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Statistical tests of additional plate boundaries from plate motion inversions

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We have investigated the application of the *F*-ratio test, a standard statistical technique, to the results of relative plate motion inversions. The method tests whether the improvement in fit of the model to the data resulting from the addition of another plate to the model is greater than that expected purely by chance. This approach appears to be useful in determining whether additional plate boundaries are justified. We confirm previous results favoring separate North American and South American plates with a boundary located between 30°N and the equator. Using Chase's global relative motion data, we show that in addition to separate West African and Somalian plates, separate West Indian and Australian plates, with a best-fitting boundary between 70°E and 90°E, can be resolved. These results are generally consistent with the observation that the Indian plate's internal deformation extends somewhat westward of the Ninetyeast Ridge. The relative motion pole is similar to Minster and Jordan's and predicts the NW-SE compression observed in earthquake mechanisms near the Ninetyeast Ridge.

1. Introduction

In the idealized framework of plate tectonics, the lithosphere is composed of a set of rigid plates and all deformation occurs at their boundaries. Since the confirmation of this model, deviations from the model have become a subject of active research. Such deviations, if localized, can be considered either plate boundaries with very slow relative motion, or zones of intraplate deformation. Three basic approaches have been used to identify such areas. Present-day deformation can be identified using earthquake seismology, heat flow, or other geophysical data. Alternatively, relative plate motion studies can establish the existence and nature of resolvable motions. Finally, the existence of a "fossil" boundary can be established from marine magnetic lineations, fracture zones, and paleomagnetic data: such regions sometimes continue to be active.

Examples of such deviations include rifting of the African continent, slow motion between North America and South America, and deformation of the lithosphere of the Central Indian Ocean, generally regarded as the type-example of oceanic intraplate deformation. The case for rifting of Africa is clear because the deformational zone (the rift valley) is easily identified both by morphology and seismicity [1]. Nonetheless, it has posed difficulties for some relative plate motion inversions [2].

The central Indian Ocean situation is more difficult to analyze, because the deformation is more diffuse. Previous studies have used all three approaches for identifying regions that deviate from the rigid plate model. The central Indian Ocean currently is the most seismically active area within the ocean basins [3–8]. Active deformation is also shown by anomalies in heat flow [9], gravity and bathymetry [10], and travel times [11]. Intraplate deformation has also been suggested by Minster and Jordan [2] from the present-day relative

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plate motions. Finally, the modern Indian plate is composed of several previously distinct plates [12–15] and seems to have preserved some weakness along the fossil boundaries.

For comparison, there is no clear seismically or bathymetrically defined boundary between the North and South American plates [16,17]. For this reason, and because no difference in motion with respect to Africa could be resolved, early models of recent plate motions treated the Americas as a single plate [18–21]. More recent studies, using more accurate data and more sophisticated inversion techniques, have been able to resolve motion between North America and South America [2,22,23]. Large displacements between North America and South America over the last 70 million years have also been shown by reconstructions using marine magnetics and fracture zones [24].

Several similar situations have been proposed, including a Caroline plate resolvable from the rest of the Pacific plate [25], and a Spitsbergen plate [26]. Microplates are also often included in analyses of complex continental regions [27,28].

Because of its importance to the detection of intraplate deformation and plate boundaries along which very slow motion occurs, our goal in this paper is to explore the use of relative plate motion data for such analyses. Specifically, we will address the question of when one is justified in assuming the presence of a plate boundary or significant intraplate deformation when a set of plate motion data are fit better by inferring a more complex plate geometry (e.g. separate West Indian and Australian, West African and Somalian, or North and South American plates). Although plate motion data do not precisely fit the underlying assumptions made when applying an *F*-ratio test, a standard statistical method, we found that with only minor modifications from conventional practice the test could be usefully applied to the results of relative motion inversions.

We examined these questions by using the compilations of relative motion data of Minster and Jordan [2] and Chase [23]. These two datasets differ in several ways. Chase [23] included data for the Philippine plate but not the Caribbean, whereas Minster and Jordan did the reverse. To facilitate comparisons, we excluded these two regions from the data. Since the two sets of data differ significantly after this exclusion, it is possible to test whether the Indian Ocean and Atlantic results depend on the dataset inverted. Chase [23] and Minster and Jordan [2] also used two different inversion algorithms; we tested for the effect of the inversion method by inverting both sets of data with the same algorithm, that of Minster et al. [22].

