Plate velocities in hotspot reference frame:

electronic supplement

W. Jason Morgan

Department of Earth and Planetary Sciences, Harvard University, Cambridge, Massachusetts 02138, USA

Jason Phipps Morgan

Department of Earth and Atmospheric Sciences, Cornell University, Ithaca, New York 14853, USA

ABSTRACT

We have made a table of 57 hotspots, giving the track azimuths of their present motions and track rates where there was age control. This electronic supplement (with 301 references) gives the supporting data for each entry in this table and has a discussion of the probable errors in azimuth/rate for each entry. It also contains a discussion of 'hotspot-like-features' considered not to show plate motion and omitted from the table.

INTRODUCTION

An important column in Table 1 is the weight '**w**', a number between 1 and 0.2. It is our estimate of the accuracy of the azimuth of the track of a hotspot. The angular difference between the observed azimuth and modeled azimuth is multiplied by this weight when making the measure of goodness of fit that we minimize to solve for best-fit. The weight **w** has no meaning in regards to rate, only the rate error bars indicate that.

The weight is based on the estimated error of the azimuth of the track (σ_{azim}), with downward adjustment of the weight at some tracks based on qualitative criteria (*e.g.*, influence of a nearby fracture zone). The general rule for assigning weight is:

$(\sigma_{azim} \leq 8°) \Rightarrow w=1.0$

$(8° < \sigma_{azim} \leq 10°) \Rightarrow w=0.8$

$(10° < \sigma_{azim} \leq 12°) \Rightarrow w=0.5$

$(12° < \sigma_{azim} \leq 15°) \Rightarrow w=0.3$

$(15° < \sigma_{azim}) \Rightarrow w=0.2.$

We have tried to determine the azimuth over as short an interval as possible, usually over about a 5 m.y. interval on fast plates (Pacific, Nazca) and over 10 m.y. on slower plates. At some places (*e.g.,* East Australian) the azimuth was determined over a longer interval; this was another reason for down-weighting an entry. If subjective factors were applied to a weight, it is discussed in the corresponding section below.

If no direction of a track can be determined, the weight is zero and instead a 'quality letter' is given in the table. ‘A’ means almost certainly a hotspot but no track (*e.g.,* Etna or Tristan da Cunha), ‘B’ means perhaps a hotspot but not too certain (*e.g.*, Massif Central), and ‘C’ means most likely not a hotspot even though some characteristics may suggest one (*e.g.,* Jan Mayen). Those with 'C' are not listed in Table 1.

To get a sense of the accuracy of our estimates of observed azimuth accuracy in Table 1, we compared our estimates of the uncertainty of each track with the difference between observed azimuth and the azimuth predicted by our best model. Excluding those azimuths given weights of 0.2, there were 49 tracks for this comparison. The root-mean-square of our estimated errors was 8° compared to a 17° standard deviation for the difference between observed and model azimuths. Using only the 35 tracks where the weight was 1.0 or 0.8, the rms of our assigned error was 6° compared to a 10° standard deviation between observed and model azimuths. Some of this difference between model and observed azimuths is of course due to the model (and the assumption that the hotspots are perfectly fixed). Where plate velocity is greater than 10 mm/yr, only 4 tracks (Cameroon, Comores, Marquesas, and Bowie) of the 49 tracks examined had differences between observed and model greater than 17°. Thus we think the estimate of error in measuring an azimuth is fairly accurate (clearly within a factor of 1.5). The observed azimuth is known to the accuracy given in the table; a more complicated model might fit the observations better.

DISCUSSION OF EACH TRACK

Eurasian Plate

Eifel (50.2°N, 6.7°E) w= 1 az= 082° ± 8° rate= 12 ± 2 mm/yr

This is the best defined track on the Eurasian plate. Also, seismic tomographic studies have shown a low velocity column beneath Eifel extending down to at least 400 km (*e.g.*, Wüllner *et al.*, 2006). We used the locations of volcanics from Lippolt (1983) to determine an azimuth (082°) and have estimated its uncertainty to be ± 8°. This track has a moderately well determined rate. Duncan *et al.* (1972) found a (poorly determined) rate of 23 mm/yr based on early published K-Ar data and stratigraphic estimates of the ages of different volcanics. (Most of their references were published between 1960 and 1971, although some were as early as the 1930's.) There was a large effort to date these volcanics by the K-Ar method in the late 70's and early 80's that is summarized in the book by Fuchs *et al.* (1983). We have chosen the two locales that have the tightest concentration of dates: Vogelsberg (200 km east of West Eifel, dated at 17 ± 2 Ma) and Rhön (260 km east of West Eifel, dated at 22 ± 3 Ma). (The Vogelsberg age has been confirmed by Bogaard *et al.*, 1999, who used the $^{40}Ar/^{39}Ar$ technique on samples from a 650 m drill core and obtained ages of 17.5 ± 0.2 and 16.8 ± 0.3 Ma.) From these (which show a coherent pattern with little scatter) and the zero-age placed at the center of Eifel as located by the tomographic study of Wüllner *et al.* (2006), we get a rate of 12 ± 2 mm/yr. Our analysis ignores the other regions along the track with large scatter in their dates – in particular there are Oligocene dates

(~30 Ma) in many of these volcanic regions which are probably related to opening of the Rhine Graben. There is still controversy as to whether or not these volcanics are a hotspot track or are related to the Alps (they are a constant distance from the Alps, *cf.* Wedepohl *et al.*, 1994). A systematic study of this track using the $^{40}Ar/^{39}Ar$ technique could resolve this question, a steady progression of ages would establish the hotspot model over other contenders.

Iceland (64.4°N, 17.3°W) w= .8 az= 075° ± 10° rate= 5 ± 3 mm/yr

We think the center of volcanism is near the center of the glacier Vatnajökull at Grímsvötn (Einarsson *et al.,* 1997) and that its European trend is a little north of east (to exit the coast at 64.8°N, 14.0°W). We choose this trend north of east because we think Iceland has a northward component over the plume, creating a 'chevron' track on the separating plates and the southward propagation of rifting towards Surtsey. This is supported by the 'V-shaped' pattern of crustal thickness extending NE and NW from the center at Grímsvötn (Allen *et al.*, 2002). We estimate the uncertainty of this azimuth to be ± 10°. The rate Europe and North America are pulling apart at Iceland is well known: 20 mm/yr full rate. Due to the asymmetric nature of Iceland spreading, we suppose the North American side is moving westward faster than the European side is moving eastward: we assume a (3/4, 1/4) division and estimate the rate of Iceland (Europe side) over the hotspot as 5 ± 3 mm/yr.

Azores (37.9°N, 26.0°W) w= .5 az= 110° ± 12°

The Azores are a difficult track. The islands with the oldest ages are all at the eastern end: Santa Maria (5.5 Ma), the eastern end of São Miguel (4 Ma), and the bank Formigas between these two (all K-Ar ages, Féraud *et al.*, 1980; 1981). The volcanoes on the western end of São Miguel and on all the other islands are dated less than 0.7 Ma (and most have had historical eruptions). We place the present hotspot just west of São Miguel, assuming that the islands between Faial and Terceira are all formed by channeled flow from the hotspot to the mid-Atlantic, and that Santa Maria is due to flow from the hotspot to a minor spreading center along the East Azores Fracture Zone (see Morgan, 1978). This location allows the channel flow from the hotspot center to go along the paths marked by these islands to the neighboring spreading ridges. The azimuth of Eurasian plate motion over this hotspot is estimated at 110° ± 12° - the strike of all the islands.

Massif Central (45.1°N, 2.7°E) w= B (az= 097° ± 12°)

This appears to have the characteristics of a hotspot (Holocene volcanics, basalts, uplift, a neighboring rift) but there is no track. The most recent summary of ages is in Downes, 1987, Fig. 2, but all the data shown there are from the earlier summary by Maury and Varet, 1980, who had only K-Ar ages measured between 1969 and 1977. We searched very hard for more recent $^{40}Ar/^{39}Ar$ measurements but the modern targets have all been on problems post-100,000 years or pre-300 Ma. The difficulties pointed out by Froidevaux *et al.,* 1974, in establishing a track here still apply. If the more pronounced north-south trend is ignored (*i.e.*, the trend offset from but parallel to the Rhone), there is a 150-km-long trend heading 097° ± 12° (from Cantal to Deves to Velay to Coirons). If there were a track, it would head across the highest part of the Alps, so perhaps any conclusive evidence for the long-term existence of this weak hotspot has been lost by erosion.

Etna (37.8°N, 15.0°E) w= A

The volcanism at Etna has all the characteristics of a hotspot (Schiano *et al.*, 2001). We have no track for Etna, but include it on the European plate just to see the direction through Italy and Greece predicted by our model. (Etna, on Sicily, would normally be placed on the African plate, but we are curious only about the European path.)

Jan Mayen (71°N, 9°W) w= C

We think this is not a hotspot but rather due to channeled asthenosphere flow from Iceland (only 600 km away) feeding the Mohns Ridge. In this region, we think the Jan Mayen Plateau is a continental fragment torn off Greenland when the Aegis ridge jumped westward to its present (Kolbeinsey) position about 35 m.y. ago (Vink *et al.,* 1984; Müller *et al.,* 2001).

Baikal (51°N, 101°E) w= .2 az= 080° ± 15°

Windley and Allen (1993) suggest a plume center at Baikal in the Hangai region of Mongolia. Here there are altitudes that reach 3900 m, Pliocene and Pleistocene volcanics (alkaline basalt), recent rifting, high heatflow, and evidence that the crust is as thin as in the Basin and Range. We suspect rifting in a continent generally initiates near a hotspot – the Baikal area would fit this pattern. But whether the 080°trend of volcanics here indicates plate motion or merely the strike of rifting is unclear, and we give this the lowest weighting.

Hainan (20°N, 110°E) w= A az= 000° ± 15°

Korea-China Border (Changbai Shan)(42°N, 128°E) w= C (az= 030° ± 20°)

Vietnam (12°N, 107°E) w= C

Russia-China Border (Xiao Hinggan) (49°N, 127°E) w= C (az= 040° ± 15°)

Mongolia-China Border (Da Hinggan-Xilinhot) (44°N, 116°E) w= C (az= 045° ± 15°)

East Baikal-Vitim (53.5°N, 113°E) w= C

We have tried to find other hotspots in Asia. Above are our guesses, in decreasing order of certainty. Of these, we think only Hainan is due to a mantle plume. There is a 250 km long north-south trend of tholeiitic volcanism from the island of Hainan to the neighboring Luichow peninsula onshore, with more recent eruptions at the southern end and Pleistocene and Pliocene to the north. An S-velocity model of the upper mantle beneath the Western Pacific and Southeast Asia has been published by Lebedev and Nolet (2003). They used over 4000 seismograms from broadband instruments to constrain a tomographic model down to 660 km depth with a horizontal resolution of 100-400 km over an area bounded roughly from 10°S to 40°N and 100°E to 140°E. In this region, many places had low velocity anomalies at shallow depths but the only place with consistent low velocities between 250 km and 600 km was a circular (~500 km radius) region centered on Hainan, suggesting this is the only hotspot in this area. We think Hainan is a hotspot (20°N, 110°E, trend 000° ± 15°), but this part of China cannot be assumed to move as part of the rigid Eurasian plate and so it is not part of our data set even though we are fairly confident of its track.

Another possible track is along the China-Korean border (42°N, 128°E), with a trend of 030° ± 20° (but as we see no evidence as to which way the volcanism may have migrated, our direction may be off by 180°). A third is in Indochina (12°N, 107°E). Whitford-Stark (1987, page 43) has proposed this to be a hotspot, on the basis of its extensive basalt flows, young age (largely Plio-Pleistocene but some Holocene), doming of the area, and lack of other tectonic cause for such volcanism. A summary of this region can be found in Barr and Macdonald, 1981, where they describe the large Vietnamese flows as being initially abundant tholeiites, changing to more abundant hawaiites. However the evidence for these being hotspots is very shaky and we weight them "C" (probably not hotspots). There are other places of latest Tertiary activity with similar 'unusual' (*i.e.,* not-andesitic, generally acidic basalts) volcanism along the eastern coast of Asia. In China these are at Qixia/Taishan (37.5°N, 120.9°E, no age, nepheline basalt), Nushan (33.1°N, 118.8°E, early Pleistocene basalt), Fangshan (32.0°N, 119.0°E, early Pleistocene olivine basalt), Zhejiang (29.5°N, 121°E, no age given, olivine and magnetite rich basalt), and Haizheng (23.3°N, 116.2°E, Quaternary sub-alkalic picrite). These are given brief descriptions as units 41-45 in Whitford-Stark (1987). Likewise, within ~200 km of the coast of the Sea of Japan in the part of Russia between Vladivostok and the Sea of Okhotsk, there are many similar volcanic features. Whitford-Stark describes these as his units 137-151. They are Pliocene age – the lava types include sub-alkaline, leucite, alkaline, and nepheline basalts, with a few units described as dacite, andesite, or trachyliparite.

We think none in the above paragraph are directly related to mantle plumes. We think these are cases of volcanism due to horizontal flow in the asthenosphere – pressure-release melting occurring where the flow encounters the change from thick lithosphere beneath Asia to the thinner lithosphere of the back-arc basin (Langin, 1999; Morgan and Phipps Morgan, 2002). The back-arc basin asthenosphere is being 'used-up' in the subduction process, new asthenosphere is needed to replace the depletion of asthenosphere and this comes from beneath the continent. The downward motion of the slab drags down a thin layer of asthenosphere (lubrication-theory style). New asthenosphere must flow into this region to replace that lost. An additional point, the asthenosphere beneath the andesite volcanoes must constantly be replaced – the fluids released by the 'de-watering' slab flowing through a stagnant mantle would soon not cause the melting that produces the andesite volcanoes, a stagnant mantle would soon be 'barren'. If the 'replacement' asthenosphere comes from beneath the continent and there is a back-arc basin (old or currently active) between the continent and the subducting region, the asthenosphere 'rises' in its flow from sub-continent lithosphere thickness to oceanic thickness. Where this rising occurs, near the continent's edge, the corresponding pressure-release can cause the small quantities of melting that we see all along the east coast of Asia. (The only other place in the world where a back-arc basin is between a subduction zone and continent is the Bering Sea – there we have the Pribilof Islands and similar small pockets of very recent volcanic activity in southwesternmost Alaska.)

There are two other places in China which might be hotspots, on the basis of recent basalt flows and high elevations: in northernmost Manchuria near the Russian border (49°N, 127°E, 040° ± 15°) and the western side of Manchuria near the Mongolian border (44°N, 116°E, 045° ± 15°). Our source for these is the *Geological Map of China*, 1990, and descriptions of each volcanic area by Whitford-Stark (1987). Another possible hotspot in Eurasia is at 53.5°N, 113°E, a few hundred kilometers east of Lake Baikal. This region has several "central type", alkali-olivine, Pleistocene volcanoes (see Whitford-Stark, 1987, and *Tectonic Map of Eurasia*, 1966). A region 300 km northeast of this (at 56°N, 118°E) has 12 Holocene volcanoes, but their descriptions (Whitford-Stark, 1987, page 26) suggest they are part of the Baikal rifting rather than a hotspot center. Evidence for all these tracks in Eastern Asia is poor and we consider them no more.

African Plate

Hoggar (23.3°N, 5.6°E) w= .3 az= 046° ± 12°

There appears to be an exceptionally large number of hotspots beneath the African continent. We agree with Burke (1996) that hotspots are more readily seen in Africa because the exceptionally slow velocity of the African plate allows them to 'burn' through. It has also been suggested that there are simply ‘more’ hotspots here, an African ‘superplume’ (Anderson, 1982; Richards *et al.,* 1988). Examination of the *International Geological Map of Africa* (1985) shows a fairly clear 046° trend of Neogene basalt flows extending 350 km from the highest elevation (Mt. Tahat, 2920 m). (We found *The Times Atlas of the World* (1985) to be particularly helpful in determining names and elevations of many features summarized in the following paragraphs.) The age dates at Hoggar (Miocene to Quaternary) are all K-Ar measurements, summarized in Fig. 2 of Rognon *et al.*, 1983. Dupuy *et al.,* 1993, conclude the chemistry of the volcanics here suggests a hotspot origin. From the size of the uncertainty in this azimuth (±12°) we normally would give this a weight of 0.5; but this being a continent and there being no evidence for an age progression, we have downgraded this to **w** = 0.3.

Tibesti (20.8°N, 17.5°E) w= .2 az= 030° ± 15°

Tibesti is a region 300 km across with the highest elevations in Northern Africa (3410 m) and has several centers of Holocene volcanism. On the same map of Africa as above, we see a trend of basic lavas extending 400 km from the higher elevations in a direction 030°. The dates here are all K-Ar (Ade-Hall *et al*., 1974; Reynolds and Hall, 1976; Jäkel, 1982) and range from 17 Ma to Recent, with no real pattern (more of the centers of recent activity are at southern end). There is more uncertainty in the azimuth (±15°) and no age progression, so we weight this 0.2.

Jebel Marra (13.0°N, 24.2°E) w= .5 az= 045° ± 8°

The active center appears to be at Deriba Crater (13.0°N, 24.2°E, 3040 m) which had a major eruption 4000 years ago. There is a clear trend (045° ± 8°) for 400 km, from Deriba through several small volcanic fields to the extensive flows at the Meidob Hills. Many K-Ar dates have been made (Vail, 1990; Franz *et al.*, 1994) but there is no apparent pattern of young to old. Excluding those K-Ar dates where more than half of the ^{40}Ar is atmospheric contamination, the age of Meidob is 6.7 Ma. However the flows between Meidob and Deriba have K-Ar ages greater than this: 16 to 36 Ma. For the older part of this track there are two choices: a slightly more northern route (037°) to volcanics near Lake Nasser (Garfunkel, 1992) or more southerly path (061°) to Bayuda (age ~70 Ma, Vail, 1990). This is the best track on the African continent (but one must accept that age patterns of continental tracks are a mess). We have downweighted this because of the confusion of ages near Deriba.

Afar (7.0°N, 39.5°E) w= .2 az= 030° ± 15° rate= 16 ± 8 mm/yr

We think there is a very large hotspot somewhere near 7°N, 39.5°E (the center of a circle of uplift 800 km across) that is related to the 29 Ma to 30 Ma (Hofmann *et al.*, 1997; Baker *et al.*, 1996) Ethiopian and Yemen flood basalts and to the rifting of the Red Sea/Gulf of Aden/Ethiopian Rift (Zumbo *et al.,* 1995). However we see no distinct lineup of volcanics or an age progression to give evidence for a track. If we assume the initial split of the continents occurred precisely over the hotspot and spreading of each arm has been symmetric since then, the distance from our chosen center of uplift (7°N, 39.5°E) and the center of the triple junction (11°N, 42°E) gives a direction (030° ± 15°) and rate (500 km / 30 Ma = 16 ± 8 mm/yr) of plate motion over the hotspot. We give this a very low weight.

Cameroon (2.0°S, 5.1°E) w= .3 az= 032° ± 3° rate= 15 ± 5 mm/yr

We have two slightly conflicting possibilities for Cameroon. One would place the hotspot at

Mt. Cameroon itself (4.4°N, 9.2°E) and the other near Pagalu at the southern end of the islands (at 2.0°S, 5.1°E). However the trend for both these cases is 032° ± 3°, so the choice between them doesn‘t matter very much. We present paragraphs justifying each choice – we prefer the second.

There is a very sharp trend, 032° ± 3°, but we are not sure if this is a track on a moving plate or volcanics coming up an old rift in the continent. Mt. Cameroon would be the obvious place for the hotspot center (it has an elevation of 4070 m and its most recent eruption was in 1982) but the trend in the exact opposite direction toward Saõ Tomé and Pagalu (formerly named Annobon) is disturbing. We think we have a mechanism to explain part of this effect. The lithosphere is thicker beneath the African continent (with correspondingly thinner asthenosphere) than beneath the Gulf of Guinea (where the asthenosphere has normal oceanic thickness). A plume rising beneath Mt. Cameroon might try to spread out into the asthenosphere in all directions, but it would encounter resistance to the north and east (where the lithosphere is thicker and the asthenosphere thinner) and would preferentially spread out southwestward and upward buoyantly into the 'easy' ocean. As the influx of mantle material spreads out from the continent, there would be some pressure-release melting as some moves upwards beneath the thinner-lithosphere ocean. (This process will be described in more detail in the section on the East Australian track.) This could explain the volcanism at Bioko (formerly named Fernando Poo) nearer the continental shelf than Mt. Cameroon but would not for Principé, Saõ Tomé, and Pagalu (which are 200, 400 and 600 km further away from Bioko). These islands would have to be the result of some new rifting lineament just starting -- perhaps their direction is parallel to the Cameroon track because the hotspot track has weakened a line through the plate and the outward flow from the plume, perpendicular as well as parallel, is creating stress to turn this weak line into a growing crack. The fracture zones here related to the early rifting of the South Atlantic strike 044°, close to but significantly different from the trend of lineament of the volcanoes (Francheteau and Le Pichon, 1972; Sibuet and Mascle, 1978). Cameroon has a clear trend; but because of these uncertainties we have weighted it low.

The paper by Lee *et al*., 1994, has changed our view of Cameroon. Here $^{40}Ar/^{39}Ar$ measurements were used to date one of the islands. The ages and distances from the southernmost island Pagalu (formerly Annobon) are as follows: Pagalu, 4.8 ± 0.2 Ma, $^{40}Ar/^{39}Ar$; São Tomé, 13 to 15.7 Ma, K-Ar, 200 km; Principe, 31 ± 2 Ma, K-Ar, 380 km. The ages of the shield-building lavas on these islands would define the track; the present-day volcanism on the continent and on the island at the shelf-edge (Bioko, or Fernando Poo) would be from on-going continental rifting occurring along this pre-weakened line. The rate is 15 ± 5 mm/yr along an azimuth of 032° ± 3°. This pattern of linear migration is confused by a K-Ar age (O'Connor and le Roex, 1992, p. 351) of 3.4 ± 1.4 Ma made on a 'moderately altered volcanic rock' from Tinhosa Grande (an islet about 25 km SW of Principe along the line toward São Tomé, 350 km from Pagalu).

