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How Rigid is the Stable Interior of the North American Plate?

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How rigid is the stable interior of the North American plate?

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Abstract. We analyze data from eight permanent GPS stations broadly distributed through the interior of the North American plate, and use the resulting velocities to estimate an Euler vector describing motion of "stable" North America as a single rigid plate. The site velocities fit the single plate model with a mean residual of 1.3 mm/yr. The residuals do not appear to reflect post-glacial rebound, and tests for differential motion between eastern and western North America at the New Madrid seismic zone show no resolvable motion within uncertainties. The residuals likely reflect observational error, and thus our estimate of the stability of the plate interior is likely an upper bound.

Introduction

A fundamental tenet of plate tectonics is that relative motion between plates is accommodated in narrow plate boundaries, while plate interiors are rigid. Plate boundaries within continents tend to be wider and more complex than oceanic counterparts, perhaps reflecting weaker, more heterogeneous continental crust. Continental interiors distant from these plate boundary zones may nevertheless behave rigidly, a hypothesis exploited in geodetic studies where it is useful to reference the velocity of a plate, crustal block, or specific site to an adjacent plate interior, e.g., stable North America. But how much "noise" is introduced by this procedure? Are continental plate interiors rigid enough to constitute a stable geodetic reference frame? The occurrence of large intraplate earthquakes such as the 1811-1812 New Madrid events [Nuttli, 1982] argues that some deformation occurs within plates.

Space geodesy can rigorously test the concept of plate rigidity. The good agreement between space geodetic measurements of relative plate velocity based on a small number of sites per major plate and plate velocities predicted from a rigid plate model [DeMets et al., 1994] demonstrates that on average most plate interiors are rigid at the level of a few mm/yr [Robbins et al., 1993; Robaudo and Harrison, 1993]. However, several mm/yr represents a significant level of error for many studies requiring a stable reference frame, and also represents a significant rate of deformation over geological time, perhaps explaining phenomenon such as New Madrid seismicity.

The University of Miami's Geodesy Laboratory analyzes data from a global network of Global Positioning System (GPS) sites for tectonic and coastal applications, including eight stations on the stable interior of North America with at least two years of data: Algonquin Park, Ontario (ALGO); Bermuda (BRMU); Fairbanks, Alaska (FAIR); North Liberty, Iowa (NLIB); Pietown, New Mexico (PIE1); Richmond, Florida (RCM5); St. John, Newfoundland (STJO); and Yellowknife, Northwest Territories (YELL) (Figure 1). We use the velocity data from these sites to investigate the rigidity of continental North America.

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Data Analysis

All eight 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 are analysed with the GIPSY software [Lichten, 1990] and non-fiducial satellite orbit and clock files provided by the Jet Propulsion Laboratory (JPL). These files are available from January 1995 onward and parts of 1994. We use P-code pseudorange and carrier phase data with a 15° elevation angle cut-off, estimating 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]. Table 1 lists north and west velocity components and uncertainties (one standard error) for the sites, based on weighted least squares fits to the position data, with weights based on the inverse variance ($1/\sigma^2$), where σ is the scaled formal error of the daily position estimates. Table 1 also lists the weighted root mean square (wrms) scatters of the daily position estimates about the best fit lines, typically 3-5 mm and 5-7 mm respectively for the north and west components.

For a perfectly rigid plate, there is no relative motion among sites on the plate interior. In reality, a variety of processes and errors contribute to real and apparent relative motion. Real motions include post-glacial rebound, deformation near a plate boundary, intraplate deformation on regional (>100km) scales, and local near-surface ground motion around the geodetic mark (monument instability). We define the residual velocity of a site as the velocity unexplained by motion of a perfectly rigid plate. It can be considered the root sum square of all real and apparent relative motions affecting a plate interior site. In discussing residuals, we consider the joint effect of monument instability and GPS errors as observational error, distinguishing this from misfit due to regional scale geological processes. To test how well the GPS velocities are described by the single rigid plate model, we invert the data to find the Euler vector that best fits the GPS data, and examine how well the predicted velocities match those observed. The best fitting pole (6.3°N, 278.2°E) and rotation