2. *F* test

The *F* test is the standard statistical test used to compare variances of distributions. We used a form of the test that compares how well two different models fit a set of data, the models differing only in that one model has fewer parameters generated from the data than the other. The test is formulated in terms of χ^2, which measures the sum of the squares of the differences between a datum, d_i^0, and model prediction, d_i^m, normalized by the variance, σ_i^2:

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

If a set of N data are fit by two models, one with r parameters ($N - r$ degrees of freedom), and a second with p parameters ($N - p$ degrees of freedom), with p greater than r, the second model should fit the data better, and $\chi^2(p)$ should be less than $\chi^2(r)$. To test if the reduction in χ^2 is any greater than would be expected simply because additional model parameters were added, the statistic:

$$F = \frac{\left[\chi^2(r) - \chi^2(p)\right]/(p-r)}{\chi^2(p)/(N-p)}$$

[29] is used. (The denominator is just the reduced χ^2, χ_ν^2, defined as the ratio of χ^2 to the number of degrees of freedom, $\nu = (N-p)$.) This statistic is F distributed with $\nu_1 = (p-r)$ and $\nu_2 = (N-p)$ degrees of freedom. The test examines the probability $P_F(F, \nu_1, \nu_2)$ of observing an F value greater than the observed value F for a random sample with ν_1 and ν_2 degrees of freedom. Thus, for example, if P_F is 0.01, there is only a 1% risk that the improvement in fit is due purely to chance.

In our application we want to know whether the fit to N relative motion data produced by a model with $p+1$ plates is significantly improved relative to a model with p plates. The p plate model has $3(p-1)$ parameters ($N-3p+3$ degrees of freedom) while the $p+1$ plate model has $3p$ parameters ($N-3p$ degrees of freedom) so the statistic F:

$$F=\frac{\left[\chi^2(p\text{ plates})-\chi^2(p+1\text{ plates})\right]/3}{\chi^2(p+1\text{ plates})/(N-3p)}$$

is tested using $P_F(F, \nu_1, \nu_2)$ with $\nu_1=3$, $\nu_2=N-3p$. This is easily done using values from Table 1 (adapted from Dixon and Massey [30]) which gives values of F, $F_{0.01}$ and $F_{0.05}$, corresponding to $P_F(F, \nu_1, \nu_2)$ for probabilities of 0.01 and 0.05.

Plate motion models do not always fit this model because the choosing of additional parameters is generally dependent on the data set or residuals from simpler models, contrary to the underlying statistical assumptions. One would thus expect the results of F tests to be biased toward resolving spurious plates. Fortunately, as discussed later, we found the test to be of practical use when a stringent maximum confidence level of 99%, rather than the more commonplace 95%, was used. Plate motion studies fit the assumptions of the F test model best when the location of a possible boundary is suggested not by the plate motion data but by independent data, such as the high seismicity of the Indian Ocean.

Before using the F test to draw any conclusions in complex situations, we tested the method for idealized cases using synthetic data and for well-understood unambiguous geometries. The two synthetic data tests were chosen to simulate two of the simpler tests conducted with real data. In the first test, we generated error-free synthetic values for Pacific–Antarctic relative motion data using locations and data types (rate, slip vector or transform azimuth) corresponding to the Minster and Jordan data. We then generated 200 synthetic sets of data, simulating the effect of noise by adding Gaussian errors with the standard deviations assigned by Minster and Jordan [2] to the error-free synthetic data. The synthetic sets of data were inverted, first for a two-plate model including the Antarctic and Pacific plates, and then for a three-plate model in which the Pacific plate is divided into two plates along the Eltanin Fracture Zone (a hypothetical boundary location discussed later). Fig. 1A shows a histogram of the values of $F(\nu_2=25)$ resulting from comparison of the two- and three-plate inversion results for each of the 200 cases. Only 11 and

TABLE 1

Values for F test, $\nu_1=3$

ν_2	$F_{0.05}$	$F_{0.01}$
10	3.71	6.55
20	3.1	4.94
25	2.99	4.68
30	2.92	4.51
40	2.84	4.31
60	2.76	4.13
120	2.68	3.95
∞	2.60	3.78