We have put the present center at a seamount roughly 80 km southwest of Pagalu. We are confident on the strike but not the location of this hotspot and have kept the weighting low. Measurements using the $^{40}Ar/^{39}Ar$ technique on this seamount, the other islands, and two seamounts between the islands that appear on the satellite gravity map (Smith and Sandwell, 1997a,b) could positively establish this track.

Madeira (32.6°N, 17.3°W) w= .3 az= 055° ± 15° rate= 8 ± 3 mm/yr

The Madeira trend has many published K-Ar ages (*cf*. Ferreira *et al*., 1975; Féraud *et al*., 1981) but the best data are the 35 rocks dated with the $^{40}Ar/^{39}Ar$ technique published by Geldmacher *et al*., 2000. The oldest rocks on Madeira are 4.4 ± 0.2 Ma (my average of Geldmacher *et al*. measurements). It and the nearest island (Porto Santo, on which the oldest samples are 13.7 ± 0.5 Ma ($^{40}Ar/^{39}Ar$, Geldmacher *et al*., 2000), have volcanic centers 72 km apart giving a rate of 72 km ÷ 9.3 mm/yr = 8 mm/yr. This trend is 055°, but we give this a large uncertainty. There is a large seamount ~20 km southwest of Madeira (at 32.6°N, 17.3°W) which Geldmacher *et al*. propose to be the 'zero' of the track. It is on a similar azimuth (~060°) and its distance from Porto Santo (114 km) gives a rate 114 km ÷ 13.7 Ma = 8 mm/yr. This is a very short trend and the edifices are very irregularly shaped, thus we give a large uncertainty to the azimuth – in particular Desertas Islands confuse the pattern. There is a large bank extending ~150 km due west of Madeira; if the center of the plume were now at the western end of this bank, the geometry of Madeira would be identical to that of the Canaries.

The longer term trend is equally difficult. Madeira to Porto Santo to Seine Seamount (the largest seamount in the immediate area) to Ampère Seamount has a trend 065° ± 5° (about a 30 m.y. average). This trend could be extended to the dated seamounts Ampère (31 Ma) and Ormonde (65 Ma); more precisely this trend would be 050° ± 5° with a rate 12 mm/yr (from Fig. 9 of Geldmacher *et al*., 2000). The trend Madeira to Lion to Josephine seamounts (030° ± 5°) is another possibility. However the shape of the swell around Madeira fairly clearly indicates that its path has been from the northeast quadrant (~045°) and given our large uncertainty we think the azimuth given in the table is a good choice.

Canary (28.2°N, 18.0°W) w= 1 az= 094° ± 8° rate= 20 ± 4 mm/yr

This is the easiest track to find in the northern part of the African plate, and we give it a weight of 1. The line from Hierro/Palma to Fuerteventura is 400 km long and 100 km wide – we have chosen an azimuth of 094° ± 8°. There are many papers on K-Ar dating the Canary Islands, but we have relied on two that use $^{40}Ar/^{39}Ar$ dating (Féraud *et al*., 1985; Staudigel *et al*., 1986). A figure showing the ages from these two papers for La Palma, Gomera, Tenerife, Grand Canaria and Fuerteventura (as well as all earlier K-Ar dates for these islands) was used to obtain a rate of 20 ± 4 mm/yr (Fig. 1 in Féraud *et al*., 1986). Geldmacher *et al*. (2005) made $^{40}Ar/^{39}Ar$ age determinations for two seamounts at the 'old' end of the Canary chain. Their Fig. 5 combines their new measurements with earlier data for the entire chain; they conclude an average track velocity of 12 ± 1 mm/yr.

Great Meteor (29.4°N, 29.2°W) w= .8 az= 040° ± 10°

There is a fairly clear trend from two small seamounts 50 and 100 km southwest of Great

Meteor to Great Meteor, and then an older trend at 020° to Irving Seamount (see Tucholke and Smoot, 1990). There is an age for Great Meteor (K-Ar ages from two samples, 11 and 16 Ma, Wendt *et al.*, 1976) and also the fact that Great Meteor is a guyot beveled only 300 m below sealevel helps establish this as a recent trend.

Cape Verde Islands (16.0°N, 24.0°W) w= .2 az= 060° ± 30°

The horseshoe pattern and no discernible age relation (see page 383 of Cahen and Snelling, 1984) among the Cape Verde Islands make this a difficult track. The largest volcano is on Fogo (14.9°N, 24.3°W), but we have chosen the center of the island group as our 'zero'. The chemistry of the Cape Verde Islands is very hotspot-like – indeed, carbonatites are found on five of the islands (Jørgensen and Holm, 2002). High quality $^{40}Ar/^{39}Ar$ dates on a single island (only ~30 km in diameter) range from 7.6 Ma to Recent (Plesner *et al.,* 2002); the complexity of volcanism in the Cape Verdes is well illustrated by the paper by Mitchell *et al.,* 1983. We think Cape Verde is a very large hotspot with lots of sub-lithospheric flow which transports rising plume material to feed a large portion of the mid-Atlantic Ridge. The very slow motion of the African plate here allows the mantle residue (formed when basalts melt to rise to the islands) to accumulate beneath the lithosphere to form a very large swell – and we suppose the depth (150 km?) to which this stiffer, less dense residue extends beneath the islands blocks the ascent of the plume and causes the recent volcanism to from a 'ring' around the true center of upwelling (*cf.* Phipps Morgan *et al.*, 1995a, for a discussion of this deep residue for the case at Hawaii). There is the hint of the swell around the islands seen beyond 300 km being more pronounced to the northeast, and we have used this asymmetry of the swell as our direction indicator, although the age of this swell averages over more than just the most recent 10 Ma that we have generally tried to use as a cutoff for each track.

St. Helena (16.5°S, 9.5°W) w= 1 az= 078° ± 5° rate= 20 ± 3 mm/yr

We choose the active center to be 16.5°S, 9.5°W, about 50 km west of Josephine Seamount at the 'zero' of the extrapolation of age-distance shown in Fig. 4a in O'Connor *et al*. (1999). We have chosen the path (azimuth of 078° ± 5°) to go down a line midway between the dated seamounts Josephine, Benjamin, Kutzov, Bonaparte, Bagration, and St. Helena (about a ±30 km scatter from this 400 km line) – see Fig 2. of O'Connor *et al* (1999). These seamounts have all be dated using the $^{40}Ar/^{39}Ar$ technique; O'Connor *et al*. (1999) concluded a rate of migration of 20 ± 1 mm/yr. However using a scatter of seamount positions of ~50 km along this 300 km long chain, the '±1 mm/yr' is far too precise – even our choice of ±3 mm/yr for the rate error is probably too precise. The most prominent topographic feature of this trend apart from St. Helena itself is Bonaparte Seamount, a guyot which comes to within 113 m of the surface 140 km west and 40 km north of the island of St. Helena (Udintsev *et al*., 1977). St. Helena itself was one of the first oceanic islands to be dated with the then-new K-Ar technique; ages of 10-12 Ma were determined then for the shield building stage (Abdel-Monem and Gast, 1967; Baker *et al*., 1967) – extrapolation of the O'Connor *et al*. $^{40}Ar/^{39}Ar$ values to St. Helena's location would suggest its true age is about twice this. There is no track east of St. Helena on the GEBCO chart but there is on the satellite gravity map (Smith and Sandwell, 1997a,b) with a seamount about every 200 km along a trend (046° ± 5°) that is 800 km long and which differs from the fracture zones in the region. Beyond this 800 km long clear-lineup there are more seamounts, three of which have been dredged and dated at 52, 78, and 81 Ma (each ± 1 Ma, $^{40}Ar/^{39}Ar$ method, O'Connor and le Roex, 1992); these have a straight line age-distance relation. Because the rate at St. Helena is so linear and the seamounts making the trend are all ~20 m.y. younger than the seafloor they are built on, we don't downgrade the weight we give this track even though its trend has the same azimuth as fracture zones in this region.

Tristan da Cunha (37.2°S, 12.3°W) w= A

Tristan is well studied and has all the characteristics of a hotspot. It had an eruption in 1961, and the shield-building stage appears to be at 0.2 Ma (K-Ar method, McDougall and Ollier, 1982). There is no nearby track for the Tristan-Nightingale-Inaccessible group, although the older part of the track is well marked by the Walvis Ridge (O'Connor and Duncan, 1990). To choose a trend here would just be assuming a trend parallel to the nearby Gough. Although we think this is a clear (although perhaps dying) hotspot, we just don't declare that it has an independently determined azimuth.

Crawford (38.8°S, 11.8°W) w= C

There is a 200 km long east-west trend of several seamounts near 38.8°S, 11.8°W (Crawford Seamount), but we think this is due to a fracture zone and not a hotspot track.

Gough (40.3°S, 10.0°W) w= .8 az= 079° ± 5° rate= 18 ± 3 mm/yr

Gough-McNish-R.S.A. seamounts mark a clear trend (079° ± 5°) that is 400 km long. We have downgraded its weighting a little bit because this trend is exactly parallel to fracture zones in the area. Gough has basalts quite distinct from Tristan, which is only 400 km to the northwest. Gough has been dated (K-Ar method, Maund *et al.*, 1988; $^{40}Ar/^{39}Ar$ method, O'Connor and le Roex, 1992) and basalts from the two seamounts have been dated ($^{40}Ar/^{39}Ar$ method, O'Connor and le Roex, 1992) and are 0.6, 8.1, and 18.8 Ma respectively. This gives a rate of migration of 18 ± 3 mm/yr. Its older track would appear to be the eastward side of the Walvis Ridge (the westward side would be from Tristan). It is a real puzzle why some hotspots are so close together (only ~400 km separation between Tristan and Gough).

Vema (32.1°S, 6.3°E) w= B

An alkalic peak on Vema Seamount (31.6°S, 8.3°E) rises to within 25 m of the surface, above an extensive flat 75 m wavecut terrace. A single altered sample was dated at 11 Ma (K-Ar method, Simpson and Heydorn, 1965) and more recently an age of 15.2 ± 0.1 Ma has been obtained ($^{40}Ar/^{39}Ar$ method, O'Connor and le Roex, 1992). Duncan *et al.*, 1978, show there are volcanics onshore Africa of the correct age (~30 Ma) to be the older part of this track. There are no nearby seamounts and so we can't define a recent track direction – our 'present position' has been moved 200 km west of the seamount to allow for estimated African plate motion in the past 15 m.y.

Discovery (43.0°S, 2.7°W) w= 1 az= 068° ± 3°

The satellite gravity map shows a clear trend (068° ± 3°) that differs from the fracture zones in the area. The line is about 500 km long, and would begin at a seamount about 350 km west of the shallowest point (426 m, at 42.0°S, 1.4°E) on the Discovery Seamounts. Discovery has been dredged; the basalt has hotspot affinities and has been dated at 25 Ma (K-Ar method, Kempe and Schilling, 1974).

Bouvet (54.4°S, 3.4°E) w= C

Basalts from Bouvet Island (54.4°S, 3.4°E) have been dated at 1.1 and 1.4 Ma (K-Ar, p. 409, LeMasurier and Thomson, 1990), a flow occurred only 2000 years ago, and it has present-day fumarole activity. However we don't think this is a hotspot but rather a place near the Bouvet triple junction on the Southwest branch of the Indian-Antarctic Ridge close to a hotspot. It is curious that this is one of three places where a hotspot-to-ridge island is on the plate opposite from the hotspot. Of the three places, the one where the recent seafloor spreading pattern is best known (Amsterdam/St. Paul), the ridge has jumped transferring the island from the near side to the opposite side. In the Azores, the magnetic pattern near Flores and Corvo is not definitively known and a ridge-jump to transfer them to the opposite side may or may not have occurred. There have been many ridge-to-paired-transform faults jumps at the Bouvet triple junction, but we don't see how this could have caused Bouvet Island to switch sides.

Shona (51.4°S, 1.0°E) w= .3 az= 074° ± 6°

There is a region along the crest of the southern mid-Atlantic Ridge, between 51°S and 52°S, where MORB has a very pronounced hotspot affinity. However the exact location of the 'Shona hotspot' proposed to account for this is not unambiguously resolved. Hartnady and le Roex

(1985) propose 'Shona Seamount' (54.5°S, 6.0°W) and this same origin point is used by O'Connor and Duncan (1990) in their reconstruction in their Fig. 7; Garfunkel (1992) proposes a point at 53.1°S, 3.0°W [as measured on his Fig. 7]; Small (1995), referring to a study by Douglass *et al*. (1995), proposes a point near the ridge crest at 51.5°S, 5.7°W. In all of these papers, the bend and discontinuity in the track near Meteor Rise is neatly explained by the large rise-jump of a segment of the mid-Atlantic Ridge south of the Agulhas Fracture Zone 80 m.y. ago (Hartnady and le Roex, 1985).

We propose the present center is at 51.4°S, 1.0°E – the point in the region where the satellite-topography map shows the highest relief. This is the eastern end of the Shona Rise, and our trend (074° ± 6°) is the trend of the Shona Ridge. This is indistinguishable from the fracture zone trend in the area, so we have given this a low weighting. An alternative hypothesis is that Sanders Seamount (52.6°S, 2.0°E) marks the present position and that the track goes through the Davis Seamounts on an azimuth 053° ± 5°, and eventually through Swazi, Zulu and Xhosa Seamounts (see the GEBCO chart for the location of these named seamounts). In this scenario, the Shona Ridge, the join between Shona and Meteor, and Meteor Rise are aseismic-ridge-like features formed at the spreading center by a plume just off the ridge (see Vink, 1984, for a discussion of the geometry of ridge-plume interactions near a fracture zone). The advantage of the second hypothesis is the track is discrete seamounts only (a better marker of plate motion over a hotspot than a continuous ridge); the disadvantage is that the geochemical anomaly at the present spreading center is between 51° and 52°S (more in accord with the Shona Ridge position). There are no ages for any of these features; mapping and dating in this region could establish the true nature of this track.

Madagascar Ridge

There are three major aseismic ridges in the Indian Ocean that are key in the determination of the long-term motions of plates over hotspots. All of these have migrated across a spreading center, with their sources presently located beneath the 'other' plate they add nothing to the present-day direction data set. The source for the Madagascar Ridge is at Marion/Prince Edward Island, its path is in accord with connecting this present hotspot with the Karoo Flood Basalt (*e.g.*, Morgan, 1981; Duncan, 1991; Duncan and Richards, 1991).

Reunion (21.2°S, 55.7°E) w= .8 az= 047° ± 10° rate= 40 ± 10 mm/yr

The oldest rocks at Piton de la Fournaise are 0.4 Ma, with continuing frequent eruptions. The other volcanic center on Réunion, Piton des Neiges, has 'shield building' lavas dated 2.1 to 0.5 Ma (K-Ar method, McDougall and Chamalaun, 1969; McDougall, 1971) with some later alkalic eruptions. We have not taken the straight-line trend from Piton de la Fournaise (on Réunion) to Mauritius (065°) but rather from Réunion to the center of the bank 100 km north of Mauritius (047°) because we think the position of Mauritius is 'pulled toward' the fracture zone at the eastern edge of the Mauritius edifice. The shield-building stage at Mauritius occurred between 7.9 and 5.1 Ma (K-Ar method, McDougall and Chamalaun, 1969) giving this track a measured rate of 240 km / 6 m.y. = 40 ± 10 mm/yr. Emerick and Duncan (1982), using the same data, obtained a rate of 44 ± 5 mm/yr (their Fig. 3, page 422).

Comores (11.5°S, 43.3°E) w= .5 (better is w=C) az=118 ±10° rate=35 ±10 mm/yr

There is a clear trend from Grande Comore (which has two historically active shield volcanoes, La Grille and Karthala) to Mayotte (250 km away) of 123° ± 5° and a longer trend (500 km long) from Grande Comore to Mayotte to Geyser Reef to Levin Bank at a trend of 100° ± 5°. We have chosen an azimuth from Grande Comore of 118° ± 10°, emphasizing the more recent 250 km of this trend. The islands have all been dated, and their ages and distance from La Grille are as follows: Karthala, 0.13 ± 0.02 Ma, 30 km; Moheli, 2.8 ± 0.2 Ma, 100 km; Anjouan, >1.2 Ma, 140 km; Mayotte, 5.4 ± 0.2 Ma, 250 km (all K-Ar ages, Emerick and Duncan, 1982). Nougier *et al.* (1986) find older ages for these islands: Moheli 5.0 ± 0.4 Ma, Anjouan 3.9 ± 0.3 Ma, Mayotte 7.7 ± 1.0 Ma (all K-Ar method). Using the later data set we find a rate of 35 ± 10 mm/yr; Emerick and Duncan (1982, their Fig. 3) get a rate of 50 ± 8 mm/yr.

However this trend (118°) is at nearly right angles to the predicted motion (045°) of the African plate based on the trends of all of the tracks from Hoggar to Reunion listed above. Why? We have considered that 'East Africa' is a separate plate with slightly more westward motion than the main part of Africa as it moves away from the East African Rift, but the numbers don't work out right, and the Reunion track agrees with our 'main-African' motion. Another possibility is the Comores hotspot track has been deflected to the east by the interaction of the 'spreading out' of the asthenosphere brought up by the plume with the thick continental lithosphere of Africa on its east as compared to the thinner lithosphere of the oceanic region on its west, but again we don't see how this mechanism can be adapted to interpret the Comores trend (probably just the opposite would result). (This mechanism will be discussed at greater length in the section on Eastern Australia and at Hawaii and the Marquesas.) Another possibility is that the plate is very slowly extending here – the 'track trend' is parallel to the axis of extension of the NW-SE trending Anza Rift system that goes from Lake Turkana in northern Kenya out to the coast of Kenya – and that Comores volcanism is not a hotspot but marks the boundary between the 'Somalian plate' and the main 'African plate'. However, this Anza Rift is a Cretaceous / Early Tertiary sedimentary basin; there is no evidence of present-day extension (Zeyen *et al.,* 1997; Bosworth and Morley, 1994). Perhaps combining these two – the sub-continent asthenosphere flows eastward, the lithosphere thickness change at the ocean/continent transition is not enough to produce pressure-release melting near the shelf edge (the age of the seafloor here is ~140 Ma), but if the Early Tertiary 'Anza Rift' thinned oceanic lithosphere in the Comores region then the melting occurs there.

In short, we really can't account for the Comores discrepancy. There is a trend (100°-125°), there is a rate (30-55 mm/yr), and the lava type and eruption style are 'hotspot-like'. The negative 'evidence' is the direction and rate 'seem wrong', the only entry in our analysis to be so discrepant. We keep the Comores azimuth and rate in our data set with a weight of **w** = 0.5; from its uncertainty error bars alone it would get 0.8, so this entry has been down-weighted one unit but kept in the data set. This is the only entry in our list where a weighting factor is assigned where the hotspot quality is not *A* or *B*, because of the unique discrepancy here we have given this a quality factor of *C*.

Kilimanjaro (3.0°S, 37.5°E) w= B

Karisimbi (1.5°S, 29.4°E) w= B

Mt. Rungwe (8.3°S, 33.9°E) w= B+

There are several 3000-m-plus volcanoes along/near the East African Rift that appear to have deep mantle magma sources: Mt. Elgon (1.2°N, 34.6°E, 4320 m, with nepheline lavas, Simonetti and Bell, 1995), Mt. Stanley (0.3°N, 29.8°E, 5120 m), Mt. Karisimbi (1.5°S, 29.4°E, 4510 m, with mafic potassic basanites, Rogers *et al*., 1992), and the interesting Mt. Rungwe (8.3°S, 33.9°E, 3170 m, with nephelinites, Furman, 1995) and Ngorongoro (3.2°S, 35.6°E, 3650 m). [One in this group, Lengai (2.7°S, 35.9°E, 2880 m) is very unique, with carbonate lavas (Bell and Simonetti, 1996) that appear to be CO_2 from the deep mantle -- this must make diamond miners weep!] The thick continental lithosphere pulling apart must cause upwelling to ‘fill the crack’ to come up from 100-200 km depth, thus giving lavas here with very small melt fraction and which are enriched with ‘deep’ components. There could also be below-the-lithosphere flow from some nearby mantle plume which would give a 'plume signature' to these lavas. (In particular we think the volcanoes in Ethiopia down to Lake Turkana are fed by channeled flow from the Afar hotspot.) Of all the volcanoes along the rift, we think Mt. Rungwe near the East Rift -West Rift - Lake Malawi juncture is the most likely candidate for a hotspot, and it has a long history of activity.

The most striking topographic features in East Africa are Mt. Kenya and Mt. Kilimanjaro. We suspect the Kenya Rift Zone, which is a recent sedimentary extension basin and which includes Kilimanjaro and Kenya and runs out to sea here toward the Comores is the important 'plate boundary' here. This is east of the better marked (via earthquakes and volcanism) Eastern and Western Rifts which run southward to Lake Malawi. We have also considered that these volcanoes mark a hotspot track on the African plate. We have great difficulties with ages on continental hotspot tracks, often there are tens of millions of years time lag before continental tracks ‘turn off’ (see for example the references on the ages along the Yellowstone and Eifel tracks). Mts. Kenya (0.1°S, 37.4°E, 5200 m) and Kilimanjaro (3.0°S, 37.5°E, 5890 m) appear equally active but we will assume that only one marks the hotspot. We assume that Kilimanjaro and its nearby neighbor 4570 m high Mt. Meru, which both have alkali affinities (Roberts and Gibson, 2003), are presently above the plume and that the 300 km separation between these and Mt. Kenya means Mt. Kenya was over the hotspot 15 m.y. ago but still erupts occasionally (this estimate based on the distance and our modeled velocity of the African plate of 20 mm/yr in this direction).

