Relative Motion of Hot Spots in the Mantle

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Reconstruction of the major lithospheric plates 21 and 38 m.y. ago implies that linear island chains and aseismic ridges were not generated by localised sources of volcanism (hot spots) that have been fixed with respect to one another. If the linear volcanic chains are formed over mantle hot spots, the spots move at rates of 0.8 to 2 cm yr^{-1} with respect to one another.

CAREY[1] suggested that many of the aseismic ridges observed on the ocean floor are manifestations of hot spots in the mantle and assumed, as Dietz and Holden[2] did later, that these aseismic ridges could be used in reconstructions of continents earlier in the Cainozoic. Wilson[3,4] further suggested that they were generated as the seafloor moved over localised zones of upwelling that are fixed with respect to one another in the mantle beneath the asthenosphere. Morgan[5,6] attributed the hot spots to convective plumes rising from the lower mantle. We explore here the assumption that the hot spots are fixed with respect to one another and therefore define a reference frame with respect to which the plates move.

Reconstruction of Plates

One test is to examine the relative positions of the major plates at some time in the past and locate one of them properly over its hot spots. If all the hot spots are fixed with respect to one another, then they should all underlie the linear volcanic chains that they generated. Minster *et al.*[7] used inversion techniques to obtain a refined version of recent relative plate motions, and made a preliminary test by comparing the trends of linear volcanic chains with those predicted. They found no observable relative motion of the hot spots during the past few million years. Because changes in spreading rates occurred between about 5 and 20 m.y. ago at nearly every major spreading centre in the oceans, their instantaneous velocities are probably not useful for periods earlier than 10 m.y. ago.

The relative positions of pairs of plates at different times earlier in the Cainozoic have been reconstructed in the North Atlantic Ocean[8], in various parts of the Indian Ocean[9–11], and in the South Pacific[12]. Spreading in the South Atlantic has been relatively constant, so that Le Pichon's[13] original pole and angular velocity are probably sufficient for our purposes. These studies allow one to interrelate the motions of all the major plates.

We reconstructed the plates to their positions with respect to one another at different times in the Cainozoic. Then, assuming the Hawaiian-Emperor chain to be the expression of the motion of the Pacific Plate over the Hawaiian hot spot, we rotated the Pacific Plate along with the reconstruction of the other plates to their positions with respect to the Hawaiian hot spot. The reasons for constraining the reconstructions to agree with the inferred relative positions of the Pacific over the Hawaiian hot spot are: (1) using other island chains in the Pacific Ocean the pole of relative motion between the Pacific Plate and the hot spots can be well determined; (2) the dating of islands along the chain is more complete than along any other; and (3) there is more complete agreement that the Hawaiian Islands were generated by a hot spot than for most of the other suggested ones. If the other hot spots did not move with respect to the Hawaiian spot, then for each of these reconstructions the linear volcanic chains should overlie the hot spot that generated them.

We considered the hot spots and linear volcanic chains listed in Table 1. These were selected because they are among the more popular ones and they have a balanced geographical distribution. We recognise that there is no unanimity as to what constitutes a well defined hot spot.

We made reconstructions for 21 and 38 m.y. ago. For earlier times, the data are not yet adequate to reconstruct the major plates reliably. For 21 m.y. we used reconstructions to anomaly 6 in the Pacific, South-east Indian and South Atlantic oceans and interpolated between earlier and later reconstructions in the North Atlantic and North-east Indian Ocean. Assuming the age of Midway Island to be 18 m.y.[14], the position of the inferred Hawaiian hot spot with respect to the Hawaiian chain 21 m.y. ago is relatively

Table 1 Hot Spots and Volcanic Chains

Hot spot	Linear volcanic chain	Fig.
Hawaii	Hawaiian Islands	1
Gough Island and Tristan da Cunha	Walvis Ridge and Rio Grande Rise	2
Réunion	Mauritius Plateau and Chagos–Laccadive Ridge	3
Kerguelen	Ninety East Ridge	4
St Paul's and Amsterdam Island	Ninety East Ridge	4
Iceland	Greenland–Iceland and Iceland–Faeroes Ridges	5
Yellowstone	Snake River Basalts	1

