RESEARCH ARTICLE

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Key Points:

- Tests of motion between Pacific and Indo-Atlantic hot spots are presented
- For the past 48 Ma fixed hot spot approximation is consistent with the results
- Prior to 48 Ma B.P. systematic error in the global plate circuits is suggested

Supporting Information:

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Tests of fixity of the Indo-Atlantic hot spots relative to Pacific hot spots

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Abstract Rates of inter-hot spot motion have been debated for decades. Herein we present updated predictions for the tracks of the Tristan da Cunha, Réunion, and Iceland hot spots assuming them to be fixed relative to Pacific hot spots. Uncertainties in Pacific hot spot rotations, which include uncertainties in the current locations of hot spots of 100–200 km, are combined with uncertainties in relative plate motions accumulated through the plate circuit to obtain the final uncertainty in the predicted positions (including uncertainties of 150–200 km in the current locations of the Indo-Atlantic hot spots). Improvements to reconstruction methods, to relative plate reconstructions, to age dates along the tracks, and to the geomagnetic reversal timescale lead to significant changes from prior results. When compared with the observed tracks, the predicted tracks indicate nominal rates of motion of only 2–6 mm a^{−1} of these Indo-Atlantic hot spots relative to Pacific hot spots over the past 48 Ma. Within the uncertainties, the rates range from no motion to rates as high as 8–13 mm a^{−1}. For reconstructions prior to 48 Ma B.P., however, the apparent rates of inter-hot spot motion are much larger, 46–55 ± 20 mm a^{−1}, if the motion occurred entirely between 68 Ma B.P. and 48 Ma B.P. Either hot spots moved rapidly before 48 Ma B.P., and slowed drastically at ≈ 48 Ma B.P., or global plate circuits through Antarctica become less reliable as one goes increasingly further into the past. Most paleomagnetic data favor the latter explanation.

1. Introduction

Hot spots are sites of intraplate volcanism or of excessive volcanism along plate boundaries. Morgan [1971, 1972] proposed hot spots to be the surface manifestations of relatively stationary deep mantle plumes, which leave tracks of age-progressive volcanism on the plates as the plates move over them. Since then, these tracks have been widely used to determine the history of plate motion relative to the deep mantle. However, despite considerable effort, how fast hot spots move relative to another, and thus the limits of the hot spot frame of reference, continues to be debated. Rising plumes in a convecting mantle cannot be completely fixed [e.g., Steinberger and O'Connell, 1998], so the question is not whether hot spots are completely fixed, but how fast the motion is between them. Over the years, the results have ranged from approximate fixity (≤5 mm a^{−1}) [e.g., Morgan, 1971, 1972; Duncan, 1981; Müller et al., 1993] to substantial and rapid motion between Pacific and Indo-Atlantic hot spots [e.g., Molnar and Stock, 1987; Petronotis and Jurdy, 1990], in some cases with rates of inter-hot spot motion estimated to be as high as 80 mm a^{−1} [e.g., Raymond et al., 2000].

Based on models of mantle flow [e.g., Steinberger and O'Connell, 1998; Steinberger et al., 2004; O'Neill et al., 2005], plume motions are in principle predictable. However, several critical parameters, including but not limited to the viscosity structure of the mantle, are not known well enough for such predictions to be truly quantitative, and as these models generally lack formal uncertainties, their reliability is difficult to assess. Nevertheless, the directions of hot spot motions may be generally predictable [e.g., Steinberger et al., 2004], but the rates are essentially unknown by a more-or-less constant multiplicative factor [O'Neill et al., 2005]. Ultimately the rates of inter-hot spot motion must come from work such as is presented in this study, with the mantle flow model parameters adjusted to match these rates.

Given the motion of one plate (e.g., the Pacific plate) over its hot spots, relative plate reconstructions can be used to predict the positions of hot spots under other plates, which can be compared with the observed tracks of the hot spots. If the plates are rigid, if all the ancient plate boundaries have been recognized and properly incorporated, and if the hot spots are fixed relative to one another, the predicted track should

Figure 1. Main components and layout of the global plate circuit through mid-ocean ridges (as used in this study). Arrows represent motion across mid-ocean ridges, except that between HS and PA, which indicates motion between the Pacific plate and Pacific hot spots.

coincide with the known trace (within uncertainties). Inconsistencies, on the other hand, give an estimate of the relative motion between hot spots (or indicate plate nonrigidity or neglected plate boundaries).

In an important study, *Molnar and Stock [1987]* used this approach to estimate average velocities of 10 to 20 mm a^{-1} between the Hawaiian and Indo-Atlantic hot spots for the past 68 million years, concluding that hot spots do not define a fixed reference frame. More than two decades of new age dates [e.g., *Duncan and Keller, 2004; Sharp and Clague, 2006; Koppers et al., 2004*], updated plate reconstructions, updated geomagnetic reversal timescale [e.g., *Cande and Kent, 1995*], and updated methods for estimating plate reconstructions relative to

the hot spots and their uncertainties [e.g., *Andrews et al., 2006*] require a new analysis. Thus, we present updated plate circuit reconstructions for the past 68 million years for the Tristan da Cunha, Réunion, and Iceland hot spots assuming them to be fixed relative to the Pacific hot spots. We build on the method of *Andrews et al. [2006]* for objectively estimating plate-hot spot rotations and their uncertainties. In addition to the uncertainties in plate-hot spot rotations, uncertainties in relative plate motions are accumulated through the plate circuit to obtain the final uncertainty (in the form of two-dimensional 95% confidence regions) in the predicted positions. Predictions are made for ages corresponding to those of magnetic anomalies commonly used in global plate reconstructions: 10.9 Ma B.P. (C50; old end of anomaly 5), 20.1 Ma B.P. (C60; old end of anomaly 6), 33.5 Ma B.P. (C130; old end of anomaly 13), 39.3 Ma B.P. (C18; center of anomaly 18), 47.9 Ma B.P. (C210; old end of anomaly 21), 56.1 Ma B.P. (C25; center of anomaly 25), and 67.7 Ma B.P. (C30/C31; center of the reversed polarity interval between anomalies 30 and 31). The ages have been assigned according to the timescale of *Cande and Kent [1995]*. We find that the predicted tracks agree with the observed tracks much better for the past 48 million years than found before. For reconstructions for 56.1 Ma B.P. and 67.7 Ma B.P., however, the predicted and observed tracks of Indo-Atlantic hot spots diverge, as found before by many workers.

2. Methods and Plate Circuits

To establish a model for Pacific plate motion relative to the hot spots, along with proper uncertainty estimates over the past 68 million years, we use the N-hot spot method of *Andrews et al. [2006]*, which provides means for deriving the plate-hot spot rotations with realistic uncertainties in the rotations. The method allows the use of any number of hot spot tracks and elliptical uncertainties of arbitrary sizes for both ancient and current locations of hot spots in estimating the rotation that minimizes the sum-squared normalized misfit. It is useful to be able to use elliptical uncertainties, as the location of an ancient hot spot track is in many places better constrained across the track, than it is along the track, because of uncertainties and gaps in the age progression along a volcanic chain. Once a best fitting rotation for a given age has been found, a covariance matrix describing the uncertainties in the rotation is determined [*Andrews et al., 2006*]. The details of the method, and how this method differs from prior methods used for determining plate-hot spot rotations, are described in *Andrews et al. [2006]*.

