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Crustal deformation around the Gulf of California

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Abstract. A number of Satellite Laser Ranging (SLR) sites in the southwest United States and Mexico, in operation for over ten years, have been supporting the global laser network measuring tectonic plate motion and providing information for studies of regional crustal deformation. Observations of the Laser Geodetic Satellite (LAGEOS) collected in 1994 by the transportable satellite laser ranging system, TLRS-4, at two sites on the Baja peninsula now provide the means to extend the network of fixed stations at Monument Peak and Otay Mountain in southern California and Mazatlan on mainland Mexico. After the third SLR occupation of Ensenada, it's estimated site motion exhibits nearly the full plate rate predicted by the NNR-NUVEL1A model for a location on the Pacific plate. At the southern tip of the Baja, the motion of Cabo San Lucas has an azimuth that is more westerly than that expected from Pacific modeled motion. This discrepancy in azimuth, in conjunction with the slower SLR recovered velocity for Mazatlan, results in an apparent 6 mm/yr faster spreading rate across the mouth of the Gulf of California than that predicted by the NUVEL-1A model. The velocities of the Monument Peak and Otay Mountain sites show the expected long-term difference from Pacific plate motion, due to their proximity to the San Andreas Fault system.

Introduction

The Satellite Laser Ranging station in Mazatlan has provided a source of highly accurate observations to the Global Laser Tracking Network (GLTN) during its operations between 1983 and 1993. Data from this station have been particularly valuable, in combination with that from Monument Peak, Quincy and McDonald Observatory, to reveal the distribution of motion at the boundary between the North American and Pacific tectonic plates [*Smith et al.*, 1990]. The Mazatlan observations have also helped the GLTN to provide improved resolution of Earth orientation and scale to the International Earth Rotation Service [*Bouchet et al.*, 1993], as well as supporting orbit determination for geopotential field development and for altimeter missions.

Bosworth et al. [1993] describe a regional campaign of transportable SLR systems on the Baja peninsula which have completed the third occupation of Ensenada, in the northern Baja, and a fourth occupation at Cabo San Lucas, at the southern tip of the peninsula. The central role played by the fixed Mazatlan station, and the increased time span of the acquired data for sites periodically visited by transportable systems, provides accurate resolution of station velocities which aid in the kinematic modelling of this complex region.

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The Gulf of California Transition Zone

The Gulf of California, which separates the Baja peninsula from the North American Continent, consists of a series of spreading centers linked by transform faults. The Gulf is a complex transition zone located between the San Andreas continental transform system in Southern California and the sea-floor spreading zone of the East Pacific Rise. Any changes in the accommodation of the Pacific-North American plate motion in the Gulf are of interest for understanding the mechanical response of the crust and the associated earthquake activity within the Gulf and along the San Andreas system (see, for example, *Press and Allen*, [1995]).

Tajima and Tralli [1992] have indicated that seismic moment slip rates are significantly less than the rates expected from the NUVEL-1 global plate motion model [*DeMets et al.*, 1990], further emphasizing the need to measure tectonic motion directly. They show that seismic to tectonic slip ratios increase from 17% in the southern region of the Gulf of California to 30% in the north. Major goals of the SLR measurements in Mexico include: (1) to complement regional Global Positioning System (GPS) campaigns in the area by providing highly accurate velocity "boundary conditions" for the denser GPS networks; and (2) establishment of the spatial extent over which one can assume rigid plate motions (i.e., the geographical limits of the zones of deformation).

The Results of the SLR Analysis

The site velocity vectors estimated in the most recent Goddard Space Flight Center SLR global solution for locations in the southwest United States and Mexico are listed in Table 1. LAGEOS measurements from the GLTN between 1980 and 1994 were processed to provide these velocities in a frame set by adopting NNR-NUVEL1A modeled motion for the north and east components of the velocity for the Greenbelt, Maryland SLR station (North America) and the north component of the Hawaiian SLR station on Maui (Pacific). The NNR prefix denotes a form of the NUVEL-1A relative plate motion model [*DeMets et al.*, 1994], placed in a No-Net-Rotation frame in a manner analogous to that described by *Argus and Gordon* [1991]. The McDonald and Monument Peak stations have been continuously operated during the last ten years, and so has Mazatlan until the beginning of 1993, but the other stations were only intermittently occupied. The Mojave station engaged in short three-month operations in 1984, 1988, 1989, 1990 and 1991, and transportable systems occupying the site at Otay Mountain tracked in 1982, 1984 and 1988.

