Long-term monitoring of creep rate along the Hayward fault and evidence for a lasting creep response to 1989 Loma Prieta earthquake

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Abstract. We present results from over 30 yr of precise surveys of creep along the Hayward fault. Along most of the fault, spatial variability in long-term creep rates is well determined by these data and can help constrain 3D-models of the depth of the creeping zone. However, creep at the south end of the fault stopped completely for more than 6 years after the M7 1989 Loma Prieta Earthquake (LPEQ), perhaps delayed by stress drop imposed by this event. With a decade of detailed data before LPEQ and a decade after it, we report that creep response to that event does indeed indicate the expected deficit in creep.

Introduction

The Hayward fault produced a major earthquake in 1868 of magnitude 6.8-7.0 (*Bakun*, 1999, *Yu and Segall*, 1996) with conspicuous surface rupture south of Oakland (O, Figure 1, *Lawson*, 1908). Earlier workers estimated the entire fault had high potential for producing large earthquakes [*Lienkaemper and Galehouse*, 1999].

The Hayward fault slips aseismically or creeps at ~4.6 mm/yr. Previously, the creep had been considered primarily shallow (0-5 km depth). Recently, however, *Bürgmann et al.* [2000] suggested that much of the northern Hayward fault might be entirely free to slip and need not originate any large earthquakes, based primarily on an analysis of short-term (1992-1997) satellite imagery. In evaluating 30-yr probabilities of major earthquakes in the Bay Region, The *Working Group on California Earthquake Probabilities* [1999, WG99] needed to evaluate the possibility of such a large free-slipping patch on the northern Hayward. For this purpose in a companion paper, *Simpson et al.* [2001, *S2001*] developed various 3-dimensional models of creep based on the best long-term surface creep rates.

In this paper, we present the constraints from the surface creep data underlying the *S2001* models. Because *WG99* needed uncertainty estimates for each variable in its probability calculations, we developed smoothed curves for the along-strike variation in mean surface creep rate within 95-percentile uncertainty bounds. In our previous work, we included many creep rates from offset cultural features and strictly limited data to before the 1989 LPEQ [*Lienkaemper et al.*, 1991; *Lienkaemper and Galehouse,* 1997]. In this paper we include post-1989 data with caveats about the impact of stress change. We focus mainly on repeated high-precision surveyed data. The data represent the most complete and reliable set of creep observations spanning the entire surveyed history of the fault [1966-1999].

Stress reduction in this region caused by the 1989 LPEQ reduced Hayward fault creep rates [*Lienkaemper et al*., 1997; *Galehouse*, 1997], most markedly at the south end. A decade later, we confirm that the effect of LPEQ on long-term rates was minimal for most of the fault (km 0-55). We measure distances southward along the fault from Pt. Pinole (P, Figure 1). However, the reduction was considerable near the south end (km 59-68) and of major impact from km 63 to 67 where creep rates had been the highest, 8-10 mm/yr, for decades before 1989. Because of this pronounced LPEQ stress response, these fastest long-term rates (km 63-67) still must be determined largely from surveyed offset cultural features measured before 1989 [*Lienkaemper and Galehouse,* 1997].

Methodology and Creep observations

The 1966-2000 surveyed creep observations are shown in Figure 2 from north to south at a uniform scale. These observations and other supporting data are available at http://quake.wr.usgs.gov/docs/deformation/hfcreep/ (*URL*) and field procedures are described in *Galehouse et al.* [1982]. Arrays mostly span ~100 m transverse to the fault.

Because our goal was to develop the most reliable set of data for characterization of along-strike variations in long-term creep rate, we wanted clear criteria for selection and rejection (Table 1, Figure 3). We rejected some arrays for land sliding or not spanning all fault traces, or for having less than the 5-yr data that we judged as minimal for adequately estimating rate. Some arrays show extremely steady signals: BART (km 20.28), LaSalle (km 23.92), and D St (km 44.56). Others show strong seasonal noisiness: Contra (km 4.49) and Rose (km 43.22). A few are dominated by large infrequent creep events years apart with slow creep between, like Encina (km 33.39) and Gilbert (km 59.09). Rockett (km 62.25) has much seasonal noise and large infrequent creep events (1-4 yr apart). We can reduce seasonal noise by down-sampling to annual samples. In effect we do this by making our annual survey of every site along the fault at the end of the local dry season. We also reject poorly sampled sites in sections of the fault where much better data are plentiful. For other sections of the fault we use short-term rates (5-7 yr), because these sites show steady creep and we have no reliable longer-term rates nearby.