The sum-squared normalized misfit, r , is expected to be approximately chi-square distributed. The Hawaiian-Emperor and Louisville tracks both limit 2 degrees of freedom and a rotation is specified by three parameters, thus resulting in an overdetermined problem with 1 degree of freedom. Values of r exceeding 3.84 are unacceptably large at the 5% significance level, and values of r less than 0.004 are unacceptably small at the 5% significance level.

Table 1. Preferred Rotations Used to Quantify the Global Plate Circuit in Making Hot Spot Track Predictions^a

Plate Pair ^b	Source Age ^c	Age (Ma)	Lat (°N)	Lon (°E)	Angle (deg)	Source
pa-wa	C5n.2n(o)	10.9	70.36	−77.81	9.48	<i>Croon et al. [2008]</i>
pa-wa	C6n(o)	20.1	74.00	−70.16	16.73	<i>Croon et al. [2008]</i>
pa-wa	C13n(o)	33.5	74.48	−64.02	27.40	<i>Croon et al. [2008]</i>
pa-wa	C18n.1n(y)	38.4	74.86	−56.21	31.41	<i>Croon et al. [2008]</i>
pa-wa	C18n.2n(o)	40.1	74.87	−54.46	32.62	<i>Croon et al. [2008]</i>
pa-wa	C21n(o)	47.9	74.52	−50.19	37.64	<i>Cande et al. [1995]</i>
pa-wa	C24n.3n(o)	53.4	73.62	−52.50	40.03	<i>Cande et al. [1995]</i>
pa-wa	C27n(m)	61.1	71.38	−55.57	44.90	<i>Cande et al. [1995]</i>
pa-wa	C28r(m)	63.8	70.55	−55.72	47.00	<i>Stock et al.^d</i>
pa-wa	C30r(o)/C31n(y)	67.7	68.94	−55.52	49.60	<i>Stock et al.^d</i>
ea-wa	C8n.2n(o)	26.6	0.00	0.00	0.0	<i>Cande et al. [2000]</i>
ea-wa	C13n(o)	33.5	−18.15	−17.85	−0.7	<i>Cande et al. [2000]</i>
ea-wa	C20n(o)	43.8	−18.15	−17.85	−1.7	<i>Cande et al. [2000]</i>
ea-lw	C5n.2n(o)	10.9	14.6	−49.1	1.53	<i>Lemaux et al. [2002]</i>
ea-lw	C6n(o)	20.1	10.8	−46.0	2.70	<i>Patriat et al. [2008]</i>
ea-lw	C13n(m)	33.3	16.2	−44.7	5.66	<i>Patriat et al. [2008]</i>
ea-lw	C26n(o)	57.9	8.8	−42.6	10.83	<i>Royer and Chang [1991]</i>
ea-lw	Reversed polarity interval between 30 and 31 (m)	67.7	2.22	−40.74	12.5	<i>Molnar et al. [1988]</i>
Plate pair	Source age	Age (Ma)	Lat (°N)	Lon (°E)	Angle/Ma (°/Ma)	Source
nb-lw	Angular velocity vector		−37.2	−23.1	0.04	<i>Homer-Johnson et al. [2007]</i>
lw-nb		30	−37.2	−23.1	1.2	
Plate pair	Source age	Age (Ma)	Lat (°N)	Lon (°E)	Angle (deg)	Source
nb-na	C6n(m)	19.6	81.1	56.5	−5.21	<i>McQuarrie et al. [2003]</i>
nb-na	C13n(m)	33.3	76.3	2.2	−9.96	<i>McQuarrie et al. [2003]</i>
nb-na	C18n(m)	39.3	−74.8	177.1	12.48	<i>McQuarrie et al. [2003]</i>
nb-na	C21n(m)	47.1	73.7	−6.1	−15.46	<i>McQuarrie et al. [2003]</i>
nb-na	C25n(m)	56.1	80.0	−0.7	−18.11	<i>McQuarrie et al. [2003]</i>
nb-na	30/31r	67.7	82.5	−0.6	−20.96	<i>McQuarrie et al. [2003]</i>
na-eu	C5n.2n(o)	10.9	67.75	133.17	2.62	<i>Merkouriev and DeMets [2008]</i>
na-eu	C6n(o)	20.1	68.62	131.76	5.03	<i>Merkouriev and DeMets [2008]</i>
na-eu	C13n(m)	33.3	63.6	137.1	7.38	<i>McQuarrie et al. [2003]</i>
na-eu	C18n(m)	39.3	57.8	140.3	8.48	<i>McQuarrie et al. [2003]</i>
na-eu	C21n(m)	47.1	52.8	142.3	9.82	<i>McQuarrie et al. [2003]</i>
na-eu	C25n(m)	56.1	46.6	145.5	12.83	<i>McQuarrie et al. [2003]</i>
na-eu	30/31r	67.7	58.4	145.9	16.31	<i>McQuarrie et al. [2003]</i>
gr-na		35	0.00	0.00	0.00	<i>Roest and Srivastava [1989]</i>
gr-na	C21n	48	62.80	−91.95	−2.61	<i>Roest and Srivastava [1989]</i>
gr-na	C24n.3n	54	55.86	−104.55	−4.44	<i>Roest and Srivastava [1989]</i>
gr-na	C25n	58	24.48	−137.25	−3.12	<i>Roest and Srivastava [1989]</i>
gr-na	C27n	62	27.36	−149.41	−3.72	<i>Roest and Srivastava [1989]</i>
gr-na	C31n	68	43.94	−145.31	−4.92	<i>Roest and Srivastava [1989]</i>
Plate pair	Source age	Age (Ma)	Lat (°N)	Lon (°E)	Angle/Ma (°/Ma)	Source
sm-lw	Angular velocity vector		−27.9	52.2	0.066	<i>Homer-Johnson et al. [2007]</i>
lw-sm		30	−27.9	52.2	1.98	
Plate pair	Source age	Age (Ma)	Lat (°N)	Lon (°E)	Angle (deg)	Source
sm-in	C5n.2n(o)	10.9	23.98	29.71	4.34	<i>Demets et al. [2005]</i>
sm-in	C6n(o)	20.1	24.52	31.20	8.59	<i>Demets et al. [2005]</i>
sm-in	C13n(m)	33.3	21.80	35.00	14.39	<i>Royer and Chang [1991]</i>
sm-in	C21n(y)	46.3	18.64	43.37	22.56	<i>Royer et al. [2002]</i>
sm-in	C22n(y)	49.0	18.94	39.62	23.20	<i>Royer et al. [2002]</i>
sm-in	C25n(y)	55.9	19.41	29.02	30.11	<i>Royer et al. [2002]</i>
sm-in	c27n(y)	60.9	18.83	24.86	35.41	<i>Royer et al. [2002]</i>
sm-in	c33n(o)	79.1	20.32	21.39	51.30	<i>Molnar et al. [1988]</i>

^aRotations for the plate pairs are given as motion of the first plate relative to the second.

^bPacific plate (pa), West Antarctica (wa), East Antarctica (ea), Lwandle (lw), Somalia (sm), Nubia (nb), North America (na), Eurasia (eu), Greenland (gr), and India plate (in).

^cAges shown here are given in the timescale of *Cande and Kent [1995]*, and (y), (o), and (m), refer to young and old ends and middle of polarity chron, respectively.

