



# **Data from Theodolite Measurements of Creep Rates on San Francisco Bay Region Faults, California**

By Forrest S. McFarland, James J. Lienkaemper, and S. John Caskey

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# Data from Theodolite Measurements of Creep Rates on San Francisco Bay Region Faults, California

By Forrest S. McFarland<sup>1</sup>, James J. Lienkaemper<sup>2</sup>, and S. John Caskey<sup>1</sup>

## Introduction

Our purpose is to annually update our creep-data archive on San Francisco Bay region active faults for use by the scientific research community. Earlier data (1979-2001) were reported in Galehouse (2002) and were analyzed and described in detail in a summary report (Galehouse and Lienkaemper, 2003). A complete analysis of our earlier results obtained on the Hayward Fault was presented in Lienkaemper, Galehouse and Simpson (2001) and updated in Lienkaemper and others (2012). Lienkaemper and others (2014) provide a new overview and analysis of fault creep along all sections of the northern San Andreas Fault system, from which they estimate by how much fault creep reduces the seismic hazard for each fault section.

From 1979 until his retirement from the project in 2001, Jon Galehouse of San Francisco State University (SFSU) and many student research assistants measured creep (aseismic slip) rates on these faults. The creep measurement project, which was initiated by Galehouse, continued through the Geosciences Department at SFSU from 2001-2006 under the direction of Karen Grove and John Caskey (Grove and Caskey, 2005) and since 2006 under Caskey (2007). Forrest McFarland has managed most of the technical and logistical project operations, as well as data processing and compilation since 2001. Data from 2001-2007 are found in McFarland and others (2007). From 2009 onward, we have released the raw data annually using this report (OF2009-1119) as a permanent publication link, while publishing more detailed analyses of these data in the scientific literature, such as Lienkaemper and others (2014).

We maintain a project Web site (<http://funnel.sfsu.edu/creep/>) that includes the following information: project description, project personnel, creep characteristics and measurement, map of creep-measurement sites, creep-measurement site information, and links to data plots for each measurement site. Our most current, annually updated results are, therefore, accessible to the scientific community and to the general public. Information about the project can currently be requested by the public by an email link ([fltcreep@sfsu.edu](mailto:fltcreep@sfsu.edu)) found on our project Web site.

## Methods

The amount of creep is determined by noting changes in angles between sets of measurements taken across a fault at different times. This triangulation method uses a theodolite to measure the angle formed by three fixed points to the nearest tenth of a second of arc (see fig.1 inset; Galehouse and Lienkaemper, 2003). For the first 14 years of measurements, the angle was measured 12 times on each measurement day; Since then, we have been measuring it eight times each day. The amount of slip between measurement days can be calculated trigonometrically using the change in average angle. The precision of the measurement method is such that we can detect with confidence any movement greater than 1-2 mm

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between successive measurement days. A discussion of errors, uncertainties, and seasonal variations can be found in Galehouse and Lienkaemper (2003).

Until 2007 we had regular measurement sites at 34 localities on active faults, and we include data from one site that had to be abandoned (SACR). These site locations are shown as triangles and site codes on the accompanying map (fig. 1) and are identified by name in table 1 and on the data sheets. In addition to the sites in the San Francisco Bay region, we had one measurement site on the San Andreas Fault in the Point Arena area, one on the Bartlett Springs Fault near Lake Pillsbury, and two on the Maacama Fault in Willits and east of Ukiah. In the past, we typically measured sites with a history of creep every two months and sites without a creep history about every three months. However, since that report we reduced the frequency of surveys at each site; which has allowed us to add several new sites north of San Francisco Bay (fig. 1), now including eleven sites on the Rodgers Creek- Maacama Fault system, seventeen sites on the Concord-Green Valley-Berryessa-Hunting Creek-Bartlett Springs Fault system, and five sites on the West Napa fault rupture that accompanied the Aug 24, 2014 South Napa earthquake (Lienkaemper and others, 2016 in press; Lienkaemper and others, 2014b; Hudnut and others, 2014; and Brocher and others, 2015). We now monitor for creep at five sites on the Greenville fault, where creep has been recently recognized by Lienkaemper and others (2013) along the northern third of the fault.

In addition to our original ten regular sites on the Hayward Fault, we established 22 additional Hayward Fault annual survey sites (shown by diamonds in figs. 1 and 2 and by name in the data sheets and in table 2). We began measuring each of these additional sites annually in 1994. Since 2010 the regular Hayward Fault sites have been only measured annually too, unless significant earthquake activity occurs.

The size of the creep monitoring network has nearly doubled over the past decade, so that the number of actively measured arrays on all fault sections now totals 89 sites. Because of this increasing scope, we will need over the next few years sites to decrease frequency in measuring sites with the lowest (0-2 mm/yr) rates of movement to be measured somewhat less frequently than those with higher rates.

## Data

Table 1 shows the least squares average rate of movement at each site, determined using linear regression, and the simple average rate, determined by dividing the total net right-lateral displacement by the total time measured. For three sites on the Calaveras fault (CV7S, CVWR, CVCR) we calculated average creep using multiple linear regression (MLR) to eliminate accelerated or retarded creep that is associated with large ( $M \geq 5.5$ ) local earthquakes (see Lienkaemper and others, 2014). All measurement sites span a fault width of 57-289 m, except sites GVRT and SGPR, which span a greater width because of site considerations. The fault width spanned is noted in table 1 and represents the distance from the theodolite on one side of a fault (IS, instrument station; fig. 1 inset) to a target on the other side (ES, end station). Angles are measured with respect to another target (OS, orientation station). All Hayward Fault sites are summarized in table 2. Each data sheet is identified in the upper left by site code and name. Hayward Fault sites are ordered from northwest to southeast using kilometer distances along the fault measured from Point Pinole (P, in Figure 2) using the grid in Lienkaemper (2006). Data sheets for all sites are available in the data folder in Excel format to facilitate analysis of the data at <http://pubs.usgs.gov/of/2009/1119/> (SFBayRegion.xls [2 regional folders: -N and -S; see Fig. 1] and HaywardFault.xls). The raw data are also available as comma-delimited files (.csv). Data for the reporting periods (2007-Present) include the average angle and its 1- $\sigma$  uncertainty. Also provided for each reading is the current site correction used; the sine of the angular difference between the fault azimuth and

azimuth of the array (IS-ES). Each measurement of apparent slip must be divided by its site correction. The data include 89 active measurement sites, including 33 on the Hayward Fault. For all sites with at least three years of surveys, we show summary plots of the creep data by fault zone for the Calaveras Fault (figs. 3 and 4), Green Valley and Bartlett Springs Faults (figs. 5a and 5b), Rodgers Creek and Maacama Faults (fig. 6), San Andreas and San Gregorio Faults (fig. 7), Hayward Fault (figs. 8 and 9) and West Napa Fault (fig. 10).

