Relative and Latitudinal Motion of Atlantic Hot Spots

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Although not all hot spots are fixed with respect to one another, the members of small groups of them seem to be fixed internally.

THE hypothesis that hot spots[1] and their underlying plumes[2] all remain fixed with respect to one another, and perhaps also to the Earth's spin axis and axial dipolar magnetic field, has recently received attention[3–5]. Atwater and Molnar[6] have shown, by rotating plates back to their 13 and 38 m.y. position, that some hot spots (notably Iceland and St Paul/Amsterdam) have probably moved with respect to one another during this time. Using a different approach we present here evidence that during the past 120 m.y. some hot spots have moved significantly with respect to each other and to the magnetic field.

We use the term "hot spot" to describe succinctly a class of localized volcanism and associated uplift characteristically found within plates (Hawaii and Tibesti, for example), but also found on divergent plate boundaries (Iceland, for example). The term is used to describe the surface feature, with no intended implications about processes below the surface, in the same way as the term "island arc" is used. In the ocean a hot spot trace is a volcanic ridge or line of seamounts which leads away from a hot spot and which is considered to have been progressively generated as the plate moved relatively over or away from the underlying source of the hot spot. Where a hot spot occurs on a spreading ridge axis, a trace is generated on each plate. The former presence of a hot spot on continental crust is expressed by relatively localized alkaline volcanic piles or subvolcanic alkaline intrusives, sometimes accompanied by more extensive flood basalts. The former position of a hot spot at any time in the past is marked by the point of that age on its trace.

Misfit

Figure 1 is a reconstruction of the Atlantic ocean and its surrounding continents about 120 m.y. ago[7], and five selected Atlantic hot spots which possess comparatively well defined traces are plotted on it at the positions that they occupied at that time. If hot spots stay fixed with respect to each other, it should be possible to superimpose the same hot spots in their present relative positions on their positions 120 m.y. ago. It is not possible to do this, and the misfit is conveniently represented by keeping one hot spot fixed, and plotting the others in their present positions relative to it. We have chosen to keep the Colorado Seamount hot spot fixed for the purposes of illustration, as it has a trace on the North American plate, and the reference frame on Fig. 1 is with respect to present North America. Although the Azores hot spot does plot at the relative position it occupied 120 m.y. ago, the three others shown from the South Atlantic fall about 20° beyond their positions at that time. This indicates that relative motion between them and the two northern hot spots has occurred at an average rate of 1.8 cm yr^{-1} during the past 120 m.y., in a direction approximately perpendicular to the general direction of relative plate motion.

Data used to plot the hot spot positions on Fig. 1, and for subsequent parts of this paper, are listed in Table 1. The positions of the two northern hot spots at 120 m.y. ago were picked from maps of seafloor age in the central Atlantic[7,8]. A certain amount of interpolation has been necessary for the Colorado Seamount hot spot traces. The early part is well defined only on the western side, and the later part only on the eastern side of the Mid-Atlantic ridge, but the age ranges of the partial traces overlap, so the interpolation is valid. Some authors (for example ref. 9) prefer to generate the New England (Kelvin) and Corner Rise seamounts from the Azores hot spot. We do not favour this, because partial closure of the central Atlantic by appropriate rotations[8] connects the Corner Rise seamounts with a point of the same age on the trace of seamounts running east from Colorado Seamount.