^dUnpublished manuscript, rotations listed by *Eagles et al. [2004]*.

Table 2. Covariance Matrix Values^a Used for the Relative Plate Motions^b

Plate Pair	Used For	Source	Source	a	b	c	d	e	f	g
pa-wa	C5	C5	<i>Croon et al. [2008]</i>	2.52	0.662	3.49	2.72	3.92	10.6	8
pa-wa	C6	C6	<i>Croon et al. [2008]</i>	2.00	0.848	2.37	1.13	1.54	4.65	8
pa-wa	C13	C13	<i>Croon et al. [2008]</i>	5.29	3.16	0.72	2.68	3.37	6.19	8
pa-wa	C18	C18	<i>Croon et al. [2008]</i>	1.48	1.04	1.61	0.982	1.34	2.24	7
pa-wa	C21	C24	<i>Stock [personal communication, 1997]</i>	49.5	4.10	75.1	2.10	4.60	119	7
pa-wa	C25	C27	<i>Stock [personal communication, 1997]</i>	19.3	−1.10	31.0	0.30	−1.8	50.9	7
pa-wa	C31	C31	<i>Stock [personal communication, 1997]</i>	76.0	−3.42	109	1.33	−2.67	167	7
ea-wa	C13–C31	C13	<i>Cande et al. [2000]</i>	2.19	0.0039	5.74	0.0041	0.0083	15.1	5
ea-lw	C5	C5	<i>Lemaux et al. [2002]</i>	0.221	0.236	−0.092	0.304	−0.167	0.245	6
ea-lw	C6	C6	<i>Patriat et al. [2008]</i>	1.028	0.883	−0.234	1.759	−1.347	2.237	6
ea-lw	C13	C13	<i>Patriat et al. [2008]</i>	0.856	0.673	−0.166	0.69	−0.374	0.582	5
ea-lw	C18–C31	C26	<i>Royer and Chang [1991]</i>	0.15	0.12	−0.09	0.11	−0.07	0.11	3
lw-nb	C5–C31	^c	<i>Horner-Johnson et al. [2007]</i>	73.116	49.887	−95.766	41.736	−67.68	132.657	8
nb-na	C5, C6	C6	<i>McQuarrie et al. [2003]^d</i>	0.5773	−0.4609	0.4223	0.4724	−0.3969	0.3577	5
nb-na	C13	C13	<i>McQuarrie et al. [2003]^d</i>	0.5686	−0.4835	0.433	0.5206	−0.434	0.3841	5
nb-na	C18	C18	<i>McQuarrie et al. [2003]^d</i>	0.1231	−0.1092	0.0959	0.1207	−0.0987	0.0884	4
nb-na	C21	C21	<i>McQuarrie et al. [2003]^d</i>	0.1119	−0.1155	0.0822	0.1484	−0.0991	0.0694	4
nb-na	C25	C25	<i>McQuarrie et al. [2003]^d</i>	0.1243	−0.1491	0.1024	0.1948	−0.1287	0.0886	4
nb-na	C31	C31	<i>McQuarrie et al. [2003]^d</i>	0.6503	−0.6436	0.4545	0.9357	−0.5599	0.4392	5
na-eu	C5	C5	<i>Merkouriev and DeMets [2008]</i>	0.0779	−0.0133	0.0925	0.0572	−0.1141	0.2978	5
na-eu	C6	C6	<i>Merkouriev and DeMets [2008]</i>	0.5661	−0.1278	0.6896	0.0758	−0.2358	0.9895	5
na-eu	C13	C13	<i>McQuarrie et al. [2003]^d</i>	0.0807	−0.0254	0.1078	0.023	−0.0409	0.1648	4
na-eu	C18	C18	<i>McQuarrie et al. [2003]^d</i>	0.1835	−0.0559	0.2449	0.0455	−0.0876	0.3697	4
na-eu	C21	C21	<i>McQuarrie et al. [2003]^d</i>	0.3029	−0.1202	0.3823	0.0778	−0.1658	0.5122	4
na-eu	C25	25	<i>McQuarrie et al. [2003]^d</i>	0.2476	−0.0822	0.2974	0.0704	−0.1206	0.3834	4
na-eu	C31	Cc31	<i>McQuarrie et al. [2003]^d</i>	0.1968	−0.0683	0.249	0.0301	−0.088	0.3216	3
gr-na	C18, C21	C21	<i>Acton [1999]^e</i>	0.1574	−0.1967	0.3899	0.2499	−0.4923	0.9775	4
gr-na	C25	C25	<i>Acton [1999]^e</i>	0.0657	−0.094	0.1778	0.1394	−0.2607	0.495	4
gr-na	C31	C31	<i>Acton [1999]^e</i>	0.0863	−0.13	0.2396	0.2012	−0.3678	0.6796	4
lw-sm	C5–C31	^c	<i>Horner-Johnson et al. [2007]</i>	65.004	63.732	−79.782	78.783	−80.493	114.321	8
sm-in	C21	C23	<i>Royer and Chang [1991]</i>	42900	77300	19900	139400	35800	9300	7
sm-in	C25, C31	C26	<i>Royer and Chang [1991]</i>	13700	28300	9200	58800	19100	6300	7

$$^a\text{Covariance matrix} = \begin{pmatrix} a & b & c \\ b & d & e \\ c & e & f \end{pmatrix} \times 10^{-9} \text{radians}^2.$$

^bCovariance matrix values are given in the reference frame fixed to the second plate in the plate pair.

^cExtrapolated from the values for angular velocity vector.

^dCalculated from partial uncertainty rotations of *McQuarrie et al. [2003]*.

^eCalculated from G. Acton's (unpublished data, 1999) partial uncertainty rotations.

A global relative plate motion circuit over the past 68 million years is also needed. Relative motion between two plates can be estimated if the plates share a mid-ocean ridge, and marine magnetic anomalies and fracture zones can be used to determine the history of seafloor spreading. The plate circuit (through Antarctica) used in this study is shown in Figure 1 and described in detail in Table 1. Most of the relative plate motion rotations adopted herein were taken from analyses using *Hellinger's [1981]* criterion for goodness of fit, associated with covariance matrix values describing the uncertainties in the rotations based on the statistical approach developed by *Chang [1988]*. Because rotations may not be available for the age of interest, some rotations were interpolated from the two published rotations closest to the age of interest (Table 1). Rotations were assigned ages according to the timescale of *Cande and Kent [1995]*. If a covariance matrix for a particular rotation was not available, we estimated it from partial uncertainty rotations, i.e., from partial uncertainty rotations of *McQuarrie et al. [2003]* for North America-Africa motion and from *Acton [1999]* for North America-Greenland motion (Table 2). For some rotations for more ancient reconstructions, neither covariance matrices nor partial uncertainty rotations were available. For these rotations, we used the closest (in age) available uncertainty estimate for the same plate pair (Table 2). To obtain the final uncertainty in the predicted positions (shown in figures as two-dimensional 95% confidence regions; all uncertainties discussed here are two-dimensional 95% confidence limits), the uncertainties in relative plate motions were

Table 3. Radiometric Age Dates Used Along the Hawaiian-Emperor, Louisville, Tristan da Cunha, Réunion, and Iceland Tracks

