Revised plate motions relative to the hotspots from combined Atlantic and Indian Ocean hotspot tracks

R. Dietmar Müller Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California 92093-0208
Jean-Yves Royer Laboratoire de Géodynamique, 06230 Villefranche Sur Mer, France
Lawrence A. Lawver Institute for Geophysics, University of Texas, 8701 Mopac Boulevard, Austin, Texas 78759-8345

ABSTRACT

We use an updated model for global relative plate motions during the past 130 m.y. together with a compilation of bathymetry and recently published radiometric dates of major hotspot tracks to derive a plate-motion model relative to major hotspots in the Atlantic and Indian oceans. Interactive computer graphics were used to find the best fit of dated hotspot tracks on the Australian, Indian, African, and North and South American plates relative to present-day hotspots assumed fixed in the mantle. One set of rotation parameters can be found that satisfies all data constraints back to chron 34 (84 Ma) and supports little motion between the major hotspots in this hemisphere. For times between 130 and 84 Ma, the plate model is based solely on the trails of the Tristan da Cunha and Great Meteor hotspots. This approach results in a location of the Kerguelen hotspot distinct from and south of the Rajmahal Traps for this time interval. Between 115 and 105 Ma, our model locates the hotspot underneath the southern Kerguelen Plateau, which is compatible with an age estimate of this part of the plateau of 115–95 Ma. Our model suggests that the 85°E ridge between lat 10°N and the Afanasiy Nikitin seamounts may have been formed by a hotspot now located underneath the eastern Conrad rise.

INTRODUCTION

During the past 20 years, our knowledge of Cretaceous through Cenozoic relative motion between major tectonic plates has increased substantially despite controversy involving absolute plate motions relative to the spin axis. A widely used method of reconstructing plates relative to a fixed mesosphere utilizes linear chains of volcanoes that display age progression and are thought to have been caused by focused spots of melting in the upper mantle assumed to be fixed relative to each other over geologically long periods of time (fixed-hotspot hypothesis) (Morgan, 1971).