Antarctic Plate

Marion (46.9°S, 37.6°E) w= .5 az= 080° ± 12°

There is a trend here (080°± 12°) that appears not to be influenced by ridge-hotspot interaction although it is possible that these are due to asthenosphere flow from 'Ob-Lena' to the Southwest Indian Ridge. If the ages of Gallieni Knoll or Africana II Rise were known in relation to the seafloor ages, perhaps the independence of this hotspot could be firmly established. Its distance from Ob-Lena is about the same as Kerguelen to Heard, or Eastern Australia to the Tasmantid track. There are a few K-Ar ages on Marion and neighboring Prince Edward island; all are less 0.5 Ma (LeMasurier and Thomson, 1990, p. 411-417), not enough to make a guess at a rate.

Crozet (46.1°S, 50.2°E) w= .8 az= 109° ± 10° rate= 25 ± 13 mm/yr

This is more a blob than a line on the satellite gravity chart, but a poorly defined short trend with strike 109°± 10° can be seen. All five island groups in the archipelago have evidence of some recent volcanism, except for Îlots des Apôtres. The easternmost islands of this group, Île de l'Est (46.4°S, 52.2°E) and Île de la Possession (46.4°S, 51.7°E), have K-Ar ages of 8.8 Ma and 8.1 ± 0.6 Ma respectively (LeMasurier and Thomson, 1990, p. 423-428). On the westernmost island, Île aux Cochons (46.1°S, 52.2°E), the oldest age is 0.4 Ma and on nearby (30 km SE) Île des Pingouins the oldest age is 1.1 Ma (Giret *et al.*, 2002). However another small island group near Cochons (Apôtres, about 20 km NE of Cochons) has a date of 5.5 Ma (Giret *et al.*, 2002), greatly confusing the picture. The 220 km length track and oldest age of 8.8 Ma gives a 25 mm/yr plate speed. Since these are all unconstrained K-Ar ages and there is large scatter introduced by the age of Apôtres, we guess the error bars for the rate are ±13 mm/yr. Perhaps a slight trend and rate can be seen here and not at Kerguelen as a result of Kerguelen being much larger in output and thus overprinting its track much like happens at the Cape Verde Islands.

Ob-Lena (52.2°S, 40.0°E) w= 1 az= 108° ± 6°

There is a 700 km long trend from a small seamount west of Ob to Ob to Lena to Marion Dufresne seamount with a strike of 108° ± 6°, best seen on the satellite gravity map (Smith and Sandwell, 1997). There are no ages on this trend and Lena (< 500 m) is shallower than Ob (< 1000 m), but we assume the western end is the young end of the track. Our model velocity for the Antarctic plate here is 8 mm/yr, suggesting the 700 km long line would take 90 m.y. to form.

Kerguelen (49.6°S, 69.0°E) w= .2 az= 050° ± 30° rate= 3 ± 1 mm/yr

The Holocene activity at Kerguelen has been confined to the southwest corner at Rallier du Baty (49.6°S, 69.0°E) , although there has also been extensive activity in the last several hundred thousand years at neighboring Mont Ross (the highest point in Kerguelen, at 1840 m) which is 40 km east of Rallier du Baty. The oldest part of the island, near the northwest coast, has K-Ar ages of up to 30 m.y., giving an estimate of migration of 3 ± 1 mm/yr. This information about Kerguelen is very nicely summarized on pages 431-433 of LeMasurier and Thomson, 1990. There is no clear direction of volcanism but we have estimated an azimuth of 050° ± 30°. Most of the Kerguelen Plateau is deeper than 1000 m, exceptions being near Kerguelen and Heard Is. A shallow area enclosed by the 200 m contour is elongated to the northeast and extends out to edge of the plateau (to where in a few tens of kilometers it suddenly drops to 2500 m depth) 250 km from Kerguelen (page 349 of Wise, Schlich, *et al*., 1992). If this is interpreted as an average of the earlier track, we have a longterm-average rate of 250 km / 43 m.y. (the age when Kerguelen separated from the Ninetyeast/Broken Ridge, Munschy *et al.,* 1992) which equals 6 mm/yr along an average azimuth of 020° ± 15°.

The exposed area of Kerguelen is less than the 'Big Island' of Hawaii, and it has an eruption history of about 30 m.y. as opposed to only 1 m.y. at Hawaii. As we suggest for the Cape Verde Islands, we think the 'stalling' of the plate at Kerguelen has allowed the accumulation of a very large less-dense, more-viscous root made of the residue of melting beneath Kerguelen. This root extends to sufficient depth to inhibit the pressure-release melting that causes surface volcanoes – *i.e.,* the upwelling of the plume at Kerguelen may be far larger than inferred from the amount of surface volcanism and we assume this large flux flows laterally in the asthenosphere to feed the mid-Indian Ridge.

A very different interpretation has been presented by Weis *et al*. (2002). They propose the origin of the Kerguelen track is now at Heard Island, moving the 500 km separating Heard from Kerguelen in the 30 m.y. since the time of major volcanism on Kerguelen. (That is, choosing an azimuth of 330° and a rate of 16 mm/yr.) Supporting this is an alignment of prominent features between Heard and Kerguelen. Two features (~60 km apart) located midway between Heard and Kerguelen were dated and both have ages within the range 18 to 21 Ma. We don't favor this model. As discussed above, there has been extensive volcanic activity on Kerguelen in the last several hundred thousand years. There are many examples of 'embarrassingly late volcanism' on continental tracks, but we know of no cases where hotspot activity is separated from a plume center by 500 km and 30 m.y. We prefer two sources, one for Kerguelen and one for Heard (begging the question why would two sources be only 500 km apart – we address this problem of paired-sources in our Inferences section).

Heard (53.1°S, 73.5°E) w= .2 az= 030° ± 20°

Heard and McDonald islands are 500 km southwest of Kerguelen. Heard (about 10 km diameter, see Clarke *et al.,* 1983) is very active with a 2742 m high volcano that has had several flows in historical times; the McDonald island group (60 km due west of Heard) is much smaller (about 2 km diameter) and has flows dated about 50,000 yrs (LeMasurier and Thomson, 1990, p. 439). The directions and distances from McDonald to Heard are about the same as from Rallier du Baty to Mont Ross, and in both cases the volcano in the east is the higher. More significantly, the 200 m and 500 m contours around Heard extend to the northeast in a pattern very similar to the shallow area northeast of Kergulen (from the bathymetry map on page 349 of Wise, Schlich, *et al*., 1991, we see a long-term trend of 030° ± 20°). We think this is another hotspot smaller than Kerguelen but perhaps responsible for part of the Kerguelen Plateau and at an earlier time for part of Broken Ridge and perhaps even Gulden Draak Knoll and Batavia Knoll north of Broken Ridge.

Gaussberg (66.8°S, 89.3°E) w= C

The very potassic volcanism (Collerson and McCulloch, 1983) at the isolated Gaussberg suggests a 'continental type' hotspot here, but there is no evidence to define a track. It does not appear to continue along the Gaussberg Ridge that extends from here to Kerguelen. Gaussberg has a diameter of about 1 km and rises to 370 m elevation; its outcrops are all pillow-structured leucites. It is apparently 55,000 years old based on K-Ar and fission track data (LeMasurier and Thomson, 1990, p. 448). See also Tingey *et al*., 1983. Its location at the edge of the continent could be the result of a plume centered somewhere beneath Antarctica – the plume's ascent there is stopped by the thick lithosphere of East Antarctica before any melting occurs. Asthenosphere flowing horizontally away from this source goes upward at the ocean-continent boundary; the resulting pressure-release-melting producing the magmas at Gaussberg. (See the description of the East Australia track for further discussion of this possible mechanism.)

Balleny (67.6°S, 164.8°E) w= .2 az= 325° ± 7°

This is a very difficult track to interpret. The track is 300 km long with no radiometric ages, but the larger islands (Sturge, Buckle, and Young) are at the southeastern end with the smaller Balleny Seamounts to the northwest. The largest and highest of the islands, Sturge, is at the southeast end of this trend, and eruptions on Buckle Island were sighted in 1839 and 1899 (LeMasurier and Thomson, 1990, p. 449). The trend of the islands and seamounts (325° ± 7°) is nearly parallel to the strike of fracture zones in this area (327° ± 3°). The trend is very sharply defined, but we give Balleny a very low weight (0.2), strongly suspecting it is fracture zone and not hotspot-plate-motion controlled. Gaina *et al*. (2000) examined Balleny in a recent paper (see especially their Fig. 20); they also concluded its alignment is probably related to the trend of the fracture zone.

Scott (68.8°S, 178.8°W) w= .2 az= 346° ± 5°

This is a short chain (5 island/seamounts, 200 km long) but with an azimuth clearly different from the fracture zones of the region. Only five samples have been collected from Scott (all in the alkalai basalt trend) and there are no ages for this track (LeMasurier and Thomson, 1990, p. 452). The largest feature, Scott Island, only 300 m across, is at the northern end which suggests a direction 180° different from what we have chosen. It could be that this chain is the result of hotspot-to-ridge asthenosphere flow coming from Erebus. Because of this uncertainty we give it a weighting of 0.2. The azimuth (346° ± 5°) comes from the satellite gravity map (Smith and Sandwell, 1997), not the GEBCO chart (which gives 002°).

Erebus (77.5°S, 167.2°E) w= A

Erebus (77.5°S, 167.2°E, 3800 m) has been in continuous eruption since its discovery in 1841. Its magmas are very similar to ‘continental’ hotspot volcanics in East Africa. The two other large volcanoes on Ross Island, Mt. Bird and Mt. Terror, each within 30 km of Erebus, are basaltic shield volcanoes with K-Ar ages of 3.8-4.8 and 0.8-1.8 m.y. respectively. There is a very clear trend of volcanism (Beaufort Is., Franklin Is., numerous recent seamounts in the Ross Sea, and Mt. Melbourne) extending 400 km almost due north of Erebus. There is also a clear alignment 200 km almost due south of Erebus (Hut Point, Brown Peninsula, Black Island, Mt. Discovery) extending even farther south to Mt. Early. We think this older part is not a hotspot trend but instead due to continental rifting along this line – the 'Terror Rift' depicted on page 20 of LeMasurier and Thomson, 1990. We think Erebus is the site of a major hotspot that has lead to the spreading of Terror Rift (and the West Antarctic Rift discussed in the next paragraph on Marie Byrd Land), but that the trend cannot be used to define plate motion. This analysis of Erebus is based on summaries in LeMasurier and Thomson, 1990, pages 20-25, 81-85, and 97-107.

Marie Byrd Land (~77°S, ~130°E) w= C

LeMasurier and Thomson, 1990, show the 'West Antarctic Rift' on Fig. I (page 2) of their review of Antarctic volcanism, and discuss (pages 10-15) that this is an area the same size as the Basin and Range of the U.S. or the East African Rift Valleys and has a thin continental crust (25 km). Some reconstructions of 'Gondwanaland' show an overlap of the Campbell Plateau with the coast of Antarctica (Marie Byrd Land) unless this rift is closed a few hundred kilometers (De Wit *et al.*, 1988) – implying that this rift has opened its full width in the last 80 Ma, the age of separation of Antarctica from the Campbell Plateau as documented by seafloor magnetic anomalies (Cande *et al.*, 1995). There are many shield volcanoes (18 large central volcanoes, 30 small satellite volcanic centers, LeMasurier and Thomson, 1990, page 147) in a 900 km long by 200 km wide band, plus the isolated Mt. Siple. Potassium-Argon data of these peaks are generally in the 0-15 Ma range, with two isolated places with ages as old as 30 Ma. We do not see any age trend in the data (see LeMasurier and Rex, 1989). We think, as LeMasurier and Thomson, 1990, pages 160-161, that these mark the northern edge of the West Antarctic rift system. But the rift itself probably signifies the presence of a hotspot, see the discussion at the end of the section on the Yellowstone track. We guess the region of most volcanism marks the spot.

Peter I (68.8°S, 90.6°W) w= B

This is a large isolated volcano 400 km north of the West Antarctica coastline and 200 km north of the continental shelf with no apparent track. The island is roughly 12 km in diameter and rises to 1700 m elevation with a small (100 m diameter) crater at the summit. Several landings have been made; the rocks are described as interbedded flows of basalt and more siliceous lava (*i.e.,* intermediate between tholeiitic and alkali-olivine basalt). One flow has been dated (K-Ar age = 12 ± 2 Ma); the crater at the summit implies much more recent activity. This information was extracted from LeMasurier and Thomson, 1990, p. 454, and Bastien and Craddock, 1976.

Note that Peter I, Marie Byrd Land, Scott, Erebus, and other volcanics extending up into the Tasman basin, are grouped as a diffuse alkaline magmatic province in the review by Finn *et al.,* 2005.

South American Plate

Rio Grande Rise and Walvis Ridge

This pair of aseismic ridges played a very important role in the development of the theory of hotspot tracks (see Wilson, 1963). There is only one good age from the Rio Grande Rise (DSDP Site 516, Mussett and Barker, 1983) but many from the Walvis Ridge (*e.g.*, O'Connor and Duncan, 1990). However it's the geometry of the ridges, not measured ages along them, that has proved so useful in finite reconstructions. The fact they are paired implies the source was centered close to the ridge, thus time and the east-west component of plate position is determined by the age of seafloor (magnetic anomalies) and the north-south component of plate motion on the two sides comes from the geometry. The measured ages along the ridges have mainly provided confirmation these assumptions are correct. Several papers have relied strongly on these ridges to find the paths of plates over a hotspot reference frame (*e.g.*, Morgan, 1983; Duncan and Richards, 1991). Note Tristan has been used as the fixed-point source of these ridges, not Gough.

Martin Vaz (20.5°S, 28.8°W) w= 1 az= 264° ± 5°

This is the best track on the South American plate -- the line of seamounts is very clear and easy to measure (1200 km long, 80 km wide) and their direction differs slightly from the fracture zone direction in this part of the Atlantic. Unfortunately there is not a measured age relation along this chain; there is a $^{40}Ar/^{39}Ar$ age of 2.4 Ma on Trindade (Bernat *et al.*, 1977) 50 km from Martin Vaz, but only this one dated point. (Martin Vaz itself has a variety of K-Ar dates ranging from zero to 80(!) Ma, pages 106 and 110 of Herz, 1977.) Where the chain reaches the Brazilian coastline (Abrolhus), ages are ~50 Ma, and at Alto Paranaíba, an equal distance farther, there is an alkaline intrusive province dated at 85 Ma (Gibson *et al.*, 1995) which is in accord with the predicted motion of South America over this hotspot, but these are too long a time-average to use for a rate. A recent discussion of this track is in Filho *et al.* (2005). Thompson *et al.* (1998) note the predicted position of the Martin Vaz track (from ~50 to 80 Ma) is several hundred kilometers inland from the coast but volcanics occur along the coast. They propose the rising plume strikes a thick continental lithosphere and melt is deflected toward the thinner-lithosphere coastal region – see especially their page 1522 and Fig. 15. This is another example of the mechanism we discuss in more detail in the section on the East Australian track and in Phipps Morgan (1997) and Morgan and Phipps Morgan (2002)

Fernando de Noronha (3.8°S, 32.4°W) w= 1 az= 266° ± 7°

This is also a very good line, the chain is 500 km long, 30 km wide, and differs from the fracture zone trend. There are several K-Ar dates around 9 Ma and a $^{40}Ar/^{39}Ar$ date of 11 Ma on

Fernando de Noronha (Bernat *et al.*, 1977). The other peaks in this chain have not been dated, although there are ~30 Ma volcanics onshore in Brazil near Fortaleza (Schultz *et al.*, 1986). We think there is 'channeled flow' in the asthenosphere (Morgan, 1978) from Fernando de Noronha toward the nearest part of the mid-Atlantic Ridge, the St. Peter and St. Paul Rocks. At an earlier time the Cerra and Sierra Leone ridges may have been associated with this hotspot.

Ascension (7.9°S, 14.3°W) w= B

This is a nice hotspot-type-island, but there is no track. The Bahia Seamounts near the Brazilian coast are in position to be the oldest part of this track: two of these have $^{40}Ar/^{39}Ar$ ages of 62 ± 4 and 78 ± 5 Ma (Cherkis *et al.,* 1992). It has been proposed that Circe seamount 500 km to the east on the African side is the real hotspot and Ascension is an on-ridge island formed by channeled flow (Minshull *et al.,* 1998). Circe (at 8.2°S, 9.3°W) has now been dated at 6.6 Ma ($^{40}Ar/^{39}Ar$, O'Connor *et al.*, 1999). It is built on seafloor ~25 Ma old so is active in some sense, their suggested location for the 'zero' is ~130 km SW of Circe. There is really not enough data in this area to decide if Ascension is over a plume or not, or if it was somehow made from a 'source' on the African side. (Ironically, Ascension is one of the ocean islands that Paul Gast (1969) first studied to show that ‘ocean island basalts’ had a different chemistry than ‘mid-ocean ridge basalts’; his idea directly led to the idea that such islands were fed by plume-like upwellings from the lower mantle.)

Guyana (5.0°N, 61.0°W) w= B

We suspect that the Guyana highlands (5°N, 61°W, elevation 2800 m) are uplifted because of a plume beneath the continent here, but there are no data to define a track.

North American Plate

Iceland (64.4°N, 17.3°W) w= .8 az= 287° ± 10° rate= 15 ± 5 mm/yr

We think the hotspot center is beneath Grimsvötn on Vatnajökull, and that the track on the North American plate for the past 10 m.y. goes through the Snaefellsness Peninsula (287° ± 10°). However there is a lot of ridge-hotspot interaction here, and the line Snaefellsness-Lange-Hof (274° ± 4°) also marks an old fracture zone, so this is down-weighted a little. As said in the entry for the Iceland track on the European plate, we think the velocity is known, 15 ± 5 mm/yr (*i.e.*, 3/4 of the total opening of the Atlantic).

Bermuda (32.6°N, 64.3°W) w= .3 az= 260° ± 15°

Bermuda has an age of 33 Ma (from drilling to its basaltic basement, Reynolds and Aumento, 1974). A fairly clear track can be traced across the continent – at Cape Fear ~65 Ma, at the Great Smoky Mountains ~75 Ma, in Missouri ~90 Ma, and in Kansas ~100 Ma based on topographic uplift and some very alkalic volcanics along this track (Morgan, 1983; Nkhereanye, 1993). However the recent part of this track has no volcanic markers other than Bermuda itself and our azimuth of 260° ± 15° is based on the asymmetric swell of the seafloor extending a little north of due east of Bermuda, about a quarter of the way to Muir Seamount.

Yellowstone (44.5°N, 110.4°W) w= .8 az= 235° ± 5° rate= 26 ± 5 mm/yr

Our primary references for the Yellowstone track are Pierce and Morgan (1992) and Smith and Braile (1994). The track is well marked by coalesced calderas, see Plate 1 of Pierce and Morgan (1992) who state (page 5) that the eastern Snake River Plain is an “80 ± 20 km wide, linear, mountain bounded trough … floored by nearly overlapping calderas its entire length”. From their Plate 1, we measure an azimuth of 235° ± 5° for the eastern part of the Snake River Plain (they state 234°). Pierce and Morgan plot the ages of the calderas in their Fig. 3 and find a rate of 29 mm/yr for the last 10 Ma (back to the Picabo Volcanic Field located between Pocatello and Craters of the Moon) to which we find an error range of ± 5 mm/yr. Anders (1994) determines the velocity of Yellowstone by a different manner – he looks at the time transgressive activity of fault movements in the mountainous 'bow wave' around Yellowstone. Using data from the last 8 m.y., Anders finds a rate of 22 ± 2 mm/yr, which he says has been corrected for the extensions of the faulting. For the most recent 2 m.y. of the track, the extensional faulting runs north-south (*e.g.*, the Teton Fault) oblique to the track of Yellowstone, and there is a small kink in the overall trend for this most recent part between the Island Park Caldera and the Yellowstone Caldera. However for the main part, between the Island Park Caldera and Picabo Volcanic Field (Plate 1, Pierce and Morgan, 1992), extensional faults cut perpendicularly across the Snake River Plain so any extension wouldn't change the direction we found above. We cannot estimate how much extension on these faults across the plain affects our rate, so we choose a rate halfway between the 'no extension' value and the rate determined by Anders (1994). Thus an azimuth of 235° ± 5° and a rate of 26 ± 5 mm/yr is our estimate of the motion of North America over the hotspot.

For the part of the Yellowstone track between 10 Ma and 16 Ma, Pierce and Morgan (1992, page 8 and Figs. 1 and 3) have a well defined track oriented 252° at a rate of 70 mm/yr. We now try to correct this for extension of the Basin and Range in the manner proposed by Rodgers *et al.,* 1990. Northeast of the Picabo Volcanic Field, the extensional faults cross the Snake River Plain essentially perpendicularly. But starting at Pocatello, on the northern extension of the continuation of the Wasatch Fault, the faults change orientation and here and further west all the Basin and Range faults are aligned north-south to NNE-SSW. There have been several papers on GPS-VLBI-SLR measurements of spreading of the Basin and Range; see Bennett *et al.*, 1998 and Wernicke *et al.*, 2000. Using measurements made at 13 permanent GPS stations in a band near 40°N, they find to first order a uniform strain rate of 0.01 μstrain/yr across the 1000 km line form east of the Wasatch Fault to west of the Sierra Nevada (with total spreading between the endpoints of 11 ± 2 mm/yr). Combining the north and east components of motion, we get a (uniform) strain rate of 0.013 μstrain/yr oriented in the direction 300°. The early part of Yellowstone's track has been stretched since its formation. The present position of the track between 16 Ma and 10 Ma is 420 km long oriented along 252° (70 mm/yr). The component of this parallel to the stretching direction (300°) is 281 km. A line now this length straining at 0.013 μstrain/yr for 13 m.y. (some started at 16 Ma, some at 10 Ma) gives a change in length of 40 km for a line initially 241 km long – giving the orientation before stretching of 248° (only 4° different) and a rate of 65 mm/yr. In order to 'correct' this stretched part to the azimuth of the more recent track (235°), the line now 281 km would have had to have been only 140 km long 'pre-any-stretching' – *i.e.,* have had 100% strain (6 times the present rate). However, even with this 140 km extension (100% extension) the rate of the Yellowstone track would not be changed much (to 57 mm/yr from the present 70 mm/yr [if the 'ages' are separated to their present day positions]) even though this would make the azimuth the same as the recent track. There are papers in which 140 km of extension in this northern part of the Basin and Range are estimated (Sonder and Jones, 1999, review several earlier papers and conclude "extension across eastern Nevada and western Utah has been placed at about 120-150 km"). Assuming this is uniform staining, constant for the last 16 m.y., we can calculate a correction of 140 km / 16 m.y. = 9 mm/yr.