Age (Ma)	Lat (°N)	Lon (°E)	Source	Comments
Hawaii				
0 ^a	19.6	204.5		At Kilauea
7.2	23.0	198.0	<i>Dalrymple et al.</i> [1974]	^b
10.3	23.5	195.5	<i>Dalrymple et al.</i> [1974]	^b
12	23.6	193.7	<i>Dalrymple et al.</i> [1974]	^b
19.9	25.7	188.0	<i>Dalrymple et al.</i> [1981]	^b
27.7	28.3	182.7	<i>Dalrymple et al.</i> [1977]	^b
31	28.9	181.2	<i>Sharp and Clague</i> [2006]	Unnamed seamount; shield and postshield stage
38.7	30.9	175.9	<i>Sharp and Clague</i> [2006]	Colahan seamount; shield stage
41.5	31.8	174.3	<i>Sharp and Clague</i> [2006]	Abbott seamount; postshield stage
46.7	32.1	172.3	<i>Sharp and Clague</i> [2006]	Diakakuji seamount; postshield stage
47.9	33.7	171.6	<i>Sharp and Clague</i> [2006]	Kimmei seamount; shield stage
50.4	35.1	171.7	<i>Sharp and Clague</i> [2006]	Koko (south); shield stage
52.6	35.9	171.1	<i>Sharp and Clague</i> [2006]	Koko (north); rejuvenated
60.9	44.0	170.0	<i>Sharp and Clague</i> [2006]	Suiko seamount; postshield stage
49.2	34.9	172.2	<i>Duncan and Keller</i> [2004]	Site 1206; Koko seamount; shield stage
55.5	41.3	170.4	<i>Duncan and Keller</i> [2004]	Site 1205; Nintoku seamount; shield stage
75.8	51.0	167.7	<i>Duncan and Keller</i> [2004]	Site 1203; Detroit seamount; shield stage
81	51.5	168.3	<i>Keller et al.</i> [1995]	Detroit north
Louisville				
0 ^a	−50.9	221.9	<i>Lonsdale</i> [1988]	
1.11	−50.4	220.9	<i>Koppers et al.</i> [2004]	Sample MTHN-7D1
13.2	−48.2	211.2	<i>Koppers et al.</i> [2004]	Sample MTHN-6D1
36.5	−41.6	195.8	<i>Koppers et al.</i> [2004]	Sample VG-3a/MSN110-1; Valerie seamount
33.9	−40.8	194.7	<i>Koppers et al.</i> [2004]	Sample VM36-02
45.5	−38.3	192.3	<i>Koppers et al.</i> [2004]	Sample VM36-03
46.3	−37.0	190.2	<i>Koppers et al.</i> [2004]	Sample VM36-04
61.4	−30.1	186.8	<i>Koppers et al.</i> [2004]	Sample SOTW-9-48-2; Currituck seamount
68.9	−27.3	185.8	<i>Koppers et al.</i> [2004]	Sample SOTW-9-52-1
76.7/78.7	−25.5	185	<i>Koppers et al.</i> [2004]	Samples SOTW-9-58-1a and SOTW-9-58-7; Osborn seamount
Tristan da Cunha				
0 ^a	−37.5	347.5	<i>O'Connor and le Roex</i> [1992]	On Tristan da Cunha island; best age estimate ranges 0.64–1.3 Ma
Walvis Ridge ^c				Comments from <i>O'Connor and Duncan</i> [1990]
30 ^d	−37.1	−7.8	<i>O'Connor and Duncan</i> , 1990	Best estimate for the age of this site is 30–31 Ma
39–40	−34.3	−5.0	<i>O'Connor and Duncan</i> [1990]	Best estimate for the crystallization age is 39–40 Ma
38–39	−34.5	−3.6	<i>O'Connor and Duncan</i> [1990]	Best estimate for the age of this volcano is 38–39 Ma
46.52/−50 ^e	−34.3	−1.6	<i>O'Connor and Duncan</i> [1990]	Total fusion age of 52 Ma and plateau age of 46.2
64	−33.0	0.0	<i>O'Connor and Duncan</i> [1990]	Apparent age of this sample is 64 Ma
50	−32.6	1.1	<i>O'Connor and Duncan</i> [1990]	Questionable sample V29-9-1; we omit this age
61–62	−32.0	2.4	<i>O'Connor and Duncan</i> [1990]	Crystallization age of this site is between 61 and 62 Ma
79	−29.1	3.0	<i>O'Connor and Duncan</i> [1990]	Best estimate for the age of the basement is 79 Ma
78–79	−28.5	2.3	<i>O'Connor and Duncan</i> [1990]	Best estimate of the crystallization age at this site is between 78 and 79 Ma
Min 69.8	−25.4	6.7	<i>O'Connor and Duncan</i> [1990]	Questionable sample, minimum age provided
Reunion				
0 ^a	−21.1	55.5	<i>McDougall</i> [1971]	On Réunion Island
7.5	−21.0	57.5	<i>Duncan and Hargraves</i> [1990]; <i>McDougall</i> [1971]	
31.5	−16.0	60.5	<i>Duncan and Hargraves</i> [1990]	Industry well NB-1
33.2	−13.1	61.4	<i>Duncan and Hargraves</i> [1990]	ODP site 706
49.3/50	−4.2	73.4	<i>Duncan and Hargraves</i> [1990]	ODP site 713; <i>Baksi</i> [2005] estimates 50 ± 2 Ma
57.2	5.1	73.8	<i>Duncan and Hargraves</i> [1990]	ODP site 715
~65.5	~20.0	~76.0	<i>Hofmann et al.</i> [2000]	Deccan traps, within 1 Ma
Iceland				
0 ^a	64.0	344.0	<i>Lawver and Müller</i> [1994]	
West Greenland ^f				
East Greenland				
49.4	67.3	−33.2	<i>Tegner et al.</i> [2008]	Sample SA-1; plateau age
47.2	67.5	−32.5	<i>Tegner et al.</i> [2008]	Sample P-175; total fusion age
49.2/49.8	66.7	−34.0	<i>Tegner et al.</i> [1998]	Samples 416822 and 416804; plateau and isochron age
47.3/48.8	68.0	−33.0	<i>Tegner et al.</i> [1998]	Samples PCT-75 and KEH-302; plateau ages

^aCurrent location of the hot spot.

^bAge dates for the younger part of the chain are not comparable in quality to the newer ages along the older part of the chain.

^cWe omit the ages along the Gough lineament.

^dConcordant sample with 30 Ma average.

^eAge is the average of weighted isochron and plateau ages.

^f*Storey et al.* [1998] estimate that 80% of the lavas erupted between 60.9 and 61.3 Ma.

Table 4. Locations and Uncertainties Used as Input Into the N-hot Spot Method

Age (Ma)	Lat (°N)	Lon (°E)	Major Axis (km)	Minor Axis (km)	Azimuth (Clockwise From North) ^a
Hawaii					
0	19.6	204.5	100	100	0
10.9	23.7	195.6	200	100	−75
20.1	25.8	187.9	200	100	−80
33.5	29.5	179.5	200	100	−70
39.3	31.1	175.6	200	100	−70
47.9	33.7	171.6	200	100	−35
56.1	41.6	170.4	250	100	−10
67.7	47.2	169.0	300	100	−15
Louisville					
0	−50.9	221.9	200	200	0
10.9	−48.6	213.0	300	100	−70
20.1	−46.3	204.3	300	100	−60
33.5	−40.9	195.0	300	100	−50
39.3	−39.6	193.6	300	100	−45
47.9	−36.3	189.8	300	100	−25
56.1	−32.5	188.0	300	100	−20
67.7	−27.7	186.0	300	100	−25

^aAzimuth is the azimuth of the major axis of the uncertainty ellipse associated with the input location.

accumulated through the plate circuit (for details, see *Chang* [1988], *Chang et al.* [1990], *Royer and Chang* [1991], and *Kirkwood et al.* [1999]).

