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New Kinematic Models for Pacific-North America Motion from 3 Ma to Present, II: Evidence for a "Baja California shear zone"

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Abstract. We use new models for present-day Pacific-North America motion to evaluate the tectonics of offshore regions west of the Californias. Vandenburg in coastal Alta California moves at the Pacific plate velocity within uncertainties (~1 mm/yr) after correcting for strain accumulation on the San Andreas and San Gregorio-Hosgri faults with a model that includes a viscoelastic lower crust. Modeled and measured velocities at coastal sites in Baja California south of the Agua Blanca fault, a region that most previous models consider Pacific plate, differ by 3-8 mm/yr, with coastal sites moving slower that the Pacific plate. We interpret these discrepancies in terms of strain accumulation on known on-shore faults, combined with right lateral slip at a rate of 3-4 mm/yr on additional faults offshore peninsular Baja California in the Pacific. Offshore seismicity, offset Quaternary features along the west coast of Baja California, and a discrepancy between the magnetically determined spreading rate in the Gulf Rise and the total plate rate from a geological model provide independent evidence for a "Baja California shear zone."

Introduction

Miocene and younger interaction between the Pacific and North American plates includes the progressive movement of the plate boundary toward the continental interior, as North America overode spreading centers separating the Pacific and other, now largely subducted oceanic plates [*Atwater*, 1989]. The current tectonic phase began 3-6 million years ago when seafloor spreading began in the Gulf of California, transferring Baja (lower) California to the Pacific plate and contributing to the formation of the "big bend" in the San Andreas transform fault in Alta (upper) California. However, seismicity offshore Baja and Alta California to the west attests to continuing tectonic complexity (Figure 1).

DeMets and Dixon [1999] derived a precise estimate of present day Pacific-North America motion, showed that this motion is significantly faster than the NUVEL-1A prediction [*DeMets et al.*, 1994], and showed that Pacific-North America motion has been steady for the last few million years within uncertainties. In this paper, we compare the estimated plate velocity to GPS site velocities in coastal Baja and Alta California, find that these rates are significantly slower than the full plate rate (Figure 1) and present an explanation for these discrepancies.

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GPS Data Analysis and Results

Site velocities (Figure 1) reflect data acquired in 1993-98 campaigns, except as noted in Table 1. Analysis procedures for this paper and *DeMets and Dixon* [1999] are identical, and follow *Dixon et al.* [1997]. Station velocities are first defined in ITRF-96 [*Sillard et al.*, 1998]. We then define stable North America by minimizing the velocities of 16 stable interior sites. Error estimation follows *Mao et al.* [1998] and *Dixon et al.* [2000].

Table 1 lists site velocities relative to North America. Observed azimuths agree with predicted Pacific plate motion using the geological model of *DeMets and Dixon* [1999] (used here because it is more precise than the GPS model; the two agree to better than 1.6 mm/yr in rate and 2.1° in azimuth). However, the observed rates are all significantly less than the predicted Pacific rate, by 3-8 mm/yr, reflecting elastic strain accumulation on nearby locked faults, and perhaps slip on additional faults offshore to the west. For CAT1 and CICE, the elastic strain effects are large, and known offshore faults accommodate additional slip, so discrepancies are expected. However, VNDP, SNI1, CADG, SLRE, SAIS and MELR (hereafter coastal Pacific sites) are located southwest of all known plate boundary faults and thus are arguably on the Pacific plate; their velocities should agree with predicted Pacific motion after correcting for elastic strain. We estimated the magnitude of these effects using the coupling model of *Savage and Lisowski* [1998] as implemented in *Dixon et al.* [2000]. The model includes a seismogenic elastic layer over a viscoelastic half space, and accounts for long term earthquake effects. For example, VNDP (Vandenburg), 100 km southwest of the San Andreas fault, is assumed to be affected by strain accumulation on this fault, with a slip rate of 34 mm/yr, locking depth of 12 km, recurrence interval of 206 years, and last earthquake in 1857. This results in a 3.6 mm/yr addition to VNDP's observed velocity (Figure 2). The San Gregorio-Hosgri fault passes close to VNDP, with a slip rate of ~2 mm/yr [*Sorlien et al.*, 1999]. Its strain correction is ~ 1 mm/yr, shown separately (Figure 2), for a total correction of 4.6 mm/yr. The purely elastic correction would be 2.6 mm/yr or 3.7 mm/yr respectively for 15 or 25 km locking depths. For northern Baja California, we calculated corrections for the Agua Blanca (4 mm/yr) and San Miguel-Vallecitos (SMV; 3 mm/yr) faults [*Bennett et al.*, 1996]. We assumed that

