GPS determination of current Pacific–North American plate motion

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ABSTRACT

Global Positioning System (GPS) data, collected by campaign-style GPS experiments at five sites along the Gulf of California in 1996 and 1998, determine a locally based estimate for current relative motion between the Pacific and North American plates. At the mouth of the Gulf of California, the Pacific plate moves 50.4 ± 3.4 mm/yr, along an azimuth of N59.0°W ± 2.7°, relative to mainland Mexico. These estimates substantiate and refine previous locally based GPS-determined rates, and agree with GPS determinations of global plate motion. A reexamination of magnetic anomalies in the gulf used in the widely accepted NUVEL-1A global plate model has yielded an average Pacific–North American relative velocity from 0.78 Ma to the present of 51.1 ± 2.5 mm/yr. The new GPS-determined velocity agrees with this estimate, supporting the ideas that the transfer of Baja California to the Pacific plate continued until ca. 1 Ma, and that the current Pacific–North American rate is greater than the 3.16 Ma average. The azimuth determination is ~5° west of the NUVEL-1A results calculated from earthquake slip vectors and azimuths of gulf transforms offsetting both oceanic and continental crust. The Tamayo fracture represents the only fault zone used in the NUVEL-1A model that offsets solely oceanic crust. This fault zone trends N60°W, consistent with the GPS-determined azimuth at the mouth of the gulf.

INTRODUCTION

Until recently, estimates of relative plate motion have relied on several-million-year averages determined from magnetic anomalies, transform-fault azimuths, and hotspot tracks, which collectively yield global plate circuits (Minster and Jordan, 1978; DeMets et al., 1990, 1994). Determining relative Pacific–North American plate motion (Fig. 1) has been hampered by its sensitivity to relatively small changes in input data. The widely accepted NUVEL-1A global plate circuit, using magnetic anomalies in the Gulf of California, predicted an average Pacific–North American velocity over 3.16 m.y. of 49 mm/yr with an azimuth of N53.9°W at the mouth of the Gulf of California (DeMets et al., 1994). Studies in the western United States showed that the rates of right-lateral slip along the San Andreas fault are significantly less than the global plate-circuit estimates for Pacific–North American motion (Sieh and Jahns, 1984; DeMets et al., 1987; Weldon and Humphreys, 1986). Distributed right-lateral slip on faults west of the San Andreas fault, and east to the Rio Grande rift in places such as the eastern California shear zone (Dokka and Travis, 1990) and the Basin and Range province, accommodates this missing plate motion. Pacific–North American motion was also determined from geologic data in California, from which slip estimates on active faults were accumulated into a relative-plate-motion vector (Weldon and Humphreys, 1986; Humphreys and Weldon, 1994). This approach predicts a Pacific–North American rela-

Figure 1. Pacific–North American plate margin in Gulf of California. ECSZ = eastern California shear zone (modified from Ortlieb et al., 1989).

Geology; April 1999; v. 27; no. 4; p. 299–302; 2 figures; 1 table.
tive velocity of 48 mm/yr along an azimuth ~7° clockwise of the NUVEL-1A direction at the same location.

Regional tectonic history indicates that Baja California has episodically shifted from the North American plate to its present location on the Pacific plate (Stock and Hodges, 1989). Completion of this transfer is assumed to have taken place by 3.6 Ma, when sea-floor spreading began in the southern Gulf of California along the Gulf Rise (DeMets, 1995). Continental deformation associated with this process could systematically cause underestimates of Pacific–North American relative motion from magnetic anomalies in the Gulf of California. Furthermore, because the NUVEL-1A prediction averages the rate over several million years, it may not reflect changes during that time interval. Recent analysis of sea-floor spreading rates has yielded a more refined Pacific–North American plate motion averaged from 0.78 Ma to the present (DeMets, 1995). The global plate models use azimuth and slip orientation along transform faults in the Gulf of California for determining plate-motion azimuth. Nearly all of these transform faults interact with continental crust; their azimuths may not directly reflect relative plate motion.