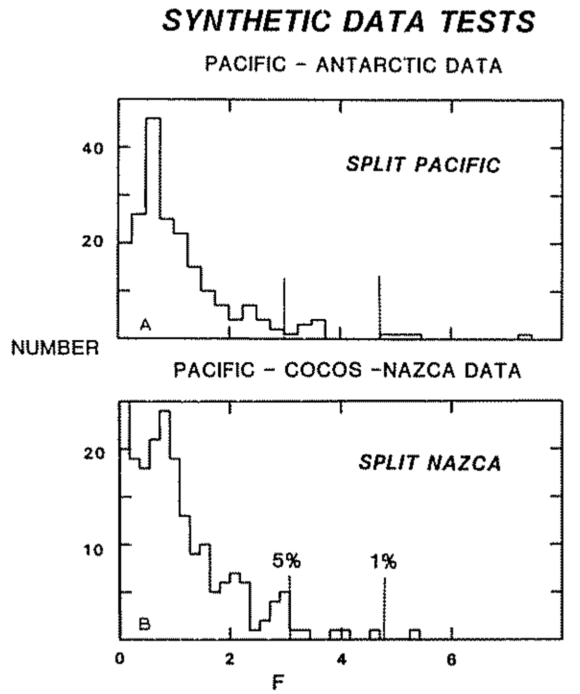

Fig. 1. F values comparing inversions of synthetic data with Gaussian errors for an hypothetical additional plate. A. Pacific–Antarctic synthetic data inverted with both undivided and divided Pacific plates. B. Pacific–Cocos–Nazca synthetic data (excluding Nazca–Cocos boundary) inverted with both undivided and divided Nazca plates.

4 of the F values are greater than would be expected for 5% and 1%, respectively, by chance. Fig. 1B shows similar results for a similar numerical experiment, conducted on data from the Pacific–Cocos–Nazca plate system using only data along the East Pacific Rise (in other words, excluding all data for the Cocos–Nazca spreading center). Here $F(\nu_2 = 22)$ measures how much the fit is improved by arbitrarily splitting the Nazca plate into two plates (at 18°S). Again, the number of cases which pass the F test at the 5% and 1% levels, 6 and 2 respectively, is approximately that expected. These numbers are close enough to the predicted incidence for 200 trials that the use of the F test seems warranted.

We also conducted tests on the actual data for simple cases. We took three plates that meet at a triple junction, and tested our ability to resolve the presence of all three plates without using data from one boundary. In these cases the data used were taken from Minster and Jordan [2], except where otherwise specified, and the Minster et al. [22] inversion algorithm was used. Table 2 shows the results of several such tests. For example, we studied the Pacific–Cocos–Nazca plate system using only data along the East Pacific Rise (in other words, excluding all data for the Cocos–Nazca spreading center). First, we inverted the data treating the Cocos and Nazca plates as a single plate, and obtained a relative motion model with $\nu = 28$, $\chi^2 = 44.8$ and $\chi^2_\nu = 1.6$ (Table 2). A second inversion, treating Cocos and Nazca as separate plates ($\nu = 25$) yielded $\chi^2 = 5.15$ and $\chi^2_\nu = 0.21$. The three-plate model is clearly better because both χ^2 and χ^2_ν are dramatically reduced. This is confirmed formally by the F test: $F = 64.2$ is much greater than the value of $F_{0.01}$, 4.7, for $\nu_1 = 3$, $\nu_2 = 25$ (Table 1). (In all tables, F is the result of the F test relative to the model in the preceding row unless otherwise indicated.) Next, we split the Nazca plate into two plates (divided at 18°S), and inverted the data as a four-plate system. The four plates fit the data better, since $\chi^2 = 3.6$ and $\chi^2_\nu = 0.16$. The F test suggests that this improved fit may not indicate that a fourth plate is really present: the fit corresponds to $F = 3.2$, which is not significant at the 99% level, because $F_{0.01} = 4.68$, although it is significant at the 95% level, as $F_{0.05} = 2.99$. We suspected the large F value might result from two Nazca–Pacific

TABLE 2

Three plate system tests

	Number of plates	Number of data	χ^2	χ^2_ν	ν	F
Pacific–Cocos–Nazca (no Nazca–Cocos data)						
Combine Cocos and Nazca	2	31	44.8	1.6	28	
Correct boundaries	3	31	5.2	0.21	25	64.2
Split Nazca at 18°S	4	31	3.6	0.16	22	3.2
Wrong CO-NZ boundary (18°S)	3	31	39.0	1.56	25	
Pacific–Cocos–Nazca (no Pacific–Cocos data)						
Combine Pacific and Cocos	2	34	1780.8	57.44	31	
Correct boundaries	3	34	10.3	0.37	28	1598.1
Split Pacific at 10°S	4	34	9.6	0.38	25	0.6
Wrong PA-CO boundary (10°S)	3	34	1241.2	44.33	28	
Pacific–Nazca–Antarctica (no Nazca–Antarctica data)						
Combine Nazca and Antarctica	2	51	242.2	5.05	48	
Correct boundaries	3	51	17.5	0.39	45	192.6
Split Antarctica at 140°W	4	51	15.8	0.38	42	1.5
Wrong NZ-AN boundary (15°S)	3	51	156.5	3.48	45	
Wrong NZ-AN boundary (140°W)	3	51	256.5	5.70	45	

data that are actually on the Easter plate boundary [31–35], but the results changed insignificantly if these data were deleted.

