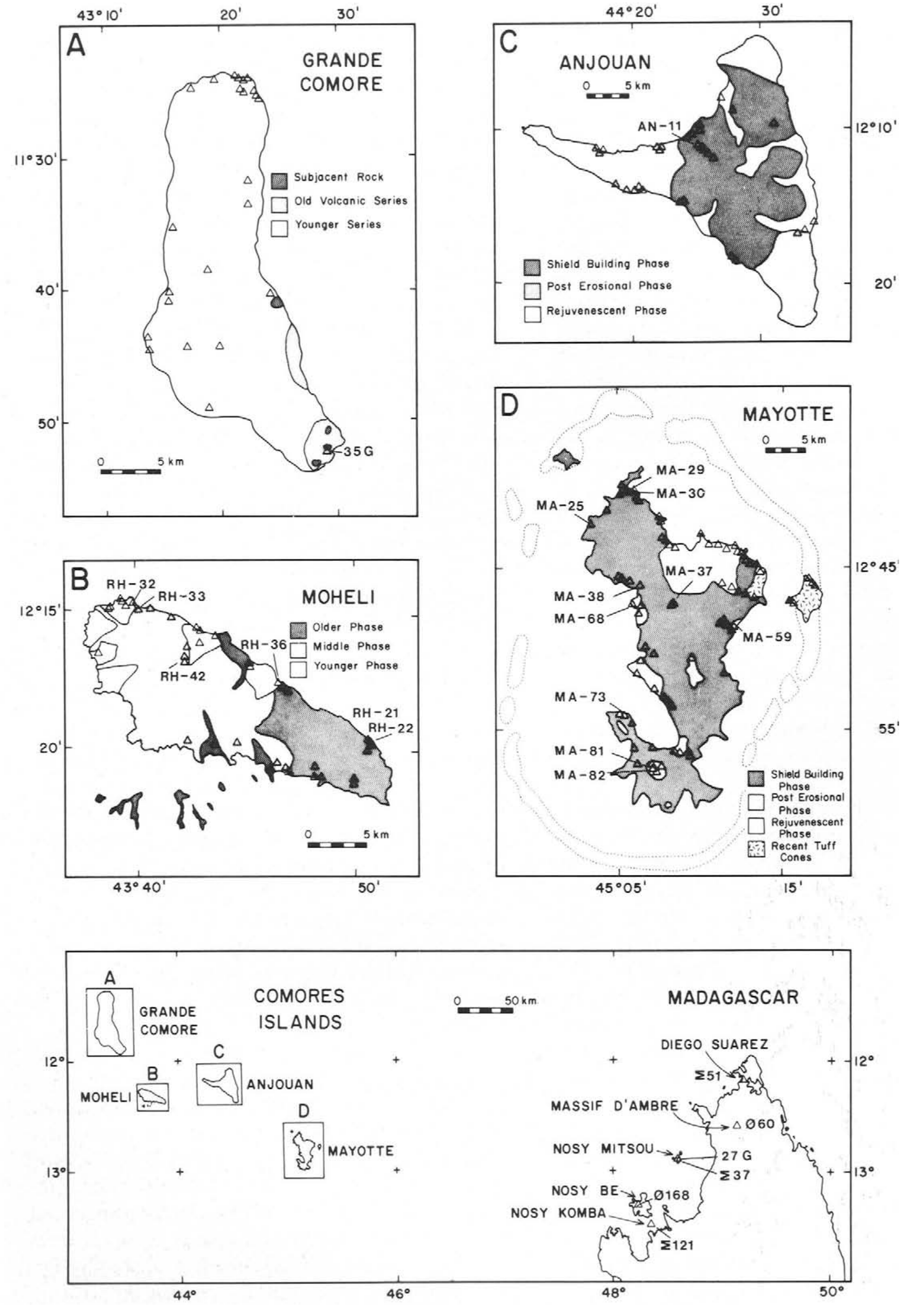

Fig. 2. Sample locations are shown for the Comores Islands and northern Madagascar volcanic rocks. Dated samples are labelled as in Table 1. Simplified stratigraphy is shown for (A) Grande Comore [8], (B) Moheli [11], (C) Anjouan [12], and (D) Mayotte [8].

National d'Histoire Naturelle, Paris, France) from the early Lacroix collections [5,14]. These include extrusive rocks from three islands immediately off the western coast, Nosy Mitsou, Nosy Komba, and Nosy Bé, and from two sites on the mainland, Massif D'Ambre and Diego Suarez, at the extreme northern tip of Madagascar. Fig. 2 shows sample locations and général stratigraphy.

