"Continued Measurement of Fault Creep in
the San Francisco Bay Area, and Continued Measurement of Creep and
Long-Baseline Deformation in Southern and Northern California"

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Final Technical Report

Investigations Undertaken 2003-2007

The report describes surface slip 2003-2007 recorded on the Hayward fault in the Bay area, and from other creepmeters on the San Andreas fault in central California and from the Coachella Valley in Southern California (see Fig. 1). Creep at numerous other locations are recorded by USGS and are not reported here.

The Hayward array data are telemetered and available at the USGS Bay Area monitoring site, but in addition we maintain an array of autonomous data loggers in case the USGS telemetry is interrupted. In addition we have initiated telemetry at other sites to permit real-time monitoring of creep in central and southern California (Table 1). Only two of these sites are operative on the Hayward fault but we plan to complete the backup telemetry starting in June 2007.

Figure 1 Location of creep-meters data from which are presented in this report. SJB=San Juan Bautista. Data may be downloaded by clicking on the appropriate creep meter on a web page displaying this same map.

Results. This report first summarizes in tabular form (Table 1) noise levels and creep rates from all thirteen creep-meters. We next describe the creep-meters with a graphical summary of their data. The creep measurements are described from north to south. Data from the Hayward array are first presented. Findings from the Parkfield earthquake follow. The report concludes with data from the southern San Andreas fault including a most unusual 28 mm amplitude creep event on the Superstition Hills fault. Additional data and numerical listings are available on the web at http://cires.colorado.edu/~bilham/CREEPDATA/HaywardCreepmeterAccess.htm and http://cires.colorado.edu/~bilham/creepmeter.file/creepmeters.htm

Table 1. Summary of creep rates and noise levels. **Telemetered sites are shown in bold type.** Columns 5 and 6 indicate the seasonal noise level peak-to-peak, and the random noise level RMS respectively. Note the creep rate on the Superstition Hills Jan-Apr 2006 following the 27 mm amplitude November 2006 creep event is twice its 2003-2006 rate. CoWR and coWT were discontinued in 2006.

Site	Location	Rate mm/yr	± mm/yr least-sq.	Annual mm	Random mm	Linear=L Events=E
cpp	**Pinole**	4.9	0.1	1	0.5	L
ctm	**Temescal**	3.5	0.1	0.5	0.25	L
coz	**Oakland Zoo**	3.1	0.1	2.5	1	E&L
chp	**Hayward**	4.8	0.1	3	1	L
cfw	**Fremont**	6.6	0.1	2.5	1	E&L
coNR	**Nyland**	9.3	0.2	4-5	3	E&L
coWR	WorkRanch	40	afterslip	3	1	log & E
coWT	Water Tank	1	0.3	2	1	E&L
co46	S. Parkfield	1	0.3	2	1	E&L
coFE	**Ferrum**	3.3	0.3	2	0.2	E&L
coSC	**Salt Creek**	1.5	0.3	1	1	E&L
coDU	Durmid	1	0.3	2.5	0.3	E&L
coSH	**Superstition Hills**	1.35 pre'06 3.22 '07	0.3 0.1	0.5	0.2	E&L

This report describes ongoing rates of aseismic slip on fault segments within the San Andreas plate boundary system measured by creep-meters installed and operated by the University of Colorado.

Fault Creep in California - a brief history of measurement

The earliest recording creep meter was installed on the Hayward fault in Berkeley in 1965 (Bolt and Marion, 1966), and measurements were expanded by Nason who installed a number of dial gauge instruments, supplemented occasionally with strip chart recorders, along the fault. Nail arrays and geodetic measurements, however, provided the spatial coverage that indicated the surface fault to be of varied width and slip rate, moving at rates of 5-9 mm/year (Lienkaemper, 1991;1992; 2006). In 1993 the University of Colorado and the USGS using Lienkaemper's findings started the installation of five continuous recording creep-meters at 15 km intervals along the fault. Their cumulative data are described in this report.

Following the 1966 Parkfield earthquake the process of aseismic slip was studied by personnel of the USGS and the Coast and Geodetic Survey on the Hayward and San Andreas faults, and by Caltech on the Imperial, Superstition Hills and San Andreas faults in the Coachella valley. The USGS consolidated measurements of fault creep on the Calaveras and San Andreas faults in central and northern California and included more than 20 creep meters in a telemetered recorded system sampled every 10 minutes and recorded at Menlo Park. Most of this network continues to the present and its operation is maintained and documented by the US Geological Survey.

