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Creepmeters on the Hayward fault

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Roger Bilham

CIRES and Dept. of GeologicalSciences,
University of Colorado, Boulder, CO 80309-0216

303 492 6189 FAX 303 492 2606 email bilham@stripe.colorado.edu

Summary

Along most of the Hayward fault, roads and pipes are repeatedly cracked by surface creep of the fault. There is, moreover, a 67% probability that a train crossing the fault will be derailed by accelerated slip on the fault during an earthquake. We measure ongoing creep at 10 minute intervals to 1/1000 inch accuracy to search for possible precursors to an earthquake, to learn more about the geometry of the creep process and to estimate the reduction in seismogenic strain accumulation resulting from creep releasing plate boundary motions aseismically. At Pinole Park (at the northern end of the Hayward fault) the rate we measure is close to the geological slip rate, suggesting that no earthquake can occur there. In contrast, a slip deficit is developing near its southern end (Fremont) to perhaps fuel a future Magnitude 6 earthquake. Throughout most of the fault the creep process is remarkably linear, a finding that in principal permits the forward prediction of creep and hence the detection of anomalous rates of creep on the fault.

This report summarises the development of a creepmeter system suitable for operation in an urban environment, and in the presence of thick layers of clay. It starts with a brief summary of findings and includes a description of the development of the instruments, which is supplemented by a discussion of the signicance of the creep signal. A manuscript in preparation for BSSA and a GRL article is attached as an appendix.

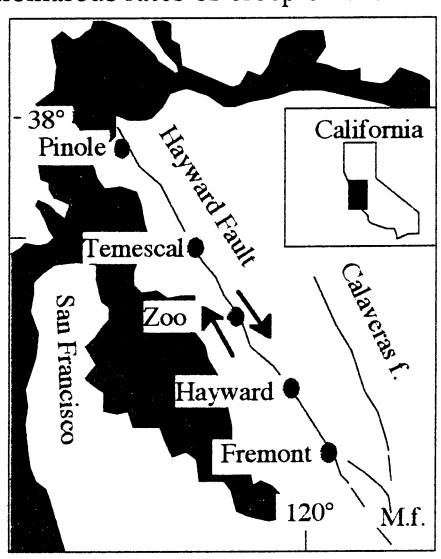


Figure 1 Distribution of Hayward fault creepmeters.

Findings

Creep rates on the Hayward fault increase from 5 to 9 mm/year over a 2 km distance in Fremont, and have done so for the past 130 years. Creep rates elsewhere on the fault, after careful elimination of thermoelastic signals, are remarkably linear at or close to the 5 mm/year rate established by measured offset fences in the past several decades. The most northern creepmeter at Pinole Park measures a 5.76 mm/year creep signal close to the geological slip rate, suggesting that there is no slip deficit there. In contrast an inferred 54 cm slip deficit (equivalent to that released in an M≈6 earthquake) has apparently developed near Fremont, at the southern end of the forecast M=7 earthquake rupture This curious rate change locally stretches the NE flank of the fault and compresses the SW flank are rates of ≈1 µstrain/yr, roughly ten times higher than plate boundary strain rates elsewhere. The inferred >100 µstrain of accumulated strain in Fremont is close to coseismic failure strains observed elsewhere and suggests that a shallow 5<M<6 earthquake may be imminent in the region. The earthquake could possibly trigger a forecast M≈7 Hayward earthquake.

Data

The creepmeter data are published on the worldwide web as 7 day, one month and several year summaries at:
http://quake.wr.usgs.gov/ QUAKES/LOWFREQ/creep/sfbay.html#Creepmeter data
A summary of the project with recent data processing is found at my web page:
http://cires.colorado.edu/~bilham/
Table 1 shows recent creep rates, noise levels and annual thermoelastic strain amplitudes, Figure 2 shows time series following the removal of annual thermoelastic signals, and Figure 3 shows recent data from Fremont.