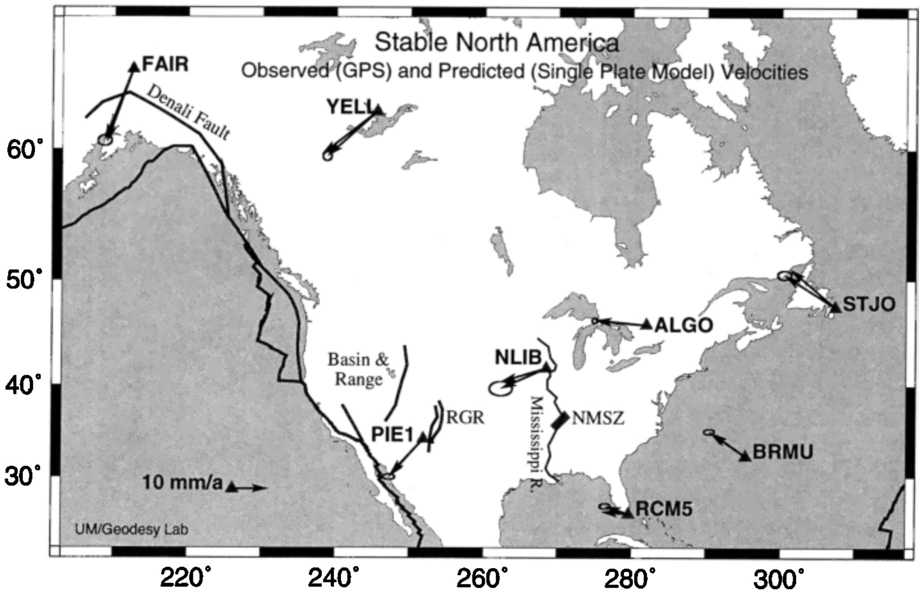

Figure 1. Stations used in this study, their GPS-derived velocities and 95% confidence ellipses, and their velocities predicted by the single rigid plate model in Table 1 (arrows with no ellipse). Major tectonic features discussed in text are also shown. RGR is Rio Grande Rift; NMSZ in New Madrid Seismic Zone.

rate (0.202°/my) give the predicted velocities and residuals (observed minus predicted velocities) in Table 1. Observed and predicted velocities are shown in Figure 1.

Deviation From A Single Rigid Plate Model

The rigid plate hypothesis explains the GPS velocity field very well (Table 1, Figure 1). The most important implication of this result is that the interior of the North American plate is rigid at least to the level of the maximum velocity residual and probably to the level of the average velocity residual, 1.3 mm/yr. The agreement between the observed GPS velocities and a rigid plate model is as good or better than results from earlier studies comparing velocities from satellite laser ranging and very long baseline interferometry to rigid plate models [Robbins et al., 1993; Robaudo and Harrison, 1993; Argus and Gordon, 1996].

By inspecting residuals and comparing to possible non-rigid plate processes and to GPS errors we may be able to distinguish between two possibilities:

1. The residuals are significant and represent the limit of plate rigidity. One or more unmodeled processes such as post-glacial rebound, plate boundary zone tectonics, or other large scale non-rigidity, perturb the velocity field at one or more sites compared to that expected for a rigid plate. However, note that even if residuals are higher than quoted errors we have not necessarily proven non-rigidity - we may

Table 1. Observed[1], Predicted[2] and Residual[3] GPS Site Velocities (mm/yr)

	North Velocity		West Velocity		Residual
	Observed[1]	Predicted[2]	Observed[1]	Predicted[2]	Vector Magnitude[3]
ALGO	1.3 ± 0.3 (3.9)	1.5	14.4 ± 0.3 (4.5)	14.2	0.2
BRMU	6.9 ± 0.3 (3.5)	6.6	10.1 ± 0.6 (6.6)	9.3	0.9
FAIR	-19.9 ± 0.6 (4.1)	-20.3	7.9 ± 0.8 (5.1)	7.3	0.7
NLIB	-5.6 ± 0.8 (3.0)	-3.8	12.7 ± 1.3 (5.5)	12.8	1.8
PIE1	-10.5 ± 0.3 (3.6)	-9.9	9.5 ± 0.7 (6.9)	9.2	0.7
RCM5	2.2 ± 0.3 (3.3)	0.6	6.5 ± 0.6 (6.6)	7.4	1.9
STJO	9.1 ± 0.5 (3.9)	10.9	14.2 ± 0.8 (6.3)	12.7	2.3
YELL	-12.5 ± 0.5 (3.9)	-12.0	13.9 ± 0.5 (5.0)	15.5	1.7