The study of fault creep was initially considered an important part of the USGS prediction effort in that surface slip on a creeping fault provides a measure of stressing rate, and reduces the amount of elastic energy to be released in future earthquakes in proportion to the depth to which creep extends (Figure 2). Creep also offered the possibility of providing a short term precursor to earthquakes. This arose from reports of a water pipe crossing the fault at Parkfield that was broken some 11 hours before the Parkfield earthquake in 1966. The occurrence of the 2004 Parkfield earthquake during the tenure of this project (1993-97) provided a (negative) test of precursory slip. Finally, evidence of slip on faults triggered by shaking on nearby faults suggested that fault creep might provide a field laboratory for studying the physics of fault slip.

The promise of accelerated fault creep as a short-term precursor to earthquakes has been shown to be baseless from the absence of surface slip in the Parkfield 2004 earthquake described in this report. In 2004 rupture initiated at depth, and surface slip was delayed by seconds, minutes and sometimes days after the mainshock, depending on the proximity of coseismic fault rupture to the surface. The surface fault during rupture is stressed, resulting in a rapid rise in shear strain at the surface above the propagating rupture. Discretized slip, as opposed to distributed shear, will not occur immediately in the surficial layers overlying the fault unless the shear strain exceeds the amount necessary to overcome friction on the surface fault. A soil layer overlying the fault will often fragment into en-echelon shears that grow and coalesce with increased slip. This delay of surface slip following moderate earthquakes was first reported on the Anatolian fault in Turkey by Ambraseys.

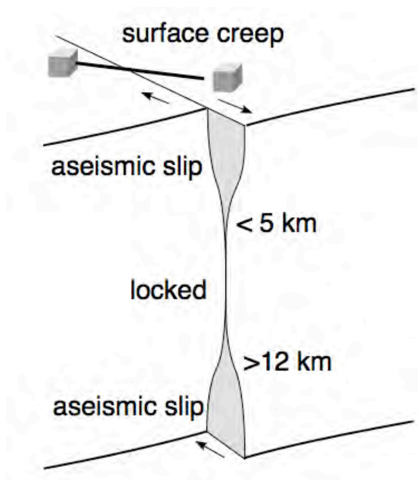


Figure 2 Shear strain applied to a plate boundary accumulates due to the presence of a locked zone on a fault that typically extends to the surface. Friction below this locked zone is too weak to lock the fault and slip proceeds steadily, loading the lower part of the locked zone toward failure. On some faults, however, friction near the surface is too weak to lock the fault and aseismic slip can occur there too. The resulting surface slip is termed fault creep. A creep meter typically includes a length standard that spans the fault obliquely (at angle ϕ) between attachment points on each side of the fault, and measures a component of the fault displacement reduced by the cosine of ϕ.

Description of creep meters At the heart of each creep-meter is a device to convert displacement of the fault to a voltage that can be transmitted or recorded on a local data logger. Transmission brings with it the ability to observe the behavior of the fault in real time, and permits daily monitoring of system operation, both essential in attempts to monitor earthquakes in real time. Telemetry in some parts of California, however, can be disadvantageous since the telemetry antenna can invite vandalism.

Our creep meters on the Hayward fault form part of a real time monitoring system so that their installation had to be undertaken in secure sites to minimize damage from vandalism. The urban setting of the Hayward fault reduced the number of sites suitable for installation: four of the instruments are in parks, and one (with the largest thermoelastic noise) is below a road.

Our creep meters in southern California have been designed to operate unattended underground for more than a year if necessary. Clock drift on the data loggers can exceed more than 10 minutes in a year so that we have visited them more frequently to download the data and adjust their clocks. We have also installed telemetry at some of these sites (see below).

Creep meter design Creep meters have hitherto used suspended wires in tubes buried across the fault (e.g. Yamashita and Burford, 1973). The wires are held in tension by a beam balance whose rotation (measured by an LVDT) provides a measure of fault displacement. A difficulty with these systems is that their length is limited to less than ≈20 m due to the low resonant period of long catenaries. We decided to try a different approach using a solid rod that slides in a telescopic jacket. The assumption is that the forces available in fault slip are large compared to the frictional stick-slip behavior of a rod in a tube. We find, in practice, that stick slip errors are less than 10 µm in 30 m long rods in correctly installed systems.

