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Plate Motions and Deep Mantle Convection

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ABSTRACT

A scheme of deep mantle convection is proposed in which narrow plumes of deep material rise and then spread out radially in the asthenosphere. These vertical plumes spreading outward in the asthenosphere produce stresses on the bottoms of the lithospheric plates, causing them to move and thus providing the driving mechanism for continental drift. One such plume is beneath Iceland, and the outpouring of unusual lava at this spot produced the submarine ridge between Greenland and Great Britain as the Atlantic opened up. It is concluded that all the aseismic ridges, for example, the Walvis Ridge, the Ninetyeast Ridge, the Tuamotu Archipelago, and so on, were produced in this manner, and thus their strikes show the direction the plates were moving as they were formed. Another plume is beneath Hawaii (perhaps of lesser strength, as it has not torn the Pacific plate apart), and the Hawaiian Islands and Emperor Seamount Chain were formed as the Pacific plate passed over this "hot spot."

Three studies are presented to support the above conclusion. (1) The Hawaiian-Emperor, Tuamotu-Line, and Austral-Gilbert-Marshall island chains show a remarkable parallelism and all three can be generated by the same motion of the Pacific plate over three fixed hot spots. The accuracy of the fit shows that the hot spots have remained practically fixed relative to one another in this 100 m.y. period, thus implying a deep source below the asthenosphere. (2) The above motion of the Pacific plate agrees with the paleo-reconstruction based on magnetic studies of Pacific seamounts. The paleomotion of the African plate was deduced from the Walvis Ridge and trends from Bouvet, Reunion, and Ascension Islands. This motion did not agree well with the paleomagnetic studies of the orientation of Africa since the Cretaceous; however, better agreement with the paleomagnetic studies of Africa and of seamounts in the Pacific can be made if some polar wandering is permitted in addition to the motion of the plates. (3) A system of absolute plate motions was found which agrees with the present day relative plate

motions (deduced from fault strikes and spreading rates) and with the present trends of island chains–aseismic ridges away from hot-spots. This shows that the hot spots form a fixed reference frame and that, within allowable errors, the hot spots do not move about in this frame.

BASIC MODEL

Let us suppose there is convection deep in the mantle. The arguments presented here do not depend on the depth of such convection—any depth from just beneath the asthenosphere to the core-mantle boundary would suffice—but, for present purposes, let us say such convection extends to a 2,000 km depth. It is common knowledge that such deep convection is improbable due to the efficiency of heat transport by radiation at this depth, but let us explore the possibility of such convection and then come back to the heat flow "proofs" of impossibility. Suppose there are several (approximately 20) plumes of deep mantle rising upward and the rest of the mantle is slowly sinking downward in a pattern analogous to a thunderhead or a coffee percolator. To add concreteness, suppose there are several "pipes" in the rigid middle mantle and that very hot lower mantle is coming upward in these pipes and being added to the asthenosphere. The more rigid middle mantle, including the "walls" of the pipes, is slowly moving downward to fill the void created below in the more fluid lower mantle, and this rigid middle mantle is being added to at its top as the asthenosphere cools and welds itself to the mesosphere. The 400 or 600 km discontinuity may mark this boundary between mesosphere and asthenosphere.

Such a model has the following features. There are about 20 pipes to the deep mantle bringing up heat and relatively primordial material to the asthenosphere (Fig. 1). Within the asthenosphere, there will be horizontal flow radially away from each of these pipes. These points of upwelling will have unique petrologic and kinematic properties, but there will be no corresponding unique downwelling points, as the return flow is assumed to be uniformly distributed throughout the remainder of the mantle. The pattern of localized upwelling without localized downwelling was suggested by the gravity map (Fig. 8, to be discussed later). How will such a flow pattern interact with the crustal plates above? A plate will respond to the net sum of all stresses acting on it (the shear stress acting on its bottom due to currents in the asthenosphere plus the stresses on its sides due to its motion relative to adjacent plates). It appears that the plate-to-plate interactions are very important in determining the net forces on a plate, that is, the existing rises, faults, and trenches have a self-perpetuating tendency. This claim is based on two observations: (1) rise crests do not commonly die out and jump to new locations (Labrador and Rockall are the only places for which the evidence strongly suggests extinct rise crests), and (2) points of deep upwelling do not always coincide with ridge crests (for example, the Galápagos and Reunion upwellings are near triple junctions in the Pacific and Indian Oceans; asthenosphere motion radially away from these points would help drive the plates away from the triple junction, but there is considerable displacement between these pipes to the deep mantle and the lines of weakness in the lithosphere which enable the surface plates to move apart). Also note the toughness of the plates as exemplified by the fact that the upwelling beneath Hawaii has not torn apart the Pacific plate.

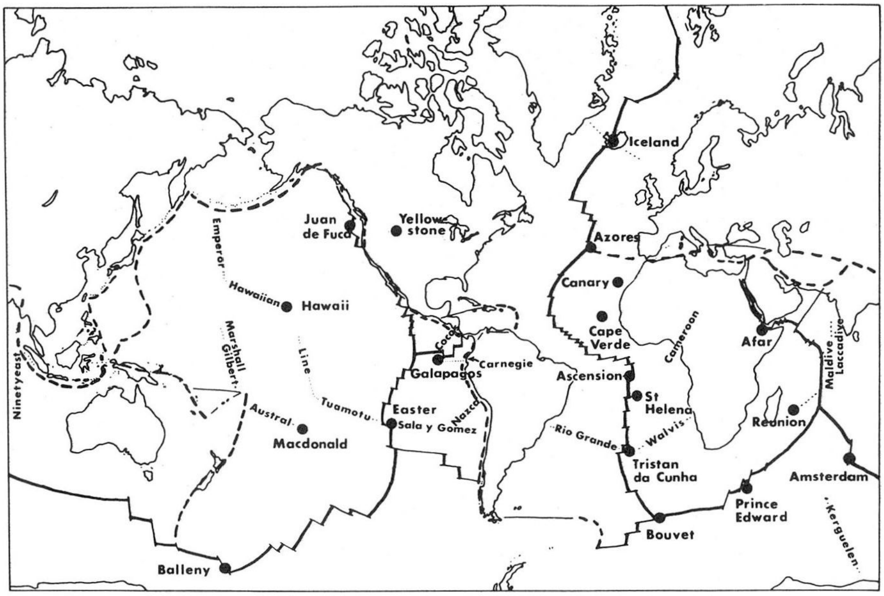

Figure 1. Map showing the locations of the probable hot spots and the names of some features cited in the text.