Our model of relative plate motions can be

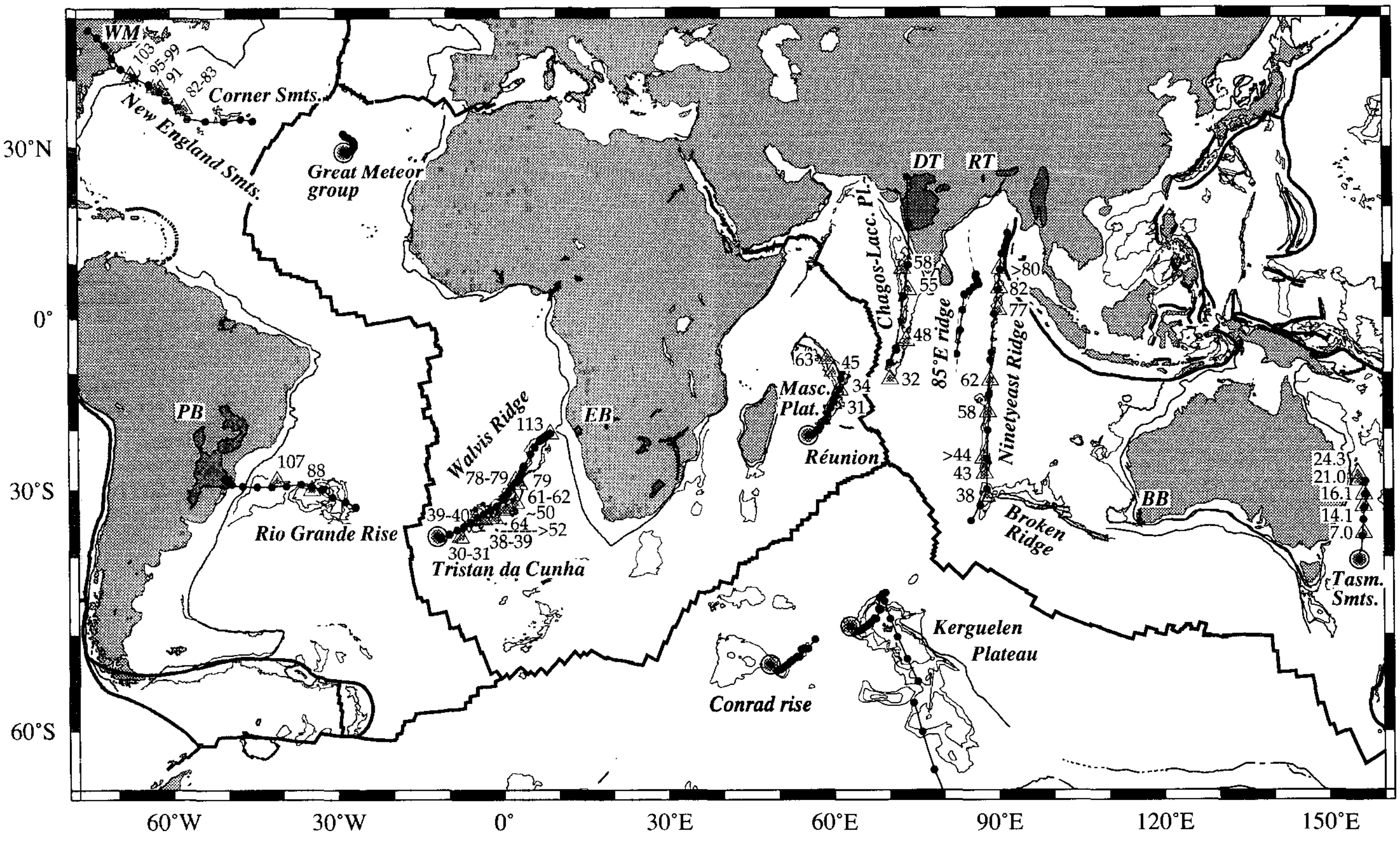

Figure 1. Major hotspot tracks in Atlantic and Indian oceans. Large shaded circles are locations of present-day hotspots. Modeled paths of plates relative to hotspots are computed in 5 m.y. intervals for following plates, hotspots, hotspot tracks, and times: Australian plate, Tasmantid hotspot, Tasmantid Seamounts, 0–25 Ma; Indian plate, Kerguelen hotspot, Ninetyeast Ridge, 35–100 Ma; unnamed hotspot on Conrad rise, 85°E ridge, 70–100 Ma; Réunion, Chagos-Laccadive Plateau–Deccan Traps, 40–70 Ma; African plate, Tristan, Walvis Ridge, 0–130 Ma; seamount 18, Great Meteor group, 0–60 Ma; Réunion, Mascarene Plateau, 0–55 Ma; North American plate, seamount 18, Corner Seamounts–New England Seamounts–younger White Mountains, 60–130 Ma, South American plate, Tristan, Rio Grande Rise–Paraná flood basalts, 70–130 Ma; Antarctic plate, Kerguelen hotspot, north Kerguelen Plateau, 0–105 Ma; south Kerguelen Plateau, 105–115 Ma; unnamed seamount on Conrad rise, 0–70 Ma. WM = younger White Mountains, DT = Deccan Traps, RT = Rajmahal Traps, PB = Paraná flood basalts, EB = Etendeka flood basalts, BB = Bunbury basalts. Triangles with numbers indicate radiometric ages of hotspot tracks (see text for references for dates).

used to show that published rotation poles for the African plate relative to a hotspot reference frame (O'Connor and Duncan, 1990; Duncan and Richards, 1991) result in unacceptable misfits with hotspot tracks on other plates, notably for the Ninetyeast Ridge (Royer et al., 1991) and the New England Seamounts. In this paper we investigate whether a set of rotation parameters can in fact describe past motions of plates around the Atlantic and Indian oceans relative to their underlying hotspots and satisfy the constraints imposed by the geometry and age progression of major hotspot tracks in this area. We combine a well-constrained relative plate-motion model with compilations of bathymetric and recently published age data from major hotspot tracks and use an interactive computer graphics technique to find the best fit of several major hotspot tracks on different plates relative to the present-day hotspots.

