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A GPS estimate of relative motion between North and South America

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Abstract. GPS velocity data are used to estimate the Euler vector describing rigid body motion of North America relative to South America. Assuming the boundary between the North and South American plates is located near the Fifteen Twenty fracture zone in the equatorial Atlantic, the Euler vector predicts extension across the Royal Trough up to 1 mm/yr, and convergence across the Barracuda Ridge at about 2 mm/yr, in agreement with geological estimates averaged over tens of millions of years. Further west, convergence between North and South America at rates up to 8 mm/yr may contribute to deformation of the Caribbean plate along its southwest boundary with South America.

Introduction

Relative motion between the North and South American plates has been recognized since nearly the beginning of the plate tectonics paradigm, and has been an integral part of global plate motion studies ever since [Ball and Harrison, 1970; Ladd, 1976; Chase, 1978; Minster and Jordan, 1978; Stein and Gordon, 1984; DeMets et al., 1990]. Estimates of the direction and rate of motion between North and South America have relied on changes in fracture zone trends and differential spreading rates in the North and South Atlantic based on magnetic anomalies. Space geodesy has the potential to measure present day motion between North and South America directly, but until recently data have been too sparse and insufficiently accurate for a robust estimate.

Since mid-1994 the University of Miami's Geodesy Laboratory has analyzed data from a global network of permanent Global Positioning System (GPS) sites for tectonic and coastal stability applications. The resulting time series currently includes four stations on cratonic South America. Data are also available from several stable South American sites occupied periodically in campaign-style experiments. Together these data allow us to estimate the Euler vector describing present day relative motion between North and South America, predict relative motion across the putative plate boundary in the equatorial Atlantic, and assess the role of these bounding plates in Caribbean plate motion and intraplate and boundary zone deformation.

Data Analysis

We used 2.5 years of data from seven permanent stations in stable North America (Table 1). South American data vary in amount and time span. Four permanent stations provide daily data except for rare outages: Kourou, French Guiana (KOUR; 2.5 years); Fortaleza, Brazil (FORT; 2.5 years); Brasilia, Brazil (BRAZ, 1.6 years); and La Plata, Argentina (LPGS; 1.2 years). Data spanning 2.0 years are also available from two sites in eastern Bolivia (INGM and SJCH), based on two occupations of stable benchmarks, each 4-5 days duration, in May-June, 1994 and 1996. All permanent sites are instrumented with standard IGS (International GPS Service for Geodynamics) systems, including TurboRogue GPS receivers sampling at 30 second rate, Dorn-Margolin antennas and choke ring backplanes. Data for INGM and SJCH were acquired with similar systems. For our analysis we use the GIPSY software and high precision satellite orbit and clock files provided by the Jet Propulsion Laboratory [Zumberge et al., 1997]. We use P-code pseudorange and carrier phase data sampled every five minutes with a 15° elevation angle cut-off, and estimate a troposphere zenith delay correction every five minutes constrained by a random walk model. Station velocities are defined in global reference frame ITRF-94 [Boucher et al., 1996]. Analytical details are summarized in Dixon et al. [1997]. Table 1 lists the tangential (north and west) velocity components and uncertainties (one standard error) for the sites, from weighted least squares, with weights based on the inverse variance ($1/\sigma^2$), where σ is the scaled formal error of the daily position estimates.

We invert these velocity data assuming North and South America are separate rigid plates, finding the best fitting Euler vector (pole location and rotation rate) describing motion of North American sites relative to South American sites, the latter velocities being minimized in a least squares sense. This is accomplished by first determining the best fit Euler vector for each plate in ITRF-94, subtracting one Euler vector from the other to determine the best fit relative Euler vector, and propagating the covariance matrices to determine errors. Our pole, the NUVEL-1A pole [DeMets et al., 1994] and corresponding 95% confidence ellipses are shown in Figure 1. These poles and ellipses, as well as a corresponding determination by Argus and Heflin [1995] based on more limited GPS data (two South American stations) are also listed in Table 2. Our pole is equivalent to the other poles within uncertainties, but as discussed below, better explains several geological features. Our uncertainties are similar to the NUVEL-1 estimate, and smaller than the previous GPS estimate, as considerably more GPS data are now available.

