NOAA Technical Report NOS 109 NGS 31

Geodetically Derived Strain From San Francisco Bay To The Mendocino Triple Junction, California

Michael W. Cline
Richard A. Snay
Edward L. Timmerman

Rockville, MD
April 1985

U.S. DEPARTMENT OF COMMERCE
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GEODETICALLY DERIVED STRAIN FROM SAN FRANCISCO BAY TO THE MENDOCINO TRIPLE JUNCTION, CALIFORNIA

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ABSTRACT. Geodetic data comprised of triangulation, trilateration, and astronomic azimuths observed since late-1906 to 1978 are used to obtain models of horizontal crustal deformation in California. The three regional models roughly cover the California Coast Ranges from San Francisco Bay ($\phi = 37^{\circ}$) northward to the Mendocino triple junction ($\phi = 40^{\circ}$) and from the Great Valley ($\lambda = 121.5^{\circ}$) westward to the Pacific Ocean.

Each of the three regions is partitioned into a mosaic of "districts" that are allowed to individually translate, rotate, and deform homogeneously as a linear function of time. By approximating the known geologic faults with district boundaries, the relative motion between districts represents secular fault slip. Because the geodetic data cover such a large area, the eastward extent of significant deformation about the San Andreas fault in this area is delineated for the first time.

To study the transient postseismic effects of the 1906 San Francisco earthquake, the data for the 1931-1978 time interval are separately modeled, and these models are compared with those for the entire time interval. Results show an asymmetric pattern about the San Andreas fault that is comprised of a dramatic drop in strain rates for areas eastwardly adjacent to the rupture trace and includes two areas where strain rates may have risen through time. Supplemental studies indicate, however, that the data for one of these areas, the Point Reyes peninsula, are of suspect quality. Throughout these investigations, directions of maximum right-lateral shear strain for the area northwest of San Pablo Bay consistently align with the trends of the Tolay and Mount Jackson faults rather than with the Rodgers Creek and Healdsburg faults, as the geologic evidence would suggest.

INTRODUCTION

The region of California affected by the San Francisco earthquake of 1906 has received intensive study over the years, beginning with the landmark report by Lawson et al. (1908). In that report Hayford and Baldwin (1908) documented the geodetically derived coseismic displacements that later proved instrumental to Reid (1910) in establishing the elastic rebound theory. More recently Thatcher (1975a) re-evaluated the 1906 rupture mechanism by capitalizing on improved analysis techniques as well as additional triangulation data and (Thatcher 1975b) went on to clarify the strain accumulation process from 1906 to the 1960's.

Beginning in the early 1970's the U. S. Geological Survey (USGS) established a number of networks in the western United States that are periodically re-observed using Electronic Distance Measuring (EDM) instruments (see Prescott et al. 1979). In the San Francisco Bay area, Prescott et al. (1981) used the changes in line-lengths determined from this decade-long monitoring program, supplemented with a collection of small-aperture fault-crossing networks or alignment arrays, to describe the slip and deformational processes presently occurring over the San Andreas, Hayward, and Calaveras faults. Savage (1983) integrates the results from these recent papers and from other investigations to supply a concise overview, both spatially and temporally, of the strain accumulation patterns along the entire reach of the California Coast Ranges.

An outgrowth of these studies is the conclusion that strain rates between earthquakes vary significantly with time, and a variety of models has been proposed to explain the temporal changes in strain rates following an earthquake. Thatcher (1983) presents two such models, including appropriate parameters, that adequately fit the geodetic data discussed previously: one model consists of an infinitely deep fault embedded in an elastic halfspace where the amount of slip on this fault varies with depth and time; the other model restricts the fault to lie within a thin elastic plate (lithosphere) that is coupled to a viscoelastic substrate (asthenosphere).

Our analysis upholds the fundamental conclusions of these previous studies--as it should since it incorporates nearly all of the same geodetic data. Where our study differs, however, is that through the technique developed by Snay et al. (1983) more data are enabled to participate in the analysis because survey projects need no longer overlap with the same geometric configuration from epoch to epoch. These additional geodetic data, while not originally observed for gauging crustal deformation, are capable nevertheless of revealing more subtle distinctions in the strain rate patterns, through increased observational density both spatially and temporally, and can be used to determine strain rates in areas far removed from the typical locations of crustal motion monitoring networks. Our study therefore differs in that we determine strain rates in the Coast Ranges northward of any previous study, we determine strain rates in the Great Valley eastward of any previous study (thereby delineating the extent of primary deformation), and we note an asymmetrical pattern of strain relaxation about the San Andreas fault that includes two areas where the models imply that strain rates rise through time (although large uncertainties are attached to the validity of those rising rates).

The data analysis procedure, implemented by the National Geodetic Survey (NGS) and entitled project REDEAM (for REgional Deformation of the EArth Models), has produced a series of mathematical models representing 16 regions of California

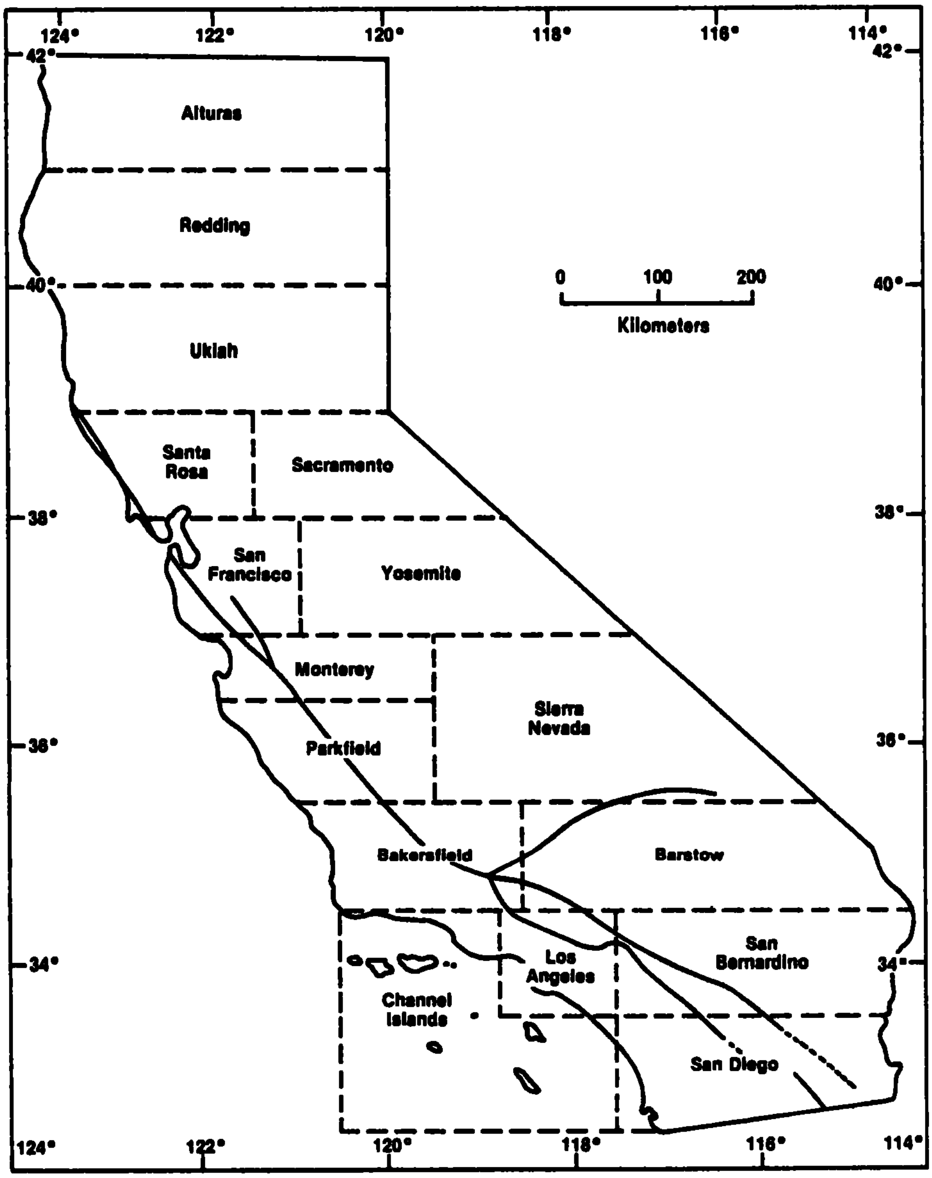

Figure 1.--Project REDEAM has derived a horizontal crustal motion model for each of 16 regions in California. Models for the San Francisco, Santa Rosa, and the western half of the Ukiah region are presented in this report.

