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Revised Long-term Creep Rates on the Hayward Fault, Alameda and Contra Costa Counties, California

By

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Abstract

Although the Hayward fault is a source of major earthquakes, it also creeps or slips aseismically, and has done so steadily for several decades (certainly since 1921 and probably since 1869). Most of the fault creeps between 3 and 6 mm/yr, except for a 4- to 6-km-long segment near its south end that creeps at about 9 mm/yr. We present results of our recent surveys to recover angles and deflection lines established across the fault in the 1960s and 1970s, but unmonitored since. We have added data from more offset cultural features to the long-term creep rate data set and made substantial improvements to the analytical method used to compute offsets. The revised creep rate values improve our knowledge of spatial and temporal variation along the fault. The more accurate revised data has reduced the estimate of the average creep rate along most of the fault from 5.1 mm/yr to 4.6 mm/yr. Creep rates in the 9 mm/yr section near the south end have remained the same.

Introduction

The approximate distribution of long-term creep rate along the Hayward fault is well known [*Lienkaemper and others*, 1991]. The purpose of this paper is to update *Lienkaemper and others* [1991] with both (1) a sizeable body of new data and (2) some significantly revised creep rates derived from offset cultural features using improved analysis. The intent of this report is to present creep rates ending before the 17 October 1989 Loma Prieta earthquake (LPEQ), because stress changes associated with that event seemed to have strongly reduced creep rates along the Hayward fault in the Fremont area (km 58 to km 68 in Figure 1) for a few years, and possibly reduced some creep rates to the north as well [*Galehouse,* 1995; *Galehouse,* 1997; *Lienkaemper and others*, 1997]. In some cases long-term creep rates shown in Table 1 do unavoidably include some time after LPEQ, but we generally judge the event's effect to be negligible in proportion to the much greater time sampled before the event. We do not intend to demonstrate the effects of

LPEQ on creep rate in this report, because short-term creep rates are subject to much greater uncertainties than are long-term rates [Langbein and Johnson, 1997]. We believe it is more useful to gather post-earthquake creep data for a few more years and then compare decade-long, post-LPEQ to this earlier long-term data.

We begin by describing improvements to the analysis of offset cultural features (Figure 2) and the results (Table 1). We then discuss new surveys on angle and deflection arrays (Table 1), and show a selection of the data in Figure 3 . Locations in the text , table, and figures are described in terms of a detailed kilometer grid shown in Lienkaemper [1992] and keyed to the numbered crosses in Figure 1. We present only a brief discussion and summary here because we intend this report as a presentation of detailed data to be followed by a summary report elsewhere.

Analysis of offset cultural features and results

Field procedures, selection criteria, and general analytical methodology were given in *Lienkaemper and others* [1991] and will not be repeated here. Three significant changes were made in our analytical methods, which we used to reanalyze all appropriate offset features. For completeness we show all offset features in Figure 2 and Table 1, including those that did not need changing. The first and probably most significant change is the elimination of assumed but uncorroborated secondary fault traces. This problem came to our attention during our analysis of deflection line data at km 43.22 ([D] in Figure 2). In *Lienkaemper and others* [1991] an additional trace was inferred here, but its existence is not sustained by the deflection data. The result was an overestimation of slip rate by about 1 mm/yr. Other such interpreted traces have been eliminated unless corroborated by independent evidence, or as in the case of km 18.43, the uncertain existence of multiple traces is included in the overall estimated error for the site.

The second change is to assume, for purposes of multiple linear regression (MLR), that fewer points reflect deformation in the fault zone. We now account more rigorously for the original waviness or irregularity in the as-built shape of the cultural feature. For example, the curb offset at

Banks Drive (Fig. 2, km 1.90 [C]) requires consideration of its original waviness to make a reasonable interpretaion of fault zone width. In theory this could be done by a statistical cutoff of 2σ error in regression fit, which is now the rule-of-thumb used by us in interpreting these features. That is, points within 2σ of best fit are generally not excluded from the final fit. However, because this is necessarily an iterative procedure, it is difficult to eliminate the human interpreter from the process because the value of 2σ computed by MLR becomes large as the interpreter permits more values in the fault zone into the MLR analysis and an additional decision criterion is needed. In practice this distinction is usually simple for the interpreter; some points are distinctly in the fault zone, while others may also be consistent with both minor deformation and with general amount of irregularity of the feature. We now generally keep such ambiguous points in the analysis, which tends to slightly reduce the amount of computed offset. We did not automate this process although doing so might further improve the consistency of the results.

A third correction also relates to the original irregularity of the feature, but it rarely applies. An example is at 4.50 (Fig. 2, 4.50 [C]) where the MLR data is clearly falsified by a gross irregularity in the feature, and a human interpreter must match the offset feature across the fault.

The revised creep rates resulting from these changes in analytical assumptions do not differ greatly from those reported in *Lienkaemper and others* [1991], but where rates did change they tend to be somewhat lower. Where these revised rates can be compared to rates from alinement array data, agreement tends to be improved. The highest rates, ~9 mm/yr, in southern Fremont were not significantly affected by these new procedures.

Analysis of alinement arrays and results

Methodology for alinement array measurement is described in *Galehouse and others* [1982], *Harsh and Burford* [1982], and *Wilmesher and Baker* [1987]. Most arrays reported on here depend on measurement of angle changes across the fault (items coded as A, in Table 1). A few arrays are deflection arrays that measure creep as the increasing misalinement of a line of marks across the fault, that were either originally straight or of a known original configuration (D, in Table 1). A few other arrays or nets are of the trilateration type as described in *Prescott and Lisowski* [1983] that measure creep using changes in length of fault-crossing lines (T, in Table 1). Many arrays were established and monitored in the 1960s and 1970s by cities and other entities, but monitoring generally lapsed in the late 1970s and 1980s. In the late 1980s and early in 1990s, we recovered many such arrays for this study. We show our results in Table 1 and in Figure 3 we have plotted creep versus time for a selection of the sites having about a decade or more of creep data with multiple surveys. Where multiple surveys were available we calculated the creep rates in Table 1 by linear regression of all data.

