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Application of the Global Positioning System to Crustal Deformation Measurements 3. Result From the Southern California Borderlands

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Five years of measurements from the Global Positioning System (GPS) satellites collected between 1986 and 1991 are used to investigate deformation in the offshore regions of southern California. GPS provides the first practical technique to make precise geodetic measurements in the region. The geodetic network is situated along the California coastline from Vandenberg (120.6°W, 34.6°N) to San Diego, with additional sites on Santa Cruz, San Nicolas, Santa Catalina, Santa Rosa, and San Clemente Islands. The precision of horizontal interstation vectors is subcentimeter, and the interstation vector rate between OVRO and Vandenberg agrees with the very long baseline interferometry derived rate to within one standard deviation. No significant motion is observed in the western Santa Barbara Channel between Vandenberg and Santa Rosa Island, 0.5±1.6 mm/yr, where the quoted uncertainties are one standard deviation. Motions in the eastern Santa Barbara Channel are consistent with compressional deformation of 6±1 mm/yr at N16±3°E. This motion is in agreement with seismicity and an independent geodetic analysis for the period 1971-1987 (Larsen, 1991). San Clemente Island is moving relative to San Diego at the rate of 5.9±1.8 mm/yr at a direction of N38±20°W. The motion between San Nicolas Island and San Clemente Island, 0.8±1.5 mm/yr, is insignificant.

INTRODUCTION

Plate tectonics predicts that the lithosphere of Earth is divided into rigid plates which move relative to each other. In this model, deformation is concentrated along the relatively narrow boundaries of these plates. The actual deformation process is complicated both spatially, as evidenced by broad zones of deformation, and temporally, as indicated by the earthquake cycle. The spatial variability of deformation along the boundary between the North American and Pacific plates in southern California is the topic of this paper. The San Andreas fault (SAF) system is the primary boundary, but other faults also contribute to motion across the plate boundary. In addition to shearing, there is both geologic and seismic evidence of compressional features, such as the east-west trending Transverse Ranges. The distribution of seismicity provides some evidence of where and how significant deformation is occurring on this plate boundary, but seismicity alone cannot determine the distribution of deformation in California. Deformation across the plate boundary can also be measured with geodetic techniques.

Over the long term, geodetic measurements of deformation across the plate boundary must equal global plate model estimates. The NUVEL 1 global plate model [*Demets et al.*, 1990] predicts that the velocity of the Pacific plate relative to the North American plate at Vandenberg is 48.9±1.4 mm/yr, directed at N37.6±1.5°W. Uncertainties quoted throughout this paper are one standard deviation. Plate model predictions roughly follow the strike of the SAF, except in the Big Bend region. U.S. Geological Survey estimates using electronic distance measurements (EDM) [*Lisowski et al.*, 1991] yield ~35 mm/yr of right-lateral motion, with small deviations in complicated regions (such as the Transverse Ranges). Recent analyses of very long baseline interferometry (VLBI) measurements by *Argus and Gordon* [1990] and *Ward* [1990] have shown that significant deformation (~10 mm/yr) occurs east of the SAF. The most elusive portion of the plate boundary (to geodesists) has been the region to the west of the SAF. Deformation there has been difficult to measure, primarily because the terrain does not lend itself to EDM. This laser-based system cannot be used in populated regions, areas of poor air quality, or over lines longer than about 50 km. Consequently, there have been very few measurements in the populated/polluted regions of southern California. The VLBI system supported by NASA's Crustal Dynamics Project [*Clark et al.*, 1987] was sparsely deployed in southern California and thus yielded little of the detailed measurements which would be useful for understanding fault slip at depth. An alternative geodetic technique, the Global Positioning System (GPS), was first used to make crustal deformation measurements in the mid-1980s. Although VLBI measurements in California have recently been discontinued, GPS measurements have been expanded from a few annual or biannual surveys in the early years to frequent and/or daily measurements across nearly every active fault in California. The subject of this paper is a region which has until recently never been measured with precise (subcentimeter) geodetic techniques: the southern California Borderlands. This is loosely defined as the offshore region shown in Figure 1.

From the faults which have been mapped in the southern Borderland, it appears that the structure of deformation should be similar to that onshore. The offshore faults roughly parallel the strike of the San Andreas in the Imperial Valley. Yet seismicity in the region (shown in Figure 2) is sparse, perhaps indicating that the structures are no longer active. Farther north, in the Santa Barbara Channel, active compressional structures have been noted, and seismicity in the eastern region is significant. Although many

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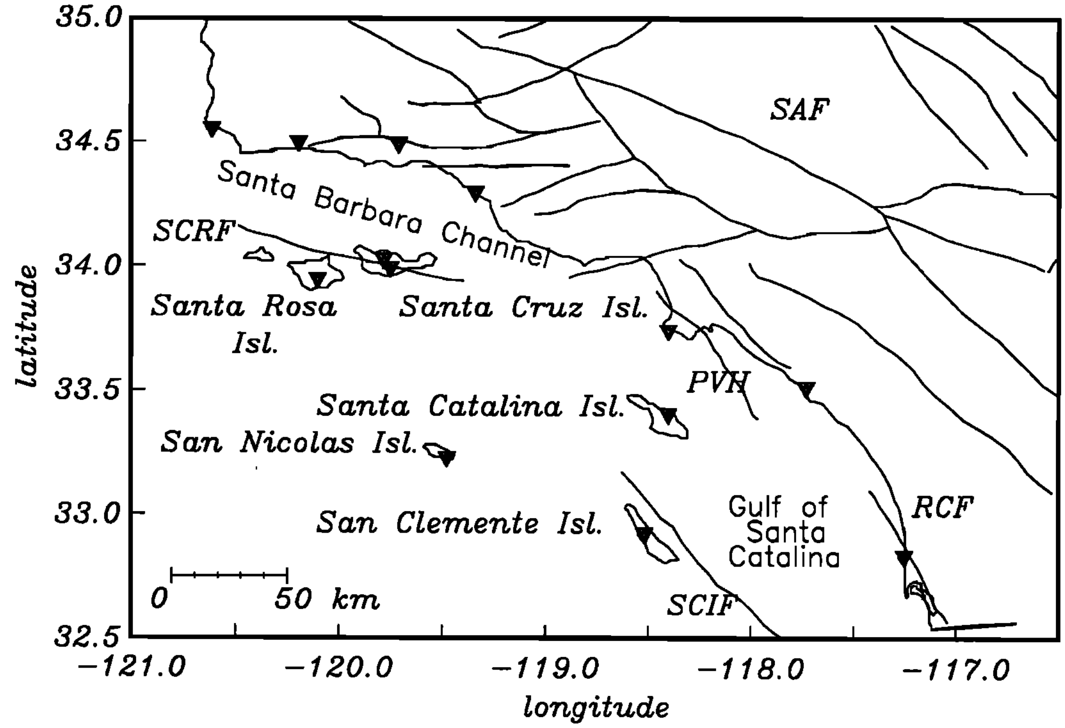

Fig. 1. The GPS Borderland network stations are shown by inverted triangles. Multiple epoch GPS measurements have been made at Nicholas (San Nicolas Island), Brush (Santa Catalina Island), Clembluf (San Clemente Island), Center (Santa Cruz Island), Devil's Peak (Santa Cruz Island), and Santa Rosa (Santa Rosa Island), where the name of the respective island is in parentheses. The locations of these sites are listed in Table 1. Coastal sites range from Vandenberg to Soledad (San Diego) with a spacing of 50 to 100 km. Also shown are several of the important faults: SAF (San Andreas fault); SCRF (Santa Cruz Island fault); SCIF (San Clemente Island fault); PVH (Palos Verdes Hill fault); RCF (Rose Canyon fault).

authors have proposed that significant deformation is occurring in the Borderlands [*Weldon and Humphreys*, 1986; *Legg et al.*, 1989], no previous geodetic measurements had been made to test these hypotheses.

The goal of this paper is to use GPS to estimate deformation rates in the Borderland region of southern California. This paper follows two previous efforts to apply GPS to measuring crustal deformation. The first was an empirical study of GPS precision and accuracy [*Larson and Agnew*, 1991; hereafter referred to as paper 1]. The second paper estimated errors associated with orbit determination (fiducial) networks [*Larson et al.*,1991; hereafter referred to as paper 2]. In the next section of this paper, I describe how the GPS data were collected and analyzed and briefly characterize the precision and accuracy that one can expect from this geodetic network. The remainder of the paper describes how GPS position estimates were converted to interstation velocities and presents an interpretation of crustal deformation in the Borderlands.

Geodetic Background

Most of these GPS measurements were made as part of a collaborative effort to measure crustal deformation in southern and central California by an informal consortium which included the Scripps Institution of Oceanography, California Institute of Technology, University of California, Los Angeles, and Massachusetts Institute of Technology. A subset of the GPS network established and maintained by this consortium was described in paper 1. One objective of the consortium was to reoccupy historical triangulation and trilateration monuments. Recent results from this effort include comparison of trilateration and GPS across the Santa Barbara Channel [*Larsen*, 1991], comparison of GPS and historic triangulation in the Borderlands [*Webb*, 1991], and deformation studies in the Ventura [*Donnellan*, 1991] and Santa Maria Basins [*Feigl et al.*, 1990]. Second, this network was occupied for GPS-derived velocities [*Murray*, 1991].