4. Geochronology

Twenty-four whole rock samples were selected from thin section examination for conventional K-Ar age determinations. Most of the samples are holocrystalline, although small amounts of glass are found in a few. The samples appear fresh in thin section, being visibly free of alteration prod-

TABLE 1

K-Ar age data for Comores Islands and northern Madagascar volcanic rocks *

	Sample No.		Phase of volcanism	K (%)	Rad. ^{40}Ar ($\times 10^{-7}$ cm^3/g)	Rad. ^{40}Ar (%)	Age $\pm$ 1σ (m.y.)
Comores:							
Grande Comore	35G	flow	shield building	1.40	0.07	5	0.13±0.02
Moheli	RH-32	flow	shield building	0.45	0.47	40	2.75±0.20
					0.49	49	2.86±0.06
	RH-21	flow	older	0.51	2.22	13	1.57±0.12
	RH-22	flow	older	1.44	1.06	44	1.94±0.02
	RH-42	boulder	intermediate	1.03	0.46	45	1.16±0.08
	RH-33	flow	younger	1.25	0.39	14	0.66±0.03
					0.37	13	0.78±0.21
	RH-36	flow	younger	0.59	0.14	15	0.63±0.02
Anjouan	AN-11	boulder	post-erosional?	0.76	0.35	39	1.20±0.03
Mayotte	MA-29	flow	shield building	0.85	1.74	30	5.41±0.26
	MA-30	flow	shield building	0.90	1.85	42	5.39±0.09
	MA-25	boulder	post-erosional	4.40	5.57	48	3.33±0.13
	MA-37	boulder	post-erosional	1.22	1.10	25	2.37±0.20
	MA-68	boulder	post-erosional	4.44	5.64	75	3.35±0.07
	MA-73	flow	post-erosional	3.05	3.84	22	3.32±0.33
	MA-81	boulder	post-erosional	2.22	3.25	62	3.84±0.12
	MA-82	flow	post-erosional	5.05	6.70	22	3.49±0.32
	MA-38	flow	rejuvenescent	1.42	0.83	28	1.53±0.10
	MA-59	flow	rejuvenescent	3.86	2.39	36	1.63±0.08
Madagascar:							
Nosy Bé	Ø168	flow		1.43	4.08	47	7.49±0.26
Nosy Mitsou	27G	flow		0.97	3.76	65	10.21±0.14
	Σ37	flow		3.92	7.10	53	4.77±0.12
Nosy Komba	Σ121	flow		4.94	19.51	25	10.38±0.73
Diego Suarez	Σ51	flow		4.85	17.74	21	9.61±0.45
					17.21	20	9.32±0.57
Massif d'Ambre	Ø60	flow		1.63	0.53	28	0.85±0.02

* Constants used: $\lambda_\epsilon = 5.81 \times 10^{-11}$ yr^{-1}; $\lambda_\beta = 4.962 \times 10^{-10}$ yr^{-1}; ^{40}K/K $= 1.167 \times 10^{-4}$.

ucts in phenocrysts and groundmass. One exception, sample MA-82, bears alteration products along cracks. Each sample was crushed, washed in distilled water, and sieved to 10–30 mesh particle size. This fraction was split into two aliquots for potassium and argon analyses. Potassium concentrations were determined in duplicate by atomic absorption spectrophotometry. Argon isotopic compositions were determined using either a high-resolution Reynolds-type or AEI MS-10S mass spectrometer, each equipped with an ^{38}Ar spike pipette system.

Table 1 represents 27 K-Ar age determinations for samples from the Comores–northern Madagascar volcanic lineament. The age data for shield-building lavas in each of the Comores Islands are listed first, followed by later stages. In the case of Madagascar where there is no simple relationship between lava types and age we list the oldest samples first.

Grande Comore. The essentially zero age (0.01 ± 0.01 m.y.) previously reported for Grande Comore [9] is consistent with currently active volcanism there, at Karthala Volcano. Sample 35G, which represents one of the oldest flows exposed on Grande Comore [8,14] yields an age of 0.13 ± 0.02 m.y., indicating that volcanism at this island began recently.

Moheli. Duplicate analyses of sample RH-32, from the northwest corner of Moheli, yield an average age of 2.81 ± 0.08 m.y., which is the oldest age obtained for this island. Two samples from the eastern coast, RH-21 and RH-22, yield an average age of 1.76 ± 0.26 m.y., succeeding the older activity by about one million years. Sample RH-42 from the central part of the island is dated at 1.16 ± 0.08 m.y., and could have been produced by the same eruptive phase. The youngest activity is represented by samples RH-33 and RH-36, from the north and northwestern coasts. They give an average age of 0.69 ± 0.08 m.y.