Table 1. Velocity Vectors of Satellite Ranging Sites in SW United States and in Mexico

Location	North Rate (mm/yr)	East Rate (mm/yr)	Error Ellipse Parameters Semi-Major (mm/yr)	Semi-Minor (mm/yr)	Orientation (°)
C. S. Lucas	11.9	-50.6	3.9	3.7	-66
Ensenada	20.4	-43.7	6.1	5.2	62
Mazatlan	-6.4	-6.8	1.2	1.1	-77
McDonald O.	-11.5	-12.3	0.8	0.7	-70
Mojave	-12.3	-11.9	3.0	2.7	-59
Mon. Pk.	14.9	-39.3	0.7	0.5	-69
Otay Mtn.	13.9	-37.2	2.9	2.8	72

Error ellipse parameters are 3σ.

The first occupation of Cabo San Lucas occurred in 1984 with a return visit in 1988, and since then, has operated in consecutive periods with Ensenada in 1992 and 1994, after Ensenada's first occupation in 1989. The technique for deriving the velocity model is described in *Smith et al.* [1990] and the global solution including all SLR observations collected through 1994 is available from the Crustal Dynamics Data Information System [*Noll*, 1993].

The SLR velocities plotted in Figure 1 for Mojave, McDonald and Mazatlan are quite similar to that predicted by the NUVEL-1A model for sites located on the North American plate. The motions of Monument Peak and Otay Mountain deviate from Pacific plate motion and this behavior is thought to be a manifestation of distributed shear across the Pacific/North America boundary zone, but Ensenada, to the south, appears to have full plate rate motion. The motion at Cabo San Lucas matches the predicted NUVEL-1A speed but with a more westerly oriented azimuth.

The SLR velocities were used to compute inter-station spherical rates, shown in Figure 2 for the full network. The rate between Cabo San Lucas and Ensenada is 5 mm/yr but this movement is smaller than the associated error estimate. However, given the full plate velocity at Ensenada, any extension along the Baja peninsula would be manifested as an azimuth misfit at Cabo San Lucas and would additionally effect the rate between Cabo San Lucas and Mazatlan. Slight east-west compression between Mazatlan and McDonald is compensated by the apparent extension of 6 mm/yr across the Gulf of California to yield insignificant length change for the line between Cabo San Lucas and McDonald, agreeing within error limits with NUVEL-1A, although the line is almost perpendicular to the spreading in this region.

In the small northern network shown in Figure 3, the motions between Mojave and Ensenada agree well within their error estimates with the NUVEL-1A predicted rate which suggests that these sites lie outside the boundary deformation zone of the San Andreas fault system. *Farina et al.* [1994] have measured a minimum of 6 mm/yr of motion across the Agua Blanca Fault Zone and the Vallecitos-San Miguel fault, from GPS campaigns carried out in 1989 and 1993. These features lie to the north of the Ensenada SLR site, and the rates reported here between Ensenada and Otay or Monument Peak suggest that another 1 to 3 mm/yr would be needed to accommodate the north-south deformation occurring in the northern Baja. *Bennett et al.* [1994] show that GPS velocity profiles across

