Present-Day Plate Motions

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Abstract. A data set comprising 110 spreading rates, 78 transform fault azimuths, and 142 earthquake slip vectors has been inverted to yield a new instantaneous plate motion model, designated Relative Motion 2 (RM2). The model represents a considerable improvement over our previous estimate, RM1 [Minster et al., 1974]. The mean averaging interval for the spreading rate data has been reduced to less than 3 m.y. A detailed comparison of RM2 with angular velocity vectors which best fit the data along individual plate boundaries indicates that RM2 performs close to optimally in most regions, with several notable exceptions. The model systematically misfits data along the India-Antarctica and Pacific-India plate boundaries. We hypothesize that these discrepancies are manifestations of internal deformation within the Indian plate; the data are compatible with northwest-southeast compression across the Ninetyeast Ridge at a rate of about 1 cm/yr. RM2 also fails to satisfy the east-west trending transform fault azimuths observed in the French-American Mid-Ocean Undersea Study area, which is shown to be a consequence of closure constraints about the Azores triple junction. Slow movement between North and South America is required by the data set, although the angular velocity vector describing this motion remains poorly constrained. The existence of a Bering plate, postulated in our previous study, is not necessary if we accept the proposal of Engdahl and others that the Aleutian slip vector data are biased by slab effects. Absolute motion models are derived from several kinematical hypotheses and compared with the data from hot spot traces younger than 10 m.y. Although some of the models are inconsistent with the Wilson-Morgan hypothesis, the overall resolving power of the hot spot data is poor, and the directions of absolute motion for the several slower-moving plates are not usefully constrained.

Introduction

Present-day plate motions can be modeled using systematic inversion methods. In our initial study [Minster et al., 1974] (referred to as paper 1), a linearized least squares algorithm was formulated and applied to an extensive, globally distributed data set. Angular velocity vectors for 11 major plates were estimated from these data, and this model was designated Relative Motion 1 (RM1). The Caribbean plate was subsequently added to this model by Jordan [1975]. Revisions and additions to the data set were begun in 1975, and an interim model was derived [Jordan et al., 1976]. We present in this paper a new relative motion model, RM2, based on a much improved data set. Consistent with our previous work, we have attempted to obtain a simple model compatible with the available high-quality observations of relative motions. Only relative motion data which involve at least one oceanic plate have been used, since the data from intracontinental environments exhibit complexities not easily described in terms of rigid plate kinematics [e.g., Molnar and Tapponnier, 1975]. We have not attempted to model the complex tectonics of the western Pacific (e.g., the Philippine plate), because little kinematical information is available concerning behind-the-arc spreading, and the assumptions fundamental to a simple plate model (e.g., triple-junction closure) may not apply.

The value of any model can be judged by its predictive capability and by its ability to withstand the test of new observations. In this respect the success of our original model, RM1, has been mixed. For example, the relative motion between the North American and the South American plates was predicted by RM1 entirely on the basis of data from other plate boundaries. Although no data yet exist which confirm directly the existence of such relative motion, the model implies that a component of north-south convergence exists between the South American and the Caribbean plates [Jordan, 1975]. It appears that some convergence is indeed required by recent studies [Talwani et al., 1976; Rial, 1978].

On the other hand, RM1 failed to satisfy an extensive set of new data collected in the South Atlantic Ocean [Forsyth, 1975; Sclater et al., 1976a]. The investigation of this failure is an important aspect of this study. We show that RM1 incorrectly predicts the plate kinematics in the South Atlantic because the presently available data are inconsistent with the plate geometry assumed in deriving RM1. We demonstrate that this inconsistency can be remedied by postulating the existence of internal deformation within the Indian plate, although alternate explanations are possible.

Other problems with the RM1 model have been noted [Jordan et al., 1976]. The well-mapped fracture zones in the French-American Mid-Ocean Undersea Study (Famous) area yield an apparent azimuth for Africa-North America motion that is due east [Macdonald and Luyendyk, 1977], whereas RM1 predicts an azimuth of 57øE, parallel to the general trends of the nearby major transform faults (e.g., the Oceanographer transform fault).
In RM1 the slip vector data from the North Pacific were modeled using a Bering plate whose motion differs from that of North America. Engdahl et al. [1977] have demonstrated that the focal mechanisms from this region can be affected by slab structure, perhaps biasing the observations. They have suggested that corrections for this bias may eliminate the need for a Bering plate. These and other problems are examined in this paper.

The Revised Data Set

The 330 data used in this study are listed in Table 1. The data locations are shown in Figure 1, delineating the major plate boundaries. These relative motion data comprise 110 rates of sea floor spreading derived from magnetic anomaly profiles, 78 transform fault azimuths, and 142 earthquake slip vectors. In compiling and editing this data set we have generally followed the guidelines in paper 1. In particular, we have excluded data from diffuse plate boundaries, specifically continent-continent boundaries. Therefore the details of Asian and Indonesian tectonics are not represented by our model.

Rate data have been determined directly from published magnetic anomaly profiles using the time scale of Talwani et al. [1971]. In paper 1, anomalies 3 and 5 were generally used to estimate rates; we thus averaged the plate speeds over the last 5-10 m.y. In this study we have redetermined the spreading rates using anomalies 2 and 2' in every instance, except for a few slowly spreading profiles where the anomalies out to 3 were employed. Hence the mean averaging interval for the rate data is less than 3 m.y. In most cases the rates were determined by comparing the corrected profiles with synthetics, generally those published by the authors of the original observational study. However, for the anomaly profiles along the Pacific-Antarctic Ridge [Molnar et al., 1975] we generated our own synthetics. For the several studies where a direct inversion for magnetization was made [Macdonald, 1977; Macdonald and Holcombe, 1978; McGregor et al., 1977], the original authors' results were used directly.

In paper 1 the directions of plate motion implied by earthquake focal mechanisms were estimated by projecting the slip vectors onto a horizontal plane. Although this procedure is almost universally adopted, it is only approximately correct for shallow thrust events in subduction zones with oblique convergence, and it can introduce a slight bias. In this study the more exact procedure of rotating the slip vectors into the horizontal plane was employed for earthquakes along inclined seismic zones. This problem is discussed in the appendix.

The most precise estimates of relative motion direction are the azimuths of well-mapped transform faults. In determining these azimuths we have used detailed bathymetric surveys where available, relying on contours which cross charted ship tracks. Interpretive diagrams have been avoided to minimize the feedback between data and plate tectonic models.

The uncertainties listed in Table 1 are based on a case-by-case subjective evaluation of the data quality. They are used to weight the data in the inversion algorithm and to derive estimates of the uncertainties in the model parameters. Although we have attempted to use a consistent set of criteria in assigning these errors, the estimates are nevertheless crude indicators of data quality. With this in mind, we have adopted a conservative stand and have deliberately overestimated these uncertainties. This bias is apparent in Figure 3, where it is seen that the sample standard deviation of the normalized residual distribution is significantly less than its expected value of 1.

Model RM2: General Description

Inversion of the data was performed using the linearized, iterative, weighted least squares algorithm described in paper 1. Our extensive experience in applying this algorithm to the plate motion problem has demonstrated to us its effectiveness. Although the algorithm involves the linearization of a nonlinear problem, convergence has always been rapid, and no difficulties associated with local minima have been evident. The uncertainties in the model parameters derived from the linear theory have proven to be effective measures of the errors induced on the model by errors in the data.