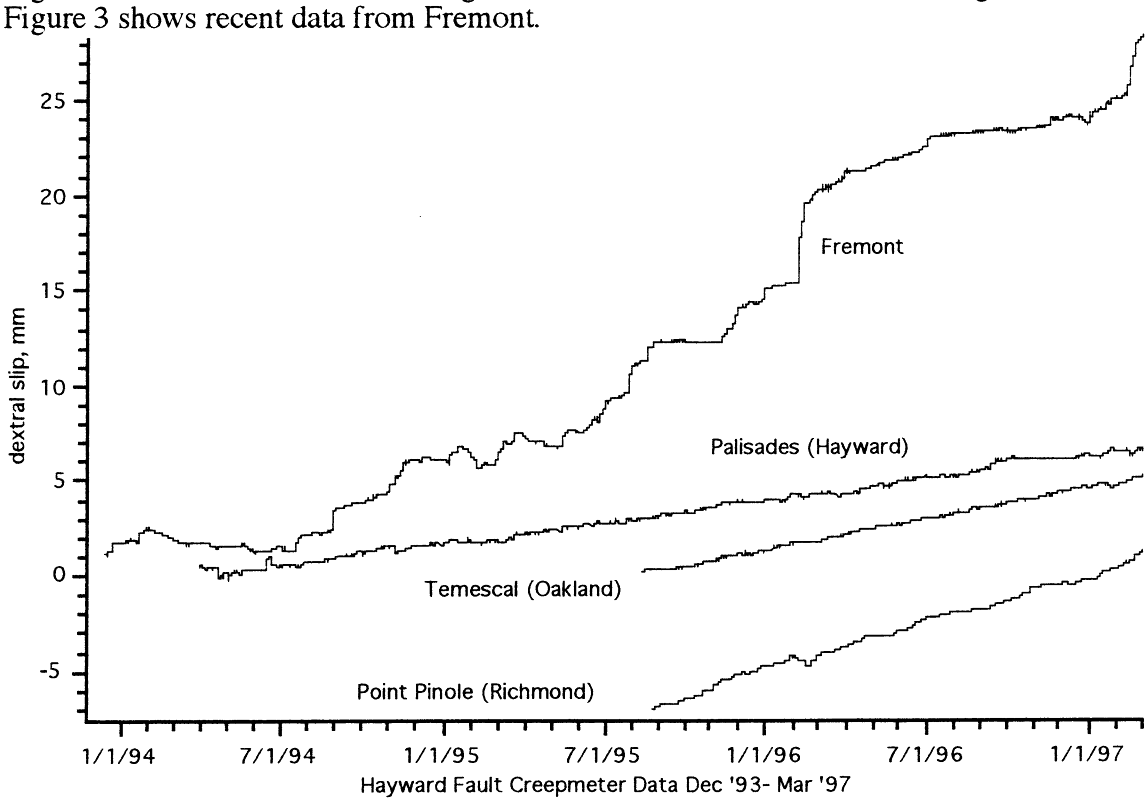


Figure 2 Data from the Hayward creepmeter array (Bilham and Whitehead 1997)

Table 1. Dextral slip rates and annual (sinusoidal) thermoelastic amplitude
The Oakland Zoo creepmeter was installed too recently to analyze for annual terms. The different values listed for Fremont depend on the averaging window and analysis method.

	dextral-creep, mm/yr	annual signal	Residual noise rms
Point Pinole	5.76± 0.05	±0.9 mm	0.2 mm
Lake Temescal	3.75±0.05	±0.15 mm	0.18 mm
Palisades St.	3.23±0.05	±0.25 mm	0.23 mm
Fremont	8.5±1 (7.7±0.3)	±0.9 mm	0.31 mm

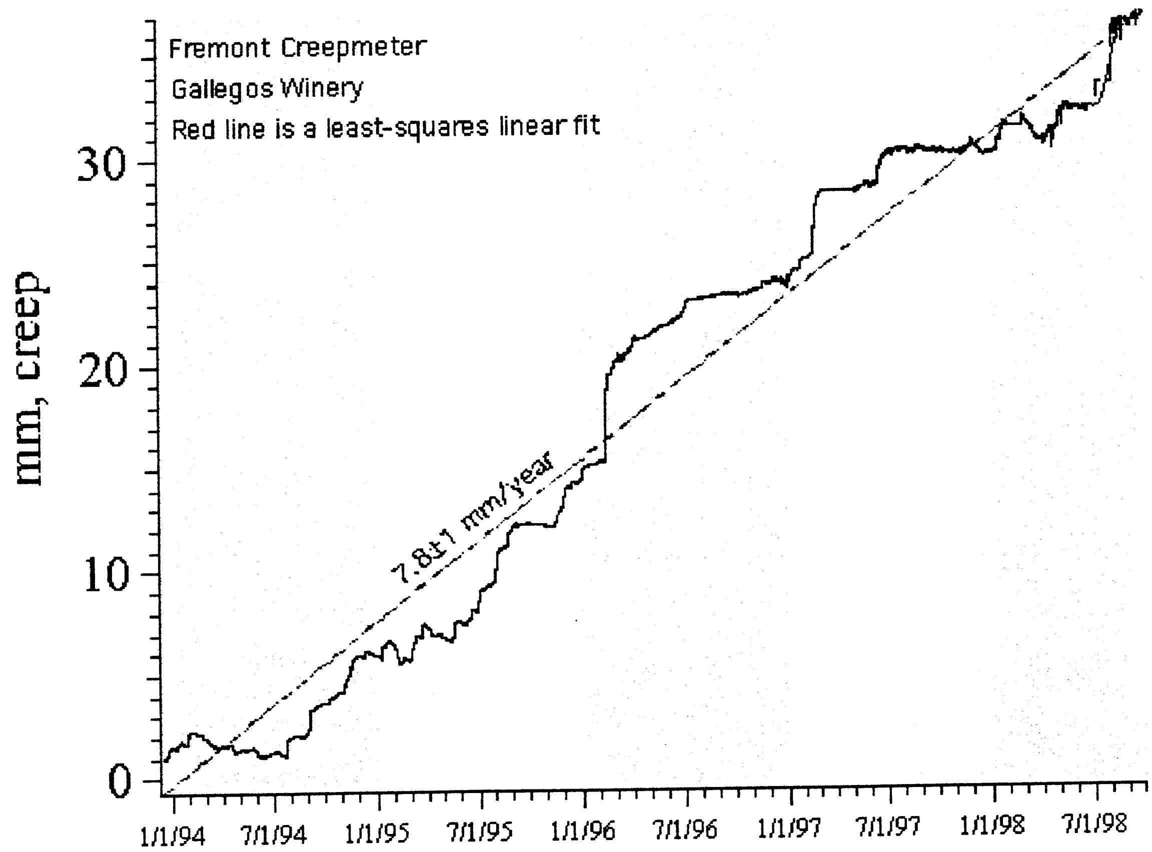


Figure 3 Data to Oct 1998 from the Fremont creepmeter at Osgood Road.