Preliminary crustal deformation rates in the Borderlands inferred from GPS data collected between mid-1986 and early 1989 were presented by *Larson* [1990]. This paper extends that analysis of data to mid-1991. The GPS data from the Borderlands thus span nearly 5 years. Figure 1 shows the geodetic network which is described in this paper. Table 1 lists the locations of the GPS stations, which extend along the California coast from Vandenberg to Soledad (San Diego). Throughout this paper, I will refer to the individual geodetic station names. Geographic locations, if needed for clarity, will be listed in parentheses. The northern Borderlands is represented by Santa Rosa (Santa Rosa Island), Devil's Peak (Santa Cruz Island), and Center (Santa Cruz Island), with the southern region including Nicholas (San Nicolas Island), Brush (Santa Catalina Island), and Clembluf (San Clemente Island). For a discussion of the coastal network which extends from Vandenberg to Fort Ord (121.8°W, 36.7°N) and further measurements in the Los Angeles Basin, the reader is directed to *Murray* [1991].

Experimental Procedure and Data Analysis

The data were collected at 15 epochs between June 1986 and June 1991. Eleven of these experiments were previously

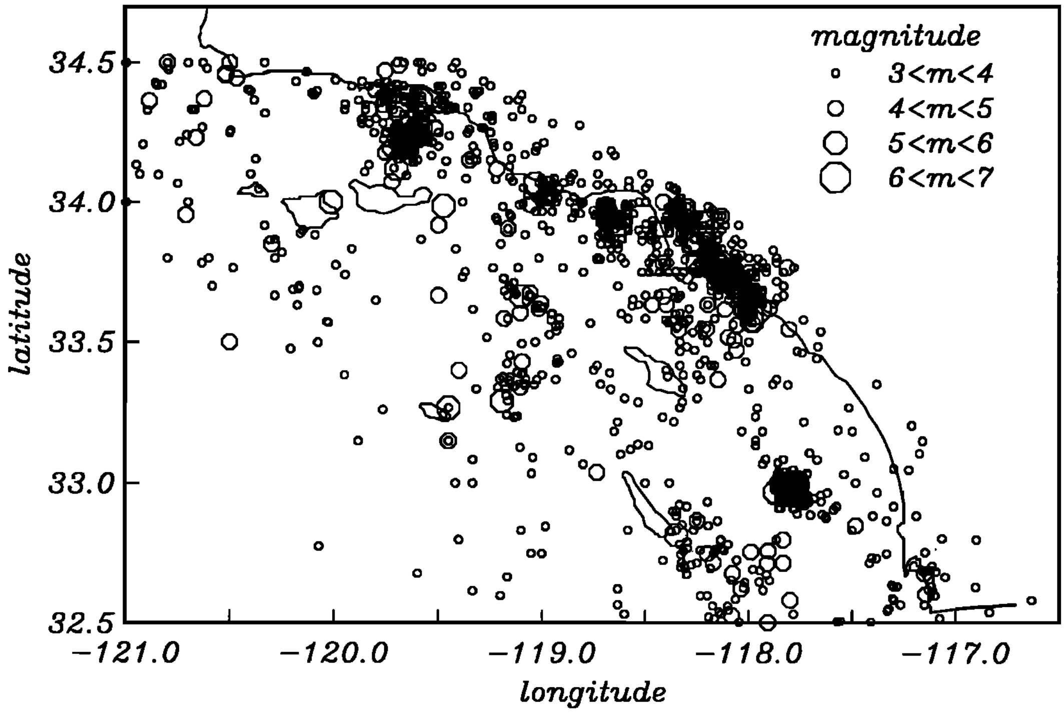

Fig. 2. Seismicity between 1932 and 1992 for the Borderland region. Data taken from the U.S Geological Survey southern California database.

described, and the reader is referred to paper 1 for further details. This section will focus on the additional data which have been analyzed since paper 1 was published. The measurement histories are shown in Table 2. The GPS data were analysed with the GIPSY software [*Lichten and Border*, 1987]. The major difference between the analysis of paper 1 and this paper is that a different reference frame has been used. As before, the reference frame is defined by a VLBI velocity model derived by Goddard Space Flight Center, GLB659 [*Caprette et al.*, 1990]. This model spans a longer time and incorporated more VLBI observations than the previous reference frame, GLB223. All 15 experiments have been reanalysed using GLB659. Additionally, a small error in the TI-4100 GPS receiver phase center has been corrected. Errors in local surveys between collocated VLBI and GPS monuments, notably that at Vandenberg, have been corrected.

In each of the experiments described in paper 1, the GPS satellites were tracked with a TI-4100 receiver. In the years following the March 1989 experiment, there were several changes in the use of GPS for measurements of crustal deformation. Since these changes may impact the interstation vector precision and/or accuracy, they need to be addressed before discussing deformation rates. The changes are of three types: additional satellite coverage, selective availability (SA), and changes in GPS receivers.

For the years between 1986 and 1989, the GPS constellation consisted of seven "block I" satellites. From that time,

TABLE 1. Borderland GPS Network

Station	Location	Longitude, deg	Latitude, deg	Height, m	Observations
Brush	Santa Catalina Island	-118.404	33.409	451	16
Center	Santa Cruz Island	-119.753	33.996	394	31
Clembluf	San Clemente Island	-118.518	32.928	297	14
Devil's Peak	Santa Cruz Island	-119.785	34.029	701	8
Gaviota	Santa Barbara County	-120.199	34.501	710	6
Lacumbre	Santa Barbara County	-119.713	34.496	1171	28
Niguel	Laguna Niguel	-117.730	33.516	238	10
Palos Verdes	Los Angeles County	-118.403	33.745	73	42
Nicholas	San Nicolas Island	-119.479	33.233	201	13
Santa Rosa	Santa Rosa Island	-120.105	33.951	495	8
Soledad	San Diego	-117.252	32.841	216	13
Solimar	Ventura County	-119.341	34.298	2	11
Vandenberg	Vandenberg AFB	-120.616	34.558	24	40

Geodetic coordinates of crustal deformation sites used in velocity analysis. Coordinates referenced to the WGS84 ellipsoid.

TABLE 2. Data Summary

	Experiment			
	J87b	M90	F91	J91
Month/year	Jan. 1987	March 1990	Feb. 1991[a]	June 1991[b]
Dates	3-7	25,27,28	7-10	4-6
Total days of data	5	3	4	3
1, Algonquin	5F	3F	4	3F
2, Blancas	-	-	3	-
3, Blackhill	-	3	4	-
4, Brush	5	-	3	-
5, Buttonwillow	5	3	4	-
6, Center	-	3	3	3
7, Churchill	5F	0	-	-
8, Clembluf	-	-	1	-
9, Fort Ord	5	-	-	-
10, Lacumbre	2	1	4	3
11, Lospe	-	-	4	-
12, Madre	-	-	3	-
13, Mojave	2F	-	-	-
14, Niguel	-	-	4	-
15, Nicholas	-	-	4	-
16, OVRO	5F	3F	4	-
17, Palos Verdes	3	3	4	3
18, Platteville	5	3F	-	-
19, Richmond	-	-	-	-
20, Soledad	-	-	4[c]	-
21, Vandenberg[d]	4	3	4	3
22, Westford	4	-	-	-
23, Devil's Peak	4	-	-	3
24, Gaviota	3	-	-	3
25, Santa Rosa	5	-	-	3
26, Solimar	4	-	4	3

Site occupations are summarized for four experiments at 26 sites, where the total days of data are listed. F indicates that the station position was not estimated, i.e. this is a fiducial site. Dash indicates the station was not scheduled to be observed during the experient.

[a]Fiducial network: Rogue receivers at Algonquin, Fairbanks, Pinyon and Kokee.
[b]Fiducial network: Rogue receivers at Penticton, Algonquin, and Goldstone.
[c]Measurements made at Scripps. Cartesian vector is 862.63908, 1640.7775, 2487.0032, in meters (H. Johnson, written communication, November 21, 1991).
[d]Local survey Vandenberg VLBI mark(7223) to 7223 RM1 recently corrected. Cartesian vector is 23.096, -0.969, 17.241, in meters (V. Nelson, written communication, October 17, 1991).

additional satellites were launched and are referred to as block II satellites. These new satellites are larger, more massive, and of different construction. Also, several block I satellites became inoperable between 1989 and 1991. GIPSY has been modified to take into account the new satellite mass, area, and phase center location. The main difference between the 1986-1989 and 1991 constellations is that more than four satellites are in view for longer periods of time (TI-4100s could only track four satellites). In California, where satellite visibility has always been optimal for reasons peculiar to DoD policies, precision seems little improved. Each observation period contained 7-8 hours of satellite tracking.