(see fig. 1) that together quantify both the historical secular and episodic horizontal crustal deformation processes over the entire state (see Snay et al. 1985). The results from project REDEAM for the San Francisco, Santa Rosa, and the western half of the Ukiah region--that area best described as the California Coast Ranges stretching from San Francisco Bay northward to the Mendocino triple junction (see fig. 2)--are discussed here along with additional studies that document the postseismic deformation since 1906.

ANALYSIS PROCEDURES AND DATA

The basic technique is to specify a mathematical model that describes geodetic position as a function of time and then to estimate the parameters of this model by a simultaneous least-squares adjustment of all pertinent geodetic data. The mathematical formulation of the model allows for both secular and episodic

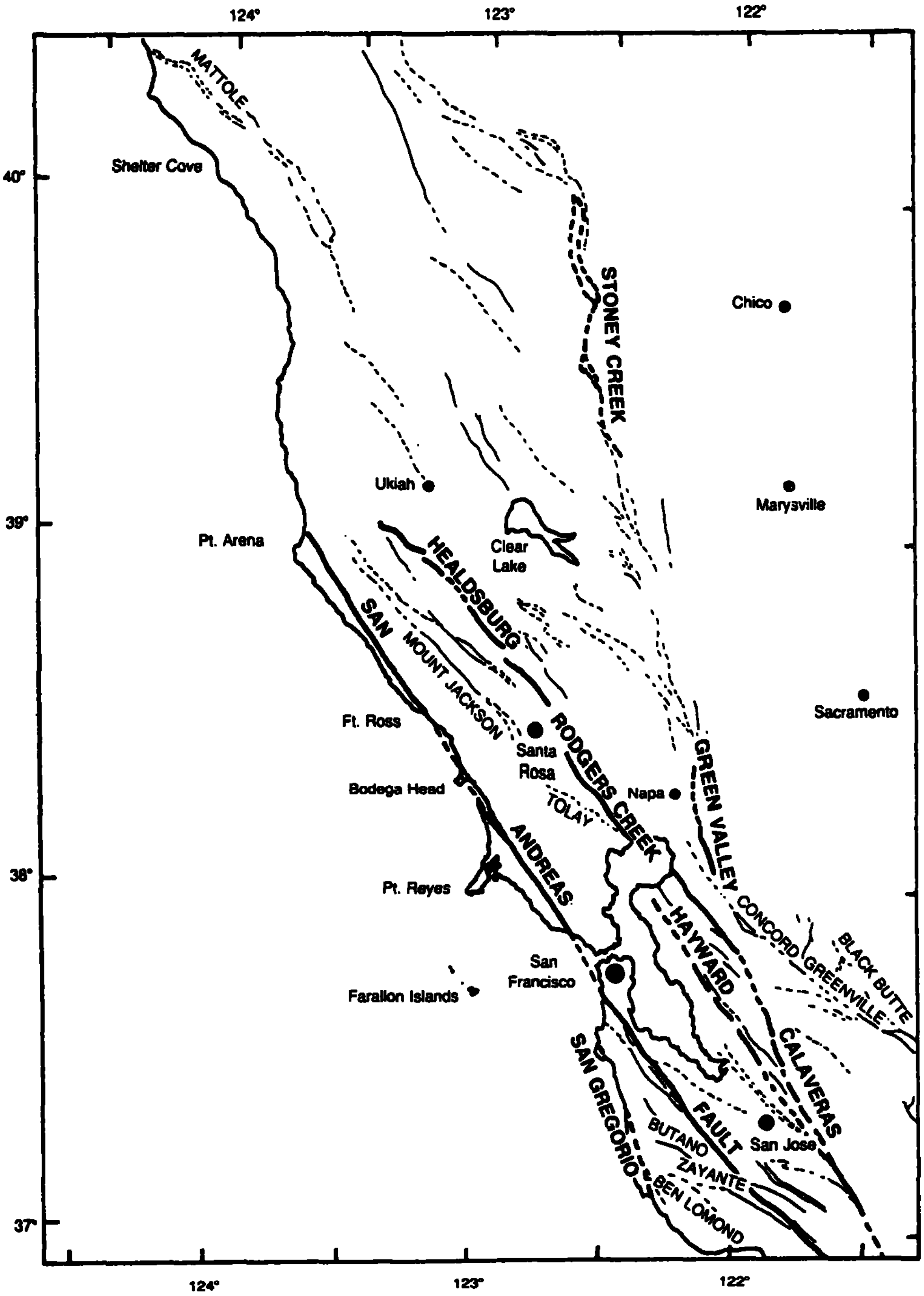

Figure 2.--Selected faults, cities, and other points in the California Coast Ranges and Great Valley for the area of the three regions modeled. The Maacama fault (not shown) parallels the Healdsburg fault after an 8-km right step.

movement of the stations, where the secular motion is modeled by dividing a region, such as the San Francisco region, for example, into a mosaic of "districts." Each district within a region is allowed to translate, rotate, and deform homogeneously at a constant rate with respect to time. By approximating the known geologic faults with district boundaries, the relative motion between districts allows for secular fault slip. This is not to say that all district boundaries correspond to faults; some districts are introduced simply to increase the spatial resolution of the secular motion. Modeled episodic motion corresponds to displacements associated with large (M>6) earthquakes; however, because of the seismic quiescence in this area following the 1906 earthquake (see Ellsworth et al. 1981) and because no geodetic data observed before the 1906 event participate in these particular REDEAM studies, no episodic motions are modeled in any of the three regions studied here. For a detailed mathematical description of the REDEAM modeling procedure, see Snay et al. (1983).

From the method of project REDEAM we are able to describe adequately the derived deformation of each district with quantities that denote the direction of maximum right-lateral shear strain (ψ) and the (engineering) shear strain rate ($\dot{\gamma}$) in that direction. Strain rates, however, are linear functions of time, in direct opposition to the nonlinear character of the strain relaxation phenomenon we intend to examine. We reconcile this conflict by noting the effect of changing the time span of the data for which the strain rate is applicable; for instance, we obtain models for all data observed from (a) late-1906 to 1978, (b) 1922 to 1978, and (c) 1931 to 1978. Figure 3 shows a station-distribution plot of the geodetic stations that were positioned more than once during the 1906-1978 interval. The stations are symbolized to represent the time between a station's earliest position determination and its most recent positioning. The district boundaries for the modeled regions are shown also.