Description of the creepmeters. The mean creep rate on the Hayward fault is 5 mm/year. A creep rate of 5 mm/year is small compared to sources of surface noise in clay rich soils that can exceed 5 mm/day. Thus at the start of the project it was necessary to develop methods to suppress noise in surface creepmeters in clay. The end mounts of some of the creepmeters extend to depths of 30 m and their construction and instrumentation in an urban setting was predictably expensive and time consuming.

The following innovative features have been included in the creepmeters to suppress noise levels. Details are to be found in a manuscript prepared for BSSA.

1. *Floating* length standards: Typically a length standard is attached to the pier on one side of the fault and the motion of the free end relative to the other side of the fault is used to indicate fault displacement. A *floating* length standard lies passively across the fault within a greased tube and the motion of the end piers relative to *each* free end are summed to measure fault slip. This arrangement causes no stresses on the end piers and permits sources of end-pier noise to be investigated independently (Bilham 1977).
2. *Bimetallic length standards* suppress integrated thermal variations at soil depths of 1-2.5 m. An invar rod within a steel tube is rigidly fastened to it at one end and is free to move at the other. The relative motion is measured and used to eliminate thermoelastic instability in the length standard. Given the factor of ten difference in coefficients of linear expansion, and their low second-order coefficients at temperatures near 10°C, an exact temperature correction to the invar length is possible. The signal has no phase delay and is subtracted from the data to reduce thermal signals to less than 0.1 mm/year.
3. *Helical Piers* to 10 m depths in clays apparently provide sub-mm annual stability (Bilham 1977). A tripod arrangement of three helical piers are screwed into Bay Area muds and welded at their upper ends to a 2 inch towing ball to which the creepmeter is fastened. At Pinole where an inclinometer system is installed within the central helical monument we record less than 1 mm of motion over two years.

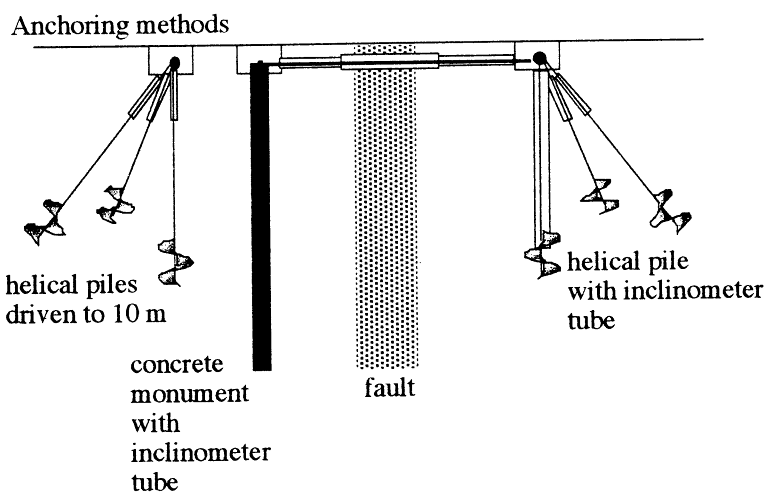
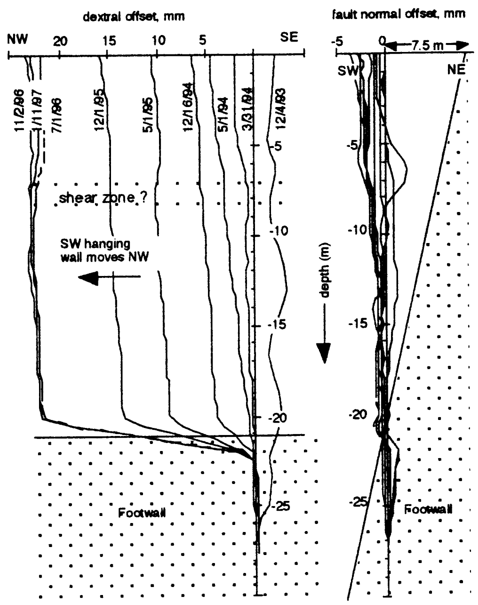


Fig. 4 Three forms of creepmeter anchor. Two involve helical piles (made from 5 cm square steel bar terminated by a propeller) and a third is a concrete pillar with an embedded inclinometer pipe for measuring tilt and deformation.

4. *Vertical tilt* The prograde rotation of the flanks of the fault anticipated to accompany fault creep is measured with borehole inclinometers (1 μrad precision) and is shown to be much greater than that expected from elastic models with locking at 8 km (see Figs. 2 &4). It would appear that creep is locked beneath Fremont at depths of less than 1 km (Bilham and Whitehead, 1997), considerably shallower than the 8-km-depth expected from analytic reasoning based on elastic half space models (Savage and Lisowski, 1995).

Our initial findings leave little slip deficit to drive earthquakes at the northern and southern ends of the Hayward fault, where the creepmeters record recent creep rates that are identical to creep rates recorded in the past few decades, and which are also identical to geological slip rates at these locations. This suggests that coseismic slip does not contribute to long term slip at these two locations.