Since the velocities of the North American sites are well defined, results are not sensitive to the particular sites used in the inversion. However for South America, quality of the individual velocity estimates varies considerably. We checked the integrity of our solution and error estimates by inverting various subsets of the data. Inversions involving only five South American stations change pole position by less than one degree in latitude and less than four degrees in longitude when we omit either of the two non-permanent stations (INGM or SJCH) or either of the two permanent stations with less than two years of data (BRAZ or LPGS). Rotation rate estimates are also insensitive to these changes.

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TABLE 1: Observed and Residual Velocities (mm/yr)

	North[1]	West[1]	Residual[2]
North America[3]			
ALGO	1.3 ± 0.2	15.3 ± 0.2	0.6
BRMU	7.3 ± 0.3	9.6 ± 0.4	1.1
NLIB	-4.9 ± 0.5	13.1 ± 0.9	1.4
PIE1	-9.9 ± 0.3	11.4 ± 0.5	1.4
RCM5	2.0 ± 0.2	6.3 ± 0.4	2.6
STJO	7.9 ± 0.3	15.6 ± 0.5	3.5
YELL	-11.9 ± 0.4	15.5 ± 0.4	0.4
South America[3]			
BRAZ	9.2 ± 0.6	0.7 ± 0.9	2.2
FORT	12.2 ± 0.3	2.6 ± 0.6	0.6
INGM	17.4 ± 2.3	1.0 ± 3.7	7.4
KOUR	10.7 ± 0.4	2.1 ± 0.7	0.6
LPGS	12.7 ± 1.0	-2.0 ± 1.3	2.2
SJCH	13.1 ± 2.2	6.8 ± 3.3	7.1

1. Relative to ITRF 94.
2. $(R_n^2+R_w^2)^{1/2}$ where $R_{n,\,w}$ are the north or west residuals (Observed - Predicted) based on Euler vector in Table 2.
3. North America site locations shown in Dixon et al. [1996]. South America site locations (°N latitude, °W longitude) are BRAZ (-15.9, 47.9); FORT (-3.9, 38.4); INGM (-18.5, 63.1); KOUR (5.3, 52.8); LPGS (-34.9, 57.9); SJCH (-17.9, 60.8).

The best fitting pole gives residuals for South America sites listed in Table 1; their unweighted mean is 3.4 mm/yr, dominated by the two stations INGM and SJCM that are not permanent stations, have limited data, and have correspondingly high velocity errors. The four permanent stations in South America have a mean residual of less than 2 mm/yr. Dixon et al. [1996] used 2.0 years of GPS data from eight stations in North America to investigate the rigidity of the interior of the North American plate. They found an average residual from a rigid plate model of 1.3 mm/yr, and suggested that this residual reflected GPS velocity errors rather than true non-rigid plate processes. As with the more extensive North American data, the mean residual for South America is likely dominated by GPS velocity errors. The average residual for the seven North American sites used in this study (Table 1) is 1.6 mm/yr, somewhat larger than the result reported in Dixon et al. [1996]. This may reflect the influence of annual errors (e.g., unmodelled seasonal atmospheric processes) whose effects on velocity estimates would be minimal for an integer number of years (e.g., 2.0 years), but would affect velocity estimates for the 2.5 year time span used here.