TABLE 1. FINITE RECONSTRUCTION POLES OF MAJOR PLATES RELATIVE TO HOTPOTS

Chron	Age (Ma)	Lat (°N)	Long (°E)	Angle (°) pos. = counterclockwise		Age (Ma)	Lat (°N)	Long (°E)	Angle (°)
North America					South America				
5	10.4	43.6	120.7	1.39	5	10.4	59.4	-45.8	1.80
6	20.5	35.0	112.2	3.38	6	20.5	65.8	-19.8	3.21
13	35.5	44.0	109.1	6.48	13	35.5	72.1	4.0	6.37
18	42.7	47.7	110.2	8.44	18	42.7	74.2	12.9	8.36
21	50.3	46.8	112.7	11.27	21	50.3	76.0	50.6	10.28
25	58.6	46.2	115.8	14.51	25	58.6	74.1	68.0	12.74
31	68.5	46.0	119.5	18.65	31	68.5	73.2	87.5	15.90
33y	73.6	49.3	119.6	21.11	33y	73.6	72.6	93.0	18.31
33o	80.2	53.4	117.0	24.58	33o	80.2	72.3	93.7	21.90
34	84.0	54.5	111.2	25.81	34	84.0	71.6	82.4	22.87
	90.0	57.4	104.4	28.21		90.0	71.7	68.1	24.01
	100.0	62.9	89.4	31.74		100.0	72.2	45.3	26.77
	110.0	66.1	77.0	37.27		110.0	71.8	24.9	30.38
M-0	118.7	66.5	63.9	41.54	M-0	118.7	68.4	9.2	33.26
M-10	130.0	65.9	56.9	45.42	M-10	130.0	67.1	10.4	34.64
Africa					India				
5	10.4	59.3	-31.6	-1.89	5	10.4	36.1	21.9	-5.81
6	20.5	50.9	-44.5	-4.36	6	20.5	40.6	4.3	-10.71
13	35.5	40.3	-43.0	-7.91	13	35.5	30.9	17.4	-19.33
18	42.7	37.7	-41.2	-9.65	18	42.7	31.3	16.9	-23.00
21	50.3	32.8	-40.8	-12.09	21	50.3	27.9	11.1	-29.06
25	58.6	30.1	-41.7	-13.89	25	58.6	24.7	6.2	-37.29
31	68.5	26.4	-40.9	-16.23	31	68.5	19.1	3.4	-53.37
33y	73.6	22.3	-39.6	-17.80	33y	73.6	18.7	2.5	-58.12
33o	80.2	18.0	-38.9	-19.98	33o	80.2	18.1	1.8	-63.00
34	84.0	19.0	-40.9	-21.53	34	84.0	17.1	2.3	-65.48
	90.0	19.4	-41.9	-23.31		90.0	16.3	5.0	-67.29
	100.0	18.9	-41.4	-25.35		100.0	14.5	10.3	-70.31
	110.0	17.7	-39.5	-26.71		110.0	13.7	10.1	-71.68
M-0	118.7	18.7	-39.7	-27.37	M-0	118.7	14.2	10.3	-72.09
M-10	130.0	16.7	-37.5	-28.52	M-10	130.0	13.3	15.5	-75.34
Northwest Africa					Central Indian Basin				
	100.0	18.8	-40.5	-25.72	5	10.4	23.7	40.6	-7.27
	110.0	17.5	-38.2	-27.34	6	20.5	27.1	31.4	-13.23
M-0	118.7	18.5	-38.0	-28.21	13	35.5	22.7	30.1	-22.47
M-10	130.7	16.2	-40.1	-27.52	18	42.7	24.0	27.8	-26.00
					21	50.3	22.1	20.4	-31.64
Madagascar					25	58.6	20.0	13.7	-39.46
					31	68.5	15.2	8.4	-55.29
M-0	118.7	18.8	-38.4	-26.67	33y	73.6	14.9	7.0	-59.95
M-10	130.0	16.2	-25.7	-23.96	33o	80.2	14.4	5.9	-64.75
					34	84.0	13.6	6.2	-67.28
Australia					Antarctica				
5	10.4	23.7	40.6	-7.27	5	10.4	64.9	102.0	-1.56
6	20.5	27.1	31.4	-13.23	6	20.5	85.3	37.3	-2.87
13	35.5	22.7	30.1	-22.47	13	35.5	72.6	5.7	-3.91
18	42.7	24.0	27.8	-26.00	18	42.7	75.6	-0.5	-4.07
21	50.3	23.3	25.9	-27.67	21	50.3	71.1	-17.6	-5.22
25	58.6	23.0	26.2	-27.86	25	58.6	73.8	-39.7	-6.28
31	68.5	18.3	26.8	-28.72	31	68.5	67.6	-23.6	-7.49
33y	73.6	18.0	26.7	-29.61	33y	73.6	64.9	-17.0	-7.79
33o	80.2	18.3	26.7	-30.16	33o	80.2	65.7	-16.1	-8.04
34	84.0	18.7	27.4	-29.49	34	84.0	72.4	-32.5	-8.21
	90.0	22.4	31.3	-28.40		90.0	82.1	-132.7	-9.79
	100.0	28.6	40.7	-27.41		100.0	63.3	173.9	-13.40
	110.0	34.6	52.6	-27.50		110.0	49.4	164.7	-17.76
M-0	118.7	40.8	65.7	-28.85	M-0	118.7	42.0	162.2	-23.45
M-10	130.0	48.9	75.5	-32.30	M-10	130.0	42.4	162.3	-30.42

