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A model for Mexican neotectonics based on nationwide GPS measurements, 1993-2001

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RESUMEN

En este trabajo combinamos las velocidades obtenidas a partir de 14 estaciones GPS de operación continua distribuidas en México, dos nuevas estaciones en la placa del Pacífico (Archipiélago de Revillagigedo) y de 178 estaciones en las placas de Norteamérica y del Pacífico, para obtener un marco geodinámico que servirá de referencia para futuros estudios de neotectónica en México realizados con GPS. Las velocidades derivadas muestran claramente que existen áreas al norte de la Faja Volcánica Mexicana que están incluidas dentro de la porción rígida de la placa de Norteamérica. El movimiento de las estaciones en México al norte de Oaxaca es también consistente con el movimiento de la placa de Norteamérica, lo cual implica un deslizamiento despreciable a través de la Faja Volcánica Mexicana. Las estaciones en la península de Yucatán se desplazan a razón de 3±1 mm/año hacia el Este con relación a la placa de Norteamérica sin existir claras evidencias geológicas que expliquen este movimiento. Las velocidades obtenidas para las islas Clarión y Socorro en el océano Pacífico son consistentes dentro de su incertidumbre con las velocidades de otros sitios en la placa del Pacífico y por consiguiente proveen una mejor determinación del movimiento de esta placa. El movimiento del Pacífico-Norteamérica en el sur del Golfo de California es de 50 ± 0.5 mm/año hacia el S55°E ±0.5°, que es consistente con las estimaciones geológicas pero ligeramente más lento que las estimaciones geodésicas recientemente publicadas de 52-53 mm/año. El movimiento de La Paz en la península de Baja California hacia el Sureste en relación con la Placa del Pacífico coincide con resultados previos que indican que Baja California se encuentra desacoplada de la placa del Pacífico. Las nuevas velocidades angulares obtenidas en este trabajo representan un marco de referencia geológico bien definido para futuros estudios geodésicos en México.

PALABRAS CLAVE: GPS, marco de referencia, placas tectónicas.

ABSTRACT

We combine velocities for 14 continuously operating GPS stations spanning Mexico, GPS sites on Socorro and Clarion islands on the Pacific plate west of Mexico, and 178 GPS sites on the North American and Pacific plates to derive plate-based reference frames suitable for GPS-based studies of North American plate neotectonics. The motions of sites in Mexico north of and including Oaxaca are consistent with North American plate motion, implying negligible slip across the Mexican Volcanic Belt.Sites in the Yucatán peninsula move 3±1 mm/yr eastward relative to the North American plate. Velocities for new GPS sites on Clarión and Socorro islands are consistent within their uncertainties with Pacific plate motion, and provide useful new constraints on Pacific plate motion. Pacific-North America motion in the southern Gulf of California is 50.8±0.5 mm/yr toward S55°E±0.5° degrees. This is consistent with 50-52 mm/yr geologic estimates, but slower than recently published 52-53 mm/yr geodetic estimates. Southeastward motion of La Paz near the tip of Baja California relative to the Pacific plate agrees with previous results suggesting that Baja California is detached from the Pacific plate. The new plate angular velocity vectors amount to a well-constrained, geologically stable reference frame.

KEY WORDS: GPS, stable reference frames, tectonic plates.

INTRODUCTION

The present deformation of Mexico is dominated by interactions between the North American, Pacific, Cocos, Rivera, and Caribbean plates (Figure 1). Earthquakes along the faults that separate these plates and numerous potentially seismogenic faults in the Mexican Volcanic Belt (Suter *et al*., 2001) pose a significant hazard. The M=8.1 Michoacán earthquake of September 19, 1985, which caused ten thousand fatalities and billions of dollars in damage, illustrated the vulnerability of areas that lie within several hundred kilometers of the Middle America subduction zone.

A key objective of geophysical research in Mexico is to characterize its present-day surface velocity field, with an underlying goal of better understanding the interseismic, coseismic, and post-seismic behavior of seismogenic faults. Implicit in this effort is the need for well-defined plate based