1. Relative to ITRF-94. Numbers in parentheses are weighted root mean square scatter of daily position estimates (mm).

2. Based on a rigid plate model with pole at 6.3°N, 278.2°E. ω=0.202°/my.

3. $(R_n^2+R_w^2)^{1/2}$ where $R_{n,w}$ are the north or west Residuals (Observed - Predicted) (mm/yr).

simply have under-estimated errors [e.g., Johnson and Agnew, 1995].

2. The residuals are not significant and are only an upper bound to plate rigidity. The plate interior is more rigid than implied by our results, but the analysis is limited by observational error (instrument plus monument effects).

The horizontal component of velocity due to postglacial rebound may perturb the measured GPS velocity field [James and Lambert, 1993]. However, inspection of velocities predicted by the ICE-4G model [Peltier, 1994] suggests that post glacial rebound is not a significant contributor to the residuals (all our sites have ICE-4G horizontal velocity components < 1.0 mm/yr).

Two sites (Pietown and Fairbanks) are near active tectonic regions associated with the Pacific-North America plate boundary zone. Pietown is near the Rio Grande Rift, adjacent to the southwest boundary of the Basin and Range extensional province. Fairbanks is about 200 km from the Denali fault, near a zone of seismicity associated with northeast striking left-lateral faults [Page et al., 1995]. However, neither site has a velocity that deviates significantly from the rigid plate model (Figure 1).

Differential motion between eastern and western North America is a possible explanation for New Madrid seismicity, consistent with hypotheses involving plate scale compressive stresses [Zoback et al., 1989; Jones et al., 1996], reactivation of an ancient weak zone near New Madrid [Hildebrand et al., 1982], and strain accumulation and subsequent release in earthquakes [Hamilton and Zoback, 1982]. On the other hand, one can also imagine local sources of stress leading to motion not manifested on a continental scale, undetected by our network. The pattern of seismicity at New Madrid delineates two NE-striking vertical faults linked by a short NW-striking fault [e.g., Himes et al., 1988]. Focal mechanisms [Herman, 1979], geology [Russ, 1982] and topography [Gomberg and Ellis, 1994] suggest two NE-striking right lateral faults connected by a NW-striking thrust or reverse fault, implying NE motion of the western block relative to the eastern block.

Table 2. Euler Vectors for Eastern and Western North America Relative to ITRF94

	Eastern North America[1]	Western North America[2]
Latitude	1.4° North	2.4° North
Longitude	276.2° East	282.0° East
Rotation Rate	0.183 °/my	0.189 °/my
Error Ellipse[3]		
Major semiaxis	5.9°	3.3°
Minor semiaxis	1.4°	0.9°
Orientation (°east of north)	13°	-19°
Mean Residual	1.4 mm/yr	0.8 mm/yr

1. Based on GPS data for ALGO, BRMU, RCM5 and STJO.
2. Based on GPS data for FAIR, NLIB, PIE1 and YELL.
3. One standard error; for 95% confidence, multiply axes by 2.45.