One of the 15 experiments (M90) was conducted during a period when selective availability had been activated. Selective availability is a degradation of the GPS signal by "dithering" of the standard GPS frequencies. The clock dither is potentially harmful, but as with many common error sources in GPS, for estimation of the vector between two receivers whose clocks are synchronized to better than a millisecond, the error introduced by SA clock dither is negligible [*Feigl et al.*, 1991; *Rocken and Meertens*, 1991]. SA implementation also includes a degradation of broadcast ephemerides. Since this analysis uses orbit improvement via fiducial networks [*Lichten and Border*, 1987], which is uncoupled to the accuracy of broadcast ephemerides, this form of SA does not affect the interstation vector estimates.

The final change in operating procedure is the introduction of new GPS receivers. In paper 1 it was suggested that using nearly identical equipment in GPS geodetic experiments was very likely responsible for the highly precise and accurate results. Changes in equipment may introduce systematic errors which were not seen in previous estimates of accuracy. The final two GPS experiments in this study (F91 and J91 from Table 2) were conducted with two new receiver types: the Trimble 4000-SST and Rogue SN8. There has been no definitive study of the effects of mixing different types of GPS receivers and antennas in the refereed literature, but *Freymueller* [1992] has found horizontal component differences no more than 4 mm on baselines of 1300 km when TI-4100 and Trimble receivers were mixed. This value would bound the error that could be expected in southern California on much shorter baselines.

PRECISION AND ACCURACY

Long-term precision of GPS interstation vectors from the Borderland network are summarised in Figure 3 and Table 3. As in paper 1, the long-term precision is calculated as the weighted RMS about the best fit line. Also shown in Figure 3 as a solid line are the precision predictions from paper 1 based on GPS networks of a similar size. The Borderland network has achieved comparable precision in the horizontal components. The vertical precision is quite poor, although most of the vertical scatter can be explained by poor fiducial control (see paper 2).

In order to assure accurate interstation vector measurements in the Borderlands, the most appropriate method would be to compare measurements from a highly accurate technique on identical interstation vectors. This is not possible, simply because no VLBI or satellite laser ranging measurements have been made at the Borderland sites. Instead, an interstation vector is shown which is of comparable baseline length to those in the Borderland network, and which was simultaneously observed and estimated. The OVRO-Vandenberg interstation vector shown in Figure 4 is 363 km long, which is the approximate span of the Borderlands network. Both OVRO and Vandenberg require local survey measurements between the VLBI and GPS marks. The Vandenberg conventional survey was recently found to be in error by almost 2 cm. The corrected survey value can be found in Table 2. VLBI experiments between these sites span nearly 5 years, with 46 observations [*Caprette et al.*, 1990].

Figure 4 displays the GPS estimates for the east-west, north-south, and vertical components of this baseline, after the VLBI predictions have been subtracted out. Thus the line at y=0 represents the VLBI solution. The VLBI one standard deviation uncertainties are small (0.5, 0.6, and 3.5 mm/yr for the east-west, north-south, and vertical components) so they have not been included on Figure 4. The GPS error bars shown are one standard deviation, as defined in paper 1. Agreement of GPS to VLBI is at the mm level in the east-west, but there is a constant bias between GPS and VLBI of 12 mm in the north-south. As was noted in paper 1, multiple measurements between OVRO and other VLBI sites in southern California are consistent with a conventional survey error at OVRO of 10 mm. The computed GPS rates for OVRO-Vandenberg agree with VLBI rates within one standard deviation. Note that agreement between GPS and VLBI has not significantly deteriorated in 1990 (when SA was in effect) or in 1991, when new GPS receiver equipment was used. The interstation vector for a less frequently measured VLBI baseline, between Palos Verdes and Vandenberg, is given by *Larson and Webb* [1992].

ESTIMATION OF STATION VELOCITIES

GPS data collected at the stations described in Table 2 (and Table 2 in paper 1) were analyzed in independent daily solutions. Each observation corresponds to satellite tracking of 7 to 8 hours. Although the data from each day are analyzed independently, station-position estimates made within a few days are highly correlated because of common error sources over these periods [*Davis et al.*, 1989]. These station position estimates, and their associated variance-covariance matrix, were then used to determine station velocities at the Borderland sites. The Cartesian position of each station was assumed to vary linearly in time. The standard weighted least squares technique was used to derive the Cartesian station velocities and positions at a nominal epoch. Since the VLBI-derived reference frame is moving with AM02 motion [*Minster and Jordan*, 1978], after the velocities of all sta-

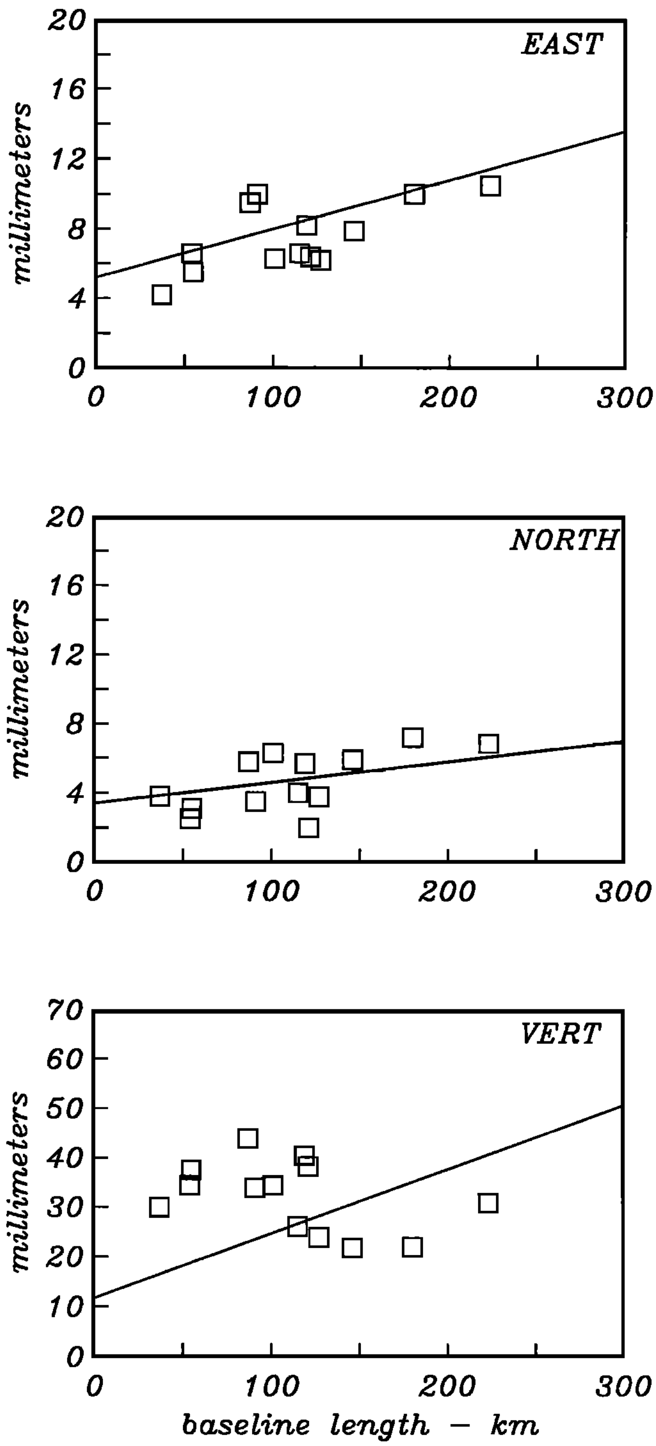

Fig. 3. Precision of interstation vectors in the Borderland Network, as defined by the weighted RMS about the best fitting line. Also shown (as a straight line) is the determination of long-term precision from paper 1. (The directions are those of a Cartesian coordinate system located at one end of the baseline, whose north is coincident with the local north, and vertical with the normal to the ellipsoid.)