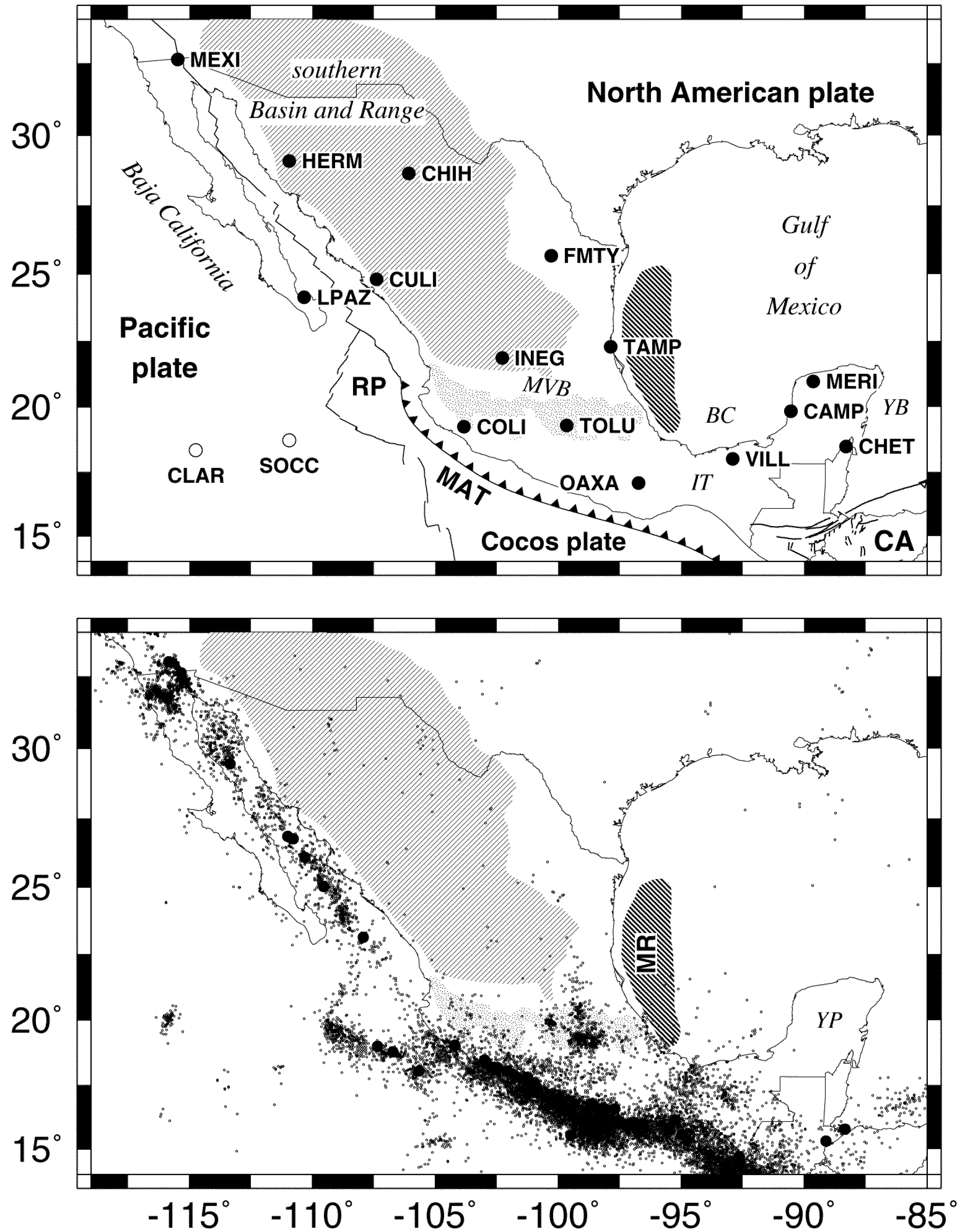

Fig. 1. (A) Tectonic setting of Mexico and locations of GPS sites in Mexico used for this study. INEGI GPS stations are shown with filled circles and open circles show locations of periodically occupied GPS sites on Clarión (CLAR) and Socorro (SOCC) islands. (B) Small and large circles show earthquake epicenters with respective magnitudes of $M_b < 6.5$ and $M_b >= 6.5$ and depths above 60 km reported by USGS for the period 1963-2002 and earthquakes of all magnitudes above depths of 30 km reported by the Mexican National Seismic Network for the period 1974-2001. Abbreviations: BC, Bay of Campeche; CA, Caribbean plate; IT, Isthmus of Tehuantepec; MAT, Middle America trench; MR, Mexican Ridges; MVB, Mexican volcanic belt; YB Yucatán basin; YP Yucatán peninsula.

geodetic reference frames relative to which the motions of sites in deforming areas of Mexico can be described. Over the past decade, the advent of precise GPS measurements has revolutionized our ability to measure surface displacements and hence estimate the present motions of the major tectonic plates. Márquez-Azúa and DeMets (2003) have quantified the present velocity field of Mexico using continuous data from a nationwide network of GPS receivers (Figure 1) that were deployed by INEGI (Instituto Nacional de Estadística, Geografía, e Informática) in early 1993. The velocities from this network provide a unique and strong basis for defining geologically useful geodetic reference frames for Mexico.

Herein, we employ GPS velocities from Mexico and from 180 additional GPS sites on the North American and Pacific plates (Figure 2) to derive angular velocity vectors that define plate-fixed reference frames for geodetic studies in Mexico and other areas on the Pacific and North American plates. The Mexican GPS velocity field reported by Márquez-Azúa and DeMets (2003) establishes the large-scale tectonic framework for our plate-based reference frame as follows: (1) lithosphere north of the Mexican Volcanic Belt moves with the interior of the North American plate within the 1-3 mm/yr uncertainties of the velocities for five INEGI GPS stations north of the Mexican Volcanic Belt, (2) the Yucatán peninsula moves eastward at ~3±1 mm/yr relative to North America, and (3) the Baja California peninsula is detached from the Pacific plate, as proposed by Dixon *et al.* (2000).

Our new plate-based geodetic model differs from previous geodetic models for this region (e.g. DeMets and Dixon, 1999; Márquez-Azúa and DeMets, 2003) in several respects. For the first time, GPS observations from Mexico are used to constrain North American plate motion, thereby reducing reference frame uncertainties in Mexico. Similarly, new GPS velocities for sites on Socorro and Clarión islands are combined with velocities for 18 additional Pacific plate sites to derive a new Pacific plate angular velocity. Finally, sites in the Yucatán peninsula are used to estimate for the first time an angular velocity vector that describes the motion of the Yucatán block in southeastern Mexico.

DATA

Estimates of the angular velocity vectors for the Pacific and North American plates and the Yucatán block are derived using data from four sources, each briefly described below. Our GPS data analysis procedures are described in the following section.

The only previously unreported data that we use are GPS obervations from campaign sites on Socorro and Clarión islands in the eastern Pacific (Figure 1). Measurements in 1997, 1999, and 2000 were made continuously at each site for 5-16 days using a dual-frequency GPS receiver equipped with a Trimble choke ring or geodetic L1/L2 ground-plane antenna. Both geodetic monuments consist of a steel pin that is epoxied into basalt. The coordinate time series for these two sites are shown in Figure 3.

Our second source of data, described in detail by Márquez-Azúa and DeMets (2003), consists of velocities from the INEGI continuous GPS network. Fourteen of the fifteen INEGI sites shown in Figure 1 began operating in February-April of 1993 and one site (CAMP) began operat-

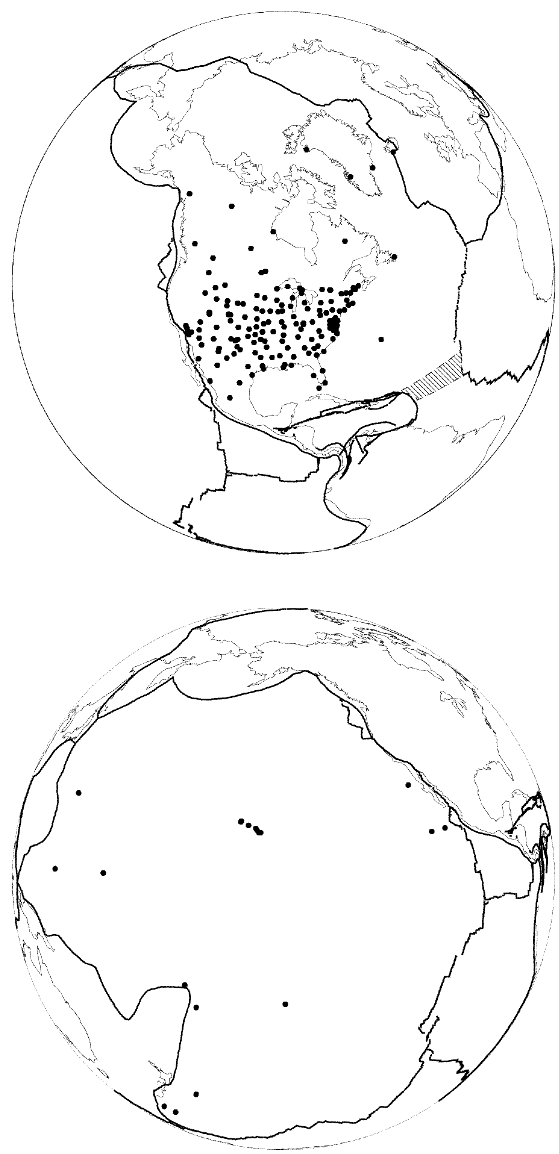

Fig. 2. Locations of GPS sites whose velocities are used to solve for the North American plate (upper) and Pacific plate (lower) angular velocity vectors.