Discussion

Although the spatial distribution of creep rate remains qualitatively similar to that shown in *Lienkaemper and others* [1991], the average of all creep rates in Table 1 north of the fast (9 mm/yr) section has generally decreased by about 0.5 mm/yr over the same part of the fault from the previous report (from an average of 5.1 ± 0.9 mm/yr on 31 observations, dropping to 4.6 ± 0.8 mm/yr on 48 observations). Although much of the change comes from improved methodology in analyzing offset cultural features, a significant improvement also derives from having recovered many older arrays, thereby allowing us to determine multi-decade, surveyed creep rates for these locations.

An initial goal of our investigation was to search for evidence of significant variations in creep rate over time. *Lienkaemper and others* [1991] suggested that creep rate on the fault appears to be constant over decades. Other than the effects of LPEQ, our investigation tends to confirm the assumption that creep does not vary significantly with time when comparing periods of a decade or more. At km 43.22 (Rose St, Hayward) we see excellent agreement over many decades. Likewise at km 1.82 and 1.90 (near Point Pinole) agreement is strong over decades. The BART tunnel data (km 20.28) suggests a steady rate over about two decades. Southern Fremont data (km

63 to 67) also tend to support relatively steady creep over many decades. Although the cultural offsets have sizeable uncertainties, they generally support the idea of steady long-term creep rates everywhere on the fault within the limits of computed errors.

Acknowledgments

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Figure Captions

Figure 1. Location of sites yielding creep rates shown in Table 1.

Figure 2. Fault creep viewed transverse to the fault. For offset cultural features [C] and deflection lines [D] in Table 1, we show models of accumulated creep versus distance along feature. Dashed lines show multiple linear regression (MLR) best fit to data. Rectangles or ovals with curved corners indicate surveyed points in the fault zone excluded from the regression. The height of curved boxes also indicate interpretative fits to data, that in a few cases differ substantially from the MLR fit.

Figure 3. Fault creep versus time. Triangles represent observations on alinement arrays. At km 20.28, initial surveys were on a 400-m wide deflection array and later (inverted triangles) on a 90-m wide array (see also Figure 2). At km 44.56 first four surveys were deflection arrays and later data are from angle changes. At km 66.3 (NE curb of Camellia Drive) offset in 1983 from R.O. Burford, unpublished data, 1983.

