FINAL TECHNICAL REPORT

AWARD# 03HQGR0080

TITLE: THEODOLITE AND TOTAL STATION MEASURMENTS OF CREEP RATES ON SAN FRANCISCO BAY REGION FAULTS

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TECHNICAL ABSTRACT

The primary objective of our investigations is to measure fault slip and creep rates on San Francisco Bay Region faults to continue a detailed monitoring program that has been funded by the USGS (NEHRP) since 1979. We have continued to make measurements across San Francisco Bay Region faults to determine the rates of present fault movement and to discover any changes in these rates that might occur. Our results can be applied to reducing losses from earthquake in the United States because any changes in the rate of fault creep, including the onset of creep on a previously “locked” fault or the cessation of creep on a previously creeping fault, could be an indication of a forthcoming earthquake.

We continue to use the triangulation method for site measurements employed by the project since 1979. Our current surveying instrument is a state-of-the-art Wild T2002 total station. We are maintaining precision that is sufficient to detect movement of more than a millimeter or two since the previous measurement. The accuracy is such that in most cases measurements have detected the actual horizontal fault movement that is occurring at the surface. We are currently measuring the amount of horizontal fault movement within a width of about 55-280 m at 31 sites on the San Andreas, Hayward, Calaveras, Concord-Green Valley, Antioch, Seal Cove-San Gregorio, Rodgers Creek, West Napa, and Maacama faults. We measure creeping fault segments about six times each year, and non-creeping segments at least twice each year. Once a year we measure 23 after-slip sites that were established on the Hayward fault and 3 sites that were established on the Calaveras fault in 2002, in conjunction with J. Lienkaemper of the USGS.

During the past two years, there have been no significant changes in the creep rates on Bay Area active faults, but initial indications of change on the Northern Calaveras and San Gregorio faults, and of creep at new sites on the Rodgers Creek fault, are noteworthy. The San Andreas fault remains locked throughout most of its length, and continues to creep at a high rate (average 12.8 mm/yr) at our San Juan Bautista site, the northern end

of the central creeping section. The Hayward fault continues to creep at a moderate rate (3.3–5.6 mm/yr). The Calaveras fault continues to show mostly consistent measurements at each site, but highly variable measurements between sites (1.6–16.1 mm/yr). Although creep was initiated at our northernmost site in 1992, the rate has slowed since 2001. We observed no unusual behavior in association with the earthquake swarm in February 2003. Measurements on the Concord-Green Valley faults are somewhat noisier than other sites, but continue to show consistent creep rates of 3.1–4.2 mm/yr. Sites on the Maacama fault show average creep rates of 4.3–6.1 mm/yr. Several years of readings on a new Rogers Creek fault site show an average creep rate of 1.8 mm/yr, the first evidence of right-lateral creep on this fault. Sites on the San Gregorio-Seal Cove fault continue to have noisy signals, but consistent trends. The creep rate at the Pescadero site appeared to increase from 0.6 mm/yr to 5.8 mm/yr in 2002, but has decreased in 2005.

We have initiated new activities to improve dissemination of the data and its significance. We created a new web site (http://virga.sfsu.edu/creep/) with information about the project, and maps and graphs of the measurement sites. We have begun to involve undergraduate and graduate students in research projects using the creep data; for example, analyzing how the details of the creep signal for the different faults compare to temporal variations in microseismicity along the faults and perhaps to seasonal rainfall variations. We have also begun to create fault rupture and stress models for various earthquake scenarios within our measurement area using stress-triggering software. When any sites show noteworthy or unusual behavior, we measure them more frequently, apply other analytical tools, and notify cognizant USGS personnel.

FINAL TECHNICAL REPORT—

THEODOLITE AND TOTAL STATION MEASURMENTS OF CREEP RATES ON SAN FRANCISCO BAY REGION FAULTS

INTRODUCTION

The primary purpose of the project is to measure fault slip and creep rates on San Francisco Bay Region faults to continue the detailed monitoring program that was started by J. Galehouse in 1979 and assumed by us in 2001. We have continued to expand the database that is used to determine "normal" or average creep rates and creep characteristics on Bay region faults and to detect any deviations from the norm. Our results can be applied to reducing losses from earthquakes in the U.S. because any changes in the rate of fault creep, including the onset of creep on a previously "locked" fault or the cessation of creep on a previously creeping fault, could be an indication of a forthcoming earthquake. The 1999 Working Group on California Earthquake Probabilities (WGCEP99) used surface creep rates as an important constraint on the expected magnitude and recurrence time for major earthquakes on the Hayward, Calaveras and Concord-Green Valley faults.

With USGS-NEHRP funding, J. Galehouse used a theodolite to monitor slip on parts of the San Andreas, Hayward, Calaveras, Concord-Green Valley, Antioch, Seal Cove-San Gregorio, Rodgers Creek, West Napa, and Maacama faults in the greater San Francisco Bay region (see Figure 1 and Table 1). In 2002 we began using a new digital total-station surveying instrument and have used the instrument since then to collect regular measurements at 31 localities along alinement arrays on Bay Region active faults. We also measure an additional 23 after-slip localities that were established along the Hayward and Calaveras faults in conjunction with J. Lienkaemper of the USGS. A major accomplishment during 2004 was our creation of a new project web site that makes information about our sites and collected data available to scientists and the general public. In this report we describe the methods used to measure creep rates, and present results obtained during the granting period (March 1, 2003 to February 28, 2005).

METHODS

The Wild T3 theodolite method was used successfully from 1979–2001 to measure rates of horizontal slip on active faults in the San Francisco Bay Region (Galehouse, 2002). During the period of our 2001–03 grant we updated the surveying equipment by acquiring a state-of-the-art digital Wild T2002 total station. We used an interim period to collect readings from both instruments and to establish a continuity of accuracy between past and future research. During the period of our 2003–05 grant we used only the T2002 for site monitoring because we are certain that its precision and accuracy are consistent with past results, and that we are continuing the high quality of data collection established by J. Galehouse during his 22 years of measurements. The surveying is largely conducted by undergraduate Research Assistants under the supervision and training of several long-term project employees and the Principal Investigators.

Measurement Method

The measurement method used in this investigation is a relatively simple triangulation method. The theodolite or total station instrument is centered and leveled over a fixed point on one side of the faults and designated as the "instrument station" (IS), which is a nail pounded into asphalt, a monument that has been installed by project personnel, or a previously-existing below-grade city monument that is fortuitously located. Traverse targets are set up over an "orientation station" (OS) on the same side of the fault as the IS and over an "end station" (ES) on the opposite side of the fault. These stations are emplaced such that a line from the IS to the ES is as perpendicular to the local trend of the fault as is logistically possible. The measured slip needs to be corrected by less than one percent if the line is five degrees from the perpendicular and by less than two percent if ten degrees from the perpendicular.