TABLE 3. Long-Term Precision

Interstation Vector	Length, km	East, mm	North, mm	Vertical, mm	Years	Observations
Palos Verdes-Brush	37	4.2	3.8	30.0	4.4	9
Clembluf-Brush	54	6.6	2.5	34.4	4.2	9
Lacumbre-Center	55	5.5	3.1	21.6	4.5	19
Soledad-Niguel	87	9.5	5.8	43.9	4.7	9
Palos Verdes-Clembluf	91	10.0	3.5	33.9	4.7	12
Vandenberg-Center	101	6.3	6.3	34.3	4.5	26
Palos Verdes-Nicholas	115	6.6	4.0	26.1	4.7	13
Soledad-Clembluf	119	8.2	5.7	40.5	4.7	11
Vandenberg-Solimar	121	6.4	2.0	38.3	4.5	9
Center-Palos Verdes	127	6.2	5.1	36.9	4.7	21
Palos Verdes-Lacumbre	146	7.9	5.9	21.8	4.5	22
Vandenberg-Nicholas	180	10.0	7.2	22.0	4.7	11
Palos Verdes-Vandenberg	223	10.5	6.8	30.9	5.0	33

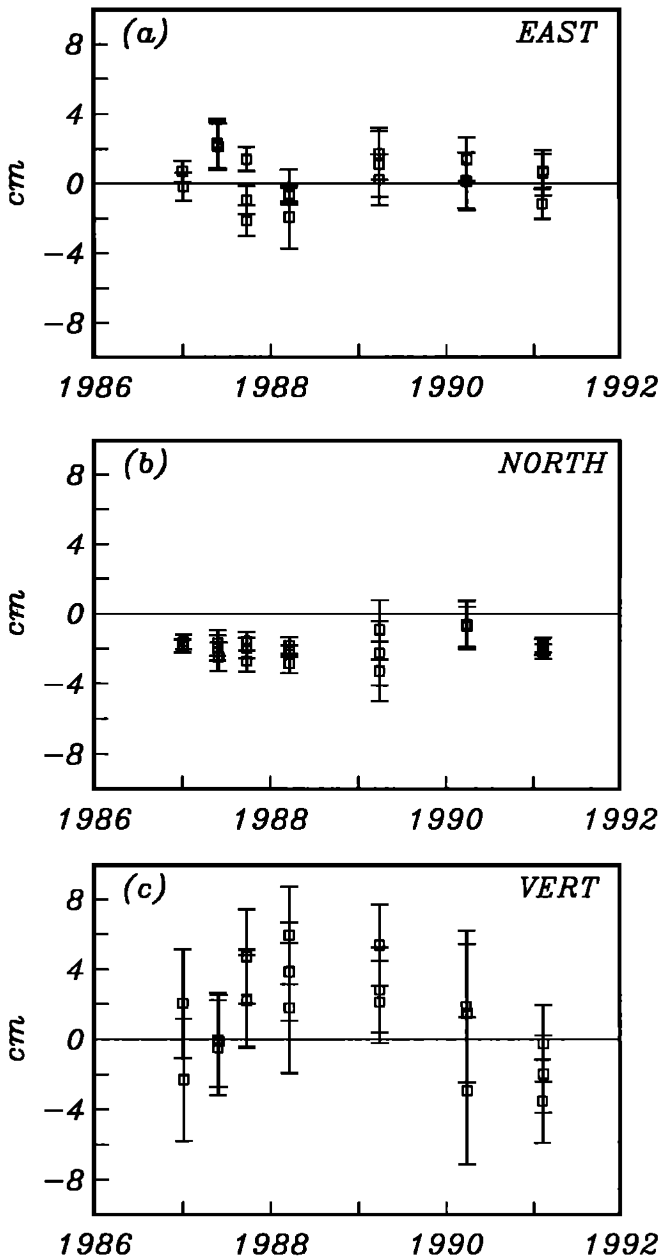

Fig. 4. Evolution of the interstation vector between OVRO and Vandenberg, where the GLB659 VLBI predicted vector has been subtracted from the GPS data. Thus the line at y=0 is the VLBI model. Components defined as in Figure 3. Local coordinate system defined at OVRO.

tions are estimated the AM02 motion for each station is calculated and removed. The station velocities that remain are relative to a fixed North American frame. As deformation in southern California is primarily horizontal (and GPS is insufficiently precise to measure vertical deformation at this time), the interstation vectors and their variance-covariance matrix are then projected onto the horizontal plane.

A total of 240 estimates of station position were used to determine the 13 station velocities and 13 nominal positions. The fit of the data to the model, as represented by the chi squared per degree of freedom, χ^2_ν, is 2.1. If the formal standard deviations correctly represented the actual scatter in the data, then χ^2_ν would be 1. One likely source of error which was not incorporated into the formal errors is fiducial network bias (paper 2). The station velocity standard deviations σ quoted throughout this paper have been rescaled so that the χ^2_ν is 1 [*Clark et al.*, 1987], i.e., $\sigma = \sigma\sqrt{2.1}$. The residuals for the 240 Cartesian station positions are shown in Figure 5, where the residuals have been normalized by their formal standard deviation. The x axis is numbered chronologically (i.e., the data from June 1986 are at the beginning and the data from June 1991 are at the end), and the y axis is in units of standard deviations. Histograms for the Cartesian station residuals are shown in Figure 6. The distributions are zero mean and are Gaussian in shape.

For discussion of relative station velocities, a reference station is needed, and Vandenberg has been adopted as the reference station for this paper. The primary reason to use Vandenberg is that it was observed in all but one of the 15 GPS experiments. Thus station velocities relative to Vandenberg are the most precisely determined. The Borderland network relative station velocities are listed in Table 4 and shown in Figure 7. The error ellipses in Figure 7 are 95% confidence regions. Simple vector subtraction can be used to determine the relative velocity between any two other sites. Since the precision of GPS interstation vectors de-

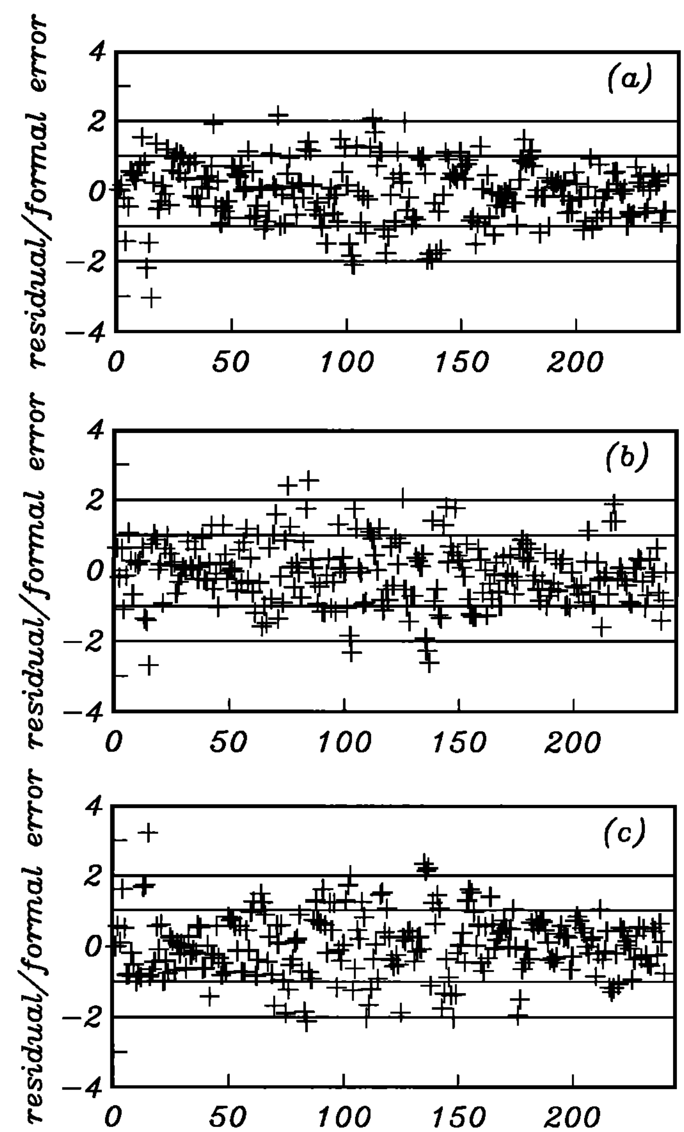

Fig. 5. Residuals for the Cartesian station positions, normalized by the standard deviation. The 240 residuals are plotted chronologically, starting with the June 1986 experiment and ending with the June 1991 experiment. Figure 5a is the X component, Figure 5b is the Y component, and Figure 5c is the Z component.

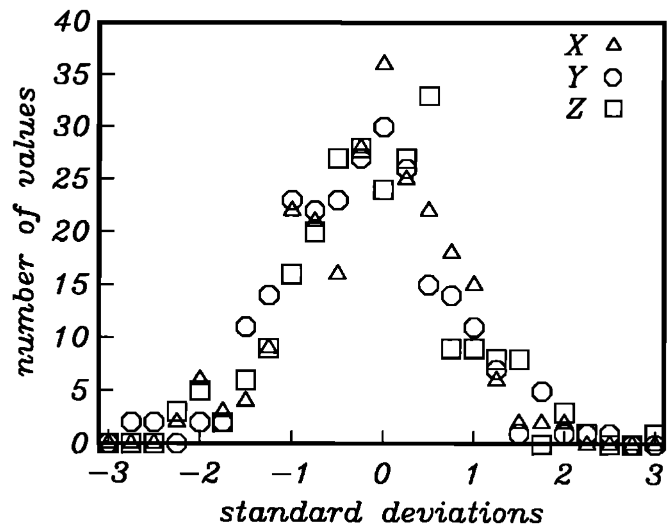

Fig. 6. Histogram plot of the normalized residuals in Figure 5, where the data were collected in bins of 0.25 standard deviations.

grades with baseline length, the velocities of stations farthest from Vandenberg generally have the greatest uncertainties. Likewise, the uncertainty of the relative velocities of stations closer together might be much smaller than indicated by the uncertainty of either station relative to Vandenberg. The station velocity standard deviation is determined by the number and quality of simultaneous measurements at the two sites, and to a lesser extent by the need for local surveys at either site. Another feature of Figure 7 is the orientation of the GPS error ellipses. Because of the geometry of the satellite constellation as it appears to networks at low- and mid-latitudes, the north-south components are better determined and almost uncorrelated with the east-west components. The principal axes of the error ellipses are thus very nearly aligned north-south and east-west.