## Acknowledgments

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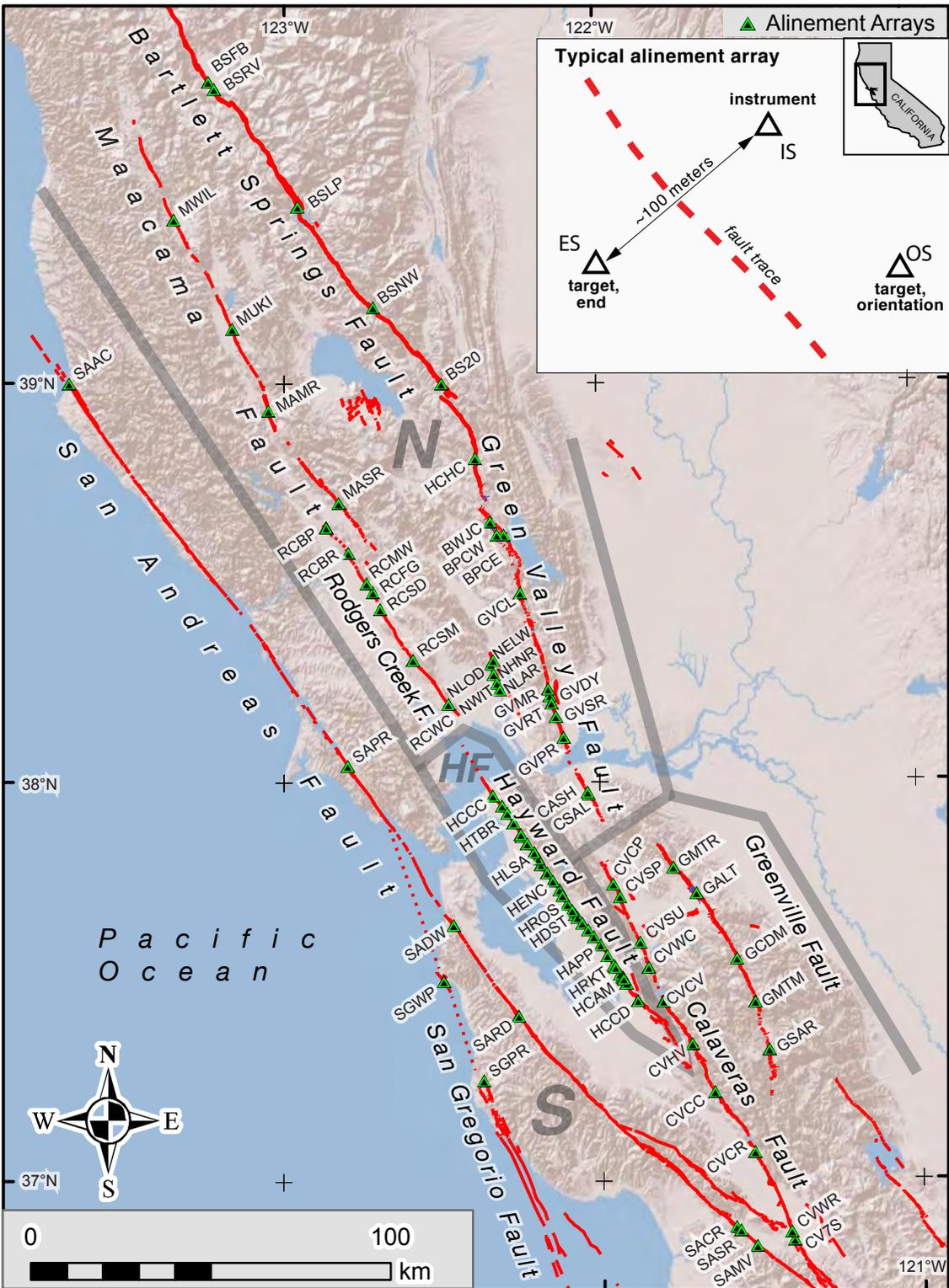
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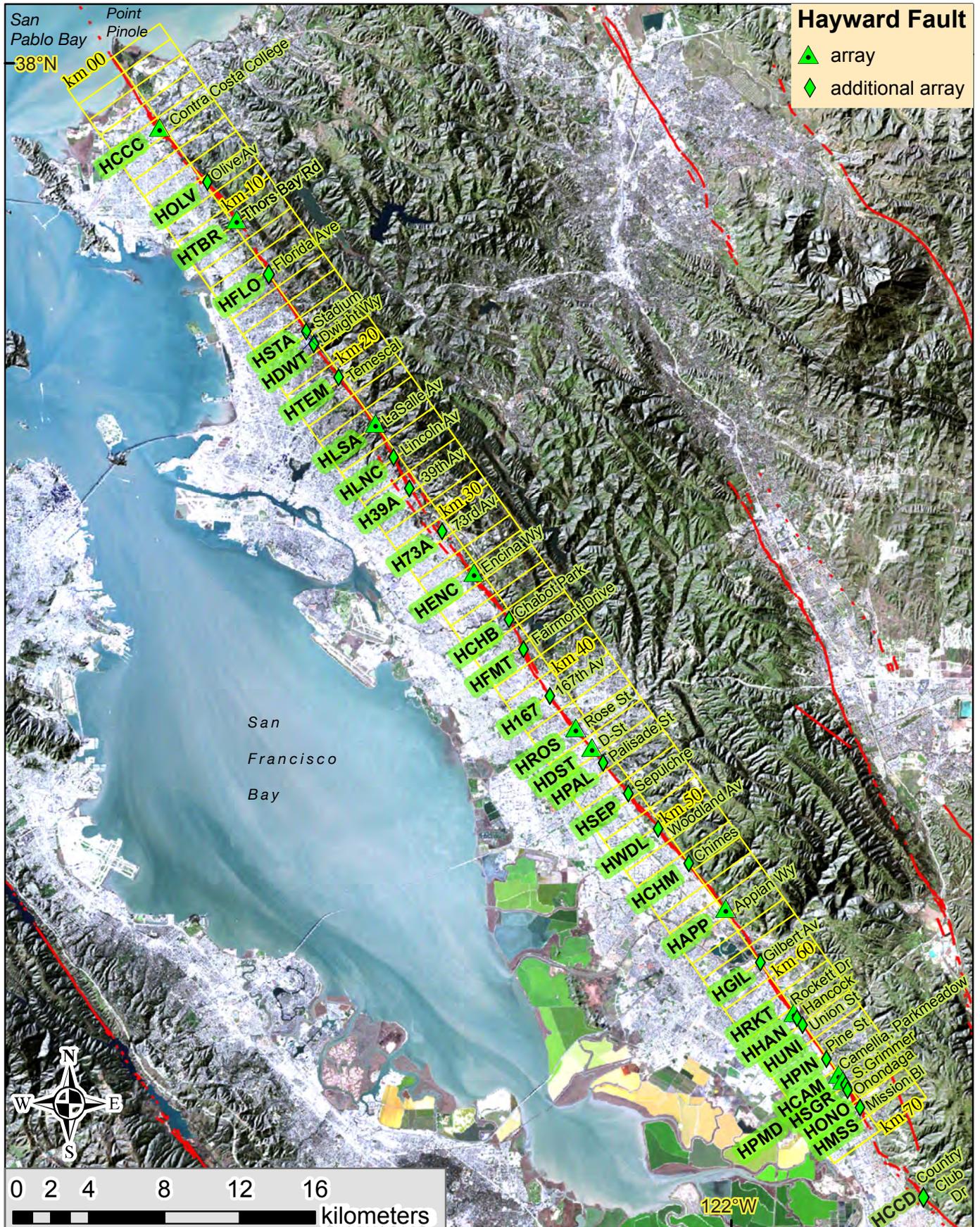
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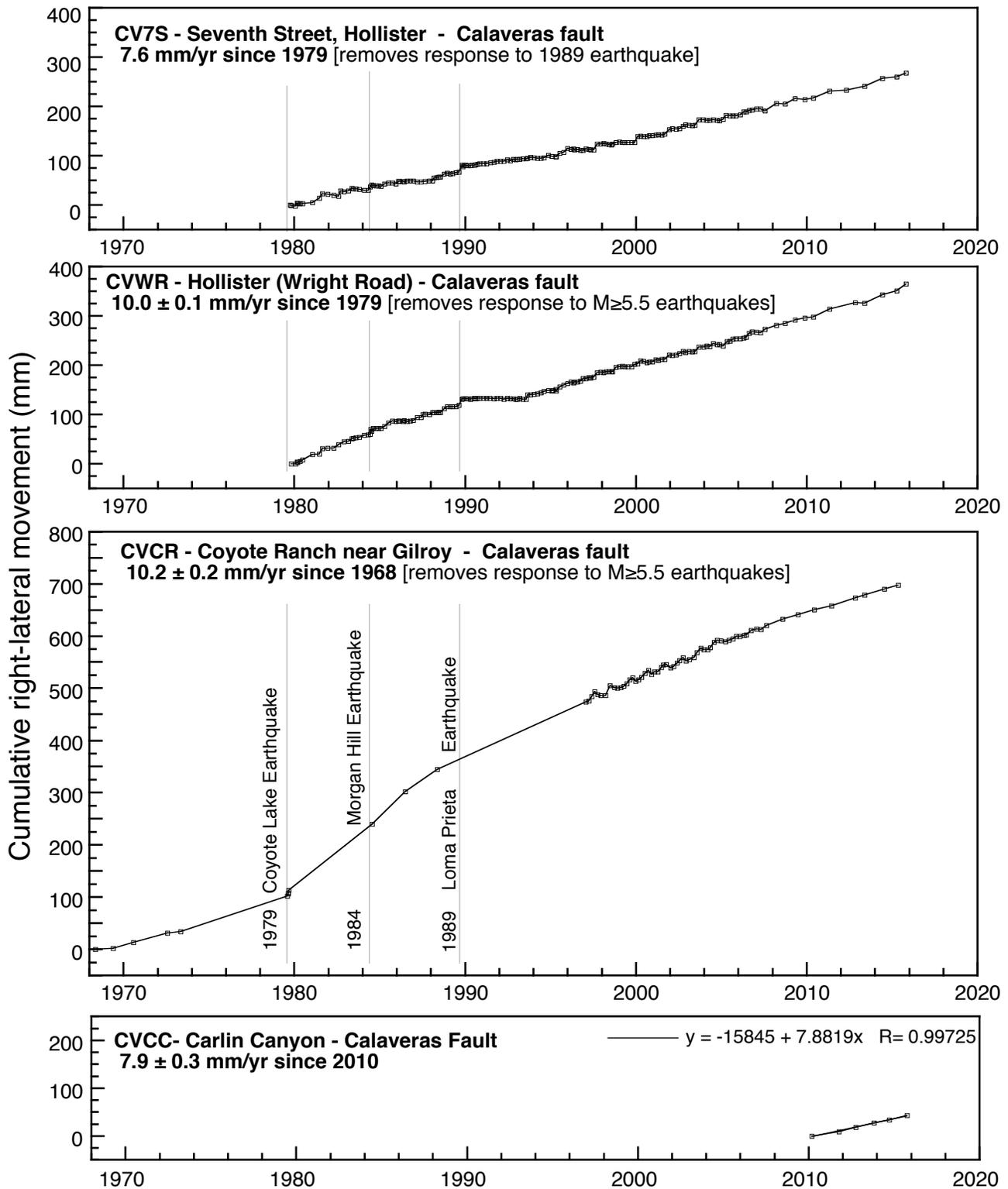


**Figure 1.** Locations of alignment arrays, San Francisco Bay region. Arrays shown as triangles Summary information for most arrays in table 1. All Hayward Fault arrays in fig. 1 and table 2. Inset is idealized array described in text. Active faults in red (USGS and CGS, 2006); Green Valley Fault (Lienkaemper, 2012); Bartlett Springs Fault (Lienkaemper, 2010); Greenville Fault (Lienkaemper, 2014, unpublished mapping); W. Napa fault, 2014 rupture (Brocher et al., 2015). Regions (gray boundaries labeled HF, N, S) indicate contents of three data file sets: Hayward Fault and San Francisco Bay Region, north and south, respectively.