ing in September, 1995. Each station velocity is constrained by ~400 station-days of data spaced at one week intervals through July, 2001. Fourteen of the fifteen sites have linear time series that yield well-constrained site velocities suitable for this analysis. Displacements of station COLI in western Mexico are strongly influenced by coseismic and postseismic motion related to the 9 Oct 1995 M=8 Colima-Jalisco earthquake (Márquez-Azúa *et al*., 2002) and are not used herein.

The above data are supplemented by more than 280 000 station-days of continuous GPS data from 160 continuously operating GPS sites on the North American plate outside of Mexico and 12 sites on the Pacific plate (Figure 2). These data greatly expand the geographic coverage of geodetic sites from both plates, which is essential for estimating accurate and precise plate angular velocity vectors. We selected sites based on their locations with respect to well-defined plate boundary structures and required sites to have two years or more of continuous observations as of March 1, 2003.

Finally, we use velocities from Beavan *et al*. (2002) for GPS sites 5507 and 5514 in the southwestern Pacific and sites MARC, NIUC, TRUK, and WSAM in the western Pacific. These sites significantly expand our geographic coverage of the Pacific plate interior and provide much-needed redundancy for this sparsely sampled plate. Since we did not process the raw GPS data from these six sites, we tested rigorously for any systematic differences between the 12 Pacific plate velocities we derived and those from Beavan *et al*. We did not find any significant differences between the two, which employ identical geodetic reference frames (ITRF2000), but different data analysis software and procedures (GIPSY versus GAMIT).

METHODS

GPS data reduction

We analyzed all GPS phase and code measurements using a standard point positioning strategy and GIPSY analysis software (Zumberge *et al*., 1997). Precise satellite orbits and clocks were provided by the Jet Propulsion Laboratory (JPL). Daily GPS station coordinates were initially estimated in a no-fiducial reference frame (Heflin *et al*., 1992) and were transformed to ITRF2000 (Altamimi *et al*., 2002) using daily 7-parameter Helmert transformations from JPL. All of the velocities we use, including those from Beavan *et al*. (2002), are specified relative to ITRF2000.

Estimation of station velocities and uncertainties

Individual site velocities were derived via linear regression of a site's coordinate time series. For sites where the GPS antenna was moved without performing an intersite geodetic tie, we also estimated the 3-D antenna offset and constrained the site velocity to remain the same before and after the antenna offset. Table 1 lists the coordinates and velocities for the sites on Socorro and Clarión islands and Figure 3 shows the coordinate time series for these sites relative to ITRF2000. The velocities and coordinates of the INEGI sites are given by Márquez-Azúa and DeMets (2003).

Following linear regression of each site's coordinate time series, we assessed the data quality and success of the point-positioning analysis strategy using the day-to-day repeatability in the site coordinates. The average day-to-day coordinate repeatabilities are 3.7 mm, 5.7 mm, and 10.2 mm

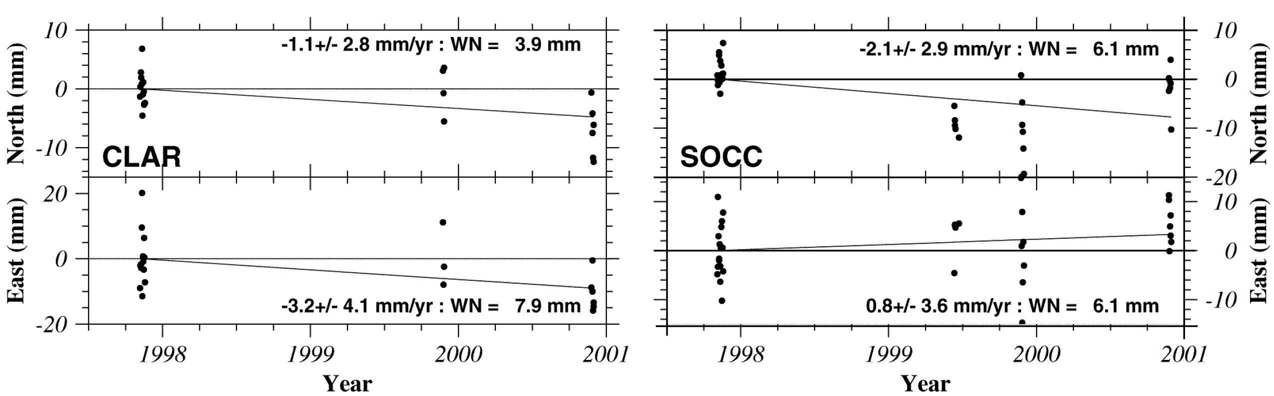

Fig. 3. Displacements of GPS sites on Clarión and Socorro islands in north and east directions referenced to motion of the Pacific plate (horizontal line). Pacific plate motion is specified by angular velocity vector given in Table 2. Geodetic reference frame is ITRF2000. The velocities given in the diagram are derived from linear regression of the residual displacements and thus show departues of the site's motion from that of the Pacific plate. The velocity uncertainty incorporates the uncertainties in both the observations and predicted Pacific plate motion. WN is the scatter (white noise) of the daily locations with respect to multi-day-average site locations.

Table 1

Horizontal GPS Site Velocities

Site	Time span	Lat. °N	Long. °E	Velocities V_n	(mm/yr) V_e
Clarión	3.1	18.34	-114.74	22.3±2.8	-59.5±4.0
Socorro	3.1	18.73	-110.94	19.7±2.8	-54.7±3.6

Velocities are specified relative to ITRF2000. Uncertainties are 1-σ. The time span gives the length of the GPS time series in years.

in the north, east, and vertical components relative to running 30-day averages. These are comparable to repeatabilities reported by many previous studies. We further reduced the respective daily scatters to 2.3 mm, 4.5 mm, and 8.1 mm in the north, east, and vertical components via estimation and removal of spatially-correlated, inter-site noise, as described by Márquez-Azúa and DeMets (2003).