An alternative consistency check for the Borderlands network solution is to inspect individual interstation vectors. Figures 8-10 display interstation vectors for Center-Vandenberg, Palos Verdes-Clembluf, and Palos Verdes-Nicholas. The solid line is the weighted least squares fit to data from only those two stations. The dashed line is derived from the weighted least squares fit to all 240 Cartesian station position estimates from the Borderland network. The agreement for the north-south components for the two methods is better than 1 mm/yr. The agreement for the east-west components is better than 2 mm/yr.

RESULTS

Northern Borderlands

The geologic evidence on the nature of offshore deformation is clearest in the Santa Barbara Channel, which is thought to be an area of north-south convergence. This interpretation is supported by geologic rates of crustal shortening just north of the channel which range from 9 to 24 mm/yr. These rates are based on restored regional and local balanced cross sections [*Namson*, 1987; *Namson and Davis*, 1988; *Yeats et al.*, 1986]. Additional evidence for the mode of deformation is provided by the local seismicity. Over the last 50 years the region shows a distinctive cluster of earthquakes in the eastern channel, just north of Santa Cruz Island (see Figure 2). Focal mechanisms in the Santa Barbara Channel [*Yerkes et al.*,1980] show a pattern of north-south compression and vertical tension which can be interpreted as north dipping thrust faults. The geologic structures basically die out from east to west, which is consistent with the lack of seismicity in the western channel. The Santa Cruz Island fault (SCRF) running east-west through the Island is thought to have been an active left-lateral strike-slip fault in the Quaternary [*Patterson*, 1978]. Geologic studies find no evidence of contemporary creep on this fault (C. Sorlien, personal communication, January 1992).

Thrust faulting is consistent with geodetic measurements of shortening. Previous geodetic studies have inferred active compression in the Santa Barbara Channel. By comparing baseline lengths from a 1971 trilateration survey and GPS-derived length estimates in 1987 and 1988, *Larsen* [1991] estimated strain rates consistent with 6±1 mm/yr of shortening across the eastern Santa Barbara Channel, at an azimuth

TABLE 4. Station Velocities Relative to Vandenberg

Station	Velocity, mm/yr	Azimuth, deg	One Standard Deviation Error Ellipse: Major Axis Azimuth, deg	Magnitude, mm/yr: Major Axis	Magnitude, mm/yr: Minor Axis
Brush	6.4	123	90	1.3	0.7
Center	5.0	106	94	0.8	0.6
Clembluf	3.7	121	93	1.6	1.0
Devil's Peak	2.0	83	100	1.1	0.7
Gaviota	2.3	107	99	1.1	0.8
Lacumbre	6.2	150	91	0.8	0.5
Nicholas	3.2	112	90	1.3	0.8
Niguel	9.2	131	95	1.4	0.8
Palos Verdes	8.0	142	91	1.0	0.6
Soledad	9.7	136	92	2.2	1.4
Solimar	8.0	151	91	1.0	0.6
Santa Rosa	0.3	20	96	1.1	0.7

of N25°E. This result is comparable to that for the region between GPS stations Lacumbre, Devil's Peak, and Solimar. For the central channel, a network including Lacumbre, Gaviota, Devil's Peak, and Santa Rosa, he found principal strain rates of 0.09 and -0.09 μstrain/yr oriented N45°W and N45°E, respectively. These rates are consistent with an interpretation of shear. Strain rates in the Santa Barbara Channel have also been estimated by comparing GPS data collected in 1987 and 1988 with triangulation data collected in the 1870s through the 1950s [*Webb*, 1991]. He found that the rate of strain accumulation over the last 100 years was consistent with shortening of 18±5 mm/yr at N20±3°E, 16±2 mm/yr at N10±4°E, and 13±4 mm/yr at N23±7°W across the eastern, central, and western portions of the channel, respectively.

Figure 7 shows that Lacumbre and Solimar are moving southeast relative to Vandenberg at 6.8±0.8 and 8.0±1.0 mm/yr, respectively. The combination of these motions with the velocity of Devil's Peak yields average shortening of 6±1 mm/yr at N16±3°E between the coast and Santa Cruz Island [*Larson and Webb*, 1992]. This estimate agrees within one standard deviation with *Larsen*'s estimate from data spanning 1971-1987. The magnitude of shortening over 4.5 years in the eastern Santa Barbara Channel is significantly less than predicted by *Webb* [1991] over 100 years, although the direction of shortening agrees within one standard deviation. Modelling of coseismic deformation in the channel does not explain the difference in shortening rates [*Webb*, 1991]. This discrepancy implies that deformation has been temporally nonuniform between 1880 and 1970. The station velocities of the central channel network are neither consistent with Larsen's interpretation of shear, or Webb's findings of significant compression. The western channel shows little significant deformation over the 4.5-year period, with relative station velocities of 2.3±1.6 and 0.3±1.6 mm/yr for Gaviota and Santa Rosa, respectively. This result contra-

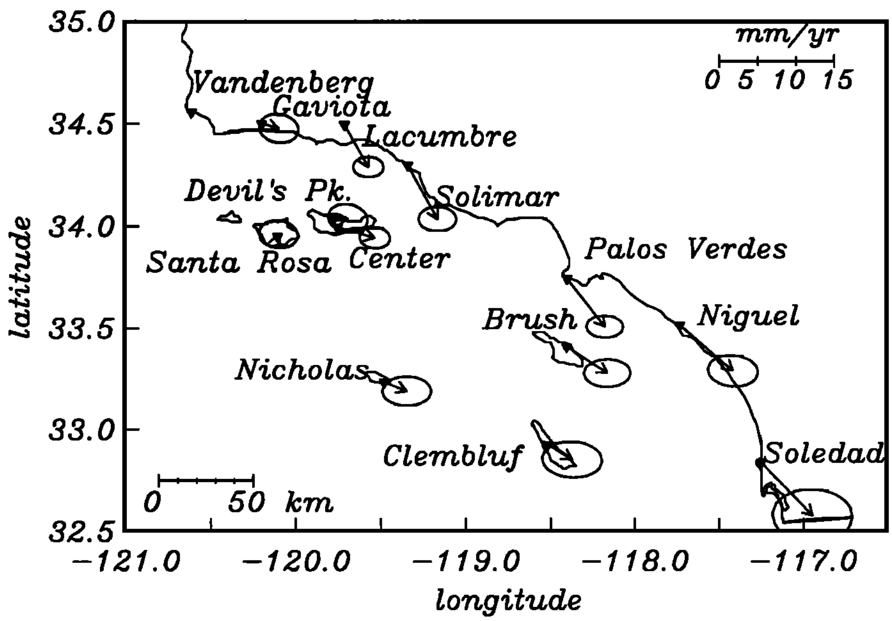

Fig. 7. Horizontal velocities of Borderland network sites relative to Vandenberg. Error ellipses are regions of 95% confidence.