In contrast, we infer from the presence of continued uneven creep near Fremont, that a curious strain anomaly must be developing near there, and that its amplitude is now sufficient to drive a M≈6 earthquake near Fremont.



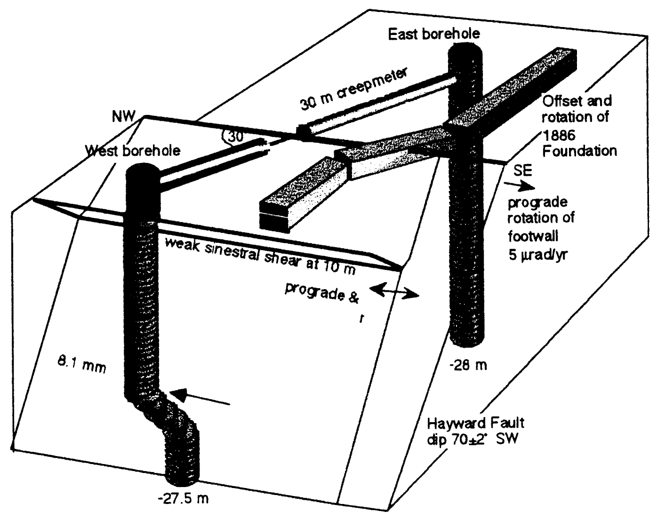


Fig. 5 Schematic Geometry of east and west boreholes in Fremont and sense of deformation. The triple-segmented rectangular object on the surface represents the foundation of the Gallegos Winery that was destroyed by the 1906 San Francisco earthquake and which has been now offset by 90 cm of creep since 1886.

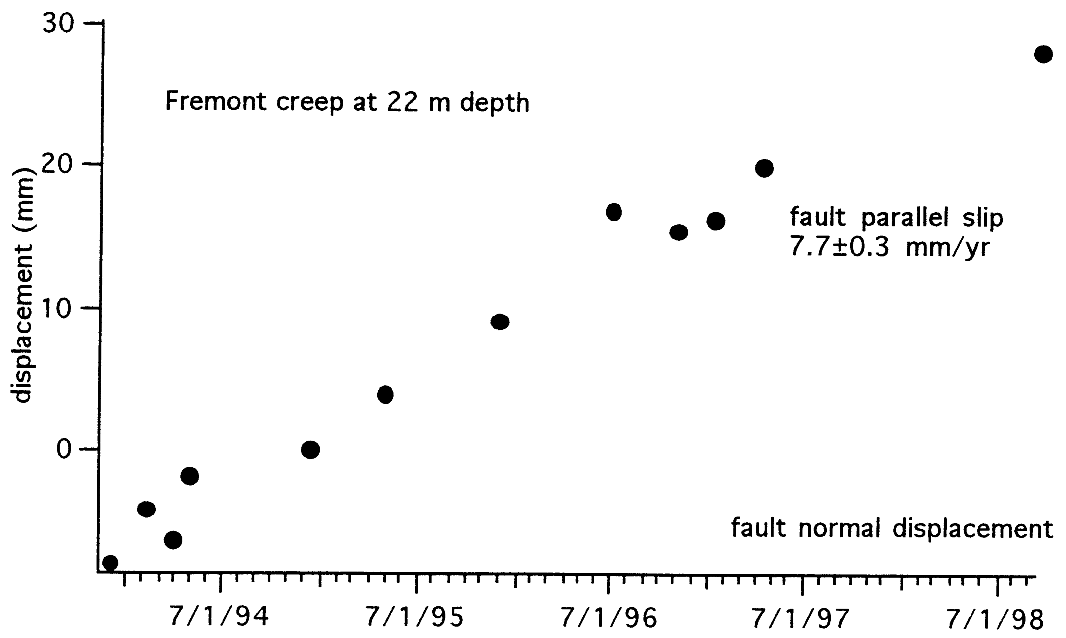


Fig.6 Data from the west borehole at Fremont Dec 93 to Sept 98. The mean offset between lowest 3 m of the hole and the uppermost 19 m of the hole is plotted as a function of time for dextral slip and for horizontal fault-normal motions. A least squares fit to the data is shown with a slope of 7.7±0.3 mm/year.

Discussion

Fault creep is a process whereby a surface fault slips aseismically in response to applied shear stress. With the notable exception of central California, creep on most faults is a shallow process and has little effect on reducing the potential for seismic slip at 2-12 km depths. However creep on the Hayward fault is believed to extend to depths of 5 km, and because the base of seismicity is at 10-12 km, creep effectively reduces the seismogenic width by >40%.

Recent data from the Hayward Fault show that our assumptions about the depth of creep may be incorrect. Inclinometer data from the Fremont creepmeter mounts indicate prograde rotation of the flanks of the fault about a point 100-300 m below the surface, and SAR imagery embracing a creep episode on the southern Hayward fault suggest creep terminating at 3 km depth near Fremont (Burgmann et al. 1998).

These findings can be reconciled with the observed ≈9mm/year creep rate by assuming that creep *events* are active in the shallow portion of an >8 km deep creeping zone (the relation between applied strain, creep rate and creep depth is discussed below), and steady creep occurs below that depth. However, a change in creeping (locking) depth from 8 to 5 km conflicts with the observed abrupt change in creep rate *along* the fault that demand a shallow (e.g. 3 to 1 km depth) origin for the depth of the transition. The along fault creep rate changes from 5 mm/year to 9 mm/year over a distance of less than 2 km, *and this rate has apparently existed since the 1868 earthquake,* because structures offset by the earthquake have been measured periodically since then (Lienkaemper et al, 1995).

