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DEFORMATION IN THE SANTA BARBARA CHANNEL FROM GPS MEASUREMENTS 1987-1991

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Abstract. Geodesy is one of the few techniques that can be used to estimate strain rates across the submerged structures in the Santa Barbara Channel. By resolving relative surface velocities, the Global Positioning System (GPS) can be used to infer crustal deformation rates independent of geologic models. GPS measurements from the period 1987-1991 have been used to derive velocities for a 8 station network bounding the channel. These estimates are based on 10 GPS experiments each of several days in length over this 4.5 year period. Precision of individual determinations of intersite vectors range from 3 to 7 mm for the horizontal components and average 20 mm in the vertical. The GPS data indicate high rates of shortening in the eastern channel (6±1 mm/yr at N16±3E) and low rates of deformation in the western channel. Comparisons with previous geodetic studies suggest that deformation in the region has not been uniform over the last 100 years.

Introduction

The Santa Barbara Channel forms a deep sediment-filled trough in the western Transverse Ranges geomorphic province. The east-west trending topography and structures of this region cut across the general northwest-southeast structural grain of California. Geologic, seismologic, and geodetic observations suggest that long- and short-term deformation is dominated by north-south to northeast-southwest shortening across the channel. Geologic rates of crustal shortening in the Santa Barbara Channel-Ventura region range from 9 to 24 mm/yr. These rates, based on restored regional and local balanced cross sections [*Namson*, 1987; *Namson and Davis*, 1988; *Yeats et al.*, 1988] interpret the deformation as occurring through blind-thrusting and detachment tectonics due to north-south convergence, involving rocks ranging in age from late Miocene through the Quaternary and Holocene. Evidence of lesser amounts of left lateral faulting is found in small faults along the northern channel, Santa Monica mountains [*Dibblee*, 1982], and channel islands [*Weaver*, 1969]. Slip rates on these faults are about an order of magnitude less than on the regional thrust faults, suggesting that these faults play a substantially smaller role in the regional deformation than the thrust faults.

Active deformation during the latest Holocene is indicated by the seismicity of the region. The Santa Barbara-Ventura area has experienced seven damaging historic earthquakes ranging from M 5.0 to M 7.3 in the last 55 years [*Yerkes*, 1985]. Focal mechanism studies of hypocenters from 1970-1975 indicate that the eastern channel is undergoing compression oriented roughly N20E [*Yerkes and Lee*, 1987], with seismic activity dying out in the western channel. Seismicity is concentrated along north dipping planes along the north side of the channel in the eastern part.

High rates of crustal shortening have been measured across the channel from geodetic analyses. Using triangulation data dating from the late-19th century, *Webb* [1991] found that the rate of strain accumulation over the last 100 years was consistent with shortening of 18±5 N20±3, 16±2 N10±4E, and 13±4 mm/yr N23±7W across the eastern, central, and western portions of the channel. *Larsen* [1991] compared lengths from electronic distance measurements in 1971 and GPS in 1987 and found a maximum strain rate of 0.137±0.03 μstrain/yr, equivalent to 6±2 mm/yr of N25E shortening in the eastern channel, and 0.09±0.02 μstrain/yr of pure shear at N45W in the central channel. Whereas the triangulation and trilateration studies must make assumptions about the uniformity of strain in a region and are insensitive to rigid body rotation, GPS measurements can retrieve the full horizontal velocity vector. In this paper, we report the results of repeated GPS measurements made in the Santa Barbara Channel region over a 4.5 year period.

GPS Data Collection and Analysis

Most of the GPS data used in this study were collected in January 1987 [*Dong and Bock*, 1989] and June 1991. The Santa Barbara Channel geodetic network is shown in Figure 1 and the locations of the sites are listed in Table 1. Additional data from Palos Verdes, Vandenberg, Center, and Lacumbre spanning 1986 through 1991 were also used in the analysis. Details associated with these experiments and a description of the GIPSY GPS software used to analyze these data can be

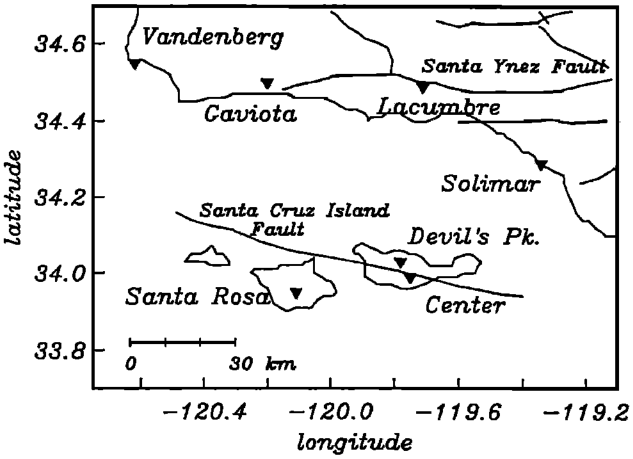

Fig. 1. GPS geodetic network used to study deformation across the Santa Barbara Channel. Palos Verdes is located 100 km southeast of Solimar.