The IS and ES are far enough apart so that both stations are likely to be out of the main zone of fault slip, yet close enough together so that accurate readings can be made (see fault width distances in Table 1). The IS to ES distance is accurately determined at each site by using at least two of three different methods. First, the distance can be measured carefully using a surveyor's tape to confirm mathematical methods. Second, an angle between an IS and ES can be measured using the theodolite or total station, the IS to ES distance can be taped to the nearest mm, and then the IS to ES distance can be calculated trigonometrically. Third, the distance can be measured using an electronic distance measuring (EDM) instrument or using the total station instrument.

The OS to IS to ES angle in degrees is determined to five decimal places using a slight modification of the measurement method that was described in detail in annual technical reports submitted to the USGS by J. Galehouse. The present method involves measuring the angle eight times on each measurement day, and then using the mean value.

Precision of Measurements

The precision of slip determinations depends on a number of factors. The instruments must be of high quality. We continued to use the Wild-Heerbrugg Model T3 Precision Theodolite that was purchased with USGS funds and used since the start of these fault creep investigations in 1979, and have recently acquired a Wild-Heerbrugg Model T2002 to improve on what was already excellent, first-order triangulation work. We have continued to use traverse targets made by Lietz and Wild, which are of excellent quality. All of these instruments are equipped with optical plummets that facilitate centering the instruments precisely over the station points. The new total station instrument is self-leveling once leveled by the operator, provides digital data sets, improves on data collection efficiency, and may improve precision.

In addition to instrument quality, precision also depends on the care and skill of the person(s) making the measurements. We have continued to use San Francisco State University undergraduate geology majors as research assistants and to keep a close check on the precision of all instrument operators by monitoring angle closure values and ranges. Some range in angle measurement is to be expected and may be primarily due to slight eccentricities in the optical plummets of the theodolite and the traverse targets. It is for this reason that the targets are rotated 180° after four angle measurements. Some of the range in angle measurements, however, may be due to a human factor. The care and accuracy with which the instrument person centers and levels the theodolite over the IS and the target operator centers and levels the traverse targets over the ES and OS are extremely important. For the more than 3000 site measurements made since 1979, the mean range in the value of the angles determined during each measurement set is about ±3 seconds. There is little difference in the precision of any of the present instrument operators. The average range of about ±3 seconds for the angle measurements in a set gives a standard deviation of about ±2.5 seconds for the mean value. This corresponds to about ±1.2 mm for a 100 m IS to ES distance and about ±2.4 mm for a 200 m distance. This assessment of the precision of the mean angle suggests that slip calculated at one mm or two between successive measurements, whether it is right-lateral or left-lateral, may not be real but may simply be due to the precision limits of the measurement method. As measurements continue to be taken, however, trends in the nature of movement are more likely to be discerned and average rates of movement can be calculated with a greater degree of confidence in the results. The overall average (mean) creep rate values shown on Figures 2 through 7 are determined from least squares linear regression and most rates have (1σ) standard deviations of ±0.1mm/yr. With the updated total station instrument this demonstrated high precision can only improve. Readings can be made more rapidly, thus reducing instrument drift, and digital recording reduces possible operator recording errors. It is also increasingly easy to double check site factors that are used in data calculations.

Accuracy of Measurements

Although the theodolite / total station measurement method can determine changes in the angle between stations at a site quite precisely, an additional concern is whether the measurement results give an accurate determination of the actual fault movement that is occurring at the surface. Of course, the results will reflect less than the total amount of movement along a fault if the zone of movement is wider than the IS to ES distance. This is an inherent aspect of the theodolite / total station method but it is probably not a significant factor at most of the measurement sites; it is certainly much less a factor than for the creepmeter method. However, the results at a particular site must be considered the minimum amount of horizontal movement that is occurring at that general location.

Accuracy errors could arise if one or more of the nails or monuments representing the various stations is moving or has moved systematically or erratically due to nontectonic causes (e.g., traffic, vandalism, subsidence, plant roots). Stations that show signs of having been disturbed are replaced. More potentially serious problems, however, can occur if any of the three triangulation stations moves in response to changes in temperature or rainfall or moves in a downslope direction under the influence of gravity (mass movement creep as opposed to tectonic creep) without any obvious signs of disturbance. Sites have been located in low-relief areas when it is possible to do so. With long-term monitoring, we are able to detect seasonal effects of rainfall (e.g., soil contraction and expansion) and then evaluate the tectonic creep signal.

RESULTS

During the grant period from March 1, 2003 through February 28, 2005, we continued to measure aseismic slip (i.e., creep) on San Francisco Bay region faults. We presently collect regular measurements at 31 localities on active faults, and have data from eight other sites that have had to be abandoned (Table 1). We are continuing to re-measure most sites with a history of creep about once every six to ten weeks and most sites without any creep history about every three to four months. In addition to our ten regular sites on the Hayward fault, we have continued to measure 23 additional sites in conjunction with J. Lienkaemper of the USGS. We have acted quickly in response to seismic activity on Bay Region faults. For example, in May 2003, when there was an earthquake on the Rodgers Creek fault, we immediately re-measured a site in the area that we had established in 2002 to improve our monitoring resolution of this fault. We have created a new web site to disseminate our site and fault creep data and have begun new data analyses to provide improved understanding of fault creep characteristics.

Creep measurements

During the past two years, there have been no significance changes in the creep rates on Bay Area active faults. The creep data collected between 1979 and 2001 and the creep characteristics of all measured faults have been summarized in Galehouse's (2001) Final Technical Report, in an Open-File report (Galehouse, 2002), and in Galehouse and Lienkaemper (2003).

San Andreas fault: The three northernmost sites (Point Arena—SA1 to South San Francisco—SA3; Fig. 2A) continue to show no detectable creep, whereas the southernmost site near San Juan Bautista (SA7; Fig. 2B) continues to show an average creep rate of 12.8 mm/yr. A new site near Aromas (SA5; Fig. 2B) that was established to more precisely define the transition between the creeping and non-creeping segments, shows no detectable creep, consistent with previously recorded data at SA6 (Fig. 2B), a nearby site that was destroyed in a major landslide and hence abandoned in 1998. However, we have only a few years of data from SA5, so these results are preliminary. We carefully monitored data collected at SA4 in Woodside (Fig. 2A), which is located on what is considered a non-creeping segment of the San Andreas fault. This site shows little or no creep prior to 1998, but evidence of slow creep (1.2 mm/yr) from 1998 through 2004. In 2005, creep on the fault relaxed and rates returned to previously seen values.

Hayward fault: The northern part of the Hayward fault (H1–H3 on Fig. 3A) continues to show creep rates ranging from 3.9–5.1 mm/yr. The southern part of the Hayward fault shows somewhat higher rates, ranging from 4.5–5.6 mm/yr (H5–H10 on Figs. 3B–3C).