RELATIVE PLATE MOTIONS

We have constructed a revised model for the early opening between Africa, India, and Antarctica based on the alignment of the Mozambique escarpment with the steep transform margin of the Coats Land coast of Dronning Maud Land, East Antarctica (Lawver et al., 1991) and a new scenario for the early opening between India and Antarctica. We assume that India rifted from Antarctica at the same time that it rifted from Australia and that Australia and Antarctica acted as a single tectonic plate. Initial rifting between India and Australia has been dated as roughly chron M-10 to M-11 (Larsen et al., 1979). By assuming a steady state of opening between India and Antarctica beginning at 130 Ma, the southern Kerguelen Plateau would have been created off margin at 118–95 Ma (Davies et al., 1989), and there is no need to assume a more complicated spreading history.

Our model includes intraplate motion in the Central Indian basin in the late Tertiary (Royer and Chang, 1991). Rotation parameters for the post–chron 34 opening of the Indian Ocean are modified from Royer and Sandwell (1989), on the basis of additional data from the Central Indian basin and the Wharton Basin. Intraplate motion in Africa and South America from 85 to 130 Ma is included (Nürnberg and Müller, 1991), as well as a refined model for relative plate motions between Africa and North America, including changes in spreading direction during the Cretaceous Normal Magnetic Superchron (Müller and Roest, 1992). South America is reconstructed with Africa for post–chron 34 (84 Ma) relative motions by using rotation poles from Shaw and Cande (1990) and for pre–chron 34 relative motions by using rotation parameters from Nürnberg and Müller (1991).

HOTSPOT TRACKS

We constructed our model of absolute plate motions (Fig. 1, Table 1) by using radiometric ages from the Walvis Ridge–Rio Grande Rise (O'Connor and Duncan, 1990), Corner Seamounts (~76–72 to 81–86 Ma from backtracking seamounts that had formed at sea level; Tucholke and Smoot, 1990), New England Seamounts (Duncan, 1984), White Mountains (Gilbert and Foland, 1986; Foland and Faul, 1977), Mascarene Plateau (Duncan and Hargraves, 1990), Chagos-Laccadive Plateau and Ninetyeast Ridge (Duncan, 1978, 1991), Tasmantid Seamounts (McDougall and Duncan, 1988), Paraná and Etendeka flood basalts (McDougall and Duncan, 1988), Monteregian Hills (Gilbert and Foland, 1986), and Deccan Traps (Baksi et al., 1987) (see Fig. 1 for geographic locations and age dates).

PRESENT LOCATIONS OF HOTSPOTS

The present locations of hotspots used in this study are based either on the occurrence of present-day volcanism or inferred indirectly, where no unambiguous information for present-day volcanism is available. Hotspot locations based on present-day volcanism are Tristan Da Cunha (37°S, 12°W), La Réunion (21°W, 55.5°E), and the Tasmantid hotspot (40.4°S, 150.5°E).

The present-day location of the hotspot that formed the New England Seamounts is most likely at seamount 18 (Tucholke and Smoot, 1990), south of the Great Meteor Tablemount. Seamount 18 (30°N, 28.5°W) appears to be the youngest seamount in the

Great Meteor group, because it displays a peaked top, whereas the seamounts north of it show flat tops, documenting erosion at sea level (Tucholke and Smoot, 1990). The present location of the Kerguelen hotspot is inferred to be underneath the western Kerguelen Plateau, following Duncan and Richards (1991) and Curray and Munasinghe (1991).

RECONSTRUCTION METHOD

Geometrically, it is relatively simple to reconstruct the motion of a single plate relative to its underlying hotspots. However, in order to use hotspot tracks from the North American, South American, African, and Indian-Australian plates in concert, the relative plate motions must be determined for each reconstruction time. The geometry of all hotspot track segments of a particular age on different plates can be considered simultaneously in order to derive a best-fit rotation relative to present-day hotspots if the hotspots are regarded as fixed in the mantle. Such a model of absolute plate motions is better constrained than one that uses hotspot tracks on only one plate for deriving rotation parameters (e.g., the African plate), which are then used to calculate the absolute motions of other plates, as O'Connor and Duncan (1990) and Duncan and Richards (1991) did.