Geometry In all our current geometries the measurement rods, of quartz fiber or graphite or invar, are fixed to an anchor on one side of the fault and pass through a PVC tube to the far side of the fault buried at a depth of 30 cm to 2 m. We have found that it is best to hold the free end of the rod in tension with a spring since, although slip on the fault rarely reverses, soil expansion can result in apparent reversals of direction that are manifest as mechanical backlash. An LVDT (linear variable differential transformer) monitors the free end of the rod relative to a second anchor on the other side of the fault. The obliquity of the rod is arranged preferably to be at 30° to the fault plane, a compromise between a shallower angle that would produce a larger signal from fault parallel motion, and a large angle that would result in a shorter rod crossing the fault (Bilham, 1989) with advantages of decreased thermal noise

Length standards The creep meter rods were originally made from 3/8" diameter invar in 3 m sections screwed together using ¼-20 threads. These were installed with a heavy coating of grease inside galvanized iron tubes (1/2" gas pipe) and the relative expansion between the two metals used to exactly remove residual thermal effects. Continuous lengths of 1 cm diameter glass-fiber coated in teflon were next used in an attempt to overcome the propensity of the invar to rust. Their initial thermal coefficient was similar to invar but the teflon coating stiffened during operation resulting in an unacceptable sensitivity to temperature. It was necessary to strip the teflon coating from them to return the rods to their original low thermal coefficient. Most recently we have used ¼" graphite rods supplied in 10' lengths and screwed together with 10-32 crimped collars. These are lighter and have a lower thermal coefficient than either quartz fiber or invar and are our length-standard of choice for all future installations.

Anchors One of the problems with measurements of surface creep is that the maximum slip signal and maximum environmental noise both occur at the surface. The fault zone tends to be a clay gouge zone of 1 to 100 m width whose dimensional stability is determined by variations in its moisture content. The resulting surface heave requires that anchors or attachment monuments must be sufficiently rigid to resist these movements, or must include additional measurements to determine any deflections that are not related to fault slip.

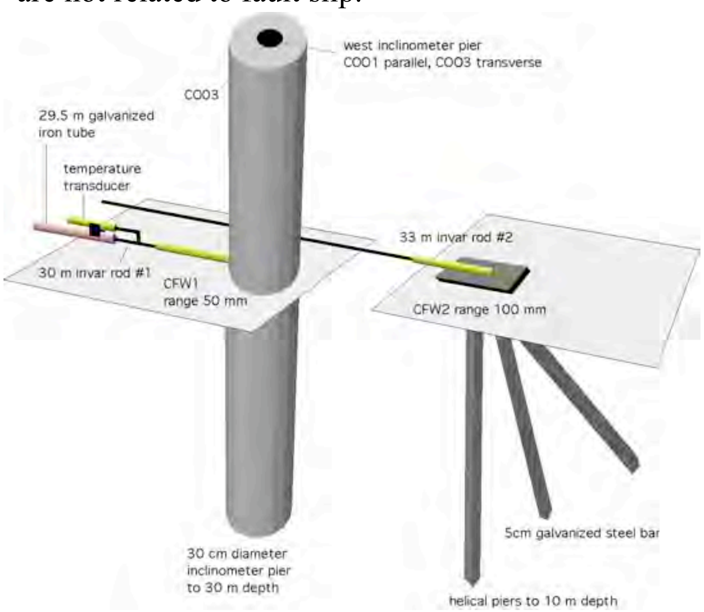


Figure 3 Two types of anchor were used in the Hayward creep-meter at Fremont - a vertical column and a buried welded tripod. After initial experiments with the vertical column we used a buried tripod on the remaining four creep meters. The vertical column was too expensive to replicate although it provided (serendipitously) an independent measure of slip where it penetrated the west-dipping fault at 26 m depth (Bilham, 1993; Bilham and Whitehead, 1997). The legs of the buried tripod are 5 cm thick steel bars with square section attached to helical vanes screwed to 10 m depth.

Electronics Early in the current award we designed a creep meter that could operate on AA batteries for a year recording slip and temperature data once each minute (Bilham et al 1993). The system is designed around the Onset Microstation data logger and a Schaevitz DCSE transducer which has a 6 mA continuous current consumption at 9-14V. To reduce the power consumption to less the 1 μA we activate the LVDT for 10 ms before sampling (Schaevitz and Onset both publish our design as an application note). Low power is obtained because the transducer is normally off. The system can operate underwater although we have found that the transducer cable seal fails after more than 2 months of submerged operation. We now use an extended sealed tube with desiccant to prolong transducer life. The data logger has a 12 bit dynamic range.