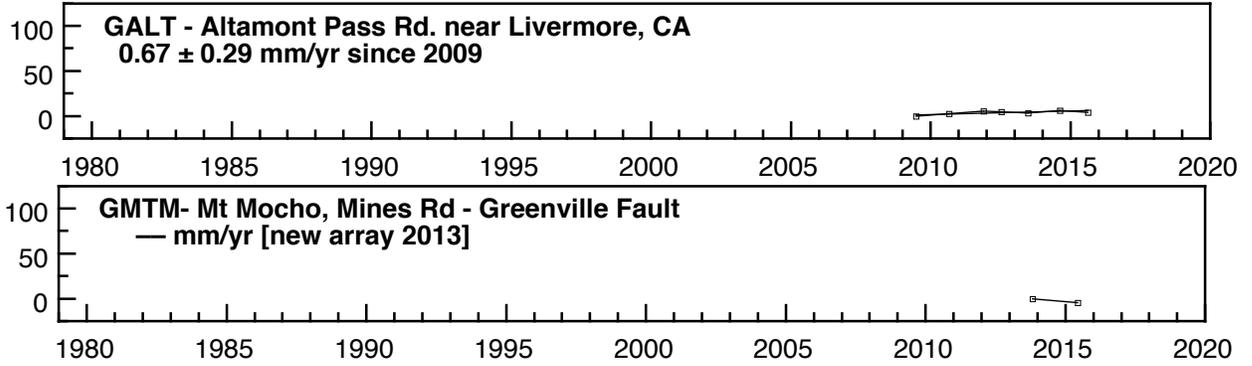
**Figure 2.** Locations of alignment arrays across Hayward Fault. Includes formerly frequent SFSU sites (triangles) and former annual sites (diamonds), see tables 1 and 2 for additional information. Yellow grid shows distance in kilometers from San Pablo Bay after Lienkaemper (2006). Faults in red zoned as active (Bryant and Hart, 2007).

# Calaveras Fault

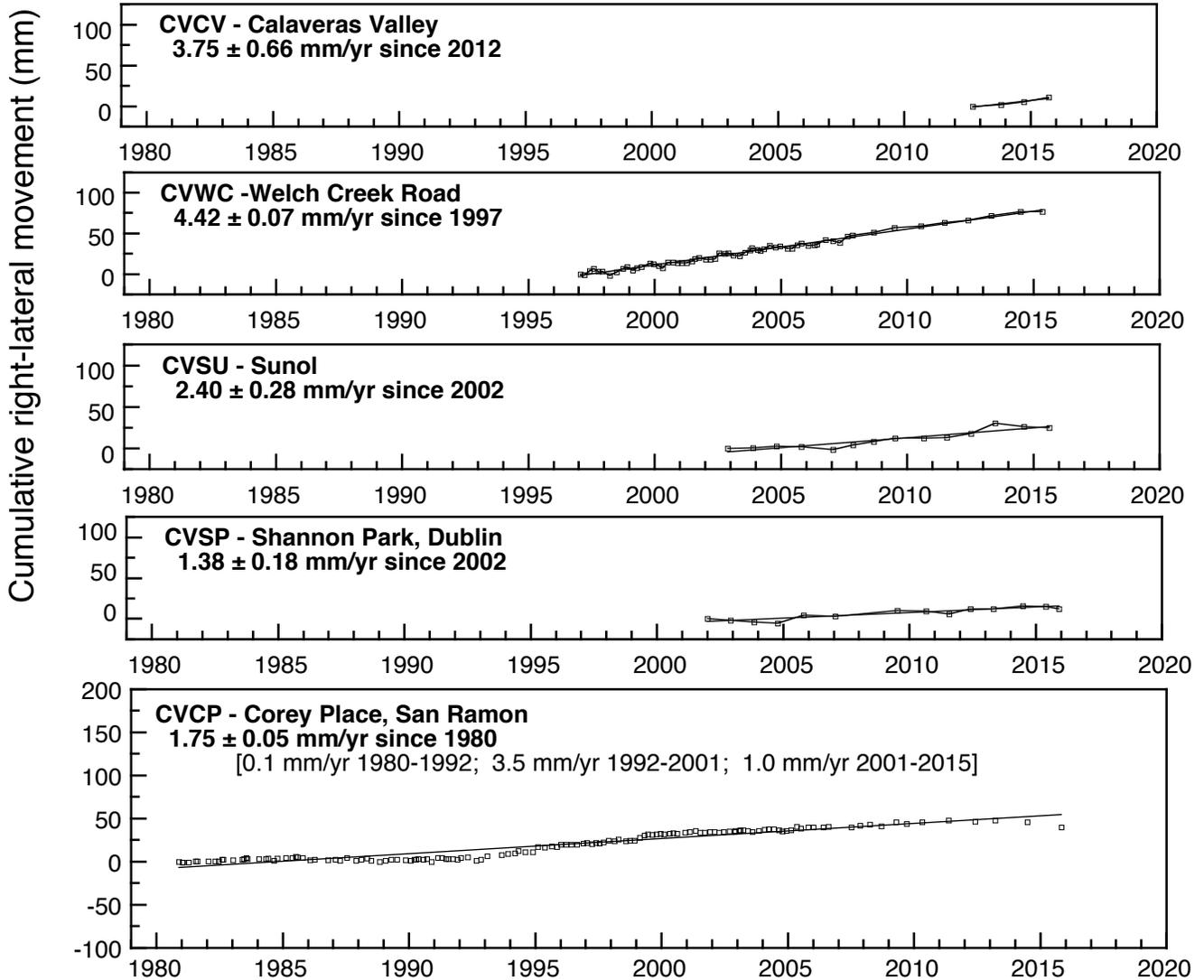


**Figure 3.** Alinement-array measurements, Calaveras Fault. Straight line through the data indicates linear regression fit to data given by associated equations  $y$  (creep, mm);  $x$  (time, yr);  $R$ , correlation coefficient. CV7S, CVWR and CVCR average rate derived by multiple linear regression to remove steps imposed by local earthquakes  $M \geq 5.5$ .

