

Moving hotspots or reorganized plates?

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ABSTRACT

Hotspot fixity and no major plate reorganization in the past ~40 m.y. are two propositions important for studying absolute plate motion and mantle dynamics. Reexamining the hotspot data with the NUVEL-1A relative plate motion model, we find that these two propositions cannot be simultaneously tenable: either hotspots have been moving relative to each other, or a major reorganization of plate motion occurred in the past ~40 m.y. Statistical compatibility tests show that hotspot rate data are incompatible with trend data, implying that hotspots have moved. Furthermore, hotspot rates are consistently lower than those predicted by best-fitting absolute plate motion models. This may be explained by hotspots moving systematically opposite to the plate motion. If so, the moving hotspots still provide a useful reference frame for defining absolute plate motion. However, all hotspot trend data, with ages as old as 40 Ma, are statistically compatible, indicating no major reorganization of plate motion in the past ~40 m.y. In this case, relative plate motion models based on young marine magnetic anomalies may be used to infer older (<40 Ma) plate kinematics, which lack direct constraints.

Keywords: plate tectonics, plate motion, hotspots, models, statistical analysis.

INTRODUCTION

Combining relative plate motions (deduced from transform fault strikes and sea-floor spreading rates) with the trends of hotspot traces, Morgan (1972a) constructed a global model of absolute plate motion and concluded that (1) there has been no major reorganization of plate motion in the past ~40 m.y. (since the formation of the Hawaiian-Emperor bend), and (2) the hotspots have remained fixed to each other in the mantle. These two conclusions have important implications for plate kinematics and mantle dynamics. The apparent fixity of hotspots has made hotspots a useful global reference frame for absolute plate motion models (e.g., Minster et al., 1974; Chase, 1978; Minster and Jordan, 1978; Gripp and Gordon, 1990, 2002). If no major reorganization of plate motion occurred in the past ~40 m.y., then relative plate motion models based on marine magnetic anomalies in the past few million years, such as the NUVEL-1A model (DeMets et al., 1994), would be applicable to the past ~40 m.y. However, both propositions were questioned by later studies (e.g., Molnar and Atwater, 1973; Molnar and Stock, 1987; Duncan and Richards, 1991; Tarduno and Gee, 1995; Cande et al., 2000; Atwater and Stock, 1998; Raymond et al., 2000; Antretter et al., 2002; Tarduno et al., 2003). Here we test these two propositions using the NUVEL-1A model with compatibility analyses of the hotspot data. Our results indicate that no major reorganization of plate motions occurred in the past ~40 m.y., but hotspots may have moved systematically.

COMPATIBILITY OF HOTSPOT FIXITY AND NO MAJOR PLATE REORGANIZATION

We test the compatibility of the two conclusions of Morgan (1972a) in two ways. First, we assume hotspot fixity and compare the predicted plate motion with hotspot data to see if major (i.e., statistically significant) reorganization of plate motion is necessary. Hotspot fixity allows construction of absolute plate motion models, such as the HS3-NUVEL1A model (Gripp and Gordon, 2002), which was derived by fitting the NUVEL-1A relative plate motion model (DeMets et al., 1994) to the HS3 hotspot data set, which includes 2 rate and 11 trend data from young (0–5.8 Ma) hotspot volcanic chains in the Pacific region (GSA Data Repository Table DR1¹).

We compared the HS3-NUVEL1A model with the AM1–2 data set (Minster and Jordan, 1978), also from the Pacific region (Table DR1) but spanning the past 10 m.y. This data set was used to constrain the AM1–2 (Minster and Jordan, 1978) and the HS2-NUVEL1 (Gripp and Gordon, 1990) absolute plate motion models. Figure 1 shows that the HS3-NUVEL1A model fits satisfactorily to both the HS3 and AM1–2 data sets, indicating no major change of plate motion in the Pacific region in the past 10 m.y.