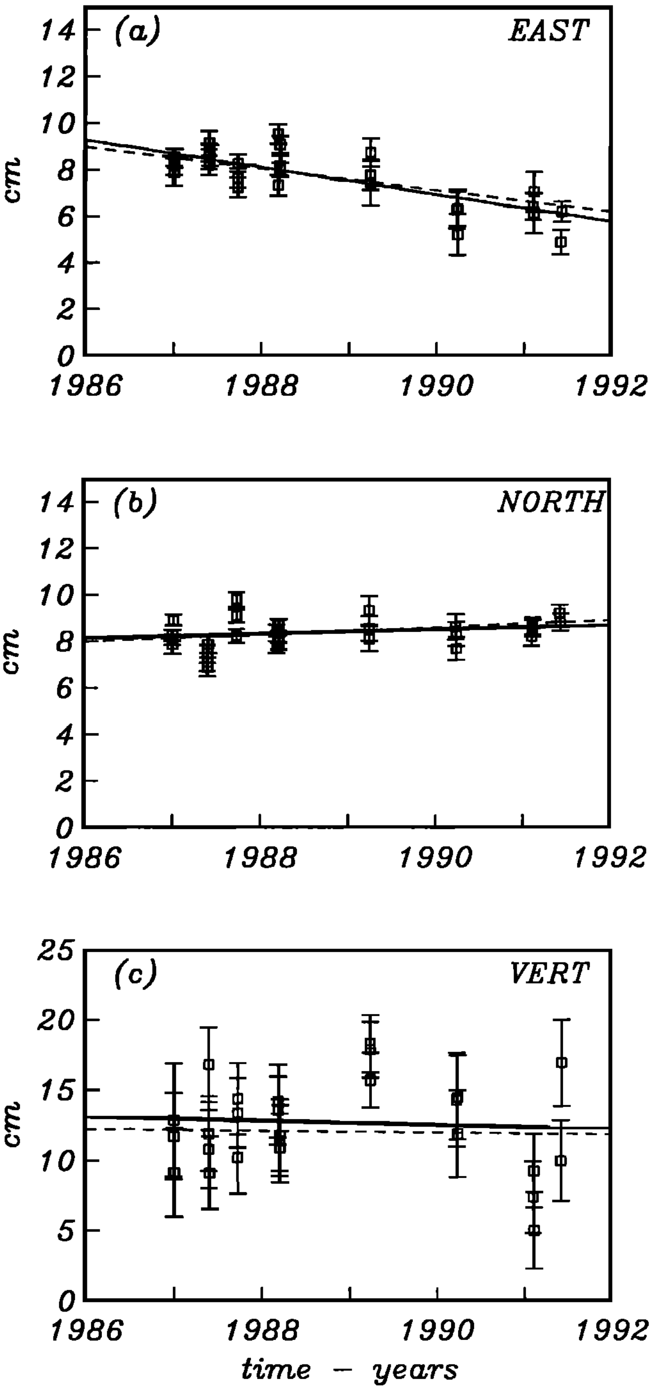

Fig. 8. Evolution of the interstation vector between Center (Santa Cruz Island) and Vandenberg. The solid line is the fit to data from simultaneous observations at these stations. The dashed line is the prediction from the network solution. The local coordinate system is defined at Center and the evolution represents the motion of Vandenberg relative to Center.

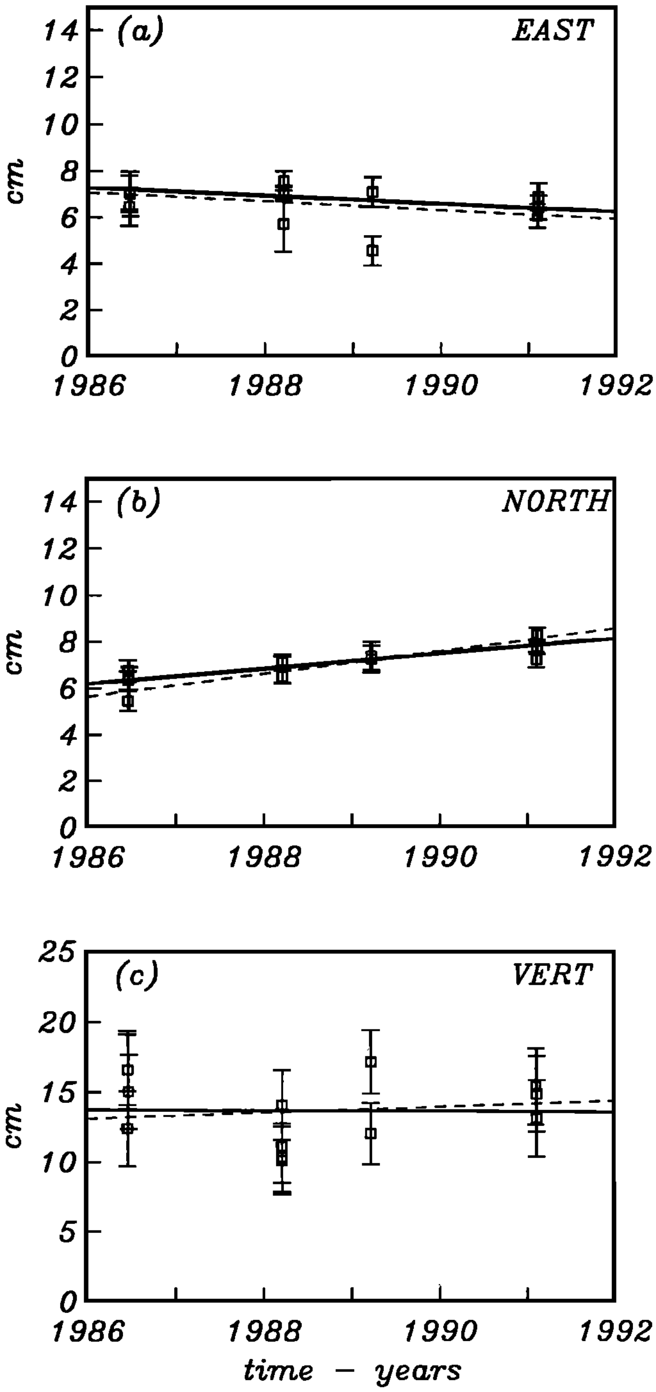

Fig. 9. Evolution of the interstation vector between Nicholas (San Nicolas Island) and Palos Verdes. The solid line is the fit to data from simultaneous observations at these stations. The dashed line is the prediction from the network solution. The local coordinate system is defined at Palos Verdes and the evolution represents the motion of Nicholas relative to Palos Verdes.

dicts the 100 year triangulation results of Webb, again implying nonuniform strain release.

Whereas Larsen's strain rates are model dependent, a simple comparison of line length changes should indicate where his study and this analysis are in agreement. Six baselines out of the eleven discussed by Larsen were measured with GPS in both 1987 and 1991. The baseline rates are summarized in Table 5. Four of the baseline length rates agree to within one standard deviation. In other words, there is no evidence of temporal variation in deformation rates over the last 20 years. The Gaviota-Devil's Peak and Gaviota-Santa Rosa 16-year baseline rates agree with the GPS derived rates within 2 standard deviations. Larsen suggests that the accuracy of the Gaviota-Santa Rosa baseline is in question but is confident in the Gaviota-Devil's Peak line. If the Gaviota-Devil's Peak and Gaviota-Santa Rosa lines are less accurate than the standard deviation which was used to calculate the length rate uncertainty, this would explain why the Larsen

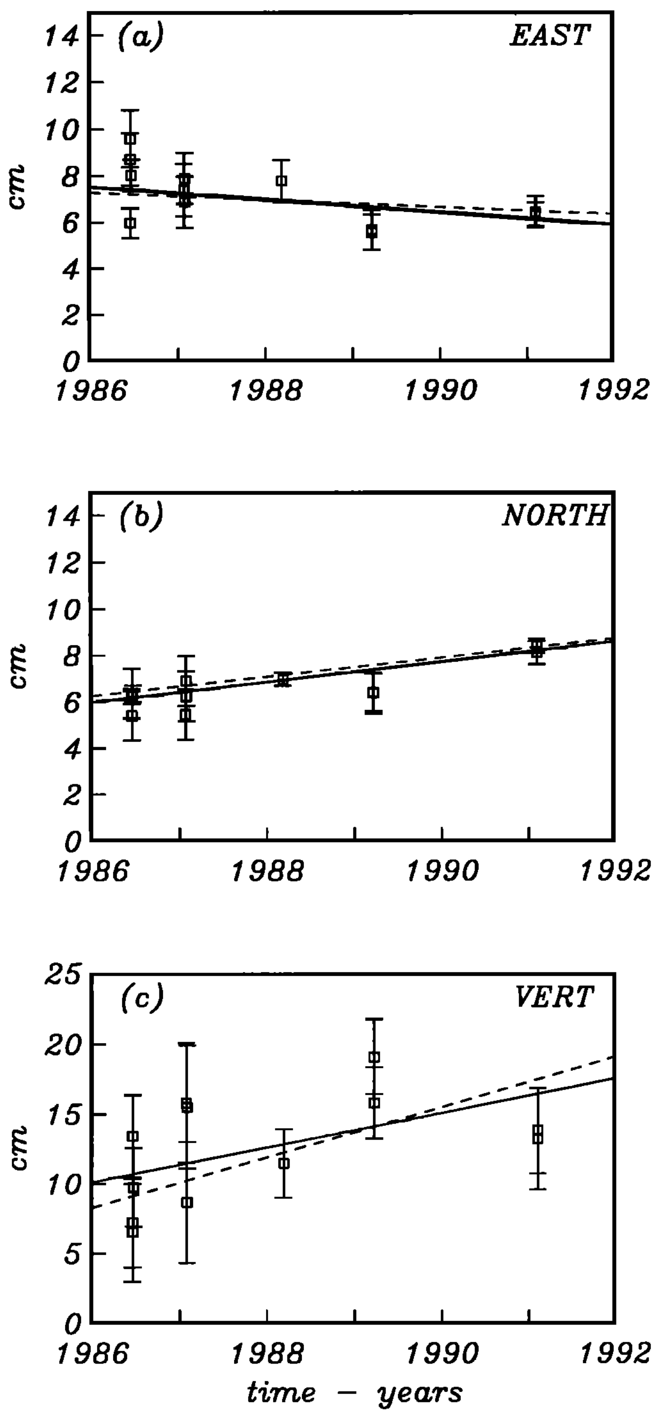

Fig. 10. Evolution of the interstation vector between Clembluf (San Clemente Island) and Palos Verdes. The solid line is the fit to data from simultaneous observations at these stations. The dashed line is the prediction from the network solution. The local coordinate system is defined at Palos Verdes and the evolution represents the motion of Clembluf relative to Palos Verdes.

estimate of significant shear in the central channel is not supported by the 4.5-year GPS results.