Site velocity uncertainties are determined using an error model that combines estimates of the white noise, flicker noise, and random monument walk present in a site's coordinate time series (Mao *et al*., 1999). We estimated the magnitudes of the white and flicker noise for each site directly from its coordinate time series and further assumed that all sites experience 2 mm/$\sqrt{yr}$ of random monument walk, in accord with estimates reported by Langbein and Johnson (1997). If we had instead assumed that random monument walk was only 1 mm/$\sqrt{yr}$, the uncertainties in all the results presented below would have decreased by approximately 20%. This would not have significantly altered our results or conclusions.

Estimation of plate angular velocity vectors

We derive the angular velocity vector that best describes the motion of a given plate or crustal block relative to ITRF2000 ($_{PLATE}\overline{\omega}_{ITRF2000}$) via a least squares inversion of GPS station velocities from that plate. The best-fitting angular velocity vector, which minimizes the weighted least-squares misfit to the station velocities using fitting functions described by Ward (1990), is used to transform the motions of individual sites from the ITRF2000 reference frame to a plate-based reference frame. This transformation is accomplished via simple vector subtraction, as follows: $_{SITE}\overline{v}_{PLATE} = {}_{SITE}\overline{v}_{ITRF2000} - ({}_{PLATE}\overline{\omega}_{ITRF2000} \times \overline{r})$ where $_{SITE}\overline{v}_{ITRF2000}$ represents the station velocity relative to ITRF2000 and $_{PLATE}\overline{\omega}_{ITRF2000} \times \overline{r}$ is a vector cross-product that represents the predicted motion of the plate relative to ITRF2000 at station location $\overline{r}$. Uncertainties in the best-fitting angular velocity vector are given by a 3x3 covariance matrix derived from the least-squares inversion of the GPS station velocities. The covariances for $_{PLATE}\overline{\omega}_{ITRF2000} \times \overline{r}$ add linearly to the covariances for $_{SITE}\overline{v}_{ITRF2000}$ to yield the uncertainty in the motion of the site in the plate-fixed reference frame. All uncertainties cited below are calculated in this manner.

RESULTS

North American plate reference frame

Figure 4 shows the velocities of North American plate sites relative to ITRF2000. Márquez-Azúa and DeMets (2003) demonstrate that five out of the six Mexican sites north of the Mexican Volcanic Belt move with the North American plate within their estimated uncertainties. Site TAMP, the lone exception, is directly onshore from the Mexican Ridges deformation belt, a submarine fold belt related to an eastward-directed gravity slide of the offshore sediments (Bryant *et al*., 1968; Buffler *et al*., 1979). Given the presumed correspondence between the eastward motions of TAMP and the offshore gravity slide, we did not use its velocity to constrain North American plate motion.

The angular velocity vector that minimizes the weighted, least-squares misfit to the velocities of the 160 North American plate sites and five Mexican sites north of the Mexican Volcanic Belt (CHIH, CULI, FMTY, HERM, and INEG) fits those data well (Figure 5). Of the 330 site velocity components, 68% of the rates deviate from their predicted values by less than 1.0 mm/yr and 68% of the residual orthogonal components are smaller than 1.1 mm/yr. The station rates exhibit the expected sinusoidal increase in their magnitudes as a function of angular distance from the best fitting pole (Figure 5). Similarly, the velocity components orthogonal to the rates are scattered randomly about zero, as expected given that the sites should not move toward or away from the pole of rotation. Reduced chi square for the best-fitting angular velocity vector is 0.98, close to the expected value of 1.0. This suggests that the GPS site velocity uncertainties we use are adequate.

The best-fitting North American plate angular velocity vector (Table 2) is strongly constrained by the numerous and widely distributed GPS velocities. For example, if we use the new angular velocity vector and its covariances to predict North American plate motion (and its uncertainties) at locations in southern Mexico, the 1σ uncertainties in the predicted site velocities are only ±0.13 mm/yr in the north and east components. For comparison, typical 1σ uncertainties for GPS site velocities that are derived from several years of continuous or campaign measurements are ±1-3 mm/yr. Use of the new North America-ITRF2000 angular velocity to transform a GPS site velocity from an ITRF2000-fixed to a