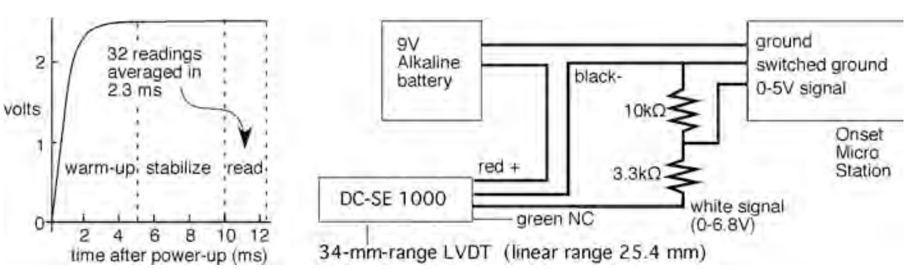


Fig. 5 Micropower creep-meter electronics made possibly by the rapid (<5ms) start-up of the DC-SE transducer.

Real time data access (this applies to most of the units indicated in Table 1). The Onset data logger couples to an Upward Innovations transmitter permitting remote telemetry of the creep meter data, but at much lower data rates (once every 10 or 15 minutes instead of once per minute). Two types of transmitter are available: satellite telemetry at $40/month or cell-phone telemetry (at $20/month). With the exception of two sites in the Coachella Valley all the creep meters are accessible via cell phone links. Scaled and calibrated creep meter data can be checked for slip with a 10 minute to 2 hour latency by entering: **www.datagarrison.com** and entering the user name **'geo'** and the password '**hobo**' plots (click on the instrument of interest).

The displayed data are shown as two or more plots. The first is of all the data since the last manual download. This is arranged to have a uniform scale of 5 mm full-scale and 0-50°C for the temperature of the instrument. The second plot is an automatically scaled plot showing the data for the week. In the absence of a creep event the data from the auto-scaled plot will appear noisy due to the high sensitivity of the displayed trace.

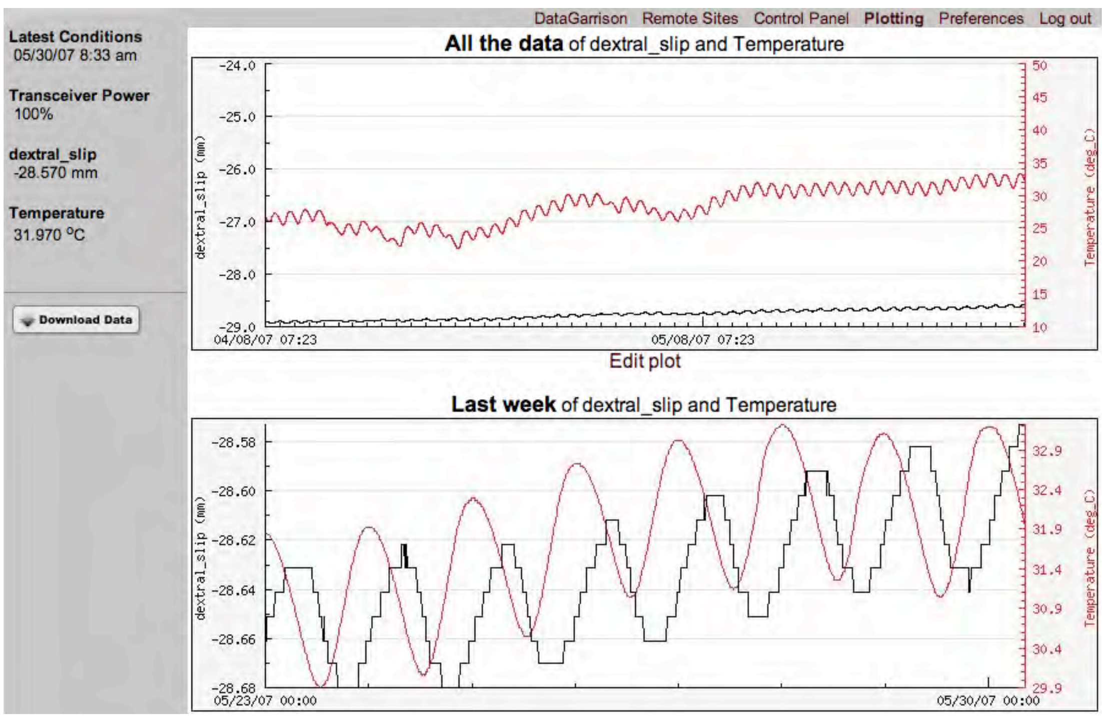


Fig 6. Recent online web data from the Superstition hills fault. The rate is ≈0.4 mm in 52 days (All the data refers to the data since the last mechanical reset to the electronics and transducer. Lower line top graph indicates a slip rate ≈3 mm/yr. The lower graph shows a diurnal thermoelastic signal (50 µm peak to peak) lagging 8 hours behind instrument temperature (≈ 1 °C). Each displacement increment ≈6 µm.