North America-South America Motion

We can use the new Euler vector to predict relative motion along any part of the plate boundary assuming its

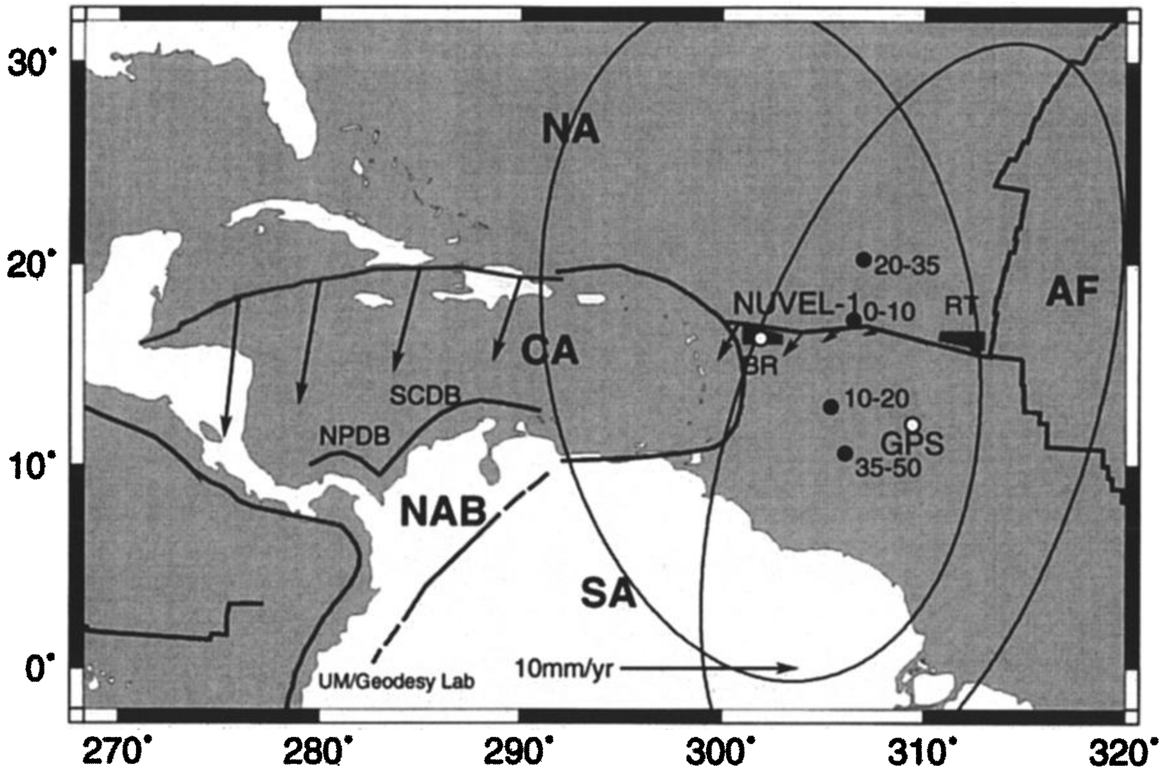

Figure 1. Major tectonic features discussed in text. Open circles are Euler poles (counterclockwise rotation, North America relative to South America) from this study (GPS) and DeMets et al. [1990] (NUVEL-1). Solid circles are four stage poles from Müller and Smith [1993] (0-50 Ma, time span in Ma). Ellipses around GPS and NUVEL-1 poles are 95% confidence regions. NAB is North Andes block, RT is Royal Trough, BR is Barracuda Ridge, NPDB is North Panama deformed belt, SCDB is South Caribbean deformed belt. Solid lines are plate or block boundaries, including Fifteen-Twenty Fracture Zone, the probable North America-South America plate boundary between Royal Trough and Barracuda Ridge. Predicted (GPS) motion of North America relative to South America along this boundary and northern Caribbean boundary shown by arrows.