Table 1. GPS velocities relative to stable North America

Site	Latitude °North	Longitude °East	Rate mm/yr	Azimuth degrees
CABO[1]	22.92	250.14	50.3±2.9	305.6±3.1
CADG	31.36	243.68	44.0±1.5	317.0±1.8
CAT1[2]	33.45	241.52	43.9±2.0	317.8±2.5
CICE[2]	31.87	243.33	41.5±1.5	316.3±1.9
CONC[3]	26.62	248.19	43.6±2.2	308.4±3.0
LPAZ	24.16	249.68	47.4±1.7	309.3±2.1
MELR[3]	30.98	244.26	44.5±1.6	313.6±1.9
SAIS	31.19	243.78	43.4±1.5	315.2±2.0
SLRE	31.26	243.84	45.2±1.5	314.6±1.8
SNI1[2]	33.24	240.49	46.2±1.6	318.1±2.0
VNDP[2,3]	34.56	239.38	46.2±1.7	317.2±2.0

1. Based on four campaigns, 1994-1998.
2. Continuous site.
3. Predicted Pacific rates here are 50.7 mm/yr (CONC), 49.6 mm/yr (MELR) and 50.4 mm/yr (VNDP) from geologic model of *DeMets and Dixon* [1999]: 49.98N, 283.89E, 0.777 °/my.

the last SMV event was the M 6.8 1956 earthquake [*Doser*, 1992], and the recurrence interval is 330 years, based on time to accumulate 1.0 meter of slip at 3 mm/yr. For the Agua Blanca fault, we assumed the last event was 250 years ago and the recurrence interval is 500 years. The northern Baja sites are far enough from other faults northeast of the SMV fault that associated strain effects should be small; we added 1 mm/yr to the site velocities to collectively represent these effects. For CABO, CONC and LPAZ, we assumed fully locked Gulf transforms down to 10 km depth, 50 mm/yr rate, 200 year recurrence interval and last event 100 years ago. This probably overestimates strain effects at these sites. To reflect the uncertainty associated with the strain corrections, we added 1 mm/yr in quadrature to the error budget.

Figure 2 shows observed and "corrected" (for strain effects) velocities as a function of latitude for coastal Pacific sites, along with predicted plate rate at the same location. Sites near the "big bend" in the San Andreas fault (VNDP, SNI1) appear to move with the Pacific plate or nearly so once short term strain effects are included. In contrast, sites in Baja California south of the Agua Blanca fault move at speeds much less than the Pacific plate rate.

Discussion

The agreement between VNDP's velocity and the NUVEL-1A model [*DeMets et al.*, 1994] has often been assumed to confirm the joint hypothesis that the model is accurate and that the station represents stable Pacific plate. Our new Pacific-North America angular velocity suggests that this agreement is fortuitous: the NUVEL-1A prediction is too slow, and VNDP's velocity is significantly less than the full Pacific plate rate (Table 1) due to large elastic strain effects. *Savage and Lisowski* [1998] point out that faults late in their earthquake cycle, such as the San Andreas fault near VNDP, have elastic strain effects that extend far from the fault.