Graphical summary of results In figure 7A and 7B we summarize surface slip rates measured in the past three years at several sites. Relative creep rates on the Hayward fault in the past 13 and past 4 years are compared on Figures 16 and 17 respectively.

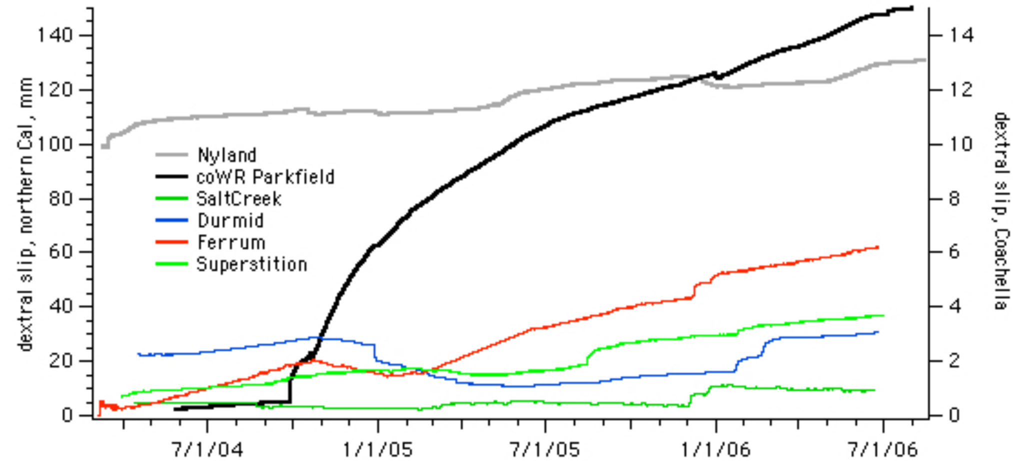


Fig 7A. Comparative rates and event amplitudes from creep-meters in central and southern California 2004-2006. The large signal at Parkfield (coWR) is caused by afterslip following the 2004 earthquake.

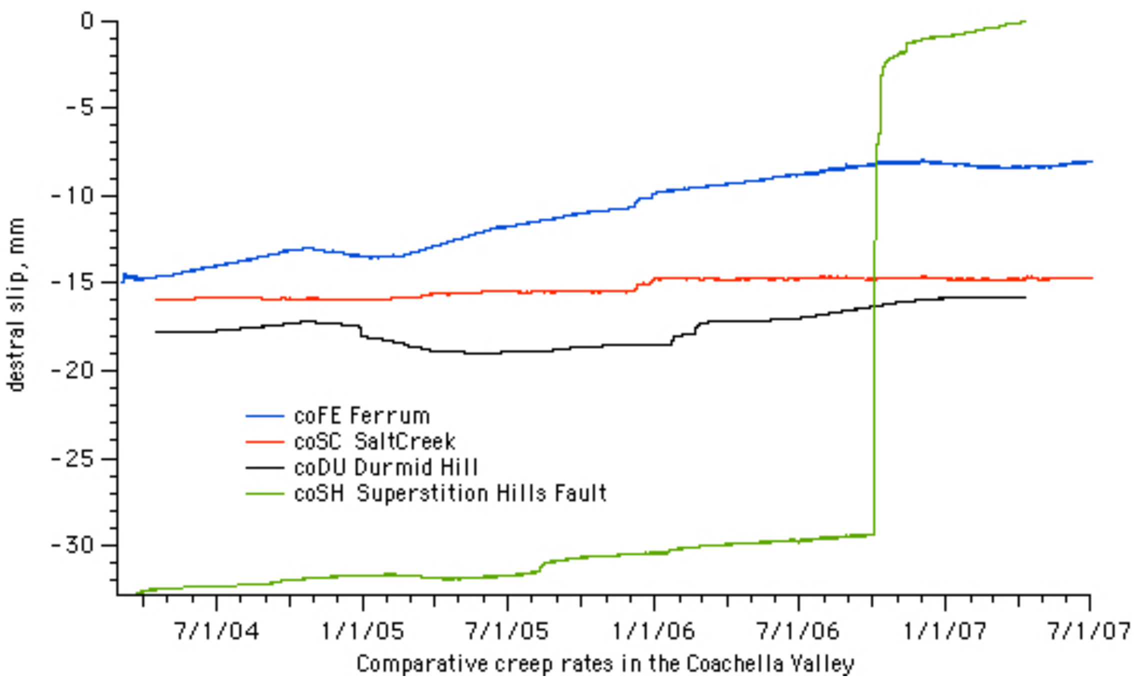
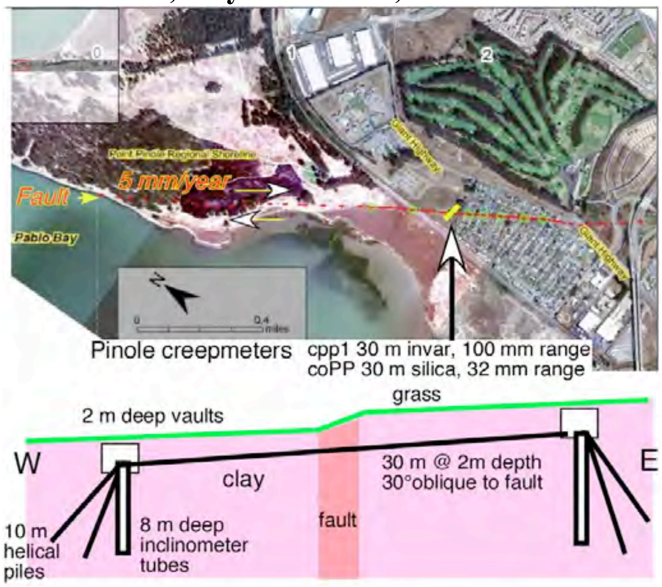