Our data show that neither of the stratigraphic subdivisions proposed by previous workers [8,11] is quite adequate to describe the evolution of Moheli. Whereas the Saint Ours divided the island into an older western region and a younger eastern region, Strong believed that the geomorphology of Moheli indicated the opposite succession, that is, with Older Phase lavas exposed on the eastern end, Intermediate and Younger Phase lavas restricted to the western end of the island (Fig. 2). Our data generally support Strong's interpretation that the morphologically distinct Younger Phase lavas are largely restricted to the western portion of Moheli. However, remnants of an early shield-building phase at 2.8 m.y. underlie the Younger Phase lavas in western Moheli, and predate the Older and Intermediate Phase lavas cropping out in the east.

Anjouan. The 1.52 ± 0.10 m.y. age assigned to Anjouan by Hajash and Armstrong [9] and our age of 1.20 ± 0.03 m.y. must be considered minimum age estimates for that island. The first sample occurs in the fissure erupted lavas of the Sima Peninsula on the northwest corner of the island [9,12], and the second is a stream cobble of unknown stratigraphic position. By analogy with Mayotte (below), where the fissure erupted lavas postdate the shield-building stage by approximately 2 m.y., the initial volcanism on Anjouan could have occurred as early as 3.5 m.y. ago. However, we do not have datable samples of shield-building lavas to test this speculation, and must conclude only that the age of earliest volcanism on Anjouan exceeds 1.5 m.y.

Mayotte. The three distinct stages of volcanism recognized on Mayotte are represented in Table 1. Samples MA-29 and MA-30 yield an average age of 5.40 ± 0.01 m.y. which estimates the age of initial volcanism at Mayotte. A cluster of ages about 3.47 m.y. dates the post-erosional fissure erupted phase. The rejuvenescent phase occurred at about 1.58 ± 0.07 m.y., followed by the recent terminal episode of tuff cone construction. The two lavas representing the rejuvenescent phase are quite different in nature. MA-59 is a highly evolved trachytic lava characteristic of the late-stage lavas which occur in various locations about the island. MA-38 is a much more primitive looking olivine basalt, which may have been generated by activity related to the subsidence of the western half of the island, described by Nougier et al. [13].

Madagascar. Although the alkaline magmatic activity in northern Madagascar covers a fairly broad geographical area, we consider this suite of samples as a single volcanic province. The lavas now exposed may have once been part of a larger single complex, much of which has since been stripped away by erosion [15]. This activity commenced at least 10 m.y. ago, as defined by the cluster of ages obtained for lavas from Nosy Komba, Nosy Mitsou and Diego Suarez. The samples from Diego Suarez and Nosy Komba are highly evolved phonolites which are stratigraphically younger than underlying basaltic lavas and associated nepheline syenite plutonic rocks exposed at Nosy Komba, for which no samples were available to us. Hence, we consider 10 m.y. to be a minimum age estimate for the onset of basaltic volcanism in northern Madagascar. The younger activity at Nosy Bé and Massif d'Ambre indicates that magmatism in northern Madagascar has continued for about 9 m.y. Basanite clasts included in the basalts at Massif d'Ambre have been tentatively correlated with the early lavas at Nosy Komba [15].

Among the various northern Madagascar sites there is no simple relationship between location, lava type, and age, as is observed in the Comores. For instance, primitive lavas of Massif d'Ambre postdate the very differentiated phonolitic lavas of Nosy Komba. The complex pattern of eruption and reactivation observed here is characteristic of intraplate volcanism in continental regions. Where linear volcanic chains can be traced onto continental lithosphere, the geometry of eruption becomes diffuse, there is a wider range of magma compositions, and the duration of volcanism is distinctly longer than at central volcanoes in the ocean basins. This is the case in the White Mountain intrusives in New Hampshire [20], which may be associated with the New England Seamounts [21], the Niger granite ring complexes associated with Ascension Island [22], and the alkaline intrusives and kimberlites in Cape Province, South Africa, which lie on the projection of the volcanic lineament emanating from Bouvet-Meteor hotspot [23]. Thicker continental lithosphere with its older, more complex structure and fabric, apparently diffuses the magmatic signal of a hotspot compared with the high fidelity recording left on oceanic lithosphere.

5. Age vs. distance

When the age of initial volcanism is plotted against the distance from active volcanism at Grande Comore, the nearly linear pattern which emerges determines the rate of migration of volcanism within the Comores Islands to northern Madagascar lineament (Fig. 3). In the hotspot interpretation this is the velocity of the Somali plate over a stationary mantle magma source. In Fig. 3 the apparent rate of volcano migration is 50 mm/yr. We note that the rate need not be perfectly linear, but that this is the simplest model consistent with our age data.