This model is compatible with the observation that oceanic island basalts are different from oceanic ridge basalts (Gast, 1968). Island type basalts, as on Iceland or Hawaii, would have access to relatively primordial material from deep in the mantle. In contrast, the ridge crests tap only the asthenosphere—the asthenosphere passively rising up to fill the void created as the plates are pulled apart by the stresses acting on them. The oceanic ridge basalts are known to be relatively low in potassium and in some trace elements. We may account for this by claiming that the asthenosphere source has been reworked and cleaned out of lighter elements in previous sea-floor spreading episodes, or that the lighter elements have had sufficient time to migrate upward (to the bottom of the lithosphere) and are not present to rise to the ridge crest where the plates are pulled apart. The oceanic island basalts are rich in potassium and have a rare earth distribution implying more fractionation, in accord with their deep primordial source. If we relate the observed island basalt fractionation to the composition of the parent rock, we should have a new picture of the composition of the deep mantle. Such an estimate will undoubtedly be higher in potassium than those estimates based on ridge basalts. The implied increased estimate of radiogenic heat production is desirable in this scheme, in that the deep convection model requires more heat production at depth than radiative transport alone can cope with.

As the Pacific plate moves over the upwelling beneath Hawaii, the continuous outpouring of basalt from this point produces a linear basaltic ridge on the sea floor—the Hawaiian Islands. Likewise, the excessive flow from Tristan de Cunha has produced the Walvis and Rio Grande Ridges in the South Atlantic. Here we require Africa to drift to the northeast (parallel to the Walvis Ridge) and South America to drift roughly northwest (parallel to the Rio Grande Ridge). Note that the transform faults between Africa and South America trend east-west; the transform faults show the *relative* motion of the African and South American plates, the

Walvis and Rio Grande Ridges show the *absolute* motion of Africa and South America (plus the effects of the migration of the hot spot, to be discussed later).

We assume that all such aseismic ridges are produced by plate motion over hot spots fixed in the mantle. Thus the aseismic ridges indicate the trajectories of the plates over fixed points and we may reconstruct continental positions with both latitude and longitude control, an important addition to paleomagnetic reconstructions. This interpretation of the aseismic ridges and island chains is identical to that presented by Wilson (1963, 1965) except that here we attribute a more fundamental nature to the hot spots—we associate the hot spots with major convection deep in the mantle, providing the motive force for sea-floor spreading.

We shall now examine three aspects of the worldwide pattern of island chains and aseismic ridges consistent with the concept of plate motions over fixed hot spots.

ISLAND CHAINS IN THE PACIFIC

There are only two presently active volcanos in the interior of the Pacific plate, Hawaii and Macdonald Seamount (Johnson, 1970). It has long been noted that the active Hawaiian volcano is at the southeast extreme of the Hawaiian chain and that there is a linear progression of the age of these islands as they become farther from Hawaii (Fig. 2). Johnson has noted that Macdonald Seamount (29.0° S.,

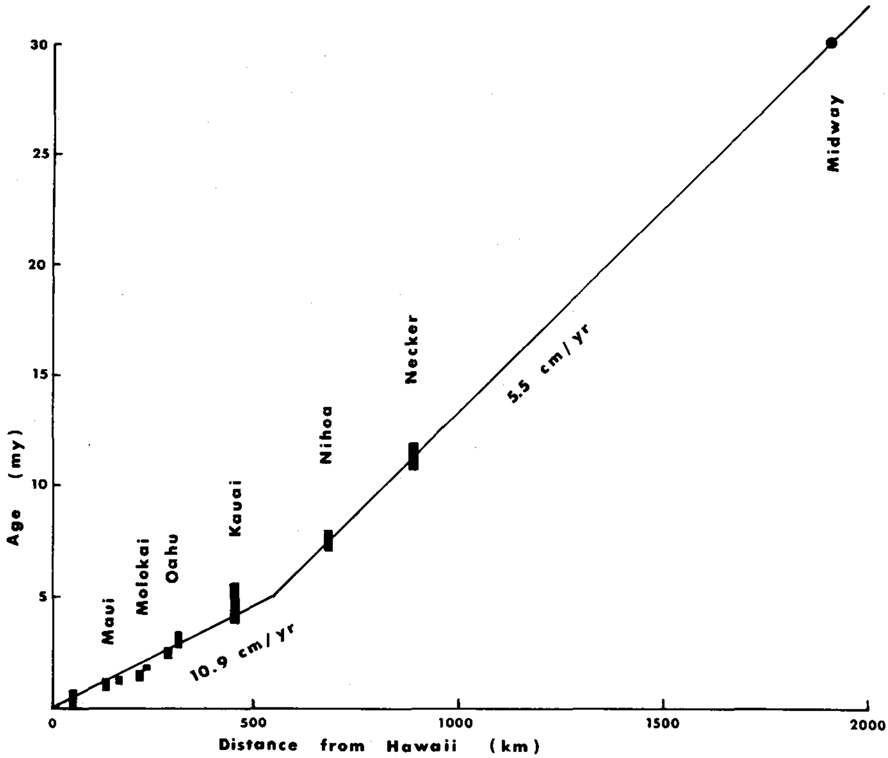

Figure 2. The ages of Hawaiian volcanos versus distance from the presently active volcano at Hawaii. The point at Midway is based on Miocene fossils; the other ages are K-Ar results reported by Funkhouser and others (1968).