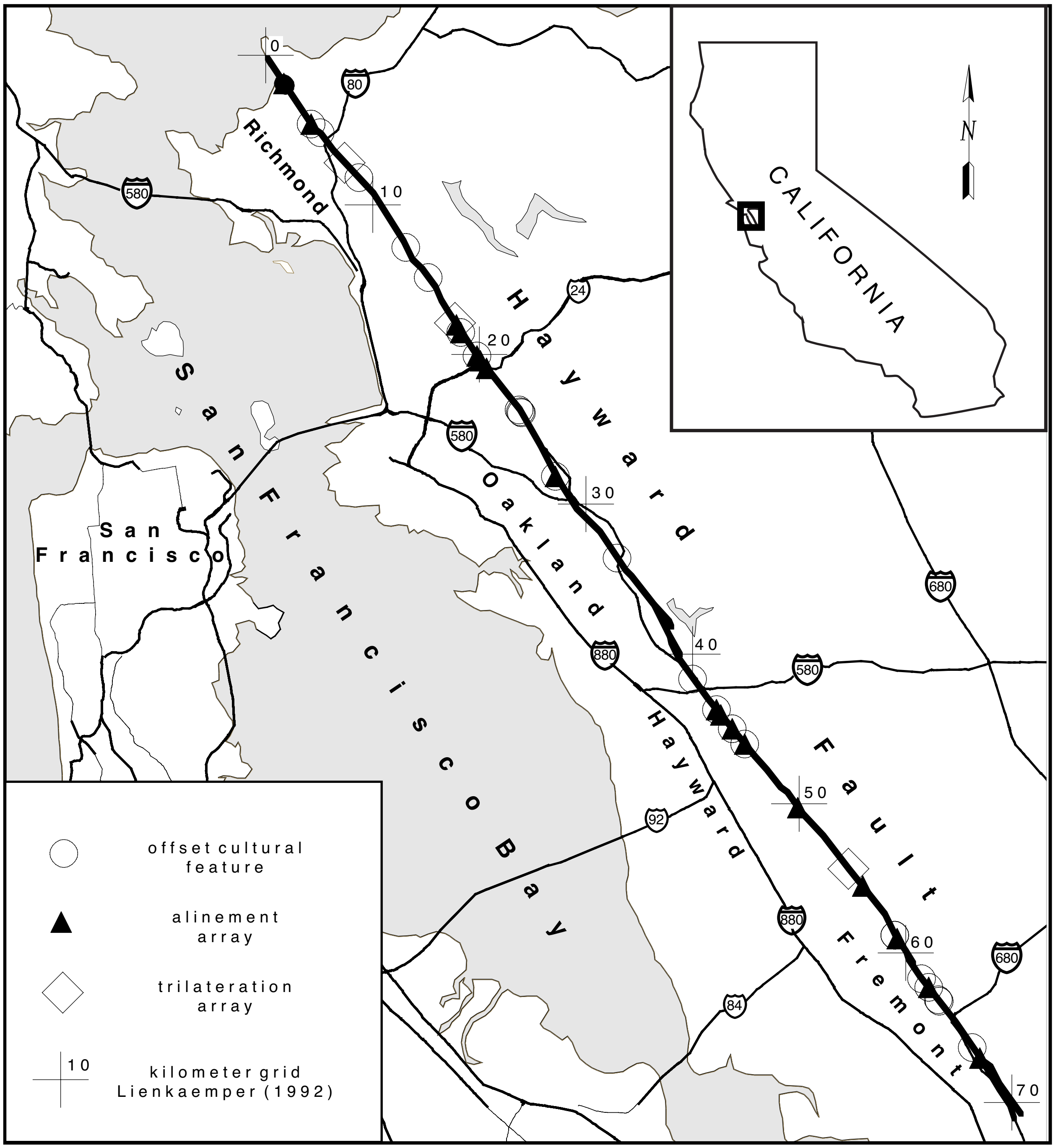
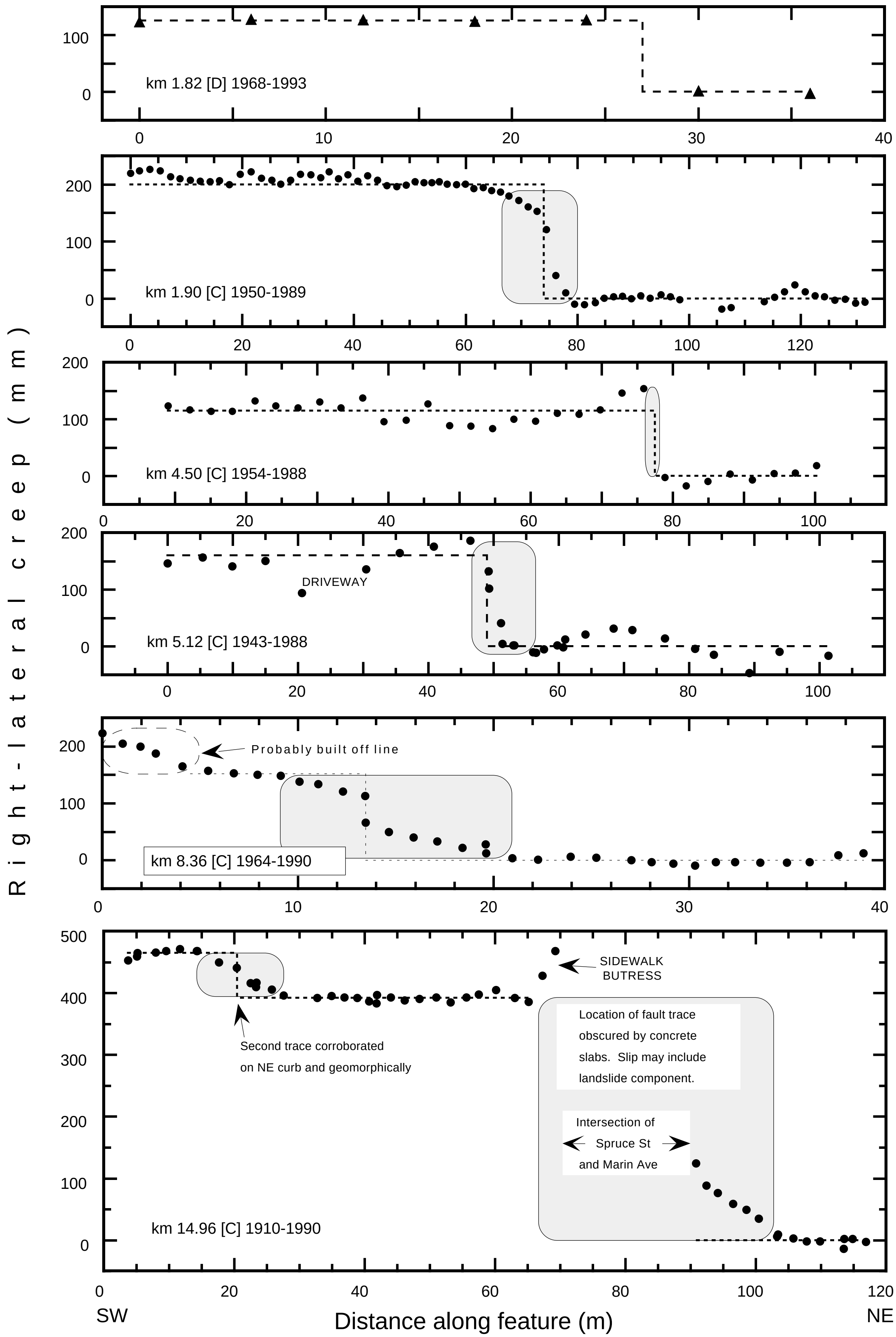

Richmond
Hayward Fault
San Francisco Bay
San Francisco
Oakland
Hayward
Fremont
CALIFORNIA
N
0
10
20
30
40
50
60
70
80
580
24
680
880
92
84
offset cultural feature
alinement array
trilateration array
10
kilometer grid Lienkaemper (1992)

Figure 1



km 1.82 [D] 1968-1993
km 1.90 [C] 1950-1989
km 4.50 [C] 1954-1988
km 5.12 [C] 1943-1988
DRIVEWAY
km 8.36 [C] 1964-1990
Probably built off line
km 14.96 [C] 1910-1990
SIDEWALK BUTRESS
Second trace corroborated on NE curb and geomorphically
Location of fault trace obscured by concrete slabs. Slip may include landslide component.
Intersection of Spruce St and Marin Ave
Right-lateral creep (mm)
Distance along feature (m)
SW
NE