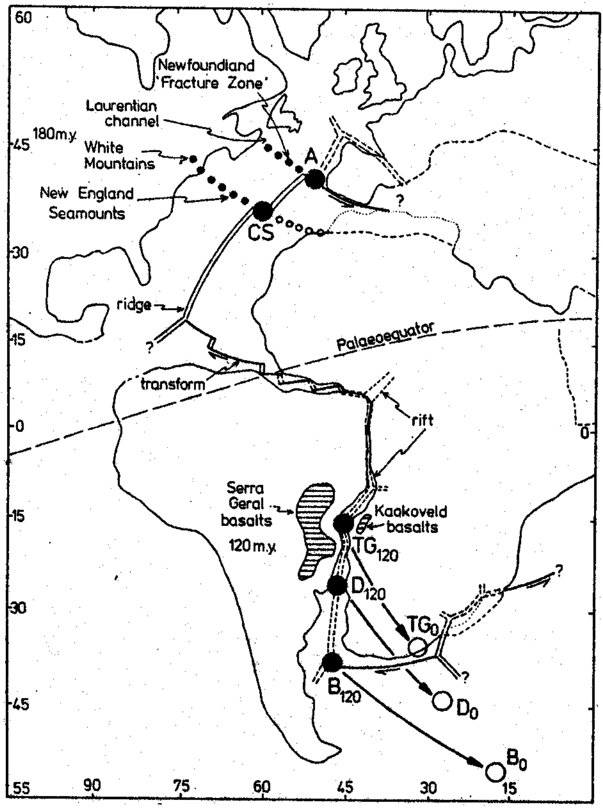

Fig. 1 Sketch of configuration of Atlantic continents, with schematic plate boundaries, for about 120 m.y. ago (from ref. 7); reference frame fixed to North America. ●, Positions of five hot spots at this time as given by their traces; •, earlier parts of traces of the two northern hot spots; ○, an interpolated older trace (see text); ○, present positions of the southern hot spots relative to Colorado Seamount hot spot kept fixed at its position relative to North America 120 m.y. ago. A, Azores; CS, Colorado Seamount; TG, Tristan da Cunha/Gough; D, Discovery Seamounts; B4, Bouvet. Large arrows indicate total motion of the three southern hot spots between 120 m.y. ago and the present relative to Colorado Seamount hot spot. Palaeoequator is around average pole at 69° N 180° W with respect to North America.

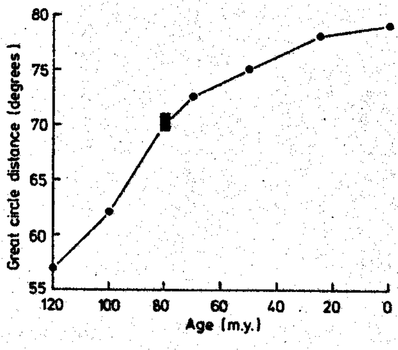

Fig. 2 Great circle motion between Colorado Seamount and Tristan/Gough hot spots during the past 120 m.y.

The relative motion between the five hot spots is set out in Table 2, showing in quantitative form what we show diagrammatically in Fig. 1. The large motion between the two groups of hot spots is clear, but there does not appear to have been significant motion between the hot spots in each group.

Relative Motion

The average rate of relative motion between the two groups has been about 1.8 cm yr^{-1}, but this rate has not been constant. Points representing particular ages on the traces from Colorado Seamount and Tristan/Gough can be picked from maps of seafloor age in the central[7,8] and

Table 1 Position and Palaeolatitude Data for Some Atlantic Hot Spots

Hot spot	Trace	Position of hot spot 120 m.y. ago	Present coordinates of hot spot	Present coordinates of hot spot position 120 m.y. ago	Palaeolatitude of position of hot spot 120 m.y. ago	Palaeolatitude of position of hot spot 180 m.y. ago
Azores	Newfoundland Ridge (or "Fracture Zone"); (eastern trace in tectonized area)	South-east corner of Grand Banks	38° N 27° W	41.5° N 48° W	26° N	29–30° N
Colorado Seamount	New England Seamounts; Corner Rise Seamounts; ill defined to present Mid-Atlantic Ridge	South-eastern New England Seamounts on Bermuda discontinuity	34° N 37.5° W	36.5° N 59° W	25° N	25–27° N
Colorado Seamount	Interpolated from continental margin to Great Meteor Seamount; Cruiser Seamount–Mid-Atlantic Ridge	Just west of Azores—interpolated	34° N 37.5° W	29° N 19° W	25.5° N	
Tristan da Cunha	Rio Grande Rise	Florianapolis	37° S 12.5° W	27° S 48° W	29° S	
Gough Island	Walvis Ridge	Cape Fria	40° S 10° W	18.5° S 11.5° E	30° S	
Discovery Seamounts	Poorly defined line of seamounts	Luderitz	47° S 6.5° W	27° S 14° E	39° S	
Discovery Seamounts	None known except one seamount just off continental margin	East of Montevideo	47° S 6.5° W	35.5° S 53° W	38° S	
Bouvet Island	Meteor Seamount chain	South of Cape Agulhas	54.5° S 3.5° E	35° S 18° E	48° S	
Bouvet Island	North Falkland Plateau; ill defined to east	South-west Argentine Basin—interpolated	54.5° S 3.5° E	45° S 59° W	48.5° S	

southern[10,11] Atlantic. This identification of the age points along the two traces assumes that the two hot spots have stayed approximately on the axis of the spreading ridge, and is justified because hot spot traces extend away on both sides of the spreading ridge. Data are given in Table 3 and the change in great circle distance with time is shown in Fig. 2. Although the shape of the curve showing the relative motion is crudely exponential, we do not attach significance to this, since it only concerns the motion between two of many hot spot groups. We think, however, that the variations in the rate of motion are significant, and this rate has varied between about 5 cm yr^{-1} (100 to 80 m.y.) and about 0.5 cm yr^{-1} (25 to 0 m.y.). It is intriguing that the time of maximum rate of relative motion coincides with a time of world wide accelerated spreading rates[7], but we have not been able to confirm this correlation for any other hot spots.