H4 (Fig. 3A) is located near the boundary between the northern and southern segments of the Hayward fault, and continues to show the lowest creep rate (3.3 mm/yr) of our sites on the fault. Several of the central sites show increasing creep rates. H7 and H8 (Fig. 3B) appear to show a small rate of increase since 1993. The two southernmost sites at Fremont (H9 and H10; Fig. 3C) ceased creeping for 6 years after the Loma Prieta earthquake, and then resumed creeping at a rate similar to the other Hayward fault sites. Creep rate at H9 may have increased slightly since 2003 (Fig. 3C). In addition to our ten regular Hayward fault sites, we continue to measure once each year 23 additional after-slip sites that were established in conjunction with J. Lienkaemper and that are used to document in detail any surface slip that could result from future seismic events (Lienkaemper et al., 2001).

Calaveras fault: Our sites on the Calaveras fault show mostly unchanging creep patterns for the past few years. Creep rates are highly variable between sites, ranging from 1.6–16.1 mm/yr (Fig. 4A). Creep at the northernmost site (CV1 in San Ramon; Fig. 4A) initiated in 1992. Creep rate at this site averaged about 3.5 mm/yr after 1992 but has apparently slowed to about 1.6 mm/yr since 2001. We observed no unusual behavior in association with the earthquake swarm in February 2003. CV3 (Fig. 4A) continues to be our fastest creeping fault, with an average rate of 16.1 mm/yr since 1968. CV3 may have slowed slightly since 1997, but the higher creep rate before 1997 is based on just a few measurements that were collected between 1968 and 1997 by others outside of our project. As with the southern section of the Hayward fault, creep rates on the southern section of the Calaveras fault slowed after the Loma Prieta earthquake, but returned to an apparently normal rate after 5–6 years (CV4 and CV5 on Fig. 4B). Since 1996, CV5 has developed a distinct pattern of episodic creep with intervals of no creep or very low creep rates between creep episodes (Fig. 4B).

Concord-Green Valley fault: In January 2005, we established a new Green Valley fault site (GV2) on Mason Road near Cordelia Junction. Only three readings have been made at this site and no conclusions can yet be drawn from the available data. The Concord-Green Valley sites (C1–C2, GV1) continue to show consistent creep rates of 3.1–4.2 mm/yr (Fig. 5). GV1 exhibits significant site noise, probably due to seasonal effects. This site was reconfigured in 1999 for logistical reasons, after which it began to show an even higher level of noise. We recently reconfigured the site again, and the preliminary measurements now seem to show a stronger (i.e., less noisy) creep signal. Creep at both sites on the Concord fault continues to show episodic behavior with 3–5 yr intervals between creep events. A 7-9 mm creep event occurred at the C1 site in late 2003. This event marks the shortest interval yet recorded between creep events (~3 yrs) at these sites (Fig. 5).

Maacama fault: Our sites on the Maacama fault continue to show creep rates of 4.3–6.1 mm/yr (Fig. 6). The creep rate at the site in Ukiah (M2 on Fig. 6) has slowed slightly since 2002 and we are watching this fault carefully for any further indications of unusual behavior.

Rodgers Creek fault: We now have several years of readings from our new sites on the Rodgers Creek fault (Fig. 6). Our initial readings over the past two years at the Santa Rosa site (RC1 on Fig. 6) showed a consistent creep rate of 3.6 mm/yr; however, after 14 readings at the site we obtain a rate of 1.8 mm/yr. Our other new site on the Rodgers Creek fault at Sonoma Mountain Road in Petaluma (RC2 on Fig. 6) was reconfigured after it seemed we were measuring downslope soil creep rather than fault creep. Our first measurements at the reconfigured site suggested rapid creep but after only 7 readings the measured creep rate is decreasing, and the results are still highly preliminary.

San Gregorio-Seal Cove fault: Sites on the San Gregorio-Seal Cove fault continue to have rather noisy signals, but consistent trends. The SG1 site on the Seal Cove fault (Princeton; Fig. 7) continues to show no indication of creep. However, readings at the SG2 site on the San Gregorio fault (Pescadero Road; Fig. 7) from 2001 to 2004 seemed to indicate a creep rate of 5.8 mm/yr since 2002, compared to a rate of 0.6 mm/yr prior to 2002. In 2005, the creep rate diminished and rates on the San Gregorio fault at SG2 are returning to those seen previously. We are watching this site carefully, however, particularly as there appears to have been a similar slight acceleration on the nearby San Andreas fault (Woodside site SA4; Fig. 2A).

New Project Web Site and Data Dissemination

During the grant period, we have created a new web site that includes the following information: project description, project personnel, creep characteristics and measurement, map of creep measurement sites, and creep site table with data plots and site descriptions. The web site makes our results accessible to anyone in the scientific community and to the general public; site URL: http://virga.sfsu.edu/creep/. We plan to update data graphs on the web site each year, or more often should important events, such as creep rate changes, arise. At any time, information about the project can be requested via email: fltcreep@sfsu.edu.

Data Analysis

We have begun to develop analytical and interpretive phases of the project that will involve the P.I.s with undergraduate and graduate student research. For example, we are conducting a comprehensive analysis of how details of the creep signal for the different faults compare to temporal variations in microseismicity along the faults and perhaps seasonal rainfall variations (Mascorro, in preparation; Mascorro, et al., in review).

We have also begun to create fault rupture and stress models for various earthquake scenarios within our measurement area using Coulomb 2.5, a stress triggering software written by S. Toda and R. Stein (http://quake.wr.usgs.gov/research/software/index.html). In the event of future Bay Region earthquakes, we can now quickly calculate patterns of expected static stress change that can help us focus our measurement efforts following future earthquakes (e.g., Grove and Caskey, 2003, showed a sample scenario in which the southern two segments of the Greenville fault rupture with about 2 m of right-lateral slip—earthquake of ~M 6.9).

CONCLUSIONS

Readings from most fault sites continue to show consistent patterns of creep, ranging from no creep on the northern San Andreas fault to a maximum of 16.1 mm/yr on the southern Calaveras fault. Any changes to the observed creep rates must be evaluated carefully, to be certain that measurements are indicating fault creep rather than seasonal effects, soil creep, or other non-tectonic signals. We now have sufficient data to suggest that several observed changes are due to creep that may be significant.

1. Northern Calaveras fault (CV1 on Fig. 4A): deceleration of creep rate since 2002 (3.5 mm/yr before 2001; 1.6 mm/yr since 2001).
2. Rodgers Creek fault (RC1 on Fig. 6): first reported right-lateral creep on this fault. Movement has averaged 1/8 mm/yr since we established the site in 2002; second site RC2 (Fig. 6) remains preliminary.
3. San Gregorio fault (SG2 on Fig. 7): after no indication of creep from 1982–2002, an apparent increase in 2002, followed by a decrease in 2005 (nearby SA4 site also showed increases followed by recent descrease).