The discrepancy between strain-corrected velocities in Baja California and the predicted Pacific plate velocity has three plausible explanations: 1. errors in the plate motion models and/or site velocity data; 2. non-rigidity of the Pacific plate; and 3. offshore slip.

Our companion study [*DeMets and Dixon*, 1999] points out the close agreement between geological and geodetic estimates of Pacific-North America motion. The two estimates are derived independently, giving us confidence in each. Our reported site velocities are based on a mix of campaign-style and continuous stations operated by several groups, with a variety of equipment types. Several continuous sites (VNDP, SNI1, CAT1, CICE) are analyzed independently by different groups. Our velocities relative to stable North America for these sites are equivalent within uncertainties to other groups [e.g., *Bennett et al.*, 1999; SCEC, 1998]. However, our velocity estimates at several coastal sites are slower than the SCEC version 2.0 estimates (mean difference at 5 sites=0.9 mm/yr). The largest difference is at VNDP, where the SCEC velocity estimate is faster by 2.7 mm/yr compared to our estimate. Use of the SCEC velocity estimate for VNDP and the elastic-viscoelastic corrections calculated here gives a corrected velocity that exceeds the expected Pacific rate by an amount larger than the quoted error. While we know of no simple mechanism that could allow VNDP to move at a rate faster than the Pacific plate, below we include the possibility of a 1 mm/yr systematic error in our results, to reflect the mean difference between our results and SCEC results at colocated sites. We preclude non-rigidity in the Pacific plate as an explanation, since our data fit the rigid plate model within uncertainties, and since the velocity estimates for VNDP and SNI1 agree with the rigid plate prediction after correction for elastic strain effects, again within uncertainties. This suggests that where significant differences between the full plate velocity and corrected coastal site velocities are observed, they probably indicate active offshore faulting.

Active faults offshore northern Baja California include the San Clemente-San Isidro (SCSI) fault zone [*Legg et al.*, 1991] and the offshore extension of the Agua Blanca fault. The Agua Blanca fault has two strands which extend offshore and turn north, the Coronado Bank and San Diego Trough-Bahia Soledad fault zones (Figure 1). *Legg et al.* [1991] suggest that the SCSI fault zone does not connect with the Agua Blanca fault onshore, but rather continues southward offshore peninsular Baja California. Thus, the difference between our four site velocities south of the Agua Blanca fault and the Pacific plate velocity should yield approximately the slip rate of this offshore fault zone (the respective velocity azimuths are very similar, consistent with simple strike slip motion in the direction of plate motion). The mean corrected rate for these four sites is 45.8±0.8 mm/yr, slower than the predicted velocity here (49.7 mm/yr) by 4±2 mm/yr, including the uncertainty associated with the viscoelastic corrections. This difference, an estimate of the slip rate for offshore faults, is similar to the geologic estimate of 1-4 mm/yr for the San Clemente fault zone to the north [*Ward and Valensise*, 1994]. If our results are systematically biased to slow values by 1 mm/yr (e.g., SCEC comparison), the offshore slip rate estimate is reduced to 3±2 mm/yr.

The acceleration of Gulf Rise spreading rates since 3 Ma (Figure 2) implies either recent or ongoing transfer of Baja California to the Pacific plate. Uncertainties in the