We think the azimuth and rate of the North American plate over Yellowstone are fairly well documented, however we have slightly downweighted this track (w = 0.8) because of the stretching of the crustal rocks along its track. If there is a mystery about Yellowstone, it's did it initially 'wander' extensively in the mantle at the time of its birth (*i.e*., where was it at the time of the Columbia River Flood Basalts?). We subscribe to the arguments of Geist and Richards, 1993, that it was deep beneath 'Oregon' and that its emergent point in the upper mantle was deflected northward by the oblique nature of the subducted plate beneath the Cascades region. As suggested by Saltus and Thompson (1995), we think there is a close connection between Yellowstone and the Basin and Range.

Raton (36.8°N, 104.1°W) w= 1 az= 240°± 4° rate= 30 ± 20 mm/yr

We think this is the best track on North America. It is mostly in the unbroken / unstretched High Plains and Colorado Plateau, so the question of azimuth modification discussed above for

Yellowstone would not apply – the extension at the Rio Grande Rift is minor. The volcanism along this track is well illustrated in Fig. 1 of Gibson *et al*. (1992) or the map by Luedke and Smith (1978). We place the 'zero' of this track at 36.8°N, 104.1°W, near the center of Holocene volcanism in the Raton-Clayton volcanic field. [An alternative position would be at 37.1°N, 103.5°W, near Mesa de Maya (100 km NE of Raton) but there is very little information on Mesa de Maya. Hager (1974) reports whole-rock K-Ar measurements of 3.5 ± 1, 3.4 ± 1, and 3.2 ± 1 Ma at Mesa de Maya. These ages are not very reliable; the samples were 'somewhat weathered', they were not baked to eliminate atmospheric argon and the radiogenic ^{40}Ar is only 3%-6% of the total argon in all the samples, and these '3.3 Ma' basalts are 100 m stratigraphically higher than a 2.5 Ma fossil layer.] With either of these volcanic fields as 'center', the strike of the track is a well determined 240° ± 4° on the Gibson *et al*. (1992) or Luedke and Smith (1978) maps.

In contrast to the clear azimuth, the rate along the track is very difficult to determine. Our main source for the Raton-Clayton field (at 'zero') is Scott *et al.,* 1990. There are 16 sites measured with mostly whole-rock K-Ar ages and 3 sites studied with zircon fission track ages; 3 ages are less than 1 Ma, 4 ages are between 1 and 4 Ma, 12 between 4 and 8 Ma, and 7 between 20 and 30 Ma. However there are large discrepancies among the measurements – ages of 4.4 ± 1.3 and 7.6 ± 1.1 Ma where obtained with repeat measurements for the same sample, as were ages of 6.9 ± 0.8 and 21.8 ± 2.2 Ma for another sample! Most interesting among the flows (which cover an area about 50 km across) are several lamprophyric rocks and kimberlites. The ages of these are also very confusing. A 9 meter basanitic dike (a lamprophyre in composition but not in texture) is dated at 24.1 ± 1.0 Ma (hornblende, K-Ar), but there is no discussion of excess argon; another dike has an age of 15.6 ± 0.7 Ma (whole-rock, K-Ar). The kimberlite diatreme contained a sandstone block containing a zircon dated by fission-track method at 30.1 ± 1.2 Ma ('which represents the time of resetting resulting from the heat of the intrusion'); a second zircon from the same sandstone gave an age of 25.5 ± 1.3 Ma. It is not perfectly clear that these fission-track ages are the age of the diatreme.

The first dated unit along this line is 120 km southwest of the Raton center, the Ocate

Volcanic Field (60 km × 40 km), which is some 50 km east of the Rio Grande Rift. This field contains some flows between 8 and 5 Ma on the highest mesas (at a present elevation of 3,000 m), some between 4 and 5 Ma at cap intermediate elevation mesas, but the most voluminous are the younger flows at lower elevations dated between 3 and 0.8 Ma. (These data, all K-Ar whole-rock ages, are from O'Neill and Mehnert, 1988).

Next in line is the Jemez / Valles Caldera structure, 240 km from the Raton center. The oldest ages reported here are 7.8 ± 0.7, 7.9 ± 0.5, 7.6 ± 0.4, and 7.8 ± 0.5 Ma in basalt flows along the northern edge of the Jemez volcanic field (all K-Ar whole-rock, Manley and Mehnert, 1981) and 7.0 – 6.7 Ma deposits in the Bearhead-Peralta units (Smith, 1999). (And of course many eruption products in the last 3 m.y.)

Next in line is the Mount Taylor field, 340 km from Raton. The best reference for ages here is Laughlin *et al*., 1993. The oldest ages they report are 3.2 ± 0.1 and 2.9 ± 0.1 Ma (K-Ar, groundmass feldspar concentrate) along the southern edge of Mount Taylor, and they have a discussion of 30 earlier reported ages of Mount Taylor, concluding that many of these (ranging from 4.1 to 9.9 Ma) are 'too old' because of excess argon. The same publication reports on the Zuni-Bandera field (420 km from Raton). Here the oldest ages are on Cebollita Mesa, located ~20 km east of the mostly <1 Ma Zuni-Bandera lavas. The Cebollita basalt was measured with the $^{40}Ar/^{39}Ar$ technique (plateau, whole-rock); the 3 measurements are 4.04 ± 0.13, 3.51 ± 0.03, and 3.97 ± 0.02 Ma – in general agreement (within 1 Ma) of earlier K-Ar measurements here. The last on this line is the Springerville volcanic field, 580 km from Raton. The oldest ages at Springerville are 8.7 ± 0.2 and 9.0 ± 0.2 (K-Ar) on Mount Baldy; there are a few ages between 5.3 and 7.6 Ma at Springerville, but over 80% of the samples studied erupted within the last 2 m.y. (Condit and Connor, 1996).

The distances from Raton and oldest ages of these units give the following rates: Ocate ~20 mm/yr, Jemez ~30 mm/yr, Mt. Taylor ~100 mm/yr, Zuni-Bandera ~100 mm/yr, and Springerville ~60 mm/yr. For this to be a continuously moving hotspot, we have to assume that the earlier parts of the track had no volcanic units that made it through the lithosphere/crust to the surface (or that they are completely covered by the more recent flows). We conclude with an almost worthless rate: ~30 mm/yr with very large error bars.

Azores (37.9°N, 26.0°W) w= .3 az= 280° ± 15°

We think the islands on the North American side (Flores, Corvo, and the large guyot dated at 4.8 Ma (K-Ar method) 50 km west of Flores [Ryall *et al.*, 1983]) have a hotspot-to-spreading-ridge origin similar to Darwin and Wolf in the Galapagos (see Morgan, 1978), although we know of only one other clear example where the 'island' is on the plate furthest from the hotspot (Amsterdam and St. Paul are on the 'Indian side' away from Kerguelen due to a recent southward jump of the SWI ridge). (Another less certain case is Bouvet.) Perhaps near Flores and Corvo there is evidence in the magnetic anomalies for a recent eastward jump of the mid-Atlantic Ridge. To determine the 'absolute' motion of the North American plate here requires knowing where the hotspot is (we have guessed somewhere near São Miguel) and the exact migration of the mid-Atlantic ridge relative to the hotspot (see Vink, 1984, for details). We have not done a complete analysis, but roughly the North American motion here is 280° ± 15°. Because of ridge interaction effects, we give this a very low weight (0.3).

New England Seamounts

The New England seamounts mark the most striking and best dated (Duncan, 1984, $^{40}Ar/^{39}Ar$ method) track in the North Atlantic. Their ages range in a linear fashion from ~100 Ma near the coast and to ~80 Ma farthest from the coast. The on-land early-extension of this track crosses the White Mountains of New Hampshire, the volcanics of the Monteregian Hills, and northwestward into the Canadian Shield west of Hudson Bay. Seaward, a less-clear continuation goes to Corner Rise. East of that, the projected age of the track is younger than the age of the seafloor on the North American side – the track then appears on the African side of the mid-ocean rift as the Great Meteor track (present-day center at 29.4°N, 29.2°W) (See Morgan, 1983, for a discussion.)

Alpha Ridge

The Alpha Ridge (and its eastern continuation, the Medeleyev Ridge) in the Arctic Ocean is apparently the Early Cretaceous and Jurassic portion of the Iceland track (*e.g.*, Forsyth *et al.*, 1986; Lawver and Müller, 1994). This tells us nothing about present-day plate motions, but raises the interesting possibility that the Siberian Traps are the origin of the Iceland plume.

Bahama Banks

Dietz and Holden (1973) proposed the Bahama Banks are a coral cap over an early aseismic ridge formed at the time of the earliest opening of the Atlantic. Using a finite motion reconstruction of 'Atlantic plates' over a fixed hotspot reference frame, Morgan (1983) tried to identify the origin point that the Banks were over at the time of their origin. At that early time the reconstructions are very uncertain, but a candidate is 'Ascension' (or within error, almost any other place in the southern equatorial Atlantic. The recent recognition of the importance of the CAMP event (centered here and southernmost Florida) as a likely cause of the opening of the Atlantic lends credence that this is a very important event which gives a direction of early plate motion over hotspots (but of course no information on the present day motion).

Anyuy (67°N, 166°E) w= B-

A region of high elevation and a recent basaltic volcano (67°N, 166°E) is on the 'North American' side of the tip of Siberia. We suspect a hotspot here, but the evidence for this is *very* weak and this is only a possibility. This is unit 128 in the compilation of Whitford-Stark (1987); see also geologic and tectonic maps of Russia (*e.g.,* Tectonic Map of Eurasia, 1966).

Indo-Australian Plate

Lord Howe (34.7°S, 159.8°E) w= .8 az= 351° ± 10°

Ball's Pyramid and adjacent Lord Howe Island are made of 'typical shield building basalt lavas' and are at the southern end of a 1000 km long straight and narrow chain of ten guyots and banks. (See map in McDougall *et al.*, 1981.) These are about 300 km east of the Tasmantid Seamounts and 200 km west of the enigmatic Lord Howe Rise, which is probably a sliver of Australia torn away about 90 m.y. ago by the opening of the Tasman Sea (Weissel and Hayes, 1977; Gaina *et al.*, 1998). Basalts on Lord Howe Island have a K-Ar age of 6.7 Ma (McDougall *et al.*, 1981). Extrapolating southward of Ball's Pyramid at the expected Australian plate motion rate for 6.7 m.y., McDougall *et al.* found a predicted 'zero age' position for this chain and noted that Flinders Seamount (at 34.7°S, 159.8°E, rising 700 m above the seafloor to 1750 m below sealevel) to be within 50 km of this extrapolated point. We have chosen Flinders to mark the present site, and used the Flinders-to-Lord Howe/Ball direction to mark the recent azimuth of this track (351° ± 10°). No ages have been measured along this chain to give a rate.

Tasmantid (40.4°S, 155.5°E) w= .8 az= 007° ± 5° rate= 63 ± 5 mm/yr

This is the best track on the Indian-Australian plate. It is well dated (McDougall and Duncan, 1988, Fig. 3) by the $^{40}Ar/^{39}Ar$ method and the rate is 63 ± 5 mm/yr. Unfortunately there is little control (*i.e.,* no seamounts) at the very young end of this 60 m.y. long continuous chain. McDougall and Duncan (1988) choose 40.4°S, 155.5°E as the 'zero-age point' – this is the epicenter of a recent large earthquake and agrees with their extrapolation southward of the southernmost seamount (Gascoyne, dated at 7.0 ± 0.1 Ma). Our azimuth is measured from this epicenter to Gascoyne. The lack of recent seamounts is the reason for the slight down-weighting of this chain.

East Australian (40.8°S, 146.0°E) w= .3 az= 000° ± 15° rate= 65 ± 3 mm/yr

This also has a well determined rate (65 ± 3 mm/yr, Johnson *et al.*, 1989, page 48). It does not have good direction control due to interaction with the continental crust. There are 4 leucitite eruptions which we think blast through the continental lithosphere undeviated by the process we describe below. These are in a very straight line (see Fig. 1.1.5 of Johnson *et al*., 1989) and are almost exactly parallel to the Tasmantid track (which is 500 km to the east of this line). Our choice of the position of this hotspot (40.8°S, 146.0°E, at the northern coast of Tasmania) is an extrapolation of the alignment and ages of the leucitite volcanics to ‘zero age’. This position of the present center is strengthened by there being many Quaternary eruptions in this general region of Bass Strait. There are many basaltic eruptions with a north/south age progression along the entire length the eastern coast of Australia. These form an irregular curved line which we think result from interaction of the plume with the contrast between continental lithosphere and oceanic lithosphere found here. We think the plume rising beneath the continent tries to spread out into the asthenosphere in all directions, but that the thick lithosphere beneath the continent tends to block the sub-lithosphere flow toward the west and so most of the flow goes eastward toward the Tasman Sea which has thinner lithosphere (the Tasman Sea all formed 95 to 52 m.y. ago, Gaina *et al*., 1998) and correspondingly has a thicker and hotter (the top part) asthenosphere. As the eastward flowing material from the plume passes from thick to thinner lithosphere near the continental edge, there is pressure-release melting and some basalts rise to be emplaced along the edge of the continent. Although the plume center is several hundred kilometers west of these basalts, the thick continental lithosphere prevents the upwelling plume from rising to a height where melting in the basalt range occurs. Along the track itself there is no basalt but there are several leucitite centers, which form deep at the continental-lithosphere thickness depth and come straight up to the surface. The ages of the basalts (33 Ma in the north to zero in the south) give a north-south velocity for the Australian plate the same as the Tasmantid line and the ages of each of the leucitite centers are same as the coastal basalts at the same latitude. (See Figs. 1.1.5 and 1.7.1 of Johnson *et al*., 1989.) We have arbitrarily given this track a weight of 0.3 – it has good age control but little direction control for its most recent part. The 4 leucitite eruptions alone, ranging in age from 17 Ma to 8 Ma, have very tight azimuth control of 003° ± 2°. See Phipps Morgan (1997) and Morgan and Phipps Morgan (2002) for further elaboration of this mechanism.

Cocos-Keeling (17.0°S, 94.5°E) w= .2 az= 028° ± 6°

Cocos-Keeling Island (at 12.1°S, 96.9°E, a carbonate atoll with no basalt outcrop, Woodroffe and Falkland, 1997) is 150 km north of a large seamount (13.7°S, 96.3°E) which in turn is at the northeast end of a 700 km long ridge that has a trend different from fracture zones in the area. This trend shows up best on the satellite gravity map (Smith and Sandwell, 1997). Not knowing any ages, we are guessing this line is a recent track and not a track of 50 m.y. ago or so. We have chosen a prominent place on the ridge as the hotspot center (17.0°S, 94.5°E), and give this a low weighting because we do not know if it is a recent or ancient track.

Christmas (10.5°S, 105.7°E) w= C

There is a trend (060°) of the Vening-Meinesz Seamounts to Shcherbakov Seamount to Christmas Island, but we think this is some older trend. Christmas Island is 'smack on' the outer ridge of the Java Trench, and we think the present emergence of Christmas Island is due to the outer-ridge uplift as the plate approaches the trench.

Ananasy-Nikitin (4.5°S, 82.6°E) w= C

There is a north-south trend that extends 500 km near this seamount, but we think this is part of an older, unknown track.

Amsterdam - St. Paul (38.7°S, 77.5°E) w= C

We think these are made by channeled flow from Kerguelen to the nearest ridge. Note that these are on the Indian plate, north of the mid-Indian Ridge, an example of islands made by channeled flow from hotspot to nearest ridge that are on the ‘opposite side’.

Ninetyeast Ridge

This is another example where an aseismic ridge is split – first written on one plate, then skips over a spreading center, and continues on the other plate. The hotspot making this is at Kerguelen; before ~38 Ma the spreading center was very near the hotspot and an aseismic ridge formed on the northward moving Indian plate (and presumably beneath what has been covered by more recent eruptions at Kerguelen. The earliest dates along this ridge were from DSDP Leg 22; the dates were fossil dates of the oldest sediment near the basement plus a lone K-Ar date (see Morgan, 1981). Now there is a series of $^{40}Ar/^{39}Ar$ ages (Duncan, 1991) for an improved fit. See for example Table 2 of Duncan (1991) or Table 1 of Duncan and Richards (1991). The projected track proceeds to the Rajmahal Traps north of Bangladesh, the presumed initiation of the Kerguelen hotspot. There are many interesting questions in the neighboring regions, for example how did the Broken Ridge splinter off part of the Kerguelen-Gaussberg Ridge *(a la* Lomonosov Ridge) and what is the significance of the Investigator fracture zone and features in the Wharton basin, but the main features of the Ninetyeast appear well understood.

Mascarene Plateau and Chagos-Lacadive Ridge

The 'zero' of this track is on the African side of the Central Indian Ridge, at Réunion. The older part of the track has been separated from the most recent part by the spreading center migrating over the source. This track adds nothing to our knowledge of present plate motions but clearly shows the connection of the Deccan Traps with the Réunion hotspot. The age progression along the track is well known since ODP Leg 115, there are now many $^{40}Ar/^{39}Ar$ dates (Duncan and Hargraves, 1990). These have been used with other data in the region to determine the history of plate motions in the Indian region (Duncan and Richards, 1991).

Nazca Plate

Juan Fernandez (33.9°S, 81.8°W) w= 1 az= 084° ± 3° rate= 80 ± 20 mm/yr

This is the best track on the Nazca plate – narrow and 700 km long. Its trend is 084° ± 3°; different from fracture zones in the area. Its origin appears to be a seamount 100 km west of Isla Alejandro Selkirk (formerly named Más Afuera) and the track runs into the Peru-Chile Trench (at O'Higgins Guyot, Vergara and Valenzuela, 1982). The seamounts at the western end, Domingo and Friday, are alkalic basalts highly enriched in incompatible trace elements (Devey *et al*., 1993). Alejandro Selkirk is 100 km from Domingo and its age has been measured as follows: 1.0 ± 0.3 Ma (3 samples, K-Ar, Booker *et al*., 1967); 0.9 to 1.3 Ma (K-Ar, Ferrara *et al*., 1969); and 1.0 and 2.4 Ma (2 samples, K-Ar , Stuessy *et al*., 1984). The largest island in this chain, Isla Róbinson Crusoe (formerly Más á Tierra) is 280 km from Domingo. Age measurements here give: 3.3 ± 0.8 Ma (2 samples, K-Ar, Booker *et al*., 1967); 2.0 to 3.9 Ma (K-Ar, Ferrara *et al*., 1969); 3.8 and 4.2 Ma (2 samples, K-Ar, Stuessy *et al*., 1984); and 4.0 ± 0.2 Ma (1 sample, K-Ar, Baker *et al*., 1987). These give rates of 100 km / 1.0 Ma = 100 mm/yr and 280 km / 4.0 Ma = 70 mm/yr for a weighted average of 80 ± 20 mm/yr. Essentially the same data is plotted in Fig. 4b of O'Connor *et al*., 1995, and is labeled "60 mm/yr". However they state "[rotation poles] have been used to adjust the length of the Juan Fernandez Chain so that it is equivalent to that which would have been formed at the latitude of the Galapagos Chain" (so that both data sets could be plotted with the same scale figures). Trying to apply their method to undo this correction in order to infer their measured rate at Juan Fernández, we found their "60 mm/yr" gets converted to 77 mm/yr. To do this we used a pole at 50°N, 101°W which we found to be the average of the three rotation poles they said they averaged, not the 59°S, 101°W that appears in their paper (a typo?). It is curious that even the best measured rates on the Pacific plate are all much faster than our predicted rates. (We expect there to be some 'fast' systematic error in the rates because if volcanism continues long after passage of the hotspot, the same distance is divided by less time; but the magnitude of this on our 'best' tracks is disturbing.) Systematic drift of the Pacific hotspot set relative to the African hotspot set could be the cause of this difference. (See for example the papers by Steinberger and O'Connell, 1998, 2000.) There are 5 large seamounts in the Juan Fernández chain rising to within 1000 m of the surface – dating these would be a powerful test of potential hotspot drift.

San Felix (26.4°S, 80.1°W) w= .3 az= 083° ± 8°

San Félix and San Ambrosio are two small isolated islands about 30 km apart. No trend for a longer track can be seen on the GEBCO chart, but a trend of 083° ± 8° weakly appears for 700 km on the satellite topography map (Smith and Sandwell, 1997). This trend is closely parallel to that of Juan Fernández and is different from the fracture zone trend in this area, but we give this a low weighting because of the only vague resolution of features along this track. San Félix is a recently active volcano – fumaroles are reported and it is listed as a Holocene volcano in Simkin and Siebert, 1994, page 145.

Easter (26.4°S, 106.5°W) w= 1 az= 087° ± 3° rate= 95 ± 5 mm/yr

The trend of the Sala y Gomez Ridge is quite clear: 087° ± 3°. O'Connor *et al*. (1995), on the basis of 8 measurements ($^{40}Ar/^{39}Ar$) show no simple model is found if either Easter or Sala y Gomez islands are chosen as 'zero' for this track but there is a simple fit with a linear rate if the origin is placed about 200 km west of Sala y Gomez. Duncan *et al*. (2003) report an additional 23 ages ($^{40}Ar/^{39}Ar$). Combining these two data sets, we find the best 'zero' is 110 km west of Sala y Gomez, at 26.4°S, 106.5°W (the site of a large seamount on the map of Rappaport et al., 1997), and the rate is a well constrained 95 ± 5 mm/yr.