The very act of a wholesale discarding of heterogeneously overlapping survey projects by observation date can undeniably alter the distributional character of the data, perhaps leaving some districts untouched by the purge while others may be nearly decimated of remaining project overlap. Figure 4 shows a station-distribution plot for the 1931-1978 interval, indicating through comparison with figure 3 that except in the western Ukiah region no major alteration in the spatial arrangements of the stations from which the strains are computed has resulted. Nevertheless, some interpretations based solely upon this method of analysis may prove questionable. For this reason we supplement our investigations with an additional form of analysis.

In the supplemental method an individual survey project containing data observed over the span of a few months is separately processed to obtain minimally constrained least-squares estimates of station positions for a representative year. The differences in these positions from survey to survey (epoch to epoch) give a displacement vector for each station common to both projects. From the vectors for a group or polygon containing at least three stations, a strain tensor is determined that quantifies the deformation over the homogeneous extent of the polygon for the elapsed time between the compared surveys. Because the polygons cover a smaller area than most REDEAM districts, the supplemental method allows an increased spatial resolution of the deformation.

The data consist of triangulation (angles), trilateration (distances), and astronomical azimuths. The earliest observations date from late-1906, following the San Francisco earthquake, and the latest observations date from 1978. The San Francisco and Santa Rosa regions each contain approximately 880 stations, 9250 directions, 1050 distances, and 30 azimuths, losing approximately 40 stations, 750 directions, 20 distances, and 7 azimuths for the 1931-1978 data-reduced models. The entire Ukiah region contains 789 stations, 6248 directions, 627 distances, and 21 azimuths, but only the results of the western half of the region are presented here. The data for this region are insufficient to support a meaningful model for the shorter time intervals considered for the other regions (see figs. 3 and 4). Data for each of the three regions extend an additional 10' in latitude and longitude beyond the adopted regional borders, helping to ensure a smooth transition in strain values from one region to another. The REDEAM model for each independently adjusted region is minimally constrained, meaning that one point or station in each region is assigned specific geodetic coordinates and this station acts as an origin of reference at which no movement is allowed. These constraints are necessary because the data contain no information concerning the "absolute" position or velocity of the network.

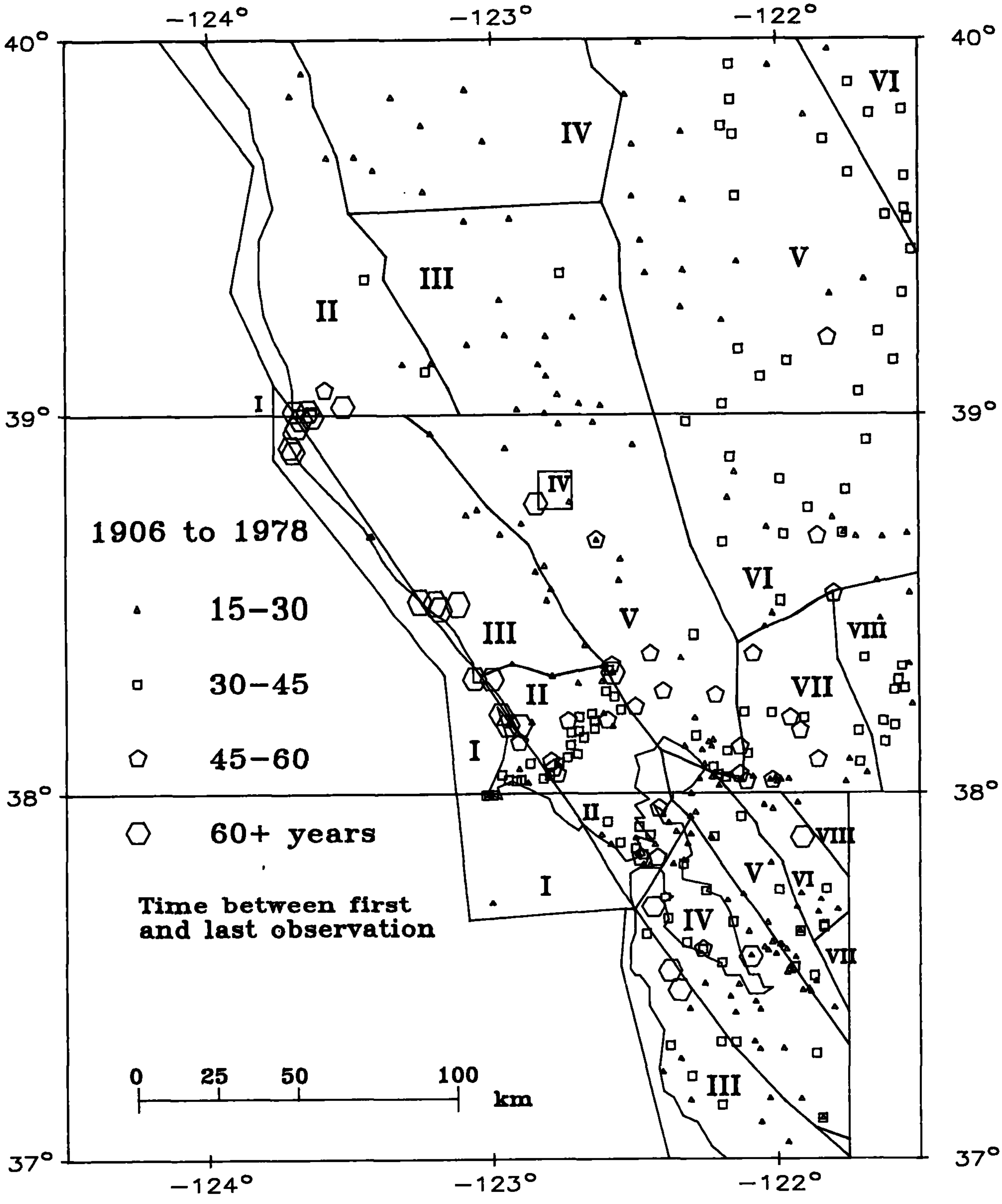

Figure 3.--Station-distribution plot for the 1906-1978 interval. The geodetic stations are symbolized to reflect the time between the earliest and latest observations at that station. Roman numerals identify the districts in each of the three regions.