Before making the final choices for our plate circuit rotations, we tested how much different available rotations affect the final predicted positions. In particular, we tested how different estimates of motion within Africa [e.g., *Royer et al.*, 2006; *Horner-Johnson et al.*, 2007] change the predicted tracks. The timing of motion between the Nubia (West Africa) and Somalia (East Africa) plates is uncertain, and the location of the boundary between these two plates has not been fully resolved. The hypothesized existence of the Lwandle plate [*Hartnady*, 2002; *Horner-Johnson et al.*, 2007] between the Nubia and Somalia plates may add further complications. *Horner-Johnson et al.* [2007] found that their data are better fit if a Lwandle plate lies along the Africa side of the Southwest Indian Ridge between the Nubia and Somalia plates. If so, published rotations for “Africa-Antarctica” motion may represent Nubia-Antarctica motion, Lwandle-Antarctica motion, Somalia-Antarctica, or some combination of, or compromise between, two or more of these [*Horner-Johnson et al.*, 2007]. In our preferred model, we account for the modest motion indicated between the Nubia and Lwandle plates. We take prior estimates for East Antarctica-Somalia or East Antarctica-Africa motion [e.g., *Royer and Chang*, 1991; *Molnar et al.*, 1988; *Bernard et al.*, 2005] as representing East Antarctica-Lwandle motion because most of the data used to constrain these estimates of motion are from the portion of the Southwest Indian Ridge separating Antarctica from the hypothesized Lwandle plate.

Motion between Nubia and Somalia began no earlier than ≈ 30 Ma B.P. [*Burke*, 1996]. We considered alternative models with motion beginning either at 30 Ma B.P. or at 10 Ma B.P. For both models the finite rotations were found by extrapolating the current Nubia-Lwandle and Nubia-Somalia angular velocities [*Horner-Johnson et al.*, 2007]. We found that the results are insensitive to these alternative assumptions and change little even if motion between Nubia and Lwandle is neglected instead (see supporting information for details).

Tests using other alternative rotations for the plate pairs are described in the supporting information. Generally, the predicted locations are similar to the ones obtained by our preferred rotations. In the case of Iceland, however, the predicted position for 68 Ma B.P. is somewhat sensitive to the choice of East Antarctica-Lwandle rotations. The choices for ages older than that of C13 were between the rotations of *Royer and Chang* [1991] combined with the rotation of *Molnar et al.* [1988] for C31 and the rotations of *Bernard et al.* [2005]. Use of the rotations by *Bernard et al.* [2005] moves the predicted position for C31 130 km northeastward from the position obtained using the rotation of *Molnar et al.* [1988] for C31. Nonetheless, all the predicted tracks lie within the 95% confidence limits of our preferred model. Our preferred rotations for describing motion before C13 (33.3 Ma) between the East Antarctica and Lwandle plates are those of *Royer and Chang* [1991] combined with the rotation of *Molnar et al.* [1988] for C31. For the younger times we use the rotation of *Lemaux et al.* [2002] for C5 and the rotations of *Patriat et al.* [2008] for C6 and C13.

Sources for the other plate circuit links are given in Table 1.

Figure 2. (a) Map showing the Hawaiian-Emperor hot spot track, input, and resulting estimate of motion of the Hawaiian hotspot relative to the Pacific plate determined with the N-hot spot method [Andrews *et al.*, 2006]. Red inverted triangles show locations of dated igneous rock samples with ages [Dalrymple *et al.*, 1974, 1977, 1981; Sharp and Clague, 2006; Duncan and Keller, 2004]. Black circles with ages and accompanying ellipses (two-dimensional 95% confidence regions) show the input into the N-hot spot method for determining rotations. Blue diamonds show the track determined from the best fitting rotations. All ages are in millions of years before present. (b) Map showing the Louisville hot spot track, input, and resulting estimate of motion of the Louisville hotspot relative to the Pacific plate determined with the N-hot spot method [Andrews *et al.*, 2006]. Red inverted triangles show locations of dated igneous rock samples with ages [Koppers *et al.*, 2004]. Black circles with ages and accompanying ellipses (two-dimensional 95% confidence regions) show the input into the N-hot spot method for determining rotations. Blue diamonds show the track determined from the best fitting rotations. All ages are in millions of years before present.

3. Hot Spot Tracks

For estimating Pacific hot spots rotations for the past 68 million years, we use the tracks of the Hawaii and Louisville hot spots because they are the least ambiguous tracks on the Pacific plate. Relatively dense age dates are available along them (Table 3), and both hot spots have been active throughout the time interval of the analysis. After completion of this work, more age dates have become available along the Louisville chain [Koppers *et al.*, 2011; Koppers *et al.*, 2012]. While these new data are crucial for further improving the detailed understanding of age progression along the chain, these new data follow the general trend established in the previous study of Koppers *et al.* [2004]. Thus, the new age data are generally consistent with our present work, as new locations assigned for the ages used in our analysis would fall close by the current locations and are within the uncertainty regions we have assigned along the chain.

Table 4 lists the locations with assigned uncertainties (two-dimensional 95% confidence regions) corresponding to C5 (10.9 Ma B.P.), C6 (20.1 Ma B.P.), C13 (33.5 Ma B.P.), C18 (39.3 Ma B.P.), C21 (47.9 Ma B.P.), C25 (56.1 Ma B.P.), and C31 (67.7 Ma B.P.) along the chains (Figures 2a and 2b) and used as input to the N-hot spot method. We take the current location of the Hawaiian hot spot to be at Kilauea at 19.6°N, 204.5°E; it was assigned a circular uncertainty with a radius of 95% confidence of 100 km. The current location of the Louisville hot spot, which we take to be at 50.9°N, 221.9°E as suggested by Lonsdale [1988], is less certain and was assigned a circular uncertainty region with a radius of 200 km. Generally, the uncertainties assigned for the ancient locations along the Louisville chain are larger than those assigned along the

Hawaiian-Emperor chain (Table 4) because the age data are sparser along the Louisville chain. Both chains are spatially well constrained in the direction perpendicular to the volcanic chain, and thus, the assigned uncertainty is smaller in this direction.

The Pacific hot spot model has then been used to predict the tracks of Tristan da Cunha, Réunion, and Iceland, and the predictions are compared with the observed tracks of these hot spots. Tristan da Cunha hot spot has a well-established age progression along its track and provides a critical test for hot spot fixity for it has remained beneath the Nubia plate for the past 70 Ma [O'Connor and Duncan, 1990]. The tracks for Réunion

Figure 3. Pacific hot spot poles of rotation (blue diamonds). Ellipses are the corresponding two-dimensional 95% confidence regions. Ages are in millions of years before present.

to have erupted at ≈ 131 – 133 Ma B.P. [e.g., *Renne et al.*, 1992, 1996] indicating the arrival of the Tristan da Cunha plume head at this time. Age data have demonstrated a clear age progression along the Walvis Ridge for the past ≈ 80 Ma [O'Connor and Duncan, 1990; O'Connor and le Roex, 1992] (Table 3). The current position of the Tristan da Cunha hot spot is taken as -37.5°N , 347.5°E on Tristan da Cunha Island and assigned a circular two-dimensional 95% confidence region with a radius of 150 km. The current location of the Tristan da Cunha hot spot is thought to be fairly well constrained beneath the island. The best estimate for the age of volcanism on the Tristan da Cunha Island ranges from 0.64 Ma to 1.3 Ma (0.64 Ma for the isochron age and 1.3 Ma for the plateau age) [O'Connor and le Roex, 1992].