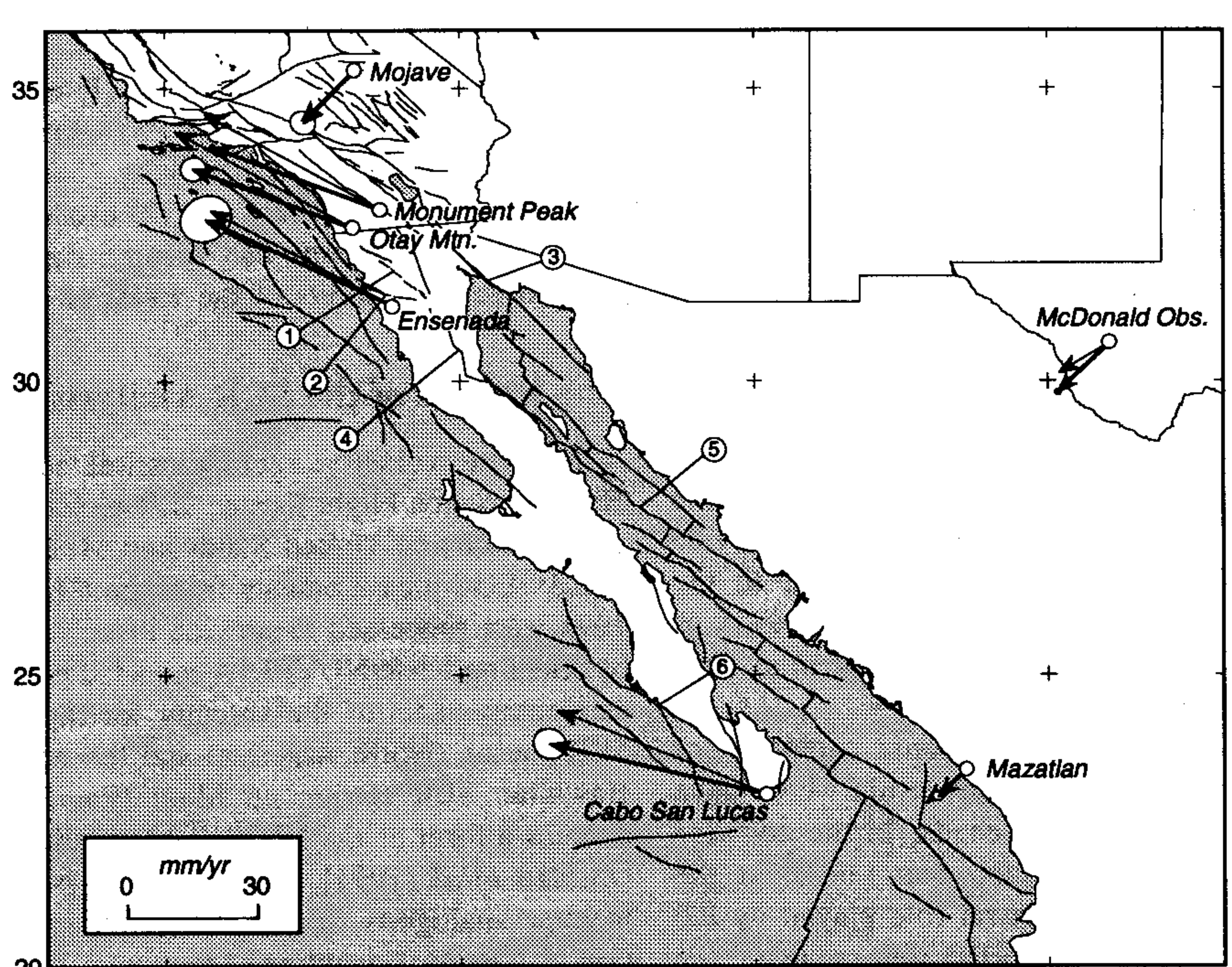


Figure 1. Tectonic motion from Satellite Laser Ranging for sites around the Gulf of California. Motions determined from SLR are those vectors shown with error ellipses, NNR-NUVEL1A vectors are shown with thinner vectors and no error ellipses. The ellipses represent 3σ errors. At Mojave the SLR vector obscures the NNR-NUVEL1A vector . Fault lines mentioned in the text are numbered as follows: 1: Vallecitos-San Miguel, 2: Agua Blanca, 3: Cerro Prieto, 4: San Pedro-Mártir, 5: Guaymas and 6: Tosco-Abreojos.