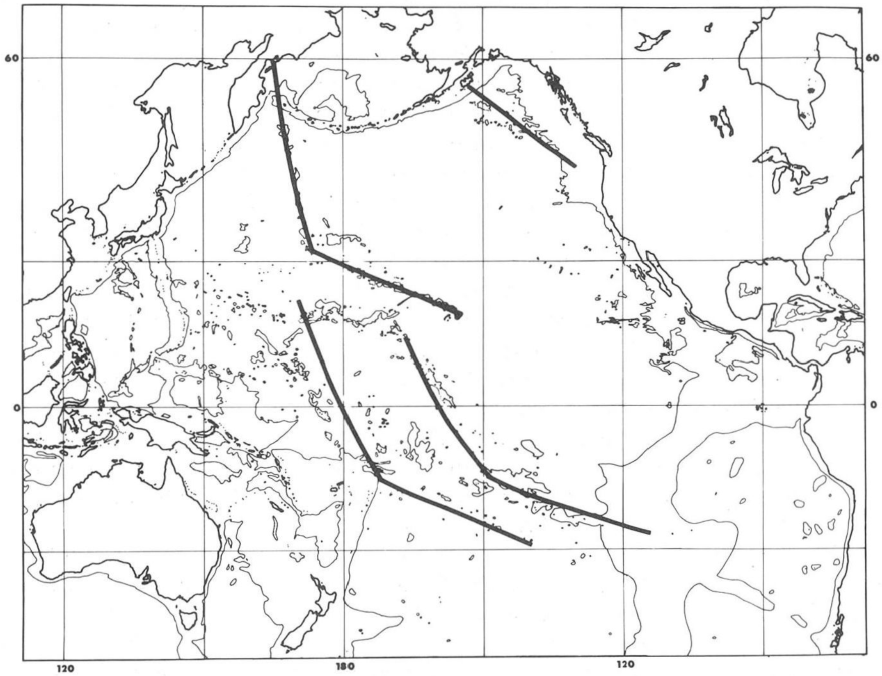

Figure 3. Hot spot trajectories constructed by rotating the Pacific plate 34 degrees about a pole at 67° N., 73° W., and then 45 degrees about a pole at 23° N., 110° W.

140.3° W.) is likewise situated at the southeastern extreme of the Austral Islands chain. Could both of these island chains have been generated by a single motion of the Pacific plate over these two hot spots? The Hawaiian chain is terminated by the Emperor Seamounts; is there an analogous feature for the Austral chain? The answer to these questions is shown in Figure 3. We have assumed three fixed hot spots located at 19° N., 155° W. (Hawaii), at 29° S., 140° W. (Macdonald), and at 27° S., 114° W. (where the East Pacific Rise intersects the Tuamotu and Sala y Gomez Ridges). The solid lines show the points which would pass over these hot spots if the Pacific plate were rotated 34 degrees about a pole at 67° N., 73° W. and then 45 degrees about a pole at 23° N., 110° W. (The fourth solid line in Figure 3, extending from the Juan de Fuca Ridge to Kodiak Island, will be discussed later.) We thus note the similarity of the Hawaiian-Emperor, Tuamotu-Line, and Austral-Gilbert-Marshall chains with the lines generated from present-day active hot spots. In particular, the Marshall-Gilbert Islands do not coincide with the proposed locus of the Pacific over the fixed hot spot. We shall use this to measure the constancy of the fixed spots, but first let us estimate ages along these chains.

We have the rate of recent motion of the Pacific plate past the fixed points from the K-Ar ages of the Hawaiian Islands shown in Figure 2, and we see that the rate may be variable with about 10 cm/yr motion for the past 5 m.y. and about 5 cm/yr before that time. (Note that all three of these island chains are nearly 90 degrees from the pole at 67° N., 73° W. and so all have essentially the same velocities.) Another point on this curve is the age of Midway Island, which has been dated pre-Miocene from drill holes through the coral cap. We estimate the age of the

Hawaiian-Emperor "elbow" two ways. (1) From a linear extrapolation of the Hawaii to Midway distance and age difference, we estimate the elbow to have an age of 43 m.y. (2) The Nazca Ridge—Sala y Gomez Ridge intersection presumably represents the equivalent feature in the eastern Pacific. The hot spot which made the Sala y Gomez-Nazca and the Tuamotu-Line Ridges is directly on the crest of the spreading rise, so the magnetic anomaly pattern adjacent to these features will directly give the age during which each feature was made. From Morgan and others (1969) we see that anomaly 13 (38 m.y.) is near the Nazca-Sala y Gomez conjunction. A third line of evidence which could have bearing on the age of this change in trend is the study by Menard and Atwater (1968) of the changes in the fracture zones pattern in the northeast Pacific. They do not find a major change at about anomaly 13 (although they note a change near the coast of California at the time of anomaly 11); the major change in this pattern occurred at anomalies 21 to 24 (55 m.y.). We shall assume that the bend in the Hawaiian-Emperor chain was made 40 m.y. ago, while keeping in mind that a 55 m.y. age for this feature cannot be ruled out. What is the age of the northern end of the Emperor or Line features? Again using the assumption that the Tuamotu-Line chain was generated at a ridge crest, we infer from the nearness of anomaly 32 that 100 m.y. is a good estimate for the age of the northernmost features.