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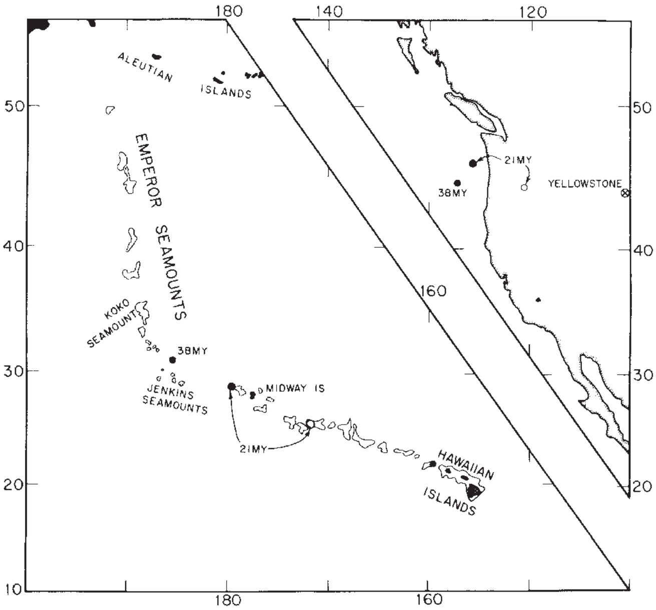

Fig. 1 Left, Hawaiian-Emperor chain and positions of the Hawaiian hot spot at the present and at 21 and 38 m.y. ago. Position at 38 m.y. ago is based on the age of Koko seamount[15]. Two estimates for 21 m.y. ago assume: ●, Jackson *et al.*[14] date of Midway or, ○, constant rate of Pacific motion over hot spot. ⊗, Present position of hot spot. Right, calculated position of Yellowstone hot spot with respect to North America at 21 and 38 m.y. ago.

well defined (Fig. 1). Assuming that the hot spots are fixed with respect to each other, the reconstructed positions of the plates at 21 m.y. show that, except for the Ninety East Ridge, the other hot spots do not underlie the aseismic ridges generated by them (Figs 2 to 5). If the 18 m.y. age of Midway approximately dates the passage of the Hawaiian hot spot, that spot cannot be fixed with respect to the others[7].

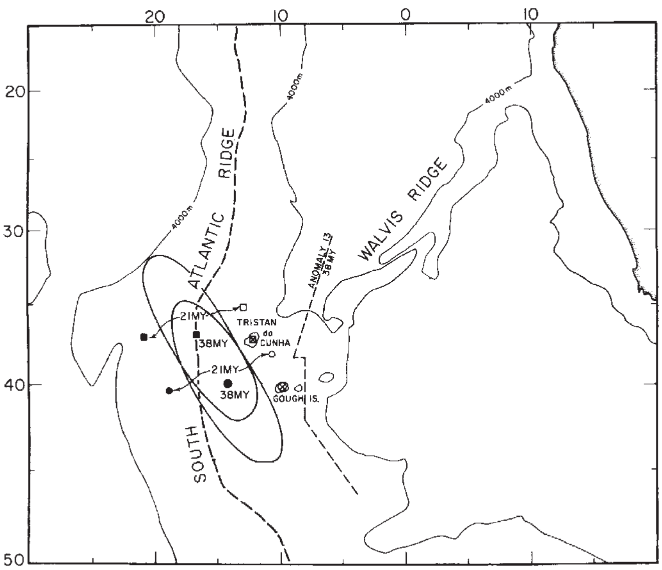

Fig. 2 Relative positions of hot spots under Gough Island and Tristan da Cunha with respect to the African Plate. Symbols as for Fig. 1. Confidence oval surrounds position for 38 m.y. ago. If fixed to the Hawaiian hot spot, the two proposed hot spots should underlie the Walvis Ridge beneath material older than 21 m.y. and 38 m.y. The calculated positions lie beneath material that had not yet been formed at these times. Therefore, at these times, they lay beneath the South American Plate, south of the Rio Grande Rise. They could not have generated these rises and also been fixed to the Hawaiian hot spot.