Global Positioning System (GPS) geodesy provides an independent estimate of global plate motions. Structural complexities of the Pacific–North American plate boundary in continental areas pose difficulties in geodetically determining relative plate motion. The narrow plate boundary in the southern Gulf of California lends itself to a geodetic survey. In the late 1980s, a GPS network was installed along the gulf by

Figure 2. GPS-determined site velocities in North America reference frame. Velocities are shown in black with 95% confidence ellipses; CICESE (CICE) was used as fiducial site, so no velocity is shown. For Cabo San Lucas (CABO), Concepcion (CONC), and Los Mochis (MOCH) sites, velocities are determined relative to North American plate motion at Mazatlan (MAZA) for each site. MOCH and MAZA lie on North American plate; CABO and CONC show Pacific plate motion. Colored vectors show Pacific–North American plate motion at our sites predicted from published Euler poles determined from globally distributed space geodesy sites; Smith et al. (1996) in blue (very long baseline interferometry), Argus and Heflin (1995) in yellow (GPS), Larson et al. (1999) in green (GPS), and NUVEL-1A (DeMets et al., 1994) in red (global plate circuit). Base map shows topography and bathymetry (from Smith and Sandwell, 1997), projected into oblique mercator frame parallel to NUVEL-1A Pacific–North American plate-motion direction (DeMets et al., 1994), using GMT (Wessel and Smith, 1991). NUVEL-1A predicted Pacific plate motion is parallel to long dimension of map; plate boundary is defined by ridge-transform segments evident in bathymetry. Grid annotations are in degrees north latitude and east longitude.
Dixon et al. (1991), who determined a current plate-velocity estimate of 47 ± 7 mm/yr with an azimuth of N57°W ± 6°. In the past decade, GPS precision has improved dramatically through enhancement of the global orbit-control network and equipment technology. We have taken advantage of these improvements by using higher precision GPS equipment and data analysis when we reoccupied a subset of the same GEOMEX network used by Dixon et al. (1991).

METHODS

Four GPS sites distributed around the mouth of the Gulf of California were occupied in campaign mode during 1996 and again during 1998 (Fig. 2). In addition, we analyzed data from a continuous site in Ensenada (CICESE). In February 1996, three observation sessions were made at the MAZA (Mazatlan) and CONC (Concepcion) sites. At MAZA the sessions lasted 23 h, 24 h, and 15 h. At CONC the sessions lasted 9 h, 21 h, and 14 h. CABO (Cabo San Lucas) was observed for two sessions, one for 25 h and the other for 19.6 h. MOCH (Los Mochis) was observed for one session of 24 h. Continuous monitoring at CICESE provided fiducial control. The 1996 survey used Trimble 4000 SSI receivers with ground plane antennas. In March 1998, four sessions for 24 h each were observed for each site. In addition to the four 24 h sessions, CABO and CONC were observed for a fifth session of 14 hours each, and MOCH was observed for a fifth session of 5 h. The 1998 survey used Trimble 4000 SSI receivers with choke-ring antennas. Data analysis was done with GPSYII software; the baseline precision was one part in $10^{-10}$ (Zumbrunger et al., 1997). The data sets from each survey were combined by differencing baselines to CICESE, so no velocity for CICESE is reported. This yielded velocities that are plotted relative to predicted motion of the North American plate at each location.

RESULTS

GPS sites MAZA and MOCH lie on the North American plate (Fig. 2). In this study we report all velocities and azimuths relative to North American plate motion at Mazatlan. Both CABO and CONC show motion consistent with previous estimates of Pacific plate motion. CABO is moving 50.4 ± 3.4 mm/yr and is directed N59.0°W ± 2.7°. CONC has a velocity of 45.0 ± 3.5 mm/yr with an azimuth of N56.1°W ± 3.2° (Table 1). The difference in azimuth determinations and velocity is representative of their respective distance from the Euler pole. Both CABO and CONC show more westward motion than predicted by NUVEL–1A (Fig. 2).