This simple test, for an ideal geometry, is very encouraging: the test finds that two plates known to be distinct are so, and rejects the addition of a spurious plate. It appears that the existence of a separate plate should be inferred using this method only if the F test indicates there is less than a 1% chance that the improvement in the fit would occur at random. To test one location of a hypothetical boundary, the 5% risk level would probably be useful since there is only a one in twenty chance of concluding that a spurious boundary was present. This risk level, however, is inadequate for testing several locations. For example, in testing five hypothetical boundaries there is roughly a one in four chance of concluding that one of the five was an additional boundary when it was not. The one in four chance seems too high. By using the more stringent 1% risk level there is only a one in twenty chance of making this error.

Table 2 also shows results for a different experiment, in which this three-plate system is inverted using an incorrect location for the Cocos–Nazca spreading center (18°S). Not surprisingly, χ^2 is much greater than for the correct location. In some cases, searching for a minimum in χ^2 may be a useful method of locating a poorly defined boundary.

For additional tests, we determined relative motions for the same three plates, by carrying out inversions that included the Cocos–Nazca boundary data but excluded all Pacific–Cocos data. As before, the three plate geometry is a much better fit to the data than a geometry in which the Pacific and Cocos plates are combined, and addition of a spurious fourth plate produces a better fit which the F test indicates is insignificant (Table 2). Moving a plate boundary to an incorrect location again dramatically increases χ^2. Table 2 also shows a set of tests for the Pacific–Antarctica–Nazca system, with similar results.

The criterion used [2,22,23] to resolve the existence of two distinct plates from the results of a relative motion inversion is that the error ellipses associated with their relative motion poles do not overlap. We found that for all practical purposes this criterion is comparable to using the F test, but it is possible that the F test will be superior in some cases. One such case (Table 3) is the Pacific–Antarctica system. Paleomagnetic studies [36,37] have documented relative motion between the North Pacific and South Pacific plates since 80 million years ago, and suggest that some of this motion may have occurred during the Cenozoic. One location that has been proposed for this fossil boundary is along the Eltanin Fracture Zone trace, along which unusual seismicity now occurs [38]. Its possible role as a former plate boundary makes it

TABLE 3

Two Pacific plates

	Number of plates	Number of data	χ^2	χ^2_ν	ν	F
Pacific – Antarctica data						
Single Pacific plate	2	31	13.0	0.47	28	
Separate North and South Pacific	3	31	11.4	0.46	25	1.2
Global inversion						
Single Pacific plate	10	315	107.8	0.374	288	
Separate North and South Pacific	11	315	106.7	0.374	285	1.0
Global Inversion — Chase data						
Single Pacific plate	11	242	73.6	0.35	212	
Separate North and South Pacific	12	242	70.7	0.34	209	2.9

a candidate for testing whether it may currently be a slowly moving, difficult to detect plate boundary.

To examine this possibility, we modeled the Pacific plate as separate North Pacific and South Pacific plates, divided along the Eltanin Fracture Zone, and compared the results of this inversion to the results for a single Pacific plate. The F test indicates that the improved fit from using two Pacific plates is insignificant, even though the error ellipses for the North Pacific–Antarctica and South Pacific–Antarctica poles do not overlap. This appears to be a result of the assigned errors σ_i, which control the size of the error ellipses but have little effect on F since F is a ratio of the χ^2 values. In other words, doubling the assigned errors would not change F, but would cause the error ellipses to overlap. We found, as discussed later, that the deliberately conservative error estimates [22] used by Minster and Jordan [2] and Chase [23] generally ensure that conclusions drawn from error ellipses and F are comparable. For example, we also examined the hypothesis of two Pacific plates by inverting all of Minster and Jordan's [2] data for models with and without separate North and South Pacific plates. The results (Table 3) again indicate that the two plates are unresolvable: the error ellipses also overlap in this case. Finally, we conducted the same experiment using the Chase [23] global dataset, which includes no India–Pacific data and thus might yield a different result. Here the separate Pacific plates are not significantly different at the 99% level, but differ at the 95% level, as for a spurious plate in the Cocos–Nazca–Pacific system.

3. North and South America

Because the North America–South America plate boundary is unidentifiable from seismicity or bathymetry, the case for present-day distinct plates rests only on the results of plate motion studies [2,22,23], although the two plates were in relative motion in the past [24]. We used the F test to examine this question, and explored several alternatives.

