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Absolute plate motions relative to deep mantle plumes

Shimin Wang [a,*], Hongzheng Yu [a], Qiong Zhang [b], Yonghong Zhao [b]

[a] Key Laboratory of Computational Geodynamics, University of Chinese Academy of Sciences, Beijing 100049, China
[b] Department of Geophysics, Peking University, Beijing 100871, China

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ABSTRACT

Advances in whole waveform seismic tomography have revealed the presence of broad mantle plumes rooted at the base of the Earth's mantle beneath major hotspots. Hotspot tracks associated with these deep mantle plumes provide ideal constraints for inverting absolute plate motions as well as testing the fixed hotspot hypothesis. In this paper, 27 observed hotspot trends associated with 24 deep mantle plumes are used together with the MORVEL model for relative plate motions to determine an absolute plate motion model, in terms of a maximum likelihood optimization for angular data fitting, combined with an outlier data detection procedure based on statistical tests. The obtained T25M model fits 25 observed trends of globally distributed hotspot tracks to the statistically required level, while the other two hotspot trend data (Comores on Somalia and Iceland on Eurasia) are identified as outliers, which are significantly incompatible with other data. For most hotspots with rate data available, T25M predicts plate velocities significantly lower than the observed rates of hotspot volcanic migration, which cannot be fully explained by biased errors in observed rate data. Instead, the apparent hotspot motions derived by subtracting the observed hotspot migration velocities from the T25M plate velocities exhibit a combined pattern of being opposite to plate velocities and moving towards mid-ocean ridges. The newly estimated net rotation of the lithosphere is statistically compatible with three recent estimates, but differs significantly from 30 of 33 prior estimates.

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1. Introduction

The theory of plate tectonics has established itself as the fundamental framework to study surface deformation, with the remarkable ability to determine the relative motions between the tectonic plates and to synthesize a wide range of observations from various fields of geology and geophysics. As the lithosphere is the cold thermal boundary layer of vigorously convecting mantle and plate tectonics is the surface expression of mantle convection (e.g., Bercovici et al., 2000; Coltice et al., 2017), absolute plate motions, referring to the motions of tectonic plates relative to the deep mantle, contain key information for linking deep mantle processes with surface tectonics and thus are critical for understanding the global dynamics of the coupled mantle–lithosphere system.

Although the relative motions between tectonic plates over the last few million years have been reasonably well determined using seafloor magnetic anomalies, transform fault strikes, earthquake slip vectors, and GPS measurements (e.g., DeMets et al., 1990, 1994, 2010), the absolute plate motions are still poorly known, as reflected by the diversity in various absolute plate motion models (e.g., Becker, 2006; Conrad and Behn, 2010; Becker et al., 2015). This diversity is mainly caused by different reference frames being defined in representing the deep mantle and different data sets being employed to constrain the models.

As the deep mantle is not a rigid body but part of a constantly convecting system, a reference frame naturally attached to the deep mantle does not exist. The existing reference frames representing the deep mantle are built upon different assumptions. For example, the no net rotation frames (e.g., Argus and Gordon, 1991; Argus et al., 2011) are associated with the assumptions that no net torque is exerted on the lithosphere by the underlying mantle and that the lateral viscosity heterogeneity in the asthenosphere is negligible (Solomon and Sleep, 1974), while the absolute reference frames established through fitting seismic anisotropy data (e.g., Kreemer, 2009; Zheng et al., 2014) are based on the assumption that the orientations of seismic anisotropy arise from the preferred alignments of highly anisotropic minerals in the asthenosphere and indicate the directions of the lithospheric plate relative to the sub-asthenospheric mantle (Savage, 1999). These reference frames can only represent the deep mantle in an average manner, as there are no distinctive features associated with these frames penetrating into the deep mantle, in contrast to the hotspot-based reference frames.

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[*] Corresponding author.
E-mail address: smwang@ucas.ac.cn (S. Wang).

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Table 1
Observed hotspot data compared with plate velocities at hotspots calculated based on T25M.

