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New kinematic models for Pacific-North America motion from 3 Ma to present, I: Evidence for steady motion and biases in the NUVEL-1A model

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Abstract. We use velocities derived from 2-4.5 years of continuous GPS observations at 21 sites on the Pacific and North American plates along with a subset of the NUVEL-1A data to examine the steadiness of Pacific-North America motion since 3.16 Ma, the transfer of Baja California to the Pacific plate, and the magnitude of biases in the NUVEL-1A estimate of Pacific-North America motion. We find that Pacific-North America motion has remained steady since 3.16 Ma, but at rates significantly faster than predicted by NUVEL-1A. In the vicinity of Baja California, our GPS-derived model and recent seafloor spreading rates in the southern Gulf of California both indicate that the NUVEL-1A model underestimates Pacific-North America rates by 4±2 mm yr^{-1}. Steady Pacific-North America motion since 3.16 Myr and increasing seafloor spreading rates since 3.58 Myr in the Gulf of California imply that Pacific-North America motion was partitioned between seafloor spreading in the Gulf of California and decelerating slip along faults in or offshore from the Baja peninsula.

Introduction

The degree to which plates can change their motions over geologically brief intervals is a key unanswered question in plate kinematics, one with important implications for the forces that drive plate motion. Ongoing geodetic measurements of plate velocities and refinements in models of several-million-year-average global plate motions [*e.g. DeMets et al.*, 1990, 1994] will enable future tests for geologically-recent changes in the velocities of most of the tectonic plates. Here, we revisit questions about recent changes in motion between the Pacific and North American plates, where geodetic measurements are more mature and more widespread and thus enable stronger tests for recent plate motion changes.

DeMets [1995] presents evidence that seafloor spreading rates across the Gulf of California, which separates Baja California from the North American plate, have accelerated by ~15% since 3.58 Myr and now significantly exceed the Pacific-North America rate predicted by the 3.16 Myr-average NUVEL-1A model [*DeMets et al.*, 1994]. This can be interpreted in at least two ways. If the Baja peninsula has moved with the Pacific plate since 3 Myr, the observed spreading acceleration directly records a post-3 Ma acceleration of Pacific-North America motion. *DeMets* [1995] instead proposes that Pacific-North America (hereafter abbreviated PA-NA) motion since 3.16 Myr has been steady, that the NUVEL-1A model significantly underestimates 3.16 Myr-average PA-NA motion, and that slip between these two plates in the vicinity of Baja California has been partitioned between accelerating seafloor spreading in the Gulf of California and decelerating slip along faults west of Baja California. In support of this interpretation, *DeMets* [1995] demonstrates that a revised model for PA-NA motion, one derived from a subset of the NUVEL-1A plate kinematic data that excludes demonstrably biased data from the Gulf of California and other plate boundaries, predicts 3.16 Myr-average PA-NA motion that agrees within uncertainties with the observed rate of seafloor spreading in the Gulf of California since 0.78 Ma. This implies that PA-NA motion has remained constant since at least 3.16 Ma. The seemingly incompatible kinematic evidence for steady PA-NA motion and accelerating seafloor spreading rates between the Baja peninsula and North American plate is reconciled by assuming that the Baja peninsula moved relative to the Pacific plate prior to 780,000 years ago.

Here, we combine new GPS-derived velocities at 21 sites from the Pacific and North American plates with a subset of the NUVEL-1A plate motion data to undertake an independent test for steady PA-NA motion since 3.16 Myr. The models we derive for instantaneous (geodetic) PA-NA motion and motion since 3.16 Ma (geologic) predict velocities in the Gulf of California and along the Baja peninsula that differ insignificantly, by no more than 1.5 mm yr^{-1} and 2°. In a forthcoming paper (*Dixon et al.*, "New kinematic models for Pacific-North America motion from 3 Ma to present, II: Tectonic implications for Baja and Alta California", to be submitted to GRL, 1999), we use GPS velocities for sites from Baja and Alta California and our improved estimates for PA-NA motion to describe the present tectonics of Baja California and Alta California and directly estimate the status of Baja California's transfer to the Pacific plate.