One alternative, suggested to us by N. Sleep (personal communication, 1982), is that the known difficulties in fitting relative motions along the Mid-Atlantic Ridge near the Azores [2] result because the Azores region is not part of the African plate. In this case, the misfit of models to the FAMOUS area data would cause an apparent relative motion between North and South America. This could occur in two ways: either the Azores region is sufficiently rigid that it should be treated as a separate plate, or it is deforming internally and should be excluded from the African plate even if it cannot properly regarded as a plate. This model may also explain the significant differences found between the North America–Africa pole determined by fitting only data on that boundary and between the North America–Africa pole determined when data for the entire globe were inverted [2]. Alternatively, the apparent North America–South America motion may result from the propagation of errors in the global model, possibly due to the internal deformation of the Indian plate. Finally, the relative motion between the Americas might be an artifact of some noisy data used in the inversion.

To examine the possibilities, we conducted a set of numerical experiments listed in Table 4. First, we used Minster and Jordan's global data (exclusive of the Caribbean plate), and inverted the data first with one American plate and then with two. The reduction in χ^2_ν and the large value of F show that the model of separate North and South American plates is superior to a model in which they are assumed to be a single plate.

Next, we grouped the data from the African plate west of 22°W and north of 35°N into an hypothetical Azores plate, and inverted the global data using this 12-plate model. χ^2_ν is reduced; the F test shows that this result is at the threshold of being significant. (Recall that, based on our experiments with adding spurious plates, we use the 99% level as the minimum acceptable.) We also inverted the data using an 11-plate model in which the Americas were combined but the hypothetical Azores plate was divided from the African plate. We found that dividing the Americas into two separate plates while keeping the Azores as part of the African plate yielded a significantly better fit to the data than modeling the Americas as a single

TABLE 4

North and South American plates

	Number of plates	Number of data	χ^2	χ^2_ν	ν	F
Global data						
MJ (combined Americas)	9	315	177.1	0.61	291	
MJ (separate Americas)	10	315	107.8	0.37	288	61.7
MJ (separate Americas, Azores)	11	315	103.5	0.36	285	3.9
MJ (combined Americas, Azores)	10	315	123.9	0.43	288	41.2 *
CC (combined Americas)	10	242	100.0	0.46	215	
CC (separate Americas)	11	242	73.6	0.35	212	25.3
North America – South America – Africa – Europe data						
MJ (combined Americas)	3	66	81.5	1.36	60	
MJ (separate Americas)	4	66	17.3	0.30	57	70.5
MJ (separate Americas, Azores)	5	66	14.8	0.27	54	3.0
MJ (combined Americas, Azores)	4	66	22.6	0.41	57	49.5 *
CC (combined Americas)	3	54	41.4	0.86	48	
CC (combined Americas)	4	54	18.8	0.42	45	18.0
Azores region excluded						
MJ (combined Americas)	3	57	21.7	0.42	51	
MJ (separate Americas)	4	57	13.6	0.28	48	9.5
North America – South America – Africa data						
MJ (combined Americas)	2	40	12.0	0.32	37	
MJ (separate Americas)	3	40	8.7	0.24	34	4.3
Different locations for North America – South America boundary						
MJ (boundary 30 ° N)	4	66	21.3	0.37	57	
MJ (boundary 25 ° N)	4	66	20.3	0.36	57	
MJ (boundary 15 ° N)	4	66	17.3	0.30	57	
MJ (boundary 10 ° N)	4	66	17.8	0.30	57	
MJ (boundary 5 ° N)	4	66	17.1	0.30	57	
MJ (boundary 0 °)	4	66	17.2	0.30	57	
MJ (boundary 5 ° S)	4	66	77.0	1.35	57	
MJ (boundary 15 ° S)	4	66	78.1	1.37	57	
CC (boundary 31 ° N)	4	54	26.7	0.59	45	
CC (boundary 25 ° N)	4	54	19.0	0.42	45	
CC (boundary 15 ° N)	4	54	18.8	0.42	45	
CC (boundary 10 ° N)	4	54	20.1	0.45	45	
CC (boundary 0 °)	4	54	20.3	0.45	45	
CC (boundary 10 ° S)	4	54	26.8	0.60	45	
CC (boundary 31 ° S)	4	54	40.4	0.90	45	

MJ is Minster and Jordan [2] data; CC is Chase [23] data.

* Denotes F test relative to third preceding line.

plate while assuming that the hypothetical Azores plate was distinct from the African plate.