The migration rate is extrapolated through the Farquhar and Amirante Islands to the Seychelles Plateau to demonstrate that the Tertiary magmatic activity there may also have been generated by the hotspot now at Grande Comore, assuming that the rate of migration of volcanism has been at least roughly constant, although the direction of absolute motion changed around 10 m.y. ago. The few rather scattered and imprecise age determinations on samples from basaltic activity at the Seychelles were obtained from an olivine dolerite dike on Praslin Island (52 ± 10 m.y., 48 ± 9 m.y.) and altered pyroxene phenocrysts from syenite dike on Silhouette Island (34 ± 7, 62 ± 12, 43 ± 8 m.y.) [7]. Further speculation concerning the temporal continuity of the early portion of this volcanic lineament from northern Madagascar to the Seychelles awaits improved geochronology for the Seychelles sites, and perhaps for dredged volcanic material from the flanks of the Farquhar and Amirante atolls. We conclude that with respect to geometry and general age progression the Comore–northern Madagascar–Seychelles trend is consistent with a hotspot origin.

6. Duration of volcanism

The volcanic evolution of Mayotte spanned nearly 5 m.y. That Mayotte continued to be active after the initiation of volcanism at Anjouan and Moheli has led some authors to question the validity of the hotspot model for the Comores lineament [13,17]. In fact, all that is required by the