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Table 1. San Francisco State University Theodolite Measurement Sites

Fault (# on Figs.2-7)	Location (# on Fig. 1)	First Measurement	Fault Width Span (m)
San Andreas (SA1)	Alder Creek in Point Arena area (#18)	1981.025	267.4
San Andreas (SA2)	Olema at Point Reyes National Seashore (#14)	1985.096	70.6
San Andreas (SA3)	Duhallow Way in South San Francisco (#10)	1980.227	205.8
San Andreas (SA4)	Roberta Drive in Woodside (#22)	1989.844	91.2
San Andreas (SA5)	Searle Rd., San Juan Bautista (#37)	2002.799	262.7
San Andreas[1]	Pajaro Gap at Aromas (#38)	2002.107	236.3
San Andreas (SA6)[2]	Cannon Road near San Juan Bautista (#23)	1989.882	88.0
San Andreas (SA7)	Mission Vineyard Rd, San Juan Bautista (#25)	1990.553	134.2
Hayward (H1)	Contra Costa College in San Pablo (#17)	1980.609	106.8
Hayward (H2)	Thors Bay Road in El Cerrito (#34)	1989.748	120.0
Hayward[3]	Florida Avenue in Berkeley (#30)	1993.112	73.6
Hayward (H3)	LaSalle Avenue in Oakland (#29)	1993.112	182.5
Hayward (H4)	Encina Way in Oakland (#28)	1993.058	105.4
Hayward (H5)	Rose Street in Hayward (#13)	1980.481	153.9
Hayward (H6)	D Street in Hayward (#12)	1980.478	136.2
Hayward (H7)	Appian Way in Union City (#2)	1979.729	125.2
Hayward (H8)	Rockett Drive in Fremont (#1)	1979.726	180.0
Hayward (H9)	Camellia Drive in Fremont (#24)	1990.115	88.6
Hayward (H10)	Parkmeadow Drive in Fremont (#27)	1992.262	157.4
Calaveras (CV1)	Corey Place in San Ramon (#19)	1980.896	111.1
Calaveras (CV2)	Welsh Creek Road and Calaveras Road (#32)	1997.066	164.1
Calaveras (CV3)	Coyote Ranch near Coyote Lake (#33)	1972.570	101.3
Calaveras (CV4)	Wright Road near Hollister (#6)	1979.805	103.4
Calaveras (CV5)	Seventh Street in Hollister (#4)	1979.745	89.7
Concord (C1)	Salvio Street in Concord (#5)	1979.748	57.1
Concord (C2)	Ashbury Drive in Concord (#3)	1979.742	130.0
Green Valley (GV1)	Watt Drive in Cordelia (#20)	1984.456	335.8
Green Valley (GV2)	Mason Road in Cordelia Junction	2005.060	
Maacama (M1)	West Commercial Avenue in Willits (#26)	1991.871	126.1
Maacama	Sanford Ranch Road near Ukiah (#31)	1993.389	263.2
Rogers Creek (RC1)	Solano Dr. in Santa Rosa (#36)	2002.628	90.5
Rogers Creek (RC2)	Sonoma Mt. Rd., in Petaluma (#35)	2002.628	99.4
Rodgers Creek[4]	Nielson Road in Santa Rosa (#16)	1980.628	209.1
Rodgers Creek[5]	Roberts Road near Penngrove (#21)	1986.721	198.7
Seal Cove (SG1)	West Point Avenue in Princeton (#7)	1979.858	266.6
San Gregorio (SG2)	Pescadero Road near Pescadero (#8)	1982.384	455.0
Antioch[6]	Deer Valley Road near Antioch (#9)	1982.890	226.2
Antioch[7]	Worrell Road in Antioch (#11)	1980.342	103.9
West Napa[8]	Linda Vista Avenue in Napa (#15)	1980.568	130.9

[1]Site abandoned soon after established for safety reasons.
[2]Site abandoned for logistical reasons. Last measurement 1998.123.
[3]Replaced by H2 as regular measurement site.
[4]Site abandoned for logistical reasons. Last measurement 1986.055.
[5]Site abandoned for logistical reasons.
[6]Site abandoned for logistical reasons. Last measurement 1990.499.
[7]Site abandoned for logistical reasons. Last measurement 2000.158.
[8]Site abandoned for logistical reasons. Last measurement 1999.044.