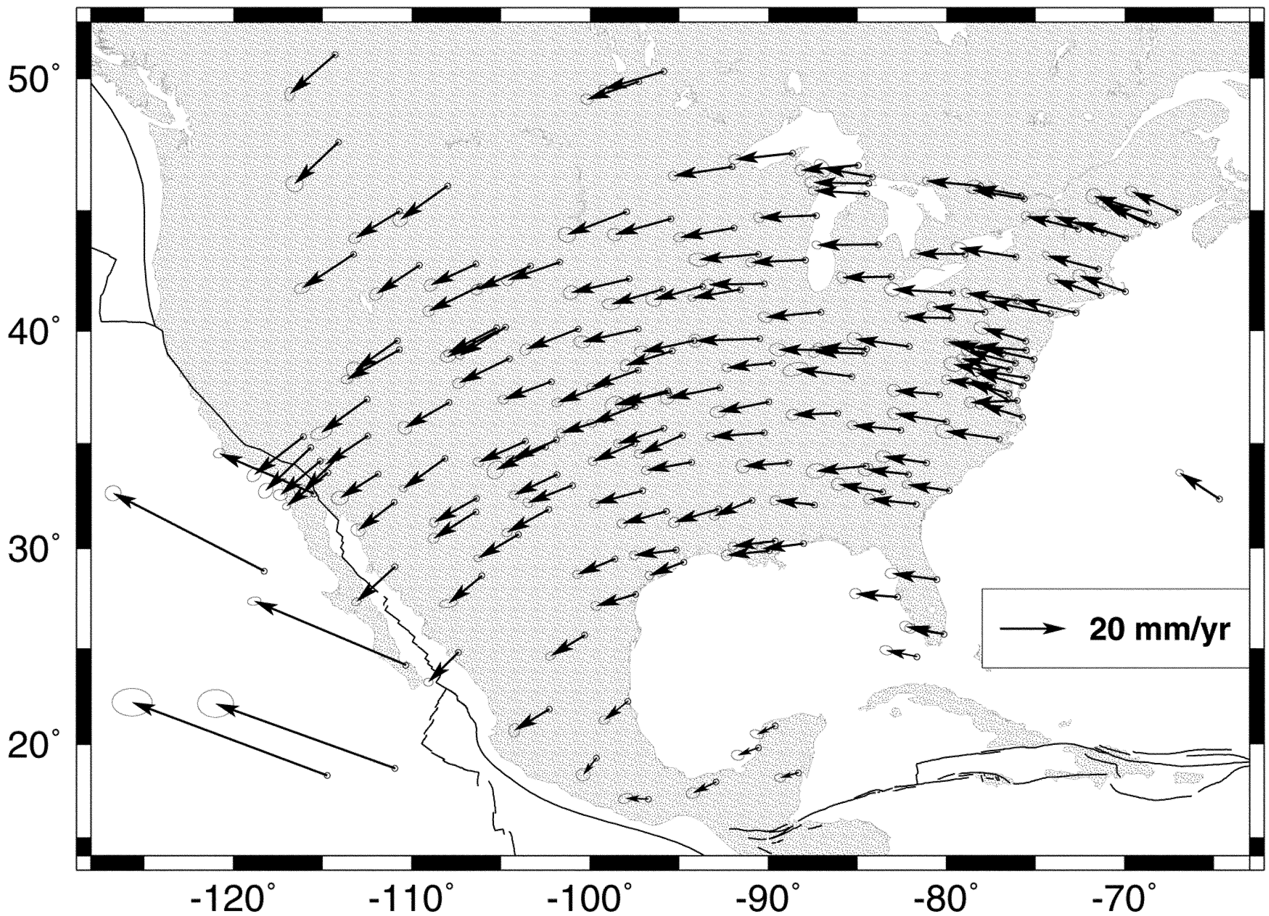

Fig. 4. Velocities of GPS sites relative to ITRF2000. Although the velocities of some Pacific and North American plate sites that fall outside the boundaries of this map are not shown for clarity, the velocities of all sites shown in Figure 2 are used in the analysis. Uncertainty ellipses are 2-D, 1-σ.

North American-fixed reference frame thus only slightly increases the overall uncertainty in the site velocity.

Previous studies that estimate the present motion of the North American plate from GPS observations rely on velocities from many fewer sites with significantly shorter time series. For example, Dixon *et al*. (1996), DeMets and Dixon (1999), Kogan *et al*. (2000), Gan and Prescott (2001), Beavan *et al*. (2002), and Sella *et al*. (2002) respectively employ velocities from 8, 16, 10, 55, 9, and 64 North American plate GPS sites, none in Mexico. In contrast, we use many more site velocities (165), some with observation time spans as long as 10.2 years. Our model thus takes advantage of the continued expansion of continuous GPS receivers in North America and the increased number of data that are available through time.

Figure 5 compares the fit of the best-fitting North American plate angular velocity vector to that of Beavan *et al*. (2002), the only study published recently enough to employ the same geodetic reference frame that we employ (ITRF2000). The Beavan *et al*. (2002) model fits the gradient in our observed rates, but misfits the perpendicular velocity components by ~0.5 mm/yr. This small, but significant difference in the model predictions results from the relatively small number of sites (9) that Beavan *et al*. use to define North American plate motion. For example, if we estimate the North American plate angular velocity vector using our own velocities for the same nine stations that were employed by Beavan *et al*. (2002), the resulting angular velocity vector is indistinguishable from that of Beavan *et al*. (2002).

Pacific plate reference frame

The 20 sites we use to estimate the Pacific plate angular velocity vector superbly define the sinusoidal change in rates as a function of angular distance from the pole of rota-