¹GSA Data Repository item 2006091, Tables DR1 (observed hotspot data and predicted plate velocities by models T22A and HS3-NUVEL1A) and DR2 (Euler vectors of T22A model), is available online at www.geosociety.org/pubs/ft2006.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

To see if this conclusion can hold for other plates and over longer time spans, we tested with the AM1 data set (Minster et al., 1974) that was used for the AM1 (Minster et al., 1974) and the P073 (Chase, 1978) absolute plate motion models. Of the 20 trend data in the AM1 data set, 6 are included in the AM1–2 data set, and 1 datum from the Iceland hotspot under the Eurasian plate involves special vector geometry (Grette and Coney, 1974) and is questionable (Minster et al., 1974). The remaining 13 trends form a reduced data set, herein called AM1D, which includes trend data from various plates (Table DR1). These hotspot trends were formed by long-lasting hotspot volcanic activities. Although age constraints are poor, it is believed that all these chains contain segments formed in the past 40 m.y. (Morgan, 1972b; Minster et al., 1974; Duncan and Richards, 1991). Because there is no clear bending of these chains, these data provide constraints on the direction of plate motions in the past 40 m.y. As shown in Figure 1A and Table DR1, the fit between the HS3-NUVEL1A model and the AM1D trend data is poor. Misfits of the predicted and the observed hotspot trends are >90° for all five African hotspots and one Antarctic hotspot, and >40° for one North American hotspot and one South American hotspot. These results would indicate significant changes of plate motion directions, hence a major reorganization of global plate motions in the past 40 m.y., if hotspots remained fixed.

In the alternative test, we assume no major plate reorganization in the past ~40 m.y. and see if the data are consistent with hotspot fixity. Under this assumption hotspot trends from different data sets would provide joint constraints for absolute plate motion. Using the NUVEL-1A model and the AM1D and AM1–2 trend data, Wang and Wang (2001) derived the T22A absolute plate motion model (Table DR2; see footnote 1). Figure 1C and Table DR1 show that the T22A model satisfactorily fits all the 22 trends of the globally distributed hotspot traces from the AM1D and AM1–2 data sets, as well as all 11 trend data from the HS3 data set. However, the predicted plate velocities are systematically lower than the observed rates of volcanic migrations at all seven hotspots where the rates are available from the AM1–2 and HS3 data sets. The ratio of the predicted to observed hotspot rates varies from 0.74 to 0.80, with an average of 0.78 (Fig. 1D). The discrepancy is consistent and similar for hotspots in other plates where the