Figure 2

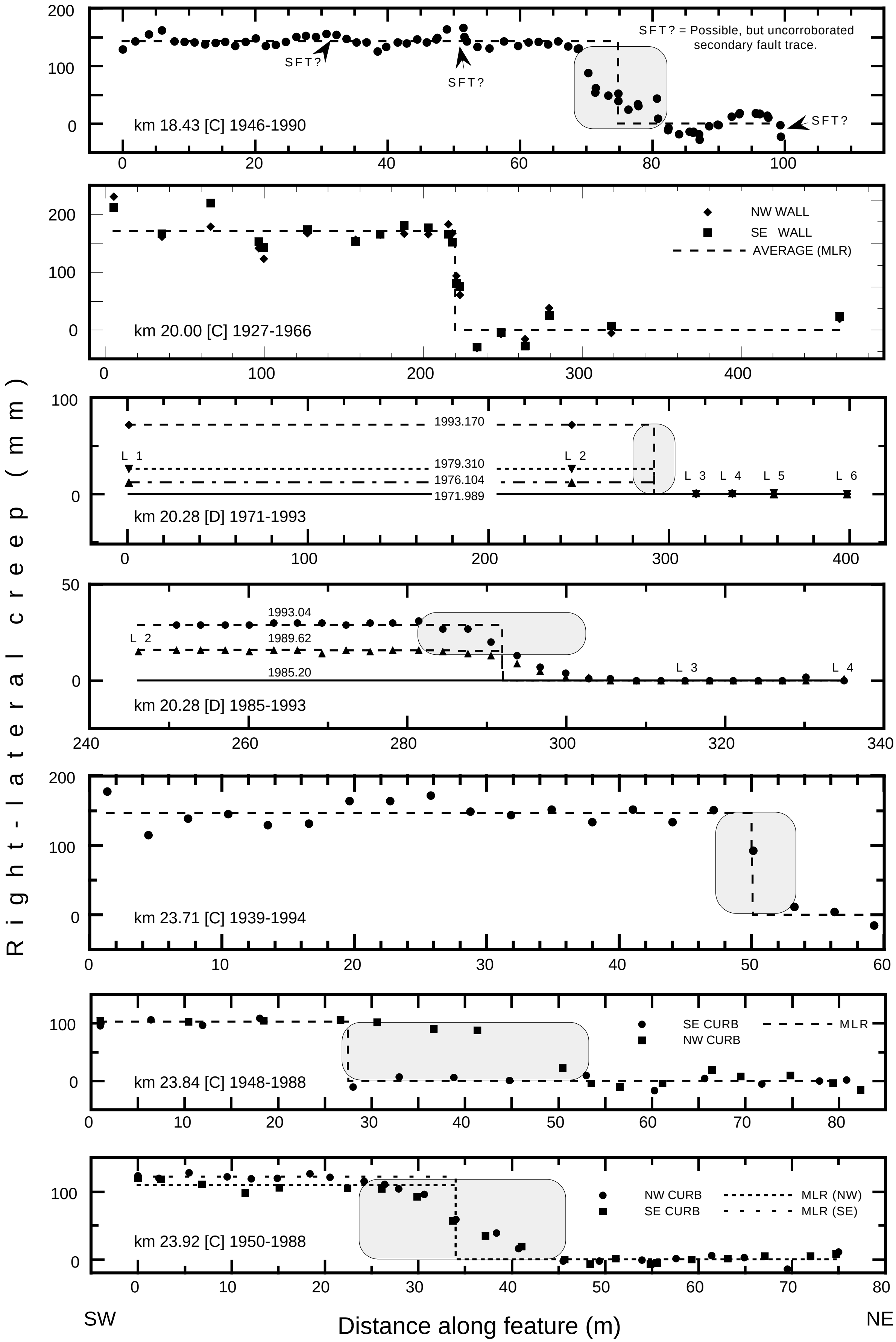


Figure 2 (continued)