No.	Hotspot	Plate	Longitude (°E)	Latitude (°N)	Hotspot trend with error (°)[a]	Hotspot rate with error (mm/yr)	Plate motion trend (°)	Plate velocity (mm/yr)	Data importance for T25M
1	Hawaii	Pacific	−155.2	19.0	304 ± 3	92 ± 3	302.01	80.79	0.038
2	Macdonald	Pacific	−140.3	−29.0	289 ± 6	105 ± 10	295.62	87.70	0.011
3	Pitcairn	Pacific	−129.3	−25.4	293 ± 3	90 ± 15	291.50	89.06	0.050
4	Society	Pacific	−148.4	−18.2	295 ± 5	109 ± 10	297.39	88.97	0.014
5	Caroline	Pacific	164.4	4.8	289 ± 4	135 ± 20	297.83	88.53	0.023
6	Galapagos	Nazca	−91.6	−0.4	96 ± 5	55 ± 8	88.04	43.84	0.125
7	J. Fernandez	Nazca	−81.8	−33.9	84 ± 3	80 ± 20	82.12	57.04	0.222
8	San Felix	Nazca	−80.1	−26.4	83 ± 8	–	80.83	55.84	0.034
9	Galapagos	Cocos	−91.6	−0.4	45 ± 6	–	40.53	74.83	0.070
10	Afar	Nubia	39.5	7.0	30 ± 15	16 ± 8	37.13	17.47	0.072
11	Canary	Nubia	−18.0	28.2	94 ± 8	20 ± 4	91.11	2.51	0.771
12	Iceland	N. America	−17.3	64.4	287 ± 10	15 ± 5	281.85	18.45	0.011
13	Reunion	Somalia	55.7	−21.2	47 ± 10	40 ± 10	48.15	19.92	0.082
14	St Helena	Nubia	−9.5	−16.5	78 ± 5	20 ± 3	81.42	16.07	0.080
15	Kerguelen	Antarctica	69.0	−49.6	50 ± 30	3 ± 1	88.67	12.63	0.039
16	Cape Verde	Nubia	−24.0	16.0	60 ± 30	–	104.80	6.96	0.012
17	Azores	Eurasia	−26.0	37.9	110 ± 12	–	107.64	3.38	0.406
18	Azores	N. America	−26.0	37.9	280 ± 15	–	275.10	19.70	0.005
19	Hoggar	Nubia	5.6	23.3	46 ± 12	–	35.88	8.12	0.462
20	Crozet	Antarctica	50.2	−46.1	109 ± 10	25 ± 13	96.73	12.93	0.393
21	Marquesas	Pacific	−139.0	−10.5	319 ± 8(12)	93 ± 7	335.94	88.60	0.002
22	Samoa	Pacific	−169.1	−14.5	285 ± 5(10)	95 ± 20	300.74	87.65	0.003
23	Louisville	Pacific	−140.6	−53.6	316 ± 5(8)	67 ± 5	300.37	75.25	0.010
24	Easter	Nazca	−106.5	−26.4	87 ± 3(8)	95 ± 5	62.23	13.84	0.042
25	Cameroon	Nubia	5.1	−2.0	32 ± 3(15)	15 ± 5	98.39	55.80	0.024
26	Comores	Somalia	43.3	−11.5	118 ± 10(12)	35 ± 10	51.00	21.21	
27	Iceland	Eurasia	−17.3	64.4	75 ± 10	5 ± 3	181.20	0.57	

[a] Parenthesized errors for 6 hotspot tracks are weight related standard errors, which are also assigned by Morgan and Phipps Morgan (2007).

A traditional approach to define reference frames for absolute plate motions is based on the use of hotspot tracks, i.e., linear chains of intraplate volcanic edifices with regular progression of eruption ages. Morgan (1971) proposed that hotspots are the surface manifestation of relatively stationary deep mantle plumes. This fixed hotspot hypothesis forms the basis for defining hotspot-based reference frames, but the validity of the hypothesis continues to be a subject of vigorous debate (e.g., Tarduno and Gee, 1995; Tarduno et al., 2003; Koivisto et al., 2014; Wang et al., 2017). Since rising plumes in a convecting mantle cannot be completely fixed (e.g., Steinberger and O'Connell, 1998), the real question is how fast hotspots move relative to each other (Koivisto et al., 2014). Previous studies have predicted inter-hotspot motions ranging from negligibly slow (Duncan, 1981; Müller et al., 1993) to comparable to plate velocities, in some cases as high as 80 mm/yr (Raymond et al., 2000).

In order to properly constrain the absolute plate motions, it is critical to identify hotspots that originate from deep mantle plumes. Although "there has always been a debate even among plume advocates about which hotspots are caused by deep-seated plumes" (Tackley, 2006), recent advances in whole waveform seismic tomography have made it possible to associate certain hotspots to deep mantle plumes. In terms of a whole-mantle seismic image technique, which combines accurate wavefield computations with information contained in whole seismic waveforms, French and Romanowicz (2015) identify 28 mantle plumes rooted at the base of the mantle, with 27 of them beneath hotspots. Hotspot tracks associated with these deep mantle plumes thus provide ideal constraints for inverting absolute plate motions and testing the fixed hotspot hypothesis.

In this paper, we present a new model for absolute plate motions. The model differs from previous models by three salient features. First, the new model is determined by fitting the observed trends of hotspot tracks *exclusively* associated with the deep mantle plumes revealed by seismic tomography (French and Romanowicz, 2015), under the constraints of the relative plate motions given by the MORVEL model (DeMets et al., 2010). Consequently, the model predicts absolute plate motions relative to the deep mantle plumes. Second, the model is obtained as a result of a novel procedure of outlier data rejection based on statistical tests. The outlier data are identified systematically through this procedure. Third, the model is the first plate motion model with the azimuth data (hotspot trends) fitting being formulated based on *exact* circular statistics, in contrast to the common practice of approximating a Von Mises distribution for angular data by a Gaussian distribution, as is widely applied in previous studies on relative or absolute plate motion models.

2. Data and inversion method

In this study, we adopt the data set of Morgan and Phipps Morgan (2007) to constrain absolute plate motions. For the 27 deep mantle plumes beneath hotspots revealed by seismic tomography (French and Romanowicz, 2015), three plumes (Tristan da Cunha, Ascension, and Bouvet) have no hotspot tracks available from the data set and three plumes (Azores, Galapagos, and Iceland) have two hotspot tracks on the adjacent plates, resulting in 27 observed hotspot trends, together with their uncertainties, as listed in Table 1.

The uncertainty of a hotspot trend datum is provided by two items in Morgan and Phipps Morgan (2007). One is an estimated standard error of the trend. The other one is a weight number between 1 and 0.2 that indicates Morgan and Phipps Morgan's estimate of the accuracy of the hotspot trend, with downward adjustment of the weight at some tracks based on qualitative criteria. A weight of 1, 0.8, 0.5, and 0.3 represents a standard error of no more than 8°, 10°, 12°, and 15°, respectively. Essentially, the weight number is an estimated upper bound for the estimated standard error. In case the standard error is underestimated, the weight related standard error upper bound may be used as an alternative measure for data uncertainty.

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