Reports

Central North Atlantic Plate Motions over the Last 40 Million Years

Abstract. *The relative motion vector for the North American and African plates has been determined from detailed charting of the trend of the Atlantis fracture zone for over 1000 kilometers in the central North Atlantic near 30°N and from identification of marine magnetic anomalies and deep-sea drilling results. The vector (pole) is located at 52.5°N, 34°W and has a magnitude (opening rate) of* 5.7×10^{-7} *degree per year. Major changes in either the pole location or the opening rate are not evident for the last 40 million years.*

Plate tectonics is now firmly established as a basis for describing the relative horizontal motions of large portions of the earth's crust (*1–3*). Studies of these motions essentially involve determinations of the magnitude (opening rate) and direction (pole location) of the relative rotation vector between crustal plates. A great deal of effort is currently being expended to obtain precise information about the plate movements. The Cenozoic history of the relative motion of the North American and African plates, which join along the Mid-Atlantic Ridge crest between the Azores-Gibraltar lineation and the equator, has recently been much discussed (*1, 2, 4–9*). Many authors have hypothesized that changes occurred during this time period in either the magnitude or direction of the relative motion for these plates (see Table 1). Changes in the rate have previously been predicated on circumstantial evidence rather than on actual dating of the oceanic crust. In contrast, recent deep-sea drilling results and sea-floor spreading interpretations (*10*) of magnetic anomalies across the ridge strongly suggest that the rate of motion may have been relatively constant in this region for the entire Cenozoic (*8, 9*). Changes in the vector direction are based on evidence from the two fracture zone surveys of van Andel *et al.* and Fox *et al.* (*6, 7*) at 11° and 24°N, respectively.

To examine further the Cenozoic history of the relative rotation vector for North America and Africa, we have recently conducted two bathymetric and magnetic surveys aboard the R.V. *Chain* (cruises 96 and 99) over the Atlantis fracture zone near 30°N on the Mid-Atlantic Ridge crest. The survey coverage of *Chain* cruise 96 together with previous *Chain* profiles extends about 1000 km across the ridge crest from 48° to 36°W (see Fig. 1). The bathymetric expression of the fracture zone (Fig. 2) is typical of other fractures in the North Atlantic (*11*). The fracture can be easily identified by its steep sides and extreme relief and by the flat sedimented floor at a distance of a few tens of kilometers from the ridge crest. Profiles over the transform segment of the fracture zone between the offset crests of the Mid-Atlantic Ridge show very extreme relief relative to other crossings of the fracture zone (Fig. 2, profiles 18, 19, 20). The deduced trend of the Atlantis fracture zone is shown in Fig. 1. It appears to be uniformly curvilinear with no major changes in trend. However, the low angles at which our tracks cross the fracture at the extremity of the survey area do not allow us to completely rule out minor changes here. Far more extensive coverage recently completed aboard *Chain* cruise 99 supports the general trend shown in Fig. 1.

Magnetic profiles in the vicinity of the Atlantis fracture were obtained on several Woods Hole cruises (Figs. 1 and 3). The *Chain* 43 profile has been projected normal to the ridge axis. These profiles are compared with a simulated profile of sea-floor spreading that has been generated with a spreading rate of 1.3 cm per year (*12*). Although these profiles are essentially parallel to the Atlantis fracture zone, changes in the spreading rate implied by our suggested correlations cannot be definitely established unless all profiles are projected precisely parallel to the fracture zone. However, it is possible that the spreading rate may have been a few tenths of a centimeter per year higher prior to approximately 10 million years ago (anomaly 5). We recognize that our proposed correlations are not entirely convincing, but we believe them to be significant, particularly in view of the recent deep-sea drilling determinations of the sea-floor age here (*8, 9*). These ages suggest a rather uniform spreading rate of 1 to 1.4 cm per year during Tertiary time. The "stretched" or "compressed" appearance of several of the magnetic profiles may re-