The inversion algorithm has been applied to the data set listed in Table 1 to obtain an 11-plate model, designated RM2. The plate geometry is identical to that of RM1, except that the Bering plate has been recombined with the North American plate and a Caribbean plate has been added. RM1, supplemented with the CAR-NOM angular velocity vector derived by Jordan [1975], was used as a starting model in the inversion algorithm. Convergence was attained in five iterations.

Model RM2 is specified in Table 2 by its geohedron [McKenzie and Parker, 1974]. Although a more compact specification is possible, this format conveniently provides an explicit relative rotation vector for each plate boundary. The RM2 geohedron is illustrated in Figure 2.

In the notation of paper 1 the quantity minimized by the fitting procedure is the variable

$$\chi^2 = \sum_{i=1}^{N} \frac{(d_i^0 - d_i^1(M))^2}{\sigma_i^2}$$

where $N = 330$ is the total number of data. The 11-plate model is specified by 30 parameters. If the data were normally distributed and the variances were exactly known, $\chi^2$ would be chi-square distributed with 300 degrees of freedom, and a sample value would lie in the interval $(300 \pm 49) 95\%$ of the time. The value of $\chi^2$ for RM2 is 109, almost a factor of 3 less than its expected value. Thus the data are fit significantly better than they would be if their assigned uncertainties were correct.

This fact is also evident from the histograms of normalized residuals plotted in Figure 3. The sample variances of these distributions are about 1/3 their expected value of unity. This discrepancy could be corrected by uniformly reducing the standard errors assigned to the data by a factor of $(3)^{-1/2}$. Such a reduction
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Table 1 (CONT.)
would not change the model but would decrease the derived model uncertainties by the same factor. However, to be conservative, we have retained the larger estimates of uncertainty.

It can be seen from Figure 3 that the distribution of normalized residuals for the slip vector data departs from the assumed Gaussian behavior in another manner: the distribution is skewed toward negative values. Much of this skewness is attributable to the predominantly left slip vectors exhibited by the Aleutians and the Kurils, a feature noted in the literature.

Because the data set is large and because the geometry of the problem is complex, the performance of RM2 cannot be fully described by these simple statistics. A complete assessment of RM2's success in explaining the observations requires that each data subset pertaining to an individual plate boundary be considered separately. For a large number of plate pairs a relative rotation vector, or at least a best fitting pole (BFP), can be determined from the data subset alone. These vectors and poles have been obtained by inversion and are listed in Table 3. The corresponding BFP's are shown with the RM1 and RM2 poles on Figures 4-6. The differences between these poles and those for RM2 measure the constraints imposed on RM2 by the simultaneous inversion scheme. These differences are not large, which is evidence that RM2 performs close to optimally in most regions. Notable exceptions involve the INDI-ANTA, INDI-PAC data subset and the Aleutians and the Kurils, a feature also noted in the literature.

Table 3. The corresponding BFP's are shown with the RM1 and RM2 poles on Figures 4-6. The differences between these poles and those for RM2 measure the constraints imposed on RM2 by the simultaneous inversion scheme. These differences are not large, which is evidence that RM2 performs close to optimally in most regions. Notable exceptions involve the INDI-ANTA, INDI-PAC, and APRC-NOAM poles, discussed below.

The estimated model uncertainties $\sigma_0$, $\sigma_\phi$, and $\sigma_\theta$ are much smaller in Table 2 than in Table 3. This is, of course, a direct consequence of the self-consistency constraints inherent to the rigid plate model, as discussed in paper 1. An impressive example of this behavior is provided by the COCO-PCF rotation vector, which is heavily constrained by two triple-junction closure conditions; these constraints reduce the nominal uncertainty of the rotation rate by a factor of 4.

It should be emphasized that the uncertainties in the model parameters given in Table 2 correspond to marginal distributions. A complete description of the model uncertainties, including the various error cross-correlations, requires the specification of a $30 \times 30$ (symmetric) variance matrix. A more complete discussion of this point is given in paper 1.
Minster and Jordan: Present-Day Plate Motions

Fig. 1. Plate geometry and geographical distribution of the data used in producing model RM2. Circles are sea floor spreading rates, squares are transform faults, and triangles are slip vectors. Seven EURA-NOAM data at high latitudes are not shown on the figure.

Listed in Table 1 are quantities which we have termed 'data importances.' As defined in paper 1, they are the diagonal elements of an orthogonal projection operator in the data space and are indicative of the distribution of information among the data (paper 1, and Minster et al. [1977]). Importances are additive and sum to the number of inverted parameters, 30 in the case of RM2. They depend on the geometry of the data set, and on the data uncertainties, but not on the actual values of the data. The final model depends heavily on the most important data and is robust with respect to the least important data.

Cumulative importances for individual plate boundaries are listed by data types in Table 2 for RM2 and in Table 3 for the best fitting vectors. The cumulative importance for all slip vector data is only 4.6, compared with 11.1 for the transform fault azimuths, despite the fact that the former outnumber the latter by nearly 2:1. This reflects the lower uncertainties---by a factor of 2 to 3---generally assigned to transform fault data. The most important datum (0.95) is the rate across the Mid-Cayman Rise [Macdonald and Holcombe, 1978]; alone, it essentially determines the relative speed of NOAM-CARB. When the entire data set is considered, 50% of the cumulative importance is associated with the 49 most important data, and only 10% with the 151 least important data. Importances are very useful for a detailed comparison of data and models, as is illustrated in the next section.

Model RM2: Detailed Assessment

This discussion is devoted to a detailed evaluation of RM2 on a region-by-region basis. The fit of RM1 and RM2 to the data for individual plate boundaries is illustrated in Figures 7--20. The data and model values are depicted as residuals with respect to the best fitting angular velocity vectors and poles listed in Table 3. Base lines provided by the best fitting vectors remove the large variations in the data functionals due to geometrical complexities and allow the models to be plotted as smooth lines on the diagrams. More important, the deviations from the locally best fitting parameters required by closure conditions are readily apparent.

The Pacific-North America boundary. It was concluded in paper 1 that the slip vector data along the Aleutian-Kuril trench system are not consistent with the NOAM-PCFC relative motion inferred from data in the Gulf of California and in the northwest Pacific. We suggested that this inconsistency was diagnostic of deformation of the North American plate and attempted to model it by including a hypothetical Bering plate in RM1. However, the BERI-PCFC pole was determined by only 10 slip vectors. Engdahl et al. [1977] pointed out that our data were a poor representation of the earthquake population along the trench and that the slip vector orientations for individual events in the vicinity of 175°E could be significantly biased by the laterally heterogeneous seismic velocity structure of the down-going slab. In the present study the number of data along this trench system has been increased to 27, including 15 high-quality slip vectors from the Kuril-Kamchatka Arc recently published by Stauder and Mualchin [1976]. Because of the evidence for bias due to slab structure presented by Engdahl et al. [1977], we assigned large uncertainties (+20°) to the data lying between 165°E and 165°W longitude. It can be seen from Figure 7 that these data are in fact systematically misfit by RM2 and the BFP in the direction observed in paper 1 and predicted by the model of Engdahl et al. [1977]. On the other hand, data from the Kuril-Kamchatka Arc are fitted by the model without difficulty, in agreement with the conclusion of Engdahl et al. [1977] that slip vectors in this region are not likely to be significantly biased by slab structure. Since the fit of the data elsewhere along the boundary is satisfactory (Figure 7), we conclude that there is little evidence for deformation within the North American plate of the sort hypothesized in paper 1.
<table>
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Total  14.273  11.134  4.593  30.000

*First plate named moves counterclockwise with respect to the second. Uncertainties are the standard deviations of marginal distributions.