We take the Mascarene/Chagos-Laccadive Ridge and most of the Ninety-East Ridge to have been produced during the past 65 m.y. by the two hot spots now at Mauritius/Réunion and St Paul/Amsterdam Islands respectively. Tentative age data at two places along each of these traces[12,13] suggest that at present these two hot spots have the same separation as they had 65 m.y. ago (about 25°), but that their separation was slightly greater (about 29°) 25 m.y. ago. No significant motion between the Mauritius/Réunion and the Tristan/Gough hot spots can be detected for the past 12 m.y. (ref. 14); the motion between 12 m.y. and 65 m.y. ago must amount to about 6° towards each other, on the basis of established plate motions[15].

Ideally, palaeomagnetic data can be used to establish how the relative motion between the hot spots has been distributed with respect to the magnetic field and by inference to the spin axis. We have estimated average palaeomagnetic poles for various plates at particular times from data contained in a recent compilation[16]. We used only non-redundant poles in reliability category *A*, and only if the age of any pole is well defined to within 10 m.y. of the age required (exceptionally 20 m.y. for the 180 m.y. and 120 m.y. ages), and we excluded poles from areas that may have suffered subsequent tectonic displacement. As

Table 2 Great Circle Distances between Hot Spots

Hot spots	180 m.y.	120 m.y.	Present		Difference between 120 m.y. and present
Azores–Colorado Seamount	10	10	9		−1
Colorado Seamount–Tristan da Cunha	—		75.5		
		57		77	+20±2
Colorado Seamount–Gough Island	—		79		
Gough Island–Discovery Seamounts	—	9	(7 to) 10.5		−2 to +1.5
Gough Island–Bouvet	—		16.5		−2.5
		19		18.5	−0.5
Tristan da Cunha–Bouvet	—		20.5		+1.5
Discovery Seamounts–Bouvet	—	9.5	10		+0.5

All measurements in degrees (1 degree ≈ 110 km).

Table 3 Increments of Motion between Tristan/Gough and Colorado Seamount Hot Spots

Age (m.y.)	Present coordinates of hot spot position at ages given				Great circle distance (degrees)	Rate of motion cm yr^{-1}
	Walvis Ridge–Gough		Colorado Seamount eastwards			
120	18.5° S	11.5° E	29° N	19° W	57	
						2.8
100	25° S	6° E	29–29.5° N	23–24° W	62	
						4.1 to 5.0
80	32° S	2° E	30–31.5° N	29° W	69.5–71	
						1.6 to 3.3
70	34° S	3° W	32.5° N	30° W	72.5	
						1.4
50	36° S	5.5° W	33° N	32° W	75	
						1.3
25	40° S	10° W	34° N	35° W	78	
						0.44
0	40° S	10° W	34° N	37.5° W	79	

Table 4 Average Palaeomagnetic Poles

Plate	180	120	Age (m.y.) 65–60	50	25
Africa	67.5° N 104° W	55° S 74° E	—	—	90° N
North America	72.5° N 94° E	69° N 180° W	(77° N 114° E ?) 85° N 163° W (ref. 5)	—	—
South America	—	83.5° S 113° W	—	—	—
India	—	—	32° S 100° E	—	—
Indo-Australia	—	—	—	70° S 54° E	76° S 89° E
Eurasia	—	—	77° N 150° E?	—	?

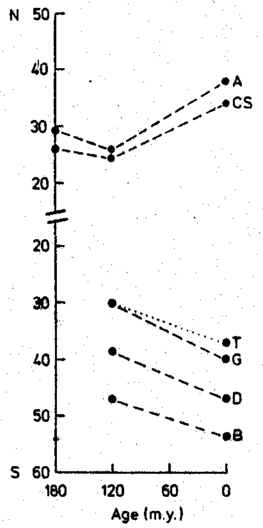

Fig. 3 Latitudinal motion between five Atlantic hot spots during the past 180 m.y. Letters identifying hot spots are as in Fig. 1.

the poles selected have restricted age ranges, any possible polar wandering as distinct from plate motion can be neglected for each age (but not between). Known plate rotations[8,15,17,18] can then be applied to the groups of poles of each age, and a combined pole defined, which can then be similarly rotated to give a consistent result for each plate.