## Greenville Fault

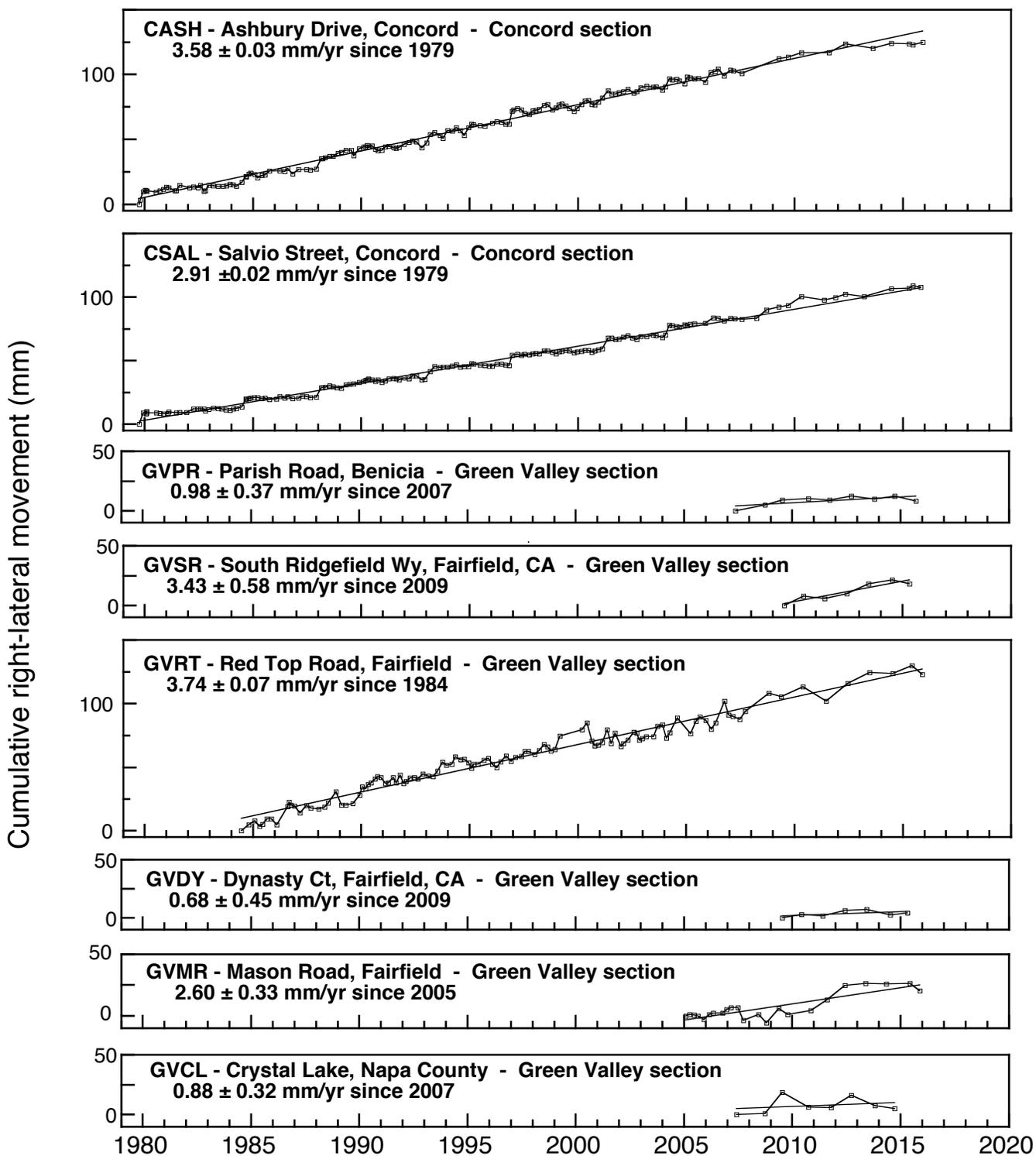


## Northern Calaveras Fault



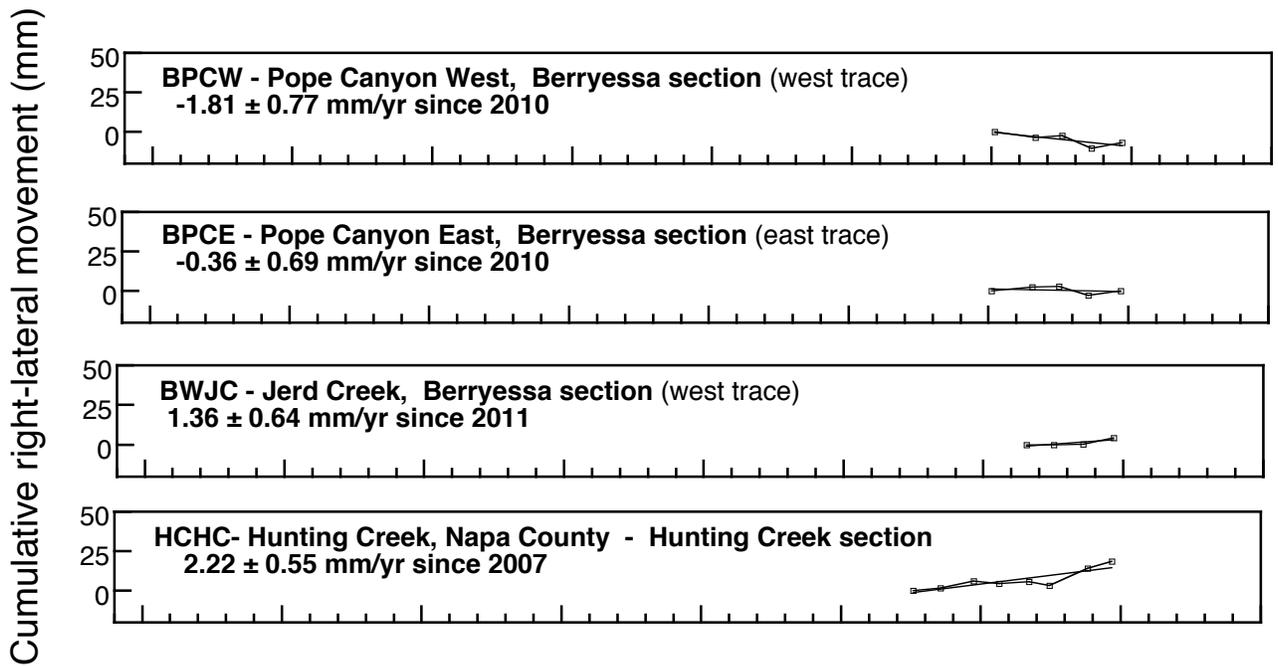
**Figure 4.** Alinement-array measurements, Greenville and Northern Calaveras Faults

# Southern Green Valley Fault (Concord, Green Valley sections)



**Figure 5a.** Alinement array measurements, Southern Green Valley Fault.

Northern Green Valley Fault (Berryessa and Hunting Creek sections)