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GPS data analysis and site velocities

To solve for Pacific and North American plate angular velocities, we use data from permanent GPS stations located on the Pacific (5) and North American (16) plates (Fig. 1 and Table 1). All stations have 2.0 or more years of data, current through early September, 1998. Data were analyzed at the University of Miami using GIPSY analysis software from the Jet Propulsion Laboratory [*Zumberge et al.*, 1997], high-precision non-fiducial satellite orbits and clocks, and procedures described by *Dixon et al.* [1997]. Station velocities are given in Table 1 and are defined in ITRF96 [*Sillard et al.*, 1998]. We selected sites far from deforming zones within North America to minimize the effect of any fault-induced elastic strain or distributed deformation on our site velocities. We also incorporate a new model for white noise and time-correlated noise in GPS coordinate time series for globally distributed sites [*Mao et al.*, 1998], which builds on earlier work by *Zhang et al.* [1997].

We solve for angular velocities that best fit GPS station velocities, seafloor spreading rates, and plate slip directions using techniques described by *DeMets et al.* [1990] and *Ward* [1990]. The data are inverted to solve for one or more angular velocities that simultaneously minimize the weighted, least-squares misfit to data from one or more plates and satisfy the condition of plate circuit closure wherever it applies. The best-fitting angular velocities and model uncertainties are given in Table 2. The misfits of the North American plate angular velocity to the 16 North American site velocities range from 0.0-2.6 mm yr^{-1} (Table 1) and average 1.0 mm yr^{-1}. The misfits of the Pacific plate angular velocity to the five Pacific site velocities range from 0.1-4.0 mm yr^{-1} (Table 1) and average 2.1 mm yr^{-1}. Values of reduced chi-square for the North American and Pacific angular velocities are 0.42 and 1.26, respectively, indicating that the station velocity uncertainties may be modestly overstated and slightly underestimated, respectively. Given the small number of data, we conclude that the site velocity and thus model uncertainties are approximately correct.

The locations of the Pacific and North American sites with respect to the best-fitting poles of rotation (Fig. 1) strongly constrain the rotation poles and angular rotation

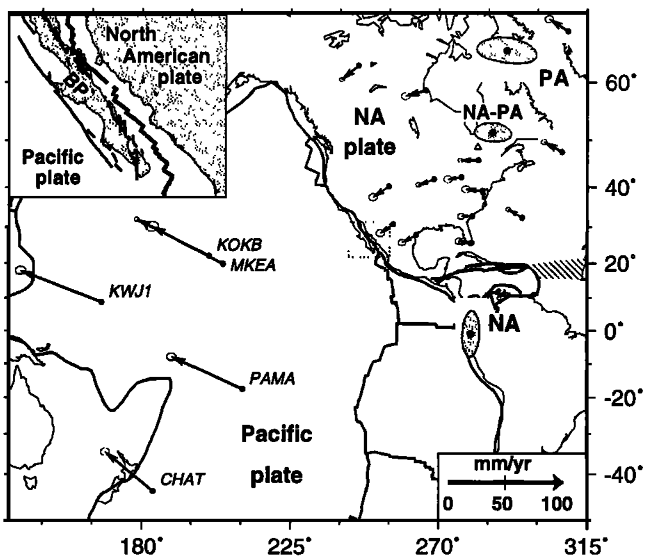

Figure 1. Velocities of permanent GPS stations used in this study (Table 1). All velocities are relative to ITRF96. One North American site, THU1 in Table 1, is located outside the map boundaries. Inset shows the Baja peninsula (BP). The best-fitting Pacific and North American plate poles (Table 2) are labeled "PA" and "NA". The NA-PA pole derived from these GPS velocities lies significantly northeast of the NUVEL-1A pole (open triangle). All confidence ellipses are 2D 95%.

Table 1. GPS Site Velocities Relative to ITRF96.