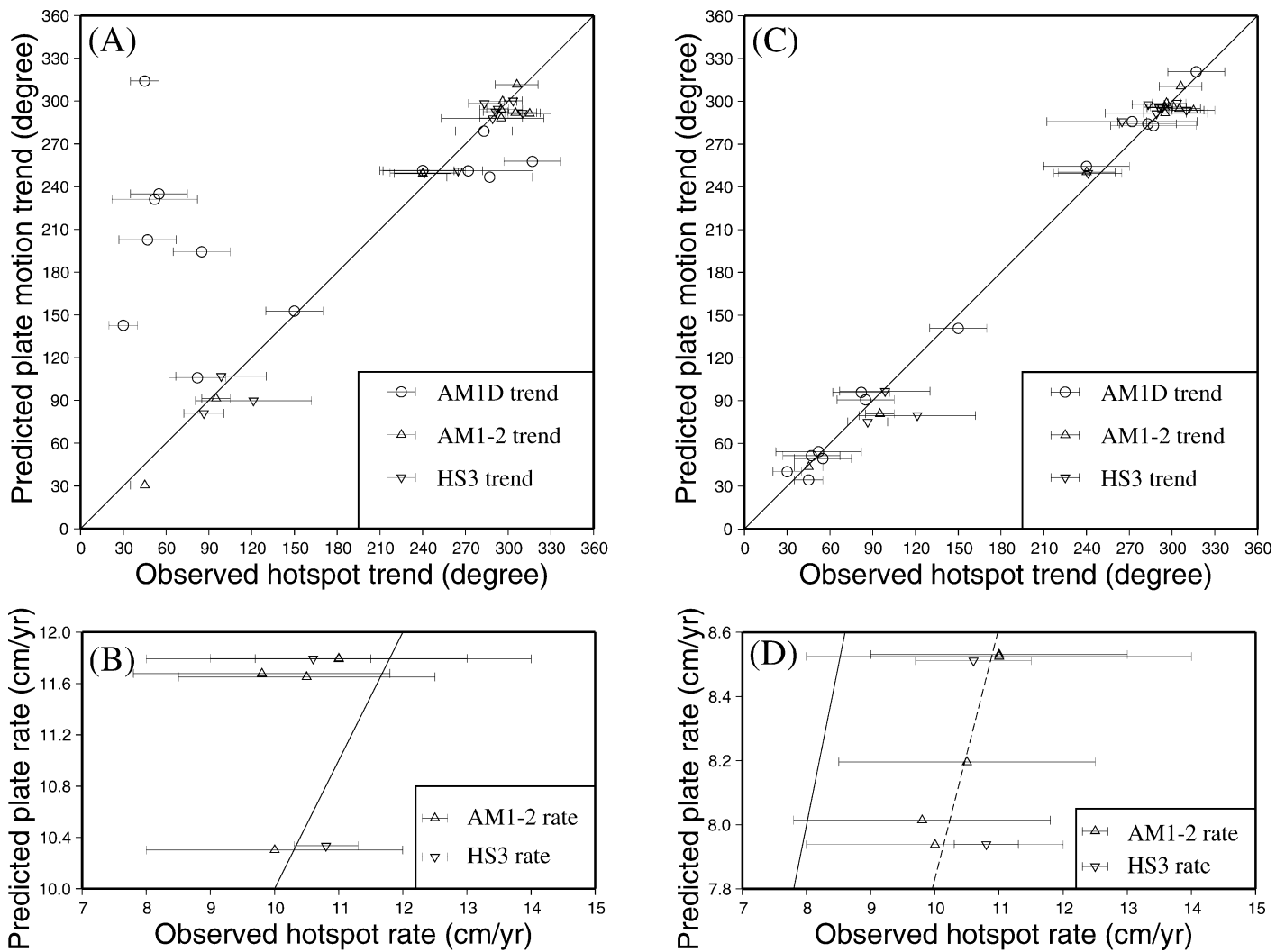


Figure 1. Comparisons of hotspot trends (A) and rates (B) with predictions of HS3-NUVEL1A model. C, D: Comparison of same hotspot data with predictions of T22A model. In all plots solid lines represent perfect correlation between predictions and data. Dashed line in D is best-fitting line to data.

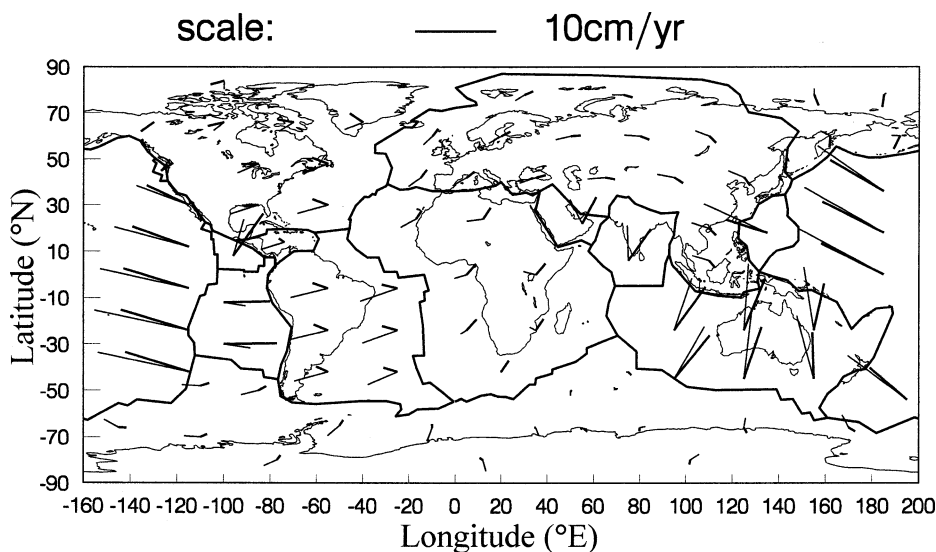


Figure 2. Absolute plate velocities predicted by HS3-NUVEL1A model (thin line) and T22A model (thick line). At each location, two velocity vectors given by the two models share a common start point.