The Réunion hot spot track comprises the Deccan Traps and Chagos-Laccadive Ridge on the India plate and Mascarene Plateau-Nazareth Bank-Mascarene Island group on the Somalia plate [Duncan and Hargraves, 1990]. The Deccan flood basalts are attributed to the arrival of the Réunion plume head beneath India at 65.5 Ma B.P. [e.g., Hofmann et al., 2000]. The current position of the Réunion hot spot is taken as -21.1°N , 55.5°E on Réunion Island. Réunion Island has experienced ongoing volcanism since 2 Ma B.P. [Duncan and Hargraves, 1990; McDougall, 1971], and Duncan [1990] notes that a large seamount currently 160 km west of Réunion may actually represent the most recent activity of the hot spot. Thus, the current location of the Réunion hot spot is assigned a circular uncertainty with a radius of 200 km to include this possible shift of the current location of the hot spot.

The location of the Iceland hot spot on the axis of the Mid-Atlantic Ridge complicates the tests of hot spot fixity. However, Vink's [1984] simple geometric model with a fixed hot spot and channeling of asthenosphere to the closest section of the rise crest uniquely predicts a location, orientation, and age progression for the Greenland-Faeroe and Voring Plateaus. These features constitute the Iceland hot spot track, and the ocean floor isochrons are used to indicate the location of the hot spot at different times. The current position of the Iceland hot spot is taken as 64°N , 344°E [Lawver and Müller, 1994] and assigned a circular uncertainty region with a radius of 200 km.

All hot spots used in this study are widely accepted as being among the most likely candidates for a deep mantle origin [e.g., Courtillot et al., 2003].

4. Results

4.1. Pacific Hot Spot Rotations and Uncertainties Since 68 Ma B.P.

Figure 3 shows the resulting poles of rotation, which are listed in Table 5, with sum-squared misfits and covariance matrix parameters. The corresponding eigenvector directions and associated 1σ uncertainties are

and Iceland hot spots are more complicated because of the interaction of each hot spot with the mid-ocean ridge [e.g., Morgan, 1978; Sleep, 2002]. However, even if the ancient locations of these hot spots cannot be identified along simple age-progressive tracks, the past history of the hot spots is tractable along features that have been generated by the hot spot activity, and quantifiable comparisons can be made between the predicted and observed tracks.

The Tristan da Cunha hot spot track comprises the Walvis Ridge on the Nubia plate and the Rio Grande Rise on the South America plate. Etendeka flood basalts in Africa and Parana flood basalts in South America can be tracked at the ends of these features and are thought

Table 5. Rotations and Uncertainties of the Pacific Plate Relative to the Hot Spots as Determined by the N-Hot Spot Method [Andrews *et al.*, 2006]

Age (Ma)	Best Fit Rotation			Covariance Matrix Values ^a						
	Lat (°N)	Lon (°E)	Angle (deg)	r^b	a	b	c	d	e	f
10.9	66.97	−73.05	9.43	1.97	0.3754	0.1500	−0.0513	0.1552	−0.0695	0.1735
20.1	70.17	−75.41	17.47	1.22	0.3733	0.1496	−0.0466	0.1474	−0.0559	0.1833
33.5	67.72	−73.15	26.58	0.04	0.3095	0.1242	−0.0114	0.1540	−0.0529	0.1683
39.3	66.76	−67.01	29.91	0.12	0.3219	0.1261	−0.0143	0.1581	−0.0561	0.1601
47.9	64.55	−67.95	34.29	0.005	0.2132	0.0538	−0.0110	0.1830	−0.0524	0.1045
56.1	56.16	−74.08	38.04	5.04	0.3281	0.0894	−0.0198	0.2257	−0.0382	0.1310
67.7	51.01	−76.67	41.74	6.08	0.3485	0.1071	−0.0036	0.2618	−0.0207	0.1682

$$^a\text{Covariance matrix} = \begin{pmatrix} a & b & c \\ b & d & e \\ c & e & f \end{pmatrix} \times 10^{-3} \text{ radians}^2.$$

^bThe sum squared normalized misfit is r .

listed in Table 6. The uncertainty regions shown in Figure 3 are two-dimensional 95% confidence regions. The uncertainties appear to get smaller with increasing age. This does not indicate decreasing uncertainty with time, however. Instead, it is a consequence of projecting the uncertainties of rotations at different distances from the origin of the coordinate system onto a two-dimensional spherical surface of fixed radius [Chang *et al.*, 1990]. The poles of Andrews *et al.* [2006] are similar to ours and are within the confidence limits of our new poles of rotation. Andrews *et al.* [2006] obtained their poles using the same method as in this study, but with older age data along the chains. Our uncertainty regions also include the coeval poles of Wessel and Kroenke [2008], except their model WK08-A pole for 47.9 Ma B.P.

Misfits for 10.9 Ma, 20.1 Ma, 33.5 Ma, 39.3 Ma, and 47.9 Ma B.P. fall within the acceptable limits, as discussed above in section 2, but misfits for 56.1 Ma and 67.7 Ma B.P. exceed 3.84 (Table 5) and are larger than those found by Andrews *et al.* [2006] for their corresponding poles of rotation. Either the Hawaiian and Louisville hot spots moved significantly relative to each other before 48 Ma B.P. or our assigned errors are too small.

4.2. Predicted Tracks

4.2.1. Tristan da Cunha

The predicted and observed Tristan da Cunha tracks have no significant differences for the past 48 million years (Figure 4). This differs importantly from earlier results, including the results of Molnar and Stock [1987]. For example, Molnar and Stock's [1987] predicted location for 48 Ma B.P. is $\approx 950 \text{ km} \pm 500 \text{ km}$ from the coeval dated volcano (labeled "46,52" in Figure 4; Table 3) on the Walvis Ridge, whereas the misfit found herein is $\approx 270 \text{ km} \pm 350 \text{ km}$, or in terms of rates about $6 \pm 7 \text{ mm a}^{-1}$. Although the predicted and observed tracks are significantly different for 56 Ma and 68 Ma B.P., the misfits are less than those found by Molnar and Stock [1987]. The misfit between the predicted and observed locations for 68 Ma B.P. (C31; location interpolated between dated samples along the chain) is $\approx 920 \text{ km} \pm 400 \text{ km}$.