Site ID	Lat. (°N)	Long. (°E)	ΔT (yrs)	$V_n \pm 1\sigma$ (mm yr^{-1})	$V_e \pm 1\sigma$ (mm yr^{-1})	Misfits V_n	Misfits V_e
			Pacific sites				
CHAT	-43.96	-176.57	2.88	34.4± 2.1	-41.3± 2.5	4.0	0.3
KOKB	22.13	-159.66	4.45	31.6± 1.2	-63.0± 1.4	-0.3	-1.0
KWJ1	8.72	167.73	2.50	26.7± 2.3	-69.4± 3.1	-0.1	-0.6
MKEA	19.80	-155.45	1.97	32.6± 2.8	-62.1± 3.8	0.8	0.1
PAMA	-17.57	-149.57	2.85	28.1± 2.1	-61.5± 2.8	-3.3	3.9
			North American sites				
ALGO	45.96	-78.07	4.45	-0.1± 1.2	-15.6± 1.4	-0.9	-0.0
ARP3	27.84	-97.06	2.59	-6.5± 1.7	-12.2± 2.1	-0.3	-2.3
BRMU	32.37	-64.70	4.45	7.4± 1.2	-12.1± 1.4	1.7	-0.8
CHA1	32.76	-79.84	2.76	0.0± 1.7	-9.7± 2.0	-0.1	2.2
CHUR	58.76	-94.09	2.20	-5.2± 2.0	-17.7± 2.5	-0.1	0.2
DET1	42.30	-83.10	2.17	-2.1± 2.0	-12.0± 2.5	-1.0	2.6
GODE	39.02	-76.83	2.19	1.6± 2.0	-14.3± 2.5	0.3	-0.6
KELY	66.98	-50.94	3.03	10.5± 2.0	-16.6± 2.4	0.1	0.7
MDO1	30.68	-104.01	2.20	-7.7± 2.0	-11.0± 2.5	0.9	-0.7
MIA1	25.73	-80.16	2.48	1.3± 1.8	-11.0± 2.2	1.3	-1.4
NLIB	41.77	-91.57	4.10	-4.7± 1.2	-13.6± 1.5	-0.5	0.6
RCM5	25.61	-80.38	2.51	1.4± 1.8	-7.2± 2.2	1.5	2.3
STJO	47.60	-52.68	4.45	9.0± 1.5	-15.7± 1.7	-0.9	-1.5
THU1	76.53	-68.77	3.08	4.4± 2.0	-20.8± 2.4	0.2	-0.4
TMGO	40.13	-105.23	2.17	-9.5± 2.0	-13.7± 2.5	-0.5	-1.0
YELL	62.48	-114.48	4.42	-12.3± 1.2	-14.7± 1.4	-0.3	1.1

Δ T represents the time span of the GPS observations that constrain the velocity. Correlations between the north and east velocity components are approximately zero. Misfits are in mm yr^{-1} and are determined relative to predictions of best-fitting angular velocities from Table 2.

Table 2. Best-fitting Angular Velocities.

Plate	Data Type	λ (°N)	φ (°E)	ω (°/Myr)	σ_1	σ_2	η (CW)	σ_ω (°/Myr)
PA-IT	GPS	-64.5	110.6	0.665	2.3°	1.0°	83°	0.010
NA-IT	GPS	-0.9	280.2	0.192	4.1°	1.6°	-2°	0.009
NA-PA	GPS	51.5	286.3	0.765	2.0°	1.0°	-85°	0.016
NA-PA	Geologic†	50.0	283.9	0.777	0.8°	0.6°	65°	0.007
NA-PA	Combined‡	50.5	284.2	0.776	0.7°	0.5°	75°	0.006
NA-PA	NUVEL-1A	48.7	281.8	0.749	1.3°	1.2°	-61°	0.012

Angular velocities designate motion of the first plate relative to the second. λ, φ, and ω are the latitude, longitude, and angular rotation rate of the best-fitting angular velocity, respectively. The lengths in degrees of the 2D, 1-sigma semi-major and semi-minor axes of the pole error ellipse are σ_1 and σ_2. η is the azimuth of the semi-major ellipse axis in degrees CW from north. σ_ω is the 1D standard error for the angular rotation rate Abbreviations: PA - Pacific plate; NA - North American plate; IT - ITRF96.

† Derived from subset of the NUVEL-1A data (see text).

‡ Derived from GPS velocities (Table 1) and subset of NUVEL-1A data.