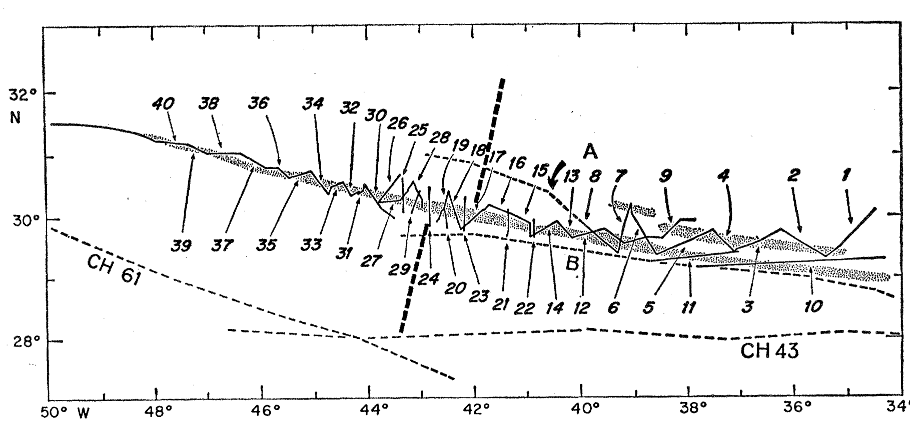

Fig. 1. Index map showing the location of bathymetric (solid) and magnetic (dashed) profiles. The interpreted trend of the Atlantis fracture zone in the Mid-Atlantic Ridge crestal region is indicated by the shading. The bold broken line indicates the ridge axis offset. Magnetic profiles *A* and *B* were made during *Chain* cruise 96. Magnetic profiles *CH43* and *CH61* are from *Chain* cruises 43 and 61, respectively.

Table 1. Comparison by authors of various histories of the opening of the central North Atlantic (below 37°N) for the Cenozoic. Comparison is made on the basis of stated or inferred parameters of the relative motion vector (magnitude, direction) of the North American and African plates. See Fig. 4 for plate boundaries. Million years, m.y.

Authors and references	Source area in Atlantic	Period of time	Pole location	Rate
Ewing and Ewing; Schneider and Vogt (*4*)	North	Before 40 or 50 m.y. ago 40 or 50 to 10 m.y. ago 10 m.y. ago to present	Unspecified Unspecified Unspecified	Slow* Zero Slow*
Phillips (*5*)	Central North (27° and 22°N)	10 to 6 m.y. ago 6 m.y. ago to present	Unspecified Unspecified	1.65 cm/yr† 1.25 cm/yr†
Le Pichon (*1*)	South and equatorial	Paleocene to early Miocene Middle Miocene Late Miocene to present	58°N, 37°W 58°N, 37°W	Slow Zero 3.7×10^{-7} deg/yr
Morgan (*2*)	South and equatorial	Present	58°N, 36°W	3.9×10^{-7} deg/yr
Fox *et al.* (*7*)	Central North (24°N)	Before 9 m.y. ago 9 m.y. ago to present	67.6°N, 16°W 58°N, 37°W	Slow* Slow*
Van Andel *et al.* (*6*)	Equatorial (11°N)	Before 10 m.y. ago 10 m.y. ago to present	Unspecified West of previous one	Slow* 1.4 cm/yr†
Peterson *et al.* (*9*)	Central North	120 to 20 m.y. ago	Unspecified	1.4 cm/yr†
Talwani *et al.* (*8*)	Central North (20°–37°N)	70 m.y. ago to present	Unspecified	1.4 cm/yr†

* Half-rate of less than about 3 cm/yr. † Half-rate.

sult from their having crossed minor fracture zones; for example, the *Chain* 43 profile probably crossed a fracture between anomaly 7 and 13. In any event the rate of 1.3 cm per year measured here for the last 38 million years [the age of anomaly 13; see (*10*)] agrees well with a previously measured rate of 1.25 cm per year, active for the last 10 million years at 27°N (*5*). It also agrees with the rate of 1.5 cm per year determined by Talwani *et al.* (*8*) from magnetic anomalies for the last 70 million years and with the rate of 1.4 cm per year between 120 and 20 million years ago determined by deep-sea drilling [see (*8, 9*) and Table 1]. These findings of a relatively constant rate for about the last 40 million years or more are in conflict with the suggestion by a number of authors [see (*1, 2, 4–9*) and Table 1] that a major hiatus in spreading occurred during this period. We believe that the drilling re-