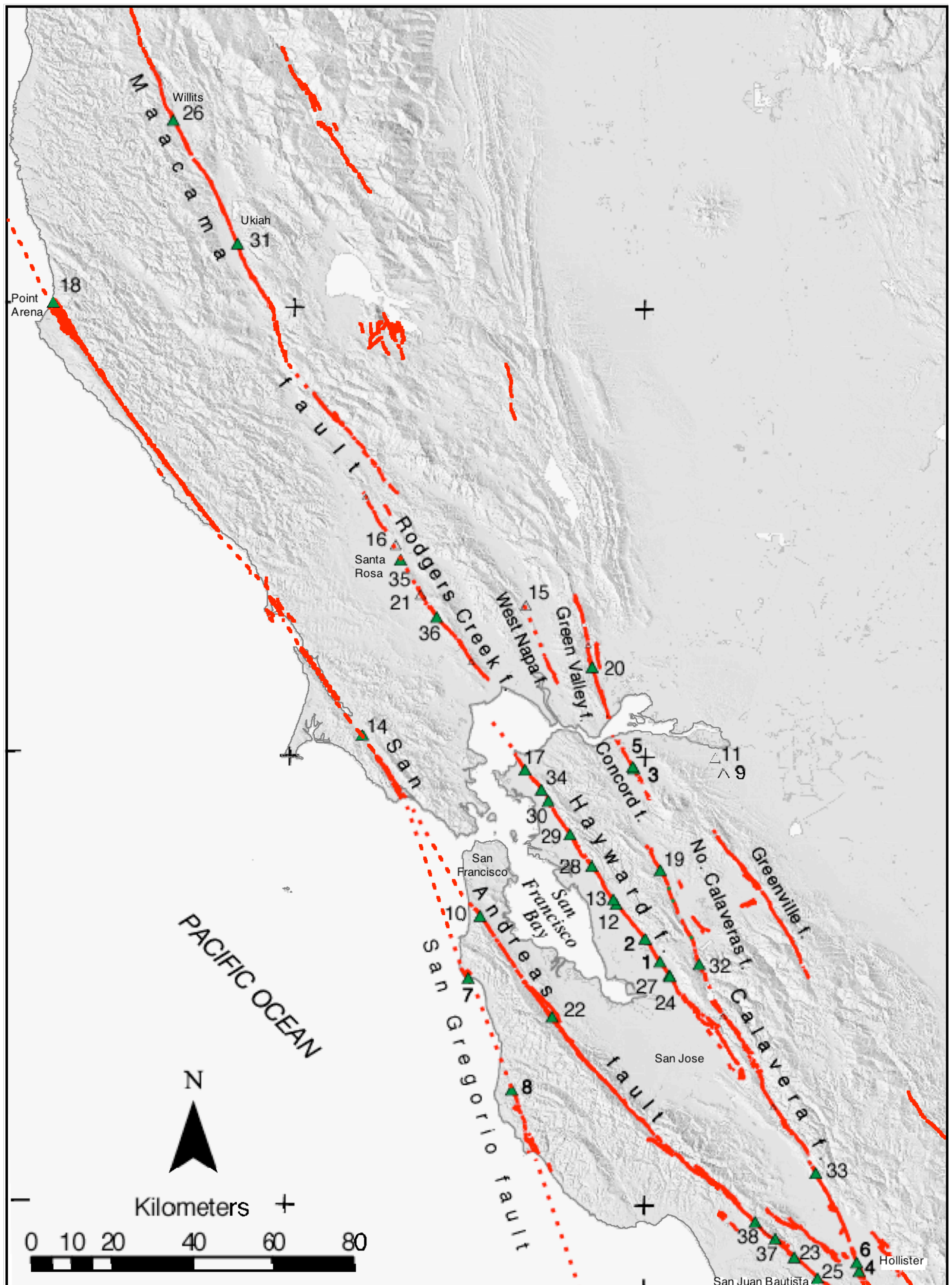


Figure 1. Numbered triangles are San Francisco State University theodolite and total-station creep measurement sites on active Bay Region faults.

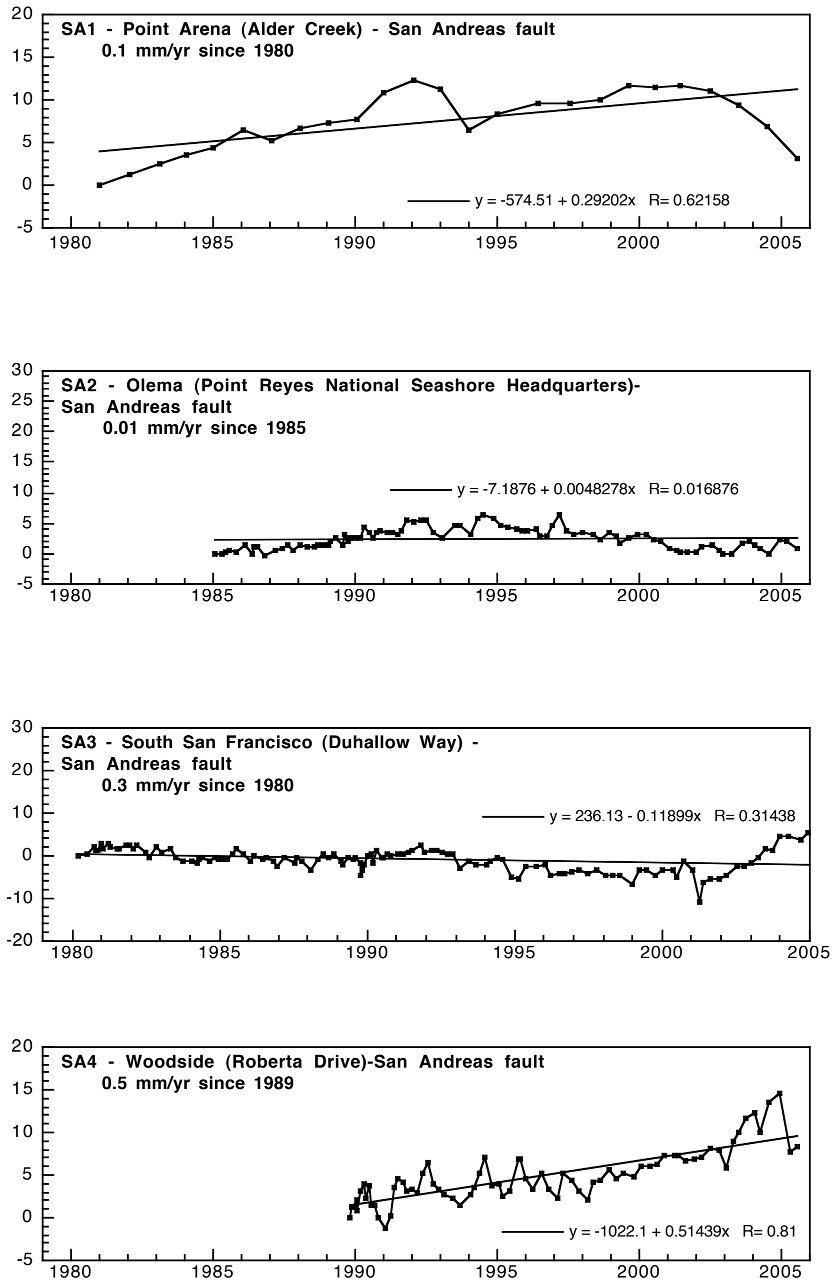


Figure 2A. San Andreas fault surface displacement from 1979–2005. Vertical axis for all graphs: Cumulative right-lateral displacement (mm). Note different vertical scales.

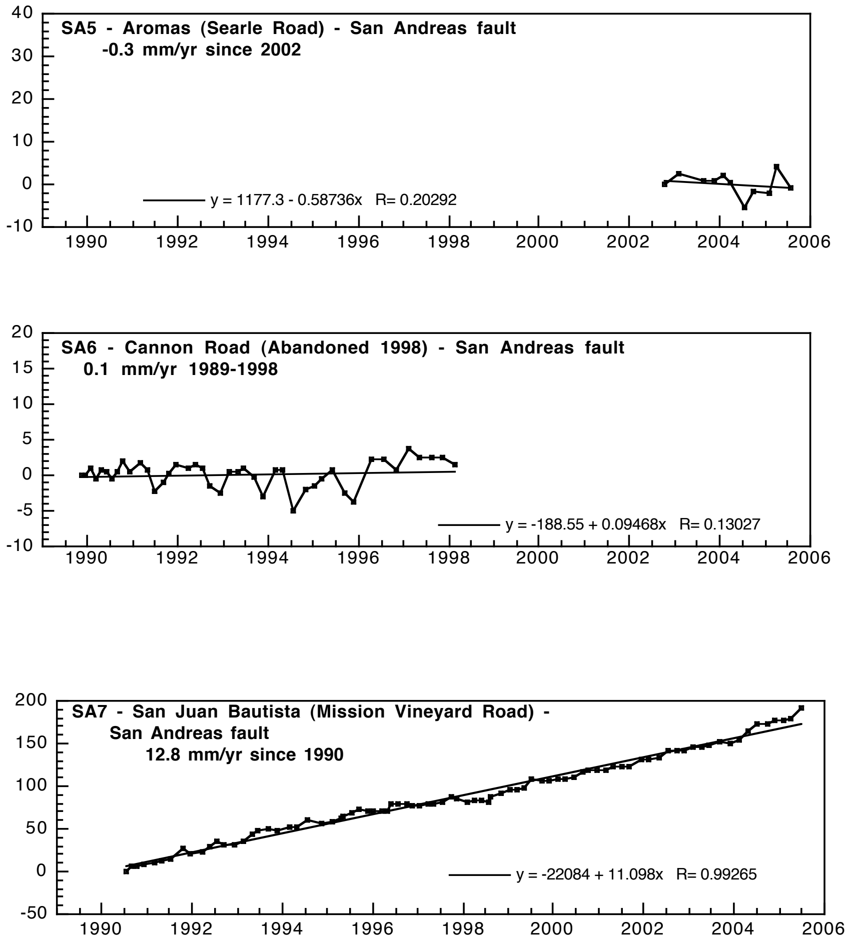


Figure 2B. San Andreas fault surface displacement from 1979–2005. Vertical axis for all graphs: Cumulative right-lateral displacement (mm). Note change in vertical scale for SA7.