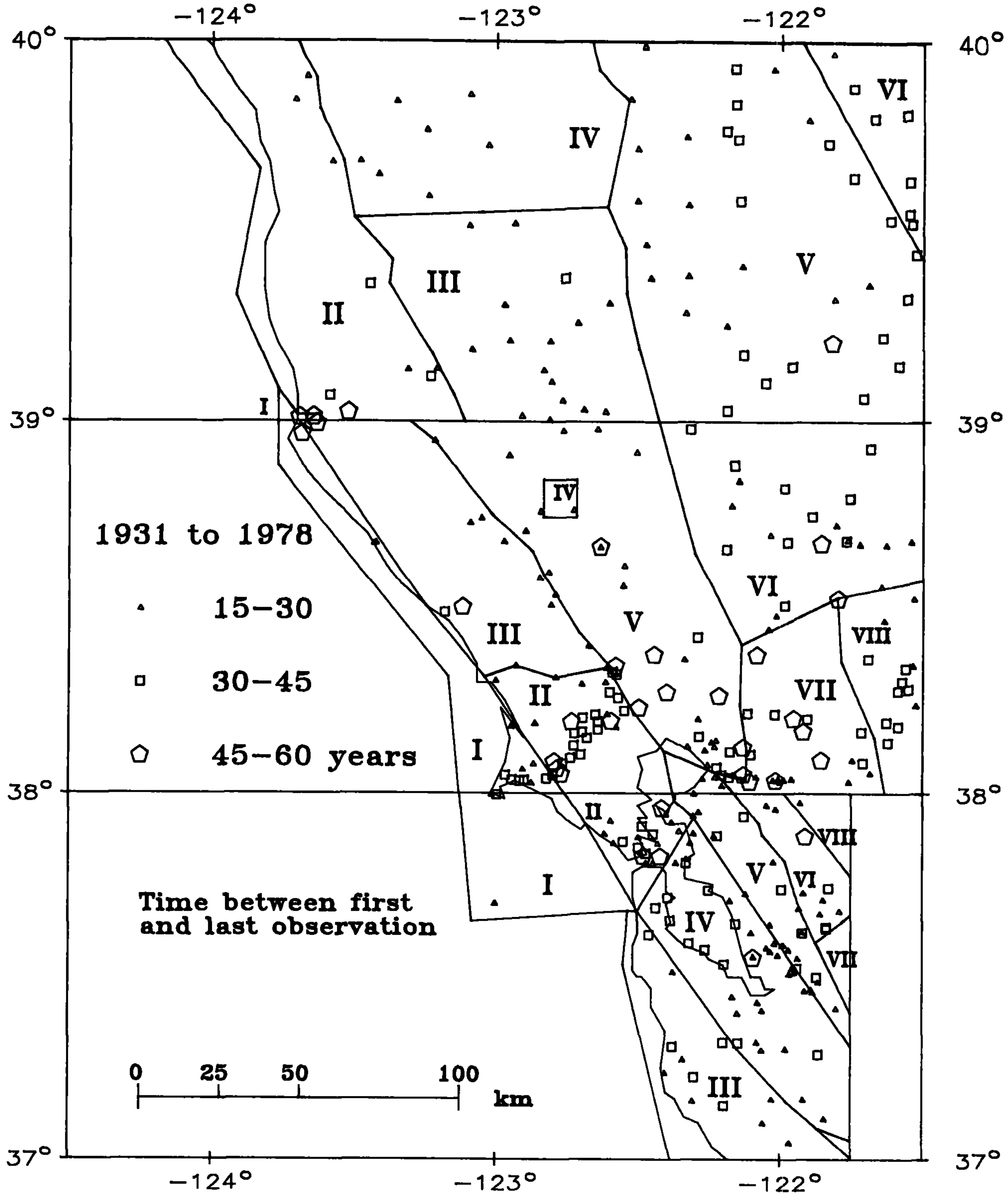

Figure 4.--Station-distribution plot for the 1931-1978 interval. Comparison with figure 3 shows that no major re-distribution of the stations results from the wholesale discarding of data observed before 1931. Roman numerals identify the districts.

Standard errors of the observations are assigned a priori according to NGS guidelines (Schwarz 1978), where the most precise direction observations of NGS receive a standard error of 3 μrad, individual azimuth observations typically have a standard error of 7 μrad, and distances are assigned a two-part standard error based upon an instrument constant and a component proportional to the length of the line measured. Uncertainties on estimated parameters throughout this report are "formal" one-standard-error estimates that are generated directly by the least-squares process, where linear error propagation is assumed. See Snay et al. (1983) for elaboration.

RESULTS

Figure 5 is a montage of the REDEAM results for the three 1906-1978 regions, where the direction of the district fill lines corresponds to the direction of maximum right-lateral shear (ψ) and the line density corresponds to the magnitude of the (engineering) shear strain rate ($\dot{\gamma}$). We adopt this "line-density" method of presenting the results over that of showing the principal strain rates of $\dot{\varepsilon}_1$ and $\dot{\varepsilon}_2$ because the magnitudes of the principal strain rates are directly related to the dilatation rates for the districts and, as Snay et al. (1983) emphasized, scale errors of several parts per million among the different distance data sets may contaminate the dilatation rates by 10^{-7} strain/yr. Scale errors have a lesser effect on $\dot{\gamma}$ and ψ, making these quantities more reliable.

Figure 5 clearly shows that for this time period moderate shear strain rates (~0.3 ± 0.1 μrad/yr) occur over a broad area in the San Francisco Bay area but become concentrated close to the San Andreas fault and build in magnitude proceeding to the northwest, reaching a maximum at Point Arena (~1.3 ± 0.1 μrad/yr). (Note, however, that the relatively small district at Point Arena straddles the fault.) In the Great Valley east of the Coast Ranges, low shear strain rates (~0.08 ± 0.07 μrad/yr) parallel the San Andreas strike direction, thereby roughly delineating the eastward extent of significant deformation. In the Coast Ranges of the Ukiah region, moderate shear strain rates (~0.3 ± 0.1 μrad/yr) again occur over a broad area, while strain rates along the coastal district of the Ukiah region, which appear extreme in figure 5, are shown in table 1 to have a large uncertainty (~0.9 ± 0.3 μrad/yr), attributable to poor station distribution (see fig. 3). For the most part, dates of observation for the strain rates determined in the Coast Ranges and Great Valley of the Ukiah region (districts III-VI) differ from the other regions and districts in that the dates range from about 1940 to 1970.

The small dark square near the center of figure 5 and within the Santa Rosa region represents the Geysers geothermal steam field near Clear Lake (district IV). As mentioned by Denlinger and Bufe (1982) the horizontal displacements of the stations inside the producing area are highly nonlinear in space and time; hence it is no surprise that our values of $\dot{\gamma}$ and ψ differ slightly from theirs considering that the REDEAM data in this district were observed during 1972 to 1977 and, for one station, 1949. Also we expand the area of geothermal deformation to include 11 stations; Denlinger and Bufe use only six stations. The REDEAM values, like those of Denlinger and Bufe (1982), nevertheless show a strain rate of an order of magnitude greater for this district over most other districts, indicating that the strain description inside the steam field should be separated from the surrounding district. Obviously because the data in this particular district all postdate 1931, the strain rate in this district is essentially unaffected by our data-shortening scheme of study.