Our choice of position of the hotspot would mean that Easter Island itself and the large submarine volcanic fields halfway between it and the East Rift of the Easter microplate are formed by channeled flow from the hotspot to the spreading center. Easter Island has been dated by several authors: a $^{40}Ar/^{39}Ar$ age of 0.13 ± 0.02 Ma, O'Connor *et al*. (1995); three K-Ar ages all 0.2 ± 0.1 Ma, Kaneoka and Katsui (1985); two K-Ar ages of 0.3 and 3 Ma (no error bars given) Baker *et al* (1974); and four K-Ar ages of 0.7 ± 0.2, 0.9 ± 0.2, 1.9 ± 0.1, and 2.5 ± 0.3 Ma, Clark and Dymond (1974). Kaneoka and Katsui discuss why they suspect the older ages (~2.5

Ma) of Baker *et al*. and Clark and Dymond result from excess argon from phenocrysts. Seamounts west of Easter have $^{40}Ar/^{39}Ar$ ages of 0.23 ± 0.08, 0.63 ± 0.18, and 2.4 ± 0.54 Ma for Moai, Pukoa, and Umu respectively (O'Connor *et al*., 1995). In our earlier ponderings on this hotspot we had tried to find a single source to fit both the Sala y Gomez-Nazca Ridge trend and the Tuamotu-Line Island trend. However in our model presented here we have added a second source, the Crough plume at 27.0 °S, 139.0°W, and obtain a much better fit for both sides.

Galapagos (0.4°S, 91.6°W) w= 1 az= 096° ± 5° rate= 55 ± 8 mm/yr

The Galápagos-Carnegie Ridge clearly marks a large hotspot track. We have taken the center at the westernmost island, Fernandina, which is the highest, most active volcano of the chain. The azimuth on the Nazca plate is 096° ± 5°. The volume of the Galápagos platform is very large. We attribute this to the very young age of the seafloor here resulting in a thinner lithosphere than at most other hotspots which permits the plume to ascend higher causing more pressure-release melting. There is a unique "horseshoe pattern" of enriched strontium and neodymium isotopic ratios in the lavas erupted in a narrow band north, west, and south of the leading volcano (Fernandina) of the platform (see Fig. 15 in White *et al*., 1993). We think this results from the very large "root" of melt-residue in the asthenosphere concentrated above the plume center deflecting the upwelling plume into rising all around this blocked region. The "ring" (on three sides) has only a deeper, lower-melting fraction very enriched in the incompatible isotopes-trace elements; the "core" has this effect diluted by more extensive melting to form the bulk of the island/platform.

We are able to find a good measurement of the rate of the Nazca plate over this hotspot. We have used K-Ar data from Cox and Dalrymple (1966), Swanson *et al*. (1974), Bailey (1976), and White *et al*. (1993) and $^{40}Ar/^{39}Ar$ data from Christie *et al*. (1992) and Sinton *et al*. (1996). From this list we omitted those influenced by the 'horseshoe pattern' – those to the north (*e.g*., Pinta and Marchena) or to the south (*e.g*., Floreana and Española) – keeping only those samples defining the center of the track between 0°S and 1°S. The excluded islands just mentioned are part of the very "enriched" ring and generally have younger ages than the center of the track. Distance was computed by projecting each sample site onto a line drawn from Fernandina down the center of the track. Of particular significance, the oldest ages measured (8.7 and 9.1 Ma, from a seamount at 2.0°S, 85.7°W) were excluded from the fit because they are along the southern edge of the platform and we considered them to be younger than the central part might show. Plots of Galápagos age data can be seen in Fig. 4(a) of O'Connor *et al*. (1995), Fig. 3 of Christie *et al*. (1992), and Fig. 3 of Sinton *et al*. (1996). Our plot was a little "cleaner" than theirs due to omitting the northern- and southernmost sites. We get a rate of 55 ± 8 mm/yr. In an oral presentation O'Connor *et al*. (2006) have reported $^{40}Ar/^{39}Ar$ ages on many samples collected by the R/V SONNE in 1999 from all along the Carnegie Ridge. From a figure shown, the ages seem in general accord with the age progression seen only on the islands — when these are published a much improved rate for this track can be determined.

Cocos Plate

Galapagos (0.4°S, 91.6°W) w= .5 az= 045° ± 6°

The strike of an aseismic ridge is not exactly the strike of plate motion over a hotspot – its strike is a combination of plate motion and ridge migration (see Fig. 3 of Vink, 1984). The Cocos-Nazca spreading center in this region has jumped southward several times, never being very far from the Galápagos hotspot. We choose the strike of the Cocos Ridge as the strike of the hotspot track on this plate. The Cocos Ridge seems always to be the result of ridge-hotspot interaction (the present growth point being Marchena and Pinta islands) but the ridge appears to have been always built on seafloor less than 5 m.y. older than the ridge itself, and we assume any bias in azimuth has been constant. Three (altered) samples were dated (K-Ar, Dalrymple and Cox, 1968) giving an age of 2.0 ± 0.1 Ma. Similarly, basalts from Cocos Island were dated at 2 Ma (K-Ar , Bellon *et al*., 1983), but from sample descriptions these basalts also appear to be too altered to give reliable ages of formation.

Pacific Plate

Last we look at the tracks on the Pacific plate. We thought the Pacific plate would be the easiest to document tracks on – nice clear island chains on oceanic plate, the fastest plate velocity which makes azimuths sharper, and the best-dated tracks on any plate. In fact it has proved the most confusing.

On the slower plates, we tried to find the best azimuth 'averaged' over the last 10 Ma. On the Pacific, there appears to be a change in azimuth of motion at about 6 Ma. [Epp (1978) and Wessel and Kroenke (1997) put this change at ~1-2 Ma; Pollitz (1986) puts the change at ~3.2-5 Ma; Cox and Engebretson (1985) at 5 Ma; but 6 Ma seems to best fit the 'kink' we have tried to fit. Cande *et al*. (1995) date this change at 6 Ma on the basis of an abrupt change in the seafloor pattern near the Pitman fracture zone on the Pacific-Antarctic ridge.] What is confusing is this kink is clear on many tracks but absent on others. This bend at 6 Ma is very clear for Hawaii, Cobb, and Foundation. (It is also evident if the northern (and not our choice of southern) track for Louisville were used.) There is no young part of the Bowie or Guadalupe tracks – these don't enter in the bend/no-bend count because there's no clear evidence of the 'zero' on these tracks. Similarly, the Caroline track is very poorly defined and a young/old 'kink' wouldn't be seen (Pollitz (1986) saw the hint of a bend here). Also, the Marquesas have a unique trend unpredicted by any model. But of the remaining, all in the central Pacific (Macdonald, Samoa, Pitcairn, Crough, Society), there is adequate data and there is no bend at 6 Ma. We don't understand why some do and some don't have this bend.

Louisville (53.6°S, 140.6°W) w= 1 az= 316° ± 5° rate= 67 ± 5 mm/yr

This is the longest chain in the South Pacific (> 4000 km), and its location far south of all other chains places a strong constraint on the pole of Pacific plate motion. The entire chain is described by Lonsdale (1988) and Watts *et al*. (1988). Nine seamounts in the chain have been dated by Watts *et al*. ($^{40}Ar/^{39}Ar$ total fusion method); these span the entire chain from 70 Ma to 0.5 Ma. Koppers *et al*. (2004) used the $^{40}Ar/^{39}Ar$ step-heating method to re-date eight of these seamounts, plus one additional seamount in the chain. These new measurements change the progression seen in Watts *et al*., 1988, very little – the entire length of the chain shows a very uniform age progression of 64 mm/yr (see Fig. 10 of Watts *et al*., 1988, or Fig. 2 of Koppers *et al.,* 2004). (Only at the oldest part of the chain, sample SOTW9-58-1, is the re-date significantly different from the total-fusion age of Watts *et al.*) Five other dates (K-Ar method) on the Hollister ridge are reported by Vlastelic *et al*. (1998). The very continuous line of seamounts (one about every 60 km) stops at 48°S, 147°W, where the chain crosses the Heezen Fracture Zone: the next prominent features are 500 km southeastward. This gap is the start of the problem – there are two prominent features you can extend to from where the gap begins, leading to two choices for the 'origin point' of the Louisville chain.

Lonsdale (1988), Hawkins *et al*. (1987), and Watts *et al*. (1988) have chosen a small seamount, with a summit depth of 3670 m, as the origin point. This is located at 50.9°S, 138.1°W. It is about 90 km southeast of a very prominent seamount at 50.4°S, 139.2°W which rises to 540 m depth and which has been dated ($^{40}Ar/^{39}Ar$ method) at 0.5 ± 0.2 Ma (Watts *et al*., 1988). The straight-line-fit of the age-distance figure of Watts *et al*. extrapolates to zero age near this point. If the 'zero' were here, the azimuth for the most recent part of the track would be 293° ± 3° and the recent rate 62 ± 3 mm/yr (the distance between the 12.5 Ma and 0.5 Ma seamounts divided by their age difference). For the longer term trend (out to ~20 Ma), the azimuth is 294° ± 3°. This azimuth for the Louisville track fits very well with our final answer for the pole position of the Pacific plate: our finding of a Pacific pole at 59.6°N, 84.6°W predicts an azimuth for Louisville of 298° (and a rate of 79 mm/yr). If this were our choice for the 'zero' of the chain, our entry for Table 1 would be Louisville, 50.9°S, 138.1°W, w=1, az= 293°± 3°, rate= 62 ± 3 mm/yr.

However, we think the local features favor a southern location for the 'zero'. The Hollister Ridge, which is a very prominent feature on the Smith and Sandwell (1997) maps of satellite-predicted bathymetry map, suggests a ‘zero’ at 53.6°S, 140.6°W. [A different southern location of the 'zero' was chosen by Epp (1978) to be at 53.5°S, 144°W by back-tracking older Louisville seamounts with a plate rotation model based mostly on Hawaii. Similarly, Wessel and Kroenke's (1997) back-tracking of Pacific plate motions places the Louisville origin at 53.6°S, 141.2°W.] There is present volcanic activity at this peak on the Hollister Ridge detected seismically using T-waves by Talandier and Okal (1996). A cruise to find the source of the volcanic signal found the depth there to be only 100 m (Géli *et al*., 1998) – the Hollister Ridge was mapped and sampled by this cruise. We have chosen this as the zero point even though there is a 100 km long shallow ridge extending southeast of this point (and one place on this ridge where there is a dredge haul with age 0 Ma); we have assumed this long narrow extension is a 'volcanic rift system' similar to that at Kilauea where a central volcano is feeding a rift whose orientation is determined by the local direction of maximum horizontal tension. The trend of the Hollister Ridge alignment, which extends northwestward directly to the last large cluster of Louisville seamounts (with the one at 48.2°S, 148.8°W dated 12.5 ± 0.4 Ma by Watts *et al*., 1988), is 316° ± 5°. The zero point has been dredged and dated at 0.09 ± 0.01 Ma (Vlastelic *et al*., 1998, using the K-Ar Cassignol technique). The distance from here to another dated peak (2.53 ± 0.04 Ma) northwestward on the Hollister ridge is 168 km, this gives a rate of 67 mm/yr. The distance from the zero to the 12.5 ± 0.4 Ma seamount is 826 km, this gives a rate of 67 mm/yr. There is 240 km of Hollister Ridge between our zero point and the Pacific-Antarctic Rise axis, and two places along this ridge have been dated older than the point of present day volcanic activity (Vlastelic *et al*., 1998; see their map). We assume these are part of the hotspot-to-ridge channel flow, which could have all ages between zero and the age of the seafloor they are constructed on.

The orientation of the Hollister Ridge is unusual. It does not fit the geometrical relationship described by Morgan (1978) based on vector addition of the component of the hotspot track perpendicular to the spreading direction and the half-spreading rate. Using our calculated best-fit value of the plate over the hotspot (79 mm/yr along azimuth 298°), and a Pacific-Antarctic half-rate of 39 mm/yr, azimuth 296°, the formula predicts an orientation of the hotspot-rise interaction of 304°. The strike of the extension of the Hollister Ridge nearest the rise crest is 310° ± 3°, only 6° different than calculated – but some mechanism other than simple plume-feeding-nearest-ridge must occur here. It is puzzling why there is just one continuous ridge and not the numerous shorter *en echelon* ridges such as seen at the nearby Foundation ridge-hotspot interaction. However our distance from present hotspot to rise crest is 230 km, this is almost exactly how close the Foundation was when it started to interact with the rise so perhaps the streaking-to-ridge pattern hasn't begun yet. This makes the shallow ridge-like segment nearest the Pacific-Antarctic Rise, where Vlastelic *et al*. (1998) have two high points (depths ~1700 m) dredged with dates of 0.34 and 0.49 Ma, all the more puzzling. Has the long, high, narrow Hollister Ridge created stresses that have fractured the plate? The Hollister Ridge creates many unsolved geometric problems and its azimuth is a much worse fit to a rigid Pacific/hotspot orientation. However we think the Hollister position better fits our criteria for defining 'active' and thus chose it as 'zero' for the Louisville chain and use this location/azimuth/rate in our table. Also note the other, more northern, postition proposed by Lonsdale/Hawkins/Watts *et al*. (50.9°S, 139.2°W) is preferred in finite reconstructions – using it the entire chain can be fit with the finite rotations determined for the other chains in the Pacific. (And of course, there is always the possibility that this hotspot is 'drifting' relative to the other hotspots.)

Foundation (37.7°S, 111.1°W) w= 1 az= 292° ± 3° rate= 80 ± 6 mm/yr

The secondmost interesting seamount chain in the South Pacific was not discovered until the last decade, based only on SEASAT data and 3 early ship tracks in this remote part of the South Pacific (Mammerickx, 1992). It has since been the target of two cruises (Sonne in 1995, L'Atalante in 1998) and is now the best-dated chain in the Pacific. The chain is 1900 km long and consists of more than 40 large seamounts (Devey *et al*., 1997; Hekinian *et al*., 1997). A total of 30 seamounts have been dated with the $^{40}Ar/^{39}Ar$ technique (O'Connor *et al.,* 1998; 2001), their ages range from 21 Ma to present. O'Connor *et al.* note that the volumes of each feature are smaller than for the Hawaiian chain; they seem to have their entire building-stage quicker than

Hawaii, thus the measured dates have less scatter. Over their entire length, they have an average azimuth of 288° ± 4° and a rate of 90 ± 4 mm/yr (our interpretation of Figs. 2, 3, and 4 of O'Connor *et al.*, 1998). They begin (at ~20 Ma) at a place where the projected track crosses a major fracture zone. The age of the seafloor here is almost the same age as the seamounts, but there is no clear evidence for an earlier portion of this chain on the opposite side of the East Pacific Rise (O'Connor *et al.*, 1998). There is an apparent gap on the Pacific side, and then there appears to be an earlier part of the track near Macdonald seamount. There are 7 seamounts dated 25 to 40 Ma near Macdonald (McNutt *et al.*, 1997) which are positioned to be an older Foundation track overprinted by the Macdonald-Rurutu system.

There is a change in morphology of the Foundation Chain at 6 Ma. Younger than this time, the chain is marked by several ridges that stretch/streak toward the nearby spreading center (O'Connor *et al.,* 2001). O'Connor *et al.* explain the spatial scatter of similar ages after this time as recording both the construction of seamounts directly over the hotspot and the construction of the ridges streaking toward the spreading center. They also state this difference could coincide with a change in direction of motion of the Pacific plate, although we think this is just a coincidence and that nearness of the hotspot to the spreading ridge is the cause of the elongate ridges. Over this interval, there are multiple narrow ridges streaking northeastward to the Pacific-Antarctic Rise. Hekinian *et al.* (1999) show that these more western seamounts differ compositionally (more alkalic) from the elongate ridges. For this last 6 m.y. portion of the track, we find a trend of 292° ± 3°, 80 ± 6 mm/yr, and we use this for our entry in Table 1. We have chosen the present position of the hotspot to be about 15 km from the crest of the Pacific-Antarctic Ridge, near the eastern end of what Maia *et al.* (2000) call South Ridge; at 37.7°S, 111.1°W. The predicted track skirts the western (older) side of each of the elongate ridges and the age-distance plot extrapolated to zero leads to this point. The elongate ridges streak northeastward when they first appear, then they appear to gradually swing clockwise and the most recent are parallel to the track – this must be some age-of-lithosphere effect. This streaking effect of *en echelon* ridges appears to be a general pattern of hotspot/nearby-ridge interaction.

We discuss a mechanism for this in the section on the Musician Seamounts.

Macdonald (29.0°S, 140.3°W) w= 1 az= 289° ± 6° rate= 105 ± 10 mm/yr

(Not MacDonald as sometimes written, this seamount was named after Gordon Macdonald by Johnson, 1970.) The Cook-Austral chain is very complicated – there appear to be multiple tracks overprinting one another. Further, the passage of a nearby hotspot 're-activates' an older track – the flexure of the lithosphere caused by the newer hotspot appears to open conduits for volcanism among the 'long-dead' track (McNutt and Menard, 1978; Menard and McNutt, 1982; McNutt *et al.*, 1997). Dickinson (1997) has recently emphasized that uplifted limestone on many islands/atolls of this group provide information with which one might be able to unravel their complicated vertical history as caused by 'expected' subsidence, glacial eustatic changes, flexure, and volcanic reactivation.

The easiest track to unravel in the Cook-Austral chain is Macdonald. Macdonald Seamount rises to within 27 m of sealevel (Rubin and Macdougall, 1989) and has had several eruptions since it was first observed in 1969 (see Johnson, 1970; Johnson and Malahof, 1971). Our choice of its track starts at Macdonald, passes by Rà Seamount, then goes to Marotiri, then Rapa, then south of Neilson Bank, then to an un-named seamount at 26.3°S, 149.0°W; the azimuth of this line is 289° ± 6°. The seamount Rà has an age of 29.2 Ma ($^{40}Ar/^{39}Ar$, McNutt *et al.*, 1997) and clearly is not part of the track made by Macdonald. The island/rocks Marotiri have mixed ages. There are 5 K-Ar measurements by Diraison (1991) which range from 3.2 Ma to 5.4 Ma and a $^{40}Ar/^{39}Ar$ measurement by McNutt *et al.* (1997) with an age of 3.8 ± 0.2 Ma. However, one other sample from Marotiri (with a very ragged $^{40}Ar/^{39}Ar$ plateau-age) gives 32.0 Ma (McNutt *et al.*, 1997). The 3.8 Ma would be in accord with a Macdonald origin; the 32.0 Ma is the correct age-distance from Rà Seamount to be in the trend of whatever constructed Rà. Next in line is Rapa, where 14 samples measured by Diriason (1991, K-Ar) give a very tight age cluster of 4.6 ± 0.1 Ma. Next along this line is a K-Ar age of 39.5 ± 0.6 Ma for Neilson Bank (from dredge ZEP2-16, Bonneville *et al.*, 2006). This K-Ar measurement was made on plagiclase microlites from the groundmass. A very small uncertainty in age is reported (± 0.6 Ma) but we note in their Table 2 the very high loss-on-ignition (> 3%) of this sample, implying it is very weathered thus raising doubts on its accuracy. Lastly, the seamount at 26.3°S, 149.0°W (Dredge ZEP2-19) was K-Ar dated at 8.8 ± 0.1 Ma. This location and age is listed in the compilation by Clouard and Bonneville (2005). They cite as reference for this value a paper by Bonneville, Dosso, Hildenbrand, and Gillot, "Hotspot tracks reconstruction in the Austral-Cook islands chain constrained by new K/Ar ages and geochemical data", which was submitted in 2004 but which has not been printed. Some of the locations tabulated in the Clouard and Bonneville compilation with this unpublished reference are included in the later Bonneville *et al.*, 2006, but not the ZEP2-19 sample and we have no metadata with which to judge the quality of this 8.8 Ma age. The age-distances of the ZEP2-19 seamount, Rapa, Marotiri and Macdonald are well fit by a straight line and we get a propagation rate of 105 ± 10 mm/yr for the Macdonald track.

West of the ZEP2-19 seamount, the extrapolated track for Macdonald passes very close to Mangaia and then onward to Rarotonga. Turner and Jarrard (1982) give results for K-Ar measurements on 11 samples from Mangaia, but most of these they classify as 'minimum age', not 'reliable'. Averaging their 5 reliable ages, we get 19.5 ± 1.3 Ma for Mangaia. Our finite motion model of Pacific history (a work in progress) using Macdonald as origin predicts a track which passes within 70 km of Mangaia at model-time 23 Ma, very close to this K-Ar 19 Ma measurement of Mangaia. Please see the short discussion of Mangaia and neighboring Rarotoga in a later section on the Cook-Austral chain.

The older ages of some seamounts/islands along this line are more difficult to interpret. Using just the 29.2 Ma for Rà and 32.0 Ma for Marotiri, the age-distance gives a velocity of propagation of 95 mm/yr. Including the 39.5 Ma for Neilson Bank, admittedly a poorer quality measurement because of the large degree of weathering, the rate is ~50 mm/yr. Taking the 95 mm/yr rate as correct, that is assuming the 39.5 Ma age for Neilson Bank is wrong by 5 m.y., we can use our finite motion model of the Pacific to determine what starting point would make Rà Seamount at 29.2 Ma. This point is in the Foundation chain near 36°S, 118°W, about 600 km west of our origin point for Foundation (37.7°S, 111.1°W). So the simple assumption that exactly the same fixed point that makes the Foundations also made the earlier seamounts of the Macdonald chain can't be true. (If this is due to hotspot drift and not multiple origin points, it implies a drift rate of 2 cm/yr. We prefer a multiple origin explanation, many sources that fade in and fade out seem to be the rule in the South Pacific.)