DISCUSSION

The results from this study provide independent estimates of Pacific–North American plate motion that confirm and refine previous estimates. The velocities determined by this study are ~3 mm/yr greater than, and directed 2°–3° counterclockwise of, the previous local GPS estimate (Dixon et al., 1991) and are closer in magnitude to and 5°–6° counterclockwise of the NUVEL–1A results (DeMets et al., 1994).

The NUVEL–1 global plate model determined average rates of Pacific–North American plate motion since 3 Ma, from five magnetic profiles that cross the Gulf Rise (DeMets et al., 1990). The Gulf Rise is the only ridge segment in the Gulf of California with well-developed magnetic anomalies. Plate-motion direction was determined from six gulf transform azimuths and 26 earthquake slip vectors. Subsequent revisions to the geomagnetic time scale implied that the ages of geomagnetic reversals used in determining NUVEL–1 were too young (DeMets et al., 1994). The resulting correction factor yields NUVEL–1A rates averaged since 3.16 Ma (DeMets et al., 1994).

Structural evolution of northern Baja California (Stock and Hodges, 1989) indicates that its transfer to the Pacific plate was completed by 3.6 Ma, when sea-floor spreading began at the Gulf Rise (DeMets, 1995). To examine whether Baja California has been part of the rigid Pacific plate since 3.6 Ma, DeMets (1995) reanalyzed magnetic anomalies from the Gulf Rise. Data indicate that since spreading commenced, the divergence rates between Baja California and the North American plate increased by ~15% ca. 1 Ma. A velocity of 51.1 ± 2.5 mm/yr results from 0.78 Ma to the present. To compare with these findings a “closure fitting rate” was derived by eliminating possible systematic errors in the NUVEL–1A global plate circuit data and excluding spreading rates from the Gulf of California. The “closure fitting rate” from DeMets (1995) is an independent estimate that agrees with the sea-floor–spreading rate from 0.78 Ma to the present. DeMets’ (1995) findings have been interpreted in two ways. First, because spreading rates between the Baja peninsula and the North American plate prior to 0.78 Ma were much slower than the full Pacific–North American plate motion, part of the Pacific–North American plate velocity may have occurred on structures other than the Gulf Rise until 0.78 Ma. It is possible that there was relative motion between Baja California and the Pacific plate until ca. 1 Ma, followed by an eastward shift of any remaining motions along faults west of the Baja peninsula to the present plate boundary. Evidence of recent movement along these faults (Spencer and Normark, 1979) indicates that southern Baja California may still move slowly relative to the Pacific plate. Alternatively, the ~15% increase in sea-floor–spreading rates could reflect a recent increase in Pacific–North American plate motion. The GPS–determined results reported here agree with the 0.78 Ma average sea-floor–spreading rate and the “closure fitting rate” (DeMets, 1995). This supports a current Pacific–North American plate-motion rate that is faster than the 3.16 Ma average.

In the past few years nonlocal geodetically determined estimates of Pacific–North American plate motion have been derived from GPS (Argus and Heflin, 1995; Larson et al., 1997) and very long baseline interferometry (VLBI) (Smith et al., 1996). The estimates presented here coincide best with those from Larson et al. (1997) (Fig. 2). The GPS global plate model from Larson et al. (1997) yielded relative Pacific–North American plate motion by using data collected over 3–5 years from nine sites on the North American plate, and four sites on the Pacific plate. None of these sites is near or along the Gulf of California. This study determined relative plate-motion velocities ~1 mm/yr greater than those reported here, and like ours, an azimuth that lies 5°–6° counterclockwise of the NUVEL–1A estimates (Fig. 2). It is important to note that while the results from Larson et al. (1997) strongly agree with those from this study, their data were collected over a longer time interval, at sites located far away from those used in this study.