These age assignments will now be compared to ages determined by drilling or dredging on atolls and guyots in the Pacific. The Mid-Pacific Mountains and Magellan Seamounts will be featured in this discussion, so we first present our interpretation of these in terms of hot spots. The Mid-Pacific Mountains (or Marcus-Necker Ridge), the Magellan Seamounts, and the Caroline Islands are here regarded as east-west island chains formed from 100 to 150 m.y. ago by a rotation of the Pacific plate about a pole near the present North Pole. This motion was not displayed in Figure 3 because all of the island chains are close together and do not have a geometry to accurately determine the pole, and also because of the complications introduced by the "wandering" hot spot, which will be discussed later. The Mid-Pacific Mountains and the Magellan Seamounts are regarded as continuations of the Tuamotu-Line and the Austral-Marshall-Gilbert chains and the Caroline Islands as the continuation of another hot spot chain not present today. Hamilton (1956) reports the following ages (here converted from his age classification name to millions of years) for dredge and core samples obtained from five guyots in the Mid-Pacific Mountains: Hess Guyot (18° N., 174° W.), 120 m.y.; Cape Johnson Guyot (17° N., 177° W.), 120 m.y.; Guyot 20171 (21° N., 171° W.), 80 m.y. On two of the guyots sampled, Horizon (19° N., 169° W.) and Guyot 19171 (19° N., 171° W.), no age older than about 55 m.y. was obtained. A younger age does not contradict these guyots being formed at about 100 m.y., as only surface samples were obtained and much older sediments may not be exposed. Hamilton and Rex (1959) summarize the fossil ages found in the Marshall Islands. Bikini (12° N., 165° E.) and Eniwetok (12° N., 162° E.), just west of the Marshall chain, have been drilled and dated. The age at the bottom of the Bikini hole (about halfway to the basalt basement) is 35 m.y., and the oldest age sample dredged from the adjacent Sylvania Guyot is 55 m.y. More important, two drill holes on Eniwetok penetrated the coral cap and reached the basalt basement. The fossils at the bottom of these holes are about 55 m.y. old. This implies that Eniwetok had a different history than that suggested by its position in the supposed hot spot trajectory. We also note that two of the Japanese Seamounts discussed in the following section on paleomagnetics (near 28° N., 148° E.) have been dredged and dated by the K-Ar method. Their ages, 80 m.y., also contradict their position on the western end of the Mid-Pacific Mountains. We thus have conflicting evidence in the western Pacific and some additional factors must be found if we are to reconcile this with the simple hotspot pattern that we observe farther east.

The solid lines generated by rotating a rigid Pacific plate over the hot spots do not exactly follow the island chains. We may use this systematic departure to estimate the rate of migration of the hot spots relative to one another. The trajectories follow the Hawaiian-Emperor and Tuamotu-Line chains fairly exactly, so we may use the departures of the Austral-Marshall-Gilbert chain to measure mobility. The measured distance from Macdonald Seamount to the turning point is 10 percent longer than the predicted distance; the distance from the turning point to the northernmost of the Marshall Islands is 25 percent less than the corresponding prediction. The rate of plate motion over the "fixed" hot spots is about 7 cm/yr (30 degrees in 40 m.y. and 40 degrees in the following 60 m.y.). Thus this hot spot moving at about 1 cm/yr relative to the others is a good measure of its mobility in the deep mantle. If we had chosen trajectories based on a more compromise set of rotations which did not agree so well with the Hawaiian-Emperor or Tuamotu-Line chains, then each of the hot spots migrating at about .5 cm/yr in this reference frame would match the observations.

Why are the Hawaiian Islands islands? In the simple model presented above the continuous eruption of deep material should make a smooth continuous ridge—what geological complexities must we introduce to get isolated episodic volcanos? We adapt Menard's (1969) model of growing volcanos to this problem. We suppose that the light fractionation from the deep plume continuously flows up but is trapped by the asthenosphere-lithosphere "interface" (not a sharp boundary but a gradual transition in rigidity). This trapped island-type basalt accumulates in pockets, analogous to oil trapped by certain formations, and its unstable situation causes vents to the surface to form, which tap the reservoir and cause volcanos at the surface. This complexity has the possibility of answering a number of questions. (1) The plume may plaster the asthenosphere-lithosphere boundary over an area 100 mi square, but a single vent to the surface can tap this reservoir and concentrate this into a single volcano (as opposed to a continuous ridge). (2) The motion of the lithospheric plate eventually displaces the vent from the area above the deep plume sufficiently far so that a new vent forms. The old vent then taps only the remains in the reservoir in its immediate vicinity and soon dies out. We thus might expect to find a simple relation among the spacing of volcanos, the rate of plate motion, and the magnitude of the hot spot (as measured by the volume of the volcanic chain). (3) The activity of each island ends with alkali-rich eruptions. This different chemistry may result from the remains in the old vent after it has migrated and has been cut off from the hot spot. Does the volume of alkali-rich basalt agree with this? Is the chemistry compatible with this less than 100 km origin? Does the start of the alkali eruptions on an old volcano coincide with the start of a new volcano next in line? (4) This model allows a volcano to continue to grow for millions of years even after it has left its source area, in agreement with the model described by Menard (1969). The bulk of Menard's data supporting this growing seamount model comes from the Juan de Fuca Ridge region. We claim this region has two minor hot spots creating the line of seamounts and guyots between Cobb Seamount and Kodiak Island and the Explorer Seamount–

Pratt-Welker guyot string farther north. (We thus limit the applicability of the growing seamount model to regions of hot spots.) The question as to whether all off-ridge seamounts are produced by minor hot spots raises interesting possibilities, but we shall sidestep this generality.

It is said, based on dredge samples, that seamounts such as Cobb Seamount are capped with an alkali-rich basalt. We claim that such a seamount is not primarily made of ocean ridge–type basalt capped in its last stages of growth with a more alkaline skin, but that it is made of the island-type basalt throughout. Dredging cannot answer this question; only deep drilling can distinguish between an alkali-rich coating or island-type throughout basalt.