†One-sigma error ellipses are specified by the azimuth $\xi_{\text{max}}$ of the major axis; lengths of the axes are geocentric angles.
The East Pacific Rise. The data set for the COCO-PCFC boundary includes a redetermination of the Siqueiros transform fault azimuth from revised bathymetry [Rosendahl, 1976]. RM2 performs very well along this boundary and constitutes a slight improvement over RM1 (Figure 8).

The data set for the NAZC-PCFC boundary has been significantly revised and augmented, especially the rate data set. Between 6° and 12°S the magnetics are poor, and the data relatively scattered (Figure 9), as might be expected for east-west profiles in the vicinity of the magnetic equator. Nevertheless, Rea's [1976a, b] data indicate a lower rate than was used in paper 1. Herron's [1972] profile at 19°S is easily readable, despite the small size of the published figure, but the bathymetry indicates that a fracture zone may be crossed to the west of the ridge. Thus the eastern part of the profile is suspect beyond anomaly 2, and we assigned a large uncertainty to the measurement. A sequence of high-quality profiles at 20°S has been discussed by Rea and Blakey [1975]. Since their published profiles are rate adjusted and could not be remeasured, we adopted their estimated spreading rate (16.1 cm/yr) and assigned it an uncertainty of 0.6 cm/yr, a conservative value in view of the datum's quality. However, this rate is less than that obtained at 19°S and is not fit well by the model. It is also difficult to reconcile this rate with the comparable rates much further north and a higher rate to the south: the profile at 28°S [Herron, 1972] yields a rate which exceeds 17 cm/yr.

The azimuths along the NAZC-PCFC boundary have been much improved by the recent bathymetric studies of Mammerickx et al. [1975] and Lonsdale [1978a, b]. However, the position of the NAZC-PCFC pole has not been significantly altered by these revisions; the RM1 and RM2 poles, and the BFP, lie very close together, well within the RM2 error ellipse.

The Galapagos spreading center. The rate data along the COCO-NAZC boundary are taken from the study by Hey [1974]. We also included a good deep-tow profile published by Klitgord and Madie [1974]. As seen in Figure 10 and in Table 1, the data along this boundary are internally consistent. A particularly satisfying feature is that the recent bathymetry of Lonsdale and Klitgord [1978] clearly requires the COCO-NAZC pole to lie north of the equator; the transforms at 84.5° and 85.3°W trend east of north. The implied shift from the RM1 pole

Fig. 2. RM2 geohedron (stereo pair). The geohedron depicts relative motions in angular velocity space [McKenzie and Parker, 1974]. Individual plates correspond to vertices. The z axis coincides with the rotation axis of the earth, and the x axis is along the Greenwich meridian. Vectors representing the three reference axes have magnitudes of 0.3°/m.y. Open circle is coordinate origin for AM0-2. Closed circle is coordinate origin for AM1-2.

![Fig. 2. RM2 geohedron (stereo pair).](image)

Fig. 3. Histograms of normalized residuals for each data type, with sample size, sample mean, and sample variance. The theoretically ideal Gaussian distributions with zero mean and unit variance are shown for comparison. Shaded area in lower histogram represents residuals for Aleutian and Kuril slip vectors, which show negative bias.
position is in complete concordance with the shift dictated by the lower spreading rates along the NAZC-PCFC boundary. It should be noted that the strike of the Panama transform fault is very consistent with the new pole position, a point we shall return to in the next section.

The Chile Rise. The slower opening rate along the NAZC-PCFC boundary also affects the motion along the Chile Rise. In particular, the RM2 rate is considerably less than the 7.6-cm/yr estimate derived from the profile of Klitgord et al. [1973], which we consider to be the best rate observation along this boundary and is the only value included in the data set. However, the RM2 rate is between this value and the lower estimates of Morgan et al. [1968] and Herron and Hayes [1969].

Eastern Pacific subduction zones. Strongly coupled to the opening of the East Pacific Rise are the convergence rates and directions along the middle American and South American trenches. We have adopted a set of slip vectors estimated by Stauder [1973, 1975] and Abe [1972] to represent the direction of subduction in South America. The residuals for these data show a slightly negative trend, although Abe's [1972] well-determined solution has a large positive residual. The negative trend could be eliminated by increasing the rate along the NAZC-PCFC boundary. However, the COCO-NOAM and COCO-CARB slip vectors also exhibit this negative residual trend, and the possibility that these data are biased, like the Aleutian slip vectors, cannot be discounted. In any case, the scatter in the data is large, the average misfit is small, and the data importances are low; hence any bias will not significantly affect the model.

Fig. 4. Poles for model RM2, with their 95% (2o) confidence ellipses. RM1 poles and best fitting poles (Table 3), where available, are also shown.
The Pacific-Antarctic Ridge. Because it is a keystone of the global model, particular attention was devoted to the PCFC-ANTA boundary. The data along this boundary are of sufficient number and quality to provide significant coupling, via the Antarctic plate, among the plates in the Pacific and the plates with boundaries in the South Atlantic and Indian oceans. The configuration of the PCFC-ANTA boundary has been investigated by Molnar et al. [1975], and our data set is based primarily on this study. Since these authors did not use synthetic magnetic profiles, we computed synthetics and re-interpreted the magnetics. A significant component of apparently asymmetric spreading is observed on many profiles [Molnar et al., 1975; Stein et al., 1977], so the rates were estimated only from pairs of corresponding anomalies on both sides of the axis. All measurements were based on anomaly 2' or younger anomalies. Transform fault azimuths were derived from the bathymetry of Molnar et al. [1975], but estimates were obtained from ship track crossings rather than their interpretive map. It is clear from Figure 11 that RM2 is very close to the best fitting vector and represents an improvement over RMI in this region. The difference in the RMI and RM2 poles is mainly attributable to the southwesternmost transform fault, an important datum (± 0.25) not included in paper 1. Some internal inconsistency of unknown origin is evident in the rate data (Figure 11): the rates are greater in the middle of the boundary than those required by the rates at the ends of the boundary. Nevertheless, most of the data are fitted within their uncertainties, and the relative rotation vector is one of the best determined in the RM2 geohedron.

The India-Pacific boundary. The data used
along this boundary, consisting entirely of earthquake slip vectors, are the same as those in paper 1, but the data north of 25°S were eliminated because of documented behind-the-arc spreading in the Lau Basin [e.g., Lawver et al., 1976]. Nevertheless, the geometry is such that a BFP could be determined from the 14 remaining slip vectors (Table 3). We observe that this best fitting pole is almost identical to the pole determined by Falconer [1973] exclusively from seismicity data along the Macquarie Ridge, a completely independent data set. However, as seen in Figures 4 and 12, both RM1 and RM2 differ significantly from this pole, a direct result of requiring closure around the INDI-PCFC-ANTA triple junction. Consequently, the global models are a poor fit to the southernmost slip vectors, determined by Banghar and Sykes [1969]. Furthermore, these models predict a significant component of compression across the Macquarie Ridge system, in disagreement with the hypothesis of Falconer [1973] that this segment is a strike slip fault. We strongly suspect that these inconsistencies result from internal deformation within the Indian plate (see below).