In view of the possibility that the Midway age does not date the formation of the island, we decided to explore the possibility that the rate of motion has been constant for 42 m.y. during the entire formation of the Hawaiian chain (Fig. 1). Although the disagreement is less than for the case above (open circles in Figs 2 to 5), the calculated positions of the other hot spots still do not lie under the traces presumed to be generated by them. Because of the various interpolations involved in the 21 m.y. reconstruction, this conclusion is, however, not inescapable.

The reconstructions for 38 m.y. ago provide a more definitive test. Dating of Koko seamount[15] constrains the Hawaiian-Emperor bend to be about 42 m.y. old[16]. Anomaly 13, a prominent magnetic anomaly used in the reconstructions of most oceans, was formed approximately 38 m.y. ago. Thus the uncertainties both in the relative positions of the major plates and in the assumed position of the Pacific Plate with respect to the Hawaiian hot spot are likely to be smaller than for other times. The relative

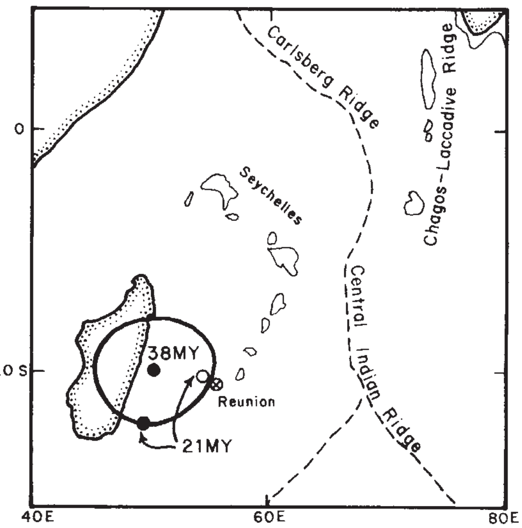

Fig. 3 Relative position of the hot spot under Réunion with respect to the African Plate. Symbols same as Figs 1 and 2. The Mauritius Plateau and the Chagos-Laccadive Ridge were continuous 38 m.y. ago[9,10]. If this hot spot generated the Mauritius Plateau, and the Chagos-Laccadive Ridge on the Indian Plate, and fixed with respect to the Hawaiian hot spot, it should lie beneath the Mauritius Plateau north-east of Réunion. It does not.

positions of the hot spots and their associated linear island chains at 38 m.y. are shown in Figs 2 to 5. Except for the possibility that a hot spot beneath Kerguelen generated the Ninety East Ridge, the calculated positions of the spots are not coincident with the chains presumed to be generated by them. If the hot spots formed these chains, they have moved 300 to 800 km with respect to the Hawaiian hot spot, that is, at rates of 0.8 to 2 cm yr^{-1}. These rates are comparable with those for relative motions of most of the plates, although they are significantly slower than those in the Pacific.

Uncertainties and Assumptions

The uncertainties in the reconstructions result from two sources: errors in individual reconstructions and validity of the assumptions. Both are difficult to evaluate. One may gain a crude, upper limit for the reconstruction errors in the following manner. The uncertainties in the positions of the poles matter very little except that they are coupled to uncertainties in the angles of rotation. The uncertainties in the angles are not likely to be greater than 1° (perhaps

2° for the Pacific hot spot rotation). Thus at the equator for each rotation, an error of about 100 km could result. For example, the position of Gough Island with respect to Africa requires four rotations (Africa→India→Antarctica→Pacific→Hawaiian hot spot). The maximum uncertainty would be about 400 km. As Gough Island does in fact lie near the equator of each of the four rotations, this estimate is a reasonable upper limit. The motion of the Iceland hot spot with respect to the North American Plate involves five rotations (North America→Africa→India→Antarctica→Pacific→Hawaiian hot spot). In three of these (the first one and the last two), the pole of rotation is near Iceland. Thus the error in relative position should be considerably less than 500 km.