rate data are available: 0.6 for Yellowstone, 0.59 for Galapagos (Nazca) (Gripp and Gordon, 2002), 0.50 for Reunion (Minster et al., 1974), 0.92 for Foundation (Pacific) (O'Connor et al., 1998), 0.89 for St. Helena, and 0.83 for Tristan da Cunha (African) (O'Connor et al., 1999). Such systematic discrepancy is unlikely due to errors in the estimated rates of migration of hotspot volcanism (Wang and Wang, 2001): systematic errors are estimated to be <2 cm/yr in hotspot rate data (e.g., Gripp and Gordon, 2002; Duncan and McDougall, 1976). A more plausible explanation is that hotspots have moved systematically in the direction opposite to plate motion (e.g., Petronotis and Jurdy, 1990; Wang and Wang, 2001), if no reorganization of plate motion occurred in the past 40 m.y.

MOVING HOTSPOTS OR REORGANIZED PLATES?

The difference between the HS3-NUVEL1A model and the T22A model is clear (Fig. 2) and statistically significant: us-

TABLE 1. ABSOLUTE PLATE MOTION MODELS DETERMINED FROM DIFFERENT COMBINATIONS OF HOTSPOT DATA SETS

Model	Euler vector of pacific plate			Misfit to hotspot data*				
	(°/Myr)	(°E)	(°N)	HS3R	AM1-2R	HS3T	AM1-2T	AM1D
T13A	0.7750	104.258	-63.168	18.658	0.959	0.580	0.562	0.396
T22A	0.7751	103.889	-63.117	18.732	0.957	0.574	0.553	0.399
T24A	0.7769	103.844	-63.166	18.490	0.940	0.574	0.555	0.399
T33A	0.7768	103.513	-63.114	18.589	0.940	0.569	0.546	0.406
T9A	0.8435	92.702	-61.021	13.466	0.433	0.478	0.434	3.127
HS3T-NUVEL1A†	1.0273	87.557	-60.518	2.200	0.154	0.462	0.557	17.155
T20A	0.8753	91.138	-61.106	10.591	0.267	0.472	0.437	4.558
R5A	0.9921	96.050	-28.865	1.126	0.021	8.985	8.065	23.451
R7A	0.9761	108.061	-12.085	0.027	0.054	17.656	12.212	26.356
HS3-NUVEL1A†	1.0613	90.325	-61.467	1.312	0.293	0.493	0.685	21.076
NNR-NUVEL1A§	0.6411	107.359	-63.036	42.167	2.723	0.671	0.461	3.712

Note: Misfit to data that are used to constrain the model is underlined and boldfaced.

*Measured by

$$\frac{1}{N} \sum_{i=1}^N (d_i^{obs} - d_i^{cal})^2 / \sigma_i^2,$$

where d_i^{obs} is the observed hotspot trend or rate, d_i^{cal} is the predicted plate velocity direction or rate, σ_i is the standard error of d_i^{obs} , and N is 11, 9, and 13, respectively, for hotspot trend data sets HS3T, AM1-2T, and AM1D, while it is 2 and 5, respectively, for hotspot rate data sets HS3R and AM1-2R.

†See Gripp and Gordon (2002) for reference.

§See DeMets et al. (1994) for reference.

ing their covariance matrixes, it can be shown that the error ellipsoids of 95% confidence of these two models do not intersect. Because both models are based on the same relative plate motion model NUVEL-1A, the difference indicates incompatibility of hotspot data

sets used in constructing these absolute plate motion models.