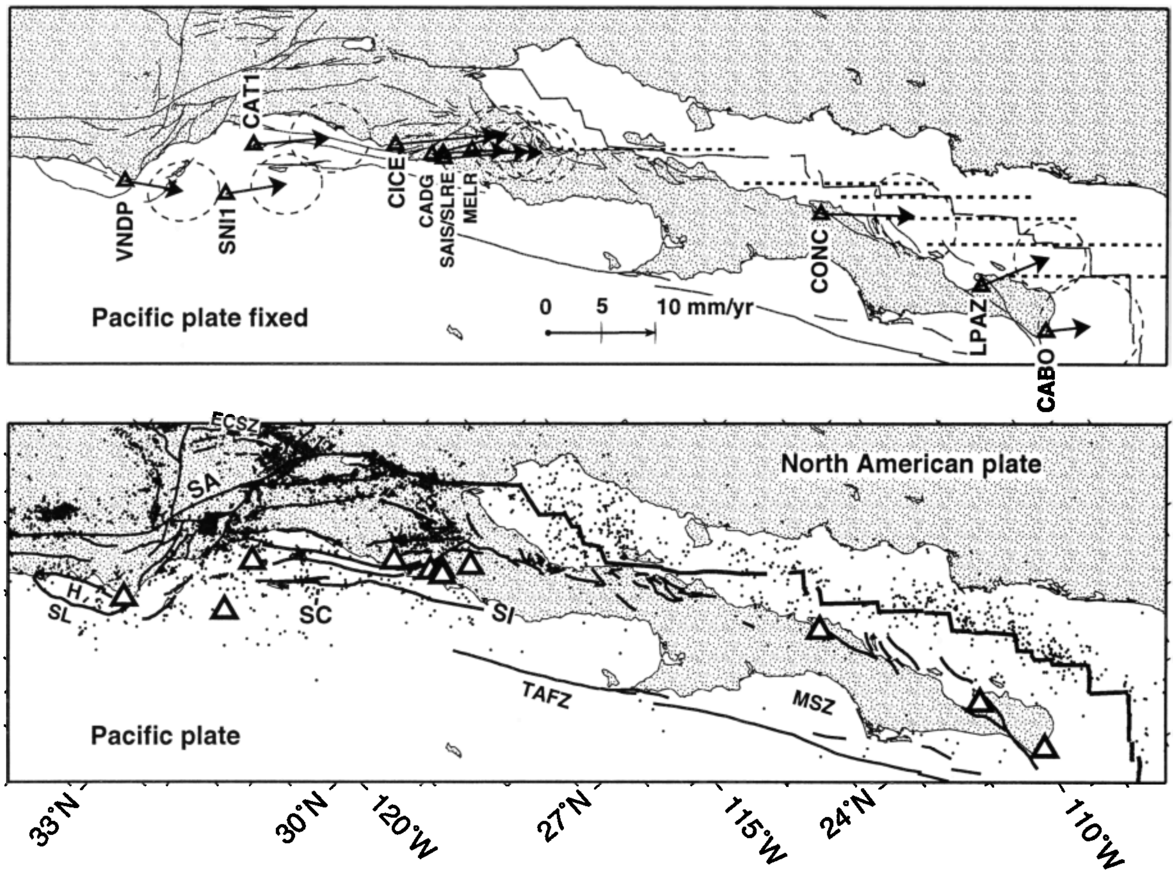

Figure 1. Seismicity, major faults, GPS site locations and velocities (relative to Pacific plate) with 95% confidence ellipses. Map projection is transverse Mercator, Pacific plate fixed; sites moving parallel to North American plate move parallel to map boundaries. Faults are: AB, Agua Blanca; H, Hosgri; SA, San Andreas; SI, San Isidro; SL Santa Lucia Banks; SC, San Clemente. ECSZ is eastern California shear zone, MSZ is Magdalena seismic zone.

magnetic anomaly record allow the possibility that some or all of peninsular Baja California south of the Agua Blanca fault has not yet fully transferred to the Pacific plate, as suggested by our GPS results and offshore seismicity (Figure 1). In fact the sea floor magnetics can be interpreted as independent evidence for offshore slip. Comparison of the predicted full plate rate for the southern Gulf (our geological model) with measured Gulf Rise