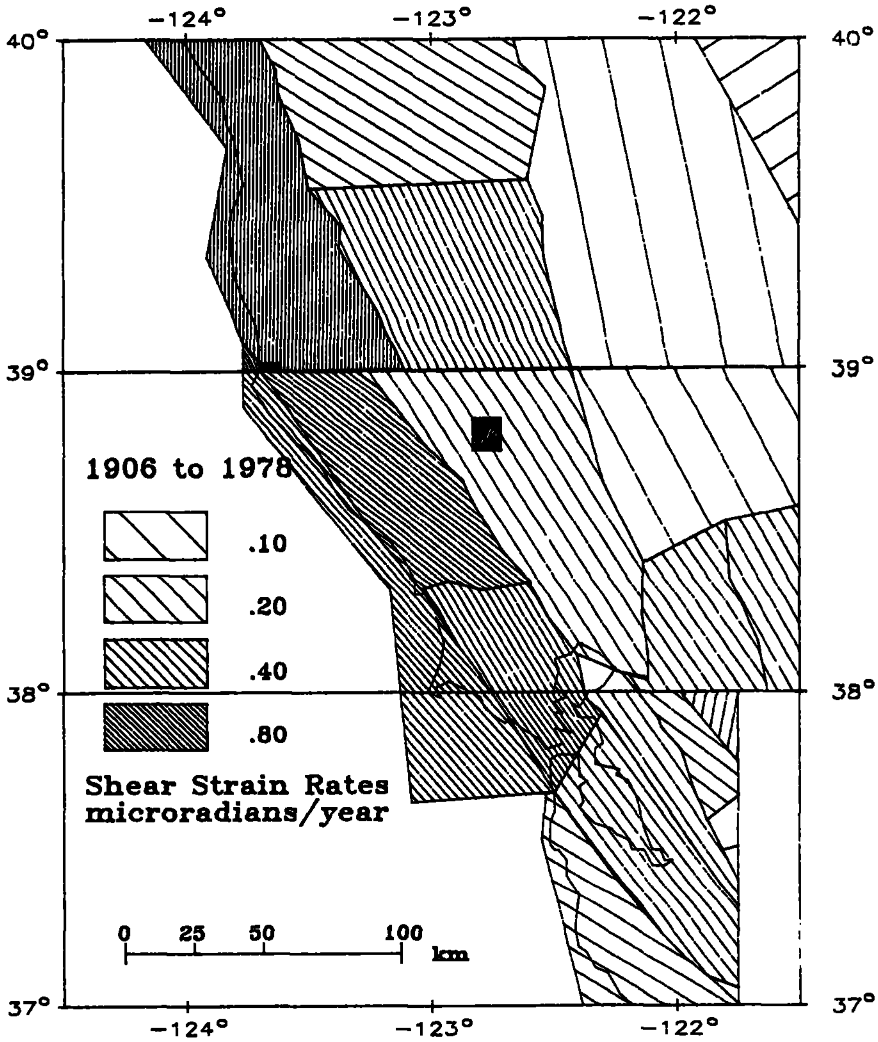

Figure 5.--Shear strain rates determined for the three 1906-1978 models. Direction of maximum right-lateral shear strain (ψ) and the (engineering) shear strain rate ($\dot{\gamma}$) in that direction are shown for each district by these line-density patterns. Values are listed in table 1.

Figures 6a and 6b quantify the changes in strain rates for the various districts of the Santa Rosa and San Francisco regions, relative to the 1906-1978 models. As mentioned previously, the data are insufficient to allow a similar depiction for the Ukiah region. Figure 6a shows that after discarding the data observed in 1906, allowing the next earliest epoch of observation to be 1922 or 1925 (depending on survey project and area), the strain rate drops appreciably for the district northeast of Bodega Head (III), as certain theoretical models predict (Thatcher 1983). This drop in the strain rate east of the ruptured San Andreas fault, however, is not mirrored in the district to the west nor is it reflected in the districts to the south. Figure 6b shows that after discarding all data observed prior to 1931, including the 1930 Point Reyes to Petaluma arc of triangulation discussed by Thatcher (1975b), the strain rate relative to the 1906-1978 model continues to decline in the district northeast of Bodega Head, and now the drop in strain rates continues over the districts to the southeast in both the Santa Rosa and San Francisco regions. This drop in strain rates east of the San Andreas fault, however, is again not mirrored in the districts to the west, and, moreover, an unexpected rise in strain rates for those western districts is evident. A similar rise in strain rates, although statistically insignificant, occurs in districts east of the Concord-Green Valley faults. A

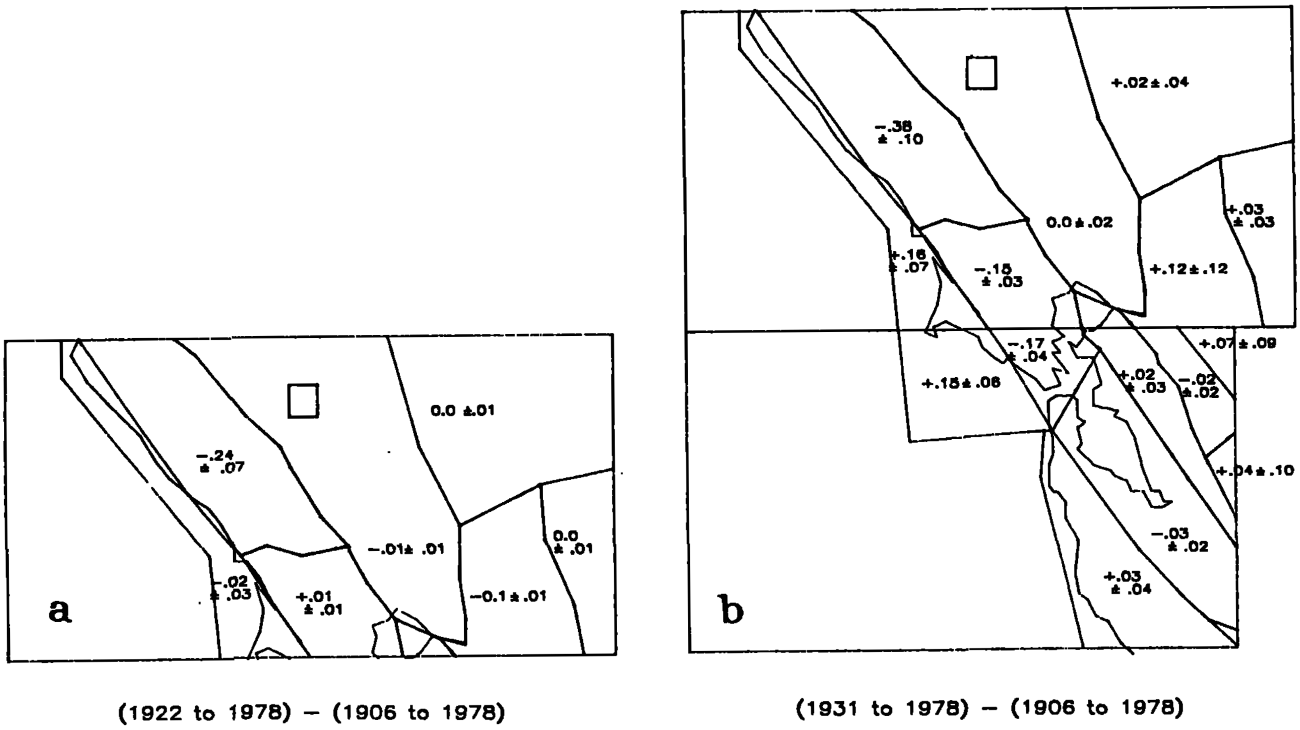

Figure 6.--Changes in shear strain rates for various time-interval models, relative to the 1906-1978 models. Figure 6a shows that after discarding the 1906 postearthquake observations, strain rates drop appreciably for only Santa Rosa district III, located northeast of Bodega Head. Figure 6b shows the effect of discarding all data observed before 1931, when compared to the 1906-1978 models.

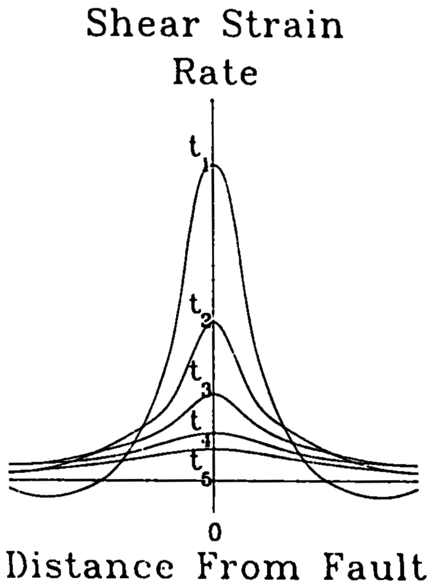

Figure 7.--Theoretical changes in shear strain rates as a function of distance from the fault for five successive times following an earthquake (from Thatcher 1983). Strain rates are predicted to drop appreciably near the fault but rise slightly at distances several rupture-depths distant from the fault.