If this misfit occurred entirely between 68 and 48 Ma B.P. and is caused solely by motion between hot spots, it indicates an early Tertiary rate of motion between the Tristan da Cunha hot spot and Pacific hot spots of $46 \pm 20 \text{ mm a}^{-1}$. Some of the motion may have occurred since 48 Ma B.P., however, so the minimum motion

Table 6. Eigenvectors and 1 σ Error (Equal to the Square Root of the Corresponding Eigenvalue of the Covariance Matrix) Determined by the N-Hot Spot Method

Age (Ma)	$\hat{w}_{\text{max}}$			$\hat{w}_{\text{int}}$			$\hat{w}_{\text{min}}$		
	Lat (°N)	Lon (°E)	1 σ (deg)	Lat (°N)	Lon (°E)	1 σ (deg)	Lat (°N)	Lon (°E)	1 σ (deg)
10.9	14.69	−151.65	1.24	−62.91	149.18	0.75	22.23	−247.80	0.46
20.1	13.46	−152.5	1.23	−69.39	157.02	0.76	15.32	−246.26	0.46
33.5	−9.60	30.30	1.12	−64.94	141.51	0.77	−22.92	−63.80	0.47
39.3	9.65	−150.16	1.14	−61.90	138.41	0.76	26.12	−244.94	0.48
47.9	−15.01	41.56	0.93	−25.49	138.90	0.72	−59.85	−75.93	0.50
56.1	8.21	−148.99	1.12	21.44	−55.74	0.78	−66.90	−78.76	0.62
67.7	3.30	−145.80	1.18	26.78	−54.13	0.80	−62.98	−62.29	0.72

Figure 4. Predicted positions of the Tristan da Cunha hot spot relative to the Nubia plate (shown with green diamonds) assuming that the Tristan da Cunha hot spot is stationary relative to Pacific hot spots. Red inverted triangles show locations for age dates of O'Connor and Duncan [1990] and O'Connor and le Roex [1992]. The point labeled "46,52" has a plateau age of 46 Ma B.P. and a total fusion age of 52 Ma B.P. The ages for Gough lineament are also shown [O'Connor and le Roex, 1992]. Ellipses (two-dimensional 95% confidence regions) show uncertainties propagated from the uncertainties in the motion of the Pacific plate relative to the Hawaiian and Louisville hot spots and relative plate motion uncertainties, combined with the uncertainty in the current location of the Tristan da Cunha hot spot. The black star is the current location of the Tristan da Cunha hot spot (at -37.5°N , 347.5°E). Dotted lines are synthetic isochrons from Müller *et al.* [2008] with ages (Ma) as labeled. All ages are in millions of years before present.

between 68 Ma and 48 Ma B.P. can be found by subtracting the motion since 48 Ma B.P. ($270 \text{ km} \pm 350 \text{ km}$) from the motion since 68 Ma B.P. ($920 \text{ km} \pm 400 \text{ km}$), which is $650 \text{ km} \pm 530 \text{ km}$, indicating a minimum rate of motion of $32 \pm 27 \text{ mm a}^{-1}$.

4.2.2. Réunion

The predicted track, which is similar to that of Raymond *et al.* [2000], is shown relative to the Somalia plate for ages 11 Ma B.P. (C5) through 39 Ma B.P. (C18) and relative to the India plate for earlier times (Figure 5). We find that the predicted and observed tracks agree since 48 Ma B.P. The 48 Ma B.P. (C21) reconstruction lies $\approx 80 \text{ km} \pm 300 \text{ km}$ from Ocean Drilling Program (ODP) site 713, dated as 49 Ma B.P. [Duncan and Hargraves, 1990]. This corresponds to a rate of motion of $2 \pm 6 \text{ mm a}^{-1}$. The 68 Ma B.P. (C31) reconstructed point lies $\approx 920 \text{ km} \pm 330 \text{ km}$ from a central location on the Deccan flood basalt province that has been dated between 64 and 69 Ma B.P. [Duncan and Pyle, 1988; Courtillot *et al.*, 1988], 65.5 Ma by Hofmann *et al.* [2000].

If this misfit occurred entirely between 48 Ma and 68 Ma B.P. and is caused solely by motion between hot spots, it gives an early Tertiary rate of motion between the Réunion hot spot and Pacific hot spots of $46 \pm 17 \text{ mm a}^{-1}$. The minimum motion between 68 Ma and 48 Ma B.P. is $\approx 840 \text{ km} \pm 450 \text{ km}$, indicating a minimum rate of motion of $42 \pm 23 \text{ mm a}^{-1}$.

4.2.3. Iceland

In Figure 6 the predicted track is shown relative to the Eurasia plate for 11 Ma B.P. and 20 Ma B.P. and relative to the Greenland plate for earlier times. These reconstructed points are made with the constraint that they always lay on seafloor older than the reconstruction age. The observed and predicted Iceland hot spot tracks agree for the past 48 million years (Figure 6). The 48 Ma B.P. reconstructed point lies $\approx 220 \text{ km} \pm 300 \text{ km}$ from mafic intrusions dated as $\approx 47\text{--}50 \text{ Ma B.P.}$ [Tegner *et al.*, 1998, 2008], corresponding to a rate of $5 \pm 6 \text{ mm a}^{-1}$ since 48 Ma B.P. The 68 Ma (C31) reconstructed point lies $\approx 1100 \text{ km} \pm 340 \text{ km}$ from the oldest lavas on the west coast of Greenland (estimated as about 60.9–61.3 Ma B.P. by Storey *et al.* [1998]; the earlier estimate for this spans a little longer).

If this misfit occurred entirely between 68 Ma and 48 Ma B.P. and is caused solely by motion between hot spots, it gives an early Tertiary rate of motion between the Iceland hot spot and Pacific hot spots of $55 \pm 17 \text{ mm a}^{-1}$. The

Figure 5. Predicted positions of the Réunion hot spot relative to the Somalia plate for 10.9 Ma through 39.3 Ma B.P. (yellow diamonds) and relative to the India plate for earlier times (purple diamonds) assuming that the Réunion hot spot is stationary relative to Pacific hot spots. Red inverted triangles show locations for age dates of Duncan and Hargraves [1990]. Ellipses (two-dimensional 95% confidence regions) show uncertainties propagated from the uncertainties in the motion of the Pacific plate relative to the Hawaiian and Louisville hot spots and relative plate motion uncertainties, combined with the uncertainty in the current location of the Réunion hot spot. The black star is the current location of the Réunion hot spot (at -21.1°N , 55.5°E). Dotted lines are synthetic isochrons from Müller *et al.* [2008] with ages (Ma) as labeled. All ages are in millions of years before present.

minimum motion between 68 Ma and 48 Ma B.P. is $\approx 880 \text{ km} \pm 450 \text{ km}$, indicating a minimum rate of motion of $44 \pm 23 \text{ mm a}^{-1}$.

4.3. Summary of the Results

The Tristan da Cunha, Réunion, and Iceland hot spots have moved insignificantly (≈ 2 to $6 \pm 7 \text{ mm a}^{-1}$) relative to Pacific hot spots since 48 Ma B.P. Prior to 48 Ma B.P., the apparent inter-hot spot rates of motion were higher, ≈ 46 to $55 \pm 20 \text{ mm a}^{-1}$, if the motion occurred entirely between 68 Ma and 48 Ma B.P. The minimum rates of motion from 68 Ma to 48 Ma B.P. are $32 \pm 27 \text{ mm a}^{-1}$, $42 \pm 23 \text{ mm a}^{-1}$, and $44 \pm 23 \text{ mm a}^{-1}$, respectively, for the Tristan, Réunion, and Iceland hot spots.