Ngatemato and Taukina lineaments (Cook-Austral)

There is a prominent alignment of volcanic structures ~80 km north of the Macdonald trend which McNutt *et al*. (1997) and Bonneville *et al*. (2006) call the Ngatemato seamounts. Three of these have been dated using the $^{40}Ar/^{39}Ar$ technique (McNutt *et al*., 1997): Maki (26 Ma), Aureka (31 Ma), and Opu (34 Ma). Another seamount, ZEP2-26, ~300 km further west of Opu in this trend, has also been dated using a K-Ar technique – 28 Ma (dredge 18 in Bonneville *et al*., 2006). These form a trend 297° ± 4° very similar to that of Macdonald, but the ages imply they are part of the Foundation line and thus don't contribute to the present-day data set.

A second 300+ km lineament made of smaller seamounts yet with sharper definition is ~150 km north of the Ngatemato line. McNutt *et al*. (1997) call this the Taukina chain. They have dated ($^{40}Ar/^{39}Ar$) two of these seamounts; Evelyn (26.0 ± 1.2 Ma) and Herema (22.5 ± 1.5 Ma). The strike of this line is 287° ± 4° but it also is 'Foundation' and not 'present-day'.

Mangaia (21.9°S, 157.9°W) w= C

This and Rarotonga form a short track about 200 km south of and parallel to the main group of the Cook Islands. Turner and Jarrard (1982) made K-Ar measurements on 18 samples from the older unit on Rarotonga, but only 2 samples meet their 'reliable' test and meet the additional criterion of 'less than 80% correction' for atmospheric argon. These two values give an average of 2.0 ± 0.1 Ma for Rarotonga. Rarotonga is 210 km west of Mangaia; this distance and 2 Ma age difference would give a rate/azimuth the same as other chains in the Cook-Austral group. However, as discussed earlier in the section on Macdonald, Mangaia (with an age of 19.5 Ma) was constructed by the Macdonald track, thus Mangaia cannot be located at an active hotspot. It has been suggested (McNutt and Menard, 1978) that the recent uplift of Mangaia (evidenced by uplifted limestones) was made by lithosphere flexure of the region surrounding Raratonga (only ~200 km away) when it erupted. Another proposal (Menard and McNutt, 1982) is that 'thermal rejuvination' caused the eruption of Raratonga and the uplift of Mangaia (reactivating earlier material emplaced in the lithosphere by Macdonald) as the Pacific plate moved past a source creating the main Cook chain around Aitutaki, Atiu, and Mauke (also only ~200 km away), or even that it was reactivated by events in the Society Islands (~1000 km away). [However, exactly how this occurs is not made clear.] The chemical characteristics of Mangaia are very interesting, but we think this is not a source from deep in the mantle and omit it from our list.

Arago (23.4°S, 150.7°W) w= 1 azim= 296° ± 4° rate= 120 ± 20 mm/yr

Bonneville *et al*. (2002) propose Arago seamount, which rises to within 27 m of sealevel, to be a source for part of the northern portion of the Austral chain. Arago has been dated at 0.23 ± 0.01 Ma (K-Ar, ZEP2-DR7, Bonneville *et al*., 2006). [There is also a date of 8.2 Ma from this same dredge, but the loss-on-ignition of this sample exceeds 2.5% and it is rejected.] There is a very distinct alignment of seamounts/islands for 1000 km northwestward of Arago – a trend through Rimatara, Maria, two unnamed seamounts, Mauke, Mitiaro, Atiu, Takutea, Manuae, and Aitutake gives an azimuth of 296° ± 4°. (This alignment could be extrapolated another 300 km to Palmerston.)

The following age-distances can be used to determine a rate. The younger volcanics of Rurutu have an age of 1.2 ± 0.5 Ma. (This is a summary made from K-Ar measurements by Duncan and McDougall, 1976; Turner and Jarrard, 1982; Diraison, 1991; and Guille *et al*., 1998.) Rurutu is about 80 km off the path of Arago, this age would represent a reactivation of an earlier period of volcanism (the older volcanics have an age ~12.1 Ma, referencing the same authors). Rurutu has a projected distance of 85 km down the Arago path. The next peak is Rimatara, but there is no reliable age for this (Turner and Jarrard, 1982, made measurements on four samples but none gave reliable ages). Next is the island Maria, 440 km from Arago. This has not been dated (more on Maria in a following section). Then are two undated, unnamed seamounts, called S3 and S1 in Figure IV-1 in Diraison, 1991. Then Mauke, which is 770 km from Arago. Eleven samples on Mauke were dated (K-Ar) by Turner and Jarrard (1982), but they list all of these as 'minimum ages' and so the 5.5 ± 0.2 Ma value is unreliable. Next is Mitiaro, 810 km from Arago. A single sample was dated by Turner and Jarrard (1982), but their 12.3 ± 0.4 age (K-Ar) was listed 'minimum'. Then Takutea, undated; then Atiu, 880 km from Arago. Atiu had 7 measurements classified as reliable by Turner and Jarrard, Keeping only the 5 of these with the higher percent of radiogenic argon, these average to give an age for Atiu of 8.1 ± 0.4 Ma. Then we have Manuae, no dating; then Aitutake, which is 1060 km from Arago. Aitutaki has two periods of activity. Dalrymple *et al.* (1975) give 3 K-Ar measurements, which average 0.7 ± 0.1 Ma. Turner and Jarrard (1982) give 17 values for the younger activity which they class 'reliable'; of these, the average of their 6 measurements with the higher percentage of radiogenic argon is 1.3 ± 0.4 Ma. Turner and Jarrard also report one reliable age of 8.0 ± 0.7 Ma for a sample from a tuff breccia (and the results of 3 measurements classed 'minimum age' in the tuff breccia which range from 6.6 to 8.4 Ma). Using the two young ages at Arago and Rurutu and the 8.1 and 8.0 Ma for Atiu and Aitutaki respectively, we get at rate of 120 ± 20 mm/yr (but note all of the ages are K-Ar). In their Fig. 5, Guille *et al.* (1998) present an age-distance plot made using dates from the same sources used above but including all the lesser-quality values which we have omitted. They don't fit a line to only the ages of this track but show that it fits the same age-distance slope as the Macdonald track. For the combined pattern they conclude three sources are needed to fit the Austral region, with a common slope of 110 mm/yr. Similarly, Chauvel *et al.* (1997) present a figure (their Fig. 1) nearly identical to Guille *et al.*, concluding 110 mm/yr rates for what they call the Tubuai, the Rurutu, and the Rarotonga trends. However we prefer the 120 mm/yr value for this track alone (with larger error bars).

N. Austral (25.6°S, 143.3°W) w= B(1.0) azim= 293° ± 3° rate= 75 ± 15 mm/yr

An older track is parallel to and ~80 km north of the Arago track. Rurutu, which has younger volcanics that we considered due to reactivation by Arago, marks the end of an alignment we call North Austral. We conclude Rurutu's older volcanics have an age 12.1 ± 0.5 Ma. A carbonate layer roughly 100 m thick overlies the older volcanics; the younger volcanics then flowed on top of this carbonate layer (Guille *et al.*, 1998; Maury *et al.*, 2000). We arrive at the 12.1 Ma age by averaging the following K-Ar measurements: 12.2 ± 0.1, 12.1 ± 0.1, and 12.3 ± 0.1 Ma measurements by Guille *et al.*, 1998 (rejecting a 12.7 Ma value because of its lower percent radiogenic argon); 12.2 ± 0.6 and 13.0 ± 0.6 Ma by Diraison, 1991 (rejecting a 'B' quality value and a 10.7 Ma value because of its extremely low potassium content and higher percentage atmospheric argon); 11.2 ± 1.0 Ma value of Matsuda *et al.*, 1984 (rejecting the two samples with extremely low percentage radiogenic argon); and 12.2 ± 0.2, 11.7 ± 0.2, and 12.0 ± 0.2 Ma by Duncan and McDougall, 1975. (There is also an 8.4 ± 0.1 Ma measurement by Duncan and McDougall – its percent potassium and percent radiogenic argon are similar to the three 'accepted' values but we don't include it in our average simply because this value is many standard deviations from the average of the 9 values we did use.)

Working backwards from Rurutu, Lotus Bank is only 40 km eastward from Rurutu and rises to within 450 m of the surface. There is an age date for Lotus Bank by Bonneville *et al.*, 2006, but this sample has the highest loss-on-ignition of any sample measured by them and we reject this 55 Ma value for determining the rate here. The next prominent feature in this line is Tubuai, 210 km from Rurutu. Its age is 9.1 ± 1.0 Ma [averaging 14 K-Ar measurements by Duncan and McDougall (1976) and Diraison (1991) and omitting 2 others as being 'less reliable']. The next feature is Raivavae, 410 km from Rurutu, which is dated at 6.5 ± 0.7 Ma. This is an average of six K-Ar measurements by Duncan and McDougall (1976) and another six by Diraison (1991). The last feature in this alignment is President Thiers Bank (600 km from Rurutu), rising to within 17 m of sealevel. Bonneville *et al.* (2002) state this bank is a guyot and probably much older than this Northern Austral track – our finite rotation model of the Pacific places the 49 Ma position of the Foundation hotspot ('zero' at 25.6°S, 111.1°W) where Thiers is today. President Thiers Bank has the metadata for one age measurement (sample from ZEP2, DR21) given in Bonneville *et al*. (2006), but the quality of this K-Ar measurement was so poor they chose not to list any value for its age in their paper. [In an earlier compilation of seamounts/islands by Clouard and Bonneville (2005), an age of 2.6 ± 0.1 Ma was given for this sample; however we don't use this value in our analysis because of its rejection in the later, more complete paper.]

Using the ages and positions of Rurutu, Tubuai, and Raivavae, we get a rate of migration of 75 ± 15 mm/yr along a strike of 293° ± 3°. Bonneville *et al*. (2002) state the Northern Austral track stopped producing magma just after Raivavae (~6.5 Ma), while still quite west of the President Thiers location. Using our finite rotation model, we 'backtrack' to find the zero at 25.6°S, 143.3°W. It is very difficult to place an error to the 75 mm/yr rate – we rejected the lesser quality data and the three remaining points very precisely define a straight line. Given the 410 km length and an estimate of 1 Ma error in the K-Ar measurements, we guess at a rate error of ~15 mm/yr. The length and linearity of the North Austral track are on a par with those that define the Society track (for example). A weight of 1.0 (the same as for Society) *could* be assigned here to use in solving for the present-day motion (all these features were made in the last 12 Ma, roughly the time range used for many entries included in Table 1). However we think this has 'died away' – no new volcanism at President Theirs Bank and no features along the further 500 km extrapolation to the 'zero'. We give the measured values for the azimuth and rate in Table 1, but don't use this in our solution. To emphasize that we think this is no longer active, we assign this a 'letter weight' and not a 'number' in the weight column. [There are many well defined short tracks in the part of the Pacific – one more doesn't add to or take away from our final best-solution for the best motion in the fixed reference frame.]

Maria/Southern Cook (20.2°S, 153.8°W) w= 0.8 az= 300° ± 4°

The southern Cook islands have four islands with ages that are not fit by the Arago of Northern Austral [or President Thiers] projected tracks. Those with ages are: Mauke (>5.5 Ma –

this is a minimum age only), Mitiaro (>12.3 Ma – also a minimum age), Atiu (8.1 ± 0.4 Ma), and Aitutake (some ages in the range 0.7 - 1.3 Ma and another group at 8.0 ± 0.7 Ma). These are all K-Ar ages reported in Turner and Jarrard, 1972. Diraison (1991) has a short discussion on each of these islands, but reports only age results measured by Turner and Jarrard. There are other undated seamounts/islands in this trend, as was discussed in the earlier section on the Arago track. The above islands and four others in the southern Cook group which have not been sampled for dating and the several seamounts between these islands and Maria atoll are aligned along a very well determined azimuth: 300° ± 4°. There is a small uninhabited atoll at 21.8°S, 154.7°W which contains four islets – Îles Maria. This island group/atoll has obviously not had any recent volcanic activity but it exhibits clear evidence of recent vertical uplift. If a hotspot source were placed a little east of here (say at 20.2°S, 153.8°W), its track would pass through the numerous seamounts/islands mentioned above, and at approximately times accordant with the ~8 Ma ages for Atiu and Aitutake. (The Arago track also passes through these, but at a much earlier time than the Maria track. Perhaps the double-hit of two tracks passing here is why the portion Aitutake to Mauke is very prominent whereas the other parts are not prominent.) There is not enough information to estimate a rate (we have chosen the 'zero' position on the basis of nearby rates). We could give this a 'letter' weight as was done just above and not use it in data set to find the motion in the fixed reference frame, but because of the two seamounts S3 and S1 (see Diraison, 1991, Fig. IV-1) between Maria and Mauke, we have kept it in our data set. We have downgraded its weight slightly because of the lack of a measured rate and the relatively short length of the track (~600 km).

This choice of location for a hotspot cannot explain the very recent volcanism on Aitutake (0.7-1.3 Ma). Also, the young age of Raratonga (2.0 ± 0.1 Ma, Turner and Jarrard, 1982), which is only 250 km south of Aitutake, could have a relation to the recent volcanism on Aitutake – see the above paragraph on Mangaia. However the Maria location does have an interesting consequence for earlier history on the Pacific plate. Putting the origin here produces a track which turns its corner at ~47 Ma and then tracks nicely up the Marshall-Gilbert trend in our finite motion reconstruction of Pacific tracks as shown in Figure 1. [Macdonald (29.0°S, 140.3°W) turns and goes up the Tokelau trend; the Northern Austral position (25.6°S, 143.3°W) also goes up the Tokelau trend, about 5 m.y. earlier than the track made by Macdonald.] The projected path of the Arago position (23.4°S, 150.7°W) bends and goes up parallel to the the Maria track. If it were the source for the Gilbert-East Marshall trend, the source would have to 'wander' ~300 km (in ~60 m.y., *i.e*. at an average rate of ~5 mm/yr). We are more inclined toward the view that hotspot locations fade-in and fade-out in the superswell region rather than drift through the mantle of a more permanent source, although of course this is only a supposition.

Samoa (14.5°S, 168.2°W) w= .8 az= 285°± 5° rate= 95 ± 20 mm/yr

The currently active seamount Vailulu'u (14.2°S, 169.1°W, 592 m depth, Hart *et al*., 2000) is at the eastern end of the Samoan chain. (The prominent topographic feature 100 km further east, Rose Island at 14.3°S, 168.1°W, is an atoll that predates the Samoan chain.) The eastern end is made of two *en echelon* ridges separated by 40 km, and we have chosen a point ~30 km south of Vailulu'u in order to have the track split the difference between these two ridges. Using the 500 km trend of the Samoan islands alone, or the 1000 km trend that includes Pasco, Lalla Rookh, Waterwitch, and Combe banks, the trend is 285° ± 5°.

Duncan (1985) made both K-Ar measurements and total fusion $^{40}Ar/^{39}Ar$ measurements on the older part of the Samoa trend, Combe (14 Ma) and Lalla Rookh (10 Ma) Banks, and obtained a rate of 77 ± 25 mm/yr. These ages extrapolate to zero at a position near Vailulu'u through the Samoan Islands of Savai'i (2.1 Ma, Ar-Ar total fusion), W. Upolu (2.7 Ma, Ar-Ar total fusion and plateau), E. Upolu (2.7 Ma, K-Ar), Tutuila (1.5 Ma, K-Ar), Ofu/Olosega (0.3 Ma, K-Ar), and Ta'u (<0.1 Ma, K-Ar) [data from Workman *et al*., 2004; Natland and Turner, 1985; McDougall, 1985; respectively]. If only the recent islands with a total span of only 400 km are used, a rate of 110 ± 10 mm/yr can be found (see data plotted in Fig. 2A of Hart *et al*., 2004). We will use an average of these (77 ± 25 and 110 ± 10), a rate of 95 ± 20 mm/yr.

It has been proposed that the age progression of the Samoan trend is not due to the Pacific plate moving over a fixed mantle plume, but rather due to the progressive 'tearing' of the Pacific plate as it moves past the north end of the Tonga trench, in transition to the change to a strike-slip fault along the Northern Melanesian Borderland. This idea is very clearly expressed in Fig. 11 of Natland, 1980. Recent GPS measurements (Bevis *et al.*, 1995; 2000) show the northern Tonga islands (Vava'u and Niuatoputapu) are moving away from the Australian plate (Fiji) at rates of ~130 mm/yr and ~160 mm/yr, respectively, while the Pacific plate (Niue and Rarotonga) is approaching the Australian plate at ~80 mm/yr. These velocities imply the Pacific plate is moving past and tearing at the corner of the trench-transform boundary at a rate that is the sum of these two, ~160 + 80 = ~240 mm/yr – a rate twice the age progression of the Samoan islands. Over the longer term, magnetic anomalies in the Lau back-arc basin show it has been spreading in a fan-shaped pattern (fastest at the northern end) for about 5 m.y. at an average (full)-rate of ~70 mm/yr. The longer-term tear-propagation-rate is then ~70 + 80 = ~150 mm/yr, still significantly faster that the rate of volcanism along the Samoan line and thus this mechanism cannot be the rate controlling factor for Samoan ages.

We think there is interaction between Samoa and the back-arc basin; the back-arc basin is now spreading very rapidly because it has a ready supply of asthenosphere flowing toward it from the plume feeding Samoa (see Figs. 1 and 3 in Turner and Hawkesworth, 1998). In a recent paper, Natland (2006) points out the extensive post-erosional eruptions from hundreds of cones aligned in a single rift system across both Savai'i and Upolu and suggests these are due to tension/flexure of the Pacific plate as it moves past this trench-transform corner. The enhanced post-erosional eruptions due to this tension make this a unique place to study the oceanic lithosphere and mantle below.

We note that the observed Samoan trend differs significantly from the 'predicted' trend based on parallelism to neighboring chains (observed = 285°, predicted/parallel = 301°). We think the interaction of the rising plume with the large directed flow of asthenosphere into the Tonga back-arc region causes this local deviation. Over the longer time period, the Samoan track 'bends' at

~45 Ma in the vicinity of the Ontong Java Plateau and has its earliest expression in the Magellan Seamount region.

Crough (26.9°S, 114.6°W) w= .8 az= 284° ± 2°

We propose there is a hotspot just south of the Easter microplate and just west of the crest of the East Pacific Rise at 26.9°S, 114.6°W. A hotspot here would pass through the very large Crough Seamount (depth ~600 m). Making a finite rotation track using parameters based mainly on the Hawaii-Emperor track, a track zeroed here would pass through Crough at ~8 Ma and then would go neatly through Ducie (24.6°S, 124.7°W, ~10 Ma), then Henderson (24.4°S, 128.3°W, ~12 Ma), Oeno (21.3°S, 130.7°W, ~15 Ma), Minerve (22.6°S, 133.3°W, ~19 Ma), Marutea (21.5°S, 135.6°W, ~22 Ma), Acton (21.3°S, 136.5°W, ~23 Ma), and so on up to just beyond Rangirora where the track turns more northward to continue up the Line Islands. In contrast, if the hotspot were centered at 'Easter', the early part of the track would not go up the Line Islands but would form a parallel line several hundred kilometers east of the Line Islands. The ages above are all guesses based on the Hawaii-Emperor prediction – there are only two measured ages along this track, Crough (24.8°S, 121.7°W) and a seamount (15.0°S, 149.0°W) just west of Rangirora at the elbow of the bend. Crough has been dated at 8.0 ± 0.3 Ma (my average of the two $^{40}Ar/^{39}Ar$ dates given by O'Connor *et al*., 1995) and the seamount at the other end has two measurements, 47.4 ± 0.9 Ma and 41.8 ± 0.9 Ma, ($^{40}Ar/^{39}Ar$ method on two samples from the same dredge, Kana Keoki RD-52, Schlanger *et al*., 1984). Of these two measurements, the 47.4 Ma age is the better – rock analyses given in Table 3 of Garcia *et al.* (1993) show sample 52-1 (47 Ma) is less altered than sample 52-2 (42 Ma).

This track through Crough, Ducie, Henderson, Oeno, Minerve, *etc*. has been proposed before (Okal and Casenave, 1985). It closely parallels the Pitcairn, Gambier, Mururoa, *etc*. track and is separated from it by only ~150 km. (It is puzzling why so many of the French Polynesia tracks print almost on top of one another, *e.g*. McNutt *et al*., 1997.) Supporting our conclusion that this is a hotspot track formed by a hotspot on the Pacific side (and not the Nazca side) is the pattern of *en echelon* ridges between 123°W and 118°W streaking northeastward from the proposed line of the track toward the nearby axis of the spreading center (Binard *et al*., 1996). The same pattern of *en echelon* ridges streaking toward the spreading center is seen where the Foundation chain approaches the rise crest (Maia *et al*., 2000) and between the Musician Seamounts and the then-crest of the Pacific-Farallon spreading center (Kopp *et al.,* 2003).

The strike of the 300 km long ridge leading away from our proposed center is very well defined, 284° ± 2°. We cannot be sure this strike is not influenced by some interaction from the neighboring Easter microplate, so we have down-graded the weighting slightly to 0.8.