With the available hotspot data, it is possible to statistically test the compatibility between hotspot trends and rates and between hotspot tracks with different ages. The results

may help to distinguish the possibilities of hotspot fixity and major reorganization of plate motion in the past ~40 m.y. To test the compatibility between hotspot trend and rate data, we divided the HS3 data set into two subsets: HS3T for trends and HS3R for rates. Similarly, the AM1-2 data set is divided into two subsets: AM1-2T for trends and AM1-2R for rates (Table 1). The compatibility of these subsets of hotspot data is tested by constructing absolute plate motion models from these data sets and seeing if the resulting models are statistically compatible, i.e., whether their error ellipsoids of 95% confidence intersect.

By fitting the NUVEL-1A relative plate motion model to various combinations of hotspot trend or rate data sets (Table 1), we constructed several absolute plate motion models. The first group of models (T13A, T22A, T24A, and T33A), all using the AM1D trend data set and various other trend data, predicts almost identical plate velocities (shown only the Euler vector of the Pacific plate) and provides good and consistent fit to all the 33 trend data from the 3 trend data sets. This indicates that the AM1D data set, sampled from globally distributed hotspots, carries sufficient information to constrain the global pattern of absolute plate motion.

The second group of models (T9A, HS3T-NUVEL1A, and T20A), based on different combinations of the HS3T and AM1-2T trend data, appears to be different from but statistically compatible with the first group of models: the error ellipsoids of 95% confidence of the first group of models are all inside those of the second group (Fig. 3). Thus all the trend data from AM1D, AM1-2T, and HS3T data sets are statistically compatible, although they represent different age spans. This argues for no major reorganizations of plate motions in the past ~40 m.y.

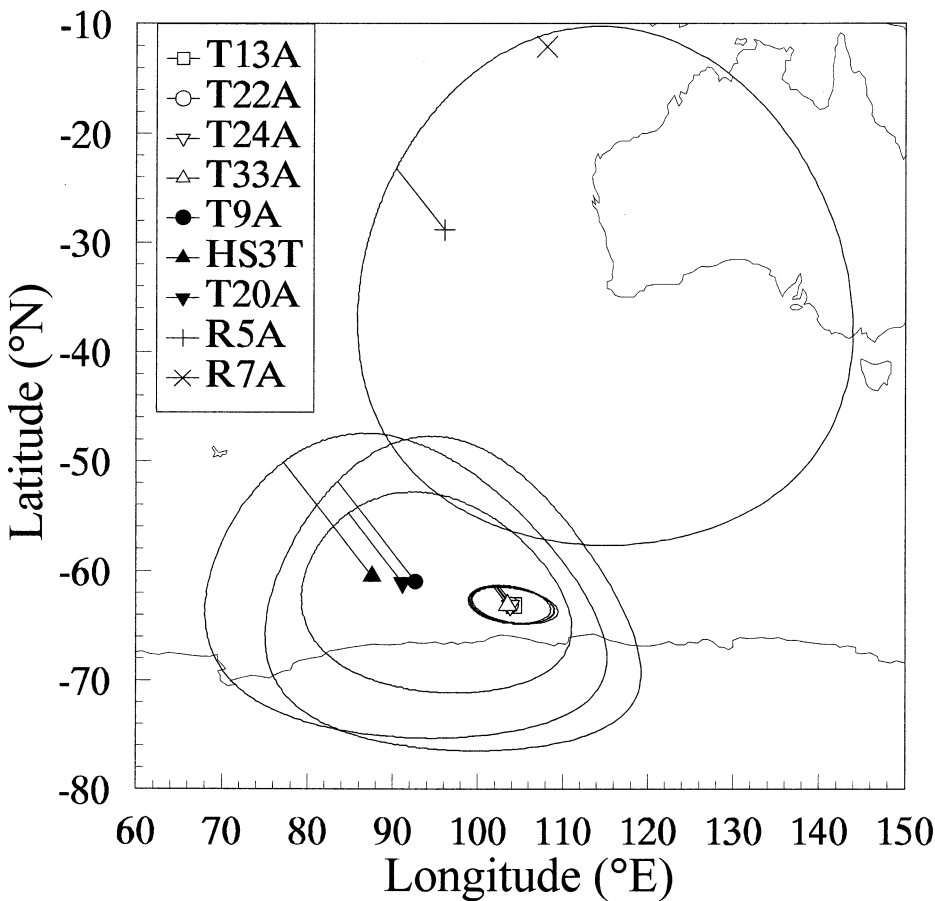


Figure 3. Euler poles of Pacific plate predicted by absolute plate motion models based on various combinations of hotspot trend or rate data (Table 1). Ellipses are intersections of error ellipsoids of 95% confidence of models with reference spherical surface, defined with radius of 0.775°/m.y. (magnitude of Euler vector of Pacific plate predicted by T22A model).