With the exceptions noted, deformation appears to be uniform between 1971 and 1991. There is one GPS result which requires discussion. Unless an active geologic feature separates two stations, it is generally assumed that the velocity of one station represents the motion of an entire region. In other words, stations very close to each other should have the same velocity, within error. As shown in Figure 7, Center (Santa Cruz Island) is moving 5.1±1.3 mm/yr at N103°E relative to Vandenberg. Devil's Peak, 4 km from Center, is moving 2.2±1.6 at N79°E relative to Vandenberg. Although more GPS data has been collected at Center than Devil's Peak, the velocity of Center is inconsistent with Larsen's 16-year baseline rate for Devil's Peak to Santa Rosa discussed above. This GPS analysis of data from Center and Vandenberg has been confirmed by an independent analysis using the GAMIT software [*Murray*, 1991]. An alternative explanation for the difference in velocities at Center and Devil's Peak is monument instability. During reconnaissance for the June 1991 measurements, the field crew discovered that the Center monument was loose, and it was subsequently recemented. Even so, the field crew estimated that only 3-4 mm motion was possible.

Southern Borderlands

The primary character of the southern Borderlands is a series of ridges, banks, and troughs, which trend northwesterly, parallel to the coastline and the Pacific-North American plate boundary. The region between the coastline and San Clemente and Santa Catalina Islands is known as the Gulf of Santa Catalina. Quaternary activity has been inferred on the San Clemente Island (SCIF), Rose Canyon (RC), and Palos Verdes Hills (PVH) faults which were shown earlier in Figure 1. All are thought to be right-lateral strike-slip faults [*Legg et al.*, 1989]. Seismicity is sparse, but by no means absent over the last 50 years. Unlike the northern Borderlands where deformation rates have been estimated using other techniques, the GPS-derived velocities from this analysis represent the first precise repeated geodetic results. Comparison of historical triangulation data to GPS data collected in 1986-1988 found that the problem was indeterminate, due to noise in the triangulation data and poor network geometry for strain modeling [*Webb*, 1991].

As shown in Figure 7, Nicholas and Clembluf (San Clemente Island) display no significant motion relative to Vandenberg at the 95% confidence level. Equivalently, there is no significant motion between Nicholas and Clembluf, 0.8±1.5 mm/yr. The velocity of Clembluf relative to Soledad is 5.9±1.8 mm/yr at a direction of N38±20°W. Brush (Catalina Island) has a slower rate relative to Soledad, 3.5±1.8 mm/yr, but at a similar direction, N28±20°W. The orientation of relative station velocities is suggestive of activity on a northwest trending right-lateral strike-slip fault such as the San Clemente Island fault. Although the geodetic network is sparse, the expected velocities can be calculated assuming the slip is being accommodated on the San Clemente Island fault, which is oriented N40°W. Figure 11 shows some simple calculations using a screw dislocation model [*Savage*, 1983]. The free parameters for this model are a locking depth and the slip rate below that depth. The screw dislocation model allows no motion perpendicular to the fault. The triangles represent the velocities of Brush, Soledad, Nicholas, and Niguel relative to Clembluf rotated onto their fault parallel and fault perpendicular components. Also plotted in Figure 11 are the screw dislocation predictions for slip rates of 3, 6, and 9 mm/yr below locking depths of 5, 12, and 19 km. The geodetic data cannot uniquely determine the locking depth and slip rate. These data prefer a slip rate no greater than 6 mm/yr.

TABLE 5. Baseline Length Rates, Santa Barbara Channel

	EDM-GPS[a] 16 years, mm/yr	GPS 4.5 years, mm/yr	Nominal Length, km
Devil's Peak-Santa Rosa	0.4±1.1	1.8±1.2	31
Lacumbre-Gaviota	0.4±1.5	0.3±1.6	45
Lacumbre-Devil's Peak	-6.6±1.7	-5.2±1.0	52
Gaviota-Santa Rosa	4.3±2.0	-1.3±1.0	62
Gaviota-Devil's Peak	4.7±2.1	-0.8±1.6	65
Lacumbre-Santa Rosa	-4.6±2.3	-3.0±1.2	70

Uncertainties are one standard deviation.

[a] *Larsen [1991].*

DISCUSSION

Are the GPS derived estimates of deformation in the Borderlands consistent with the NUVEL 1 North American-Pacific plate motion? In order to compare GPS and NUVEL 1, the Cartesian station velocities derived in the previous section must be tied to a well defined global reference frame. The GPS station velocities and nominal positions estimated in the previous section are loosely tied to GLB659, the VLBI global reference frame used to define the fiducial coordinates in each GPS experiment. Due to a combination of poor fiducial networks, as discussed in paper 2 and the

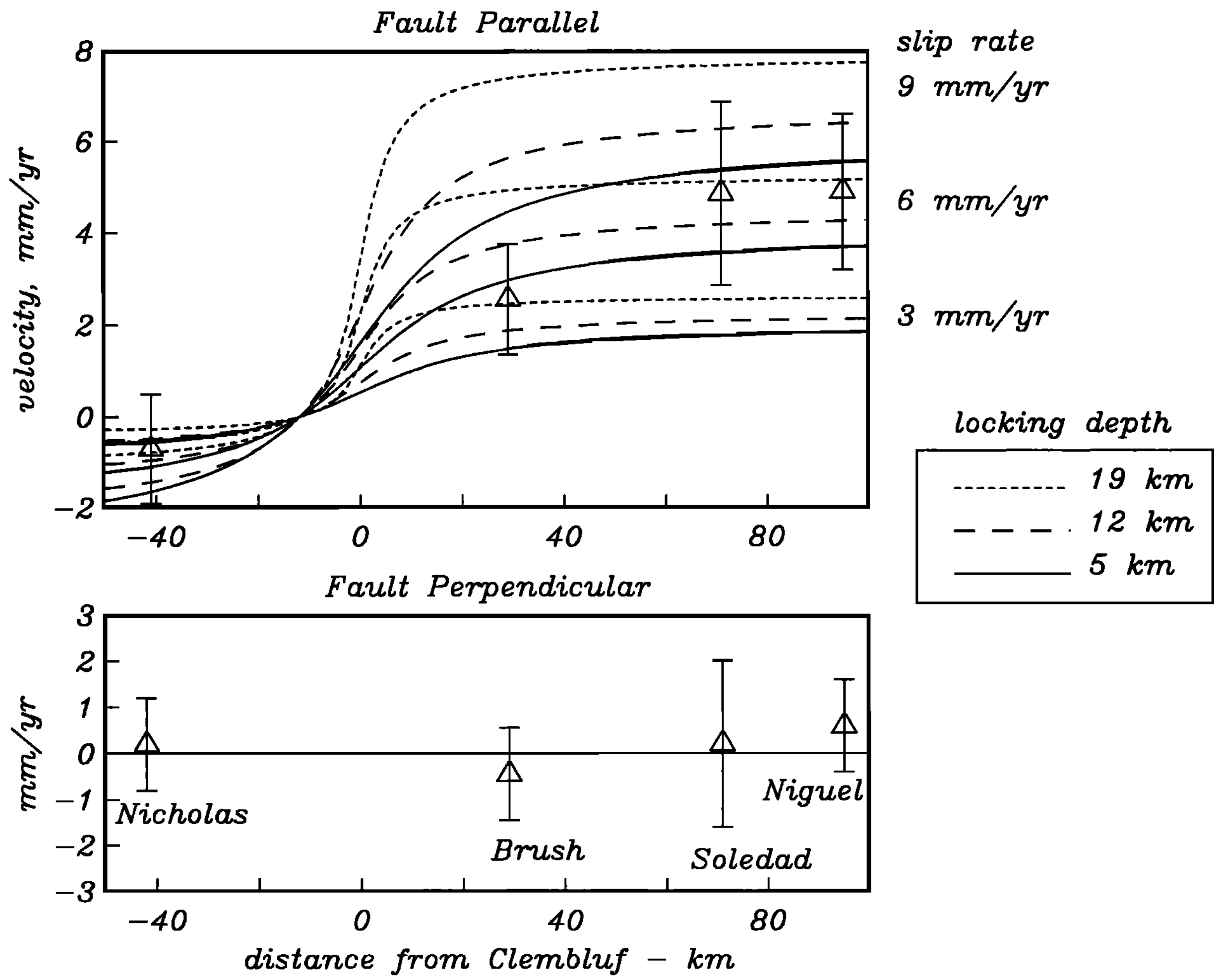

Fig. 11. Screw-dislocation-model velocity predictions assuming that slip is occurring on the San Clemente Island fault. The triangles indicate velocities between Clembluf (San Clemente Island) and Brush (Santa Catalina Island), Nicholas (San Nicolas Island), Soledad, and Niguel, with one standard deviation error bars. Velocities were translated to fault parallel and fault perpendicular components and plotted as a function of the fault perpendicular distance from Clembluf. The models are calculated assuming slip rates of 3, 6, and 9 mm/yr, with locking depths of 5 (dotted), 12 (dashed), and 19 (solid) km.