To develop 95%-confidence uncertainties for the data selected as most reliable (Table 1, Figure 3); we calculated mean rates using linear regression (LR). LR rates compare favorably with simple averages (net creep over elapsed time), except for Rockett (km 62.25), where the LPEQ stress effect requires us to restrict surveyed data to the decade before 1989. The LR mean rate at Rockett (5.6 ± 0.3 mm/yr) greatly exceeds the simple average, (4.6 mm/yr), but agrees with our 28-yr average rate from the adjacent offset curb (1967-93, 5.3 ± 0.4

mm/yr). We have used both the LR mean and the curb rates to develop our 95-percentile curves.

Along-Strike Variation in Surficial Creep Rate

For input into the modeling in *S2001*, we developed smooth curves (Figure 3) of the mean creep rate as it varies along strike by computing best-fit polynomials in 3 sections (see *URL*). For km 62.25-69 we used an interpolation scheme to compute discrete values. For upper and lower bound curves, we applied identical fitting and interpolation procedures. However, because we felt that this left too many outliers, we added additional uncertainty of ± 0.3 mm/yr to the 95-percentile limits. We believe that these curves represent the most accurate representation of long-term surface creep rate as it varies along the fault. These curves express uncertainty with the considerable caution needed for modeling earthquake probability.

Integration of the polynomial curves in Figure 3 gives a mean rate of 4.6 ± 0.5 mm/yr (km 0-62; uncertainty is ± 2σ plus an additional ± 0.3). However, the curves show significant variation from north to south. The fastest creep is at the south end in Fremont, a pronounced 9 mm/yr high, and the slowest is in Oakland (3.66 ± 0.11 mm/yr, mean of 5 sites). The *S2001* models show the Oakland low as the fault's most distinct and largest locked patch or potential seismic source.

We no longer ask *if* the fault creeps in Oakland [*Lienkaemper and Borchardt,* 1988]. Because of our focus there, long-term rates in Oakland now rank among the best resolved. Long-term monitoring of creep along the entire fault zone supplies data critical for detailed modeling, which has considerable impact on applications to earthquake forecasting and hazard estimation.

LPEQ Creep Response

We previously described the short-term impact of stress reduction from the 1989 LPEQ on Hayward fault creep [*Lienkaemper et al.,* 1997; *Galehouse,* 1997]. We now have 10-yr of frequent observations both before and after the event and can summarize its more lasting impact. Because many of our sites were added shortly before and shortly after LPEQ, we needed to be able to estimate pre-LPEQ rates for these newer sites. We did this for all sites by using discrete values of mean creep rate of our best-fit curve (Figure 3). To compute observed creep response (Figure 4) we used these mean long-term rates to compute the amount of creep to be expected in the post-LPEQ survey interval for each site.

Computation of total creep observed after LPEQ required some assumptions for some sites near the south end (km 63-67) as shown by the gray lines in Figure 2. For Camellia (km 66.29) we include 21 ± 16 mm of triggered right-lateral LPEQ slip in post-LPEQ slip measured by re-survey of the adjacent curb. Pine (km 65.29) showed 19 mm of triggered LPEQ slip surveyed on benchmarks. We reconstruct the post-LPEQ slip at Parkmeadow (km 66.67) and Prune (km 67.02) assuming 20 mm of triggered slip followed by no slip in the 2-3 yr after LPEQ.

From the creep expected during this interval based on long-term rates, we then subtracted the amount observed during that survey interval for each site (Figure 4). The expected LPEQ creep response used for comparison we computed as the (left-lateral) creep modeled (instantaneously) on a completely free-slipping (i.e., frictionless) Hayward fault using the preferred LPEQ model of *Lienkaemper et al.* [1997].

Ten years after LPEQ, the correlation of expected to observed creep response is satisfactory and the deficit is distinct and seemingly permanent (Figure 4). The majority of the fault (km 0-50) has minor response as expected because it is far from the earthquake rupture (Figures 1 and 4B). However nearer the earthquake at the south end (km 63-67) the response was profound (Figures 3 and 4B) and at its greatest matched the deficit predicted by the model. Misfits to the model could result from such factors as heterogeneous elasticity in the crust and variations in rheology and depth of creep along the fault. Expected response (km 63-67), ranged from –36 to -44 mm (i.e., left-lateral); observed response ranged from –31 to -48 mm. Recent major earthquakes such as the M7.9 1906 and M7 1989 LPEQ caused significant stress changes on adjacent faults. The observed ~40 mm deficit in creep on the southern Hayward fault fully a decade after LPEQ suggests a permanent slip deficit consistent with the stress change that caused it. A permanent offset in the creep history of a fault differs markedly from dynamically triggered creep step, which generally resembles a creep event consistent with the background creep rate.