Having minor hot spots at the Juan de Fuca Ridge offers an explanation as to why this ridge exists in the first place. The North American and Pacific plates could quite logically have their present motions without there even being an oblique Juan de Fuca Ridge; but placing one of the world's driving mechanisms here assures the continuing existence of a spreading ridge at this location—a ridge that may change its orientation but must pivot about this hot spot.

PALEOMAGNETISM

Francheteau and others (1970) have presented a polar wandering diagram for the Pacific plate based primarily on studies of the magnetic field around seamounts. Figure 4a is a reproduction of their Figure 17 with the following changes. First, we assign definite, though of course possibly inaccurate, ages to each pole position based on our understanding of their discussion of the possible ages of each seamount. The number in the name of each pole position shows our estimate of its age in millions of years. Second, we have greatly enlarged the error circle of the Midway data point. Francheteau and others used the Midway determination of Vine (1968), and Vine (personal commun.) states their estimate of the error is

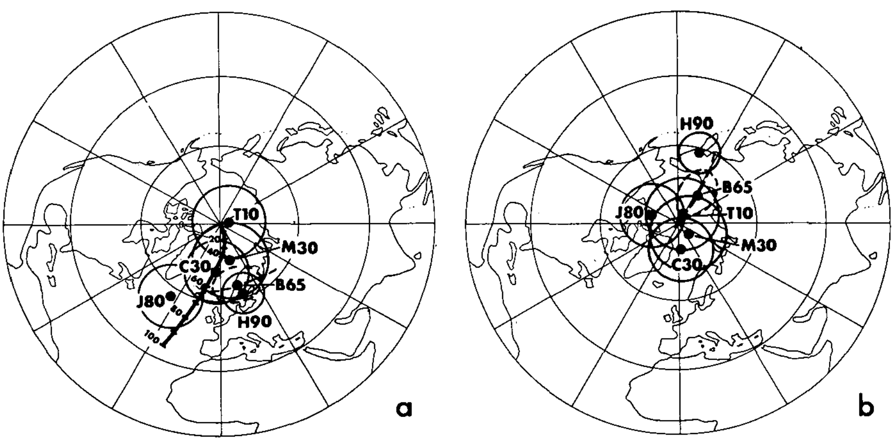

Figure 4. (a) The Pacific paleomagnetic pole positions of Francheteau and others (1970) and the polar wander curve predicted by the motion shown in Figure 3. (b) The paleopoles are "corrected" for the presumed motion of the Pacific plate; the paleopoles of all ages should now coincide at the north pole.

too small. The measured drill core samples were all from the same flow and the scatter reported represents differences in the single flow, not the scatter that might result from polar migration about the average dipole if many flows had been sampled. In addition to the paleomagnetic data points, Figure 4a also shows a predicted polar wander curve for the Pacific plate made from the rotations needed to make the hot spot trajectories shown in Figure 2 (0.85°/m.y. for 40 m.y. about a pole at 67° N., 73° W.; 0.75°/m.y. for 60 m.y. about a pole at 23° N., 110° W.). Each dot on the polar wander curve shows the predicted position for successive 10 m.y. ages. The observed paleomagnetic pole positions should coincide with the dot for its age if (1) the motion of the Pacific plate is as described above, and (2) the magnetic pole does not migrate relative to the fixed hot spots. Figure 4b shows the paleomagnetic data corrected for the predicted motion of the Pacific plate. In principle we have taken the inclination and declination of the original measurement, rotated the Pacific plate back to its orientation at the time the feature was magnetized, and computed the position of the paleopole at that time. Ideally all data points would form a tight cluster about the "north" pole. We see that, except for the Hawaiian Seamounts of presumed 90 m.y. age, there is excellent agreement between the predicted polar wandering and the observed paleomagnetic positions.

The African plate offers another test of a paleoreconstruction based on plate motion over hot spots versus paleomagnetic data. The Walvis Ridge is the most conspicuous aseismic ridge in this region, but there are also submarine ridges trending northeast away from present-day active volcanos at Reunion Island, Bouvet Island, Ascension Island, and the Cape Verde and Canary Islands. A similar trend exists for St. Helena Island and the Cameroon trend, but here we have the peculiar situation of an active volcano at both ends of the trend. Perhaps the trapped basalt at the asthenosphere-lithosphere boundary has taken nearly 100 m.y. to find a vent to the surface at Mt. Cameroon—if so, we have a mechanism to account for the anomalously young ages (Eocene) of much of the activity in the Marshall and Gilbert island chains as discussed above. A rotation of 27 degrees about a pole at 25° N., 55° W. was found to best fit this data, and the trajectories of the hot spots on the African plate based on this are shown in Figure 5. The time at which a hot spot was beneath points on these trajectories was computed by assuming linear interpolation between 110 m.y. and the present—the uniformity of this motion is based on the JOIDES results in the South Atlantic.

Figure 6a shows the paleomagnetic pole determination of Africa as tabulated by McElhinny and others (1968). The pole positions B14, B15, B16, B17, B18, and B19 in McElhinny and others' classification were used. Numbers representing the age of the site are used to identify each pole. The solid line shows the polar wandering curve predicted for the motion of Africa shown in Figure 5. Figure 6b shows the paleomagnetic data corrected for the presumed motion of Africa, analogous to how Figure 4b was obtained from 4a. The clustering at the "north" pole is not as good as the Pacific data. We may claim this is due in part to the slower motion of Africa, hence the migration of the hot spots would be more noticeable than in the Pacific. The African data does not lend support to the hypothesis presented here, but it could be reconciled with this model if there was an episode of rapid polar wandering between 90 and 110 m.y. ago. Such polar wandering would be a rapid shift of the whole mantle (in which all the hot spots would move in unison) to a new axis of rotation, as envisaged by Goldreich and Toomre (1969).