Table 1.--Shear strains for the various models and time intervals

Region/District	1906 - 1978		1922 - 1978		1931 - 1978		1931 - 1978	
	$\dot{\gamma}$*	ψ**	$\dot{\gamma}$*	ψ**	$\dot{\gamma}$*	ψ**	$\dot{\gamma}$*	ψ**
Ukiah								
I	1.29±0.12	N32W± 3						
II	0.89±0.27	N 1E± 8						
III	0.40±0.08	N27W± 5 #						
IV	0.21±0.09	N59W±13 #						
V	0.07±0.03	N12W±15 #						
VI	0.10±0.07	N58E±19 #						
Santa Rosa								
I	0.59±0.06	N42W± 4	0.57±0.07	N43W± 4	0.75±0.09	N43W± 4	0.76±0.09	N44W± 4
II	0.51±0.03	N32W± 2	0.52±0.04	N34W± 2	0.36±0.04	N33W± 4	0.41±0.05	N33W± 4
III	0.68±0.09	N52W± 4	0.43±0.11	N60W± 7	0.30±0.13	N55W±12	0.27±0.13	N57W±14
IV	1.89±0.44	N22E± 9	1.89±0.44	N22E± 9	1.93±0.42	N21E± 8	1.96±0.41	N22E± 8
V	0.22±0.04	N33W± 5	0.21±0.04	N33W± 5	0.22±0.04	N29W± 5	0.21±0.04	N25W± 6
VI	0.08±0.07	N29W±23	0.08±0.07	N28W±24	0.10±0.07	N40W±20	0.10±0.07	N40W±20
VII	0.29±0.08	N35W± 7	0.28±0.08	N38W± 7	0.41±0.09	N41W± 6	0.40±0.09	N41W± 6
VIII	0.27±0.12	N30W±14	0.27±0.12	N30W±14	0.30±0.12	N29W±12	0.30±0.12	N29W±12
IX	NA		NA		NA		0.64±0.14	N66W± 8
San Francisco								
I	0.51±0.07	N41W± 4			0.67±0.09	N46W± 4		
II	0.65±0.05	N35W± 2			0.48±0.06	N39W± 4		
III	0.20±0.05	N59W± 9			0.23±0.06	N55W± 8		
IV	0.32±0.04	N37W± 4			0.29±0.05	N37W± 5		
V	0.27±0.09	N35W±10			0.29±0.09	N37W±10		
VI	0.24±0.06	N53W± 7			0.22±0.06	N43W± 8		
VII	0.02±0.08	N76E±100			0.06±0.08	N33E±42		
VIII	0.32±0.14	N11E±14			0.39±0.17	N12E±13		

*μ rad/yr   ** degrees   # most dates of observations extend from about 1940 to 1970

30-km-wide band of "strain-change indecision" about the Hayward and Calaveras faults stretches between these "falling and rising" areas east of the San Andreas fault. Values of ψ and $\dot{\gamma}$ for the three 1906-1978 regions and the data-reduced models are listed in table 1 for comparison.

Because observations span district boundaries, the strain determinations from district to district within a region are not independent of each other, causing minor changes in strain values to be mimicked in districts neighboring those that experience large changes. Likewise, because of the 10' overlap in data from region to region, districts I and II along the border of the San Francisco and Santa Rosa regions contain nearly identical observations, thus showing nearly identical changes in strain rates.

A rise in strain rates through time at distances several rupture-depths away from strike-slip faults is predicted by certain theories, as shown by Thatcher (1983) from whom our figure 7 is adapted. These REDEAM results have the appearance of being the first observational evidence for this theorized feature of postseismic deformation along strike slip faults, but as stated previously, our strain-rate increases derived for the eastern districts are statistically insignificant (see fig. 6b). Also we hesitate to advance these derived strain-rate increases as supportive of the theories presented by Thatcher because the rising strain rates

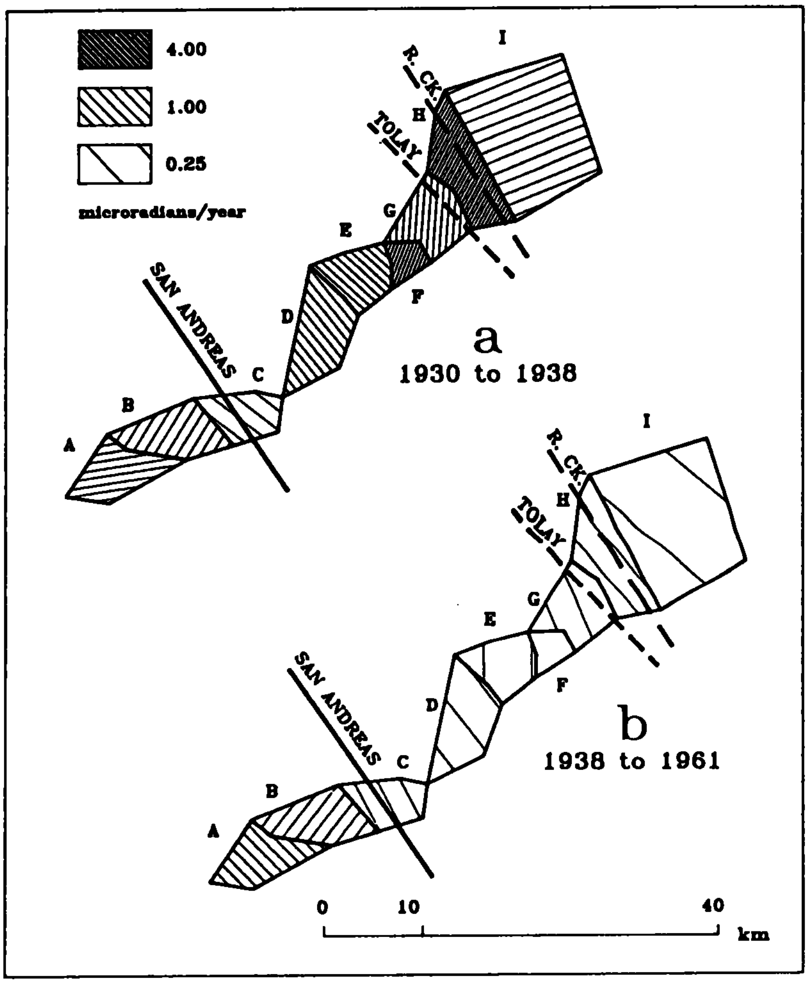

Figure 8.--Shear strain rates determined for polygons of stations comprising the Point Reyes to Petaluma arc of triangulation. Figure 8a shows strain rates between 1930 and 1938; Figure 8b shows strain rates between 1938 and 1961. Similar results are presented by Thatcher (1975b).

for districts immediately west of the San Andreas fault are discordant in that the pattern is asymmetric about the rupture trace. Because of the previous work of Thatcher (1975b) and Thatcher (1983) the strain rate decline in districts eastwardly adjacent to the San Andreas fault can reasonably be assumed to be the primary result of postseismic relaxation; however, the statistically significant rise in strain rates to the west of the San Andreas fault, primarily controlled by data on the Point Reyes peninsula, deserves further investigation. We therefore turn to the supplemental method of analysis.

We use the supplemental method to investigate the Point Reyes to Petaluma arc, observed during 1930, 1938, and 1961. Thatcher (1975b) previously studied this arc of triangulation and obtained the strains for a series of polygons by a least-squares fitting of observed angle changes using Frank's (1966) method. As previously described, we use least-squares determined displacement vectors to obtain our description of the strain field. Another difference is that Thatcher (1975b) used only the observations specific to the particular polygons, while we use the entire triangulation projects, including the long brace lines of observation involving stations at Fort Ross and Mount Tamalpais, ensuring for our solution a greater geometric rigor for the arc as a whole. We then present the results in the manner consistent with our previous results; i.e., the line-density patterns introduced in figure 5. The strain patterns for the

Point Reyes to Petaluma arc are shown in figure 8a for 1930 to 1938 and in figure 8b for 1938 to 1961.