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found in *Larson and Agnew* [1991]. The number of daily observations at each site is noted in Table 1 and range from a high of 41 for Palos Verdes to only 7 at Gaviota.

The precision of the interstation vectors over 3-5 days, as defined by the weighted RMS about the weighted mean, is similar to those reported by *Larson and Agnew* [1991], with horizontal precisions of 5 mm and vertical precisions of 20 mm. As a measure of accuracy, we compared the baseline evolution for Palos Verdes and Vandenberg (223 km) with a recent VLBI model [*Caprette et al.*, 1990]. Figure 2 displays the GPS estimates for the east-west, north-south, and vertical components of this baseline, after the VLBI predictions have been subtracted out. The dotted lines are the VLBI one standard deviation limits. The GPS error bars are one standard deviations. The values from the Santa Barbara Channel experiments (shown by the arrows) agree well with the long-term trend.

TABLE 1. Experiment Sites

Station	Longitude	Latitude	Observations	Years
Center	-119.75	33.99	31	4.5
Devils Peak	-119.78	34.03	9	4.5
Gaviota	-120.20	34.50	7	4.5
Lacumbre	-119.71	34.49	28	4.5
Palos Verdes	-118.40	33.74	41	5.0
Santa Rosa	-120.11	33.95	8	4.5
Solimar	-119.34	34.30	12	4.5
Vandenberg	-120.62	34.56	39	5.0

Table 1. Nominal coordinates for experiment sites, defined on the NAD83 reference ellipsoid. One observation is equivalent to 7 hours of data.

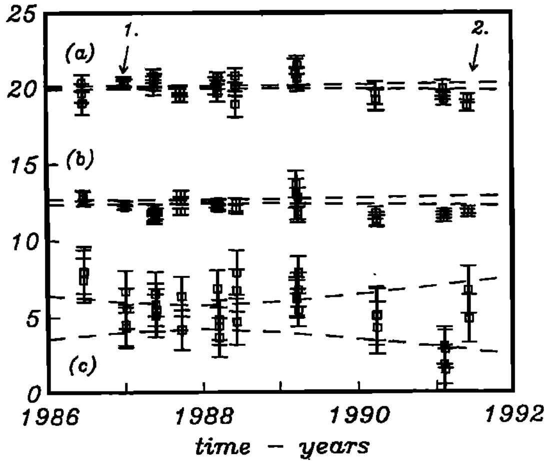

Fig. 2. Evolution of the Palos Verdes-Vandenberg (a) east-west, (b) north-south, and (c) vertical components, where the GLB659 VLBI predicted vector has been subtracted out. The dashed lines are one standard deviation limits. The directions are those of a Cartesian coordinate system located at one end of the baseline, whose north is coincident with the local north, and vertical with the normal to the ellipsoid.

Velocity and Strain Analysis

Two techniques are used to assess deformation that has accumulated during the 4.5 year period of study. Relative site velocities can be examined directly. Alternatively, a strain analysis can be used to determine the average over a network. Since this GPS network is sparse, the only advantages of strain analysis is that strain rates are easier to interpret with respect to the regional geology and can be compared with other geodetic analyses.

Station velocities are calculated from daily GPS estimates of position by modeling the Cartesian station coordinates as varying linearly with time. The estimated parameters, station positions at a reference time and station velocities, are calculated using weighted least squares. For interpretation of relative station velocities, interstation vectors are formed and projected onto the horizontal plane.

The strain rate tensor for sub-regions of the Santa Barbara Channel network is computed using the weighted least squares technique of *Drew and Snay* [1989], which assumes that strain is uniform in space and time. The horizontal strain rate tensor is represented by principal strain rates and their orientation, and network rotation.

Results

If data from the two major experiments only (January 1987 and June 1991) are used to derive station velocities, the chi squared per degrees of freedom (χ^2_ν) is 0.6. This χ^2_ν simply reflects that one can fit a line to two points perfectly and that the short-term precision of GPS interstation vectors is better than the formal errors would predict [*Davis et al.*, 1989]. By adding 8 additional experiments conducted between June 1986 and February 1991, 175 observations of station position are used to determine the 8 station velocities in the GPS network, with a χ^2_ν of 2.1. The additional data provide a more accurate estimate of the station velocities, as well as a more realistic velocity uncertainty. Some of the variance can be explained by differences in fiducial networks between 1986 and 1991 [*Larson et al.*, 1991]. The standard deviations quoted hereafter have been scaled so that the χ^2_ν is 1.