Palaeolatitudes derived from the average pole for 180 m.y., and perhaps the other average poles, may have errors larger than the differences we are attempting to detect as the selected data scatter over significant areas, up to 15 to 20° across. But as the average poles for 180 and 120 m.y. have been selected and then deliberately rotated so as to be compatible with total subsequent plate motion for those plates involved, palaeolatitudes derived from them may be more reliable than those obtained from separate average poles for each plate, which do not coincide when subsequent plate motion is removed. The average palaeomagnetic poles given in Table 4 should be regarded as present estimates, and only for the restricted age ranges given. No motion of the African plate with respect to the dipole field is required by the palaeomagnetic data for the past 25 m.y. (ref. 19).

Seventeen poles for the Eurasian plate 60 m.y. ago are almost all closely grouped, but the average pole they define is not compatible with an average pole for North America[5] when the appropriate North Atlantic motion[8] is removed (Table 4, in brackets). Three poles in the Eurasian group plot 20° away from the main group, and their position is more compatible with the North American pole. In view of this uncertainty, we have not used the 60 m.y. poles to define palaeolatitudes for the Atlantic hot spots, as the error is potentially as much as 20°. Phillips and Forsyth[20] have previously discussed this discrepancy.

Palaeolatitudes derived from average poles are probably of variable reliability and only relatively small changes in one or more of the average pole positions may make a great deal of difference to the inferred motion of particular hot spots with respect to the magnetic field and the spin axis. The palaeolatitudes we derive show that all the hot spots have moved differing amounts with respect to the magnetic field for at least some parts of the last 120 m.y., but the precise amounts for each hot spot we regard as less certain.

Palaeolatitudes of the Atlantic hot spot positions 120 m.y. ago, and for the two northern hot spots at 180 m.y. ago, are given in Table 1. The discrepancies between the palaeolatitudes at 120 m.y. and the present latitudes of the hot spots are set out in Table 5, and shown graphically in Fig. 3. First, the results show that the total motion between the two groups of hot spots with respect to latitude is nearly as great as their motion with respect to each other during the past 120 m.y., indicating that aggregate relative longitudinal motion has been subordinate, at least for these particular hot spots (see also Fig. 1). Second, each group of hot spots has moved an approximately equal distance away from the equator toward the poles of their respective hemispheres. Duncan and others[3] showed that Eurasian palaeomagnetic data for 60 m.y. ago can be interpreted as indicating a large northward motion of the Iceland hot spot (about 20°) since this time. In view of the uncertainty in the palaeomagnetic data, we would suggest that although relative northward motion of this hot spot is probable, the amount of motion may be more modest. We estimate from known plate motions[8], allowing for uncertainty across the Labrador Sea, that the Iceland hot spot has not moved more than 5° away from the Azores and Colorado Seamount hot spots during the past 60 m.y. On the basis of the North American average palaeomagnetic pole[5], this indicates no more than about 8° of northward motion of the Iceland hot spot during this time.

Table 5 Latitudinal Motion of Hot Spots

Hot spot (trace east or west)	Latitude/palaeolatitude change from 120 m.y. to present	Differences between hot spots (degrees)
Azores (W)	12° N	+3 to +3.5
Colorado Seamount (W)	9° N	
Colorado Seamount (E)	8.5° N	
Gough (E)	10° S	+16.5 to +19
Discovery Seamount (E)	8° S	0 to −2
Bouvet (E)	6.5° S	−1.5 to −3
Tristan da Cunha (W)	8° S	—
Discovery Seamount (W)	9° S	—
Bouvet (W)	6° S	—

More Hot Spots

We have attempted to extend this study to the two hot spots of Mauritius/Réunion and St Paul/Amsterdam Islands. The palaeomagnetic data perhaps suggest that Mauritius/Réunion has moved northwards about 10° in the past 65 m.y. and that all or almost all of this relative motion occurred before 25 m.y. ago. On the same basis St Paul/Amsterdam has moved northwards about 16° since 65 m.y. ago. If a very tentative estimate is made of its position 50 m.y. ago, extrapolating from a point suggested to be 45 m.y. old[13] and using the Australian palaeomagnetic pole, it is possible that the overall relative northward motion of this hot spot may have reversed for a while between 50 and 25 m.y. ago.

The only other hot spot for which data are available is Hawaii; the palaeomagnetic data cannot resolve any motion of this hot spot in the past 70 m.y. (ref. 4), but the equatorial sedimentation data[4] perhaps suggest it has moved slightly southwards[21], perhaps up to 5° in the past 40 m.y. By implication, the other hot spots on the Pacific plate which seem to be approximately fixed with respect to Hawaii[2,4] may be moving in a similar manner.