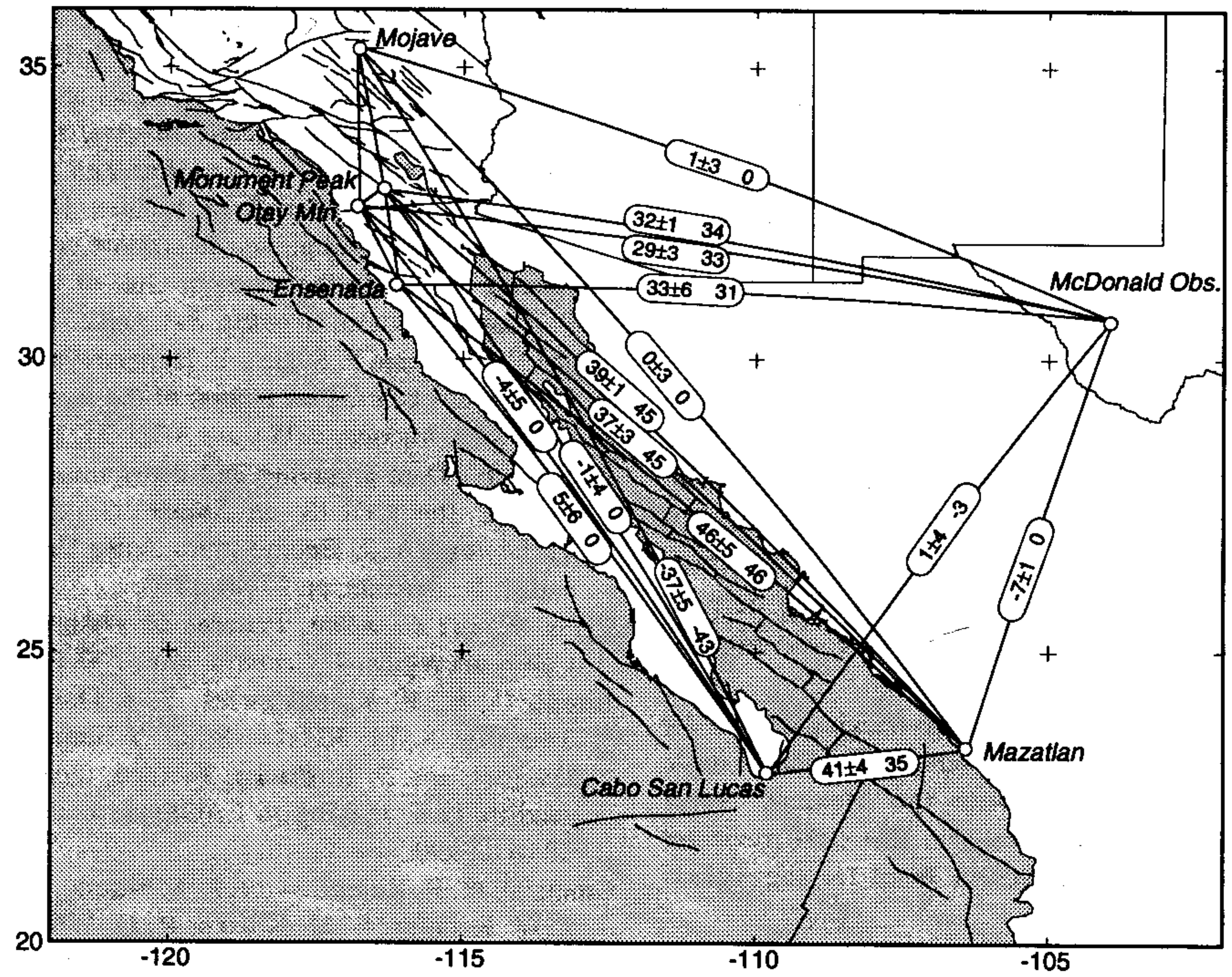
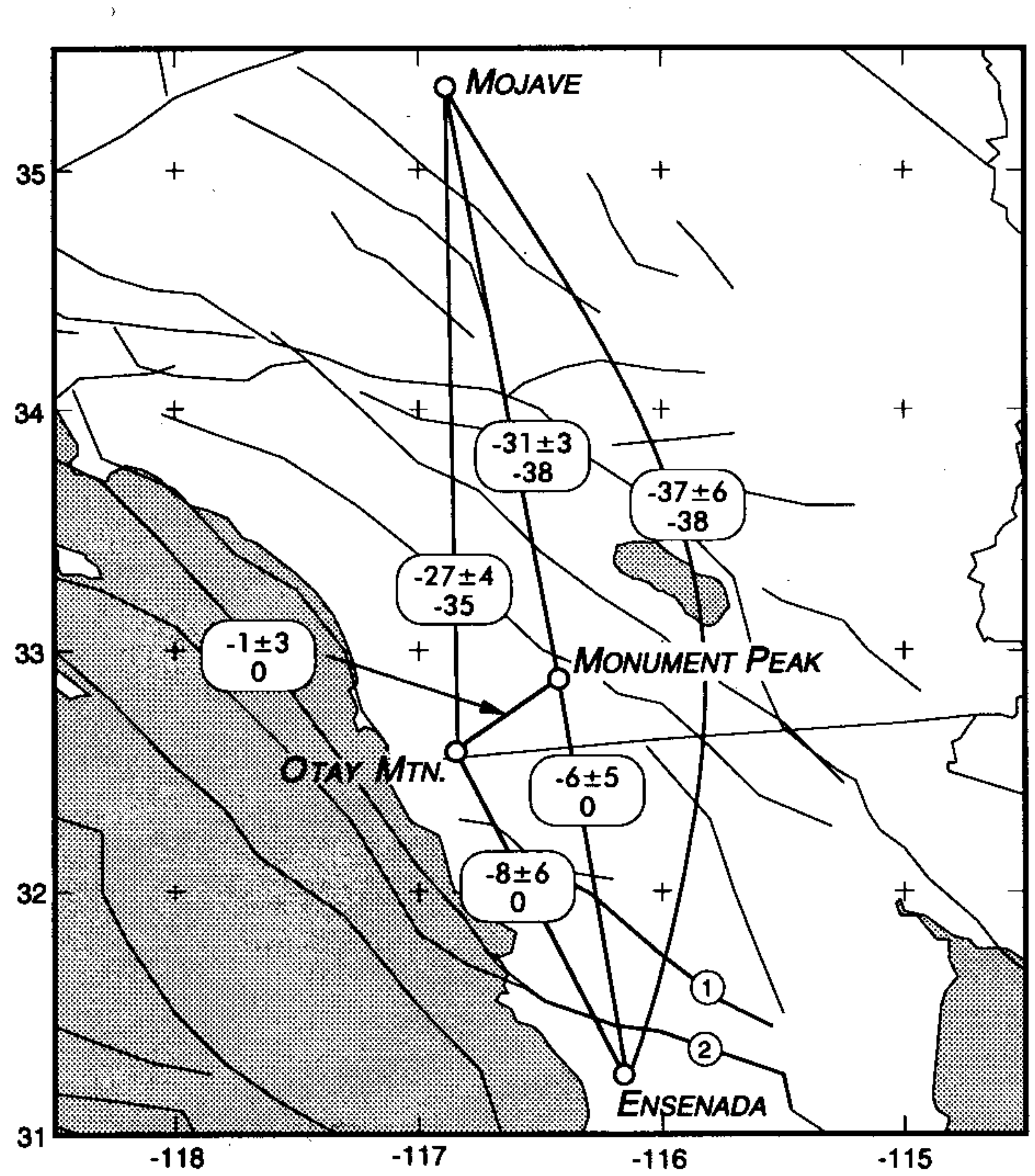