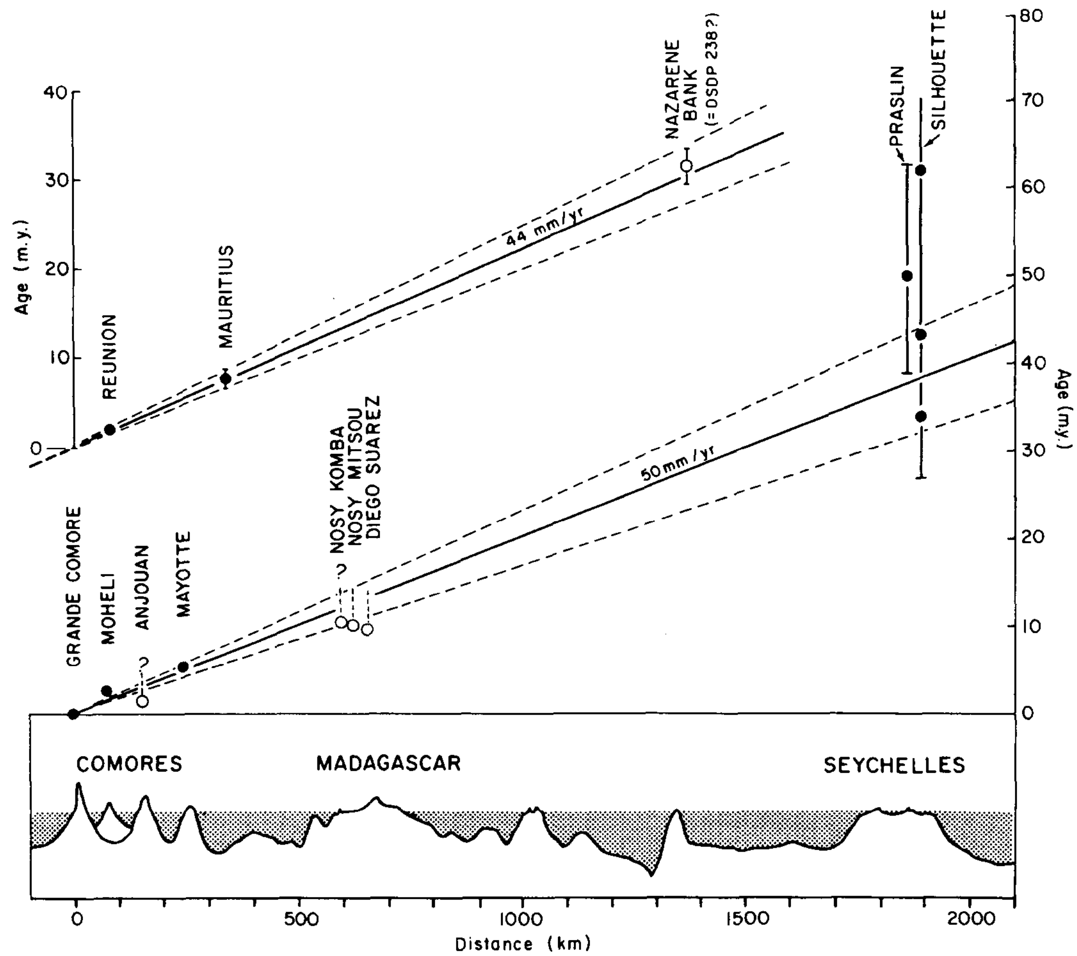

Fig. 3. A. Distance from present hotspot activity at Grande Comore, measured along the trend of the Comores Islands to Seychelles Islands lineament, is plotted against ages of initial volcanism at several localities (Table 1, and [7,9]). The solid circles represent best age estimates of initial volcanism, whereas the open circles represent minimum ages of volcanism at each site. A rate of migration of volcanism of 50 mm/yr best fits the new K-Ar ages for shield-building lavas at Grande Comore and Mayotte and the minimum age of volcanism in northern Madagascar. Igneous activity in the Seychelles at about 40 m.y. B.P. is consistent with this trend. Generalized topography from reference 4. B. Reported radiometric ages along the Reunion hotspot trend [24,25] yield a rate of migration of volcanism of 44 mm/yr. An early Oligocene age for DSDP site 238 on the southern end of the Chagos-Laccadive Ridge [26] provides a minimum age for the Nazarene Bank region of the Mascarene Plateau, which was sundered from the Chagos-Laccadive Ridge by spreading across the Central Indian Ridge about 32 m.y. ago.

hotspot model is that the age of *initial* volcanism by progressive along the island chain. The cessation of shield-building volcanic activity at a given island occurs when the supply of magma is cut off from the mantle source. A small volume of late stage lavas may erupt sometime later, following crystal fractionation in shallow magma chambers, until liquid in those chambers is depleted. The continuity of magma supply must be related to the velocity of the lithospheric plate over the mantle source and to the size of the melting anomaly.

Fig. 4 demonstrates an empirical relationship between the duration of volcanism at individual islands and absolute plate velocity. In constructing this diagram we have used all data available for oceanic hotspot traces from five major plates

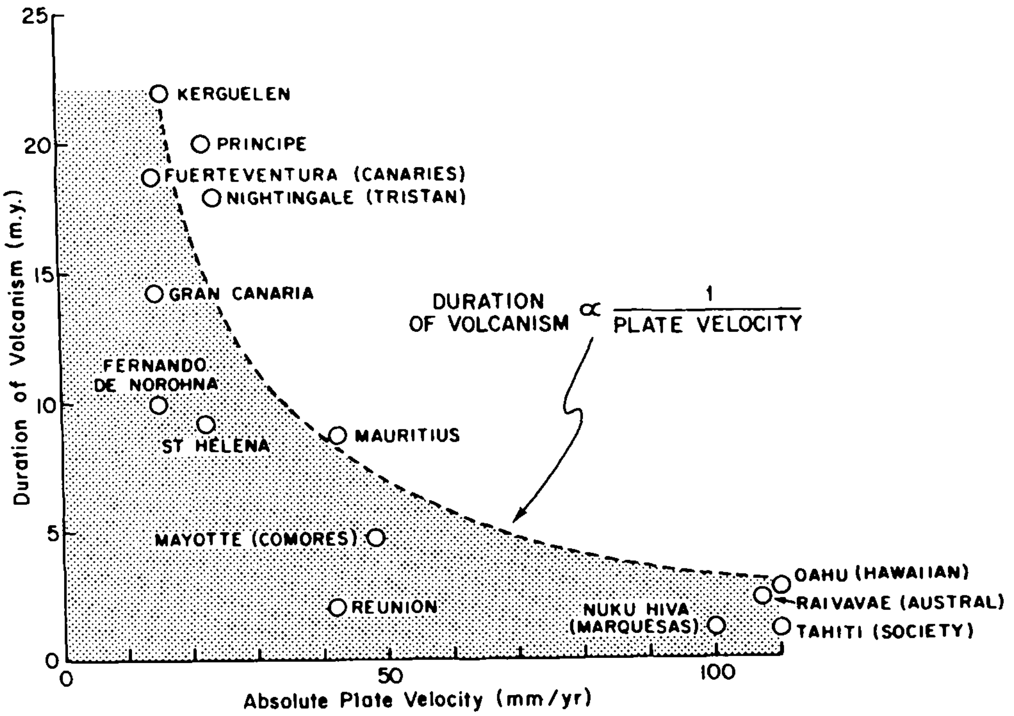

Fig. 4. Duration of volcanism at oceanic islands is proportional to the inverse of plate velocity over mantle hotspots, which determines how long magmas are available for eruption. The dashed curve fits the maximum observed eruptive histories. Other data fall below this line due to incomplete sampling or unfinished volcanism. Plate velocities from reference 3. Reported geochronologies from references 24–36.

(Pacific, South American, African, Somali, and Antarctic). We restricted our attention to intraplate hotspots only since hotspots on plate boundaries do not penetrate existing lithosphere. The duration of volcanism is calculated from the range of radiometric ages reported for complete lava sequences from oceanic islands. The plate velocities are measured from the hotspot reference frame [3].