The slip rate change implies an along-strike linear strain increase of approximately 1 μstrain/year, confirmed by the development of Stuivers Lagoon, a sag pond that now underlies the artificially maintained Lake Elizabeth. The 9 mm/year creep rate on the southern Hayward fault is equal to the inferred geological slip rate on the fault.

Three concerns about the seismic hazard potential of the Hayward fault emerge from these observations. The first two follow from our ignorance of the mechanisms of accelerated creep in Fremont, the other admits alarm at the apparently dangerously high level of strain developed in Fremont.

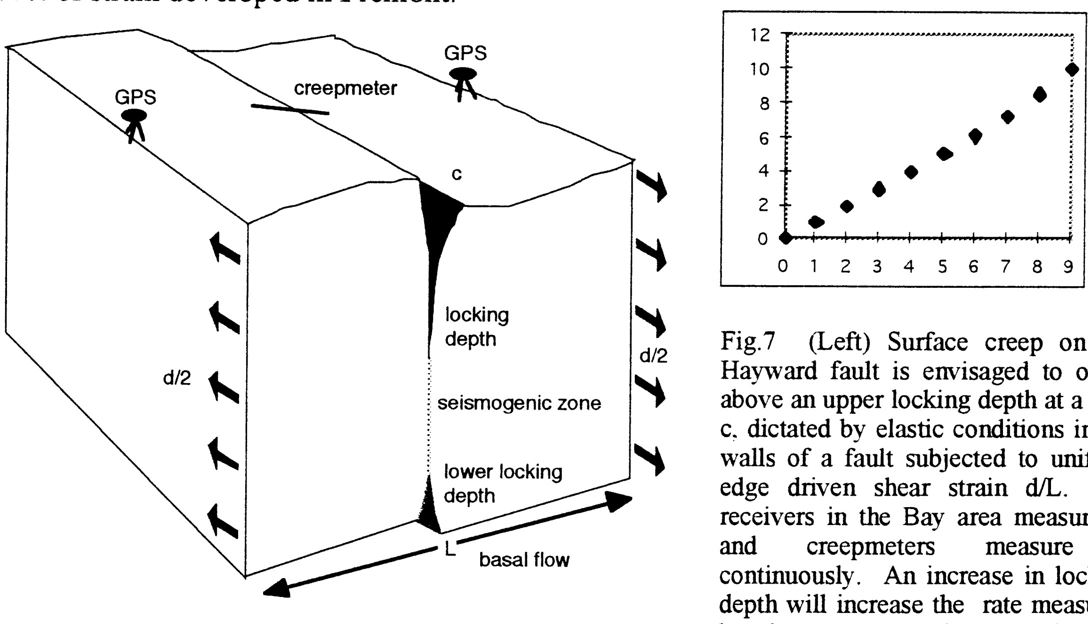


Fig.7 (Left) Surface creep on the Hayward fault is envisaged to occur above an upper locking depth at a rate, c, dictated by elastic conditions in the walls of a fault subjected to uniform edge driven shear strain d/L. GPS receivers in the Bay area measure d, and creepmeters measure c continuously. An increase in locking depth will increase the rate measured by the creepmeter but not the rate measured by the GPS array. An increase in shear strain rate would be measured by both GPS geodesy and the creepmeter.(Right) Creep rate (mm/yr vertical axis) vs creep locking depth (km, horizontal axis) appropriate for Hayward fault model given observed geodetic stressing rate (Savage and Lisowski, 1993).

1. **Shallow creep at rates equal to the inferred long term slip rate?** Only in central California does the long term slip rate on the fault equal the surface creep rate and this only in the central 25% of the creeping fault. An abnormally high applied shear strain (locally exceeding the 9 mm/year geodetic rate) may be present in south Fremont driven by some fraction of the Calaveras fault slip budget transferred across the Mission Hills from the Calaveras fault (Bilham and Bodin, 1992). This is not evident in the current GPS measuring systems in the Bay Area which are of low spatial density. Additional displacement data to distances of up to 5 km from the fault are needed if we are to reveal the subsurface mechanisms involved (Fig.2).

2. 3D creep processes and maximum credible earthquake If creep does not extend to the currently accepted 5 km depth (Savage and Lisowski, 1995) but to 2 or 3 km depth instead, the seismogenic area of the Hayward fault may be 10-20% larger than believed hitherto (Fig. 2). This would raise the maximum credible earthquake by perhaps 0.2 magnitude units (e.g. to M7.4), with a corresponding increase in surface accelerations. To explain the high rate of creep near Fremont contiguous with rates that fall to half over distances of a few km, requires a more complex mechanism for shallow creep than has been proposed hitherto. Recently, we discovered that the fault in Fremont dips at 75° to the SW (Bilham and Whitehead, 1997), implying that 2D models of fault creep are of limited value. 3-D dislocation modeling can attempt to explain the observations but if they are to be meaningful they should be tightly constrained by off-fault displacement data, which currently do not exist in the region.