The horizontal and vertical components of the interstation vectors between Vandenberg and the six stations in the Santa Barbara Channel geodetic network are shown in Figure 3. The straight lines are the simultaneous fit of station positions and velocities to data from all 8 stations. Velocities of the Santa Barbara Channel stations relative to Vandenberg are shown in Figure 4 and listed in Table 2. The error ellipses are regions of 95% confidence. Horizontal strain rates for sub-networks which span the western, central, and eastern channel are shown in Table 3. Because of the sparse networks, we have a uniquely determined case and cannot determine the significance of the fit of the data to the model. Nonetheless, they are useful for comparison with previous geodetic studies.

Discussion

Much of the scientific interest in the Santa Barbara Channel and Transverse Ranges has centered on the development of the east-west structures of this region. The major element of this evolution is the evidence for intense north-south shortening over the last 2 million years, while to the north and south of the Transverse Ranges the deformation has been dominated by

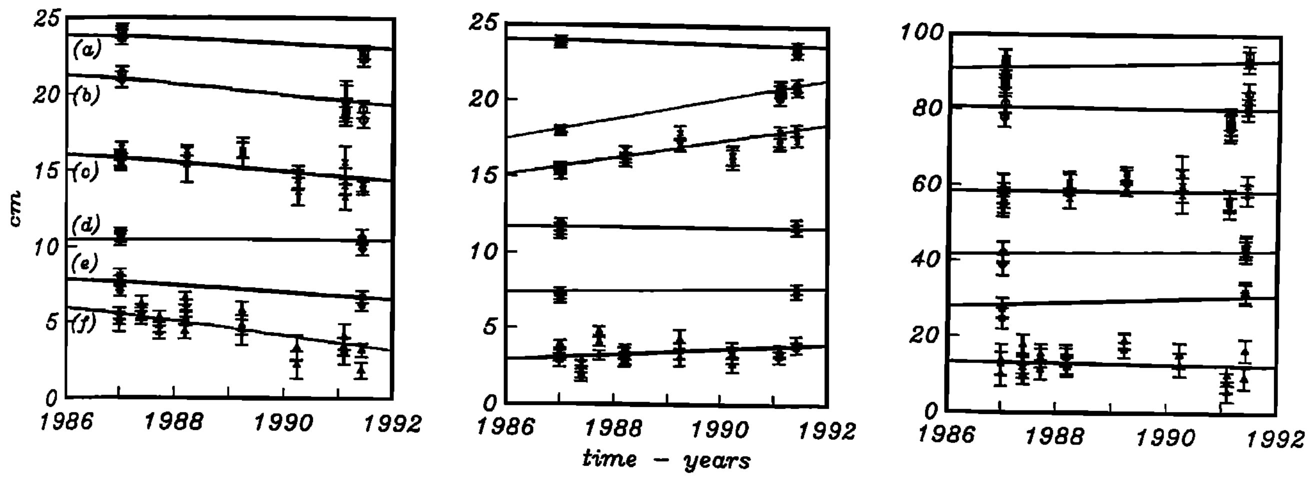

Fig. 3. Evolution of the east-west, north-south, and vertical components of the interstation vectors between Vandenberg and (a) Devil's Peak; (b) Solimar; (c) Lacumbre; (d) Santa Rosa; (e) Gaviota; (f) Center. The straight lines are the predictions from the weighted least squares velocity model.

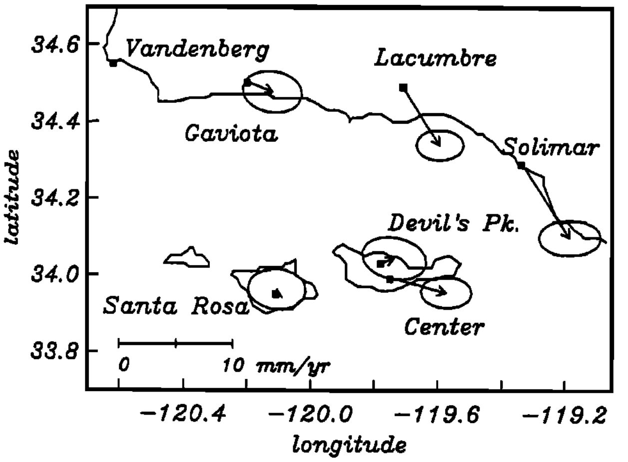

Fig. 4. Station velocities relative to Vandenberg. Error ellipses are regions of 95% confidence.