We note from Fig. 4 that the maximum observed duration of volcanism at oceanic islands is negatively correlated with plate velocity. That is, very slowly moving plates such as Antarctica and Africa allow hotspots to supply magmas to oceanic islands for 20 m.y. or more (e.g., Kerguelen and Nightingale). Conversely, short-lived eruptive histories characterize islands on fast moving plates such as the Pacific.

The data appear to reflect an inverse relationship between plate velocity and the duration of volcanism at oceanic islands. One curve expressing this correlation fits many of the points in Fig. 4. Other data fall below this line, probably due to incomplete sampling of the entire volcanic sequence at those islands, or to the fact that volcanism has not completed its course (e.g., Reunion).

When compared with other hotspot-generated oceanic islands, the 5 m.y. duration of volcanism at Mayotte is not unusually long, but is commensurate with the intermediate absolute velocity of the Somali plate over the hotspot now under Grande Comore. Alternative models for intraplate volcanic traces now appear less attractive because they do not predict a correlation between plate velocity and volcano evolution. Leaky transform faults, for example, would tap the asthenosphere uniformly on all plates, regardless of plate velocity. The difficulty in accepting a hotspot origin for islands with extended periods of volcanism [13,17] stems from the fact that the prototype hotspots are on the Pacific plate (e.g., Hawaii, Tahiti) where volcanism lasts only 1 or 2 m.y. years at each volcano. It seems now that oceanic islands on the Pacific plate present one extreme of a spectrum of eruptive histories related to hotspot volcanism.

7. Absolute motion modeling

Because at least two hotspot traces are needed to determine an absolute pole of rotation for the Somali plate, we use existing data from the age-progressive Reunion-Mascarene Plateau lineament in conjunction with the Comores data for those calculations. The former trend includes Reunion, formed 2 m.y. ago [24], Mauritius, formed 7.8 m.y. ago [25], the Mascarene Plateau and the Chagos-Laccadive Ridge, which has been split off from the Mascarene Plateau by spreading across the Central Indian Ridge (Figs. 1 and 5). Age control on the older portion of this feature is provided by a 32 m.y. minimum basement age at DSDP site 238 on the southern end of the Chagos-Laccadive Ridge [26] and a 65–70 m.y. age for the Deccan Traps in India, at the northern extent of the lineament [37,38].

The portion of the Reunion trend used for the calculation of the 0–10 m.y. Somali plate pole of rotation includes Mauritius, Reunion and an unnamed seamount which lies 170 km west of Reunion [4], which we suggest marks the current location of hotspot activity. Since this seamount is not nearly as evolved as Grande Comore (the zero-age location of the hotspot responsible for the Comores line), the equivalent zero-age location for the Reunion trend lies between Reunion and the nearby seamount. We calculate its position from the intersection of the distance abcissa with the 44 mm/yr line which passes through the Reunion and Mauritius data (Fig. 3). Using the geometry and geochronological control provided by the Comores and Reunion trends, we derive a pole of rotation for the Somali plate located at 77°S, 50°E. For the period 0–10 m.y. the rate of rotation about this pole is 0.497°/m.y. Earlier estimates of Solami plate absolute motion [1,39] have been derived from multi-plate inversion of spreading rates and directions, which are often poorly known for Indian Ocean spreading ridges and result in some contradictory relative motions (e.g., *Compression* across the East African Rift [1]). Such absolute motion calculations are not well constrained but more accurate knowledge of Indian Ocean spreading ridge histories will improve the multi-plate solutions.

8. Neogene tectonics of the Somali plate

Intraplate volcanic lineaments, or hotspot tracks, provide a valuable frame of reference for plate tectonic modeling. If sub-lithospheric magma sources (hotspots) remain stationary in the mantle over geologically significant lengths of time, then these lineaments track the rate and direction of lithospheric plate motion with respect to the mantle. This motion has been designated "absolute" motion to distinguish it from plate-plate relative motions [1].

In order to use hotspots to model absolute plate motions, it is necessary to demonstrate that hotspots remain fixed with respect to one another. Estimates of inter-hotspot motion have varied from 15 mm/yr to negligible motion, depending on the geographical location examined and the period of time considered 1,40–42]. With improvements in knowledge of the history of relative motions between plates and increased radiometric age determinations from critical volcanic lineaments, recent studies of the hotspot framework find less than 5 mm/yr of inter-hotspot motion over the past 100 m.y. [2,3]. Since this is an order of magnitude less than lithospheric plate velocities, hotspots can be a useful reference frame.