5. Discussion

The new results contrast with those found by Molnar and Stock [1987], Petronotis and Jurdy [1990], and Raymond *et al.* [2000], who found significant inter-hot spot motion between the Pacific and Indo-Atlantic hot spots both before and after the age of the Hawaiian-Emperor bend ($\approx 48 \text{ Ma B.P.}$). The results are consistent for all the hot spots examined here (insignificant inter-hot spot motion since 48 Ma B.P., and

Figure 6. Predicted positions of the Iceland hot spot relative to the Eurasia plate for 10.9 Ma and 20.1 Ma B.P. (blue diamonds) and relative to the Greenland plate for earlier times (turquoise diamonds) assuming that the Iceland hot spot is stationary relative to Pacific hot spots. Reconstructed points are made with the constraint that they lay on seafloor older than the reconstruction age. Red inverted triangles show locations for age dates of Tegner *et al.* [1998, 2008] and Storey *et al.* [1998]. Ellipses (two-dimensional 95% confidence regions) show uncertainties propagated from elliptical uncertainties in the motion of the Pacific plate relative to the Hawaiian and Louisville hot spots and relative plate motion uncertainties, combined with the uncertainty in the current location of the Iceland hot spot. The black star is the current location of Iceland hot spot (at 64°N , 344°E). Dotted lines are synthetic isochrons from Müller *et al.* [2008] with ages (Ma) as labeled. All ages are in millions of years before present.

much higher rates for earlier times), which suggests the possibility of a common cause for the observed pre-48 Ma B.P. misfits other than high rates of inter-hot spot motion.

When establishing the plate circuit, we implicitly assumed that there were no additional plate boundaries active during the time span of the analysis. The idea of a missing plate boundary, however, has been long suggested [e.g., *Molnar et al.*, 1975; *Suarez and Molnar*, 1980; *Gordon and Cox*, 1980; *Morgan*, 1981; *Duncan*, 1981; *Acton and Gordon*, 1994]. In particular, paleomagnetic tests of the plate motion circuit have long indicated the existence of an unmodeled plate boundary, particularly within Antarctica. *Acton and Gordon* [1994] rotated paleomagnetic poles from the continents through the global plate motion circuit through Antarctica into the Pacific plate reference frame. They compare these with indigenous Pacific plate paleomagnetic poles. We point to the comparison for ages greater than the bend in the Hawaiian-Emperor chain, i.e., 56 Ma B.P. and 65 Ma B.P., which indicate significant differences between indigenous poles and rotated poles. The sense of the difference is that rotated poles predict less northward motion of the Pacific plate than is observed from the indigenous poles. This is in the same sense as the difference we observe in the misfit to the hot spots tracks [cf. *Acton and Gordon*, 1994, Figures 6 and 7].

When we compare the results for the age span of 56 to 66 Ma B.P. shown in Figures 2b and 2c of *Dobrovine and Tarduno* [2008] with the results for approximately coeval poles shown in Figures 2, 3c, and 3d of *Acton and Gordon* [1994], we observe that circuit tests by *Dobrovine and Tarduno* [2008] indicate misfits similar to those found by *Acton and Gordon* [1994] for this age range. Although *Dobrovine and Tarduno* [2008] have a different interpretation, we take their results as confirming the conclusion of *Acton and Gordon* [1994] that the global plate motion circuit fails the paleomagnetic test at these ages.

New paleomagnetic inclination data from the Louisville chain [*Koppers et al.*, 2012] imply that the location of the hot spot has remained relatively stable between 70 and 50 Ma B.P. This is suggested to contrast with the approximately 15° southward motion of the Hawaiian hot spot relative to the spin axis between about 80 and 50 Ma B.P. [e.g., *Morgan*, 1981; *Gordon and Cape*, 1981; *Gordon*, 1982; *Cox and Gordon*, 1984; *Petronotis and Gordon*, 1999; *Tarduno et al.*, 2003; *Koivisto et al.*, 2011] and could indicate that the Hawaiian and Louisville hot spots have moved significantly relative to each other before 50 Ma B.P. [*Koppers et al.*, 2012]. Nevertheless, for the time span of our analysis, the old and new results are within their confidence limits also consistent with Hawaiian and Louisville hot spots having the same latitudinal shift, which could be explained by true polar wander. Moreover, the global results are consistent with Pacific and non-Pacific hot spots having complementary shifts relative to the spin axis, consistent with the fixed hot spots [*Morgan*, 1981; *Gordon and Cape*, 1981; *Gordon*, 1982].

In contrast to the results and conclusions of many prior studies, here we have shown with up-to-date reconstructions and age dates that within the uncertainties, the fixed hot spot hypothesis cannot be excluded for the past 48 Ma. Given the results of paleomagnetic tests, a plausible cause for the apparent pre-48 Ma B.P. inter-hot spot motion is unmodeled motion across Antarctica. *Cande et al.* [2000] note that the timing and magnitude of the plate motion in the West Antarctic rift system remain poorly known because of a lack of magnetic anomaly and fracture zone constraints on seafloor spreading.

For many years, the bend in the Hawaiian-Emperor chain was believed to be ≈ 43 Ma old and in the absence of any major plate reorganization at that age; the timing was thought to be evidence indicating moving hot spots. Newer age dates affect these conclusions. *Sharp and Clague* [2006] and *Duncan and Keller* [2004] report incremental heating $^{40}\text{Ar}/^{39}\text{Ar}$ ages for the Hawaiian-Emperor chain. In particular, *Sharp and Clague* [2006] show that the initiation of the Hawaiian-Emperor bend is at ≈ 50 Ma B.P., which coincided with a major reorganization of northern Pacific spreading centers [*Atwater*, 1989] and the initiation of magmatism in the Izu-Bonin-Mariana arc system, consistent with the formation of the bend by changed Pacific plate motion [*Gordon et al.*, 1978; *Atwater*, 1989; *Norton*, 2000]. The initiation of the bend has also been linked to chron 21 reorganizations in the southern Pacific [e.g., *Wessel et al.*, 2006; *Cande et al.*, 1982, 1995]; *Whittaker et al.* [2007] reported a major plate reorganization event between Australia and Antarctica at 50–53 Ma B.P., perhaps linking all the above mentioned together.

As the formation of the bend has thus been linked to plate reorganizations, not to change in motion of the plume itself, and the hot spots have been herein shown, within uncertainties, to remain stationary relative to one another for the past 48 Ma, a failure in the plate circuit used to make the predictions remains an attractive option to explain the systematic apparently higher rates of inter-hot spot motion before 48 Ma B.P.

6. Conclusions

We show that for the past 48 million years, three key Indo-Atlantic hot spots nominally move $2\text{--}6\text{ mm a}^{-1}$ relative to Pacific hot spots with 95% confidence limits that include no motion and rates as fast as $8\text{ to }13\text{ mm a}^{-1}$. For this time interval, the fixed hot spot approximation is consistent with the observations.

Prior to 48 Ma B.P., however, the apparent rates of inter-hot spot motion are much higher, $46\text{--}55\text{ mm a}^{-1} \pm 20\text{ mm a}^{-1}$, if the motion occurred entirely between 68 Ma and 48 Ma B.P. A possible cause for the high apparent rate of pre-48 Ma B.P. motion is a systematic error in the global plate circuits used to make the predictions. Published paleomagnetic tests of the global plate circuit over this time interval indicate that the global circuit fails but that the fixed hot spot circuit does not. A potential candidate for the global circuit failure is pre-48 Ma B.P. motion between East and West Antarctica.

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