Strain relaxation, brought about by increased transient slip at intermediate depths (between about 10 and 30 km) along the San Andreas fault, corresponding to the modified infinite elastic halfspace model of Thatcher (1983), is indicated when the direction of maximum right-lateral shear is oriented perpendicular to the ruptured fault, as indicated in figure 8a for polygons A and B west of the San Andreas fault and for polygons F-I near the Tolay and Rodgers Creek faults. Directions of shear for polygons C-E (fig. 8a) are aligned approximately parallel with the San Andreas fault, indicating strain buildup. Note that the pattern is distinctly asymmetric relative to the San Andreas fault. Figure 8b shows that, with the exception of polygon B, strain buildup is the dominant mode of deformation from 1938 to 1961, indicating as Thatcher (1975b) contends that the transient postseismic effects in this particular area continued for approximately 30 years.

Our analysis is not the first to note an asymmetry in displacements across the San Andreas fault. Hayford and Baldwin (1908) note that:

> For points on opposite sides of the fault of 1906, and at the same distance from it, those on the westward side are displaced on an average twice as much as those on the eastern side. This statement applies especially to points within 10 kilometers (6 miles) of the fault. For points farther away, the ratio becomes more than two to one.

Until now their statements received little weight, probably because they constrained their solution by holding two stations fixed in position, and, as Prescott (1981) demonstrates, interpretations based on the relative displacements of stations are extremely sensitive to the applied constraints. Thatcher (1975b) similarly obtained an asymmetric strain pattern in his study of the Point Reyes to Petaluma arc, but attributed the discrepancy to observational errors suggested by triangle misclosures twice the norm involving those stations west of the San Andreas fault. Our results on the Point Reyes peninsula also hint at these same observational errors, primarily in figure 8b where the directions of maximum right-lateral shear for polygons A and B are nearly 90° opposed, implying that strain on the Point Reyes peninsula is nonhomogeneous. But geologic cross sections by Taliaferro (1951) of the Point Reyes peninsula show no major faults penetrating a basement complex of quartz diorite (granite), implying that shear strain should be homogeneous over the entire peninsula. The determination of these supplemental strain values is further complicated due to the loss and resetting between 1938 and 1961 of two key stations, one in polygon A and the other in B. The resettings are not coincident with the original locations. Thus weak evidence supports a different coseismic and, presumably, a different postseismic strain response across the San Andreas fault (Hayford and Baldwin 1908), but stronger evidence tends to discount the strain rate changes on the Point Reyes peninsula noted by our REDEAM studies as representing observational errors.

Polygons G and H at the northeastern end of the Point Reyes to Petaluma arc indicate that significant shear strain is accumulating over the Tolay and Rodgers Creek faults. Our REDEAM analysis of the Santa Rosa district just north of this arc (III) indicates that the direction of maximum right-lateral shear strain (N52°W± 4°) agrees closely with the strike of the Tolay and Mount Jackson faults (N55°W) and that this close correspondence remains invariant regardless of the

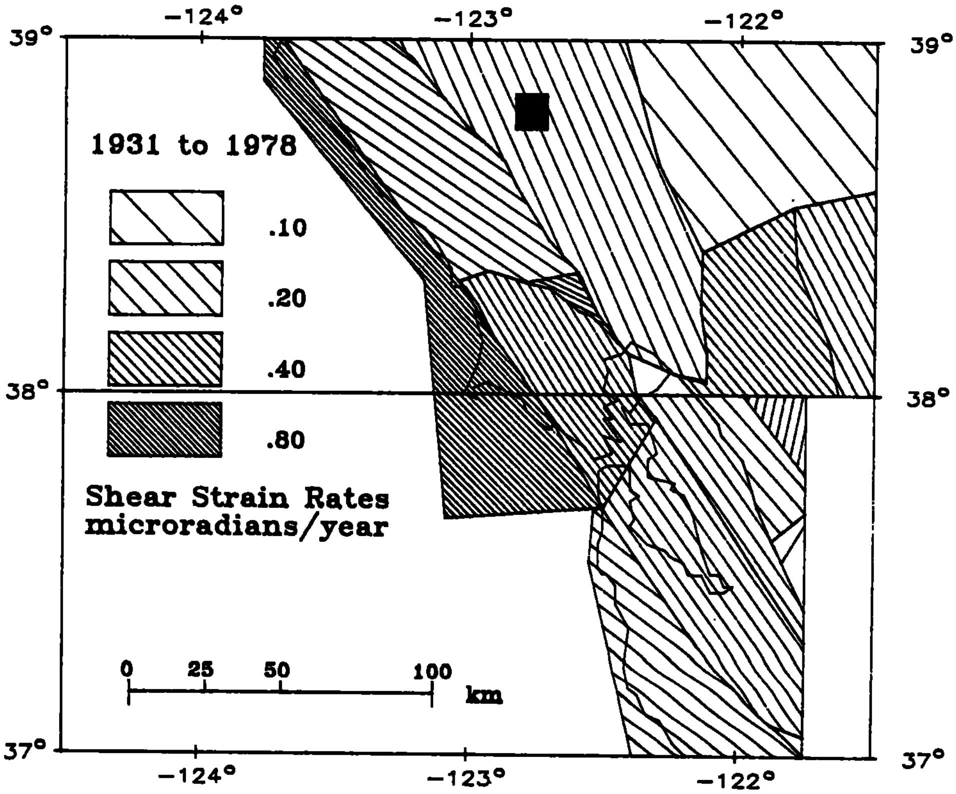

Figure 9.--Shear strain rates determined for the 1931-1978 models. In the Santa Rosa region an additional district approximates the area between the Tolay and Rodgers Creek faults, indicating that directions of maximum right-lateral shear strain (ψ) are aligned along the trends of the Tolay and Mount Jackson fault zones for the area northwest of San Pablo Bay.

different time-interval models. This direction of maximum right-lateral shear strain, however, is determined from a less than optimal station distribution in this district, being heavily influenced by stations near Fort Ross (see fig. 3). To better determine that the direction of maximum right-lateral shear for this general area does indeed correspond more with the strike of the Tolay and the Mount Jackson faults rather than with that of the Rodgers Creek and Healdsburg faults (N43°W), as the geologic evidence would suggest (see Herd 1979; or Herd and Helley 1977), we added another district to the REDEAM 1931-1978 Santa Rosa model. Figure 9 and table 1 show the results of this test. The geodetic data thus indicate that the direction of maximum right-lateral shear strain for the area northwest of San Pablo Bay is aligned with the trends of the Tolay and Mount Jackson faults. (Note that the distinction between the Healdsburg and parallel Maacama fault requires only an 8-km right step, affecting two stations in Santa Rosa district V, as shown in figs. 3 and 4. Strain values in either district III or V will not be appreciably affected by this distinction.)

DISCUSSION AND SUMMARY

As mentioned in the introduction of this report, the USGS maintains a number of strain monitoring networks throughout the San Francisco and Santa Rosa regions. Results for our 1931-1978 San Francisco region agree well with the USGS results documented by Prescott et al. (1981) except perhaps for the areas east of the Calaveras fault. Prescott et al. (1981) contend that little deformation occurs east of the Calaveras fault, but their conclusion apparently depends heavily on how the data are proportioned, as their table 1 indicates. Their results, therefore, are not dissimilar from ours.