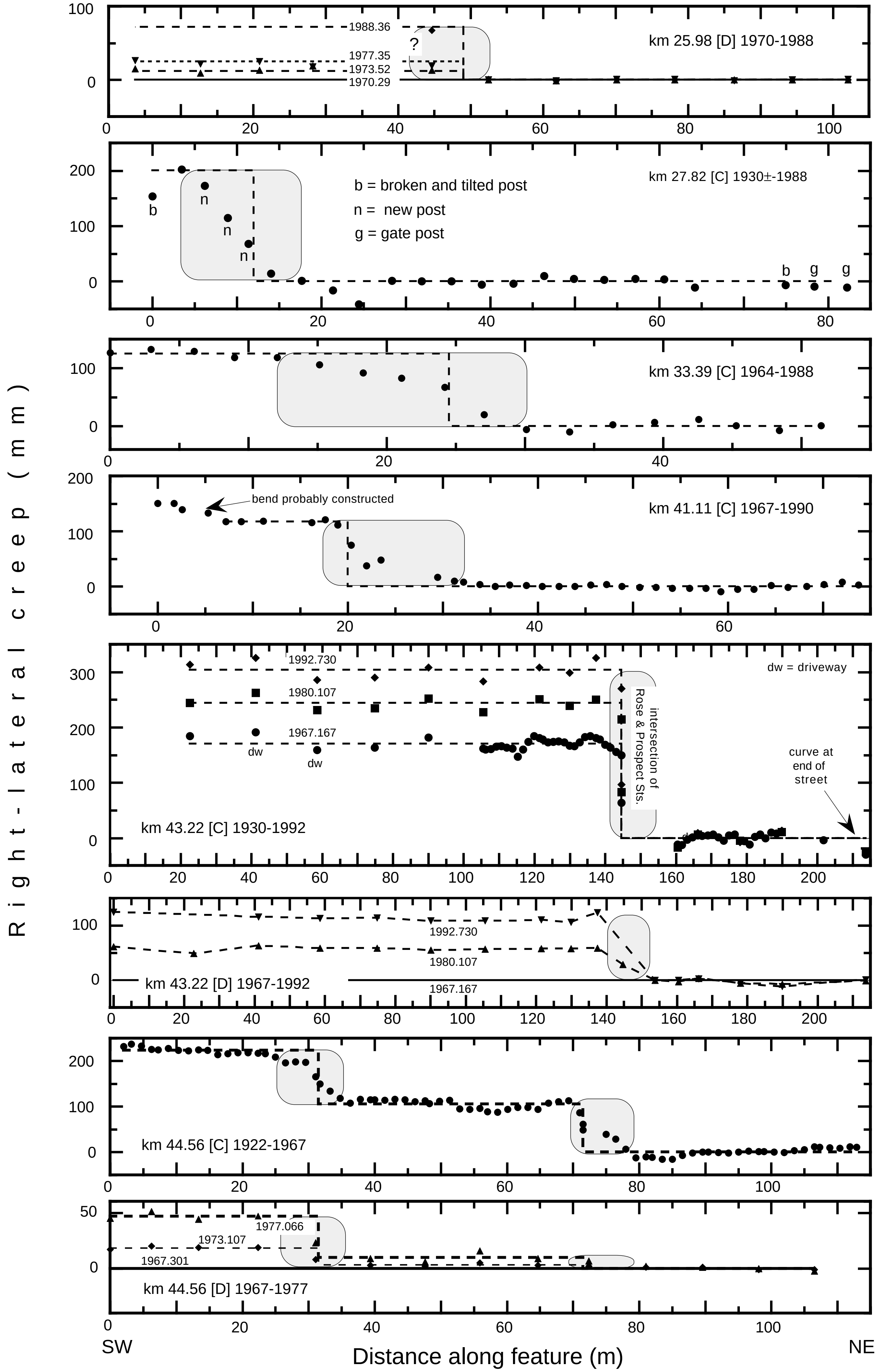


Figure 2 (continued)

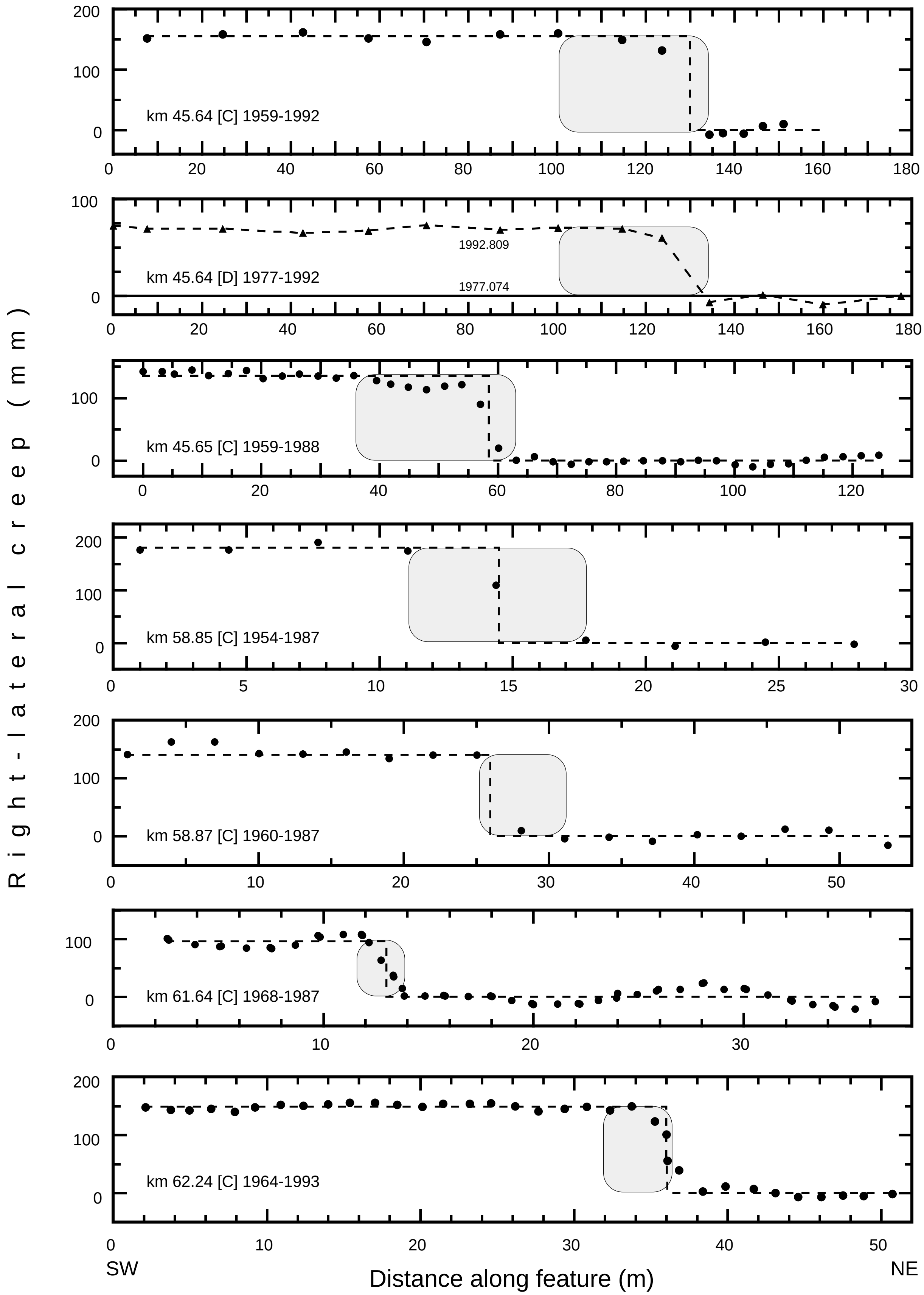


Figure 2 (continued)