Along the continental transform in California, Humphreys and Weldon (1994) determined motion of the Pacific plate relative to North America by accumulating geologically constrained slip rates along faults into an integrated path-vector solution, which yields relative plate velocity and azimuth. Because plate-motion velocities decrease with proximity to the Euler pole, rates for California cannot be directly compared to those for the mouth of the gulf. It is important to note, however, similar to the results reported here, the relative-plate-motion azimuths determined by Humphreys and Weldon (1994) are directed counterclockwise from that of the NUVEL–1A model.

The GPS–determined plate motion azimuth lies ~5° counterclockwise of the NUVEL–1A

<table>
<thead>
<tr>
<th>Baseline</th>
<th>Velocity components (mm/yr)</th>
<th>Velocity vector (°W of N)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>East</td>
<td>Error</td>
</tr>
<tr>
<td>CABO</td>
<td>-43.19</td>
<td>3.07</td>
</tr>
<tr>
<td>CONC</td>
<td>-37.36</td>
<td>3.19</td>
</tr>
<tr>
<td>MOCH</td>
<td>0.84</td>
<td>3.67</td>
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CABO = Cabo San Lucas, CONC = Concepcion, MOCH = Los Mochis.
prediction of 53.9°W ± 2° at the mouth of the gulf. The global plate model reflects the more northwestward azimuth of central gulf transform faults. These faults may not be sufficient indicators of plate motion because they offset continental crust. Fault orientations may be controlled by preexisting structures, or they may reflect an earlier phase of Baja California–North American motion azimuth (Argus and Gordon, 1990; DeMets et al., 1990). Oceanic crust, in contrast, is stronger and less sensitive to structural heterogeneity. Therefore, fracture zones that offset oceanic crust exclusively may be a more reliable source for azimuth interpretation. The only fracture zone in the region to offset solely oceanic crust is the Tamayo transform, which lies at the mouth of the gulf. The trend of this transform is N60°W (DeMets et al., 1990), within 1° of our GPS-predicted azimuth of N59.0°W.

CONCLUSIONS

The new GPS determination of relative Pacific–North American plate motion reported here refines the local estimates made by previous GPS studies in the late 1980s, and agrees with GPS determinations of global plate motions. The calculated velocity is slightly greater than the NUVEL-1A rate determined from magnetic anomalies in the Gulf of California (DeMets et al., 1994), but it is indistinguishable from the 0.78 Ma average (DeMets, 1995). This result supports the idea that current motion is faster than the 3.16 Ma average. The azimuth of relative plate motion at the mouth of the gulf is ~5° counterclockwise from that of the NUVEL-1A model, consistent with those from the GPS-derived global plate model (Larson et al., 1997) and geologic determination from Quaternary slip vectors (Humphreys and Weldon, 1994). Reliance of NUVEL-1A on central Gulf of California transform orientations may bias the model. The Tamayo fracture zone, however, which offsets entirely oceanic crust, trends N60°W, an azimuth indistinguishable from the GPS result reported here.

ACKNOWLEDGMENTS

This paper originated as Antonelis’s senior thesis at Central Washington University. The project was supported by the National Aeronautics and Space Administration, Solid Earth Science Program grant NAGW-3826 to Central Washington University. Equipment support was granted from National Science Foundation Academic Research Infrastructure Program, grant EAR-9512212 to University Navstar Consortium (UNAVCO), and was matched by Central Washington University. We especially thank Gordon Seitz and Eileen Llona for assistance in collecting GPS data and UNAVCO for equipment support of the 1996 experiment. We gratefully acknowledge the assistance of Todd Williams and Sam VanLaningham in figure preparation. We thank Roland Burgmann and Richard Sedlock for helpful reviews.

REFERENCES CITED


Spencer, J. E., and Normark, W., 1979, Toso-Abrejos fault zone: A Neogene transform plate boundary within the Pacific margin of Baja California: Geology, v. 7, p. 554–557.


Manuscript received August 31, 1998
Revised manuscript received December 8, 1998
Manuscript accepted January 5, 1999