Bartlett Springs Fault

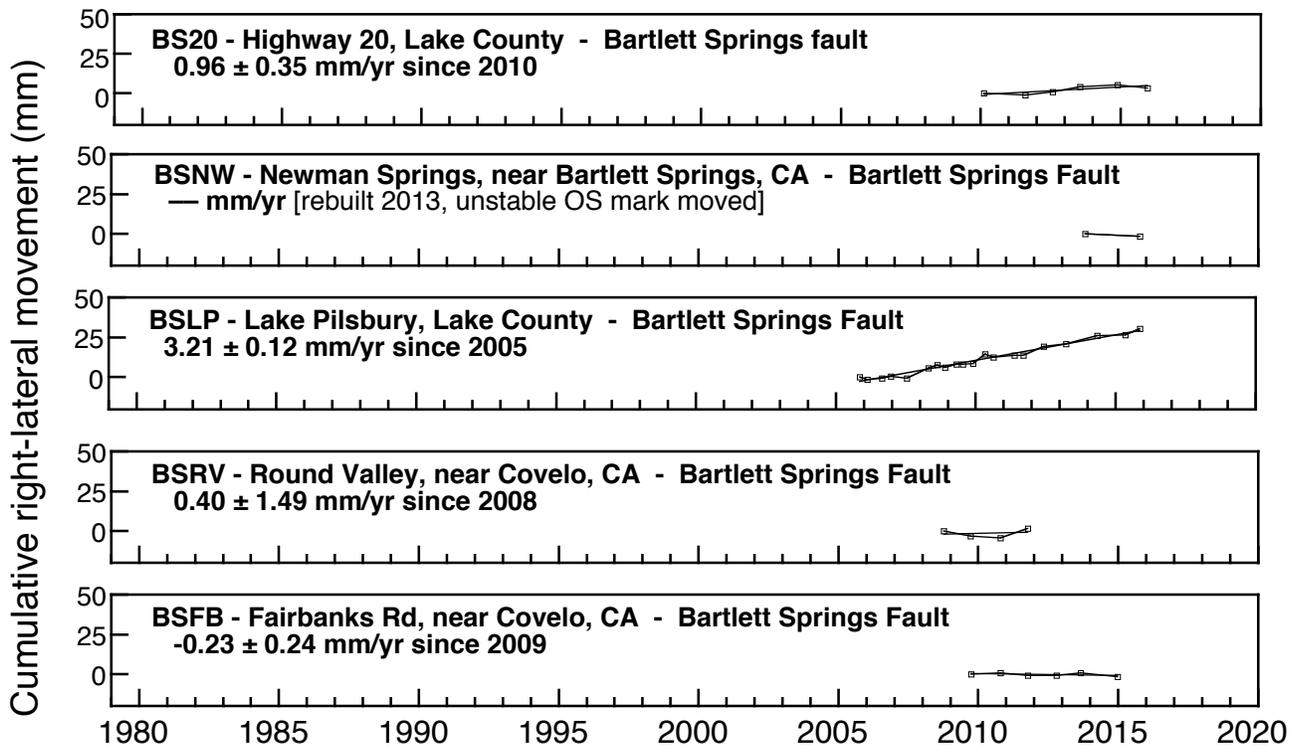
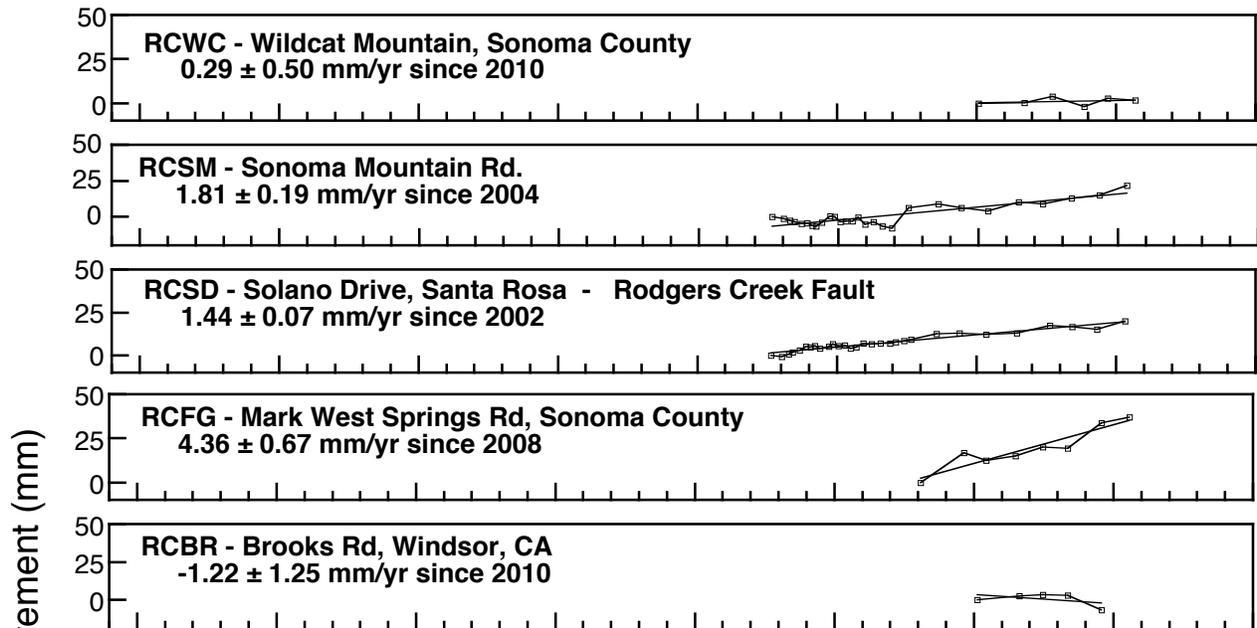
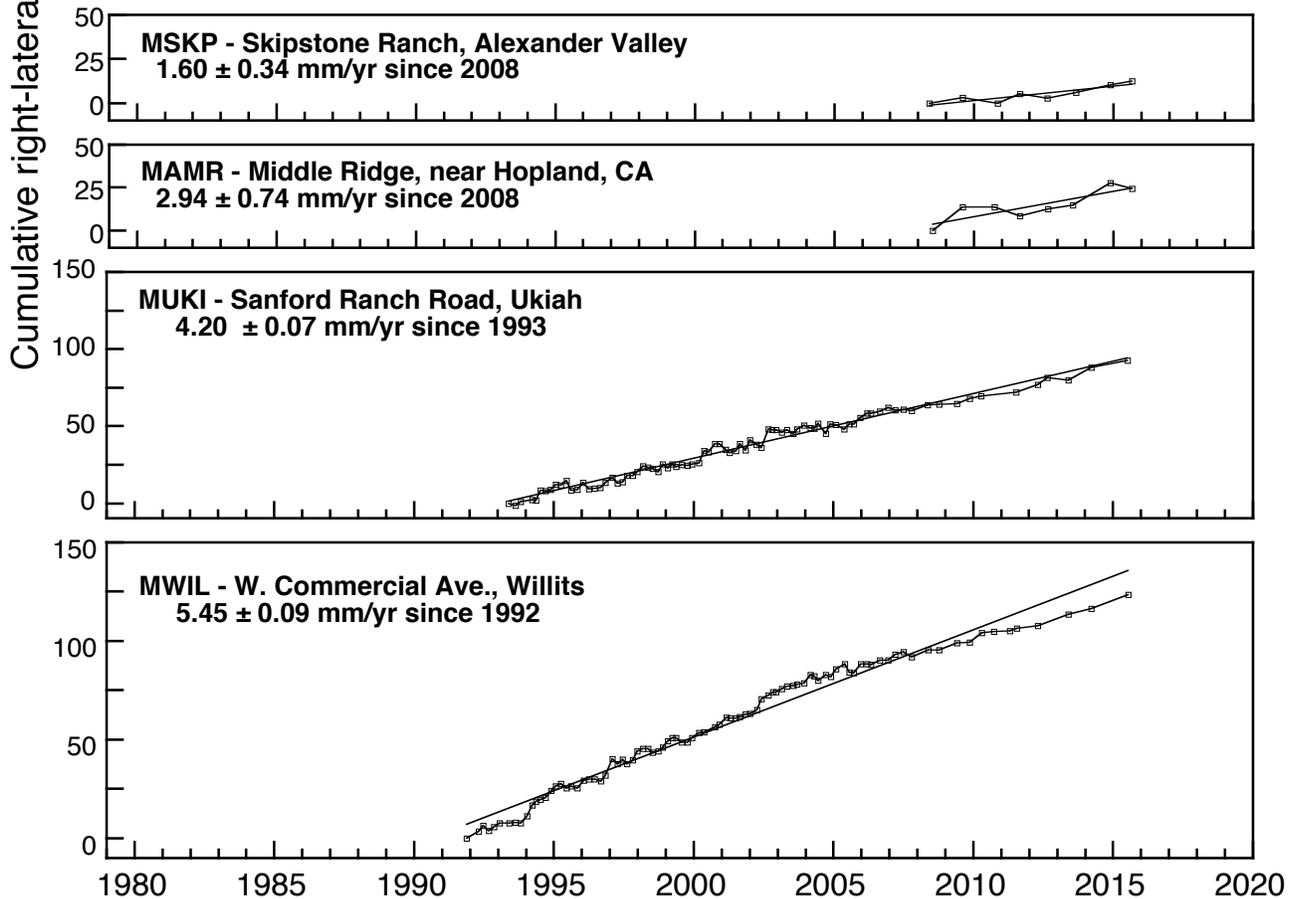


Figure 5b. Alinement array measurements, Northern Green Valley and Bartlett Springs Faults