McElhinny[5] showed that the apparent motion of the Iceland hot spot with respect to the magnetic field[3] is more likely to be due to relative motion between hot spots than to a rotation of the mantle containing fixed plumes with respect to the lithosphere as a whole[3,22]. Our conclusion that some groups of hot spots have moved significantly with respect to each other confirms this suggestion. The rate of motion between two small groups of hot spots is comparable with rates of plate motion, and has varied by an order of magnitude over the past 120 m.y.; the maximum rate of separation for these two groups appears to coincide with a temporary global increase in spreading rates[7]. The two or three hot spots within each of these two groups do not, however, seem to have moved significantly with respect to their partners for the maximum lengths of time that they can be observed (180 and 120 m.y.). While moving apart and remaining essentially fixed internally, the two groups of Atlantic hot spots seem to have rotated somewhat relative to one another (Fig. 1). Differential motion of hot spots with respect to the magnetic field and spin axis occurs and for the few hot spots we have studied it seems to have been predominantly in a poleward direction, though not all seem to move toward the pole of the hemisphere in which they occur. The poleward motion may also be intermittent, and even reversible. Data from other hot spots are desirable, but it is unfortunate that although there are many hot spots[23], there are few, if any, others that have clearly marked traces with well defined ages along them and that can be observed for comparable periods of time to those in the central and southern Atlantic.

Satisfactory Hypothesis

We think that the idea that deep mantle plumes[2,24] underlie hot spots is at present the only satisfactory hypothesis available to account for hot spots, especially to explain their persistence as discrete localized anomalies, in some cases for 180 m.y. This is particularly the case for those hot spots which are on the axes of spreading ridges, and which have remained so for long periods; these are epitomized by the hot spots on the axis of the central and southern Mid-Atlantic Ridge. Although these hot spots have moved with respect to one another, and to the position of the spreading ridge at 120 m.y. ago (Fig. 1), they are still on, or near[14], the axis. The jumping of a restricted length of spreading ridge axis is probably a related phenomenon, and in several cases this is clearly associated with hot spots. It may occur repeatedly in a consistent direction, and this leads to apparent asymmetrical spreading[25]. Examples of ridge axis jumping occur at the Galapagos[26,27], St Paul/Amsterdam Islands[15], south of Australia[25], and in Iceland[28]. The inference we make is that whatever is under the hot spots controls the position of the ridge, and not the reverse; the presence of underlying deep mantle plumes seems to us the only available hypothesis that will account for this.

We suggest that within small groups of hot spots, the hypothesis that they are fixed with respect to one another may be valid, especially for short periods of a few tens of millions of years, but which hot spots belong to a particular internally fixed group may be hard to prove. The hypothesis that all hot spots are fixed with respect to one another and form an independent global reference frame is, however, clearly not valid.

The groups of hot spots that we have shown to remain essentially fixed internally have an approximate maximum horizontal dimension of 2,000 km. This is of the same order as the large swells that occur in East Africa and the Red Sea area, which are about 1,500 km across. We interpret the pattern of alkaline volcanism on abrupt topographic and structural uplifts each about 200 km across within these swells as showing the presence of four or five hot spots in each swell. The Cameroon zone also defines an ellipse about 1,500 km across and contains at least six discrete hot spots on uplifts, although a large overall topographic swell is not present. Apart from these examples, it is difficult to make a similar grouping of many of the remainder of the 120 hot spots we recognize, although some tentative suggestions can be made. Menard[29] has recently demonstrated the occurrence of low amplitude positive topographic anomalies 1,000 to 2,000 km across, and without obvious associated hot spots, in the North-east Pacific. We point out that similar large swells without associated hot spot volcanism are especially prominent in southern Africa, although the amplitude of these features is larger, and all but one are in continental lithosphere.

It may be that the large scale swells and internally fixed groups of hot spots reflect conditions at a depth comparable to their horizontal dimensions, and that the smaller uplifts and hot spots, of which there might be only one in some large swells (Hawaii?), reflect conditions at shallower depths. We speculate that the large swell may represent a broad, very slowly upwelling column, and that the smaller uplifts and hot spots within them represent smaller, more strongly heated and more rapidly rising columns within the large slowly rising column. The implications of the poleward motion of the few hot spots we have examined are not clear to us, and we think speculation on this is perhaps unjustified until well distributed data from other hot spots become available. If it is accepted that deep mantle plumes[2,24] underlie hot spots, then information relating to processes at the core-mantle boundary, and perhaps in the core, might eventually be extracted from the distribution and relative motion of hot spots. Our observations of the motion of some hot spots during the past 120 m.y. indicate that, if hot spots relate to mantle convection, this convection is probably highly complex and perhaps unlikely to be successfully modelled in terms of a small number of Rayleigh-Benard cells.

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