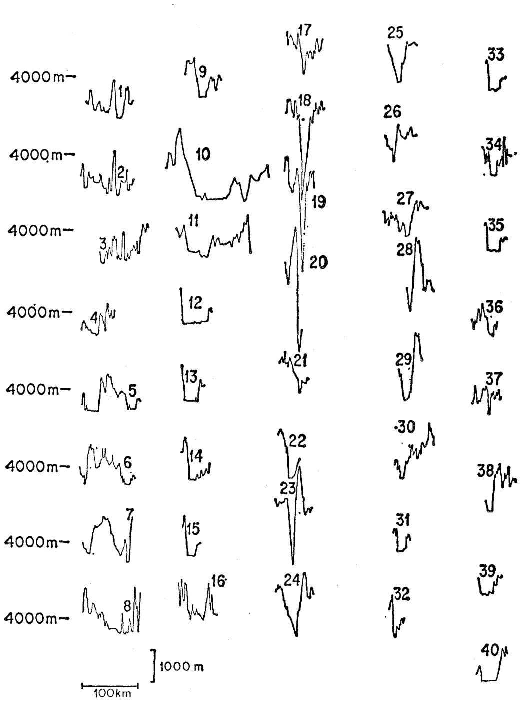

Fig. 2. Bathymetric profiles across the Atlantis fracture zone. Depth are in uncorrected meters. Vertical exaggeration is 40 : 1. Profiles are numbered approximately successively from east to west. The southerly end of each profile is to the left. The data were obtained on *Chain* 96 and *Chain* 21 (Nos. 10 and 11).

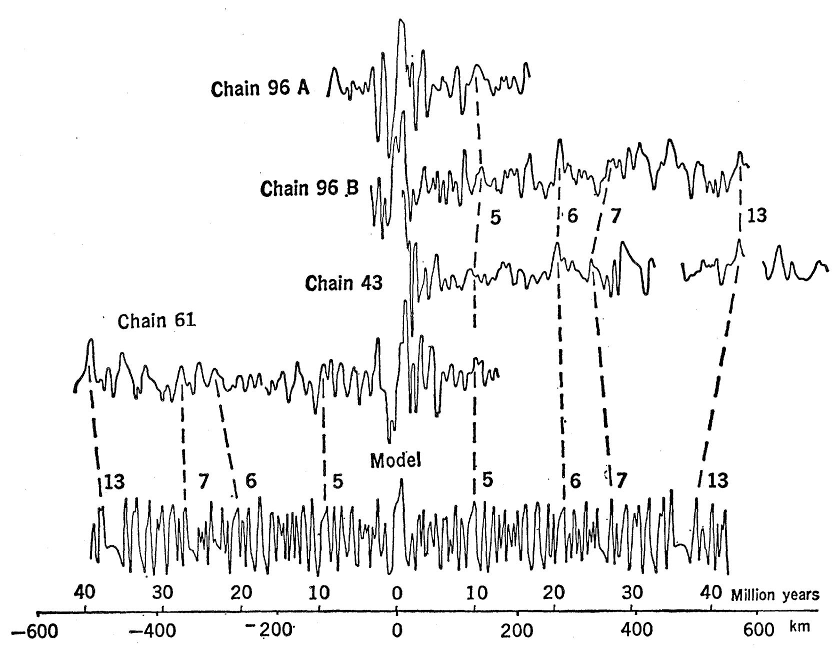

Fig. 3. Magnetics profiles in the survey area (see Fig. 1). Profiles are approximately strike-normal to the ridge axis; *Chain* 43 is projected strike-normal; the others are plotted relative to distance along the track measured from the ridge crest. The data are compared with a simulated sea-floor spreading profile (*12*) based on alternately normal and reversely magnetized blocks in a layer that is 2 to 3.7 km below sea level. Magnetization of the blocks is ±0.01 emu/cm³ with the centermost block at the ridge crest being +0.02 emu/cm³. The latitude of the model is 30°N, and the strike of the ridge is 17°E. The numbered anomalies are those proposed by Heirtzler (*10*).

sults and our magnetic anomaly charting show rather conclusively that there has been no major hiatus (pause) in the opening of the central North Atlantic (south of 37°N) for the last 40 million years or more.

To completely describe the rotational vector inferred by our study, we determined the location of the relative motion pole by plotting normals to the fracture zone strike, determined at intervals of 1° longitude, on a 30-inch (76.2-cm) stereographic projection of the North Atlantic (*2*). These great circle projections intersect in the North Atlantic near 52.5°N, 34°W (see Fig. 1). In fact, 95 percent of the intersections fall within a 4° radius of this position. Morgan and Le Pichon (*1, 2*) have calculated the most recent position of the central North Atlantic rotation pole by graphic and analytic techniques, respectively, from the strikes of transform faults on the Mid-Atlantic Ridge between 30°N and slightly south of the equator. The location of their poles, based on nearly the same data, is near 58°N, 37°W (Table 1), a location that may not be significantly different from the pole we have determined for the last 40 million years. In fact, Morgan's projected normals intersect in a tight group very close to our pole [figure 8 in (*2*)]. This suggests either that a few poorly determined strikes of transform faults on the Mid-Atlantic Ridge have biased their pole location to the north or that the plates are behaving nonrigidly. We favor the former suggestion and propose that a better estimate of the central North Atlantic relative motion vector location is at 52.5°N, 34°W.