With a decade of detailed data before LPEQ and a decade after it, we report that the instantaneous sinistral creep response modeled on a frictionless fault seems to explain the deficit in creep observed in the past decade. However, rather than occurring instantaneously after LPEQ, creep ceased for the time needed to restore the former dextral stress level on the fault.

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Figure 1. Hayward fault creep monitoring sites (bold dots) having best-determined, long-term creep rates (Figures 2 and 3, Table 1). Distances along fault given as km southward from Point Pinole (P) using grid of *Lienkaemper* [1992]. SF, San Francisco; O, Oakland; H, Hayward; F, Fremont; CR, Calaveras Reservoir; SPB; San Pablo Bay; 1989 LP, 1989 Loma Prieta Earthquake rupture.

Figure 2. Observations of right-lateral creep along the Hayward fault from repeated surveys, 1966-2000. Locations given as distances as described in Figure 1.

Figure 3. Variations in creep rate along the Hayward fault. Rates reflect mean values and 2σ uncertainty determined from linear regression versus time (Table 1). Curves reflect 95-percentile confidence range in the data (gray pattern); see text. Locations (P, O, H, F) as in Figure 1.

Figure 4. Creep response observed since 1989 LPEQ versus that expected from simple elastic model [see text and *Lienkaemper et al.,* 1997] plotted to show A) correlation and B) relation to distance along the fault.

LIENKAEMPER ET AL.: HAYWARD FAULT CREEP AND STRESS RESPONSE
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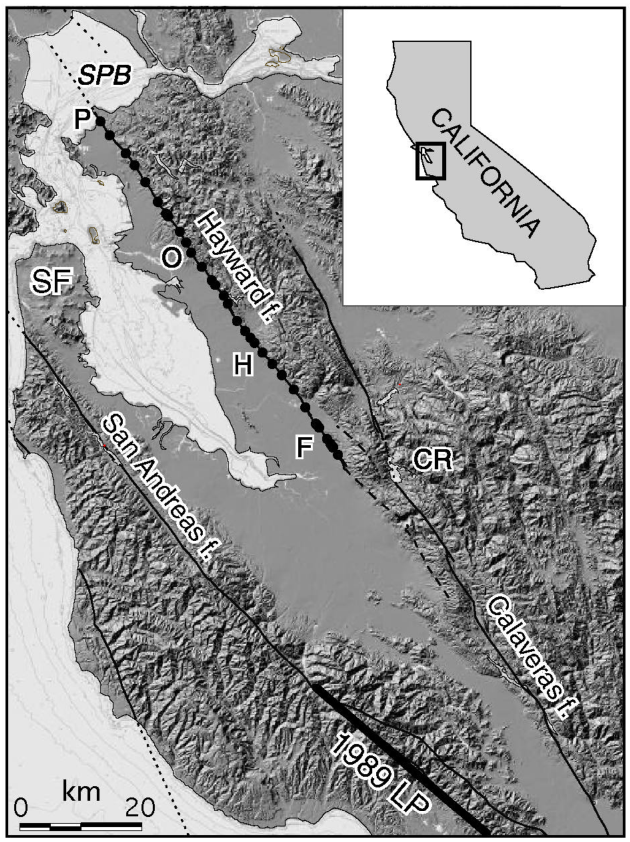
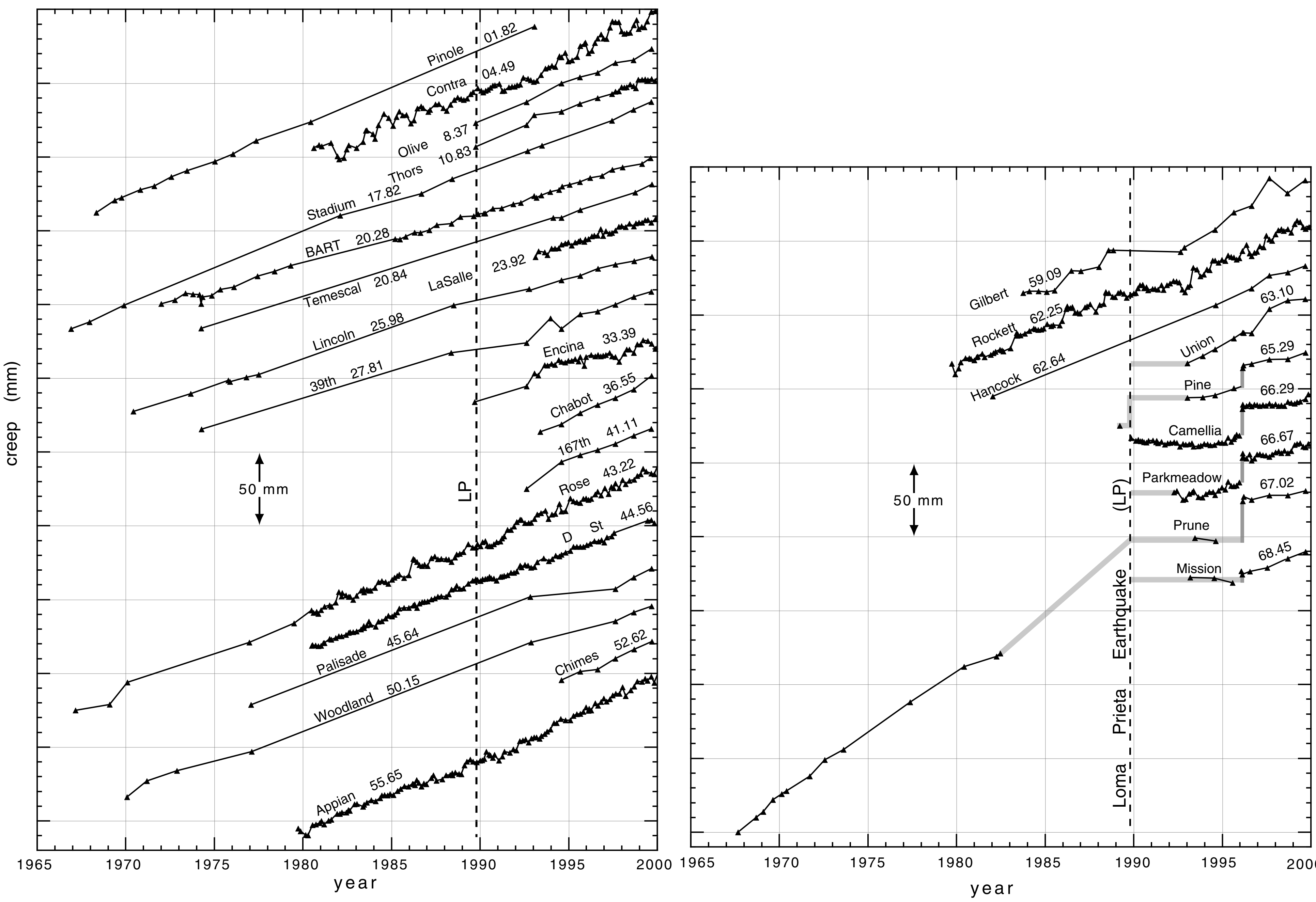