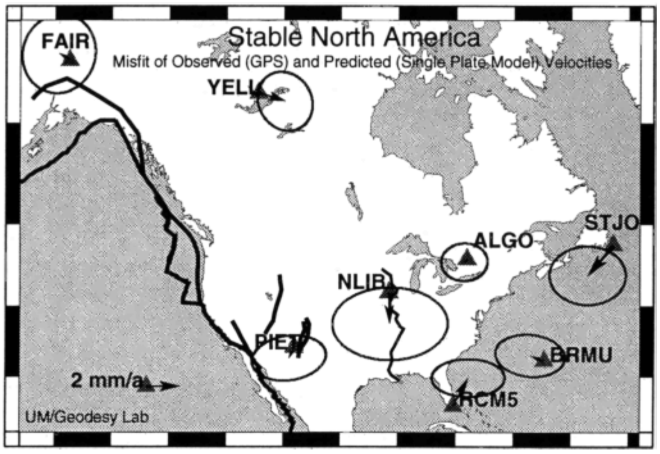

Figure 2. Similar to Figure 1, showing velocity residuals (Table 1) and 95% confidence ellipses. Note scale change.

Local geodetic data suggest strain accumulation here [Liu et al., 1992; Weber et al., 1996]. To investigate whether this motion occurs on a continental scale, and whether current space geodetic data can resolve it, we split stable North America into blocks east and west of the Mississippi River, solved for separate Euler vectors (Table 2), and predicted relative motion between the blocks at New Madrid.

The Euler poles for the eastern and western blocks overlap at 95% confidence (Table 2). Although the variance is reduced in the two plate model, an F-ratio test [Stein and Gordon, 1984] shows the reduction is not significant, no more than expected from adding more degrees of freedom. Solving for relative motion at New Madrid (36.5°N, 89.5°W) gives 2±1 mm/yr of southward motion of the west block relative to the east block, indistinguishable from zero at 95% confidence, and different in direction from the seismological and geological estimates cited above. The 95% confidence ellipse around the velocity estimate allows less than 0.5 mm/yr of NE motion of the west block relative to the east block. Together with the F-ratio test and overlapping error ellipses, this suggests that the small misfit of GPS velocities to the single rigid plate model is not due to differential motion at New Madrid.

Our results have implications for interpretation of local geodetic data. Liu et al. [1992] predict 5-7 mm/yr of strike-slip motion across New Madrid, while Weber et al. [1996] favor slower rates. Our data show no evidence for significant motion manifested on a continental scale.

Since the velocity residuals do not correlate in any obvious way with post-glacial rebound, Pacific-North America boundary zone tectonics, or differential motion between eastern and western North America at New Madrid, and since the magnitude of the residuals is smaller than 95% velocity errors for all but two sites (Figure 2), we conclude that the single rigid plate model adequately explains the data. The plate is likely more rigid than implied by our residuals, and agreement between data and model is limited by observational error (GPS error and monument instability). Conversely, presuming a rigid plate model, the similarity between residuals and 95% velocity errors argues that we have not grossly over- or underestimated errors. The residuals also suggest a bound on monument instability effects (unmodelled here) on site velocity estimates.

Discussion

Our main result is that the velocity field of the North American interior is consistent with a rigid plate to better than 2 mm/yr. Our estimate of rigidity is derived from misfits between data and model, and does not depend on estimates of GPS velocity error nor a detailed understanding of error sources. The misfits do not appear to reflect motion across the New Madrid seismic zone or postglacial rebound, and most likely reflect observational error. Thus our estimate of the plate interior's rigidity is an upper bound.

Argus and Gordon [1996] analyzed VLBI data from stable North America and other cratons. Their results are in good agreement with ours, namely that plate are rigid to 2 mm/yr or better. This agreement is surprising, considering the relatively short time span for our GPS data (two years) compared to VLBI results (many stations have data spanning nine years or more). The quality of a velocity estimate based on a time series of position estimates depends on both the quality and total time span of observations. Since it is unlikely that GPS position estimates are significantly more accurate than VLBI position estimates, our expectation is that longer VLBI time series should agree better with the rigid plate model. The apparent lack of improvement using the longer time series has interesting implications. One possibility is that the rigidity of the North American plate interior is in fact limited to the level of current agreement between the model and space geodetic data (1-2 mm/yr). Another possibility is that both GPS and VLBI velocities are limited in accuracy by some common mode error whose influence is not greatly reduced with longer observing time. Monument stability is a potential common mode error, although current models suggest that this noise source has a $1/\sqrt{\text{time}}$ influence on velocity estimates [e.g., Johnson and Agnew, 1995].

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