Table 2: Euler Vectors Describing Relative Motion Between North and South America

	Latitude	Longitude	ω	Error Ellipse[1]			σ_ω
	°N	°E	(°/my)	σ_{max}	σ_{min}	ζ_{max}	(°/my)
This Study	12.0	-50.6	0.13	6.8	3.0	-19	0.03
NUVEL-1A[2]	16.3	-58.1	0.14	5.9	3.7	-9	0.01
Argus and Heflin [1995]	6.5	-55.6	0.28	8.3	7.4	-55	0.12
Stage Pole, 0-10.4 Ma[3]	17.2	-53.5	0.19				

1. ζ_{max} is orientation of long axis, degrees clockwise from north. Axes are one standard error; for 95% confidence, multiply by 2.45.
2. DeMets et al. [1994].
3. Müller and Smith [1993].

location is known. Most workers place the boundary between North and South America in the equatorial Atlantic, between the Mid-Atlantic Ridge and the Lesser Antilles subduction zone where plate geometry allows the shortest possible route. Müller and Smith [1993] place the boundary at the Fifteen-Twenty fracture zone, near the Royal Trough and Barracuda Ridge (Figure 1).

Figures 1 and 2 plot the relative velocity of North America with respect to South America along the Fifteen-Twenty fracture zone, or along the northern Caribbean plate boundary, using the new GPS-based Euler vector. East of the Euler pole (east of 50°W) we predict slow oblique extension with a minor left-lateral component (~1 mm/yr), statistically insignificant. Boundary-normal extension reaches a maximum of about 1 mm/yr at the triple junction with the Mid-Atlantic Ridge, decreasing westward. Given the slow extension rate, it is not surprising that a well-organized spreading center has not developed. Closer to the Lesser Antilles trench oblique convergence is predicted, with a maximum convergence rate of about 2 mm/yr near the trench. The predicted change from extension to convergence corresponds approximately with a change in morphology along the Fifteen-Twenty fracture zone from the Royal Trough in the east (extensional feature) to the Barracuda Ridge in the west (convergent feature).

It is interesting to speculate on the long term stability of the plate boundary and Euler vector. The similarity between the NUVEL prediction and our GPS result implies stability over at least several million years. Müller and Smith [1993] calculated six stage poles spanning the last 68.5 million years. Their four stage poles for the last 50 million years are remarkably similar and also very similar to our result; all four stage poles lie within our 95% confidence ellipse, and within the smaller region of overlap between our ellipse and the NUVEL-1 ellipse (Figure 1). All possible poles located within this overlap region predict extension at the Royal Trough and convergence at the Barracuda Ridge. Müller and Smith [1993] also estimated cumulative deformation from Chron 30 (67.5 Ma) to Chron 5 (10.0 Ma), obtaining 70 km of convergence across the western Barracuda Ridge, 30 km of convergence across the eastern Barracuda Ridge, and 30 km of extension across the Royal Trough, with most of the extension accumulating after Chron 21 (49 Ma). The corresponding average deformation rates over these periods are 1.2 mm/yr convergence (western Barracuda Ridge), 0.5 mm/yr convergence (eastern Barracuda Ridge) and 0.8 mm/yr extension (Royal Trough, after 49 Ma). Given the similarity of the stage pole for the last 10 million years to earlier poles and to our GPS-based pole (Table 2), similar rates may apply over the last ten million years as well. The similarity between these very long term average deformation rates and the GPS prediction (Figure 2) is remarkable, and suggests that North America-South America motion has been steady for the last ~50 million years. The steadiness of pole position and local deformation rate over such a long time may seem surprising, since finite rotation around an Euler pole usually changes plate boundary geometry sufficiently that pole positions must evolve with time [Harrison, 1972]. The slow rate of rotation may account for the longevity of this tectonic regime and the equivalence of geodetic and geologic rates; after 50 million years, the amount of rotation is only about 6.5°.