Figure 7B Comparative creep rates in the Coachella Valley illustrating the absence of accelerated slip on the Southern San Andreas fault at the time of the slip episode on the Superstition Hills Fault.

The following pages examine creep data from individual locations starting at the northermost location on the Hayward Fault and progressing southward.

Point Pinole, Hayward Fault, 37 59.35N 122 21.27W



The data from the northernmost creep meter on the Hayward fault show a steady 4.98 mm/yr creep rate at Point Pinole, with varying noise levels that characterize three periods of operation (Figure 9). The noisiest data occurred when a submerged cable failed during a period when funding to maintain the instrument was unavailable (2000-3).

Fig.8 Map view and cross-section Pinole creep-meter Map from Lienkaemper web site.

The creep meter initially consisted of an invar rod enclosed within a steel tube lying freely within the fault zone. Transducers in the period 1995-2003 measured the two changing gaps between steel buried tripods drilled to 6 m depth, 30 m apart and 7.5 m to the west and east of the fault respectively (Figure 8). Their outputs were summed to provide the creep signal, and the difference in length between the galvanized-iron and invar was used to correct for thermal variations influencing the length of the invar. A fault in the 100 m underground signal cable to the transmitter caused the intermittent loss of two of these signals 2000-4. The cables were replaced in 2004 and an independent data logger started in order to circumvent future transmission losses (J2215). The first unit uses the same invar rod now monitoring a single transducer signal from the eastern end. Measurement of the differential thermal signal has been discontinued. The second transducer uses a quartz fiber length standard from which its original teflon coating has been stripped. (We found that the thick teflon coating provided by the manufacturer increased the thermal coefficient from 0.5 ppm/°C to 5 ppm/°C). The annual thermal signal is now equivalent to less than 2 mm/yr.

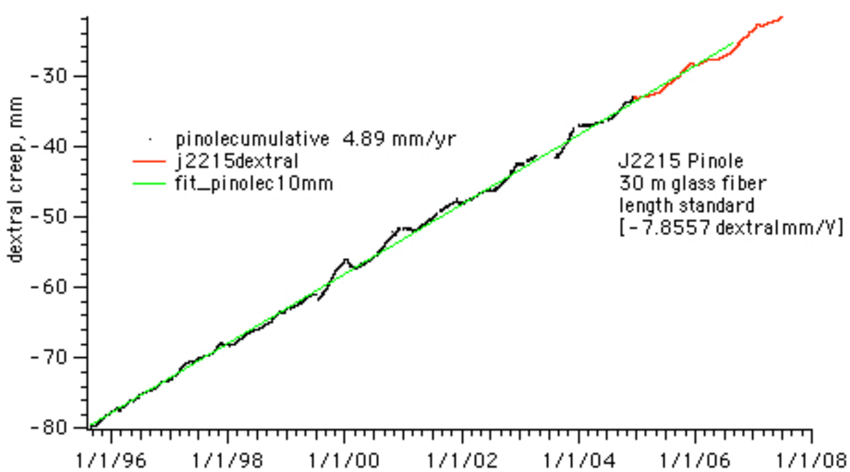


Fig. 9 Creep data from Point Pinole 1995-2007 at the northern end of the Hayward fault. Digital temperature and displacement data at sampling rates from 2 minutes to 10 minute intervals are available on the web at http://cires.colorado.edu/~bilham/CREEPDATA/PointPinoleCreep.htm