2. **130 µstrain near the Hayward fault in Fremont?** As a result of 40 cm of accumulated differential fault displacement between north and south Fremont, the minimum along-fault strain that has developed since the 1868 earthquake is 130 µstrain. (Fig. 3) It may in fact be more than this, and is certainly the cause of the M>4 events that have occurred at depth near here. However, the surface fault is evidently close to elastic failure conditions, 100 µstrain being the condition commonly observed to accompany coseismic slip. However, the actual strain may exceed 130 µstrain if rheologies are heterogeneous. The abrupt change in creep rate of 4 mm/year in south of Fremont Town Hall is assumed to have developed symmetrically across the fault, that is, ±2 mm/year on each fault flank. The absence of elevated topography on the SW side of the fault, and the development of a pronounced sediment-filled sag pond on the NE side of the fault (Bilham and King, 1986), suggests that elastic strain accumulation is not a symmetric process. It is possible that tensile surface strain now exceeds 200 µstrain near Lake Elizabeth.

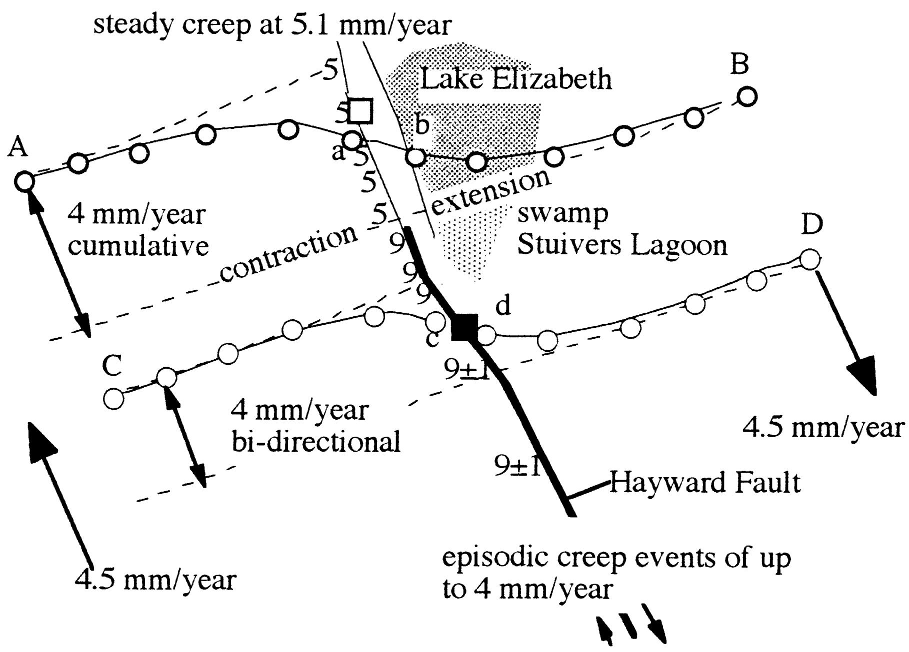


Fig. 8 Sketch of 10 km of the Hayward Fault in Fremont where creep rates approximately double. Two strands bound a horst near Fremont City Hall (Open square, 50 cm of slip since 1868).). Small circles= hypothetical GPS control-points. Filled square = Gallegos winery creepmeter (90 cm of slip since 1868). A depression (shaded) coincides with the region where 20-40 cm of extension has occurred. The Loma Prieta event caused this part of the fault to slip left-lateral and then lock for 4 years. Slip resumed in 1993 on the creepmeter and was captured by SAR imagery (Burgmann et al. 1998). The fault-normal scale of the arc-tan function for AB and CD deformation is unknown. We plan to install a GPS array in the area bBAa extending 10 km east, and a radar line near bB.

Maintaining the Hayward creepmeter array

It is considered important that creepmeters be maintianed indifinitely because they form a fundamental element of a creep-rate alarm system (http://quake.wr.usgs.gov/QUAKES/LOWFREQ/creep/sfbay.html#Creepmeter data). The maintenance of the creepmeters is not competitive with innovative science, nor does it pretend to be. Notwithstanding the lackluster nature of monitoring creep, it would be irresponsible to ignore this important manifestation of active tectonics in view of USGS responsibilities to the several million people that live on the fault. For example, consider the possibility of not recording an hypothetical 3 cm/day creep signal on the fault in the few days preceding a damaging earthquake. The chances of this occurring are slim, but the seismic, geodetic, and geological investment of the USGS in the Bay Area hazards program is gigantic compared to the costs of *maintaining* the creepmeters which, after all, monitor the most visible manifestation of activity in the region. Collaborators in Menlo Park (Jim Lienkaemper, Doug Myren, Vince Keller, John Langbein and Malcolm Johnston) consider the creep signal a high priority for measurement. The PI, however, would be content to transfer this component of the program to Menlo Park.

Perhaps the most appealing reason for maintaining the creepmeters is that we have established that creep rates (except at Fremont) are remarkably linear. This means that we are now in a powerful position to *recognize* anomalously fast creep, such as is alleged to have preceded the 1966 Parkfield earthquake by 11 hours. We would recognize a significant rate change in a less than a few hours (the creepmeter array samples every ten minutes via satellite), but a similar signal might elude Jon Galehouse's NEHRP triangulation arrays because they measure several Bay Area faults at many month intervals.