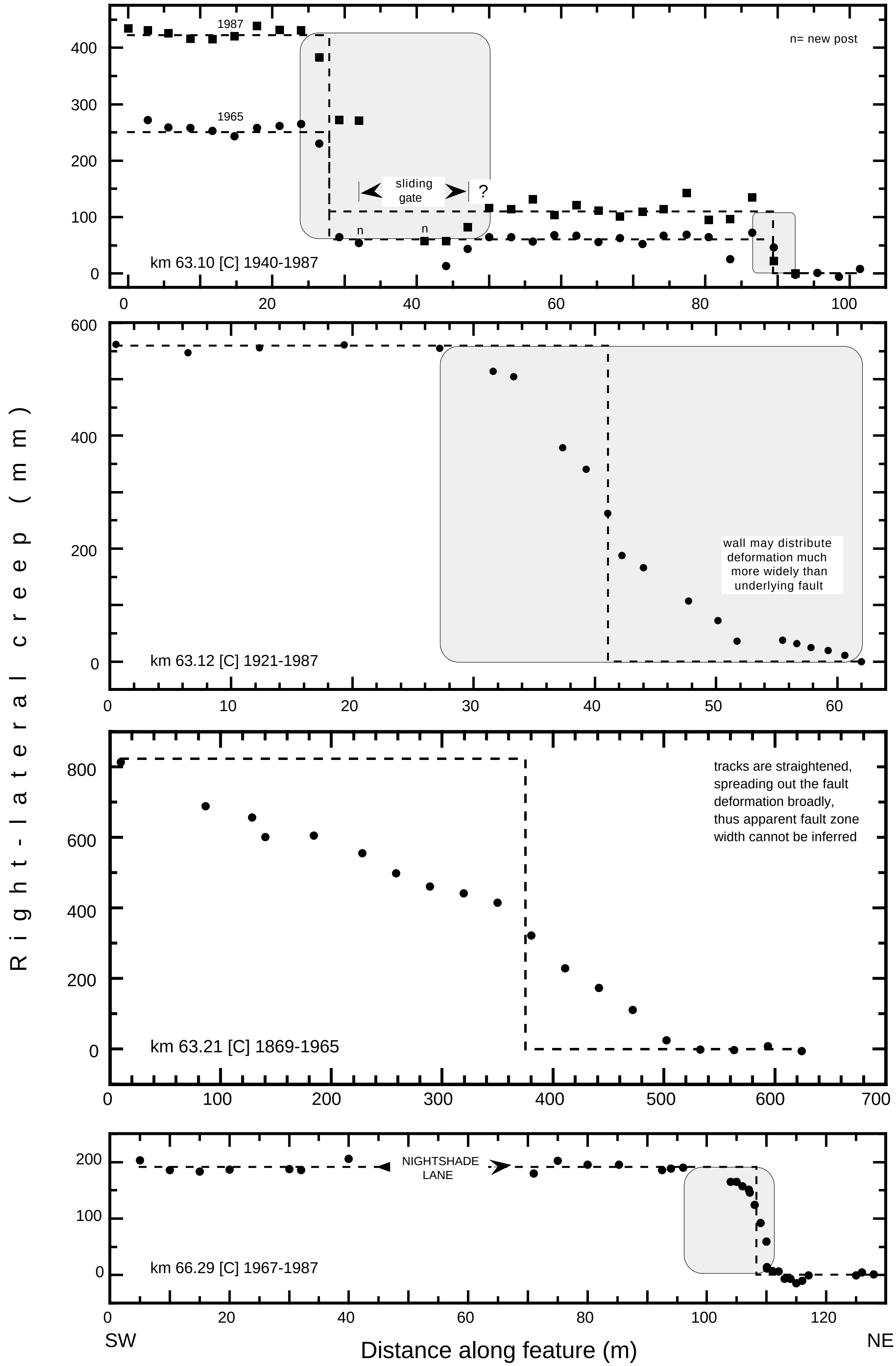


Figure 2 (continued)