Temescal Park, Hayward Fault, 37 59.35N   122 21.27W

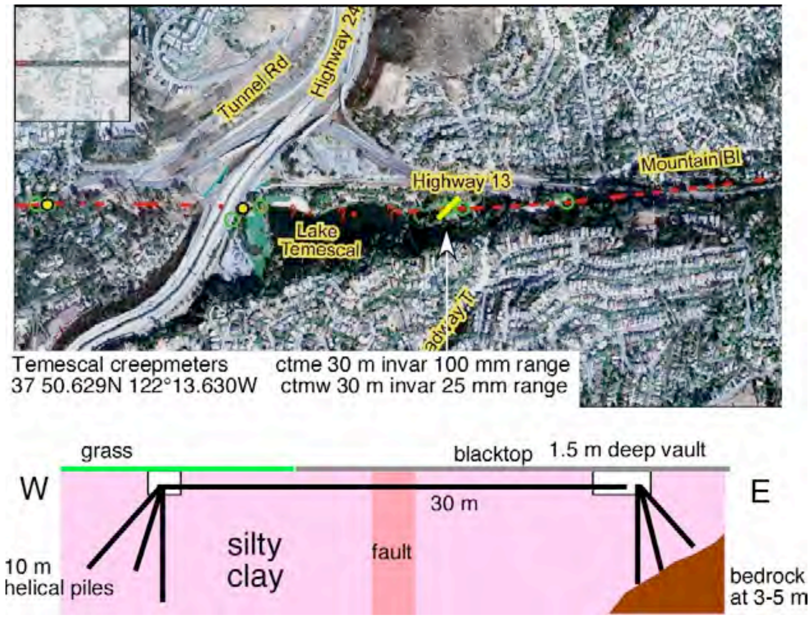


Fig. 10 Map and cross-section of the Temescal creep-meter.

The creep-meter at Temescal was initially constructed like the Pinole creep-meter to have two transducers and a "floating" length-standard. This was abandoned for a simpler single transducer arrangement in 2004. Creep has fractured the surface into a series of en echelon cracks near the children's playground, that were partly removed during resurfacing in June 2007. The instrument floods to a depth of 2 m each year by the overflow of Temescal Creek, and this has occasionally caused loss of data. The mean creep rate is 3.3 mm/year uninterrupted by creep events. Noise levels are less than 1 mm/yr. Bedrock is within 5 m of the surface. Numerical data are available on the web.
http://cires.colorado.edu/~bilham/CREEPDATA/Temescal%20Park.htm

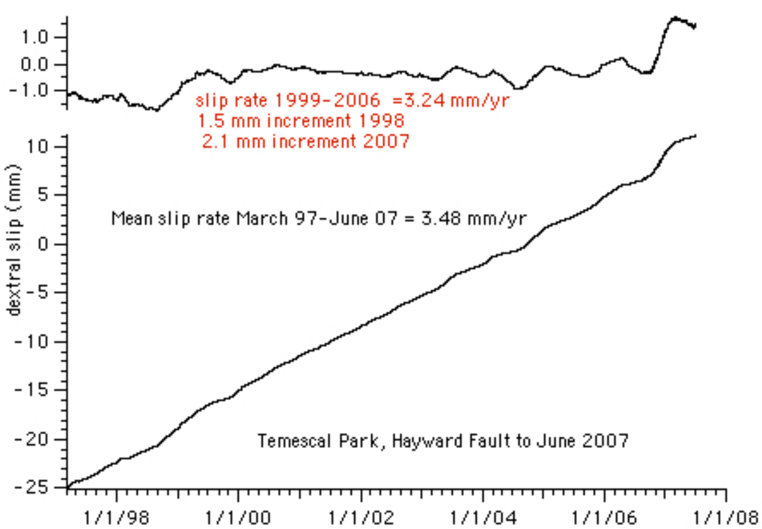


Fig. 11. Temescal creep is typically featureless at a rate of 3.24 mm/yr with a superimposed thermoelastic signal with <1 mm annual amplitude. However, in 1999 and again and again in 2007, rates increased in the early part of each year incrementing aseismic offset by 1.5 and 2.1 mm respectively.