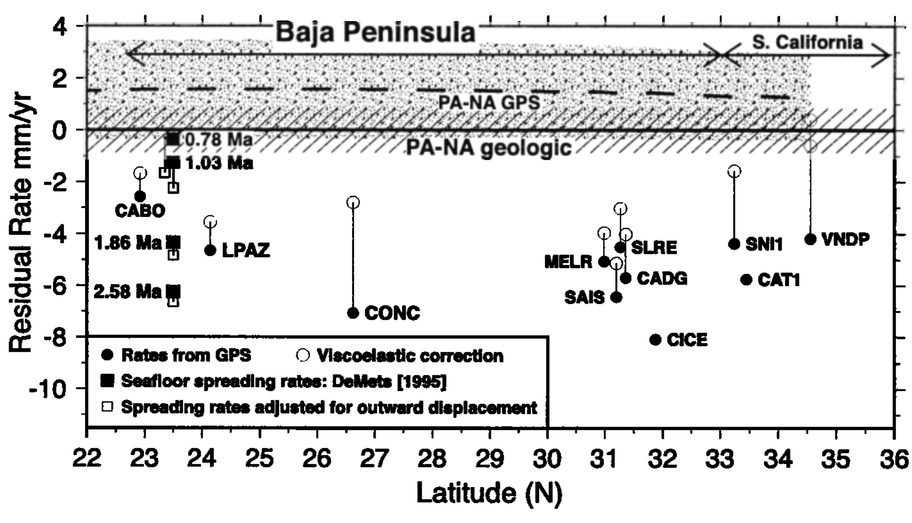

Figure 2. Rate residuals relative to fixed Pacific plate vs latitude. Points on stable Pacific plate have zero velocity in this diagram, as predicted by the geological model of *DeMets and Dixon* [1999]. GPS-based plate motion model agrees with the geological model within one standard error (shaded region). Solid circles are measured GPS velocities, open circles include correction for elastic strain accumulation. Squares are seafloor spreading rates in southern Gulf of California, with and without correction for outward displacement [*DeMets*, 1995].

spreading rates from Chron 1n (0.78 Ma), corrected for outward displacement [*DeMets*, 1995] shows a deficit of 1.5 mm/yr (Figure 2), consistent with additional faulting.

We are aware of no peninsula-crossing faults south of the Agua Blanca fault capable of transferring offshore motion into the main Gulf plate boundary. Slip on the SCSI fault or other offshore fault thus may continue south along the entire west coast of Baja California, or may cross the southern peninsula on unmapped structures. One candidate structure to accommodate offshore motion is the Tosco-Abreojos fault zone, which controls angular bathymetric escarpments, and in places cuts the youngest seafloor strata [*Spencer and Normark*, 1979, *Normark et al*, 1987]. However, this fault is well removed from most of the seismicity in the continental borderland and we propose instead that the SCSI fault zone continues south-southeast just offshore most of Baja California, connecting with a north-northwest-trending zone of seismicity in Bahia Magdalena, which we term the Magdalena seismic zone (Figure 1). The Magdalena seismic zone could be related to several known faults in the area such as the Alcatraz fault [*Yeats and Haq*, 1981], Santa Margarita fault [*Normark et al.*, 1987, Todos Santos fault [*Fletcher and Munguia*, 2000], or other unnamed Quaternary faults found in reconnaissance field studies in Bahia Magdalena [*Fletcher et al.*, 2000].

The GPS results reported here, combined with evidence for active faulting, seismicity, and the deficit between the rate of young sea floor spreading in the Gulf and the geological plate rate, imply that transfer of Baja California to the Pacific plate is not quite complete, several million years after the inferred plate boundary jump. Perhaps continued offshore slip on the "Baja California shear zone" (symmetric with and analogous to the eastern California shear zone; Figure 1), is kinematically favored, as it allows some strain to bypass the restraining big bend of the San Andreas fault. This effectively isolates Baja California as a block or microplate, analogous in some respects to the Sierra Nevada block. The difference is that Baja California's tectonic isolation is waning, as offshore slip declines and the block becomes "welded" to the Pacific plate, whereas the eastern California shear zone presumably grows with time as the plate boundary migrates inland.

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