## Rodgers Creek Fault

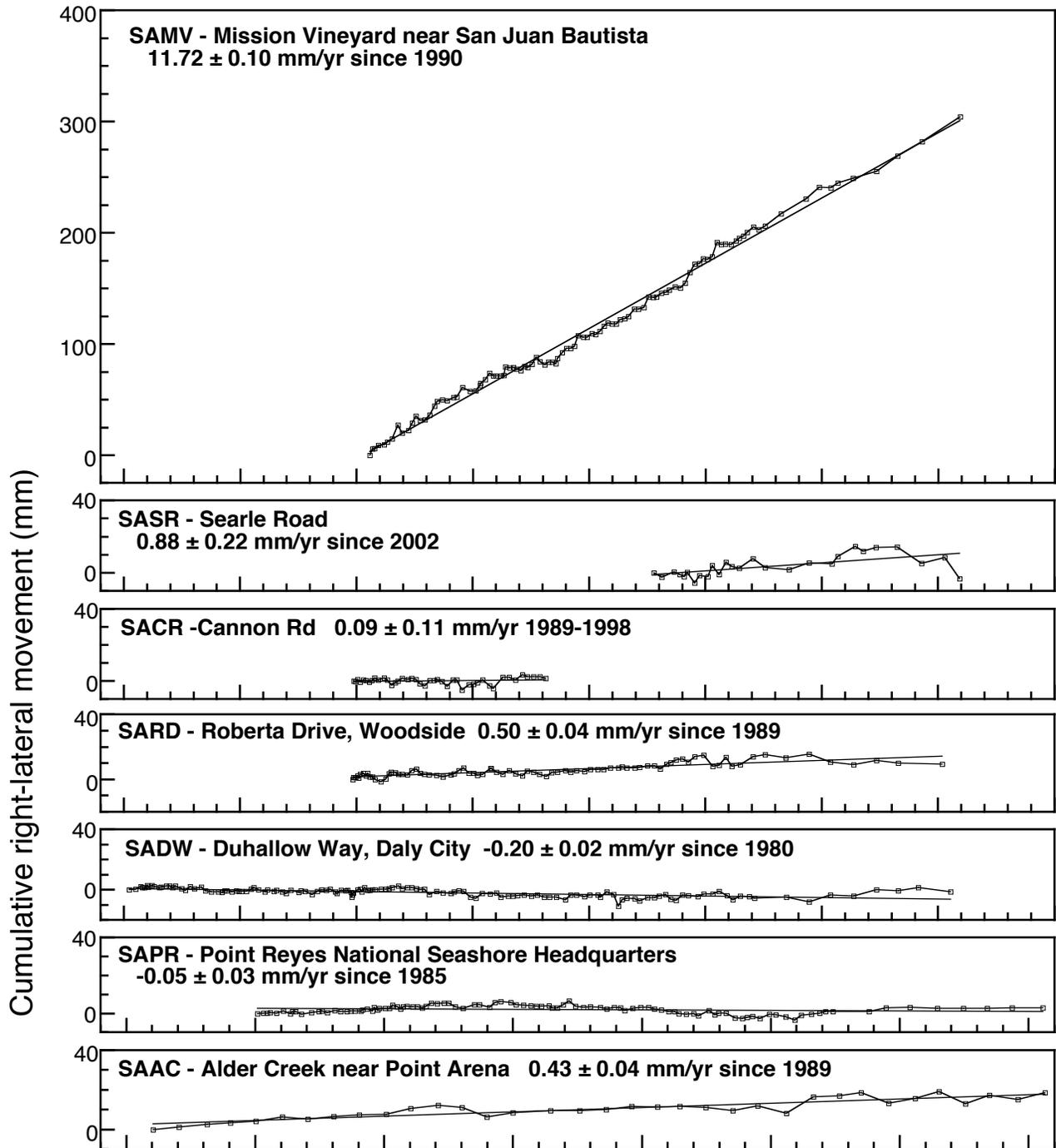


## Maacama Fault

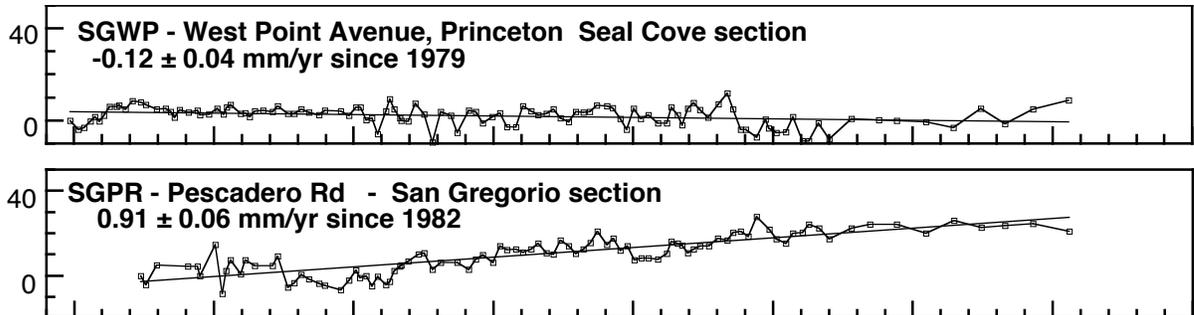


**Figure 6.** Alinement array measurements, Rodgers Creek and Maacama Faults.

## San Andreas Fault

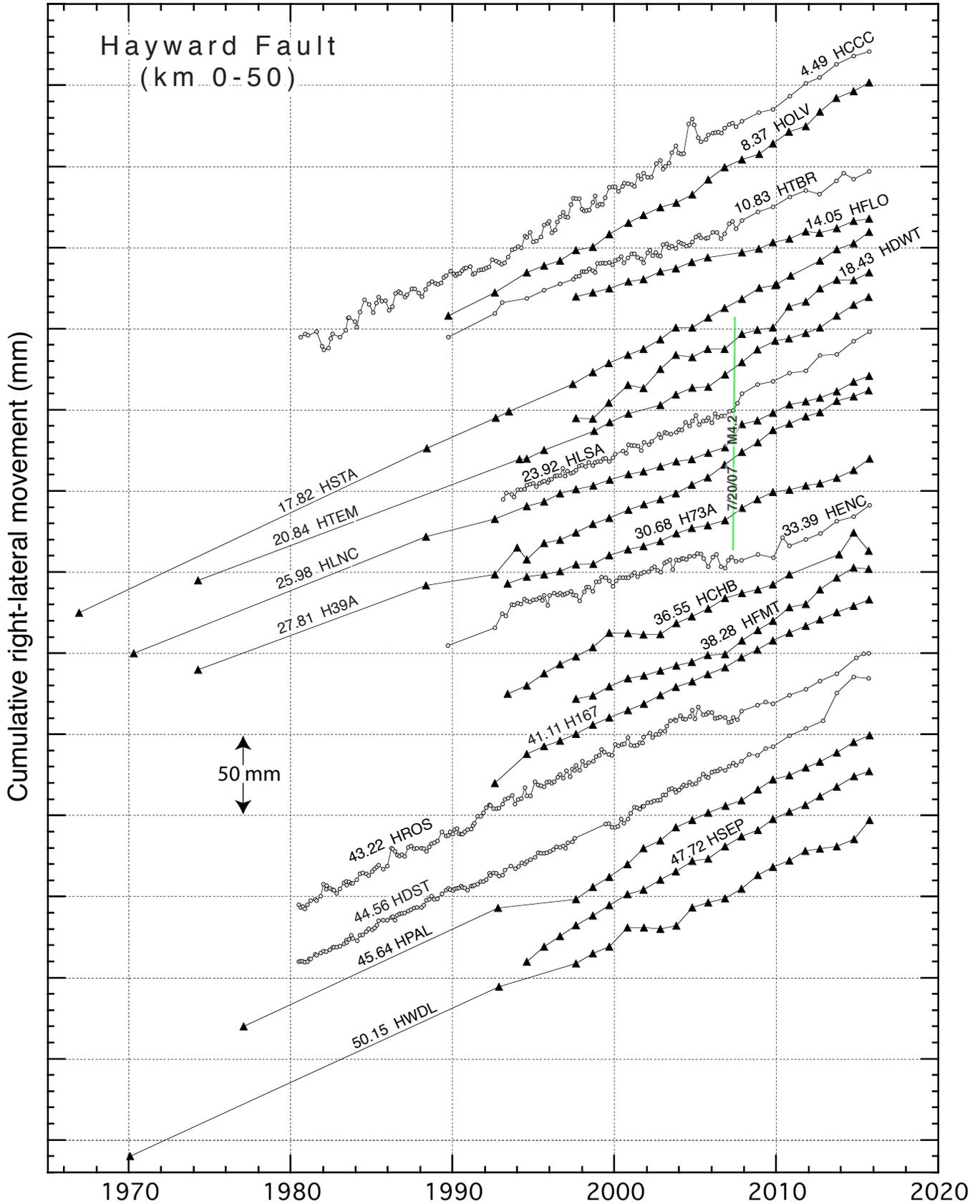


## San Gregorio Fault



1980 1985 1990 1995 2000 2005 2010 2015 2020

**Figure 7.** Alinement array measurements, San Andreas and San Gregorio faults.



**Figure 8.** Alinement array measurements, Hayward Fault, sites from km 0 to 50, labeled by km distance (Table 2, Fig. 2).