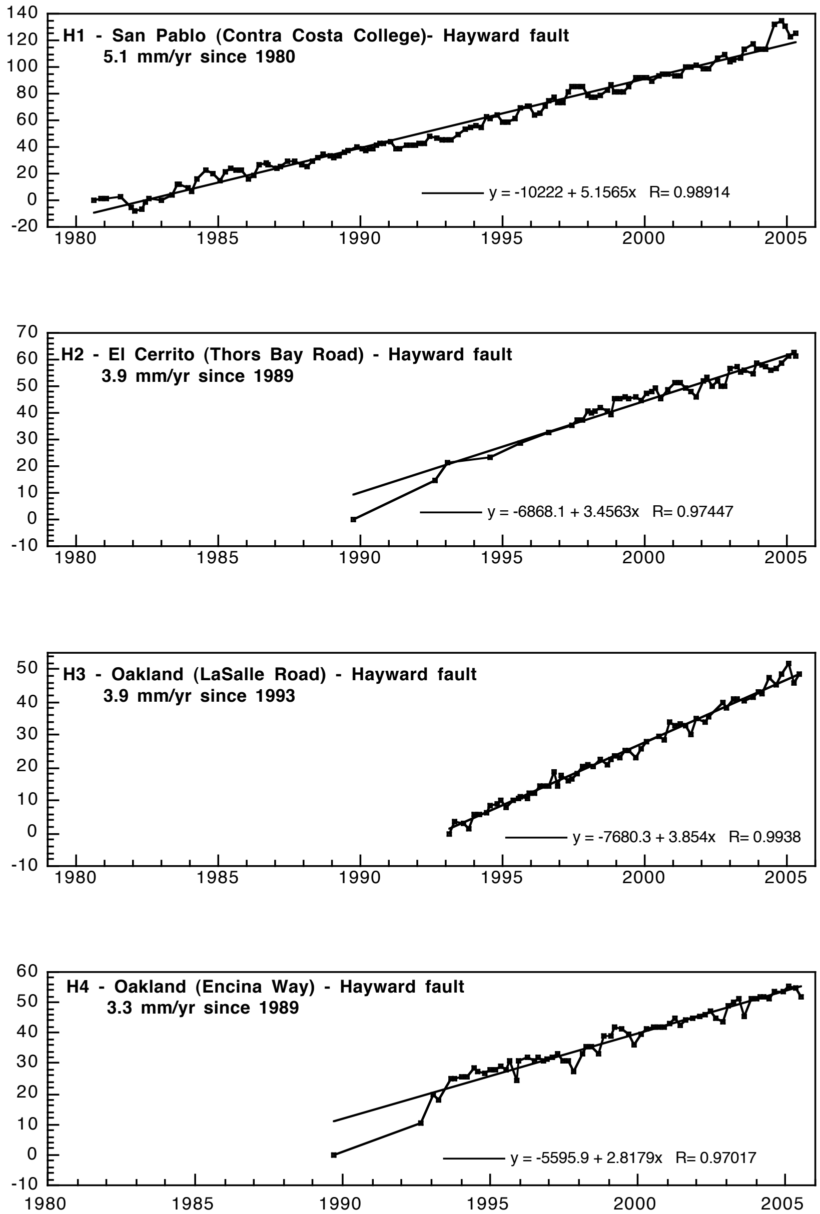


Figure 3A. Hayward fault north surface displacement from 1979–2005. Vertical axis for all graphs: Cumulative right-lateral displacement (mm). Note different vertical scales.

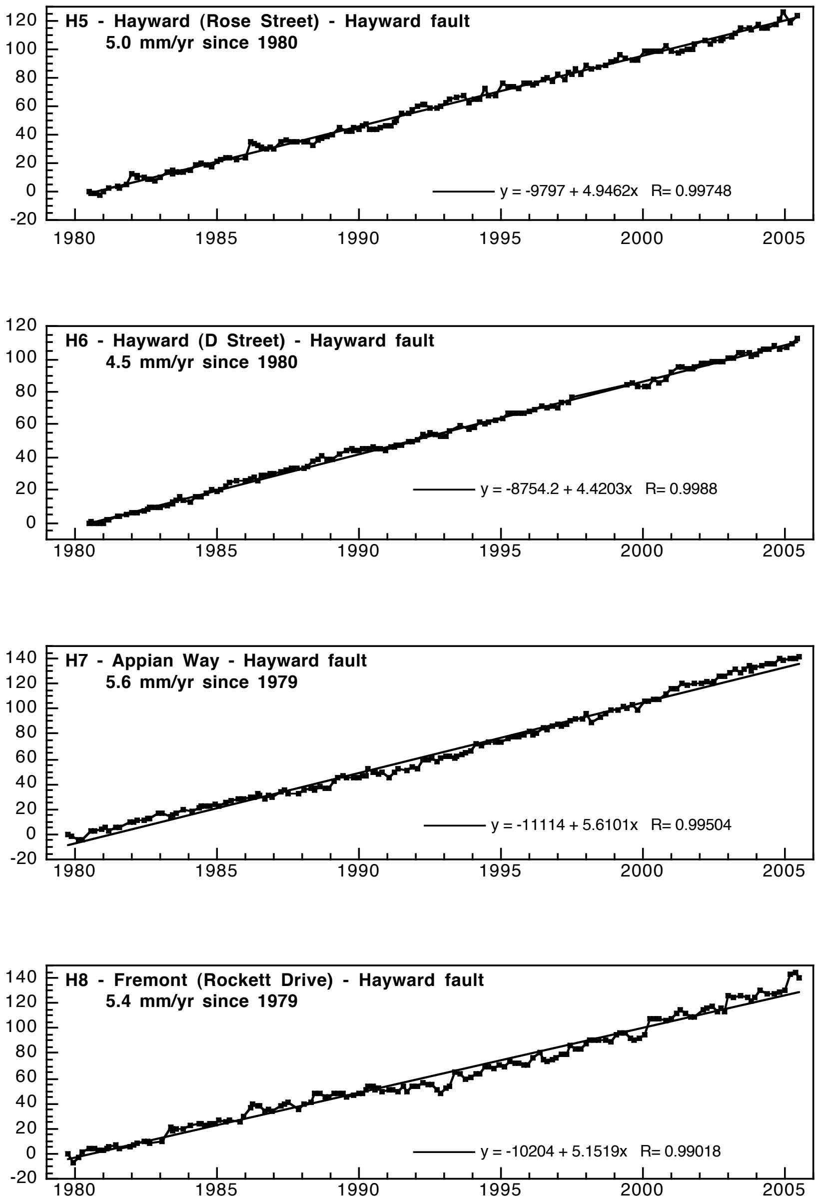
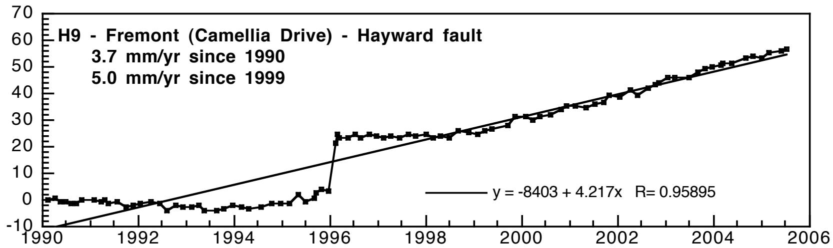