MODEL RESULTS

Modeled hotspot tracks computed in 5 m.y. intervals are plotted in Figure 1. They document a good agreement between the model results and the geometry and ages of the major hotspot tracks in the Atlantic and Indian oceans, at least back to chron 34 (84 Ma), and indicate little motion of these hotspots relative to each other. Reconstructions for times older than chron 34 involve larger uncertainties of relative plate motions during the Cretaceous Normal Magnetic Superchron and the M-anomaly sequence, especially in the Indian Ocean, and consequently sparser age control of the hotspot tracks.

The pre–chron 34 reconstructions relative to the hotspots are based on the Walvis Ridge–Rio Grande Rise–Paraná flood basalts hotspot trail and the New England Seamounts–White Mountains–Monteregian Hills hotspot trail. The genetic relations between the oceanic tracks and continental flood basalts of similar age in the Indian Ocean are not well determined and are controversial (cf. Curray and Munasinghe, 1991) (Ninetyeast Ridge and possibly 85°E ridge).

Our model suggests that the present-day Kerguelen hotspot formed the Ninetyeast Ridge after 100 Ma, but prior to that time the hotspot was on the Antarctic plate and formed the south Kerguelen Plateau (Fig. 2D). The Kerguelen hotspot was never coincident with the Rajmahal Traps, and the south Kerguelen Plateau appears to have formed after India rifted from Antarctica; otherwise it would be contiguous with the Antarctic continental margin. This solution is compatible with the mapped geometry of the Ninetyeast Ridge and would predict a location of the Kerguelen hotspot underneath the southern Kerguelen Plateau, at the time of its formation, 118–95 Ma (Davies et al., 1989) (Fig. 2D). This solution would also predict that there is no northward extension of the Ninetyeast Ridge north of 18°N, since that is the northernmost location on the Indian plate where the hotspot was located before it was transferred to the Antarctic plate at ~100 Ma. Our model predicts that the Kerguelen hotspot, at 118 Ma, was located ~1000 km south of the Rajmahal Traps, which are dated as 108–128 Ma (Baksi et al., 1987). This prediction indicates that the Rajmahal Traps may not have been directly produced by the Kerguelen hotspot. The hotspot was at least as far away from the Bunbury basalts in southwestern Australia when they were created (age: 105–136 Ma; Playford et al., 1976). However, if the initial Kerguelen mantle plume affected a 2000-km-diameter area of rifted, thinned continental and oceanic crust, then, following White and McKenzie's (1989) model, both the Rajmahal Traps and the Bunbury basalts may have been generated as a result of enhanced decompression melting caused by elevated temperatures along the incipient continental margins.

We also test the hypothesis that the 85°E ridge may have been produced by the Crozet hotspot, as suggested by Curray and Munasinghe (1991). By using our model, we find that the southern part of the 85°E ridge can be well matched by assuming a present-day location of a hotspot under the eastern part of the Conrad rise, at 53.4°S, 48.4°E, east of Lena Tablemount. The calculated path (Fig. 1) follows the observed two bends in the 85°E ridge but can only be tracked to ~10°N, east of Sri Lanka at 115 Ma. Prior to 115 Ma, this hotspot would have been under the Antarctic continent (Fig. 2D). This model also explains the observed apparent discontinuity of the hotspot track left by the Conrad rise hotspot between the southern end of the 85°E ridge at ~8°S and the continuation of the track northeast of the Conrad rise on the Antarctic plate (Fig. 1). A major ridge jump northward between chrons 31 (68.5 Ma, Fig. 2B) and 25 (58.6 Ma, Fig. 2A) transferred the hotspot from the Indian to the Antarctic plate so that no trace of the hotspot is left on the Indian plate south of the observed termination of the 85°E ridge.