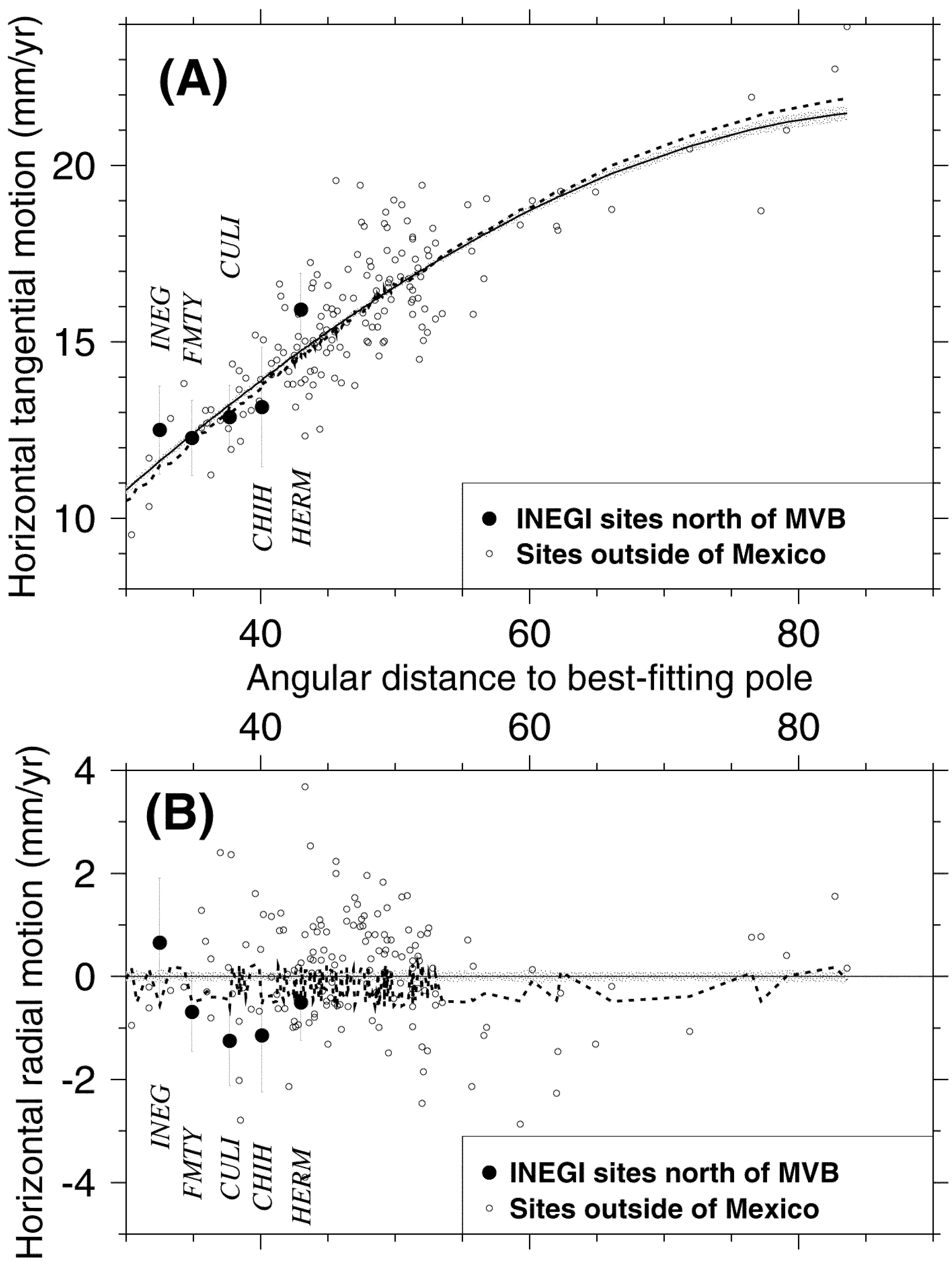

Fig. 5. Velocity components for 160 North American plate and five INEGI sites relative to predictions (bold line) of the best-fitting North American plate angular velocity vector (Table 2). Dashed line shows predictions of North American plate angular velocity vector from Beavan *et al.* (2002). The geodetic reference frame for both models is ITRF2000. A-The tangential velocity component for each site is determined by projecting the observed site velocity onto the small circle centered on the best-fitting pole and passing through the site. All error bars are 1-σ. B-The radial component of the horizontal velocity is perpendicular to the tangential component and should be zero since sites should not move toward or away from the pole of rotation. Stippled regions show 1-σ uncertainties in the model predictions. MVB is Mexican Volcanic Belt.

Table 2

Plate angular velocity vectors

Plate	N	χ^2_ν	Angular velocity[1]			Covariances					
			Lat	Long	ω	σ_{xx}	σ_{yy}	σ_{zz}	σ_{xy}	σ_{xz}	σ_{yz}
NA	165	0.98	-5.66	-84.55	0.194	0.15	1.60	1.18	0.02	-0.01	-1.18
PA	20	0.65	-63.69	109.28	0.677	6.82	2.26	3.09	0.95	-0.18	-0.12
YU	4	0.37	-7.4	-80.3	0.125	5.1	4838.2	591.4	16.5	-5.0	-1675.8
NA-PA	185	0.95	50.18	-76.13	0.766	6.87	3.86	4.27	0.97	-0.19	-0.13
YU-NA	169	0.97	2.4	88.0	0.070	5.3	4839.8	592.5	16.5	-5.0	-1675.8

Reference frame for single plate angular velocity vectors is ITRF2000 and second listed plate for relative angular velocity vectors. Positive angular rotation rates correspond to counter-clockwise rotation about the pole. *N* is the number of GPS site velocities used to determine the best-fitting angular velocity vector. χ^2_ν is the weighted least-squares fit divided by the number of velocity components (2**N*) minus 3, the number of parameters adjusted to fit the data. Latitude and longitude are in degrees north and east, respectively. The rotation rate ω has units of degrees per million years. Angular velocity covariances are Cartesian and have units of 10^{-9} radians^2 per Myr^2. Abbreviations: NA, North America; PA, Pacific; YU, Yucatán block.

tion (Figure 6). The Pacific plate station velocities typically agree within ±2 mm/yr with the predictions of their best-fitting angular velocity vector, with an overall root-mean-squares misfit of 1 mm/yr. Our RMS fit is comparable to but slightly worse than the 0.6 mm/yr RMS misfit reported by Beavan *et al*. (2002) for their 12-station Pacific plate solution.

The best-fitting Pacific plate angular velocity vector (Table 2) predicts site velocities that are remarkably similar to those predicted by the Beavan *et al*. (2002) model (Figure 6), differing by only fractions of a millimeter per year at nearly all locations. Relative to the Pacific plate, the residual motions of the new sites on Socorro and Clarión islands (Figure 7) are smaller than their estimated uncertainties. Both sites thus move with the stable plate interior within their still-substantial uncertainties (±4 mm/yr).

Pacific-North America motion

Simultaneous inversion of the 20 Pacific plate and 165 North American plate station velocities yields an up-to-date estimate for the relative motion of the Pacific and North American plates (Table 2). The new Pacific-North America angular velocity vector predicts a seafloor opening rate along the Gulf rise in the southern Gulf of California of 50.8±0.5 mm/yr, in excellent accord with the 50-52 mm/yr geologic estimate of DeMets and Dixon (1999). For comparison, the GPS-based angular velocity vectors from DeMets and Dixon (1999) and Beavan *et al*. (2002) predict respective opening rates of 53.1±1.5 mm/yr and 52.3±0.3 mm/yr at the same location in the southern Gulf of California. Motion predicted by our new angular velocity vector is slower than but consistent within uncertainties with the prediction of the DeMets and Dixon (1999) model, which employs a slightly older geodetic reference frame (ITRF97) and many fewer geodetic velocities. In contrast, the difference between the prediction of our own model and that of Beavan *et al*., both of which use ITRF2000, significantly exceeds their combined uncertainties.

To test whether the significant difference between the velocities predicted by our own model and that of Beavan *et al*. (2002) stems from the subset of sites whose velocities are used to derive each model, we modified our North American station velocities so that we used only the velocities from the nine North American plate sites that Beavan *et al*. employed. An inversion of these nine station velocities and the 20 Pacific plate station velocities described above gives a modified model for Pacific-North America motion that predicts a seafloor spreading rate in the Gulf of California of 51.8 mm/yr. Within uncertainties, this agrees with the 52.3 mm/yr rate predicted by the Beavan *et al*. (2002) model, but is faster than the 50.8 mm/yr rate derived from the 160 North American plate station velocities described above. We conclude that the faster Pacific-North American plate motion predicted by the Beavan *et al*. (2002) model is principally an artifact of the limited number of sites that they used to estimate North American plate motion.

Yucatán block reference frame

Transformation of the INEGI GPS velocities into the North American plate reference frame (Figure 7) reveals that all four INEGI GPS sites located on or near the Yucatán peninsula move eastward relative to the plate interior. With re-