Motions about the Azores triple junction. The plate boundaries which form the Azores triple junction are individually well constrained. Figure 13 is a residual plot for the northern Mid-Atlantic Ridge data. The longitude of the EURA-NOAM pole is reasonably well fixed by the precise azimuth data along the Charlie-Gibbs transform fault and a number of fault plane solutions in the Arctic, but its latitude is more uncertain. Both the RM1 pole and the BFP lie near the mouth of the Lena
River, the position most compatible with the rate data. The RM2 pole is several degrees further south (65.8°N, 132.4°E), and its fit to the rate data south of 60°N is not as good. However, this pole is more consistent with the conclusions reached by Chapman and Solomon [1976] in their study of northeast Asian tectonics.

The data set along the Azores-Gibraltar line is considerably improved over our previous study. We deleted the datum east of Gibraltar because of its probable involvement with the Alboran plate [Andrieux et al., 1971] but added three new slip vectors west of Gibraltar. The most important addition, however, is the azimuth of the Gloria transform fault (0.783), well defined by Laughton et al. [1972, 1975]. This datum places a strong constraint on the longitude of the AFRC-EURA pole. Although the individual slip vectors are not particularly well determined, their variation from northwest compression on the east to southwest extension on the west requires that the pole be not far south of the boundary, a conclusion established by McKenzie [1972]. As a result, the pole is very tightly constrained, and the RM2 solution is very close to the BFP (Figures 6 and 14).

The data set south of the Azores on the Mid-Atlantic Ridge has also been improved. Several special studies have yielded much better magnetics, and these imply a significantly lower rate during the last 3 m.y. than was used in paper 1. The azimuth data along the AFRC-NOAM boundary have also been revised. In paper 1 the general trends of the Oceanographer transform fault (S77°E) and the Atlantis transform fault (S81°E) were used and were well fit by RM1. In the present data set these azimuths have been deleted and replaced by the azimuths of transforms A (S88°E) and B (S89°E) in the Famous area [Macdonald and Luyendyk, 1977]. The difference between the azimuths of the major transform faults and transforms A and B has been attributed to a change in the direction of plate motion within the last 5 m.y. [Macdonald, 1977; Fox et al., 1978; Atwater and Macdonald, 1977]. A slip vector showing east-west motion on the Oceanographer transform fault [Udas et al., 1976], supporting this conclusion, has also been included.

The revised data along the AFRC-NOAM boundary are internally consistent, as indicated by the performance of the best fitting angular velocity vector, but the AFRC-NOAM azimuth data are poorly fitted by RM2 (Figure 15). It is clear that the misfit is forced by the closure condition about the Azores triple junction. To satisfy the triple junction condition, the AFRC-NOAM pole must be on the great circle connecting the EURA-NOAM and AFRC-EURA poles (Figures 4 and 6). The BFP is not; it lies to the west near the northeastern tip of Greenland, as is required by the revised azimuth data. The triple-junction great circle cannot be shifted to include the
AFRC-NOAM BFP without seriously misfitting the data along one or both of the other boundaries. For example, any good fit to both the AFRC-NOAM and the EURA-NOAM data set yields an AFRC-EURA pole that is much to the west of the RM2 pole and implies compressive motion along the entire Azores-Gibraltar line, a prediction in flagrant disagreement with the observed earthquake mechanisms. Hence the RM2 solution is significantly different from the AFRC-NOAM BFP. The RM1 and RM2 poles are each included within the other's 95% confidence ellipses. Both models predict directions of AFRC-NOAM motion which match the observed general trend of the Oceanographer transform fault but which misfit the azimuths of transforms A and B by about 10°.

A possible explanation for this discrepancy concerns the way the RM2 data set averages over time. It is conceivable that the east-west trends observed in the Famous region are so recent that the pole shifts required by this reorientation are not represented in the data from the other plate boundaries.

However, we believe that this explanation can be rejected. The location of the great circle connecting the EURA-NOAM and AFRC-EURA poles is fixed by truly 'instantaneous' data, i.e., the slip vectors in the North Atlantic and along the Azores-Gibraltar Line. Therefore the conflict is among data which involve little or no time averaging.

Perhaps the east-west transforms observed in the Famous area are not unbiased indicators of AFRC-NOAM motion. This would be the case, for example, if these short fault segments were leaky in the sense of Menard and Atwater [1969], i.e.,
if a component of extension existed across these faults. For this explanation to be correct, the rate of opening normal to the faults would have to be about 0.4 cm/yr. Although the field data do not appear to support this hypothesis [Detrick et al., 1973; Arcyana, 1975; Choukroune et al., 1977], the ability of these studies (as well as ours) to resolve such a component is an open question.

The incompatibility of the Famous trends with the RM2 model remains problematic. It is interesting to note, however, that the RM2-predicted azimuths are essentially perpendicular to the rise-crest segments in the Famous area.

The Americas: One plate or two? A major conclusion of paper 1 was that significant relative motion exists between North and South America. The present study supports this conclusion, although direct observational evidence for NOAM-SOAM motion is still lacking. An inversion of the global data set was performed with the Americas grouped into a single plate. This model was rejected because it does not satisfy the relative motion data in the Atlantic.

In particular, the following are true:
1. The rates along the AFR-NOAM boundary are misfit, model values being 0.4 cm/yr too low.
2. The azimuths along the AFR-SOAM boundary yield systematically positive residuals of about 5°.
3. The EURA-NOAM pole is shifted northward to 81°N, 118°E, well outside the RM2 95% confidence ellipse. Consequently, the variation in rates along this boundary does not match the observations.
4. The AFR-EUR pole is shifted westward to 12°S, 36°W. Such a pole implies compressive motion along the entire Azores-Gibraltar line. As noted above, this consequence is in direct conflict with the extension observed on the western portion of this boundary.

We conclude that a nonzero NOAM-SOAM angular velocity is required by the revised data set. To derive RM2, we adopted the convention of paper 1 and partitioned the AFR-NOAM and AFR-SOAM data sets at 15°N, where the distance between the Mid-Atlantic Ridge and the West Indies Arc is at least 12°.

This grouping affords an excellent fit to the data along the AFR-SOAM boundary (Figure 16). One datum on this boundary deserves particular mention. Eittreim and Ewing [1975] have mapped a recent, apparently continuous fault within the Vema fault zone. Their data yield a remarkably well determined azimuth of relative motion; we assigned this datum an uncertainty of ±2°, the lowest given to any direction datum. Its residual computed from RM2 is only 0.4°. In contrast, the residual computed from the model with a single Americas plate is nearly 5°.

Although some motion is required, the NOAM-SOAM angular velocity vector is not precisely constrained. This is indicated by the large confidence ellipse associated with the pole (Figure 16). It is also evident that the RM2 pole is nearly 30° north of the RM1 pole, completely reversing the sense of motion predicted along the boundary postulated to lie somewhere between 10° and 20°N. Discussion of the inferred relative motion may be found in a later section.