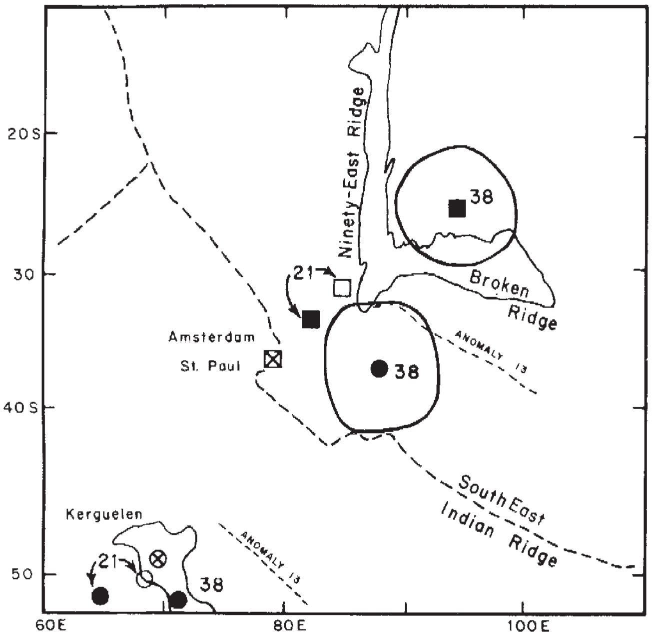

Fig. 4 Relative positions of hot spots beneath St Paul's and Amsterdam Islands with respect to the Ninety East Ridge on the Indian Plate (squares); and of Kerguelen hot spot with respect to the Kerguelen Plateau on the Antarctic Plate (circles) and with respect to the Indian Plate for 38 m.y. ago (closed circle with confidence oval). Symbols as in Figs 1 and 2. If either of these hot spots had generated the Ninety East Ridge and were fixed with respect to the Hawaiian hot spot, it should lie between the Ninety East Ridge and Kerguelen 21 and 38 m.y. ago. If a hot spot exists beneath Kerguelen and generated the Kerguelen Plateau, it should have lain beneath it during the past 38 m.y. The data do not rule out the possibility that a hot spot beneath Kerguelen, fixed with respect to Hawaii, could have generated both of these features. No such feature beneath St Paul's and Amsterdam Islands could have produced the Ninety East Ridge.

Since the above error estimates tend to be excessive, we performed a more realistic calculation. We were not able to treat the uncertainties in a statistically rigorous manner, so we simply estimated the maximum uncertainty in each of the finite rotations and explored the range of possible combinations of them. This procedure allowed determination of ovals describing the largest possible errors in the relative positions of the hot spots with respect to the plates. These ovals are shown in Figs 2 to 5 for the reconstructions for 38 m.y. ago. They show that the relative motion of any given hot spot with respect to the Hawaiian hot spot can be reduced by about a factor of two. Because the uncertainties are not independent, it is not, however, possible to reduce all of the motions this much.

Apart from assuming the Vine-Mathews hypothesis to be correct so that given anomalies on opposite sides of a

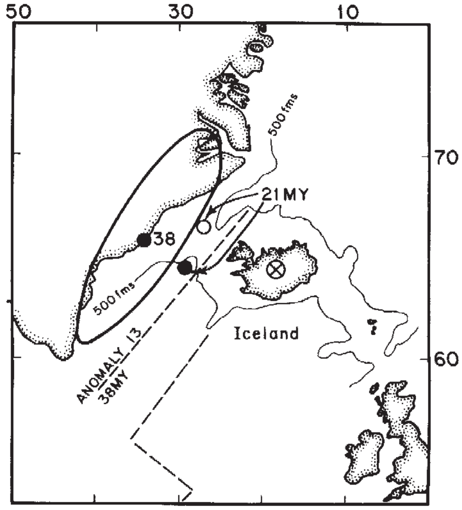

Fig. 5 Relative positions of a hot spot beneath Iceland with respect to the North American Plate. Symbols as in Figs 1 and 2. If the ridges between Greenland and Iceland and between Iceland and Europe were produced by a hot spot beneath Iceland, it would have been centrally located with respect to Greenland and Europe during the past 38 m.y. When fixed with respect to Hawaii, it is found to have underlain the North American Plate during this time, and therefore could not have generated the Iceland–Faeroes Ridge.

spreading centre were formed at the same place, the crucial assumption is that the plates are rigid. There seems to be no reason to doubt this in the oceanic areas. We neglected deformation along the East African Rift, because it is much smaller than the uncertainties discussed above. The possibility of deformation in Antarctica is difficult to eliminate. Motion between East and West Antarctica has occurred since the Jurassic[17–19] and seems to have continued into the Cainozoic[12]. The reconstruction of the South-West Pacific Ocean at 38 m.y. does not require younger deformation[12], so we assume that Antarctica has behaved rigidly since then. In any event, if deformation has occurred since 38 m.y. ago in the same sense as earlier, it seems that the resulting relative positions of the hot spots and associated linear chains would differ even more than shown in Figs 2 to 5.