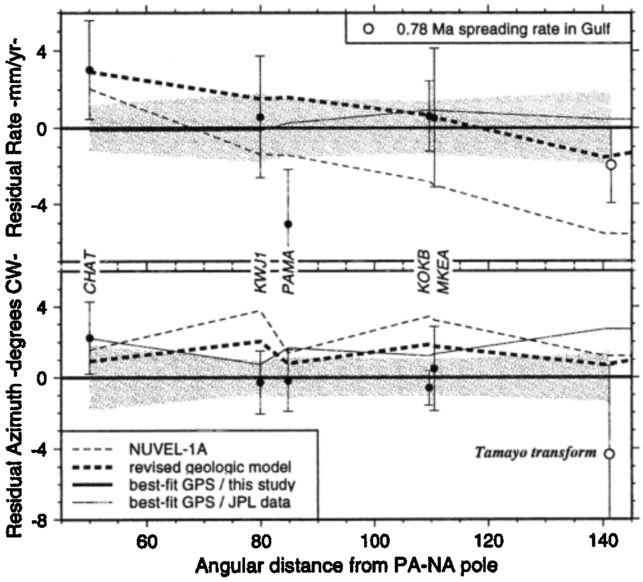

Figure 2. Rates (upper panel) and azimuths (lower panel) at Pacific (PA) plate GPS sites relative to the North American (NA) plate shown as residuals from velocities predicted by the best-fitting GPS-derived PA-NA angular velocity (Table 2). All data and model uncertainties are 1σ. PA-NA rates predicted by models derived from GPS velocities from the University of Miami and JPL agree everywhere to better than 1 mm yr^{-1}. We expect the differences in the model predictions to diminish as the station observation time spans increase and new GPS stations are established on the Pacific plate. Site names refer to sites from Figure 1.

rates for both plates. Geodetic rates for both plates show the expected sinusoidal increase with angular distance from the pole and the radial rate components scatter symmetrically about their expected value of zero. To assess the robustness of our solution, we also derived North American and Pacific plate angular velocities from GPS station velocities from the Jet Propulsion Laboratory (Mike Heflin, pers. commun., 1998). The predictions of our best-fitting North American angular velocity differ from those of the angular velocity we derived from the JPL data by only 0-1.3 mm yr^{-1}. The site distribution and observation time-spans at the North American sites are thus sufficient to give robust solutions for the North American plate angular velocity regardless of small differences in analytical techniques or station selection. Velocity differences at the five Pacific plate sites are somewhat larger, from 1-3 mm yr^{-1}, likely reflecting differences in our analytic techniques and the time spans of the data used to solve for individual station velocities. None of our conclusions change significantly if we use velocities from JPL instead of our own.

A rigorous test for changes in Pacific-North America motion since 3 Ma

To test for significant changes in PA-NA motion since 3.16 Ma, we used a variant of the statistical test for plate circuit closure [*Gordon et al.*, 1987] to compare motion over geodetic intervals (several years) and geologic intervals (several million years). Short-term Pacific-North America motion is determined from the 21 GPS velocities from Pacific and North American plate sites (Table 1). Pacific-North America motion since 3.16 Myr is constrained by a modified subset of the NUVEL-1A data that excludes all 77 PA-NA data and thus estimates PA-NA motion solely from global plate circuit closures. If motion has remained steady since 3.16 Myr, then a model that fits both sets of data simultaneously should differ insignificantly from a model that fits the geodetic and geologic data separately. A significant difference in the fits of the two models would indicate that geodetic and geologic plate velocities cannot be combined without violating global plate circuit closure requirements.

We use only 906 of the 1122 NUVEL-1(A) data to solve for the PA-NA closure-fitting angular velocity. The data that we use and reasons for excluding the remaining data are described by *DeMets* [1995] and are not repeated here. In addition to these changes, we also adjusted data uncertainties such that reduced chi-square for individual data types have their expected values of 1.0.

Simultaneously fitting the 42 (2*21) geodetic velocity components and the 906 plate kinematic data described by *DeMets* [1995] gives a weighted least-squares misfit χ^2 of 810.2. Fitting both sets of data separately and summing their individual misfits gives a combined χ^2 of 807.4. Three additional parameters are adjusted in the latter model. Applying the *F*-ratio test for plate circuit non-closure gives $F = 1.1$. This is lower than the value for *F*, 2.6, that would indicate that the fits of the two models differ significantly at the 95% confidence level. A model in which the two sets of data are fit simultaneously thus fits the data nearly as well as a model in which they are fit separately. Pacific-North America motion estimated over the past few years and the past few million years is thus identical within uncertainties.

Repeating the above test using all the NUVEL-1A data except for the 77 PA-NA data gives a different result.