Caribbean plate motion. Although a Caribbean plate was not included in the RM1 model derived in paper 1, the topic of Caribbean plate motion was treated in detail by Jordan [1975]. He derived a NOAM-CARB angular velocity vector using a spreading rate of 2.2 cm/yr across the Mid-Cayman Rise estimated from topographic decay [Holcombe et al., 1973]. For the present study we were fortunate to have available a much more reliable rate (2.0 ± 0.4 cm/yr since 2.3 m.y. B.P.) determined from a magnetic profile across the Mid-Cayman Rise by Macdonald and Holcombe [1978]. This rate is essentially identical to the previous estimate. Four slip vectors from the Molnar and Sykes [1969] set used by Jordan [1975] were deleted, one from the West Indies Arc, because it may lie south of the CARB-NOAM-SOAM triple junction, and three from Hispaniola and the Puerto Rico Trench, where the data show internal scatter and the stress and strain fields are complex [Jordan, 1975]. A slip vector for the 1976 Guatemala earthquake [Kanamori and Stewart, 1978] was added. The changes to the direction data shifted the NOAM-CARB pole northwest from the position computed by Jordan [1975]. It can be seen from Figure 5, however, that this shift is in the direction least constrained by the data, as indicated by the orientation of the RM2 confidence ellipse. Jordan's pole lies within this confidence ellipse, and the difference between these poles is not resolvable by the present data set (Figure 17).

The CARB-SOAM pole (Figure 4) is also shifted with respect to Jordan's solution, but, again, the shift is along the major axis of the error ellipse. This pole is unconstrained by data along the CARB-SOAM boundary, so its 95% confidence ellipse is quite large. The change in its location reflects the shifts in both NOAM-SOAM and NOAM-CARB poles. Nevertheless, Jordan's conclusion that a component of north-south motion exists along this boundary is unaffected (Table 5).

The Bouvet triple junction. RM1 did not predict correctly the relative motions of SOAM-ANTA and AFR-ANTA [Forsyth, 1975; Sclater et al., 1976a]. In paper 1, these boundaries were very poorly constrained by data, but this deficiency has been remedied by a number of recent special studies (Table 1). RM2 provides an excellent fit to the data around Bouvet triple junction (Table 1, Figures 16 and 18), whereas RM1 performs miserably. Three explanations for this discrepancy were investigated:
1. RM1 is located in a local minimum of the fitting function manifold. This possibility can be dismissed; inverting the RM1 data set with RM2 as a starting model yields the published RM1 solution.
2. The SOAM-ANTA and AFR-ANTA vectors are very sensitive to small errors in the RM1 data set. This possibility can also be excluded; the error ellipsoids for these vectors are actually quite small (paper 1, Table 5, and Figures 5 and 7). The prediction error computed from the RM1 variance matrix is much smaller than the RM1 misfit to the new data. If the new data along the SOAM-ANTA and AFR-ANTA boundaries are excluded from the revised data set, a solution similar to RM1 is obtained.
3. The global data set is inconsistent with the plate geometry assumed by RM1. Hypothesis 3 is our preferred explanation and was in fact advocated by Forsyth [1975] in his original study of this problem. For reasons detailed below, we believe that the data set for plate motions about the Indian triple junction are inconsistent with our model, and we ascribe this inconsistency to internal deformation within the Indian plate.

Plate motions in the Indian Ocean. This brings us to the major difficulty that we encountered in constructing RM2; as pointed out by Jordan et al. [1976] and Minster and Jordan [1977], each of the three legs of the Indian triple junction are populated by internally consistent data, but the three best fitting vectors sum to a vector (the closure vector) significantly different from zero (Table 3 and Figure 6).

The AFRC-ANTA boundary is densely populated by good observations. The 6 rates, 6 transform faults, and 11 slip vectors along this boundary constrain the angular velocity vector very well. The most important of these data is the well mapped Melville transform fault ($\phi = 0.53$) near the northeastern end of the boundary [Engel and Fisher, 1975], which controls the latitude of the pole. RM2 performs close to optimally along this boundary (Figure 18).

As noted by McKenzie and Sclater [1971], the transform faults along the central Indian and Carlsberg ridges tightly constrain the INDI-AFRC pole, and these constraints have been strengthened by improved bathymetry [Engel and Fisher, 1975]. As shown on Figure 19, there is a minor discrepancy between the rate data and the transform fault azimuths: the northermost rates are too large by a few tenths of a centimeter per year. In an effort to fit these rates the best fitting vector skews slightly with respect to the transform fault data, and RM2 is actually a better fit to the azimuths than the BFP. However, the Carlsberg Ridge is opening slowly and lies close to the magnetic equator; the magnetics along this boundary are not of exceptional quality [McKenzie and Sclater, 1971], and we are not disturbed by this slight misfit.

The problem of data inconsistency is evident along the southeast Indian Ridge. The data are not quite as good along this boundary, but they determine a BFP and angular rate which constitute an acceptable fit (Figure 20). RM1 fits these data very well, but RM2 fits poorly; the RM2 pole is significantly different from the BFP (Figure 6) and does not match the gradient in the spreading rates. The situation is now clear: RM1 satisfies the INDI-AFRC and INDI-ANTA data but misses badly along the AFRC-ANTA boundary; RM2 corrects the misfit but then does not satisfy the INDI-ANTA data. The most comprehensive local study of this triple junction was published by McKenzie and Sclater [1971]. Their instantaneous motion model is also shown on Figures 18-20. It is different from either RM1 or RM2 but does not constitute a better solution.

The motion of Arabia. In the Gulf of Aden the rates obtained by Laughton et al. [1970, Table 1] are used directly. These data show very little scatter and are fitted by RM2 very well. The only other data used in the inversions are two rate estimates in the Red Sea [Allan and Morelli, 1970], and these are also well fitted. Because of the mediocre quality of the azimuth data and the variety of possible interpretations of Red Sea tectonics [e.g., Le Pichon et al., 1973], we did not attempt to model the northern Red Sea in this work. Since the Arabian plate is unconstrained along its other boundaries, the RM2 and best fitting ARAB-AFRC vectors are identical.

The Indian Plate Problem

Although RM2 is a very good fit to the data set as a whole, we have not been able to fit the Indian Ocean data satisfactorily by an RM2 type model. These discrepancies may simply result from bad data, contaminated by systematic observational errors that we do not understand. We are aware that data bias is the probable explanation for the misfit to the Aleutian slip vectors; in paper 1, we attributed this misfit, evidently incorrectly, to internal deformation within the North American plate. The existence of systematic errors in the Indian Ocean data obviously cannot be ruled out at this time. However, because its implications are important, an alternate hypothesis—internal deformation within the major plates—deserves investigation.

In RM2, Indian Ocean tectonics are modeled by three plates, ANTA, AFRC, and INDI. There is no geological or seismic evidence for deformation within Antarctica; in fact, the intraplate seismicity of Antarctica appears to be the lowest of any major plate [e.g., Tarr, 1974]. In contrast, both the African and the Indian plate are characterized by high intraplate seismicity, and observations of significant post-Miocene intraplate deformation have been reported [e.g., McKenzie et al., 1970; Sykes, 1970b; Eittreim and Ewing, 1972].