NW-SE shear strain along the San Andreas Fault (SAF) system. In addition, there is ample and strong evidence from paleomagnetic studies for large scale block rotations of 3-7 degrees clockwise per million years for the western Transverse Ranges [*Hornafius et al.*, 1986].

The most striking result from the GPS measurements is the distinct change in velocities from west to east, with the stations in the western channel indicating little motion relative to Vandenberg. The velocities of Lacumbre and Solimar (relative to Vandenberg) are nearly three times too large to be explained by right lateral shear strain associated with the SAF [*Eberhardt-Phillips et al.*, 1990].

Compression of 0.109±0.01 μstrain/yr at N16±3E in the eastern channel is slightly less than *Larsen's* [1991] value, 0.137±0.03, for a slightly different network over a 17 year period. Rotation estimates for the eastern channel are equivalent to 3.3±1.5 degrees clockwise per million years and are in good agreement with paleomagnetic studies cited previously. The 4.5 year GPS results for the central network do not agree with *Larsen* [1991], who found significant shear, or *Webb*'s [1991] interpretation of high rates of compression. The low relative velocities in the western channel are in contrast to the high strain rates predicted by *Webb* [1991]. These independent geodetic analyses strongly suggest that strain rates have not been constant across the channel over periods of 20-100 years.

One puzzling result is the contradictory station velocities on Santa Cruz Island. The motions of Center and Devil's Peak disagree by more than two standard deviations, although they are separated by only five km. Since identical equipment were used at each site at each epoch, receiver bias is not responsible for these disparate signals. One explanation would be that our

TABLE 2. Station Velocities Relative to Vandenberg

Station	Velocity Magnitude mm/yr	Velocity Azim. deg.	95% Error Ellipse Maj. Axis mm/yr	95% Error Ellipse Min. Axis mm/yr	95% Error Ellipse Azim. deg.
Center	5.2	104.5	2.2	1.4	94.2
Devil's Peak	2.0	73.1	2.8	1.9	100.9
Gaviota	2.5	99.9	2.6	1.7	96.6
Lacumbre	6.2	147.6	2.2	1.4	91.1
Palos Verdes	8.2	137.4	2.8	1.6	91.3
Santa Rosa	0.4	-1.0	2.6	1.7	94.7
Solimar	8.0	146.9	2.7	1.6	90.6

TABLE 3. Strain Rates

Network	χ^2_v	Rotation 10^{-8}/yr	Principal Strains 10^{-8}/yr		Azimuth deg.
Western	1.14	3.7±1.0	-2.0±0.5	7.3±1.9	-3±5
Central	1.96	4.0±0.5	-5.8±1.1	3.5±1.1	8±3
Eastern	1.01	5.7±2.6	-10.9±1.0	6.0±1.1	16±3

Western: Vandenberg, Gaviota, Santa Rosa.
Central: Lacumbre, Gaviota, Santa Rosa, Devil's Peak.
Eastern: Lacumbre, Solimar, Devil's Peak.

GPS analysis is flawed in some way, but independent analysis of data from Center using the GAMIT software [*Hager et al.*, 1991] agrees with our velocity to better than 1 mm/yr.

Although the stations straddle the Santa Cruz Island fault, the observed signal is inconsistent with both creeping [Sorlien, personal communication] and a simple locked fault [*Patterson*, 1979]. Previous geodetic analysis by *Larsen* [1991] found that the distance between Devil's Peak and Santa Rosa changed by only 6 mm in 17 years, which is consistent with the 4.5 year GPS results for Devil's Peak. Some of the signal could be due to monument instability. During reconnaissance for the 1991 survey, it was found that the Center monument was loose and could be rotated 3-4 mm. Our final conclusion is simply to remind the reader that we cannot assume that the motion of a single monument accurately depicts the tectonics of a large region. Future GPS measurements will be necessary to completely understand the tectonics of Santa Cruz Island.

Conclusions

The analysis of GPS data collected between 1987 and 1991 confirms geologic and seismic evidence that the Santa Barbara Channel is an complicated and actively deforming region. North-south compression is indicated in the eastern channel, with little deformation in the west. Rotation may be an important mechanism for deformation as well. The variation between strain rates determined over 4.5, 17, and 100 years suggests that deformation may be non-uniform. These data also imply that with an appropriate network, GPS measurements should be able to resolve block rotations in the western Transverse Ranges.

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