Because there are no rate data in the AM1D data set and only two rate data in the HS3 data set, only two models may be constructed using the hotspot rate data alone: the R5A model constrained by the AM1–2R data set, and the R7A model constrained by the AM1–2R and HS3R data sets (Table 1). Figure 3 shows that the Euler vector of the Pacific plate of the R7A model is inside the error ellipsoid of that of the R5A model, indicating that the hotspot rate data from AM1–2R and HS3R are statistically compatible with each other. However, these two models are statistically incompatible with most models constrained by hotspot trend data alone, suggesting that hotspot rate data are incompatible with trend data. This implies that hotspots have been moving with respect to each other.

DISCUSSION AND CONCLUSIONS

Among the hotspot data sets used in this study, the AM1D data set may have the largest uncertainties, although some recent studies show that these estimated trends are generally of good quality. For example, the trends for the African hotspots Tristan da Cunha and Reunion estimated by Minster et al. (1974) are in good agreement with studies by O'Connor and le Roex (1992) and by O'Connor et al. (1999), and the trend of the St. Peter's and St. Paul's Rocks hotspot estimated by Minster et al. (1974) is consistent with the NE-trending volcanic chain at the Sierra Leone Rise (e.g., Meyers et al., 1998).

Our model sensitivity tests confirm the self-consistency of the AM1D data set and its consistency with the trend data from the AM1–2 and HS3 data sets. We found that, excluding any one datum from the AM1D data set, the Euler vector of the Pacific plate constrained by the remaining AM1D data is almost identical with the result of the T13A model (Table 1), constrained by the entire AM1D data set. In an extreme case, we used only one datum from the AM1D data set, the well-constrained Tristan da Cunha trend on the African plate, together with the AM1–2 and HS3 data sets to construct an absolute plate motion model, and the resulting Pacific Euler vector is statistically compatible with and very close to the T22A result, but significantly different from the HS3-NUVEL1A result. Thus our conclusions are unlikely to change by potential uncertainties of some hotspot trends in the AM1D data set.

The fixity of hotspots has been questioned by many workers. One argument for the moving hotspots, for example, is the well-known misfit between the observed and predicted Pacific hotspots tracks in a reference frame fixed to Atlantic and Indian Ocean hotspots (e.g., Molnar and Stock, 1987). Although the motion between East and West Antarctica may have contributed to this misfit (e.g., Duncan

and Richards, 1991), inclusion of recently determined motion of East Antarctica and West Antarctica (Cande et al., 2000) improves the fit only slightly (Raymond et al., 2000). However, there is increasing evidence for substantial relative motions between hotspots (e.g., Tarduno and Gee, 1995; Antretter et al., 2002; Tarduno et al., 2003).

Our analysis suggests that the motion of hotspots may be systematically opposite to the direction of plate motions. If so, the moving hotspots still form a useful global reference frame for defining absolute plate motion and mantle convection (Wang and Wang, 2001), and previous models constrained by hotspot trend data alone, such as the Cenozoic plate motion models by Gordon and Jurdy (1986), are still valid. Furthermore, the lack of evidence of major reorganization of plate motion in the past 40 m.y. may have important implications: it suggests that relative motion models constructed from marine magnetic anomalies of the past few million years, such as the NUVEL-1A model, may be used to infer plate kinematics for the past 10 m.y. or even older (<40 m.y.), for which times there are no direct constraints. This needs to be further tested as new data become available, because the trend and rate data currently available for old hotspot traces are limited in both quantity and quality.

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