For comparison, we performed similar experiments using Chase's [23] global dataset (exclusive of the Philippine plate). Comparison of a 10-plate model, with the Americas combined, to an 11-plate model with separate Americas also yields an improvement that F indicates is real. (The number of plates differs from the Minster and Jordan [2] models because Chase [23] divides the African plate into two plates: a western African plate and an eastern Somalian plate.) We could not perform Azores plate tests on the Chase [23] data because this data includes only one point in the "Azores plate" region.

To see whether these results are caused by errors propagating from data from the rest of the globe, we also examined inversions based only on the data from the Atlantic plates (North America, South America, Europe, and Africa) and found very similar results. Table 4 shows that the two Americas can be easily resolved; the Azores plate again is almost significant (at the 95% level, but not at the 99% level). The Chase [23] data for the same plates also shows resolvable North and South America plates. In fact, the two Americas remain resolvable both if all the Azores data are excluded from the inversion or if only data south of the Azores triple junction (i.e. a North America–South America–Africa system) are inverted (Table 4). These results are summarized by Fig. 2.

Having found that the distinction between North and South America was robust in our inversions, we tested various locations for the boundary. Table 4 and Fig. 3 show that for both

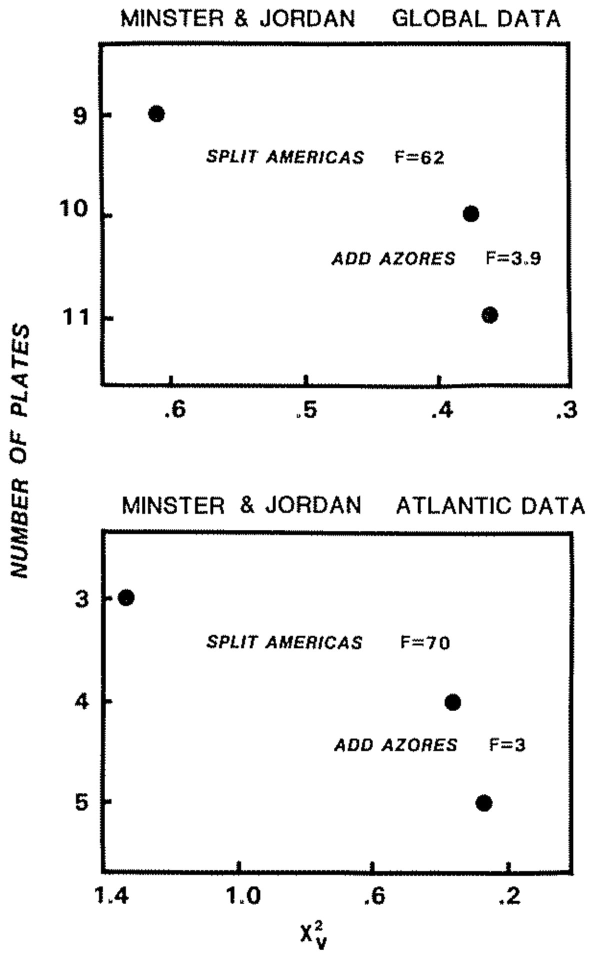

Fig. 2. Summary of results for separate North and South American plates and a possible Azores plate. The separate Americas are clearly resolvable: the Azores plate is just below the threshold of significance

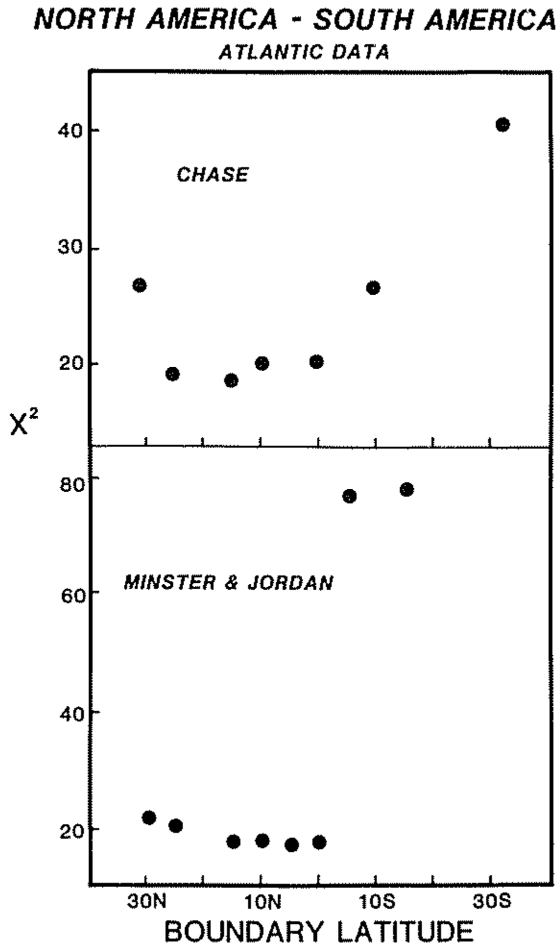

Fig. 3. χ^2 values for inversion of Atlantic relative motion data using different locations of the North America–South America boundary