Pitcairn (25.4°S, 129.3°W) w= 1 az= 293° ± 3° rate= 90 ± 15 mm/yr

Pitcairn was recognized as a hotspot by Duncan *et al*., 1974, and their paper summarizes the geology of Pitcairn and gives the best age data (K/Ar) for the older lavas (Tedside) on this island: 0.88 ± 0.04 Ma. The origin for the Pitcairn track is Adams Seamount (at 25.4°S, 129.3°W, 90 km east of Pitcairn) which has recent flows and rises to 60 m from sealevel (Binard *et al*., 1992). There is a clear trend of 293°± 2° defined by about ten seamounts/atolls leading to Îles Gambier. Gambier (630 km from Adams) is dated (K/Ar) at 5.7 ± 0.1 Ma (see Guillou *et al*., 1994). There appears to be a slight 'bend' in this track, beyond Gambier the alignment is best fit with 290°± 3°. At Fangataufa (1025 km from Adams) the substantial flows (pillow lavas) are reached only in the drill hole in the center of the lagoon; the drill holes around the rim of the atoll bottomed in hydroclastic volcanics. Samples near the bottom at the center are dated at 12.85 ± 0.15 Ma and 12.95 ± 0.20 Ma (K/Ar, Guillou *et al*., 1993). At nearby Mururoa (1050 km from Adams), we find an age of formation of 11.6 ± 0.2 Ma – we have taken an average of the four oldest ages (K/Ar, Gillot *et al.,* 1992) obtained from deep drill holes from near the center of the lagoon as was done at Fangataufa. These ages and distances give a rate of migration of 90 ± 15 mm/yr. This rate is slower than other published estimates for Pitcairn (Jarrard and Clague, 1977, Fig. 9; Duncan and Clague, 1985, Table 3; Guillou *et al.,* 1994, Fig. 2) due to our extra weight for Fangataufa. The Pitcairn line then continues on to Tematangue, Duc de Gloucester, and

Hereheretue (none of these are dated) on a course pointed towards Tahiti (the projected rate would have it at the present position of Tahiti at ~27 Ma). In the next section, we explore the possibility that the Pitcairn track generated the Tarava seamounts a little south of the Society islands.

Tarava Seamounts

The Tarava seamounts (near 19°S, 152°W, formerly named the Savannah seamounts) are a short chain parallel to and about 200 km south of the Societies. These were extensively surveyed by the ZEPOLYF cruises, and two of the seamounts in this chain have been dated and have K-Ar ages of 43.5 Ma and 36.1 Ma (Clouard *et al*., 2003). [Another age, 55 Ma, is shown on a map in Clouard *et al*. (2003, Fig. 5); but no metadata for this age are given – only an acknowledgment of a personal communication from Anthony Hildenbrand in Paris]. A map by Clouard (2000, Fig. 6.22) discusses the possibility that the Tarava chain was constructed by the Pitcairn track. We have made reconstructions of finite tracks which agree with this, a track with a fixed Pitcairn would pass parallel to the Tarava chain with the '29 Ma' point of our model only 100 km from the seamount dated 36 Ma (K-Ar method) – and with a little hotspot wander (100 km /30 Ma = 3 mm/yr) the Pitcairn track could pass down the center of the chain. Clouard *et al*. (2003, Fig. 4) present another model in which the finite-motion extension of the Foundation track creates the Tarava chain. There is an 'Emperor' trend as well as 'Hawaiian' in the Tarava seamounts, using a 'fixed' Foundation the '57 Ma' point of our finite-motion-model passes within 100 km of the seamount dated 55 Ma. We suppose that both of these tracks crossed the Tarava region at different times in its history.

Society (18.2°S, 148.4°W) w= .8 az= 295°± 5° rate= 109 ± 10 mm/yr

The first question is where to put the zero-point for the Society chain. We place it at 18.2°S, 148.4°W, approximately midway between the small island Mehetia (elev. 435 m) and the large seamount Moua Pihaa (min. depth 180 m), both ~100 km southeast of Tahiti. The main part of

Mehitia was formed at ~70 ka (Binard *et al*., 1993); Moua Pihaa is listed at ~200 ka in the tabulation by Clouard and Bonneville (2005). We take the Society azimuth to be 295° ± 5°. It is a very short chain (~500 km long, oldest age < 5 Ma) and we downgrade its weight to 0.8. The Society chain has more age determinations than any other chain, the results of 295(!) measurements are listed in the compilation by Clouard and Bonneville (2005). All of these are K-Ar measurements, from at least 5 different labs. Instead of making a plot of all of these data and trying to evaluate inter-lab differences, we have chosen to average the rates determined by the various authors.

Dymond (1975), from 56 K-Ar measurements on rocks form Moorea and Tahiti, obtained a rate of 112 ± 12 mm/yr. (This velocity was obtained from his angular rate of 1.08 °/my about the Minster *et al*. (1974) pole and then applying the age correction from 'old' decay constant he used to the 'new' K-Ar decay constants as given in Dalrymple, 1979). However his measurements are from only two neighboring islands spanning a total distance of only ~80 km distance with a total age span of only ~1 my, so his error estimate should be increased. Duncan and McDougall (1976) measured 57 K-Ar measurements from samples collected on all of the islands (covering a distance of 400 km). Upon applying the same 'old' to 'new' decay-constant correction, this gives a rate of 109 ± 10 mm/yr. In their later summary paper (McDougall and Duncan, 1980), no new data for the Society chain is presented, but this decay-constant-correction is applied to their previous 1976 data. Brousse and Léotot (1988) give a rate of 111 ± 2 mm/yr; they used only the previously published data but broke them down into groups (A) beginning of island formation, (B) beginning of sub-aerial volcanics, and (c) end of volcanic formations. In his thesis, Diraison (1991) measured 141 new K-Ar ages from lavas and 32 new ages from plutonic rocks collected from many places in French Polynesia, and 380 previously published ages were re-examined for quality. He fits this with a slope of 111 ± 2 mm/yr; our fit to his figure gave a slope of 104 mm/yr. The results for the Society chain are given in the paper by Diraison *et al*. (1991); using the new data and again breaking into groups of shield and post-shield, they get a rate of 111 ± 2 mm/yr (our fit to this data is also 111 mm/yr). Lastly, the paper by Guillou *et al*. (1998) shows essentially the same data, again separately marking shield stage from post-shield stage lavas and obtaining a rate of 111 mm/yr. Our fit to this last figure gives a slightly slower rate, 102 mm/yr. We think ± 2 mm/yr underestimates the error, and take the error to the ± 10 mm/yr. Trying to combine these various determinations, we get a rate for the Society migration of 109 ± 10 mm/yr.

Northern Tuamotu

The location for the source of this feature is identical to that of the Easter track on the Nazca plate: 26.4°S, 106.5°W. We think from ~50 Ma to 30 Ma, this fixed hotspot position generated the northern part of the Tuamotu platform as an aseismic ridge. The seafloor beneath this ridge also has this 50 Ma to 30 Ma age span, *i.e.*, the ridge was built on 'zero age' seafloor. Younger than ~25 Ma, the ocean crust is younger than the hotspot track predicted by our finite-motion history of hotspot tracks, and thus no aseismic ridge or seamount chain extends any closer to Easter source. On the opposite side of the East Pacific Rise, the Nazca ridge has ages ranging from ~30 Ma to 45 Ma from our finite-motion reconstruction (the earlier part having been subducted) with the seafloor having the same age as the track. This hotspot (Easter) is still active, but since it has no measurable azimuth/track on the Pacific plate, we weight it 'C'. The situation here is similar to the relation of the Rio Grande Rise in the South Atlantic to Tristan da Cunha – for a period of time aseismic ridges (the Walvis and Rio Grande) were built on both sides of the Atlantic but when the hotspot was no longer centered right at the spreading center, the ridge ceased on one side (with no further track) and an island chain (rather than a continuous ridge) commenced on the other side. Note that our choice of 'Easter' to be the source of the northern Tuamotu feature is the same as that used by Fleitout and Moriceau (1992), and that they also use a point near our 'Crough' (which they name 'L1') for southern part of Tuamotu and the Line Islands.

Pukapuka (~14°S, 140°W to 115°W) w= C

The Pukapuka ridge is a very narrow (10-30 km), very long (2000 km, from ~139°W to 118°W), very continuous (1000 m+ local relief at least every 100 km) feature [from a digital map made using data from Smith and Sandwell, 1997]. The ridge's strike is very well constrained: 278° ± 3°. Sandwell *et al*. (1995) give $^{40}Ar/^{39}Ar$ ages for seven places along this ridge plus two more for islands at its westernmost end. The rate determined from these dates, ~220 ± 40 mm/yr, is roughly twice the plate motion velocity. The azimuth of the ridge (278° ± 3°) differs but slightly from the azimuth of plate motion predicted for here from extrapolation of nearby hotspot azimuth (289°). However we don't think this azimuth can be used to constrain the plate motion over a fixed hotspot because of the large discrepancy in rate.

Instead we think this ridge marks a narrow 'river' of asthenosphere flowing away from the excess of asthenosphere being produced in the superswell region toward the asthenosphere-starved East Pacific Rise (Phipps Morgan *et al*., 1995b, Fig. 4). As the asthenosphere flows horizontally from the region of thicker (older) lithosphere toward the thinner (younger) lithosphere near the spreading center, there is a slight decrease in depth. The resulting pressure-release melting produces the volcanics seen on the surface above this channel. Geochemical evidence from samples along the Pukapuka ridge (Janney *et al*., 2000) supports melting occuring at shallower depths (just below the lithosphere) and not from the greater depths as would be the case at a hotspot. Along the axis of the East Pacific Rise, a peak of 'E-MORB' signature occurs at 18°S (where the Pukapuka extension would intersect the EPR); this fades off to normal-MORB chemistry over a range of 300 km north and south of this peak (Mahoney *et al*., 1994; Kurz *et al*., 2005). This suggests the EPR is receiving a large non-depleted component, which we think this channel is transporting from the superswell region. Lastly, for the 400 km between its eastern end and the East Pacific Rise, the Pukapuka ridge fans out in a diffuse delta pattern in a region called the Rano Rahi seamount field – the Rano Rahi field looks like several other 'elongate ridges' making a direct connection between hotspot and nearby ridge. The Hollister ridge, the easternmost part of the Foundation chain, the Musician ridges, a series of ridges eastward of the Line Islands between 13°N and 5°N, and possibly the Necker Ridge are features like this. Figure 13 of Kopp *et al*. (2003) schematically shows this model for the case of the Musician chain.

We think this scheme of channeled asthenosphere flow from a region of excess to a spreading center provides a general framework to explain the Pukapuka ridge (and similar features). However why this is ~2500 km long and not ~500 km maximum as the other cases, why it is so incredibly straight, and why the ages measured along it roughly monotonically decrease as they do toward the East Pacific Rise is not accounted for with this model.

Marquesas (10.5°S, 139.0°W) w= .5 az= 319° ± 8° rate= 93 ± 7 mm/yr

The Marquesas track is the one Pacific track that differs markedly from the trend of all its neighboring tracks. It is a short chain, ~450 km long, ~180 km wide, with its oldest ages only ~5 Ma. The shortness and width make it difficult to determine an azimuth for the track. We use 319° as measured from the topographic map (Fig. 1) of McNutt and Bonneville (1999). Azimuths determined by others are 326° by McNutt *et al*. (1989), 320° ± 5° by Brousse *et al*. (1990), and 308° by Duncan and McDougall (1974). Gripp and Gordon (2002) used an azimuth of 310° ± 12°. Strictly following our rule for converting estimated error of the azimuth into weighting, the weight would be 0.8. Given the fact this is the one track very not-parallel with its neighbors, and the uncertainty of what this implies as discussed in the next paragraph, we give it a weight of 0.5. Desonie *et al*. (1993) have made fourteen $^{40}Ar/^{39}Ar$ measurements here. Their line for rate 93 ± 7 mm/yr in their Fig. 3 best-fits the data measured using only the $^{40}Ar/^{39}Ar$ method; we prefer this value (down-playing the K-Ar measurements). (Note Desonie *et al*. prefer their other line in this same figure, 74 ± 6 mm/yr, which they obtained by fitting the oldest ages of each volcano using both K-Ar and $^{40}Ar/^{39}Ar$ methods.) Earlier published values for the rate of Marquesas migration are 104 ± 18 mm/yr (McDougall and Duncan, 1980) and 111 mm/yr (Brousse *et al*., 1990).

Why the Marquesas trend is so different from its neighbors has been the object of much speculation. McNutt *et al*. (1989) propose the Marquesas Fracture Zone has strongly influenced the surface expression of an otherwise normal fixed-hotspot/moving-plate scenario: "… the Marquesas plume is simply too weak to penetrate normal oceanic lithosphere unless given an easy conduit to the surface, such as a fracture zone." We don't understand exactly how this weakness 'pulls' the trend off-parallel, but our extrapolated 'zero position' of the Marquesas is exactly on the Marquesas Fracture Zone Ridge as they propose. Just how the fracture zone is a zone of weakness is not clearly explained in their paper, but Sleep (2002, the top part of his Fig. 1) does explain this clearly. Sleep's model requires flow of asthenosphere away from the Marquesas area southward across the Marquesas Fracture Zone. Then pressure-release-melting forms the ridge where the lithosphere lid changes from ~70 km thick (50 Ma seafloor on the north side) to ~65 km (42 Ma seafloor on the south side of the Marquesas Fracture Zone). However his model does not explain how the islands of the Marquesas align differently from the plate motion. In our section on Hawaii, we discuss how the chain can be deflected as asthenosphere spreads away from the plume not symmetrically but with greater asthenosphere flow going towards the 'easy' (thinner lithosphere) side of a fracture zone. In that section we refer to a finite element flow model of hotspot-source/fracture-zone interaction (Yamamoto *et al.*, 2005). But this model cannot be used with the observed trend of the Marquesas to infer the 'true' azimuth of the plate over the hotspot here – to the contrary, we used the estimated deflection between 'true' (which we can determine at Hawaii because of its track has a longer duration than in the Marquesas) and observed azimuths to find the parameters of the viscosity structure and thickness of the asthenosphere needed to make the model work. It has also been suggested (*cf.* Courtillot *et al.*, 2003, Fig. 4) that the 'superplume' region that includes the Marquesas is different from other plumes – the hotspots here are rooted at the 660 discontinuity and not at the core-mantle boundary. In such models there could be 'wander' and the track would not record plate motion and rate. This is a possibility, but such models don't predict how much or which direction the track would wander. The many short tracks in French Polynesia are all very parallel to one another and record the same plate velocity rate (within experimental error); why would this one track (Marquesas) behave differently from the others? For any of the reasons above, we might conclude we can't use the Marquesas to determine a Pacific plate motion azimuth and rate, but we do use it and its misfit contributes to the error ellipse of our final analysis.

Superswell Region

This concludes our discussion of the Pacific superswell region, roughly defined as the region enclosed by the Easter, Marquesas, Samoa, and Foundation features. This region is marked by shallower-than-normal seafloor (by ~500 m), numerous volcanic chains, and a warmer-than-typical mantle *(e.g.* McNutt and Fischer, 1987; Sichoix *et al.*, 1998). The anomalous nature of this area has lent much support to non-plume models of mantle convection (the website <httm://www.mantleplumes.org/> describes many of these models and the discussion about them). We think the essence of these non-plume models is most clearly presented by Anderson (2005, page 44): "The plate hypothesis assumes that the upper mantle is near the melting point and is variable in fertility, temperature, and solidus temperature. A small change in temperature, volatile content, and composition can have a large effect on melt volumes for a near-solidus mantle. Plate and plate tectonic-induced perturbations can generate 'melting anomalies'." [The 'plate tectonic-induced perturbations' in this region being overall plate tension with the volcanoes regarded as stress indicators.]

We think the geodynamic nature of this region is perhaps best interpreted as shown in Fig. 4 of Courtillot *et al.* (2003) or Fig. 14 of Davaille *et al.* (2003). An important variation of this is shown in Fig. 2 of Jellinek *et al.* (2003) or Fig. 4 of Gonnermann *et al.* (2004). In these figures, we see from shadowgraphs of narrow plumes rising from a hot bottom boundary layer that the bases and rising columns of plumes get swept toward the regions with the most uprising – there are thus many, many more plumes in a 'superswell' region. This general pattern is portrayed even more clearly, but even more schematically, in Fig. 17 of Jellinek and Manga (2004). [Their Fig. 17 is reproduced here as our Figure 4.] Our interpretation of the superswell region is that a very large amount of upward transport from the core/mantle boundary region overwhelms the normal geothermal profile of the earth and leads to consequences not present above narrow rising plumes. We think for almost all of the mantle, asthenosphere (being brought up by plumes from the core/mantle boundary region) is warmer than the mantle below the asthenosphere; this excess of (potential) temperature makes the asthenosphere stable against convection from just below. (That is, a mid-ocean rise has no 2-D style mantle 'roll' rising from deeper, the needed material flows in horizontally from asthenosphere supplied at the nearest plume.) But perhaps an extreme excess of a broad rising plume in the superswell region creates a mantle with the same (potential) temperature as asthenosphere, and instabilities that don't exist elsewhere can exist here. In any case, this is a very anomalous, very interesting region; understanding this will likely lead to a big advance in geodynamics. We shall return to this point in the conclusions section at the end of this paper.

Caroline (4.8°N, 164.4°E) w= 1 az= 289° ± 4° rate= 135 ± 20 mm/yr

The best paper on this track is Keating *et al.* (1984). Three island systems in the Carolines have been dated (K/Ar): Truk (~11 Ma), Ponape (~6 Ma), and Kusaie (~1 Ma). Since this paper there have been two studies with additional K/Ar measurements (Dixon *et al.* (1984) for Ponape and Lee *et al.* (2001) for Truk); these additional data don't change the averages in Keating *et al.* (1984). From the age/distance plot in Fig. 8 of Keating *et al.* (1984), we get a rate of migration of 135 ± 20 mm/yr and see that the 'zero age' extrapolation is to 4.8°N, 164.4°E, 165 km east of Kusaie. In an earlier abstract, Keating *et al.* (1981) chose a zero-point at 4.8°N, 165.7°E, ~130 km east of here, at what was then thought to be a prominent seamount. In this abstract, they also refer to a Micronesian legend of a submarine volcanic eruption in this vicinity ('four day open-ocean voyage SE of Ponape'; Kerr, 1981). However, in their 1984 paper they discuss the results of a later survey and conclude the 'seamount' chosen as the origin had been mislocated due to a navigation error. The Caroline track appears to have a 'bend' at 6 Ma; the younger part from Ponape to Mokil to Pingelap to Kusaie has an azimuth of 289°± 3°, the older part from the vicinity of Yap through many atolls to Truk to Oroluk to Ponape has an azimuth of 274°± 4°.

The observed azimuth (289°±4°) of the Caroline track is not in great agreement with our predicted direction of the Pacific plate in this region (297°). There is evidence for a "Caroline plate" with a motion slightly different from Pacific plate motion (Weissel and Anderson, 1978; Hegarty *et al.,* 1983), but this cannot account for this direction difference as the Caroline plate is located in the West and East Caroline Basins, well south of the Caroline Islands located on the Pacific plate and separated by the Sorol Trough and Mussan Trench.

Euterpe [Musicians] (10.0°S, 144.0°W) w= C

This is not considered to be an active hotspot, but an active hotspot at 10°S, 144°W active prior to 80 Ma would be in position to make the Musician Seamounts (ages 80 to 100 Ma) according to our finite-plate-rotation model. The Musician chain has special interest because of the striking example of an ancient series of *en echelon* ridges between seamounts and spreading center (see the figures in Kopp *et al*., 2003). Other examples of this 'streaking' of *en echelon* ridges is evident along the Line Islands between the Clarion and Clipperton Fracture Zones (where the actively spreading seafloor is close in age to that of the seamounts), near Crough Seamount (where the seamount is close in age to the then-position of the spreading center), and at the easternmost end of the Foundation chain. Euterpe is a muse of music, hence the name choice for this mythical hotspot.

Hawaii (19.0°N, 155.2°W) wt= 1 az= 304° ± 3° rate= 92 ± 3 mm/yr

Hawaii is so well studied we don't need lots of documentation for its track. We choose a 'zero' at 19.0°N, 155.2°W, northeast of the location of Loihi (18.9°N, 155.3°W) by half the spacing of the parallel 'Loa' and 'Kea' trends of volcanoes. For the most recent 6 Ma, the azimuth is 304°± 3°, the line from Hawaii to Kauai. Earlier than Kauai, the trend is 288°± 2°. Clague and Dalrymple (1987, see the data in their Fig. 1.5) give a rate for the Hawaiian track of 92 ± 3 mm/yr. In our analysis, we shall see our model is best fit if the rate at Hawaii is 81 mm/yr. It has been pointed out that all Hawaiian ages (as opposed to Emperor ages) are K-Ar measurements and there might be a systematic bias is the K-Ar values. Adding 10% to each

Hawaiian measurement would also serve to make the 'bend' at 47 Ma instead of the extrapolated 42 Ma. Sharp and Clague (2002; 2006) conclude a 47-48 Ma age for the bend based on their $^{40}Ar/^{39}Ar$ measurements of seamounts close to the bend.

For the most recent 2 Ma, the strike of volcanic centers is 321° – along both the string from West Molokai to Loihi and the parallel string from East Molokai to Kilauea. We think this deviation of the most recent alignment from the longer term trend is due to interaction between the plume and the Molokai Fracture Zone (Morgan and Phipps Morgan, 1994). The age of the ocean crust on the north side of the Molokai Fracture Zone is ~80 Ma and the age on its south side is ~90 Ma. We think the flux of new asthenosphere rising in the plume doesn't spread out symmetrically beneath the Pacific plate in this case, but spreads out preferentially toward the north where the lithosphere is thinner. The age difference here makes only ~5 km difference in the thickness of the lithosphere, but if viscosity changes strongly enough with depth, there could be enough asymmetric divergence to deflect the center of the plume the maximum of 100 km required to produce the observed track. Yamamoto *et al*. (2005) used a finite element code to investigate lithosphere/asthenosphere/plume interactions. In the case of an obliquely oriented fracture zone passing over a plume, the deflection of the track is similar to that observed at Molokai. A complementary situation occurs near Midway where the track crosses from 'old' seafloor north of the Murray Fracture Zone to 'young' seafloor on the south. The chain appears 'sucked' toward the younger side as it approaches the Murray Fracture Zone (*cf*. Fig. 1.14 of Clague and Dalrymple, 1987). Note 'multiple tracks' of parallel volcanic chains replace a narrow linear chain at the Murray crossing (~25 Ma) just as at the Molokai crossing (~2 Ma), but with the opposite sense.

Socorro/Revillagigedos (19°N, 111°W) w= C

This short alignment of three islands (their 400 km total separation and age span from 0 to 2.4 Ma give rate/azimuth of 160 mm/yr and 261°) is mentioned as a possible track by Duncan and Clague (1985), but we think these islands are due to rise/fracture zone interactions at the intersection of the Rivera Rise and Rivera Fracture Zone.