SPB
P
O
Hayward f.
SF
H
F
CR
San Andreas f.
Calaveras f.
1989 LP
0
km
20
CALIFORNIA

Figure 1



Pinole 01.82
Contra 04.49
Olive 8.37
Thors 10.83
Stadium 17.82
BART 20.28
Temescal 20.84
LaSalle 23.92
Lincoln 25.98
39th 27.81
Encina 33.39
Chabot 36.55
167th 41.11
Rose 43.22
D St 44.56
Palisade 45.64
Woodland 50.15
Chimes 52.62
Appian 55.65
LP
50 mm
creep (mm)
year
Gilbert 59.09
Rockett 62.25
Hancock 62.64
63.10
Union
65.29
Pine
66.29
Camellia
66.67
Parkmeadow
67.02
Prune
Mission
68.45
Loma Prieta Earthquake (LP)
1965
1970
1975
1980
1985
1990
1995
2000

Figure 2

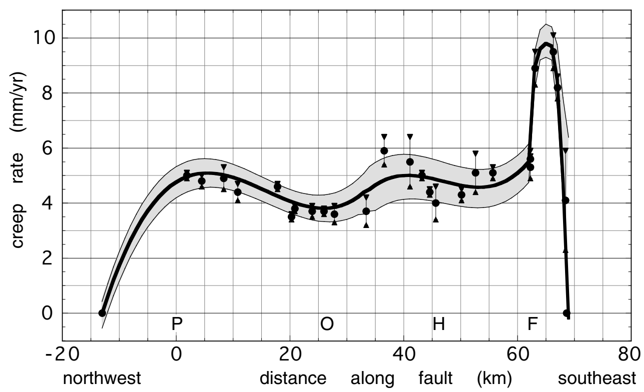
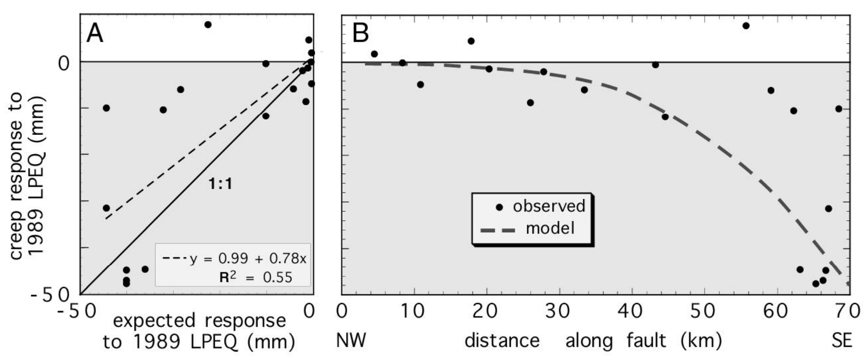