Chase's [23] and Minster and Jordan's [2] data, a location near 15°N used in their studies gives the minimum χ^2. J.B. Minster (personal communication) pointed out that this is how the boundary location was chosen. This location can be established only imprecisely because the minimum in χ^2 is fairly broad. The data are sparse: neither dataset contains rate data between 21°N and 5°S. The differences in fit between adjacent trial boundary locations result from one or two azimuthal data. Given the noise in the data, we interpret the result as suggesting that the best choice for the boundary location is between 25°N and the equator. This is consistent with previous studies suggesting a location between 15°N and 23°N from transform orientations [39], and near 13°N from ridge crest topography [40]. The boundary, of course, can be either sharp or a diffuse zone. These questions can only be resolved by additional data.

4. Indian Ocean system

The plate motion data and geometry for the Indian and African plates is substantially more complicated than in the Atlantic. The region is known to be deforming internally in at least two major regions. Active extension is occurring at the African rift valley, and significant intraplate deformation within the Indian plate is suggested by seismicity and other geophysical data.

Chase [23] treated the Indian plate as a single rigid plate, and modeled the African rifting by the motion between a Somalian (East African) plate and a (West) African plate. The Somalian plate is, therefore, bounded on the west by the African rift valleys and bounded on the east by the Central Indian ridge, its boundary with the Indian plate. Minster and Jordan [2] pointed out that the relative motion data were fit badly, as indicated by the misclosure of the Indian Ocean triple junction, and modeled the Indian plate's internal deformation by separate Australian and West Indian plates. They also considered a separate Somalian plate, but found that this model predicted compression rather than extension at the African rift valley.

We attempted to understand this complex problem by investigating several questions. First, we examined whether the differences between the results of Chase [23] and Minster and Jordan [2] for Africa–Somalia motion are due to the data that were inverted or the methods of inversion used. We inverted the Chase [23] data using the Minster et al. [22] algorithm, and found an SO-AF pole at 72°N, 35°E, much closer to Chase's [23] pole (71°N, 35°E) than to the Minster and Jordan [2] pole (43°S, 48°E). It thus appears that the different inversion methods are not the cause of the discrepancy.

Next, we examined the effect of the different datasets by determining Somalia–Africa (SO-AF) motion after replacing Minster and Jordan's [2] Arabian data with Chase's, but otherwise using Minster and Jordan's data for all other plate pairs. As noted in the two previous studies, the location of the Somalia–Africa–Antarctica triple junction (on the Southwest Indian Ridge) must be assumed. We obtained SO-AF poles at 66°N, 162°E and 27°N, 161°E for SO-AF-AN triple junctions at 51°S, 29°E and 44.5°S, 40°E respectively. These poles, like Chase's predict extension across the rift valley. Thus, the differences in relative motion along the East African rift between the Chase [23] and Minster and Jordan [2] models can be explained by the data used for Arabia, as suggested by Minster and Jordan [2].

Next, we attempted to use the F test to compare the relative significance of the internal deformation of the Indian and African plates. We used the Chase [23] dataset, in which the location of the SO-AF boundary was implicitly fixed, since all data east of 40°E on the Southwest Indian Ridge was deleted. The Indian plate deformation was modeled by splitting the Indian plate into West Indian (WI) and Australian (AU) plates, as was done by Minster and Jordan [2]. It is unclear where the boundary should be placed, or whether the deformation is too diffuse to be modeled by such a method.

The results are shown in Table 5 and Fig. 4. As noted by Chase [23], a model with an undivided Indian plate but separate West African and Somalian plates fits the data significantly better than a model with an undivided African plate. Alternatively, models with separate West Indian and Australian plates and an undivided African