A comparison between our 1931-1978 Santa Rosa region and the results of Prescott and Yu (1985) is more difficult to make because of the differences in analysis methods and areal coverages of the data. The comparison allowable, however, implies three differences that are more related to lack of data than to actual differences in the strain values themselves: (1) no USGS data reach far enough eastward to effectively touch our Santa Rosa districts VI-VIII where our data indicate that strain rates may have risen through time, (2) the USGS observations spanning the Tolay and Rodgers Creek faults have an insufficient time history (4 years) to substantiate our finding that the direction of maximum right-lateral shear strain for the area northwest of San Pablo Bay is aligned with the trends of the Tolay and Mount Jackson faults rather than with the Rodgers Creek and Healdsburg faults, and (3) the USGS observations show no displacement, even out to the Farallon Islands, for stations west of the San Andreas fault and north of the Golden Gate, although large uncertainties are associated with both those particular USGS observations and with our results as we previously mentioned.

Because the results for our 1931-1978 REDEAM models do not differ significantly from the USGS results obtained over the past decade, we may safely assume that the 1931-1978 REDEAM models are free of any major transient effects of the 1906 earthquake. Our supplemental studies of the Point Reyes to Petaluma arc also support this conclusion by showing that the most dramatic effects of postseismic relaxation continued for about 30 years, becoming subdued during the 1938 to 1961 time interval.

Strain rate changes obtained by comparing the 1906-1978 time interval models with those of the 1931-1978 models clearly reveal the most obvious transient effect of strike-slip postseismic relaxation: a significant decline in strain rates with time near the rupture trace. The most dramatic example of this relaxation effect occurred northwest of both the 1906 epicenter (ϕ = N37° 42', λ = W122° 30'; Ellsworth et al. 1981) and the site of the maximum recorded surface offsets (Point Reyes Station, ϕ = N38° 04.0', λ = W122° 48.5'; Lawson et al. 1908).

The less pronounced transient effect of postseismic strike-slip relaxation as predicted by certain theoretical models, or that of rising strain rates in areas several rupture depths distant from the surface trace, may possibly be borne out in these REDEAM studies; however, the asymmetric character of the two areas of rising rates in relationship to the San Andreas fault (one being too close to the rupture trace, the other too far away) and the presence of large observational errors in the western area indicate that the rising strain rate changes are suspect and cannot be used reliably to argue for a confirmation of the theoretical predictions.

The REDEAM models for the San Francisco, Santa Rosa, and Ukiah regions nevertheless roughly delineate the extent of significant deformation eastward of the San Andreas fault. Models for the Santa Rosa region show that the direction of maximum right-lateral shear strain for the area northwestward of San Pablo Bay is aligned with the trends of the Tolay and Mount Jackson faults rather than with the Rodgers Creek and Healdsburg (Maacama) faults, as the geologic evidence would suggest.

ACKNOWLEDGMENTS

We thank all the people who gathered and prepared the geodetic data for this study. We also thank Ken Hurst (Lamont-Doherty), who helped in preparing the San Francisco region model; Allen J. Pope (NOAA), who supplied formulas for error analysis; and Robert H. Hanson (NOAA), who developed the software for the computer generated graphics displayed throughout this report. Reviews by Dennis G. Milbert, David T. Sandwell, and David C. McAdoo substantially improved the final presentation.

REFERENCES

Denlinger, R. P., and Bufe, C. G., 1982: Reservoir conditions related to induced seismicity at the Geysers steam reservoir, northern California. Bull. Seismol. Soc. Amer., 72, 1317-1327.

Ellsworth, W. L., Lindh, A. G., Prescott, W. H., and Herd, D. G., 1981: The 1906 San Francisco earthquake and the seismic cycle: in, D. W. Simpson and P. G. Richards, eds., Earthquake Prediction, An International Review, Maurice Ewing Ser., vol. 4, pp. 126-140, Am. Geophys. Union, Washington, D. C.

Frank, F. C., 1966: Deduction of earth strains from survey data. Bull. Seismol. Soc. Am., 56: 35-42.

Hayford, J. F., and Baldwin, A. L., 1908: Geodetic measurements of earth movements: in, A. C. Lawson (Chairman), The California Earthquake of April 18, 1906--Report of the State Earthquake Commission, vol. 1, pp. 114-145, Carnegie Institution of Washington, Washington, D. C.

Herd, D. G., 1979: Neotectonic framework of central coastal California and its implications to microzonation of the San Francisco Bay region: in, E. E. Brabb, ed., Progress on Seismic Zonation in the San Francisco Bay Region, U. S. Geol. Surv. Circ. 807, pp. 3-12.

Herd, D. G., and Helley, E. J., 1977: Faults with Quaternary displacement, northwestern San Francisco Bay region, California. U. S. Geol. Sur. Misc. Field Studies Map MF-818, scale 1:125,000, 1 sheet.

Lawson, A. C. (Chairman) and others, 1908: The California Earthquake of April 18, 1906--Report of the State Earthquake Commission, 2 vol., 641 pp., Carnegie Institution of Washington, Washington, D. C.

Prescott, W. H., 1981: The determination of displacement fields from geodetic data along a strike slip fault. J. Geophys. Res., 86, 6067-6072.

Prescott, W. H., and Yu, Shui-Beih, 1985: Geodetic measurements of horizontal deformation in the northern San Francisco Bay region, California. In press.

Prescott, W. H., Savage, J. C., and Kinoshita, W. T., 1979: Strain accumulation rates in the western United States between 1970 and 1978. J. Geophys. Res., 84, 5423-5435.

Prescott, W. H., Lisowski, M., and Savage, J. C., 1981: Geodetic measurement of crustal deformation on the San Andreas, Hayward, and Calaveras faults near San Francisco. J. Geophys. Res., 86, 10853-10869.

Reid, H. F., 1910: Permanent displacements of the ground: in, A. C. Lawson (Chairman), The California Earthquake of April 18, 1906--Report of the State Earthquake Commission, vol. 2, pp. 16-28, Carnegie Institution of Washington, Washington, D. C.

Savage, J. C., 1983: Strain accumulation in the western United States. Ann. Rev. Earth Planet. Sci., 11, 11-43.

Schwarz, C. R., 1978: The TRAV-10 horizontal network adjustment program. NOAA Tech. Mem., NOS NGS-12, National Geodetic Information Center, NOAA, Rockville, MD, 52 pp.

Snay, R. A., Cline, M. W., and Timmerman, E. L., 1983: Regional deformation of the earth model for the San Diego region, California. J. Geophys. Res., 88, 5009-5024.

Snay, R. A., Cline, M. W., and Timmerman, E. L., 1985: Horizontal crustal deformation models for California from historical geodetic data. Bull. Royal Soc. New Zealand, in press.

Taliaferro, N. L., 1951: Geologic sections across the bay area counties showing sub-surface structure: in, O. P. Jenkins, ed., Geologic Guidebook of the San Francisco Bay Counties, Calif. Div. Mines Geol. Bull., 154, plate 1.

Thatcher, W., 1975a: Strain accumulation and release mechanism of the 1906 San Francisco earthquake. J. Geophys. Res., 80, 4862-4872.

Thatcher, W., 1975b: Strain accumulation on the northern San Andreas fault zone since 1906. J. Geophys. Res., 80, 4873-4880.

Thatcher, W., 1983: Nonlinear strain buildup and the earthquake cycle on the San Andreas fault. J. Geophys. Res., 88, 5893-5902.

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