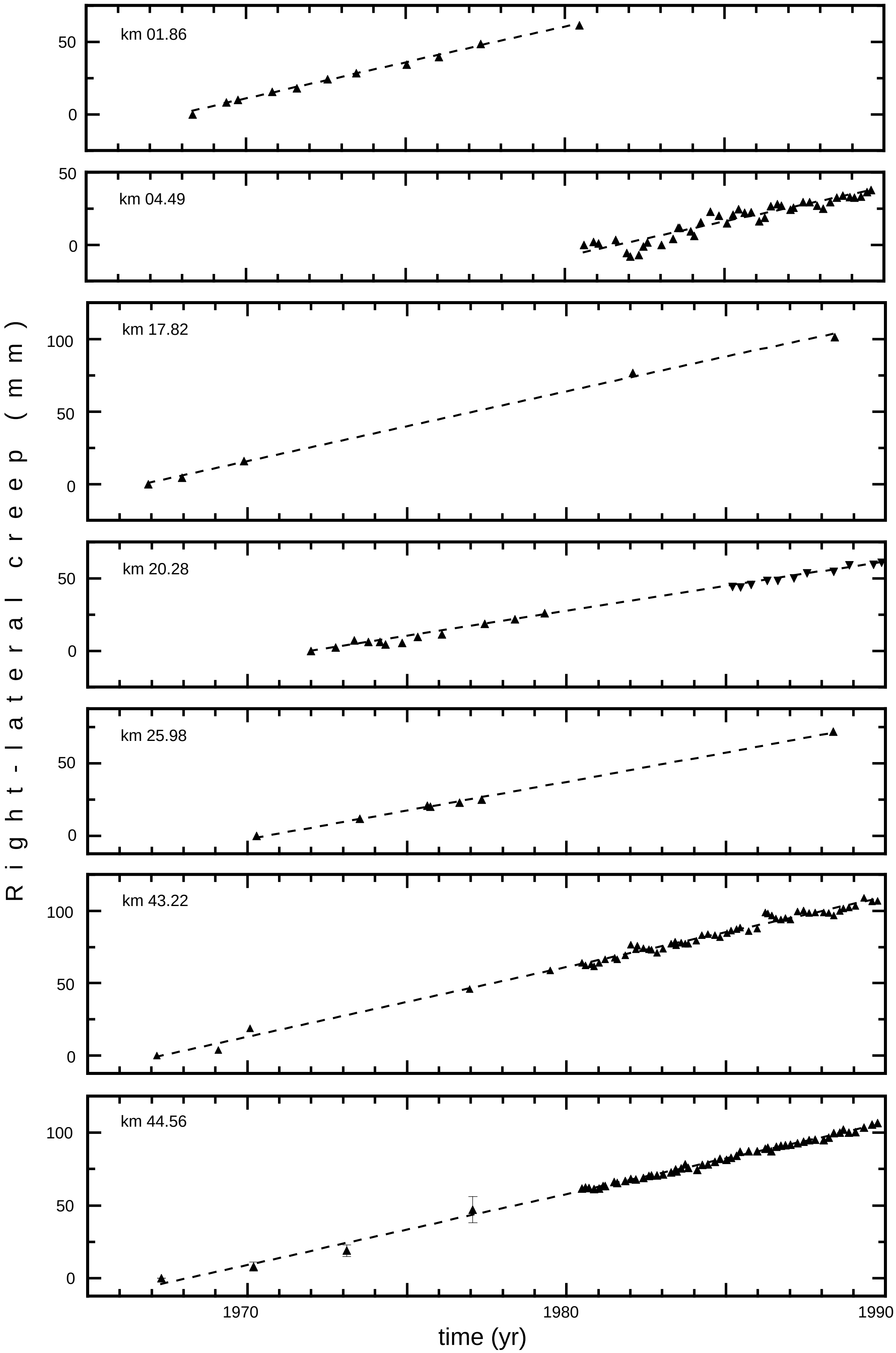

km 01.86
km 04.49
km 17.82
km 20.28
km 25.98
km 43.22
km 44.56
Right-lateral creep (mm)
time (yr)
1970
1980
1990

Figure 3

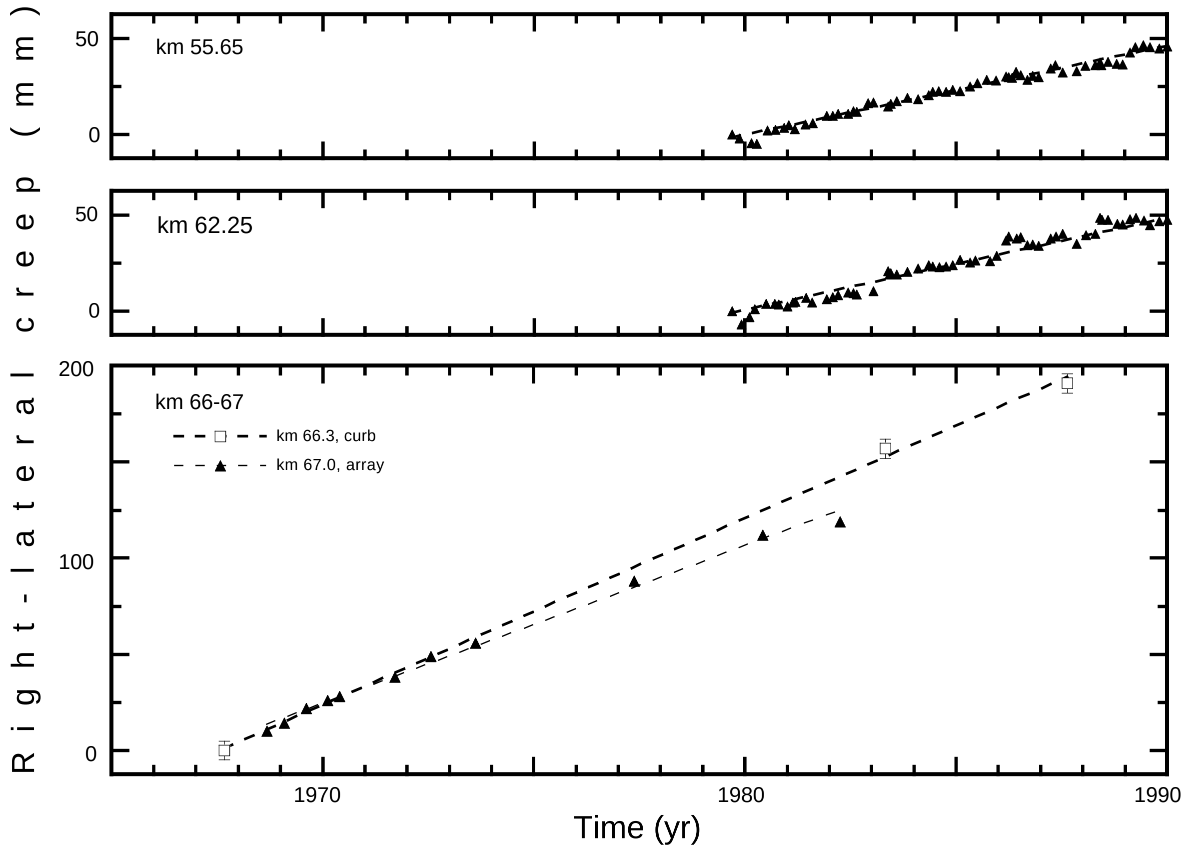


Figure 3 (continued)