As noted by previous workers [2,3], the azimuths of the Comores–northern Madagascar and Reunion-Mauritius volcanic chains do not match the geometry predicted from fitting other contemporary hotspot traces on the African plate. Instead, both trends extend east-west rather than northeast-southwest for the period 0–10 m.y. B.P. (Fig. 5). This discrepancy is significant and demands that either these two hotspots are moving relative to other hotspots beneath Africa, or there is some relative lithospheric motion between west

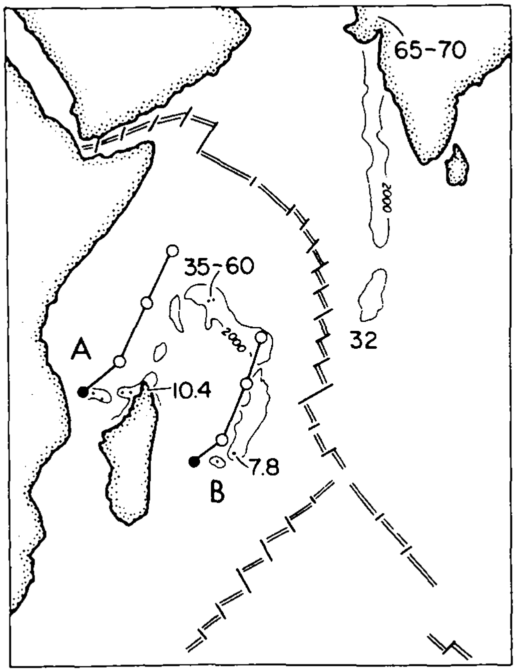

Fig. 5. Hotspot paths predicted by African absolute motions [3], which are shown as solid lines connected by circles of 20 m.y. increments, are systematically offset from the observed paths for the Comores (*A*) and Reunion (*B*) hotspots, outlined by the 2000 m bathymetric contour. The difference between predicted and observed paths can be used to determine Somali-African relative motion between 0 and 10 m.y. B.P. For the period 10–60 m.y. the predicted paths parallel the observed paths, indicating no significant relative motion prior to about 10 m.y. ago. The reported ages for the Comores trend are from this paper and reference 7; for the Reunion trend, from references 24–26, 37, 38.

Africa and the western Indian Ocean Basin. Because the Comores and Reunion trends are systematically offset from the predicted paths, it is not likely that random motion between these and other African hotspots has taken place. Also, volcanic and seismic activity along the East African Rift has long been proposed to define part of a plate boundary between the African and Somali plates [39,43–45], so the second alternative is the favored explanation.

Given that hotspots form a fixed frame of reference, the possibility now exists of estimating the initiation, magnitude and direction of relative motion between the African and Somali plates by subtraction of Somali absolute motion from African absolute motion, each determined from the volcanic lineaments on the respective plates. This opportunity is attractive because previous attempts to model the relative motion between the two plates have yielded widely variable results. This is due to the diffuse and complex nature of deformation across the East African Rift, and to the consequent lack of sufficient relative motion data with which to constrain the Euler pole.

Based on the apparent termination of surface expression of the rift at about 20°S latitude, Baker et al. [43] placed the pole of rotation at 28°S, 37°E, noting that this solution implied non-rigid deformation to the south. McKenzie et al. [45] proposed a pole of rotation for the Somali plate at 8.5°S, 31°E, based on a triple junction solution using relative motion data from the Red Sea and the Gulf of Aden. This pole would indicate primarily transform motion for the East African Rift south of the equator.

Using improved azimuth data from reevaluated transform faults in the Red Sea and the Gulf of Aden, Chase [39] derived a triple junction solution which placed the pole of rotation at 71.1°S, 144.6°W. This suggests that some form of rifting should occur farther to the south than is geologically evident. The nature of this section of the plate boundary remains largely unknown. The rate of extension along the Rift predicted by Chase's model is 6 ± 4 mm/yr at 5°N, which is greater than that derived from geological evidence, that is, 0.4–1 mm/yr [44]. Chase's model is, however, more in keeping with the geophysical evidence than is the 10 mm/yr compression predicted by Minster and Jordan [1] in an aborted attempt to fit the Somali-African relative motion into a worldwide kinematic model of plate motions. The latter authors concluded that intracontinental boundaries may not be reconciled with rigid plate kinematics.

Estimates of the total amount of crustal separation along the East African Rift also vary widely, from 30 to 65 km of extension in Ethiopia and 10 to 30 km in Kenya [44,45]. It is possible that voluminous young volcanic rocks flooding the rift floor may obscure the amount of separation to some degree [44], and that the total amount of relative motion across this complex intracontinen-

TABLE 2

Absolute and relative motions for the Somali plate, western Indian Ocean

Plate	Absolute rotation (0–10 m.y.)			Reference	Relative rotation: SM-AF (0–10 m.y.)		
	Lat. (+°N, −°S)	long. (+°E, −°W)	ω * (°/m.y.)		lat. (+3N, −°S)	long. (+°E, −°W)	ω * (°/m.y.)
Somali	−77.0	+50.0	−0.497	this paper			
African (1)	+61.0	−45.0	0.22	[3]	−63.6	+2.3	−0.33
(2)	+18.76	−21.8	0.14	[1]	−66.2	+9.3	−0.48
(3)	+65.0	−30.0	0.15	[2]	−69.1	+18.8	−0.37
(4)	+31.8	−61.3	0.20	[39]	−67.2	−24.0	−0.41

* The angular velocity is positive when the rotation is clockwise, viewed from the earth's center.

tal boundary cannot be reliably estimated by apparent crustal separation.