Perhaps the strongest justification for the reconstructions used here comes from the estimated relative position of the Pacific and North American plates, for 38 and 29 m.y. (ref. 20). These reconstructions place the extinct Pacific-Farallon spreading centre a few hundred km west of North America at 38 m.y. ago, and within 200 km of the coast 29 m.y. ago. These calculated positions agree well with those inferred from the magnetic anomalies in the Pacific Plate west of California[21,22] and their differences are far less than the maximum uncertainties cited above.

We carried out one other check. If there was some unknown deformation within one of the plates or if the reconstruction between one pair of plates was grossly in error, and if the hot spots were fixed, then an additional, arbitrary rotation exists that when added into the sequence of rotations would allow all of the aseismic ridges to overlie their respective hot spots. To carry out such a search rigorously is expensive and tedious. But a manual examination using a globe revealed no such arbitrary rotation. For instance, rotations that caused the Iceland hot spot to lie beneath the Iceland-Faeroes ridge invariably left the Walvis Ridge far north of the hot spot inferred to lie at present beneath Gough Island or Tristan da Cunha.

Implications for Plate Motion

If the hot spots are fixed with respect to each other, what does this imply for plate motions and the origin of linear volcanic chains? First[7], it requires that Midway be considerably older than the date given by Jackson *et al.*[14]. Second, more than one of the pole positions and finite rotations used here must be grossly in error. Third, there must be a large internal deformation within Antarctica since 38 m.y. ago, in some sense different from that calculated to have occurred earlier in geological time[12]. We consider a simpler interpretation to be that the hot spots do not define a fixed reference frame, that the Hawaiian hot spot moves at velocities with respect to the others that are comparable to the velocities of relative plate motions, and that the others also move with respect to one another. Burke *et al.*[23] reached a similar conclusion concerning motions among the various Atlantic hot spots since the Cretaceous, and McElhinny[24] concluded that hot spots could not be fixed both with respect to one another and to the spin axis of the Earth. Although relative motion of the hot spots of the magnitude suggested here does not prove that plumes do not exist, it does refute one of the most appealing aspects of the idea: a fixed reference frame with which to describe the motions of the plates; and it removes a strong impetus for placing their origin in the lower mantle.

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Sequence of Events in Plasma Membrane Assembly during the Cell Cycle

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Major components of the plasma membrane double during interphase. Some minor components also double, but others show fluctuations. Decreased expression by immune cytolysis of H-2 antigenicity during interphase is explicable in terms of decreased membrane fragility. These results are compatible with a model in which plasma membrane assembly occurs throughout interphase and in which cytokinesis is essentially a physical process.

THE importance of the cell surface in biological processes makes knowledge of the mechanism of its assembly highly pertinent. At present, for example, it is not known whether the components are synthesised predominantly during mitosis or during interphase. The development[1–9] of a technique[10,11] of separating cells by size according to their position in the cell cycle has enabled us to make some initial observations[12] on the assembly of cellular membranes; we found that the protein, as well as some specific enzymes, of nucleus, mitochondria and endoplasmic reticulum doubles during interphase. A procedure for isolating plasma membrane[13,14] has now enabled us to study the assembly of its components during the cell cycle. An extension of previous observations[15] on the expression of surface antigens provides further support for a model for the assembly of the plasma membrane[16–18].

Ratio of Surface Area to Volume

Like most cultured cells, those used in this study double in volume between G_1 and G_2 (ref. 6). Since they are spherical the surface area increases by a factor of $2^{2/3}$ or approximately 1.6; the extra 0.4 is presumably made up