Caribbean Plate Motion and Internal and Plate Boundary Zone Deformation

Sykes et al. [1982] suggested that convergence between North and South America helps drive eastward motion of the Caribbean plate with respect to North and South America, pointing out that this driving force could be

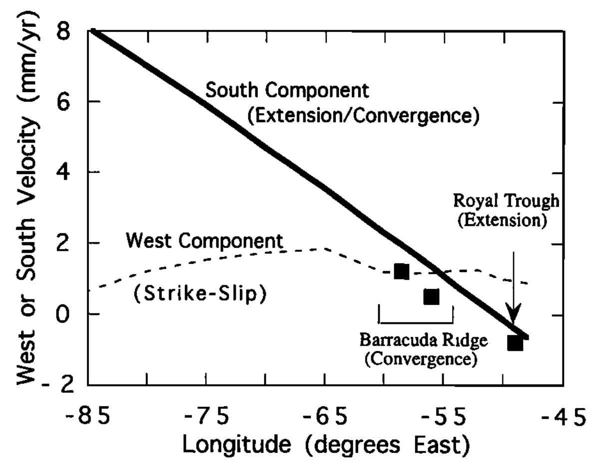

Figure 2. Predicted south (heavy solid line) and west (light dashed line) velocity components of North America relative to South America, similar to plate boundary-normal and -parallel components, computed along Fifteen-Twenty fracture zone in equatorial Atlantic (46°W-60°W) or along northern Caribbean plate boundary (60°W-85°W). Positive south velocity implies convergence, negative south velocity implies extension. Solid boxes are shortening/extension rate estimates for comparison to south component, from Müller and Smith [1993] (68 Ma -10 Ma average, Barracuda Ridge; 49 Ma-10 Ma average, Royal Trough). Size of box gives approximate error assuming ±10% uncertainty in shortening/extension estimate and ±5 Ma uncertainty in age.

significant given the lack of other driving forces such as ridge push or slab pull. In this "squeezed pumpkin seed" model, the Caribbean plate is extruded to the unpinned east, overriding old Atlantic seafloor. The western part of the northern Caribbean plate boundary, where we predict convergence between North and South America at about 8 mm/yr (Figures 1 and 2), is a mainly east-west trending transform fault cutting oceanic crust. The pumpkin seed model implies that corresponding compressional stresses normal to this plate boundary are not accommodated here by local deformation. Rather, they are transmitted across the boundary and through the rigid plate to drive plate motion.

It is also possible that other mechanisms drive Caribbean plate motion [e.g., Russo and Silver, 1996] and convergence between North and South America is accommodated via deformation of the Caribbean plate interior or its northern or southern margins. Since the Caribbean plate interior and most of its northern margin are relatively rigid oceanic crust, deformation should mainly occur on its southern margin with South America, where weaker continental crust and thick sedimentary prisms can readily deform. Along the southeast boundary of the Caribbean plate, manifestations of present-day compressional deformation are generally subtle. Relative motion between the Caribbean and South American plates is accommodated here by strike slip motion along an east-west striking transform fault system. However along the southwest boundary of the Caribbean plate the situation is quite different. North of Panama, the North Panama deformed belt [Silver et al., 1990] (Figure 1) includes a broad zone of young sediments undergoing active folding and thrust faulting, consistent with roughly north-south shortening and compressional stress. Limited GPS data suggest that significant north-south convergence is accommodated here [13±10 mm/yr; Dixon, 1993; 11±5 mm/yr, Kellogg and Vega, 1995]. To the east, a similar fold and thrust belt (South Caribbean deformed belt) lies north of Colombia and Venezuela. The relative convergence rate here may be higher due to northward motion of the North Andes block with respect to South America (Figure 1). Of the total convergence rate of 19±3 mm/yr postulated by Kellogg and Bonini [1982], perhaps a third reflects North America-South America motion, while the remainder may reflect northward motion of the North Andes block [Kellogg and Vega, 1995]. Thus limited available data suggest shortening rates along the southwest boundary of the Caribbean plate that are comparable to the predicted rate of convergence between North and South America. This observation, coupled with the westward increase in both the rate of North America-South America convergence and manifestations of compressional deformation along the South America-Caribbean plate boundary, is consistent with the idea that most of the convergence between North and South America is accommodated by local deformation on or near the southern margin of the Caribbean plate. While very preliminary, this discussion illustrates the possibility that with improved plate kinematic and intraplate deformation data, it may be possible to elucidate some dynamical aspects of Caribbean plate motion.

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