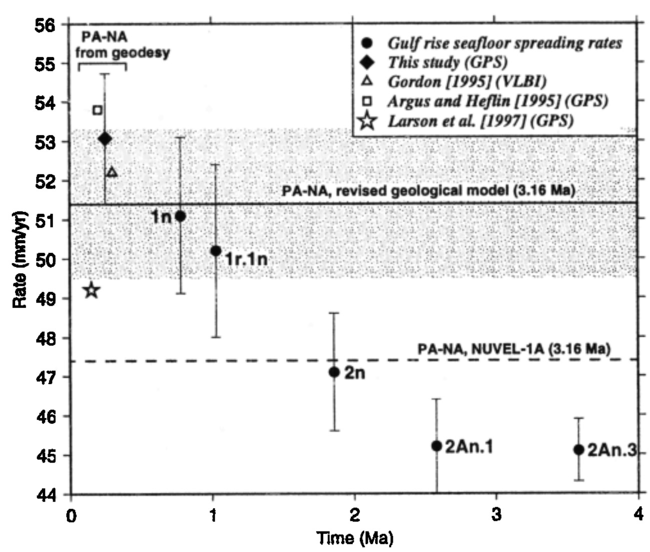

Figure 3. Seafloor spreading rates across the southern spreading segment in the Gulf of California compared to rates predicted at that location by alternative models for PA-NA motion (modified from *DeMets* [1995]). All uncertainties, including the stippled region, are 1σ.

Models that fit the geodetic and geologic data simultaneously and separately differ significantly at the 98.5% confidence level. The NUVEL-1A data are thus not consistent with steady PA-NA motion since 3.16 Myr; however, this is almost certainly an artifact of systematic biases in some of the NUVEL-1A data.

Figure 2 reinforces these results. The velocities of the five Pacific plate sites relative to the North American plate are fit nearly as well by the angular velocity we derived from the modified NUVEL-1A data as by the angular velocity that best fits the GPS velocities. In contrast, the NUVEL-1A PA-NA angular velocity fits the data more poorly, presumably due to systematic biases in some of the NUVEL-1A data [*DeMets*, 1995]. Changes to geologic kinematic data that reflect advances since 1990 in our understanding of global plate kinematics are presently underway (C. DeMets and R. Gordon, 1999].

Discussion

Our determinations for PA-NA motion for the present and 3.16 Ma (Figs. 2 and 3) both give rates of 51-53 mm yr^{-1} in the southern Gulf of California, each with standard errors of ±2 mm yr^{-1}. These rates are consistent with the 51.4±2 mm yr^{-1} average rate of seafloor spreading in the southern Gulf of California since 0.78 Ma [*DeMets*, 1995] and with the predictions of PA-NA angular velocities (Fig. 3) that were derived from VLBI data [*Gordon*, 1995] and GPS data that were available as of several years ago [*Argus and Heflin*, 1995]. All of these observations suggest that Pacific-North America motion has been steady at ~52±2 (95% limits) mm yr^{-1} since at least 3.16 Myr. Newly available PA-NA rotations for longer intervals predict that displacement rates in the southern Gulf of California have been 52-57 mm yr^{-1} since ~8 Ma, in good accord with the results reported here (J. Stock, pers. commun., 1999).

Most kinematic evidence (Fig. 3) thus indicates that PA-NA motion in Baja and Alta California is ~4±2 mm yr^{-1} faster than predicted by NUVEL-1A. Although the PA-NA rate we predict significantly exceeds that derived by *Larson et al.* [1997], we view the results reported here as a direct outcome of improvements in GPS site distribution, longer GPS time series, improvements in analytical techniques, and geodetic reference frames not available to *Larson et al.* [1997].

The evidence for accelerating seafloor spreading between the Baja peninsula and North American plate (Fig. 3) and steady PA-NA motion since 3.16 Myr can be reconciled if we assume that the Baja peninsula moved relative to the Pacific plate prior to ~1 Myr. Faults west of the peninsula that display evidence for Holocene slip (e.g. the Tosco-Abreojos and San Isidro fault zones described by *Spencer and Normark* [1979] and *Legg et al.* [1991]) presumably accommodated some or all of this motion. Assuming that steady PA-NA motion since 3.16 Myr has been partitioned between faults in the Gulf of California and faults west of the Baja peninsula, increasing seafloor spreading rates in the Gulf of California imply a corresponding decrease in slip along faults to the west. The present slip rates along these faults are best addressed by comparing the velocities of coastal sites to the predictions of the Pacific plate angular velocity derived here. We address this in our forthcoming paper.

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