No other plate contains a variety of aseismic ridges so that a direct test of the

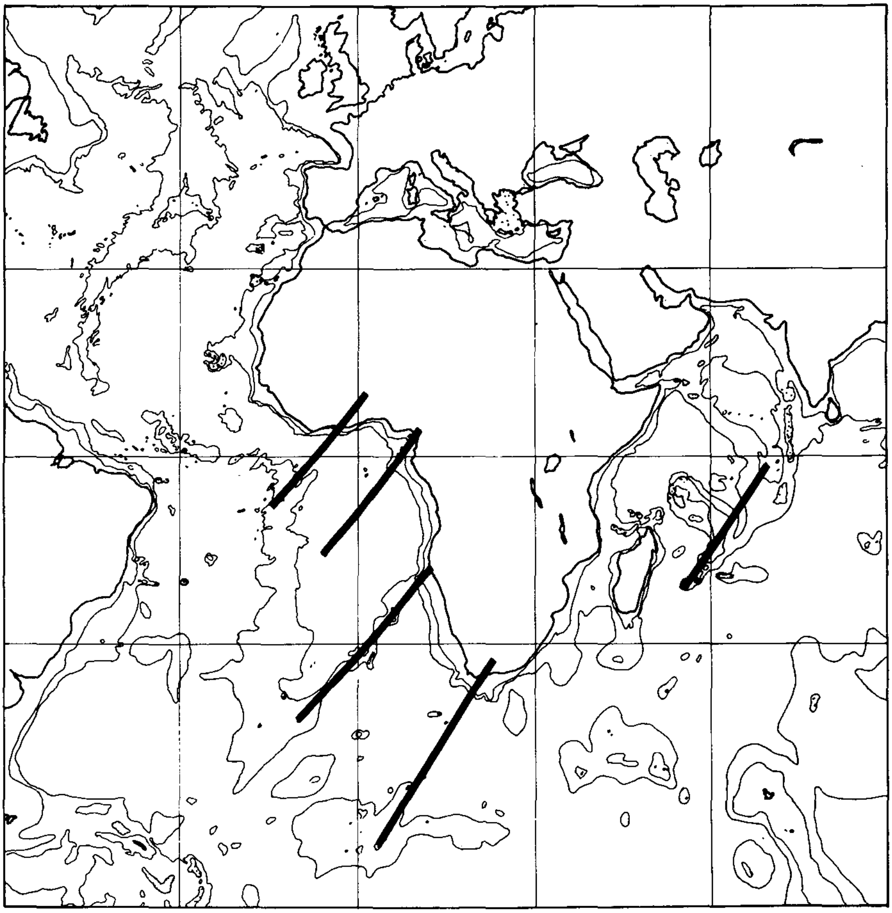

Figure 5. Hot spot trajectories constructed by rotating the African plate 27 degrees about a pole at 25° N., 55° W.

motions inferred from the ridge pattern and from paleomagnetism may be made. However, we may use the deduced motion of Africa and the Pacific together with the known relative motions of the plates to infer the motion over the mantle for the other plates. A tentative inference of the motion of North America, based on a counterclockwise rotation of Africa over the mantle about 30° N., 60° W. and the clockwise rotation of North America relative to Africa about 60° N., 30° W., shows that North America has rotated 30 degrees clockwise about the present north pole since mid-Cretaceous time. North American Tertiary paleomagnetics cluster near the present North Pole but the Cretaceous paleopoles are distinctly different, in the Bering Sea, in agreement with the pattern shown here for Africa.

PRESENT MOTION OF THE PLATES

Table 1 lists the components of an angular velocity vector for each crustal plate. The relative motions of adjacent plates have been determined from fracture zone

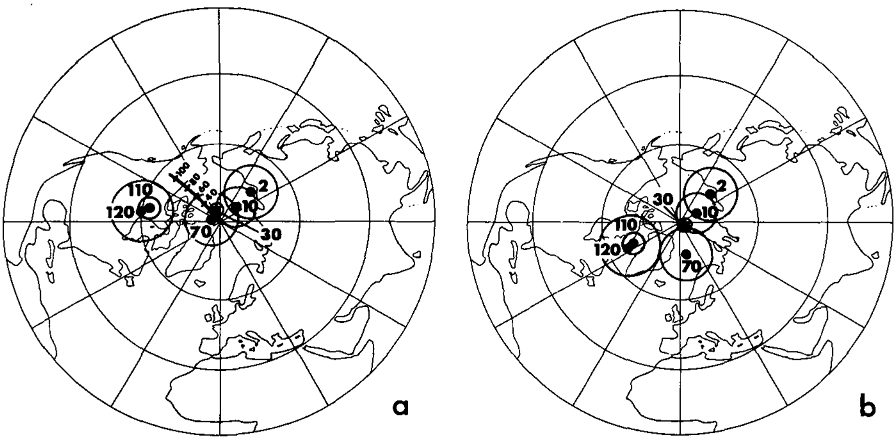

Figure 6. (a) African paleomagnetic pole positions of McElhinny and others (1968) and the polar wander curve predicted by the motion shown in Figure 5. (b) The paleopoles are "corrected" for the presumed motion of the African plate; the poles of all ages should now coincide at the North Pole. The discrepancy of the 110 and 120 m.y. poles may be due to a shift of the entire mantle shell relative to the core.

strikes and spreading rates for most ridge systems and Table 1 attempts a synthesis of this data into a worldwide self-consistent model. Table 2 shows relative motions computed from the vectors in Table 1 for most of the spreading pairs. The reader may compare these relative motion poles and rates with his own favorite data to judge accuracy of this synthesis. (A paper discussing the data used to arrive at Table 1 is in preparation.)