Figure 3B. Hayward fault south surface displacement from 1979–2005. Vertical axis for all graphs: Cumulative right-lateral displacement (mm). Note different vertical scales.



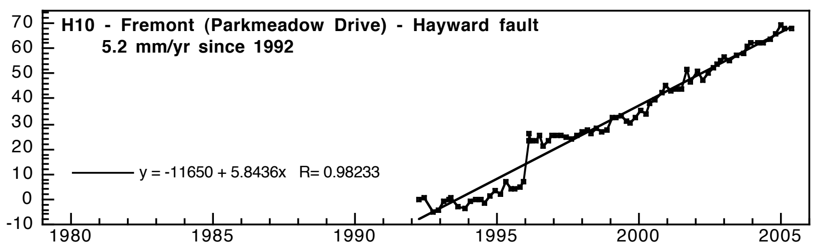


Figure 3C. Hayward fault south surface displacement from 1979–2005. Vertical axis for all graphs: Cumulative right-lateral displacement (mm).

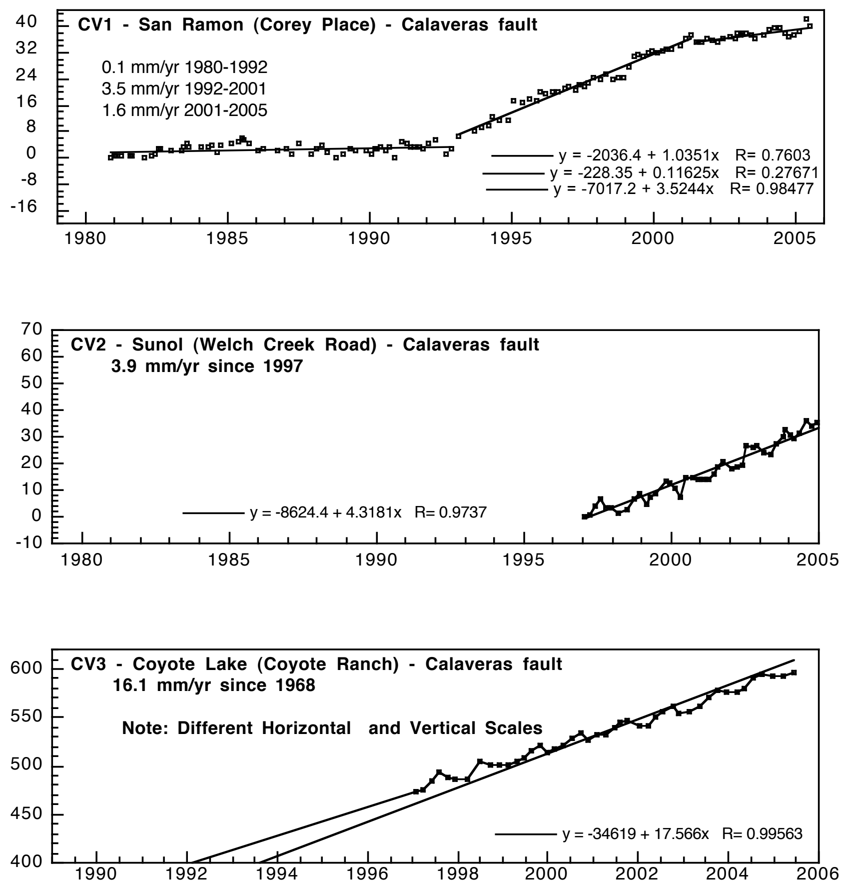
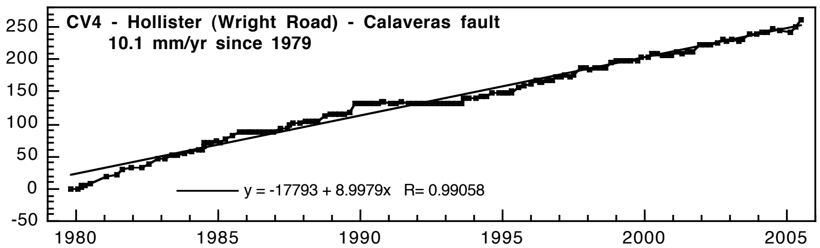


Figure 4A. Calaveras fault surface displacement from 1979–2005. Vertical axis for all graphs: Cumulative right-lateral displacement (mm).



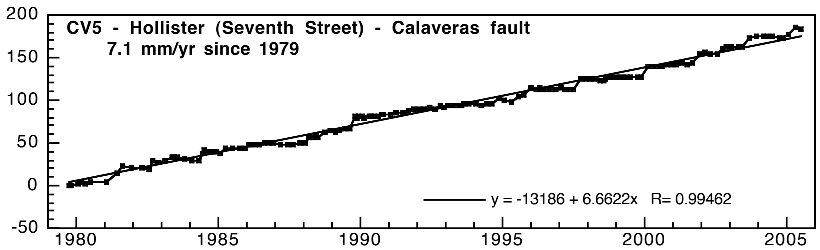


Figure 4B. Calveras fault surface displacement from 1979–2005. Vertical axis for all graphs: Cumulative right-lateral displacement (mm). Note different vertical scales.