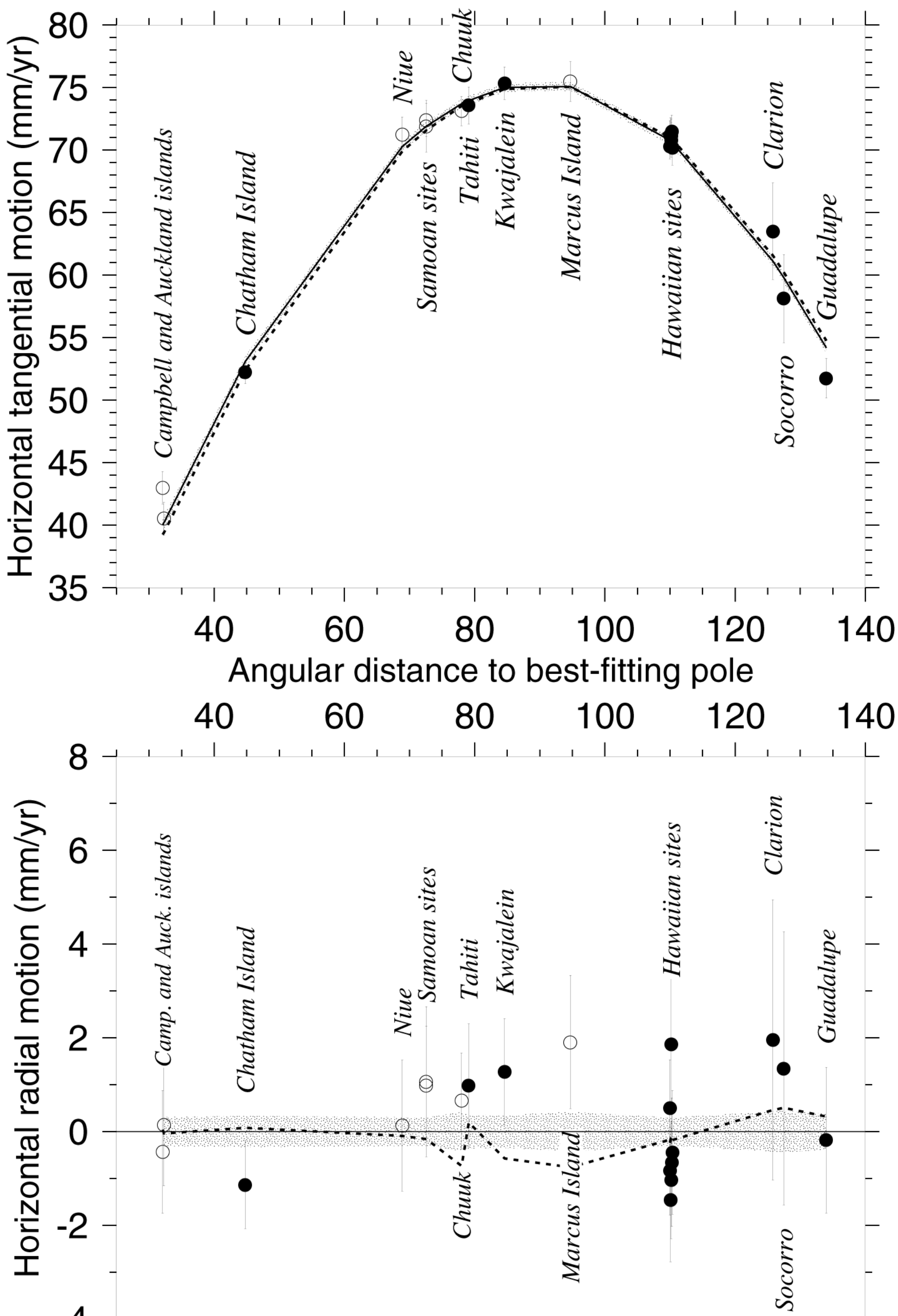

Fig. 6. Velocity components for Pacific plate sites relative to predictions (bold line) of their best-fitting Pacific plate angular velocity vector (Table 2). Dashed line shows predictions of Pacific plate angular velocity vector from Beavan *et al*. (2002). The geodetic reference frame for both models is ITRF2000. Velocities shown with solid and open circles are from our own analysis and that of Beavan *et al*. (2002), respectively. Upper - Tangential velocity components. See caption to Figure 5. All error bars are 1-σ. Lower - Radial velocity components. See caption to Figure 5. Stippled regions show 1-σ uncertainties in the model predictions.

spective speeds of 2.9±1.4 mm/yr, 3.1±1.2 mm/yr, 4.6±1.2 mm/yr, and 1.7±1.3 mm/yr, sites CAMP, CHET, MERI, and VILL illustrate remarkably consistent motion that differs from North American plate motion at very high confidence levels (Márquez-Azúa and DeMets, 2003). Possible explanations for the apparent eastward velocity bias include the following: (1) problems with the raw data or biases introduced by our analysis procedures, (2) an elastic crustal response to frictional locking of the Middle America subduction zone, (3) postseismic afterslip or viscoelastic flow in response to large historic earthquakes within several hundred km of the Yucatán peninsula. None however are convincing, for reasons described by Márquez-Azúa and DeMets (2003). Given the absence of evidence for the above explanations, Márquez-Azúa and DeMets (2003) conclude that these four sites define an independent Yucatán block. They note however that the only independent geologic evidence for the existence of such a block consists of a few scattered, small earthquakes in the Campeche basin west of the Yucatán peninsula (Figure 1). Marine seismic reflection profiles from the Yucatán basin east of the peninsula do not reveal any folding or faulting of young sediments that could accommodate eastward translation of the peninsula (Rosencrantz, 1990). Additionally, there appear to be no prominent structures such as active grabens that might accommodate extension in the Isthmus of Tehuantepec (Barrier *et al*., 1998).

If an independent Yucatán block exists, it constitutes a natural geological reference frame for GPS-based studies of deformation in southeastern Mexico. Given that the data needed for a strong test for its existence will not be available for at least several more years (see discussion), we assume for now that there is a distinct Yucatán block and invert the velocities for stations CAMP, CHET, MERI, and VILL to estimate its best-fitting angular velocity vector (Table 2). Relative to the North American plate, the best fitting Yucatán-North American plate angular velocity vector predicts motion of 3.0±0.7 mm/yr toward S82°E±10° degrees near the geographic center of the Yucatán peninsula. Uncertainties in the velocities predicted by this model increase rapidly with distance from the Yucatán peninsula since no data from outside the Yucatán peninsula constrain the model.