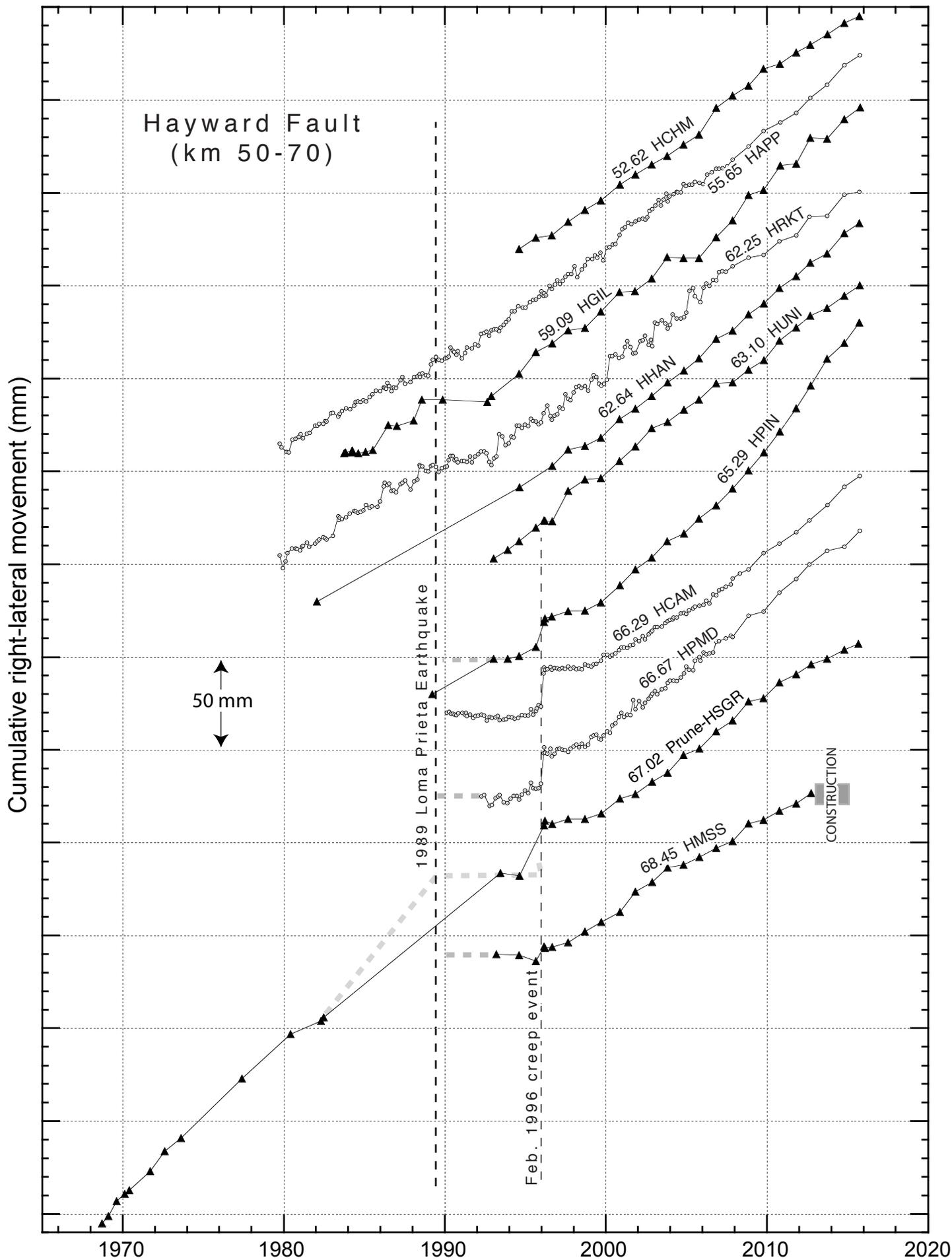
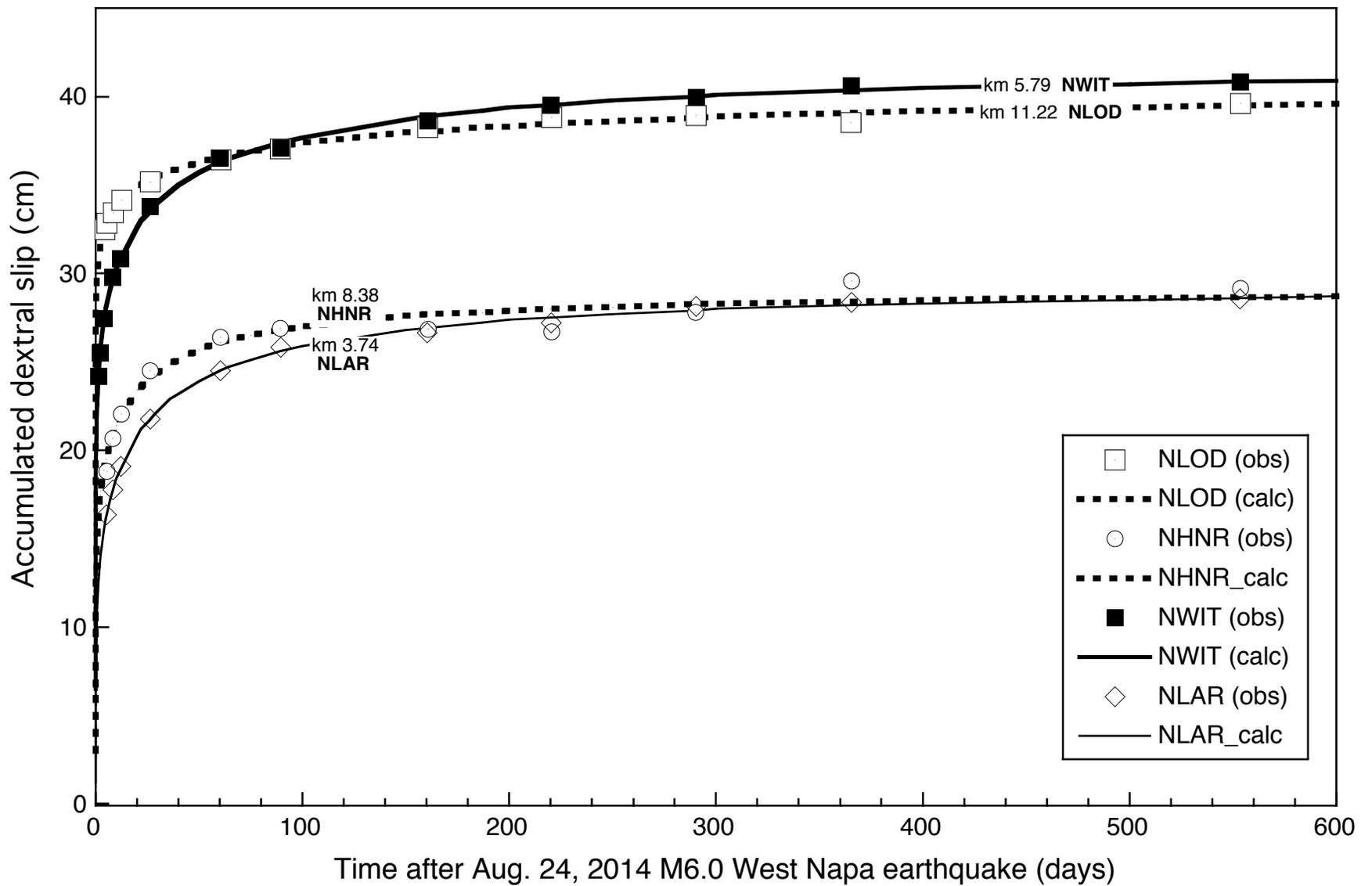


Figure 9. Alinement-array measurements Hayward Fault, sites from km 50 to 70.



**Figure 10.** Alinement array observations across the West Napa Fault rupture associated with the Aug. 24, 2014 earthquake. Total slip based on adjacent offset cultural features. Calculated curves based on AFTER best fit (Boatwright and others, 1986). Array NELW on a branch fault had no afterslip. See Lienkaemper and others (2016).

**Table 1a.** Average Rates of Right-Lateral Movement, San Francisco Bay Region (Southern data set, region **S**, Fig. 1)

Site Code	Fault	Site Name	Longitude (WGS84)	Latitude (WGS84)	Length (m)	Linear regression average creep rate (mm/yr)	± (mm/yr)	Ave.* creep rate (mm/yr)	yr <sup>2</sup>	
CV7S	Calaveras	Seventh Street	-121.40631	36.84952	89.656	7.7	0.09	7.4	36.1	MLR rate; 1989 step
CVWR	Calaveras	Wright Rd	-121.41381	36.86982	108.700	10.0	0.1	10.1	36.0	MLR rate; 1989 step
CVCR	Calaveras	Coyote Ranch	-121.52521	37.06981	89.431	10.2	0.2	14.8	46.0	MLR rate; '79, '84 eqk. steps
CVCC	Calaveras	Carlin Canyon	-121.64941	37.22206	158.199	7.9	0.3	7.7	5.6	
CVHV	Calaveras	Halls Valley	-121.71616	37.34233	167.404	0.4	1.4	-0.8	5.1	Missed trace: abandoned 2015
CVCV	Calaveras	Calaveras Valley	-121.80616	37.45050	146.650	3.7	0.7	3.8	3.0	Replaces Marsh Road Site
CVWC	Calaveras, Northern	Welch Creek Rd	-121.85183	37.53570	158.534	4.3	0.1	4.2	18.3	
CVSU	Calaveras, Northern	Sunol	-121.87693	37.59850	243.224	2.4	0.3	1.9	12.7	
CVSP	Calaveras, Northern	Shannon Park	-121.93713	37.70649	144.730	1.4	0.2	0.9	13.9	
CVCP	Calaveras, Northern	Corey Place	-121.96083	37.74569	111.204	1.8	0.1	1.2	34.9	
GSAR	Greenville	San Antonio Rd.	-121.47562	37.32678	99.315	—	—	-1.4	1.2	New site 2014
GMTM	Greenville	Mount Mocho	-121.51785	37.44750	70.811	—	—	-2.4	1.6	Installed late 2013
GCDM	Greenville	Cedar Mt. (Mines Rd.)	-121.57385	37.55581	86.641	—	—	-4.0	1.3	New site 2014
GALT	Greenville	Altamont Pass Road	-121.69817	37.72060	88.408	0.7	0.3	0.7	6.2	
GMTR	Greenville	Morgan Territory Rd.	-121.77063	37.78659	102.689	—	—	12.2	1.3	New site 2014
SAMV	San Andreas	Mission Vineyard Rd	-121.52171	36.83502	134.663	11.7	0.1	12.0	25.4	
SASR	San Andreas	Searle Rd	-121.57280	36.87453	262.687	0.9	0.2	-0.3	13.2	
SACR	San Andreas	Cannon Road	-121.58611	36.88261	88	0.1	0.1	0.2	8.2	Abandoned 1998
SARD	San Andreas	Roberta Dr	-122.26154	37.41700	91.176	0.5	0.04	0.4	25.3	
SADW	San Andreas	Duhallow Way	-122.46564	37.64419	205.637 <sup>1</sup>	-0.2	0.02	0.0	35.0	
SAPR	San Andreas	Point Reyes	-122.79796	38.04398	70.880	-0.05	0.03	0.1	30.4	
SAAC	San Andreas	Alder Creek	-123.69059	38.99986	265.982	0.4	0.04	0.5	34.6	
SGPR	San Gregorio	Pescadero Rd	-122.37294	37.25450	454.945 <sup>1</sup>	0.9	0.06	0.6	33.2	
SGWP	San Gregorio, Seal Cove	West Point Ave	-122.49664	37.50369	262.033	-0.12	0.04	0.2	35.7	