If creep is to be measured anywhere, this is the fault it on which it can be justified. People have a habit of calling Menlo Park and inquiring about anomalous slip. The creepmeter array permits informed answers. The corollary, however, of the currently well behaved linear performance of the northern fault is that perhaps it will continue to be well behaved indefinitely, and can be equally well be measured using triangulation methods. This decision should be based on the probability of anomalous slip occurring late in the earthquake cycle. Since we have no data to indicate that anomalous slip will, or will not occur, the sensible option is to operate the array until the next large earthquake.

Potentially the creep signal contains intriguing time-dependent clues about stresses applied to the fault: both shear stress and normal stress. Anomalous changes in creep rate can occur because of a physical change in friction on the fault or because of a change in shear rate applied to the fault. The change in friction could be physical (e.g. fluid or chemical changes) or could be caused by a change in fault-normal stress. Creep anomalies as a result are ambiguous. If the depth of creep remains constant, creep rate is a proxy for *shear strain* rate applied to the fault. If the shear strain rate remains constant, variations in creep indicate changes in fault zone friction or normal stress variations. In principle, because the northern creep signal-to-noise ratio is 25:1(0.2 mm in 5 mm), the three northern creepmeters can detect 4% changes in *annual* applied shear strain rate, which is approximately 5-10 times more precisely than can GPS geodesy in the region (3 mm noise, 5 mm annual signal), but the creepmeters alone would be unable to distinguish between locking-depth changes and applied strain-rate changes. *In conjunction with GPS* it is possible to distinguish between these two effects. Perhaps variations in fault-normal and fault-parallel strain signals influence fault behavior. We plan to combine GPS and creep data to establish noise levels in estimating locking depth stability over 6-18 month periods (GPS data are accurate to not more than about 3 mm horizontally so shorter time windows are too noisy given a 5 mm/year signal).

Speculations about spatial creep acceleration/deceleration in Fremont

In contrast to the northern Hayward fault, creep near Fremont is episodic, faster and more complex. One interpretation of the data is that we observe the same 5 mm/year creep signal as we do elsewhere on the fault, but that, in addition, we observe a 4 mm/year episodic component superimposed on this signal.

But why does slip on the Hayward fault increase in rate southward near Fremont Town Hall? The rate almost doubles over a distance of 1-2 km, which it has been doing steadily for more than 130 years (Lienkaemper et al. 1991). A minimum estimate for the consequent strain increase is 1 μstrain/year based on the 4 mm/year increase in slip observed here. Thus unless dissipated in some other way, fault parallel strains have now reached a minimum of 130 μstrain on each side of the fault. Tensile strain exists to the NE and contraction on the SW. It is also possible that much of the strain is to one side of the fault. These levels of strain are close to, or exceed, those released in the epicentral regions of many earthquakes. Could this location be near the nucleation zone of a Hayward fault earthquake? The southern segment of the fault has been assigned a >20% probability for failure in the next 30 years (Working Group, 1994), and appears to be a likely location for rupture initiation (Bilham and Whitehead, 1997).

Confirming persistent tensile strain development adjoining the fault to the NE is Lake Elizabeth centered on the former location of a sag pond, known on early maps of Fremont as Stuiver's Lagoon. The fault-splays near lake Elizabeth have been trenched by Pat Williams and others who find that slip on the NE trace degenerates into a drape fold dipping to the NE as it passes southward. Accelerated fault slip is taken up by a second trace stepping to the west.

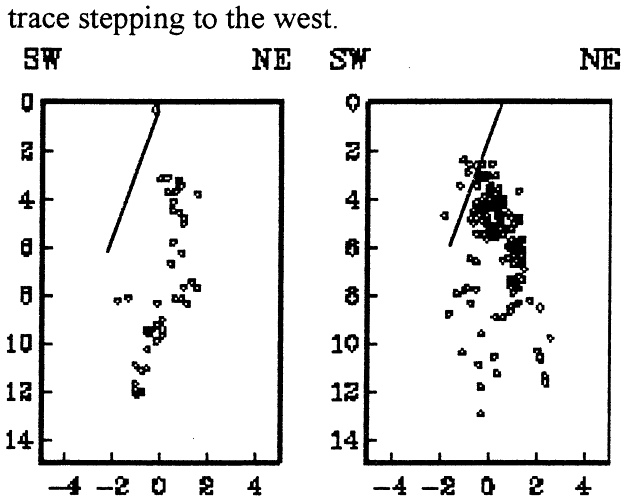


Fig. 9. Seismic sections across the fault from 10-km-north and 10-km-south of the Fremont creepmeter with the observed dip of the fault in red (Bilham and Whitehead, 1997)

The 'conventional' explanation for a change in fault slip-rate is that the fault is locked to a depth of approximately 4.5 km along the northern fault and to a depth of roughly 8.5 km along the segment south of Fremont (see Figure 3). However, this is inconsistent with the <2 km distance over which fault slip rates change at the surface. Simple models show that a patch 4.5-8.5 km deep is expected to show rate changes distributed over a >5 km along-strike distance. Burgmann et al. (1998) argue that an abrupt termination of slip occurred near Fremont when fault slip caught up following creep quiescence following the Loma Prieta earthquake, but although the SAR imagery on

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which this was based are too noisy to yield details of the structure, they do suggest that slip extends to depths of at least 3 km.