The model also implies that the 85°E ridge hotspot track was formed near the midocean

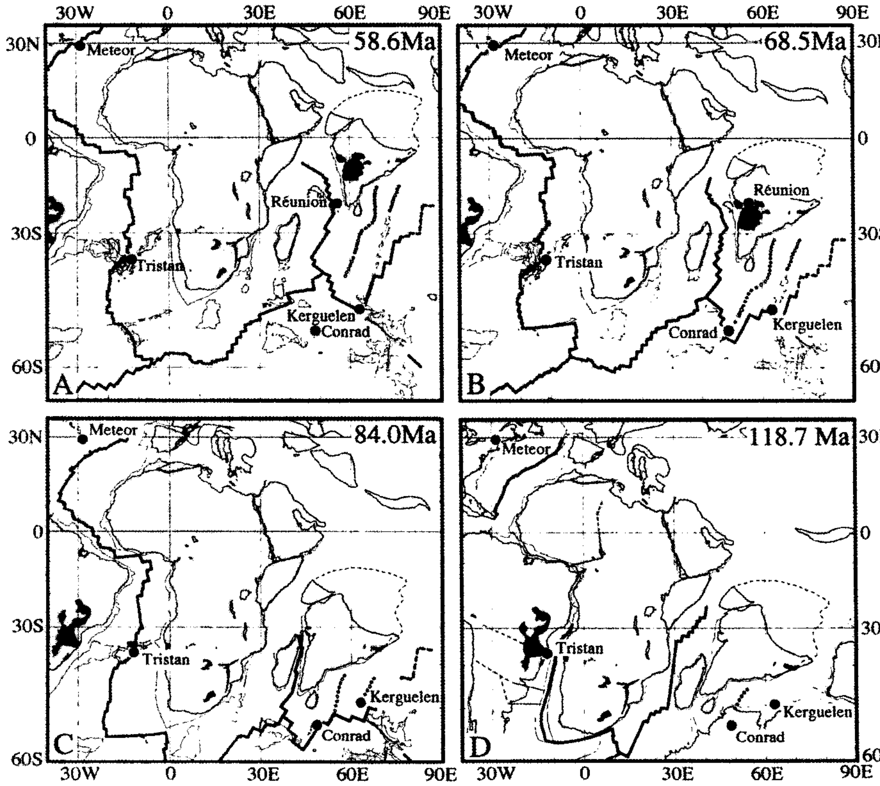

Figure 2. Reconstructions of plates relative to major Atlantic and Indian ocean hotspots using rotation poles listed in Table 1. Solid circles are present locations of hotspots. Black areas are flood basalts. Also shown are boundaries between oceanic and continental crust, paleo–mid-ocean ridges, and 2000 and 4000 m bathymetric contours of reconstructed hotspot tracks.

ridge (Fig. 2) on very young ocean crust. This location was predicted by Liu et al. (1982) on the basis of the negative gravity field over the 85°E ridge, indicating that it was formed on young lithosphere ~5–15 m.y. old and buried by sediments later, when it was ~40–80 m.y. old. Evidence for a present-day mantle plume under the Conrad rise is found in its high geoid/topography ratio of ~2.7 m/km and relatively low plateau height of ~2.6 km, classifying it as a thermal swell (Marks and Sandwell, 1991). However, the isostatic compensation of the Marion Dufresne, Lena, and Ob seamounts indicates that large parts of the Conrad rise were formed in the Late Cretaceous on relatively young sea floor (Diament and Goslin, 1986).

Our results also show that if the major hotspot tracks in the Atlantic and Indian oceans are used in concert for constructing a plate-motion model with respect to the hotspots, seamount 18 in the Great Meteor group results in a track that matches the New England Seamounts, White Mountains, and Monteregian Hills. O'Connor and Duncan (1990) had concluded, using their absolute rotation parameters for Africa, that a present-day location of a hotspot in the Great Meteor group does not result in a trail that matches the New England Seamounts.

CONCLUSIONS

Using an updated model of relative plate motions, as well as the bathymetric expression and published radiometric ages of the hotspot tracks left by Tristan da Cunha, seamount 18 in the Great Meteor group, Réunion, Kerguelen, and the Tasmantid hotspot, we show that both data sets can be combined to construct an internally consistent plate-motion model that does not indicate major motion between hotspots within the past 84 m.y. The older part of our model, back to 130 Ma, is subject to larger uncertainties, because both the relative plate motions and the ages of hotspot trails are less well known. The tracks left by the Great Meteor and Tristan da Cunha hotspots between 84 and 130 Ma result in a model that places the Kerguelen hotspot south of the Rajmahal Traps, underneath the southern Kerguelen Plateau between 100 and 115 Ma. The results of our model also suggest that the 85°E ridge south of 10°N may have been caused by a hotspot that was transferred from the Indian to the Antarctic plate by a major ridge jump between chrons 31 (68.5 Ma) and 25 (58.6 Ma) and is now located underneath the eastern Conrad rise.

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