Our data (Fig. 1) do not show more than one relative rotation pole during the late Cenozoic for the central North Atlantic, contrary to the findings of Fox *et al.* and van Andel *et al.* [see (*6, 7*) and Table 1]. Van Andel *et al.* surveyed an area closer to the equator, the Vema fracture near 11°N, which may represent the behavior of a plate system different from the central North Atlantic system [for example, see (*13*)]. Fox *et al.* fitted two small circles generated about two different relative motion poles (see Table 1) to relatively short segments of a fracture zone at 24°N. We do not believe that their solution is unique, because a rather large family of small circles can be made to fit short arc segments. Indeed, we do not find their postulated fit to

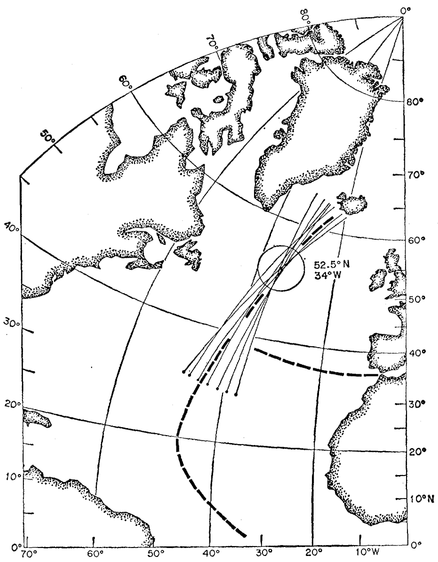

Fig. 4. Stereographic projection of the North Atlantic showing the intersection of great circles projected at right angles from the trend of the Atlantis fracture zone. The dashed lines show the boundaries between the North American, European, and African plates along the Mid-Atlantic Ridge and the Azores–Gibraltar lineation.

the fracture zone trace entirely convincing [see figure 1 in (*7*)].

The Atlantis fracture zone is about 24° from the relative motion pole that we have determined. When we combine this observation with the spreading rate of 1.3 cm per year, we find the angular rate of opening of the central North Atlantic to be about 5.7×10^{-7} deg per year (*14*). This rate differs markedly from rates offered by Morgan and Le Pichon [3.9 and 3.7×10^{-7} deg per year (Table 1)]. About one-half of the discrepancy can be accounted for by moving Morgan and Le Pichon's pole southward to the location we specify and recalculating the rate (then about 4.6×10^{-7} deg per year). The remaining discrepancy may result from the fact that we have used a single spreading rate observation along the ridge crest to calculate the angular opening rate, whereas Le Pichon and Morgan have determined essentially an "average" from several observations of spreading rates. Also, Le Pichon included a large number of South Atlantic rates, which may not be applicable to the North Atlantic. Of course, our rate may actually be somewhat high, a reasonable supposition in view of the rather poor correlation of the observed magnetic profiles with simulated profiles of sea-floor spreading. For example, if the spreading rate were lower by 0.1 cm per year, the angular opening rate would be decreased by about 0.5×10^{-7} deg per year. Alternatively, the discrepancy may indicate nonrigid plate behavior or the existence of additional small plates in the North Atlantic. Our rate does lend further support to the ideas of Morgan and Le Pichon (*1, 2*) and of Ball and Harrison (*13*)—that the central North Atlantic and the South Atlantic represent different plate systems separated somewhere near the equator. This deduction follows from the observation that the rotational parameters of the central North Atlantic plates as determined here result in large discrepancies between calculated and observed motions when extrapolation is made to the South Atlantic.

J. D. PHILLIPS
BRUCE P. LUYENDYK
Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543

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12. The time scale employed is from Heirtzler *et al.* (*10*) for the period 40 to 4.66 million years ago and from A. Cox [*Science* **163**, 237 (1969)] for the period 4.50 million years ago to the present. The computer program used to calculate the simulated profile is similar to the one described by M. Talwani and J. R. Heirtzler, in *Computers in the Mineral Industries*, G. Parks, Ed. (Stanford Univ. School of Earth Sciences, Stanford, Calif., 1964), p. 469.
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14. If θ is the distance in radians between the relative motion pole and the point of interest on the ridge (common plate boundary), then V_θ is the relative speed at this point, equal to twice the spreading rate, and is given by $V_\theta = R_E \omega \sin \theta$ where R_E is the earth's radius and ω is the angular opening rate. When V_θ, R_E, and θ are known, ω can be determined.
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