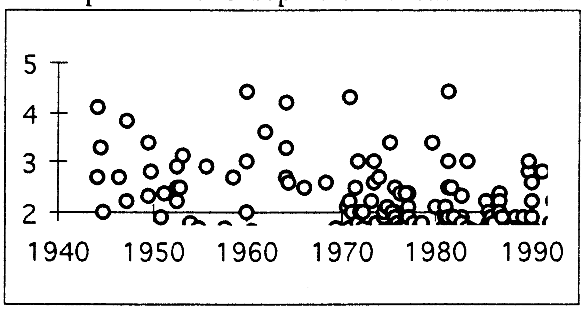

Fig. 10 Earthquakes in a ±0.3° area centered on Lake Elizabeth, Fremont, 1940-1998. Seismic moment accumulation in this volume (based on observed strain rate) is equivalent to an M4 earthquake each year. The rate of occurrence of these events is ten times less. The cumulative moment is equivalent to an M6.

Possible questions related to the observed change in creep rate include:

i. Is the change in creep rate spurious? Were the rate change distributed over the entire 5 km length of the horst stepover in Fremont the Savage and Lisowski model would be acceptable, and the accumulated strain at an acceptably low level (<50 μstrain since 1868). The data on creep rates are sufficiently reliable and spatially dense for this to be refuted.

ii. Has the inferred local strain development been dissipated in small local earthquakes? The total shear displacement developed in Fremont is 4 mm *130 = 52 cm. If this were released on a patch 2 km on a side it would be equivalent to a 5<M<6 earthquake. Actual seismic release is closer to one M4.7.

iii Is creep in a normal faulting sense occurring on an east-trending fault beneath Lake Elizabeth. Aseismic slip on an unmapped splay fault to the east would release the inferred strain change as subsidence, and could perhaps be linked to slip on the Mission Hills Fault.

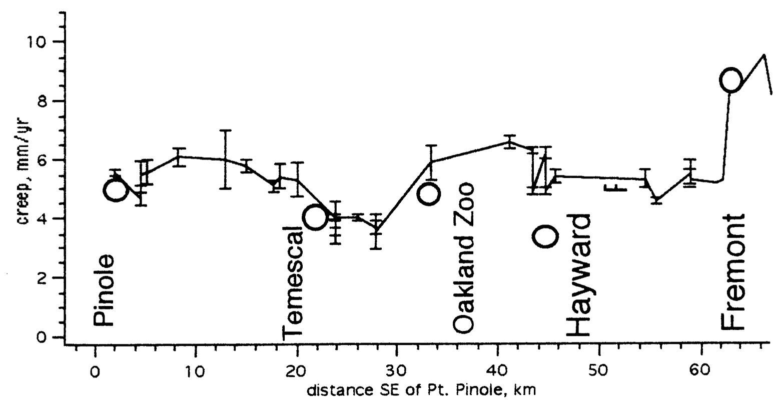

Fig.11 Slip rate along the fault from offset curbs etc (Lienkaemper & Gale-house data) and creep meter data. The Hayward result is low because the creepmeter incompletely spans a second trace of the fault.

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APPENDIX: ARTICLE TO BE SUBMITTED TO BSSA

CREEP AND FAULT ZONE-DEFORMATION ON THE HAYWARD FAULT, CALIFORNIA, MONITORED BY A NEW CREEPMETER ARRAY

Roger Bilham

CIRES and Dept. of Geological Sciences, University of Colorado at Boulder

Abstract. Creep rates on the Hayward fault average 5.5 mm/year except at the southern end of the fault near Fremont where creep locally exceeds 8.5 mm/year. Five new creepmeters have been installed to monitor creep remotely, and to provide an immediate measure of coseismic slip of up to 2 m should this occur. The creepmeters are 30-m-long and consist of invar and/or glass-fiber rods that cross the fault at 30°. They are anchored to each side of the fault zone in heavy clays and silts by steel, helical-screw piles to <10 m depth, and/or vertical pillars equipped with borehole-inclinometer linings to <30 m depth. Measurement precision is ≈ 2 μm over a range of up to 2 m, and data are telemetered to Menlo Park every 10 minutes. Rainfall is manifest as a transient displacement signal at some of the sites with a duration of less than 10 days and an amplitude less than 1 mm. The annual thermoelastic signal at each site is approximately sinusoidal, has an amplitude of less than 2.5 mm, and is apparently reproduceable at each site. When this is removed from creep data the residual creep data exhibit RMS noise levels of approximately 0.2 mm. In contrast to the linear creep signal observed along most of the fault, the creep rate at Fremont averages 8.5 mm/yr with a significant contribution from episodic creep events. Recent creep rates at Point Pinole and at Fremont at the north and south ends of the fault are similar to the geological slip rates observed at these locations suggesting that surface earthquake ruptures are confined to the central part of the fault.

Introduction

The Hayward fault is one of three sub-parallel dextral fault zones active within the San Andreas system in central California. It can be traced at a mean strike of N35W for a distance of 80 km from a releasing bend beneath San Pablo Bay to south of Fremont, where the locus of recent and geological slip is transferred east to the Calaveras fault via the Mission Fault. Microearthquakes occur near the fault to a depth of 12-13 km. Creep on the Hayward fault occurs both below and above a locked seismogenic zone. The deep slip rate below 12 km is estimated to be 9 mm/yr based on the offset of geological