\*Average = total slip/total time

<sup>1</sup>Combined ESE and ESW lengths

<sup>2</sup>Number of years of observation

**Table 1b.** Average Rates of Right-Lateral Movement, San Francisco Bay Region (Northern data set, region N, Fig. 1)

Site Code	Fault	Site Name	Longitude (WGS84)	Latitude (WGS84)	Length (m)	Linear regression	Ave.*		yr <sup>2</sup>	
						average creep rate (mm/yr)	± (mm/yr)	creep rate (mm/y r)		
BPCE	Berryessa	Pope Canyon, East trace	-122.29829	38.62156	99.040	-0.4	0.7	0.0	4.6	
BPCW	Berryessa	Pope Canyon West trace	-122.32086	38.62179	76.096	-1.8	0.8	-1.5	4.6	
BWJC	Berryessa	Jerd Creek, West trace	-122.34194	38.65523	86.598	1.4	0.6	1.5	3.1	
BS20	Bartlett Springs	Highway 20	-122.49721	39.00138	163.948	1.0	0.4	1.1	5.9	
BSNW	Bartlett Springs	Newman Springs	-122.71436	39.19380	141.000	—	—	-0.7	1.9	OS replaced, read 2015
BSLP	Bartlett Springs	Lake Pillsbury	-122.95726	39.44560	102.186	3.2	0.1	3.0	10.0	
BSRV	Bartlett Springs	Round Valley	-123.22755	39.74003	184.164	0.4	1.5	0.6	3.0	Destroyed
BSFB	Bartlett Springs	Fairbanks Road	-123.24823	39.75875	101.345	-0.2	0.2	-0.3	5.2	Not read 2015
CASH	Concord	Ashbury Drive	-122.03524	37.97189	133.189	3.6	0.03	3.5	36.2	
CSAL	Concord	Salvio Street	-122.03824	37.97569	57.110	2.9	0.02	3.0	36.1	
GVPR	Green Valley	Parish Rd	-122.11316	38.11413	140.446	1.0	0.4	1.0	8.3	
GVSR	Green Valley	S. Ridgefield Way	-122.13680	38.16584	117.287	3.4	0.6	3.2	5.8	
GVRT	Green Valley	Red Top Rd	-122.15054	38.19848	343.750	3.7	0.1	3.9	31.4	
GVDY	Green Valley	Dynasty Court	-122.15560	38.21861	175.568	0.7	0.5	0.8	5.8	
GVMR	Green Valley	Mason Rd	-122.16186	38.23603	143.137	2.6	0.3	1.9	10.8	
GVCL	Green Valley	Crystal Lake	-122.24806	38.47626	95.442	0.9	0.3	0.7	7.3	LR exclude '09,'12. Not read '15
HCHC	Hunting Creek	Hunting Creek	-122.38873	38.81388	179.400	2.2	0.5	2.7	7.1	Not read 2015
MSKP	Maacama	Skipstone Ranch	-122.82647	38.70320	111	1.6	0.3	1.7	7.2	
MAMR	Maacama	Middle Ridge	-123.05070	38.93464	144.300	2.9	0.7	3.4	7.1	
MUKI	Maacama	Sanford Ranch Rd	-123.16748	39.13906	288.753	4.2	0.1	4.2	22.1	
MWIL	Maacama	W. Commercial Ave	-123.35612	39.41242	124.869	5.4	0.1	5.2	23.7	
NLAR	West Napa	Las Amigas Rd	-122.31640	38.23422	76.05	— <sup>3</sup>	—	—		Afterslip of Aug 24, 2014 M6.0
NWIT	West Napa	Withers Rd	-122.32516	38.25157	138.95	— <sup>3</sup>	—	—		"
NHNR	West Napa	Henry Rd	-122.33650	38.27316	70.8	— <sup>3</sup>	—	—		"
NLOD	West Napa	Leaning Oak Dr	-122.34426	38.29809	64.720	— <sup>3</sup>	—	—		"
NELW	West Napa	Ellen Wy	-122.33782	38.30813	85	—	—	—		"
RCWC	Rodgers Creek	Wildcat Mountain	-122.47916	38.19870	109.680	0.3	0.5	0.3	5.6	
RCSM	Rodgers Creek	Sonoma Mtn. Rd	-122.59046	38.30928	137.926	1.8	0.2	1.7	12.7	
RCSO	Rodgers Creek	Solano Drive	-122.69446	38.43687	90.502	1.4	0.1	1.6	12.7	
RCFG	Rodgers Creek	Fountaingrove Blvd.	-122.71750	38.47995	76	—	—	--	--	Abandoned 2015
RCMW	Rodgers Creek	Mark West Springs Rd.	-122.73807	38.50169	152.000	4.4	0.7	5.0	7.4	
RCBR	Rodgers Creek	Brooks Road	-123.79490	38.57730	65.951	-1.2	1.3	-1.5	4.5	Not read 2015
RCBP	Rodgers Creek	Bridle Path	-122.86539	38.64186	121.5	—	—	—	0.0	

\*Average = total slip/total time

<sup>1</sup>Combined ESE and ESW lengths

<sup>2</sup>Number of years of observation

<sup>3</sup>Slip associated with M6.0 earthquake exhibits logarithmic decay over time, not linear (Lienkaemper and others, 2016)

**Table 2. Average Rates of Right-Lateral Movement, Hayward Fault**

Distance from Pt. Pinole (km)	Site:	Site Name	Longitude (WGS84)	Latitude (WGS84)	Length (m)	Linear regres- sion		Average*		Note
						average creep rate (mm/yr)	± yr	creep rate (mm/yr)	yr†	
4.49	HCCC	Contra Costa College	-122.33902	37.96918	142.58	5.2	0.1	5.0	35.1	**
8.37	HOLV	Olive Drive	-122.30959	37.94252	142.62	5.5	0.1	5.5	26.0	
10.83	HTBR	Thors Bay Road	-122.29294	37.92449	119.20	3.6	0.1	3.9	26.0	
14.05	HFLO	Florida Avenue	-122.27340	37.89980	126.11	2.7	0.04	2.7	18.1	1
17.82	HSTA	Memorial Stadium	-122.25061	37.87066	~161	4.8	0.03	4.8	48.8	
18.43	HDWT	Dwight Way	-122.24107	37.86447	132.35	5.1	0.2	5.0	18.1	
20.84	HTEM	Temescal	-122.23137	37.84853	153.92	4.3	0.1	4.2	41.5	
23.92	HLSA	LaSalle Ave	-122.21005	37.82638	182.84	4.2	0.1	4.6	22.6	
25.98	HLNC	Lincoln	-122.19863	37.80999	110.41	3.7	0.1	3.8	45.4	
27.81	H39A	39th	-122.18931	37.79504	137.81	4.4	0.1	4.1	41.4	
30.68	H73A	73rd	-122.16977	37.77426	89.81	3.4	0.1	3.4	22.4	
33.39	HENC	Encina Way	-122.15148	37.75453	123.80	2.5	0.1	3.3	26.1	
36.55	HCHB	Chabot Park	-122.12993	37.73184	170.05	4.0	0.1	4.0	22.3	
38.28	HFMT	Fairmont	-122.12131	37.71749	166.64	4.6	0.2	4.4	18.1	
41.11	H167	167th	-122.10578	37.69495	90.35	4.7	0.1	4.9	23.1	
43.22	HROS	Rose Street	-122.09121	37.67983	153.77	4.5	0.04	4.4	35.2	
44.56	HDST	D Street	-122.08162	37.67021	110.86	4.6	0.03	5.0	35.2	
45.64	HPAL	Palisade	-122.07397	37.66270	131.66	4.9	0.2	4.6	38.7	
47.72	HSEP	Sepulchre	-122.05902	37.64798	107.14	5.4	0.1	5.6	21.1	
50.15	HWDL	Woodland	-122.04140	37.63097	66.58	4.5	0.1	4.5	45.7	1
52.60	HCHM	Chimes	-122.02325	37.61422	118.65	6.3	0.1	5.9	21.1	
55.65	HAPP	Appian Way	-122.00193	37.59240	132±2	5.8	0.04	5.8	36.0	
59.09	HGIL	Gilbert	-121.98094	37.56645	89.26	5.7	0.1	5.8	32.0	2
62.25	HRKT	Rockett Drive	-121.96187	37.54210	103.23	5.4	0.1	5.4	36.0	
62.64	HHAN	Hancock	-121.95914	37.53942	88.51	6.4	0.2	6.0	33.7	2
63.10	HUNI	Union	-121.95584	37.53614	168.10	6.5	0.1	6.5	22.7	2
65.29	HPIN	Pine	-121.94181	37.51973	97.65	7.6	0.3	7.6	26.5	2
66.29	HCAM	Camellia Drive	-121.93528	37.51235	88.35	4.8	0.1	5.0	25.6	2
66.67	HPMD	Parkmeadow Drive	-121.93262	37.50960	156.91	6.4	0.1	6.1	23.5	2
67.02	HSGR	S. Grimmer	-121.93046	37.50720	129.54	5.8	0.2	6.1	33.2	2
67.21	HONO	Onondaga	-121.92894	37.50516	72.88	3.3	0.2	3.2	32.4	2,3,**
68.45	HMSS	Mission	-121.92182	37.49629	168.94	5.3	0.2	4.4	21.6	2,4,**
74.22	HCCD	Country Club Drive	-121.88548	37.45340	94.4	—	—	—	0.0	

1) Array may miss significant fault traces

2) Slip rate includes considerable slow-down following 1989 Loma Prieta Earthquake

3) Array misses a major creeping fault trace

4) Not read in 2013 due to construction

\*Average = total slip/total time

\*\*Estimated value using simple average for missing data

†Number of years observed

HSTA Stadium array rebuilt in Sept. 2012, needs new L (IS-ES) measurement