Figure 3. Relative spherical rates between SLR sites in the northern network in mm/yr. Top values represent the SLR rates with 3σ uncertainties and the bottom rates are from the NUVEL-1A model. The Vallecitos-San Miguel fault is denoted by the number 1 and the Agua Blanca fault by 2.

Northern Mexico are consistent with NUVEL-1 rate estimates for the total relative plate motion, with a 40 mm/yr slip rate along the Cerro Prieto fault and 8 mm/yr along the Agua Blanca fault, with extension on the San Pedro-Mártir fault.



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Discussion and Summary

The analysis of GPS data collected at Cabo San Lucas and Mazatlan in 1985 and 1989 by *Dixon et al.* [1991] indicates a slightly lower rate and more westerly azimuth relative to the NUVEL-1 vector at Cabo San Lucas with respect to North America. The SLR vector at Cabo San Lucas reported by *Smith et al.* [1994], before the recent occupation had been completed, also exhibited a significant westerly azimuth difference from NUVEL-1. The improved estimate in our latest solution confirms the persistence of this azimuth discrepancy but we see the station's speed is close to that predicted by NUVEL-1A, which would be expected from the revised time scale on which the later NUVEL-1A model is based. *Dixon et al.* [1991] raised the possibility of a 'Gulf discrepancy' which could be caused by slip along the Tosco-Abreojos fault located off the western shore of southern Baja. Part of the observed difference at Cabo San Lucas could alternatively be due to their comparison with plate motion predicted by the slightly faster, original NUVEL-1 model. However, the relative motion between the Cabo San Lucas and Mazatlan SLR sites also suggests more east-west extension across the Gulf of California than is modeled by NUVEL-1A.

The possibility of bias in geodetic measurements across the Gulf caused by episodic seismic moment release has been postulated by *Tajima and Tralli* [1992]. Their numerical calculations of surface deformation predict a possible 15 mm westward displacement in the central Baja due to the June 18, 1988 Guaymas Basin earthquake transform event. The Cabo San Lucas and Mazatlan stations are outside the zone of significant coseismic motion for this event, which makes it an unlikely explanation for any westward discrepancy at Cabo San Lucas. However, the large deformation computed by *Tajima and Tralli* [1992] for Guaymas Basin suggests that isolated events closer to the SLR baseline across the Gulf could contribute to the average displacement.

The SLR results presented here have been derived from campaigns of no less than three occupations spanning at least five years at each location, and the intermittent nature of the measurement campaigns makes it difficult to detect evidence of non-uniform motion at the Cabo San Lucas and Ensenada locations and to assess the near-field influence of transform events in the Gulf section of the San Andreas fault. The recent SLR deployments have confirmed that contemporary slip rates across the southern Gulf of California are constant over a five year time span. A third GPS observational campaign in the southern Baja would provide another check on the uniformity of motion over ten years. Future extension of the space geodetic network in the southern Baja will certainly help to provide new scientific insights on this unique tectonic region.

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