The relative motions are found by subtracting vectors in Table 1, so any constant vector may be added to all the vectors in Table 1 without affecting the relative motions. We have added that constant vector so that, in addition to satisfying the relative motion data, it also satisfies the hot spot data. The heavy vectors in Figure 7 show the motion of the crustal plates over each hot spot; in each case the vector is closely parallel to an aseismic ridge or island chain. Thus the hot spots form a reference frame fixed in the mantle, and Table 1 and Figure 7 show the absolute motion of each plate over the mantle. The good agreement between the arrows in Figure 7 and the trends of the island chains–aseismic ridges leads to two conclusions: (1) there has not been a major reorganization of plate motion in the past 40 m.y. or so, and (2) the hot spots have remained relatively fixed in the mantle. The slight disagreement is most pronounced in the Atlantic region where the slowly spreading plates are most vulnerable to "noise"—the magnitude of this divergence suggests that each hot spot wanders at less than ~½ centimeter per year.

Kaula's (1970) recent gravity map of the earth is shown in Figure 8. This is an isostatic anomaly map computed for spherical harmonics of order 6 through 16, so the features of 1,000 to 10,000 kilometers length are displayed. Note that there are gravity highs over Iceland, Hawaii, and most of the other hot spots (Galápagos is a conspicuous exception). Such gravity highs are symptomatic of rising currents in the mantle; the less dense material in the rising current produces a negative gravity anomaly, but the satellite passes closer to the elevated surface pushed up by this current and the net gravity field is positive. From formulas in Morgan

TABLE 1. ABSOLUTE MOTIONS OF THE CRUSTAL PLATES IN DEGREES/M.Y.

Plate Name		W_x	W_y	W_z
AM	American	.023	−.022	−.140
PA	Pacific	−.173	.334	−.702
AN	Antarctic	−.117	−.033	.268
IN	Indian	.459	.315	.350
AF	African	.149	−.112	.147
EU	Eurasian	−.050	.052	.039
CH	Chinese	−.145	.176	.223
NZ	Nazca	−.118	−.314	.616
CO	Cocos	−.693	−.921	.624
CR	Caribbean	−.180	.430	.090
JF	Juan de Fuca	.907	1.234	−1.512
PH	Philippine	1.295	−.694	−.859
SM	Somalian	.113	−.143	.181
AR	Arabian	.412	−.025	.352
PR	Persian	−.367	.023	−.141

(1965) we can estimate the size of the rising current. Take 10 mgal excess and 1,000 km diameter as typical for the hot spots; such a geoid high could be produced by a mass deficiency of 10^{20} gm centered at about 300 km depth, or roughly a cylindrical plug 100 km in diameter extending from the surface to 600 km depth with a density deficiency of 1 percent.

Note the paradox: both rising currents and oceanic trenches are associated with positive gravity anomalies. This behavior has been explained by Kaula and others as due to flow in a nonuniform viscous material. At the rises, the light ascending current buoys up the surface for a net positive gravity effect (and descending currents of the same pattern would pull down the surface for a net gravity minimum). However, a deep lithospheric plate may push down onto a hard bottom surface. If the lower surface supports part of the weight of the sinking plate, the top surface will not be depressed by the flow pattern and the satellite will sense only the excess mass of the plunging lithosphere for a positive gravity effect.

TABLE 2. RELATIVE PLATE MOTIONS DEDUCED FROM TABLE 1

	Latitude (°N.)	Longitude (°E.)	Spreading Rate (cm/yr)
EU-AM	60	135	1.2
AF-AM	62	−36	1.8
AM-PA	54	−61	3.9
PA-AN	−69	99	5.8
AF-AN	−24	−16	1.7
IN-AN	7	31	3.7
AR-AF	36	18	1.9
AR-SM	28	22	2.0
IN-SM	16	53	3.3
SM-AN	−19	−26	1.5
CO-PA	44	−113	10.5
CO-NZ	1	−133	4.6
NZ-PA	64	−85	8.2
NZ-AN	51	−90	2.6

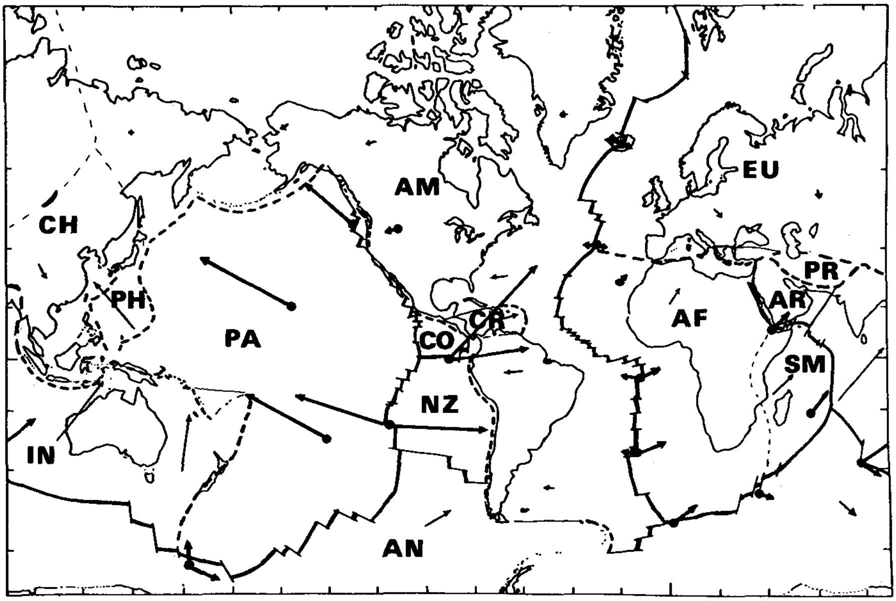

Figure 7. The present motion of the plates over the hot spots. This motion is computed from Table 1 and agrees with the relative motion data, as well as with the trends of the aseismic ridges–island chains. The length of each arrow is proportional to the plate speed.