Table 1. Right-lateral creep rates on the Hayward Fault

Distance[1] km	Item code[2]	Creep rate mm/yr	±	Item Age yr	Error in age ±	T (initial)	T (final)	Comment[3]
1.82	D	5.1	0.1	25	0.002	1968.333	1993.058	Point Pinole Regional Shoreline (PPRS), USGS (N=2)
1.82	A	5.0	0.3	12	0.002	1968.333	1980.459	PPRS, HB82 (N=12)
1.90	C	5.0	0.2	39	0.5	1950.5	1989.836	Banks Dr, NW curb
4.49	A	4.7	0.3	9	0.002	1980.610	1989.596	Contra Costa College, SFSU #17 (N=42)
4.50	C	4.5	0.6	34	1	1954	1988.415	El Portal School, NW fence
5.12	C	4.4	0.4	45	0.5	1943.5	1988.415	Bowhill Ln, NW curb
7.25	T	5.5	0.3	7	0.1	1975.1	1982.200	RICHMOND net, *Prescott & Lisowski* [1983] (N=10)
8.36	C	5.7	0.2	25	0.2	1964.8	1990.068	Olive Av, NW curb
12.93	C	6.0	1	51	2	1919	1969.96	San Pablo tunnel centerline (600-m spacing); EBMUD
14.96	C	5.8	0.2	80	2	1910	1990.068	Marin Av, SE curb (may include landslide component)
17.82	T	4.7	0.1	22	0.002	1966.912	1988.41	STADIUM net, USCGS & USGS (N=5)
17.97	A	4.9	0.2	19	0.002	1973.271	1992.666	Prospect St, DJR & this study
18.43	C	4.1	1.3	44	0.4	1946.4	1990.068	Dwight Wy, NW curb, ave. of extreme interpretations
18.44	A	3.9	0.8	9	0.65	1983.15	1992.615	Dwight Wy, DJR & USGS
20.00	C	4.4	0.5	39	0.8	1927.3	1966.036	Claremont water tunnel, average of wall offsets, EBMUD
20.00	A	4.6	0.3	5	0.002	1968.142	1973.047	Claremont water tunnel, EBMUD
20.28	D	3.4	0.1	18	0.002	1971.989	1989.620	BART tunnel, south bore; BART & this study (N=22)
20.84	A	3.8	0.3	20	0.002	1974.258	1994.118	Broadway Bl, City of Oakland & this study
23.71	C	2.7	0.3	55	1	1939	1994.115	Montclair Park, SE fence
23.84	C	3.0	0.3	39	0.1	1948.9	1988.361	Medau Place, NW curb
23.85	C	3.0	0.2	39	0.1	1948.9	1988.361	Medau Place, SE curb
23.91	C	3.1	0.2	38	0.1	1950.3	1988.361	La Salle Av, NW curb
23.92	C	2.7	0.2	38	0.1	1950.3	1988.361	La Salle Av, SE curb
25.98	D	4.0	0.1	18	0.002	1970.290	1988.358	Lincoln Av, City of Oakland & USGS, L91 (N=7)
27.81	A	3.7	0.2	14	0.002	1974.274	1988.358	39th Av, City of Oakland & USGS, L91
27.82	C	3.5	0.6	58	9.5	1930	1988.361	39th Av, EBMUD reservoir, NW fence
33.39	C	5.3	0.3	24	0.002	1964.762	1988.361	Encina Wy, SW curb
41.11	C	5.1	0.2	23	0.06	1967.21	1990.107	167th Av, SE curb
43.22	C	5.1	0.3	62	0.5	1930.5	1992.019	Rose St, NW curb; City of Hayward (N=5)
43.22	A	5.0	0.1	25	0.002	1967.167	1992.019	Rose St, City of Hayward & this study (N=7)
43.22	A	4.9	0.1	9	0.002	1980.482	1989.748	Rose St, SFSU #13 (N=55)
43.62	A	5.0	0.2	25	0.002	1968.107	1992.751	Simon St, City of Hayward & this study (N=4)
44.56	C	5.0	0.3	45	0.7	1922.5	1967.5	D-St, NW curb
44.56	D	4.8	0.8	10	0.0	1967.301	1977.066	D-St, deflection nails, City of Hayward
44.56	A	4.9	0.1	9	0.002	1980.479	1989.748	D-St, SFSU #12 (N=55)
44.72	A	4.3	0.3	22	0.002	1971.186	1993.068	City of Hayward & this study (N=4)
45.64	C	4.7	0.2	33	0.5	1959.5	1992.809	Palisade St, NW sidewalk centerline, this study
45.64	A	4.7	0.4	16	0.002	1977.074	1992.809	Palisade St, City of Hayward & this study (N=2)
45.65	C	4.7	0.2	29	0.5	1959.5	1988.454	Palisade Street, SE curb
50.15	D	4.4	0.2	23	0.002	1970.077	1992.866	Woodland Av, City of Hayward & this study (N=5)
54.45	T	5.3	0.3	16	0.5	1965	1981	UNION net, *Prescott & Lisowski* [1983] (N=6)
55.65	A	4.7	0.1	10	0.002	1979.729	1989.596	Appian Wy, SFSU #2 (N=57)
58.85	C	5.5	0.4	33	0.5	1954.5	1987.115	Shinn Station, guardrail (now destroyed)
58.87	C	5.3	0.3	27	0.5	1960.5	1987.115	U. S. Gypsum warehouse, NW fence
59.09	A	5.7	0.8	5	0.002	1983.759	1988.568	Gilbert Av, WB87 (N=9)
61.64	C	5.2	0.3	18	0.2	1968.8	1987.232	Fremont Senior Center, SE curb
62.24	C	5.3	0.2	28	.56	1964.73	1993.041	Rockett Dr, NW curb
62.25	A	5.5	0.1	10	0.002	1979.729	1989.599	Rockett Dr, SFSU #1 (N=57)
63.10	C	8.9	0.3	47	0.3	1940.3	1987.636	Union St, NW fence of warehouse
63.12	C	>8.5	0.3	66	0.9	1921.9	1987.636	Union St, NW wall of warehouse
63.21	C	>8.5	0.6	96	0.1	1869.7	1965.685	Irvington, railroad tracks; Southern Pacific survey data
66.29	C	9.5	0.3	20	0.1	1967.7	1987.636	Camellia Dr, NW curb, L91
67.02	A	8.2	0.2	14	0.1	1968.7	1982.3	South Grimmer Bl, HB82 (N=11)

[1]Distance measured along fault from San Pablo Bay shoreline using *Lienkaemper* [1992]

[2]Codes: A, angle change surveyed across fault. Multiple observations are time regressed; C, cultural feature surveyed. Offset computed by multiple linear regression (MLR); D, Deflection monuments in linear array. Offset computed by multiple linear regression; T, trilateration array. Creep rate derived from line length changes

[3]Comment notes: BART, data of Bay Area Rapid Transit district; analysis, this study; DJR, data of D.J. Russell, written communication, 1992; analysis, this study; EBMUD, data of East Bay Municipal Utilities District; analysis, this study; HB82, *Harsh & Burford* [1982]; analysis, this study; L91, *Lienkaemper and others* [1991]; N, number of observations; SFSU #1, San Francisco State University array number [*Galehouse*, 1995]; WB87, *Wilmesher and Baker* [1987] data; analysis, this study.