Tectonic implications

Transforming the INEGI GPS velocities into the newly-derived Pacific plate and North American plate reference frames (Figure 7) clearly demonstrates the utility of employ-

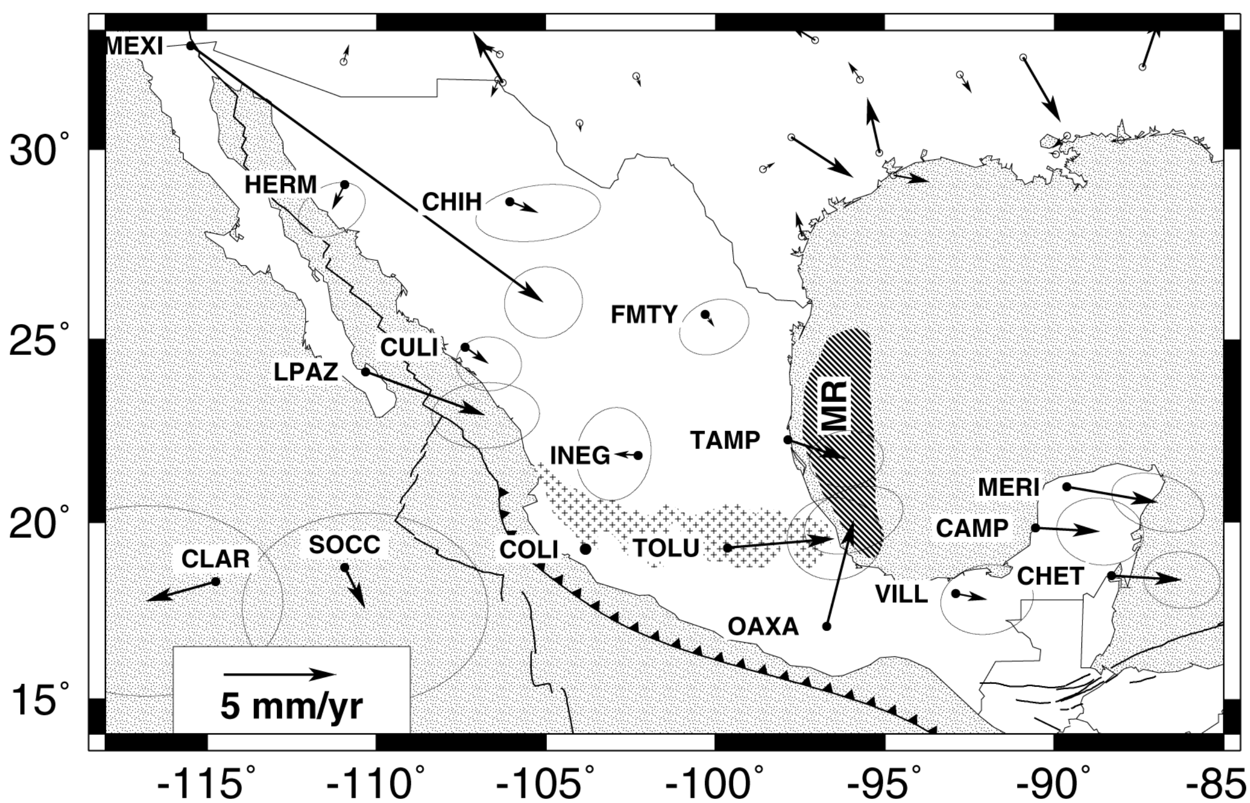

Fig. 7. Residual velocities of INEGI GPS sites and GPS sites on Socorro and Clarión islands relative to either the Pacific plate (CLAR, SOCC, LPAZ, and MEXI) or the North American plate (all other sites). Uncertainty ellipses are 2-D, 1-σ. Abbreviations: MR, Mexican Ridges deformation belt.

ing plate-based geodetic reference frames to describe GPS-derived site velocities. In contrast to the site velocities that are shown in Figure 4, which are difficult to interpret because they are referenced to ITRF2000, the station velocities shown in Figure 7 clearly reveal large-scale block motions such as the eastward motion of Yucatán peninsula sites relative to the North American plate and the southeastward motion of the southern Baja California peninsula relative to the Pacific plate. Evidence that the Yucatán peninsula may be part of a previously unrecognized crustal block that is trapped between the stable interiors of the Caribbean and North American plates is surprising and has important implications for future tectonic studies of southern Mexico. A strong test for the existence of an independent Yucatán block will almost certainly require new geodetic measurements, which are easier to relate to neotectonic deformation than are structural or paleomagnetic observations. In particular, a strong test will require new continuous GPS stations in the Yucatán peninsula and the Isthmus of Tehuantepec (of which there are presently none) and several years of continuous observations at these new stations in order to reduce their velocity uncertainties to a level small enough (±1-2 mm/yr) for a strong test (Blewitt and Lavallee, 2002).

A second topic that is critical for future studies of the tectonics of southern Mexico is whether areas south of the Mexican Volcanic Belt and west of Villahermosa in Tabasco (site VILL) move with the North American plate interior or are instead detached from North America, possibly along faults in the Mexican Volcanic Belt. At least two lines of evidence suggest that the Mexican Volcanic Belt is not a major detachment zone. Detailed structural studies of the numerous faults within the Mexican Volcanic Belt indicate that Neogene motion across the volcanic belt appears to be limited to NNW-SSE-oriented extension of only 0.2±0.05 mm/yr (Suter *et al.*, 2001). In addition, the geodetic direction at site OAXA, south of the Mexican Volcanic Belt, agrees well with the elastic shortening direction predicted by an elastic half-space model in which Cocos-North America convergence across the Middle America subduction zone is responsible for elastic strain accumulation in southern Mexico (Márquez-Azúa and DeMets 2003). Geodetic measurements now being made by assorted groups along the Pacific coast of Mexico will enable strong future tests of the hypothesis that the North American plate extends south of the volcanic belt.

A third unanswered question is whether the apparent eastward motion of site TAMP is related to east-directed gravity sliding at the basal detachment underlying the submarine Mexican ridges deformation belt, and if so, whether other near-coastal areas could be affected similarly. We cannot exclude the possibility that the apparent eastward motion of TAMP is caused by instability of the building in which the geodetic monument is anchored, or that it represents a subtle eastward bias introduced by our data processing procedures. If the latter were true, it could also explain the eastward biases at the four Yucatán peninsula sites. Future geodetic measurements stretching along and inland from the Gulf Coast would constitute a strong basis for distinguishing between these alternatives.

Finally, tectonic studies of the Baja California peninsula would benefit significantly from continued improvements in estimates of present Pacific plate motion. For example, geodetic evidence that GPS stations in the Baja California peninsula are moving relative to the Pacific plate interior implies that faults along the Pacific coast of the peninsula still carry measurable slip (Dixon *et al.*, 2000). Estimates of the magnitude of such slip depend critically on accurate estimates of the motion of the Pacific plate in the vicinity of the Baja peninsula. Using our newly estimated Pacific plate angular velocity vector (Table 2), transformation of the geodetic velocity for the GPS station LPAZ near the southern end of the peninsula to a Pacific plate reference frame yields residual station motion of 5 ± 1 mm/yr toward S69°E±12°. The station motion is intermediate between the motions of the adjacent North American and Pacific plates and is consistent with a model in which much of the Baja California peninsula is detached from the Pacific plate.

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