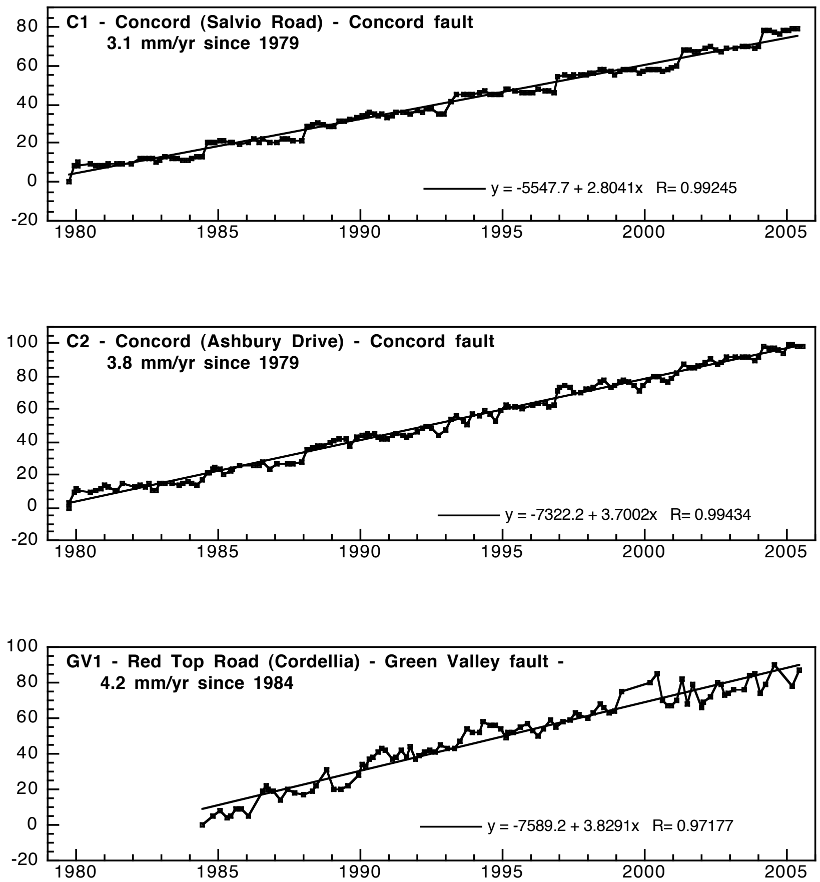


Figure 5. Concord–Green Valley fault surface displacement from 1979–2005. Vertical axis for all graphs: Cumulative right-lateral displacement (mm).

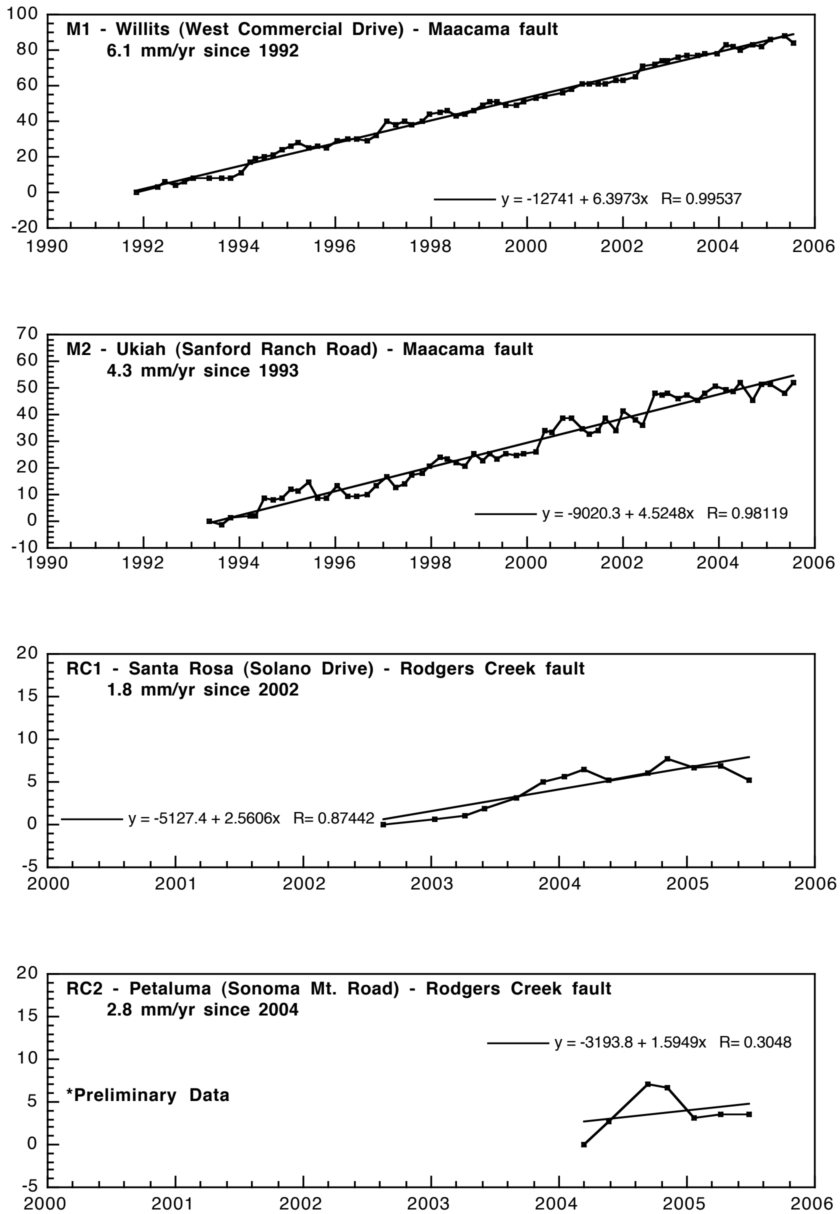


Figure 6. Maacama and Rodgers Creek faults surface displacement from 1990–2005. Vertical axis for all graphs: Cumulative right-lateral displacement (mm). Note different vertical scales.

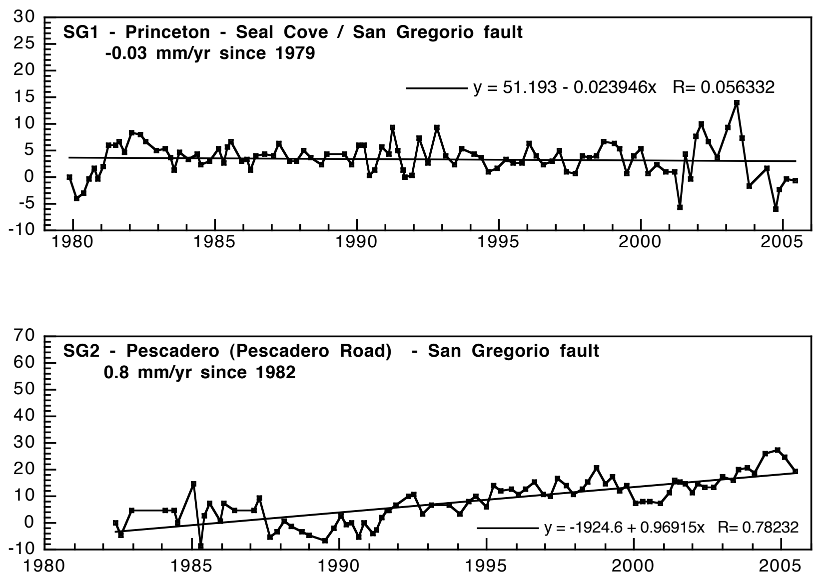


Figure 7. Seal Cove–San Gregorio fault surface displacement from 1979–2005. Vertical axis for all graphs: Cumulative right-lateral displacement (mm). Note different vertical scales.