creep rate (mm/yr)
10
8
6
4
2
0
P
O
H
F
-20
0
20
40
60
80
northwest
distance along fault (km)
southeast

Figure 3



A
B
creep response to 1989 LPEQ (mm)
0
-50
-50
0
expected response to 1989 LPEQ (mm)
1:1
y = 0.99 + 0.78x
R^2 = 0.55
observed
model
0
10
20
30
40
50
60
70
NW
distance along fault (km)
SE

Table 1. Best Long-term Creep Rates Along Hayward Fault

		creep rate (mm/yr)				time interval (yr)		
dist-ance (km)	site	*sim-ple ave.* [5]	*linear regres-sion*	±2σ	time (yr)	*initial*	*final*	*remarks*
1.86	Pinole	5.1	5.0	0.1	25	1968.333	1993.058	begun by Harsh & Burford (1982)[1]
4.49	Contra	4.8	4.8	0.2	19	1980.609	1999.890	bimonthly
8.37	Olive	5.1	4.9	0.4	10	1989.748	1999.677	annual
10.83	Thors	4.6	4.4	0.3	10	1989.748	1999.868	begun as annual, now bimonthly
17.82	Stadium	4.7	4.6	0.1	33	1966.912	1999.658	annual; begun as USCGS trilateration net
20.28	BART	3.6	3.5	0.1	28	1971.989	1999.622	deflection array, begun as laser alinement[2]
20.84	Temescal	3.8	3.8	0.1	25	1974.258	1999.696	annual; begun by City of Oakland
23.92	LaSalle	3.8	3.7	0.2	7	1993.112	1999.890	bimonthly
25.98	Lincoln	3.6	3.7	0.1	29	1970.290	1999.696	annual; begun by City of Oakland
27.81	39th	3.7	3.6	0.3	25	1974.274	1999.660	annual; begun by City of Oakland
33.39	Encina	3.6	3.7	0.5	10	1989.693	1999.888	bimonthly; highly episodic, regress 1 obs/yr
36.55	Chabot	6.0	5.9	0.5	6	1993.389	1999.679	annual
41.11	167th	5.8	5.5	0.9	7	1992.620	1999.660	annual
43.22	Rose	5.0	5.0	0.1	33	1967.167	1999.830	bimonthly; begun by City of Hayward
44.56	D St	4.3	4.4	0.1	19	1980.478	1999.830	bimonthly
45.64	Palisade	4.1	4.0	0.6	23	1977.074	1999.677	annual; begun by City of Hayward
50.15	Woodland	4.4	4.3	0.2	30	1970.074	1999.677	annual; 73 m long; whole fault zone included?
52.60	Chimes	5.1	5.1	0.7	5	1994.592	1999.696	annual
55.65	Appian	4.9	5.1	0.2	20	1979.729	1999.830	bimonthly; regress 1 obs/yr
62.25	Rockett	4.6	5.6	0.3	10	1979.726	1989.808	bimonthly; pre LP creep rate
62.25	Rockett	–	5.3	0.4	28	1964.730	1993.041	curb offset (Lienkaemper and Galehouse, 1997)
63.10	Union	–	8.9	0.6	47	1940.3	1987.636	fence line offset (L91)
66.29	Camellia	–	9.5	0.6	20	1967.7	1987.636	curb offset (L91)
67.02	Prune	–	8.2	0.4	14	1968.7	1982.3	annual; begun by Harsh & Burford (1982)[3]
68.45	Hetch	–	≥4.1	1.8	41	1952	1993	offset of major pipeline[4]

1-we recovered 1968 deflection array in 1993

2-most data supplied by BART. We surveyed laser and deflection arrays in 1993 to link data sets

3-in 1982 Prune Ave. widened and renamed South Grimmer Blvd. In 1993 we recovered City survey of 1982

4-pipeline built in 1952 and replaced at fault in 1969, so rate could be 7 mm/yr instead

5-simple average: net creep divided by net elapsed time