From our estimate of Somali plate absolute motion and many published estimates of African plate absolute motion [1–3,39], we calculate Somali-African relative motion for the period 0–10 m.y. B.P. (Table 2). In spite of the variability in reported African absolute motion, the calculated Somali-African relative motion poles are all closely grouped in the extreme south Atlantic (Fig. 6), consistend with roughly east-west extension across the East African Rift. Using one estimate of African absolute motion [3], the pole for Somali-African separation is located at 63.6°S, 2.3°E. The 0.33°/m.y. angular velocity about this pole translates to a linear velocity of 32 mm/yr at 5°N. The implied 320 km of total separation across the East African Rift at this latitude during the past 10 m.y. is many times greater than has been estimated from geological considerations. This discrepancy may result, in part, from underestimating the African absolute velocity and/or overestimating the Somali absolute velocity (our northern Madagascar ages are minimum estimates). Increasing African absolute velocity or decreasing Somali absolute velocity forces the Somali-African relative motion pole to lie to the northwest of our calculated pole. This change would predict a component of transform motion along the East African Rift, which would decrease the component of crustal separation. It is possible, too, that the East

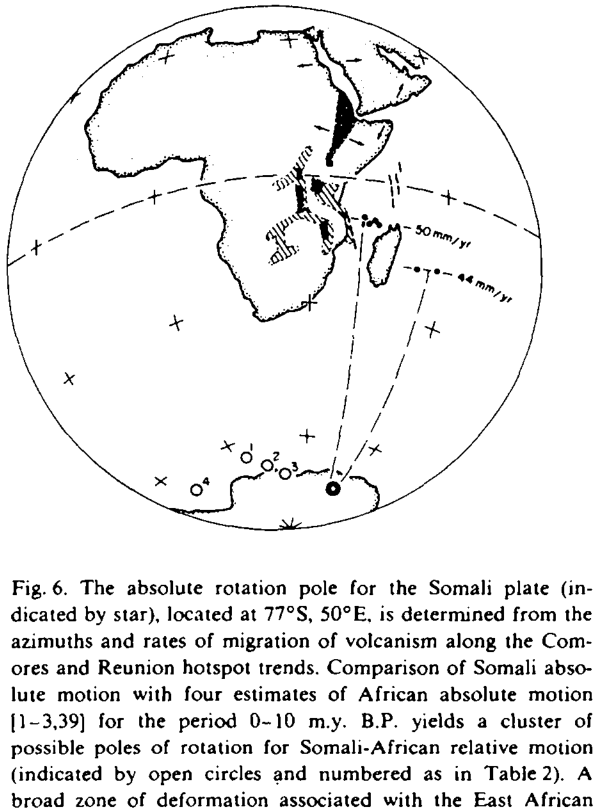

Fig. 6. The absolute rotation pole for the Somali plate (indicated by star), located at 77°S, 50°E, is determined from the azimuths and rates of migration of volcanism along the Comores and Reunion hotspot trends. Comparison of Somali absolute motion with four estimates of African absolute motion [1–3,39] for the period 0–10 m.y. B.P. yields a cluster of possible poles of rotation for Somali-African relative motion (indicated by open circles and numbered as in Table 2). A broad zone of deformation associated with the East African Rift is marked by Tertiary to Recent volcanism (heavy shading) and seismicity (light shading) [47]. Four recognized fracture zones (heavy dashed lines) in the western Indian Ocean [46] are shown to be oblique to the Comores trend. These are thought to have been formed during Madagascar-Africa separation but present seismicity [19] indicates reactivation.

African Rift may be too complex to be modeled by what we understand as simple rigid plate tectonic theory, and that separation is taking place over broad horizontal and vertical dimensions. This is corroborated by the diffuse zone of seismicity, associated with the East African Rift [47], as indicated in Fig. 6.

The hotspot paths predicted by the African absolute motion [3] for the period 10–60 m.y. (Fig. 5) parallel the northern Madagascar–Seychelles and Mascarene Plateau lineaments. When the calculated Somali-African separation during 0–10 m.y. is added, the older portions of the predicted and observed hotspot tracks coincide geometrically. This indicates that no significant relative motion between the Somali and African plates occurred prior to about 10 m.y. ago.

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