lack of global station coverage during this 5-year period, the GPS Cartesian station velocity standard deviations are no better than 5 mm/yr. Nonetheless, relative station velocities have standard deviations of 0.5-1.5 mm/yr in the horizontal components. To properly define the GPS station velocities in a global reference frame, we need one station defined in both the Borderland GPS and global VLBI frames. Only one station in the GPS Borderland Network, Vandenberg, has been precisely (standard deviations of 0.5, 1.2, and 1.0 mm/yr for the X, Y, and Z components, respectively) measured by VLBI. The GPS Borderland network is connected to the VLBI global frame by adding the GPS station velocities, relative to Vandenberg, with the Vandenberg velocity from GLB659. The velocity of any GPS station i in the global frame $V_i^{globalframe}$ is defined as follows:

$$V_i^{globalframe} = (V_i^{gps} - V_{vndn}^{gps}) + V_{vndn}^{vlbi} \quad (1)$$

V_{vndn}^{vlbi} and V_{vndn}^{gps} are the VLBI and GPS-derived velocities for Vandenberg, respectively. V_i^{gps} is the GPS derived velocity. The discrepancy between NUVEL 1 and these new crustal deformation estimates can then be represented by a residual vector, V_i^{resid}, which is defined

$$V_i^{resid} = V_i^{globalframe} - V_i^{nuvel} \quad (2)$$

where V_i^{nuvel} is the NUVEL 1 prediction assuming that station i is on the Pacific plate. The NUVEL 1 residual velocity vectors are shown in Figure 12 and listed in Table 6. The solid error ellipse in Figure 12 is the 95% confidence region for $V_i^{globalframe}$, where the GPS and VLBI standard deviations have been combined assuming that GPS and VLBI errors are independent. The dotted error ellipse is the 95% confidence region reported by *DeMets et al.* [1990]. The only GPS stations which indicate agreement with the NUVEL 1 model within one standard deviation are Santa Rosa and Gaviota. As expected, stations in the eastern Santa Barbara Channel and the coastal stations of the southern Borderland network indicate discrepancies ranging from 5 to 8 mm/yr. Both Nicholas and Clembluf fall short of NUVEL 1 predictions by 3 mm/yr in the east-west component but agree within 95% confidence limits.

These GPS results are also relevant to kinematic models of southern California. In the mid-1980s, two such models were developed to describe the distribution of motion in southern California. *Bird and Rosenstock* [1984] attached the Borderlands to the Pacific plate and predicted significant convergence across the Transverse Ranges. *Weldon and Humphreys* [1986] proposed that the offshore faults were active and that the region west of the San Andreas fault was rotating counterclockwise relative to North America. Both groups of researchers used the RM2 [*Minster and Jordan*, 1978] estimate of relative plate motion to bound their models. The GPS estimates of deformation derived in this paper disagree with both kinematic models. Bird and Rosenstock overpredict the motion of Soledad relative to North America, and predict no deformation across the Gulf of Santa Catalina. Conversely, Weldon and Humphreys overpredict the contribution of structures in the Gulf of Santa Catalina by 5 mm/yr (when the plate model is corrected from RM2 to NUVEL 1). Also, the Weldon and Humphreys velocity path across the western Transverse Ranges should be corrected to reflect offshore deformation in the eastern Santa Barbara Channel.

The offshore data are also in agreement with recent analyses of VLBI data. *Ward* [1988] suggests that 20% of the plate motion south of Vandenberg might be offshore. When this prediction is adjusted from the RM2 to NUVEL 1 model, it is in good agreement with the 5 mm/yr observed in the southern Borderlands. The sense of motion, right lateral shear, is also in agreement with his "megashear" zone. *Ward* [1990] also indicates that from 1 to 5 mm/yr could be accommodated in the southern Borderland.

CONCLUSIONS

Nearly 5 years of GPS data collected between 1986 and 1991 have been analyzed in order to determine crustal defor-

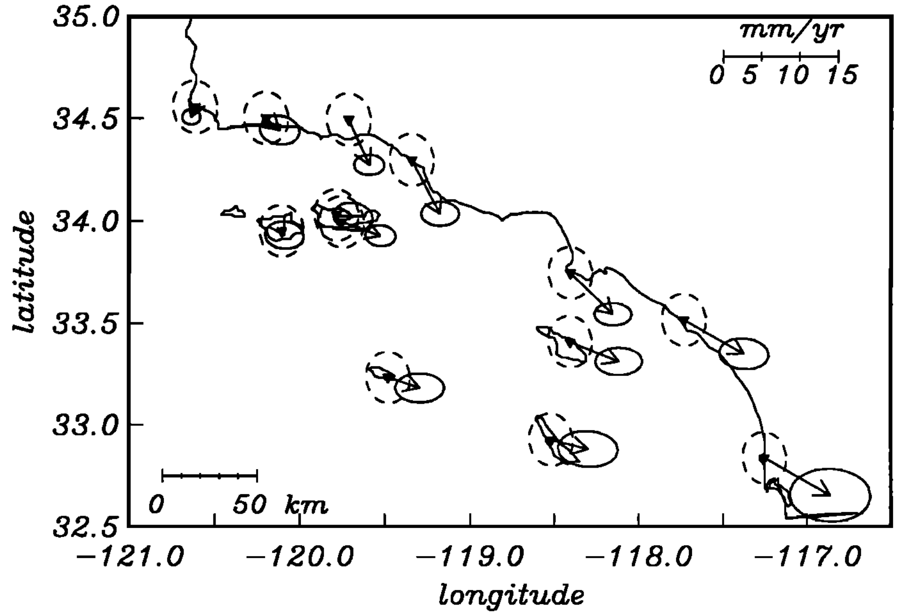

Fig. 12. Residual Borderland velocity to NUVEL 1, as defined by equation (2). Error ellipses are regions of 95% confidence for the GPS estimates (solid) and the NUVEL 1 global plate model (dotted).

TABLE 6. GPS Residual to NUVEL

Station	Velocity, mm/yr	Azimuth, deg	One Standard Deviation Error Ellipse: Major Axis Azimuth, deg	Magnitude, mm/yr: Major Axis	Magnitude, mm/yr: Minor Axis
Brush	6.9	112	85	1.8	1.7
Center	5.3	110	1	1.6	1.5
Clembluf	5.0	104	94	2.1	1.8
Devil's Peak	2.2	97	63	1.7	1.7
Gaviota	2.3	132	68	1.7	1.7
Lacumbre	6.4	155	4	1.6	1.5
Nicholas	4.3	109	87	1.8	1.7
Niguel	9.0	119	98	1.9	1.7
Palos Verdes	7.7	134	41	1.6	1.6
Soledad	9.8	120	92	2.5	2.1
Solimar	7.9	152	22	1.7	1.6
Santa Rosa	0.7	149	166	1.7	1.6
Vandenberg	1.4	201	173	1.4	1.2

mation rates in the offshore regions of southern California. Significant shortening, 6±1 mm/yr at N16±3°E, is taking place in the eastern Santa Barbara Channel. Farther west in the channel, there is no significant motion between Santa Rosa Island and Vandenberg, 0.3±1.6 mm/yr. Deformation in the southern Borderland is consistent with right lateral strike slip motion at N40°W, indicating that there are active structures in the Gulf of Santa Catalina.

While there is now geodetic evidence of offshore deformation in southern California, there are still many questions which can be answered by future GPS measurements. The question of deformation in the western Santa Barbara Channel remains unresolved. *Webb* [1991] predicts high deformation rates, 13±4 mm/yr at N23±7°W of compression, whereas 4.5 years of GPS measurements find interstation velocities no greater than 2.3±1.6 mm/yr. This discrepancy is consistent with nonuniform deformation rates. The GPS measurements of deformation in the western channel can be strengthened by repeating measurements to San Miguel Island (directly west of Santa Rosa Island), which was first observed in 1988 for comparison with historical triangulation.

The integrity of the GPS network in the Borderlands depends on the stability of the monuments. This instability can be confirmed on San Nicolas and San Clemente Islands, where alternate marks have been measured relative to Nicholas and Clembluf with GPS at least once in the last 5 years. There are GPS measurements to at least five monuments on Santa Cruz Island, opening up the possibility that these data could be used to study present-day motion of the Santa Cruz Island fault, as well as the stability of the main mark at Center. Although there is little evidence for deformation between San Nicolas and Santa Barbara (119.0°W, 33.7°N) Islands [*Junger*, 1976], this could be confirmed by repeating measurements made in 1988.

The application of GPS to measurements of crustal deformation is no longer in its infancy. These results indicate the kinds of questions that can now be answered with geodetic data rather than kinematic models. GPS technology is far easier to use than EDM, and the closer station spacing makes it preferable to the VLBI measurements which were made for the Crustal Dynamics Project. Eventually regional analyses such as those by *Feigl et al.* [1990], *Donnellan* [1991], and *Larsen* [1991] and this one can be incorporated into a complete surface velocity model of southern California.

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