Guadalupe (27.7°N, 114.5°W) w= .8 az= 292° ± 5° rate= 80 ± 10 mm/yr

A straight line of ten seamounts extends northwestward (azimuth 292° ± 2°, see map by Davis *et al.,* 1995) from Isla Guadalupe (28.0°N, 118.3°W). Fieberling Seamount (980 km from Guadalupe) has an age of ~20 Ma (Lonsdale, 1991). Jasper Seamount (460 km from Guadalupe) has an age of ~11 Ma (there are $^{40}Ar/^{39}Ar$ ages of 10.3 and 10.0 Ma here, but the seamount is reversely magnetized and magnetic stratigraphy implies that the bulk of the seamount was constructed shortly before the ages of lavas dated, see Pringle *et al.,* 1991). Guadalupe itself has an age of ~6 Ma. [Guadalupe has had some very recent eruptions, but Batiza *et al.* (1979) measured K/Ar ages of 5.4 ± 0.8 and 3.7 ± 0.4 Ma (note the 5.4 age is suspect because the K_2O for this sample was not measured directly but inferred from a neighboring sample). Jarrard and Clague (1977) tabulate K/Ar ages by Engel and Engel (1970) of 5.8±1, 6.1±1, and 6.9±1 Ma. However, this data could not be found in the paper they referenced, only a general sentence stating the oldest exposed rocks on Guadalupe were between 5-7 Ma.] These distances/ages give rates of migration of 70 mm/yr and 92 mm/yr, respectively. The chain bends slightly past Fieberling and becomes more sparse. Erben Seamount, on this extension, has a fossil-determined age in the range 19-22.5 Ma (see Jarrard and Clague, 1977). Erben is 1410 km from Guadalupe, which would give a rate in the 80-110 mm/yr range.

The problem with the Guadalupe track is there is no young part. Simple extrapolation to ‘zero age’ would place the origin at 27.7°N, 114.5°W on the Vizcaino Peninsula on the Pacific coast of Baja California. There is a large eruptive active volcano 200 km east of this, at Tres Virgenes (27.5°N, 112.6°W) on the Gulf of California side of Baja. Two large calderas near Tres Virgenes have an age of approximately 1 Ma, Tres Virgenes itself may have had some eruptions in Holocene time (Sawlan, 1991). Sawlan suggests that these andesitic/rhyolitic magmas “may be derived by remelting the subduction-modified source that yielded the [neighboring] Miocene calcalkaline arc magmas”. Further, “lamprophyric dikes intrude the older medium-K calcaline andesite … south of Tres Virgenes". We think the 'zero' for the Guadalupe track is on the Vizcaino Peninsula (with no present volcanic marker) and that the volcanism at Tres Virgenes is due to channeled flow from this center towards the Gulf of California rise segment in the Guaymas Basin. Because there is no data to mark the track younger than 5 Ma, we have slightly downweighted this track (w = 0.8).

Cobb (46.0°N, 130.1°W) w= 1 az= 321° ± 5° rate= 43 ± 3 mm/yr

The Cobb-Eickelberg chain is very clear. Fifteen sample ranging in age from 9 Ma to 0 Ma ($^{40}Ar/^{39}Ar$) give a rate of 43 ± 3 mm/yr (Desonie and Duncan, 1990). The 'zero' is not at Cobb Seamount (which rises to within 34 m of the surface). The age-distance plot extrapolates to zero age at Axial Seamount (at 46.0°N, 130.1°W) astride the Juan de Fuca Ridge. The more recent 6 Ma track trends 321° ± 5°; older than 6 Ma is harder to determine but is about 306°. The older part of this track (~30 Ma to ~20 Ma) appears to be the Patton-Murray-Miller trend (Parker-Jones-Pathfinder might be a fracture zone alignment), but we have not made the finite rotation reconstructions to investigate this. [Dalrymple *et al.,* 1987, have a map with age dates pertinent to this.]

Bowie/Pratt-Welker (53.0°N, 134.8°W) w=.8 az= 306° ± 4° rate= 40 ± 20 mm/yr

This is a difficult track. The older part (Kodiak to Welker) has a clear line of large seamounts and a fairly clean age progression: Kodiak = 23.9 ± 0.6 Ma, Giacomini = 20.9 ± 0.4 Ma (both Turner *et al*., 1980, K/Ar), and Welker = 14.9 ± 0.3 Ma (Dalrymple *et al.,* 1987, $^{40}Ar/^{39}Ar$). The younger part forms a well constrained line with seven large seamounts giving an azimuth of 306° ± 4°. In addition to the age of Welker, Hodgkins has a K/Ar age of 2.8 ± 0.2 Ma (Turner *et al.,* 1980) and Bowie has an age of ~1 Ma (its normally-magnetized summit pinnacle has been sampled and has a K/Ar age of 0.07 ± 0.07 Ma, but the seamount overall is reversely magnetized which implies the bulk of Bowie was formed prior to 0.69 Ma; Cousens *et al.,* 1985). If the ages of Hodgkins and Bowie are accepted as correct, then the 'zero' of the chain is about 50 km southeast of Bowie (*i.e.,* 53.0°N, 134.8°W); if these are both very late-stage eruptions the 'zero' would be further southeast, much nearer the Tuzo Wilson Knolls (51.4°N, 131.0°W) or Dellwood Seamounts (50.8°N, 130.9°W) – see the next paragraph. [If the zero were at this more distant location, the azimuth of the recent track would be slightly different (310°) but still within our error bars.] Nataf and VanDecar (1993) found seismic evidence of a plume structure in the upper mantle in the general vicinity of Bowie (actually centered ~150 km north of Bowie); this adds to our confidence that Bowie and not Tuzo Wilson or Dellwood is the site of the plume. The age progession is difficult to interpret, but a rate of 40 ± 20 mm/yr fits the data [the older part is better fit with a faster rate (~58 mm/yr) and the younger part is better fit with a slower rate (~29 mm/yr)].

However this is a difficult choice. There would be 'more parallelism' between the Pratt-Welker and Cobb tracks if the southern location were the zero. Chase (1977) proposed the Tuzo Wilson Knolls to be the origin of the track. Other papers that discuss a possible hotspot in this area are Cousens *et al.,* 1983 and Cousens *et al.,* 1985. Other papers very relevant to the interpretation of this region are Riddihough *et al.,* 1980; Botros and Johnston, 1988; and Carbotte *et al.,* 1989 – from these you can see the contortions of the northern part of the 'Explorer Ridge', perhaps to keep the ridge centered over a hotspot. Cousens et al. (1985) suggest there may be two hotspots in this area – one near Bowie and another at the southern location. These make two intertwined tracks; in addition to the 2.8 Ma age for Hodgkins given above, there are older ages for Hodgkins and neighboring Davidson and Denson seamounts – see their Fig. 5. Our conclusion is there is a plume source near Bowie and plume-to-ridge interaction is presently contributing to the volcanism in the Tuzo Wilson/Dellwood region and is 'attracting' the Explorer ridge causing the westward jumps. The earlier history of this hotspot and similar plume-ridge interaction created the 'dual' track noted by Cousens *et al.* (1985).

Emperor / Line / Marshall-Gilbert / old-Louisville trend

In the course of this work, we constructed a finite rotation model for the Pacific. This was used to explore for possible connections of present and past tracks, *e.g*., is the Austral-Cook trend an overprint of an earlier Foundation track (no); are the Societies an overprint of an earlier Pitcairn track (quite possible). New models of finite Pacific motion have recently been published (Wessel *et al*., 2006; Andrews *et al*., 2006). The tracks generated with these models are <u>very</u> similar to those made with our model. There are differences in the predicted rates along the tracks between these models, but the paths of the tracks are very similar. In particular, comparing our rates [=a] to those of Wessel *et al*. (2006) [=b] to Andrews *et al*. (2006) [=c], for the Hawaiian track we get a=75, b=92, c=82 mm/yr for the average velocity between 0 and 30 Ma. Earlier, a=74, b=51, c=64 mm/yr between 30 Ma and the 'bend'; and a=80, b=59, c=69 mm/yr for the average velocity between between the bend and 65 Ma. We can make no significance to these differences in rates because we spent very little effort in trying to established ages at our turning points – or effort was to determine the paths of the tracks, not the ages along the paths (largely because of skepticism in using radiometric ages without checks, but also because continuity of paths was our objective). [Because of this, we don't think our model should be compared to finite rotation models derived for the Atlantic/Indian (*e.g*., O'Neill *et al*., 2005) until our age control is better established.] There are differences in rates between these models we think are significant – those parts of the tracks older than ~65 Ma. Our old tracks go much faster than Wessel *et al*. (2006); we have the Line, Marshall, *etc*., go faster and extend farther north than they, as discussed in the next paragraph.

Our (preliminary) finite rotation model for the Pacific (Table 2) and the figure of the finite tracks (Figure 1) shows that fixed sources can quite accurately match the 'northerly' trends of the 50 to 90 Ma portions of the hotspot tracks. In this figure, the Emperor track is generated using the Hawaii location for the start of this track, the Line track is generated using the location for Crough, the Tokelau trend is tracked using an origin at Macdonald, the East Marshall (Ratak)-Gilbert-Tuvalu (formerly Ellice) trend is fit with an origin at 'Maria' (not active now, but part of the superswell that may have been active at the time these were generated), and the Louisville trend with its origin at Louisville. (The latitudes and longitudes of these origin points are given in Table 1.) There are many shorter trends in the western Pacific parallel to this trend – for example the Musicians, a small group of seamounts southeast of Hess Rise, the western Marshalls (Ralik chain), a short alignment west of but parallel to the Line Islands, and others. These trends are all fit by the finite rotation poles determined mainly by the Emperor and Louisville tracks for a rigid Pacific plate. Where age-distance variation along a track can be used to determine a rate, the rates are in accord with the model rates at those places we have looked. However, for these short chains, the (fixed) sources have to turn on/turn off as appears to be fairly common in the superswell region.

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FIGURE CAPTIONS

Figure 1. Predicted finite tracks in the Pacific using the rotation parameters given in Table 2.

TABLE 1. AZIMUTH AND RATE OF EACH TRACK

HOTSPOT	PLATE	Lat (°N)	Long (°E)	Weight	Azobs (*)	± (°)	Vobs (mm/yr)	± mm/yr	Azmdl (°)	Vmdl (mm/yr)
Eifel	eu	50.2	6.7	1.0	082	±8	12	±2	080	5
Iceland	eu	64.4	-17.3	0.8	075	±10	5	±3	072	3
Azores	eu	37.9	-26.0	0.5	110	±12	N.D.*	N.D.	079	6
MassifCentral	eu	45.1	2.7	**B**	N.D.	N.D.	N.D.	N.D.	081	5
Etna	eu	37.8	15.0	**A**	N.D.	N.D.	N.D.	N.D.	083	6
Baikal	eu	51.0	101.0	0.2	080	±15	N.D.	N.D.	100	5
Hainan	ch	20.0	110.0	**A**	000	±15	N.D.	N.D.	N.D.	N.D.
Hoggar	af	23.3	5.6	0.3	046	±12	N.D.	N.D.	045	9
Tibesti	af	20.8	17.5	0.2	030	±15	N.D.	N.D.	042	11
JebelMarra	af	13.0	24.2	0.5	045	±8	N.D.	N.D.	045	13
Afar	af	7.0	39.5	0.2	030	±15	16	±8	044	16
Cameroon	af	-2.0	5.1	0.3	032	±3	15	±5	062	14
Madeira	af	32.6	-17.3	0.3	055	±15	8	±3	061	4
Canary	af	28.2	-18.0	1.0	094	±8	20	±4	070	5
GreatMeteor	af	29.4	-29.2	0.8	040	±10	N.D.	N.D.	101	4
CapeVerde	af	16.0	-24.0	0.2	060	±30	N.D.	N.D.	087	8
StHelena	af	-16.5	-9.5	1.0	078	±5	20	±3	075	15
TristanDaCunha	af	-37.2	-12.3	**A**	N.D.	N.D.	N.D.	N.D.	080	17
Gough	af	-40.3	-10.0	0.8	079	±5	18	±3	079	17
Vema	af	-32.1	6.3	**B**	N.D.	N.D.	N.D.	N.D.	067	17
Discovery	af	-43.0	-2.7	1.0	068	±3	N.D.	N.D.	073	17
Shona	af	-51.4	1.0	0.3	074	±6	N.D.	N.D.	071	17
Reunion	af	-21.2	55.7	0.8	047	±10	40	±10	043	17
Comores	af	-11.5	43.3	0.5	118	±10	35	±10	047	17
Kilimanjiro	af	-3.0	37.5	**B**	N.D.	N.D.	N.D.	N.D.	047	16
Karisimbi	af	-1.5	29.4	**B**	N.D.	N.D.	N.D.	N.D.	049	16
MtRungwe	af	-8.3	33.9	**B+**	N.D.	N.D.	N.D.	N.D.	049	16
Marion	an	-46.9	37.6	0.5	080	±12	N.D.	N.D.	106	9
Crozet	an	-46.1	50.2	0.8	109	±10	25	±13	102	9
Ob-Lena	an	-52.2	40.0	1.0	108	±6	N.D.	N.D.	107	9
Kerguelen	an	-49.6	69.0	0.2	050	±30	3	±1	096	9
Heard	an	-53.1	73.5	0.2	030	±20	N.D.	N.D.	094	9
Balleny	an	-67.6	164.8	0.2	325	±7	N.D.	N.D.	052	6
Scott	an	-68.8	-178.8	0.2	346	±5	N.D.	N.D.	044	5
Erebus	an	-77.5	167.2	**A**	N.D.	N.D.	N.D.	N.D.	037	4
Peter_I	an	-68.8	-90.6	**B**	N.D.	N.D.	N.D.	N.D.	124	1
MartinVaz	sa	-20.5	-28.8	1.0	264	±5	N.D.	N.D.	259	19
FernandoDoNoron	sa	-3.8	-32.4	1.0	266	±7	N.D.	N.D.	260	19
Ascension	sa	-7.9	-14.3	**B**	N.D.	N.D.	N.D.	N.D.	257	19
Guyana	sa	5.0	-61.0	**B**	N.D.	N.D.	N.D.	N.D.	266	18
Iceland	na	64.4	-17.3	0.8	287	±10	15	±5	292	16
Bermuda	na	32.6	-64.3	0.3	260	±15	N.D.	N.D.	261	18
Yellowstone	na	44.5	-110.4	0.8	235	±5	26	±5	235	17
Raton	na	36.8	-104.1	1.0	240	±4	30	±20	239	18
Azores	na	37.9	-26.0	0.3	280	±15	N.D.	N.D.	284	18
Anyuy	na	67.0	166.0	**B-**	N.D.	N.D.	N.D.	N.D.	157	7
LordHowe	au	-34.7	159.8	0.8	351	±10	N.D.	N.D.	001	63
Tasmantid	au	-40.4	155.5	0.8	007	±5	63	±5	000	66
EasternAustr	au	-40.8	146.0	0.3	000	±15	65	±3	006	70
Cocos-Keeling	au	-17.0	94.5	0.2	028	±6	N.D.	N.D.	033	70
JuanFernandez	nz	-33.9	-81.8	1.0	084	±3	80	±20	081	62
SanFelix	nz	-26.4	-80.1	0.3	083	±8	N.D.	N.D.	080	61
Easter	nz	-26.4	-106.5	1.0	087	±3	95	±5	097	61
Galapagos	nz	-0.4	-91.6	1.0	096	±5	55	±8	086	48
Galapagos	co	-0.4	-91.6	0.5	045	±6	N.D.	N.D.	045	81
Louisville	pa	-53.6	-140.6	1.0	316	±5	67	±5	300	76
Foundation	pa	-37.7	-111.1	1.0	292	±3	80	±6	283	88
Macdonald	pa	-29.0	-140.3	1.0	289	±6	105	±10	295	88
Arago	pa	-23.4	-150.7	1.0	296	±4	120	±20	298	88
N.Austral	pa	-25.6	-143.3	**B**	293	±3	75	±15	296	88
Maria/S.Cook	pa	-22.2	-154.0	0.8	300	±4	N.D.	N.D.	299	88
Samoa	pa	-14.5	-169.1	0.8	285	±5	95	±20	301	88
Crough	pa	-26.9	-114.6	0.8	284	±2	N.D.	N.D.	285	89
Pitcairn	pa	-25.4	-129.3	1.0	293	±3	90	±15	291	89
Society	pa	-18.2	-148.4	0.8	295	±5	109	±10	297	89
Samoa	pa	-14.5	-168.2	0.8	285	±5	95	±20	301	88
Marquesas	pa	-10.5	-139.0	0.5	319	±8	93	±7	295	88
Caroline	pa	4.8	164.4	1.0	289	±4	135	±20	299	89
Hawaii	pa	19.0	-155.2	1.0	304	±3	92	±3	302	80
Guadalupe	pa	27.7	-114.5	0.8	292	±5	80	±10	294	54
Cobb	pa	46.0	-130.1	1.0	321	±5	43	±3	317	44
Bowie	pa	53.0	-134.8	0.8	306	±4	40	±20	327	42

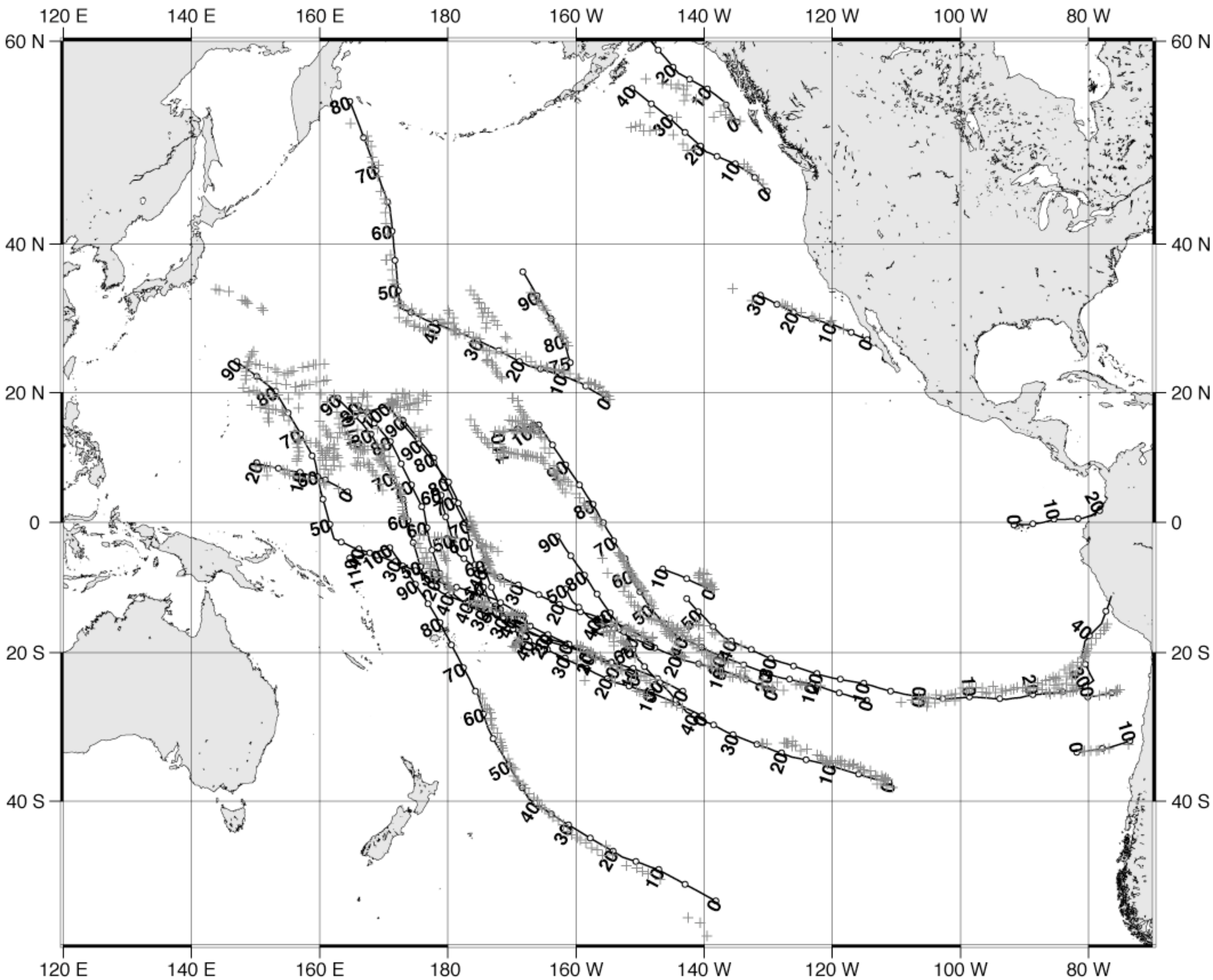
Note: Entries are the hotspot and plate its track is on, its location (latitude, longitude), its weight 'w' (see Introduction in text for explanation of w), the observed azimuth (usually from most recent ~5-10 m.y.) with estimated error, the observed rate with estimated error, and the azimuth and rate predicted by our model.

* N.D. = not determined

TABLE 2. PACIFIC FINITE ROTATION MODEL

Time (Ma)	Lat (°N)	Long (°E)	Angle (°)
6	59.6	-84.6	4.8
10	63.9	-77.7	8.0
18	68.4	-77.8	13.4
30	67.1	-77.5	21.9
42	67.3	-72.2	29.6
47	65.9	-65.5	33.2
57	56.8	-77.0	38.0
64	51.7	-78.7	41.2
80	45.2	-81.3	52.0
100	43.5	-78.2	66.7
110	49.9	-80.9	70.3
120	48.7	-84.5	76.6

Note: This provisional rotation model for Pacific plate motion is based on finite tracks on the Pacific and Nazca plates. It is referred to in the discussion many times and is included here for completeness even though it needs further tuning.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