To investigate hypothetical intraplate deformation, we have chopped these plates into two pieces and modeled each as a rigid entity, as we did for NOAM and SOAM. This procedure is obviously unsatisfactory for representing widely distributed strain, and we are implicitly assuming that most of the deformation is localized within a relatively narrow zone.

Deformation of the African plate. Active extension across the African rift valleys is well documented [e.g., McKenzie et al., 1970; Maasha and Holnar, 1972; Le Pichon et al., 1973]. To test the hypothesis that the RM2 misfit along the INDI-ANTA boundary stems from ignoring this deformation, another global inversion was performed. The data along the African plate boundaries in the Red Sea and west of 20°E were assigned to a Nubian plate (NUBI), and the data east of 40°E were assigned to a Somalian plate (SOMA). We arbitrarily assumed that the position of the NUBI-SOMA-ANTA triple junction is somewhere between 20° and 40°E. Since we did not feel justified in specifying its position more accurately, the 10 data along the southwest Indian Ridge in this interval were deleted. As expected, the resulting model is a better fit to the data set than RM2. In particular, the INDI-ANTA angular velocity vector is very close to the best fitting solution in Table 3, and the fit to data along this boundary is much
improved. However, the resulting SOMA-NUBI pole is at 43°S, 48°E, and the angular rate is 0.17°/m.y., which implies east-west compressive motion across the African rift valleys at a rate exceeding 1 cm/yr! This prediction clearly contradicts the geophysical evidence. If a nonzero component of extension is imposed on this boundary, the fit to the INDI-ANTA data set is degraded with respect to RM2.

Therefore problems with RM2 in the Indian Ocean cannot be remedied by simply postulating internal deformation in Africa, because the resulting model violates other constraints. Although the evidence for extension across the African rift zone is compelling, we have not been able to resolve this motion successfully in our global modeling studies, a conclusion also stated in paper 1.

In a recent parallel study, Chase [1978] has produced a global plate model which predicts opening of the rift valleys. The differences between his model and the model described above are evidently due to differences in the inverted data sets. We note that Chase's poles do not provide a satisfactory fit to our data set along the RM2 AFRC-ANTA boundary. Also, the misfit to the INDI-ANTA data set described for RM2 is a feature of his solution as well.

Deformation of the Indian plate. The hypothesis that the Indian plate is deforming is suggested by two aspects of the RM2 fit discussed in the previous pages: RM2's performance is unsatisfactory along both INDI-ANTA and INDI-PCFC boundaries. To test the hypothesis that INDI deformation is responsible for these discrepancies, the western portion of the Indian plate (WIND) was separated from the eastern portion (AUST). Six INDI-ANTA data within a transition zone between 90° and 130°E were deleted. Data on the Indian plate boundaries west of 90°E were assigned to WIND, and data east of 130°E were assigned to AUST. With this configuration the global data set was inverted. The resulting AUST-WIND angular velocity vector is labeled A in Table 4. Again, introduction of more model parameters permits a better fit to the observations: The remaining data along the southeast Indian Ridge are satisfied, and the AUST-PCFC pole lies within 2° of the INDI-PCFC BFP of Table 3.

From Table 3 we can estimate the hypothetical AUST-WIND vector independently of the data along the southeast Indian Ridge. Deformation of the Indian plate can be approximated by the closure vector of the circuit WIND-APRC-ANTA-PCFC-AUST. This vector can be calculated using the best fitting angular velocity vector for each boundary traversed by the circuit. The result is not unique, since the PCFC-AUST rate is not constrained, and a one-parameter family of closure vectors is therefore generated. To specify a member of this family, we arbitrarily chose to minimize the relative velocity of AUST with respect to WIND at a point along the Ninetyeast Ridge. Numerical experiments show that the result is quite insensitive to this point's location. The derived angular velocity vector is labeled B in Table 4.

In view of the uncertainties involved (and the ad hoc criterion used to construct vector B), the two solutions in Table 4 are remarkably similar. Both imply slow compressive motion between WIND and AUST in a northwest-southeast direction.

Our modeling procedures do not require the existence of a specific boundary separating the Indian plate into two portions. However, we speculate that any deformation within the Indian plate may in fact be localized in the vicinity of the Ninetyeast Ridge. This linear feature behaved as an active transform fault in the Cretaceous [e.g., McKenzie and Sclater, 1971; Schlich, 1975; Sclater et al., 1976b], and although it has been commonly considered to be quiescent during recent times, Stein and Okal [1978] have suggested that it is now the site of significant seismic and tectonic activity. The nature of this tectonic activity is undoubtedly complex, but Stein and Okal argue that the bottom morphology and seismic source mechanisms are consistent with northwest-southeast compression in the region, in agreement with the angular velocity vectors in Table 4. Vector A predicts a rate of deformation of about 1 cm/yr, computed at 15°N, 90°E. This rate is equivalent to a strain rate of 10-8/yr, if the deformation were distributed over a zone 1000 km wide, and is grossly compatible with the level of regional seismicity [Stein and Okal, 1978].

In summary, the hypothesis that deformation is occurring within the Indian plate suffices to resolve the difficulties encountered in fitting the instantaneous relative motion data. Although the nature of this deformation remains speculative, at least a partial localization of the deformation in the vicinity of the Ninetyeast Ridge is suggested by other observations. We note that if extension across the African rift zone is incorporated into the plate tectonic model, deformation within the Indian plate predicted by the model will be greater.

Predictions and Implications

Along plate boundaries where data are not available or where interpretation is hindered by geological complications, RM2 provides a useful basis for predictions and comparisons of global motions with local field evidence. We discuss here a few selected examples. In this discussion, prediction errors were calculated using the quadratic form described by Jordan [1975].

Central California. Because of possible bias associated with extension in the Basin and Range Province, data along the San Andreas fault system were not used in the inversion (Figure 1). In central California, RM2 predicts a rate of relative motion between the Pacific and North American plates of 5.6 ± 0.3 cm/yr, in a direction N35°W ± 2° (Table 5). On the basis of geological evidence, Hall and Sieh [1977] estimate a slip rate of 3.7 ± 0.3 cm/yr along the San Andreas in central California, averaged over three millennia, which agrees with Thatcher's...
where. Based on our earlier discussion of this hypothesis. Boundary and of Figure 7, we favor the second cant fraction of this motion is taken up elsewhere. Based on our earlier discussion of this boundary and of Figure 7, we favor the second hypothesis.

If one attributes the bulk of the discrepancy to deformation distributed within the Basin and Range province, then one must postulate a global extension of this province of about 2 cm/yr, in a direction N25øW. In contrast, Thompson and Burke [1973] estimate that the Basin and Range underwent 100 km of extension in N55øW direction during the last 15 m.y., equivalent to an average rate of 0.7 cm/yr. Their results are generally compatible with Davis and Burchfiel's [1973] suggestion that the Garlock fault is a major intracontinental transform, with a horizontal displacement rate subsequently evaluated by Clark and Lajoie [1974] at 0.7 cm/yr during Holocene time. Therefore, geological evidence indicates that Basin and Range extensional tectonics do not constitute a sufficient explanation of the discrepancy between RM2 and observations in central California. In particular, RM2 remains about 1.2 cm/yr faster than the estimated rate of slip on the San Andreas fault corrected for the contribution from the Basin and Range. An attractive hypothesis is that some of the PCFC-NOAM relative motion is accommodated on fault systems west of the San Andreas. For example, Weber and Lajoie [1977] conclude that right lateral slip has occurred along the San Gregorio fault zone during the last 200,000 years, with a rate ranging from 0.6 to 1.3 cm/yr. This observation appears to reconcile observed and calculated rates, but there does remain a slight azimuthal discrepancy, and such agreement might well be fortuitous.