The gravity measurements appear to offer the best method to assess the strength of the different plumes. More measurements are needed as the geoid maps change dramatically each year (compare Kaula's 1970 statements with those of earlier years). In choosing the possible plumes shown in Figures 1 and 7; the gravity measurements were augmented by what is known locally as the "Hess Gravity Theorem," namely that one does not need a gravimeter to measure gravity, one needs only to look at the topography. This is a corollary of the statements made above; the flow patterns associated with positive gravity anomalies raise the surface, thus high topography means positive gravity and vice versa. We thus look for those abnormally shallow places in the oceans, such as the areas near the Galapagos, the Juan de Fuca Ridge, and Prince Edward Island. The National Geographic Society globe has contours at particularly apt intervals and spiderlike fingers radiate away from many of these topographic highs. Whether the unusually high Tibetan Plateau or southern Africa should be considered symptomatic of a subcontinental hot spot is an open question; the more uniform oceans are more amenable to this type of analysis. The best case for a present day subcontinental hot spot could be made for the Snake River flood basalts in analogy to the Deccan Traps of the early Reunion hot spot.

The data presented in this paper, the parallelism of the Pacific island chains, the agreement of this motion of the Pacific with the paleomagnetic results, and the agreement of the present relative motions of the plates with the trends of the island chains–aseismic ridges all substantiate that plate motion over mantle hot spots is a valid and useful concept but this data contributes little to the hypothesis that these hot spots provide the motive force for continental drift. The case for this

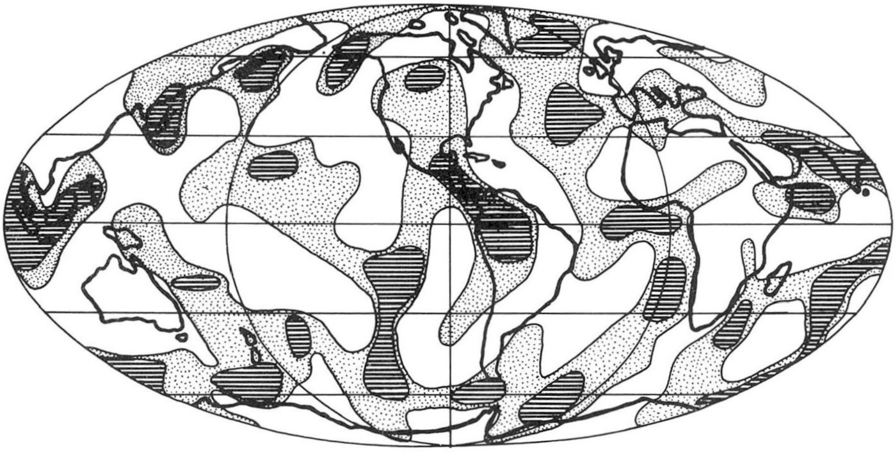

Figure 8. Isostatic gravity map of the earth, redrafted from Kaula (1970), to emphasize positive anomalies. The shaded areas show regions of positive anomalies; the heavier shaded areas show regions where the anomalies are greater than +20 mgal. Note the correlations of the gravity highs with Iceland, Hawaii, and most of the other hot spots.

association rests on three facts: (1) Most of the hot spots are near a ridge, and a hot spot is near each of the triple ridge junctions; (2) the gravity and regional high topography suggests that more than just surface volcanism is involved at each hot spot; and (3) neither rises nor trenches appear capable of driving the plates, implying that asthenospheric currents acting on the plate bottoms must exist.

The symmetric magnetic patterns and the mid-ocean position of the rises suggest that the ridges are passive. The first deduction of plate tectonics was that if two plates are pulled apart, they split along some line of weakness and *in response,* asthenosphere rises to fill the void. With further pulling of the plates, the laws of heat conduction and the temperature dependence of strength dictate that future cracks appear right down the center of the previous "dike" injection. If the two plates are displaced equally in opposite direction or if only one plate is moved and the other held fixed, perfect symmetry of the magnetic pattern will be generated. The axis of the ridge must be free to migrate (as shown by the near closure of rises around Africa and Antarctica). If the "dikes" on the ridge axis are required to push the plates apart, it is not clear how the symmetric character of the rises is to be maintained.

The best argument against the sinking lithospheric plates providing the main motive force is that small trench-bounded plates such as the Cocos do not move faster than the large Pacific plate. Also, the slow compressive systems, as in Iran, would not appear to have the ability to pull other plates, such as the Arabian plate, away from other units. The pull of the sinking plate is needed to explain the gravity minimum and topographic deep locally associated with the trench system (see Morgan, 1965), but we do not wish to invoke this pull as the main tectonic stress.

We are left with sublithospheric currents in the mantle. The question now is whether these currents are great rolls—mirrors of the rise and trench systems—or whether they are localized upwellings, that is, hot spots. Also, how deep do such currents extend? The circumstantial evidence seems to favor the hot spot mode, but there are several tests which could answer this question. (1) The most dramatic proof would be to seismically detect the shadow cast by a deep plume (the large time delay of teleseismic events in Iceland may be a plume effect). (2) Assumptions as to the magnitude of each plume and of the stresses at rise, fault, and trench plate-to-plate boundaries could be made and, the directions of the resulting plate motions could be deduced from these simplified dynamics. (3) A re-evaluation of the heat flow problem may show that convection deep in the mantle is necessary to remove heat from the lower mantle. The near equality of the oceanic and continental heat flux may be explained in terms of hotter than normal asthenosphere flowing away from each hot spot. (4) Finally, a continuing study of the Cenozoic and Cretaceous sea-floor spreading may show that major reorganizations of the spreading pattern coincide with the disappearance or emergence of new hot spots.

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