TABLE 5

Indian and African plate deformation

	Number of plates	Number of data	χ^2	χ^2_ν	ν	F
Chase global dataset						
Combined Americas, AF-SO, IN	9	242	108.6	0.50	218	
Combined AF-SO, combined IN	10	242	81.9	0.38	215	23.4
Separate AF-SO, combined IN	11	242	73.6	0.35	212	8.0 *
Combined AF-SO, WI-AU 71° E	11	242	74.8	0.35	212	6.7 *
Combined AF-SO, WI-AU 75° E	11	242	76.0	0.36	212	5.8 *
Combined AF-SO, WI-AU 80° E	11	242	75.8	0.36	212	5.7 *
Combined AF-SO, WI-AU 91° E	11	242	76.4	0.36	212	5.1 *
Combined AF-SO, WI-AU 115° E	11	242	76.5	0.36	212	5.0 *
Combined AF-SO, WI-AU 145° E	11	242	81.2	0.38	212	0.6 *
Separate AF-SO, WI-AU 71° E	12	242	63.0	0.30	209	11.7 **
Separate AF-SO, WI-AU 75° E	12	242	62.9	0.30	209	12.0 **
Separate AF-SO, WI-AU 80° E	12	242	62.8	0.30	209	12.0 **
Separate AF-SO, WI-AU 91° E	12	242	64.0	0.31	209	10.4 **
Separate AF-SO, WI-AU 98° E	12	242	64.3	0.31	209	10.1 **
Separate AF-SO, WI-AU 115° E	12	242	64.6	0.31	209	9.7 **
Separate AF-SO, WI-AU 124° E	12	242	68.8	0.33	209	6.7 **
Separate AF-SO, WI-AU 145° E	12	242	71.9	0.34	209	1.6 **

All models but first have separate North and South Americas.

* F test relative to separate Americas, combined AF-SO, combined IN

** F test relative to separate Americas, separate AF-SO, combined IN.

plate also reduce χ^2 but not as much as the model with separate Somalian and West African plates, regardless of the location of the boundary between the West Indian and Australian plates. Thus, any attempt to determine the location of the West

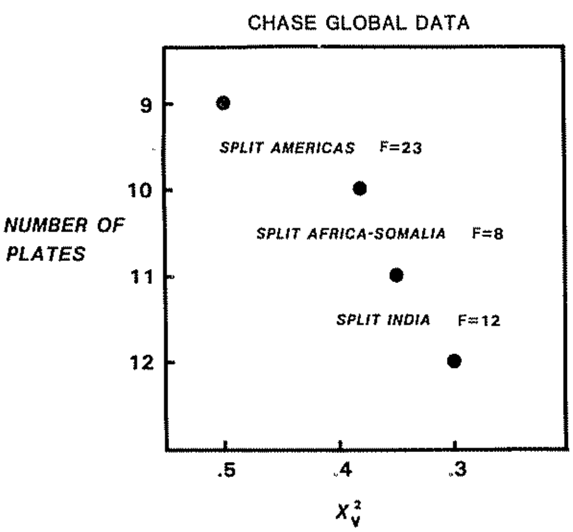

Fig. 4. Summary of results for splitting the Indian and African plates. In addition to separate West African and Somalian plates, separate West Indian and Australian plates can be resolved.

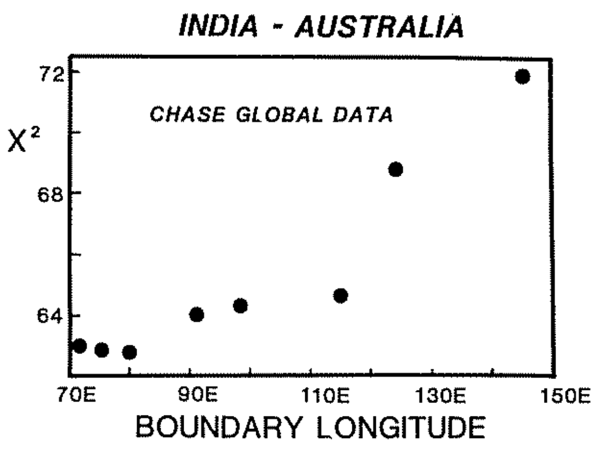

Fig. 5. χ^2 values for inversion of Chase [23] global relative motion data using different locations of the West India–Australia boundary. The model contained separate African and Somalian plates.

Indian–Australian plate boundary should probably use a model including a Somalian plate.

For models including a separate Somalian plate, the minimum value of χ^2 occurs when the West India–Australia boundary is placed at 80°E (Fig. 5). As the data are sparse, the minimum is broad and the location is imprecise. However, the result is generally consistent with the observation that the Indian plate's internal deformation extends somewhat westward of the Ninetyeast Ridge [3–11], at least in the northern portions of the plate. The AU-WI pole (52°S, 27°E) is similar to Minster and Jordan's [2] and predicts the NW-SE compression observed in earthquake mechanisms near the Ninetyeast Ridge [4]. As for North America–South America relative motion, conclusive resolution of such a subtle boundary will require more data than currently available.

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