Relative motion of North and South America. As argued above, relative motion between North and South America is required by our data set. Figure 5 and Table 2 indicate that the NOAM-SOAM vector is poorly constrained, and a wide range of possible relative velocities are allowed by the data. Very little direct evidence for this relative motion exists, and the movement could be distributed across a broad zone between, say, 10ø and 20øN. Since the relative velocities are predicted to be small, the deformation may be largely aseismic. However, some seismicity does exist. For example, a magnitude 6.2 earthquake occurred October 23, 1964, at 19.8øN, 56.1øW. The mechanism for this event is consistent with right lateral strike-slip motion in a direction N55øW [Molnar and Sykes, 1969; J. Dorel, personal communication, 1973], which does not disagree with the RM2 prediction of N71øW ± 5ø (Table 5). It is, however, inconsistent with the RM1 model, which predicts left lateral motion.

Southern boundary of the Caribbean plate. RM2 predicts a component of north-south convergence across the CARB-SOAM boundary. Although the rates are somewhat higher, the azimuths for CARB-SOAM motion are almost identical to those deduced by Jordan [1975] using the RM1 model. Consequently, Jordan's conclusions concerning motions along this boundary are substantiated by this study. They are also supported by Ladd's [1976] model of Tertiary plate motions. Direct evidence for north-south compressive motion has been obtained by Talwani et al. [1976] from an analysis of multichannel seismic reflection records from the south margin of the Venezuelan Basin and by Rial [1978] from a study of focal mechanisms in Columbia and Venezuela. No such compression is predicted by a model which assumes a single American plate. We take this to be an additional argument in favor of modeling NOAM and SOAM as two separate plates with a zone of decoupling between 10ø and 20øN.

Jordan's [1975] portrayal of the tectonic relationships in the Panama Basin is also compatible with RM2. The RM2 COCO-NACZ pole lies north of the equator, and the Panama transform fault, as mapped by Lonsdale and Klitgord [1978], closely approximates a small circle about this pole, even though it was not used in the inversion. Thus RM2 is consistent with the hypothesis that the Panama Basin east of this transform is not acting as a separate plate, as suggested by Molnar and Sykes [1969] and Lonsdale and Klitgord [1978], but in fact is part of the Nazca plate. Although RM2 predicts a slightly lower NACZ-CARB rate than RM1, the azimuths of relative motion are nearly identical (Table 5) and are consistent with the hypothesis that the motion is accommodated by a left lateral transform fault along the southern continental margin of Panama [Jordan, 1975].

Subduction of southern Chile. Seismic activity along the Chile trench decreases sharply south of the NACZ-ANTA-SOAM triple junction [Tarr, 1974]. Few earthquakes (only one with
Minster and Jordan: Present-Day Plate Motions

5347

mₚ ≥ 6) have been reported in this region between 1963 and 1975. The RM2 predicted convergence rate between ANTA and SOAM is only 2.1 ± 0.2 cm/yr (Table 5), 6.7 cm/yr less than the subduction velocity north of the triple junction and 30% lower than the RM1 prediction. Yet other convergence zones with comparable rates such as the West Indies Arc or the South Sandwich Trench are significantly more seismically active. If our model is correct, then subduction in southern Chile takes place largely aseismically, or this boundary constitutes an extensive seismic gap.

The Owen fracture zone. The Owen fracture zone represents the INDI-ARAB boundary [e.g., McKenzie and Sclater, 1971] and exhibits only weak seismicity. As shown in Table 5, RM2 does predict a low rate of relative motion between these two plates, but the predicted azimuths do not agree well with the observations. At 14°N, Laughton's [1970] bathymetric map indicates an azimuth of N30°E for the Owen fracture zone, compared with the model value of N55°E ± 14°; and at 22°N a fault plane solution by Sykes [1967] has a slip vector orientation of N50°E, versus a model value of N83°E ± 9°. Taken at face value, these data suggest that the INDI-ARAB pole should be translated to the northeast. Interestingly, the inversion with INDI separated into WIND and AUST, described above, yields an WIND-ARAB pole positioned 3° north of the RM2 pole. The azimuth calculated at 14°N, 59°E is N44°E, in better agreement with the observations, although the azimuth calculated at 22°N, 62°E is nearly identical to that for RM2.

Absolute Motions

The RM2 geohedron (Table 2 and Figure 2) completely describes the relative motion model. To specify an 'absolute' reference frame, we need only to choose an origin in angular velocity space. A particular frame of interest in discussions of plate dynamics is one fixed with respect to the average position of the deep mantle, assumed to be rigid or at least to have typical internal motions much slower than the motions of the plates; we refer to this frame as the mean mesospheric frame.

In paper 1 we constructed an absolute motion model based on the Wilson-Morgan fixed hot spot hypothesis and concluded that this hypothesis was consistent with the available instantaneous motion data. However, we noted the difficulties in estimating rates and directions of hot spot migration that are compatible with the short time intervals appropriate to the relative motion model, especially for hot spot traces on the slower plates. Because of these difficulties we are intrinsically limited in our ability to construct more refined tests of the Wilson-Morgan hypothesis and to discriminate among various instantaneous absolute motion models using hot spot data.

To investigate this limitation, we have derived an absolute motion model by again inverting hot spot data but restricting the data set to include only those constraints on hot spot migration pertinent to the last 10 m.y. This time span is really the minimum interval for which good hot spot data can be obtained, although it exceeds by over a factor of 3 the mean averaging interval for the spreading rate
### Table 7. Model AM1-2

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</tr>
<tr>
<td>AFRC</td>
<td>18.76</td>
<td>33.93</td>
</tr>
<tr>
<td>ANTA</td>
<td>21.85</td>
<td>91.81</td>
</tr>
<tr>
<td>ARAB</td>
<td>27.29</td>
<td>12.40</td>
</tr>
<tr>
<td>CARB</td>
<td>-42.80</td>
<td>39.20</td>
</tr>
<tr>
<td>COCO</td>
<td>21.89</td>
<td>3.08</td>
</tr>
<tr>
<td>EURA</td>
<td>19.23</td>
<td>6.96</td>
</tr>
<tr>
<td>INDI</td>
<td>47.99</td>
<td>9.36</td>
</tr>
<tr>
<td>NAZC</td>
<td>-58.31</td>
<td>15.21</td>
</tr>
<tr>
<td>NOAM</td>
<td>-61.66</td>
<td>5.11</td>
</tr>
<tr>
<td>SOAM</td>
<td>-82.28</td>
<td>19.27</td>
</tr>
</tbody>
</table>

Symbols and conventions are the same as in Table 2.

However, even supposing that the Wilson-Morgan hypothesis is valid, which we have not proved, with what precision can the motions of the plates in the mean mesospheric frame be predicted by the hot spot data? The answer to this question is indicated by the standard errors of estimation listed in Table 7. Although the absolute velocities of the fast moving oceanic plates (e.g., PCFC) have relative errors which are small, the relative errors for the slowly moving continental plates (e.g., EURA) are quite large and in some cases exceed 100%. Hence the absolute motion directions of several plates, particularly ANTA and EURA, are not usefully constrained by the hot spot data used in this experiment. For example, at the position of Iceland the motion of EURA with respect to the mean mesospheric frame is predicted by AM1-2 to be N83°W at 0.4 cm/yr, nearly diametrically opposed to the direction of the Wyville-Thompson Ridge, the presumed hot spot trace. But no significance should be assigned to this discrepancy, since the formal prediction errors (1σ) are ±162° and ±0.8 cm/yr, respectively, and since the actual azimuth of the Iceland hot spot trace over the last 10 m.y. is not really known (paper 1, p.566).

With these large uncertainties in mind it is interesting to compare the hot spot model with absolute motion models based on other criteria. Three such alternate models are listed in Table 8 (see also Figure 2). AM0-2 is the unique absolute motion model constructed by requiring that the lithosphere as a whole possess no net rotation, a criterion discussed and applied in paper 1 and by Liboutry [1974] and Solomon and Sleep [1974]. AM2-2 corresponds to Burke and Wilson's [1972] hypothesis that the African plate is stationary with respect to the mantle.
RM1 and RM2 are significantly different relative motion models in that RM1 lies well outside the possibility of a nonrigid hot spot geometry is allowed. Several authors have concluded that averaged over geologically long periods of time (>40 m.y.), hot spots have relative velocities with magnitudes of the order of 1 cm/yr [Morgan, 1972; Burke et al., 1973; Molnar and Atwater, 1973; Molnar and Francheteau, 1975]. In some sense our conservative assignment of large errors to the hot spot data in Table 6 may account for the uncertainties generated by small random motions among the hot spots, but appropriate caution in interpreting any hot spot model must be exercised until better data and more rigorous tests are available.

Nevertheless, several previously published conclusions regarding present-day absolute motions appear to be warranted; these are common to all of the models in Table 8: 1) Plate speeds correlate negatively with total continental area (paper 1). 2) Plate speeds correlate positively with the fraction of plate boundary being subducted [Jordan and Minster, 1974; Forsyth and Uyeda, 1975]. 3) Plate speeds correlate positively with macroscopic colatitude [Solomon et al., 1975]. Simple mechanical models have been formulated to explain the first two of these correlations [Forsyth and Uyeda, 1975; Solomon et al., 1975; Kaula, 1975], but their true dynamical significance is still quite speculative. For example, Solomon et al. [1977] have suggested that these aspects may have very little to do with dynamics; they argue that the absolute plate motions characteristic of Tertiary time exhibit none of the correlations stated above. Although we eye their reconstructions and modeling assumptions with some skepticism [cf., Jurdy, 1978], we agree that more refined tests of the mechanical models must be formulated.

Perspective
RM2 is a significantly better representation of present-day plate motions than RM1. In a recent parallel study, Chase [1978] has presented a global plate motion model generally quite similar to RM2. Some significant differences between these two models do exist, most being ascribable to differences in data selection and interpretation, but the overall agreement is encouraging. These studies should receive even more rigorous tests of the plate tectonic hypothesis. We continue to be impressed by how well the large data sets (330 members in Table 1) are described by simple models with very few parameters (30 for RM2).

We have noted, however, several problem areas where the plate model does not adequately fit the observations. These discrepancies deserve special scrutiny: they may be the manifesta-
cions of tectonic processes or other physical phenomena not now understood. For example, if our hypothesis that the Indian plate is not being driven rigidly is confirmed by better data in the Indian Ocean, then several questions must be addressed. How is the deformation distributed within the plate? What is the nature of the forces driving the deformation? Consider the hypothesis that the deformation is localized in the vicinity of the Ninetyeast Ridge: then a situation exists where on two opposing plates at approximately equal distances from their common boundary (a spreading center), there are two
north-south trending zones of deformation, one exten-
sional (the African rift) and one compres-
sional (the Ninetyeast Ridge). This unusual
configuration should provide a strong discrimi-
nant for force-balance models of the sort pro-
duced by Forsyth and Uyeda [1975], Solomon et
al. [1975], and Richardson et al. [1976]. Of
course, more data are required before this hy-
pothetical situation can be accepted as reality.
Throughout the bulk of this paper the problems of
continental tectonics have been carefully
avoided. It is clear that in most regions of
Intracontinental deformation, the plate model
has only limited utility. However, global plate
motions do provide the displacement boundary
conditions required to understand the kinematics
and dynamics of tectonics in complex regions
[e.g., Molnar and Tapponnier, 1975]. These com-
plex regions include not only the continental
interiors but also zones of deformation along
the continental margins [e.g., Jordan, 1975] and
even boundaries between the oceanic plates them-
selves. It is possibly complexities of this
latter type which are responsible for the dif-
ficulties that we experienced in obtaining clo-
sure about the Azores triple junction.
Unlike the relative motions the absolute mo-
tions of plates in the mean mesospheric frame
cannot be precisely constrained. Absolute mo-
tion models have been derived from a number of
kinematical hypotheses, and although they are
grossly similar, significant differences among
them do exist. In our opinion, model AM1-2
with its attendant uncertainties (Table 7) rep-
resents the most satisfactory description
available from the present observations. On the
basis of these absolute motions a number of
empirical correlations appear to be warranted,
but how these correlations relate to the funda-
mental forces driving the plates is only specu-

Appendix

In the interpretation of earthquake mechanisms
along subduction boundaries, most authors assume
that the direction of relative plate motion is
given by the horizontal projection of the slip
vector (e.g., paper I). If the convergence is
oblique to the trench axis, this procedure
yields a biased estimate of the direction of
relative motion. Instead, the slip vector should
be rotated into the horizontal plane, which re-
quires correcting the slip vector azimuth by an
amount $\alpha$ given by

$$
\alpha = \arccot \left( \frac{\cot(T_A - T_F)}{\sin P_F} \right) + T_F - T_A
$$

where $T_F$, $P_F$ and $T_A$, $P_A$ are the azimuth
and plunge of the poles of the fault plane and aux-
iliary plane, respectively.

This correction was applied to the data from
the Aleutian-Kuril, South American, and Tonga-
Kermadec trenches. The statistical information
is summarized below:

<table>
<thead>
<tr>
<th></th>
<th>$\alpha$</th>
<th>$\bar{\alpha}$</th>
<th>$\alpha_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOAM-PCFC</td>
<td>0.6°</td>
<td>0.3°</td>
<td>2°</td>
</tr>
<tr>
<td>NAZC-SOAM</td>
<td>0.9°</td>
<td>0°</td>
<td>2°</td>
</tr>
<tr>
<td>PCFC-INDI</td>
<td>1.1°</td>
<td>-0.9°</td>
<td>4°</td>
</tr>
</tbody>
</table>

This correction is clearly minor. Thus as was
pointed out by Chase [1978], omitting this cor-
rection does not give rise to a significant
systematic bias in the data.

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typscript. We thank our many colleagues who
allowed us to use their data in advance of pub-
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