In figures 16 and 17 we compare data from instruments to the north and south of Temescal to search for possible propagation of these accelerated periods of slip . No clear signal is apparent.

Oakland Zoo, Hayward Fault, 37°50.63N 122°4.36'W

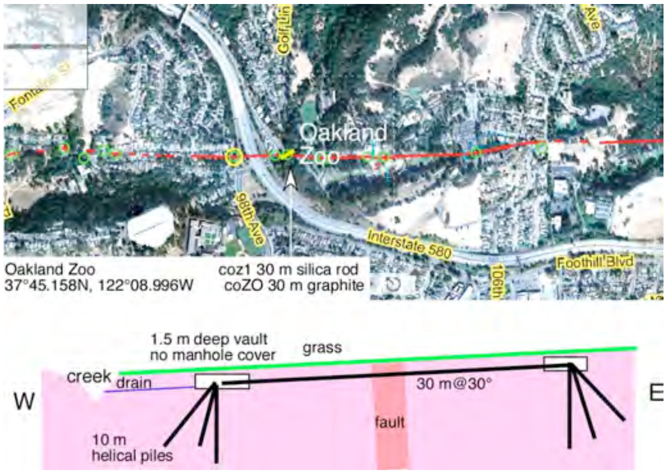


Figure 12 Map and section for the Oakland Zoo Creep meter. Landscaping near the creep meter in 2006 lead to interrupted operation. New cables were subsequently installed and a backup telemetry system with independent power is installed to circumvent future data loss. Water runs continuously through the creep meter pipes through the fault zone and drains into the nearby creek. The manhole is completely buried by soil covered with grass.

An independent telemetry system provides instant access to recent data.
http://cires.colorado.edu/~bilham/CREEPDATA/OaklandZooCreepmeter.htm user=geo pswrd=hobo
The mean creep rate at Oakland Zoo since 1997 has been 3.08 mm/yr. Excluding a 6.5-mm-amplitude creep event in 2004 the mean creep rate here is only 2.39 mm/year. Calibrated and edited data for 1997/2007 are available as a downloadable 3.2Mb file .
http://cires.colorado.edu/~bilham/CREEPDATA/OaklandZooCreepmeter.htm
The data are in two columns delimited by a space. The first column is the time MM/DD/YY HH:MM:SS in GMT and the second is the dextral displacement in mm (only the first two decimal places are meaningful).

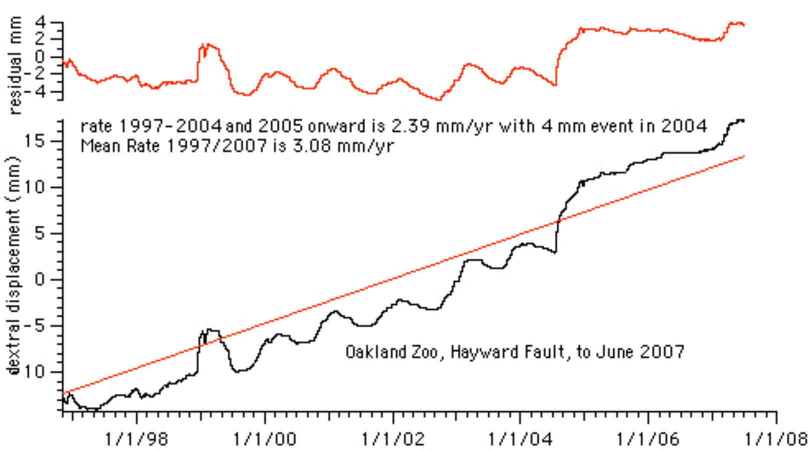


Fig. 12 The mean creep rate at Oakland Zoo since 1997 has been 3.08 mm/yr. However, if a 6.5-mm-amplitude creep event in 2004 is excluded, the mean creep rate here falls to 2.39 mm/year.

Transmission errors and cable short circuits in one of the transducers rendered the data suspect for the period Feb to Mar 05. Careful editing of data in this period reveals a creep rate of 2.6 mm/year before and after a 6.5 mm creep event in 2004, which had a duration of roughly 4 months. The creep event has a possible precedent in Sept 2002 but this earlier event was smaller and is masked by the seasonal signal which has been significantly reduced in post 2003 data. Each creep event was accompanied by a number of local microearthquakes on the Hayward fault**.**

Palisades Road, Hayward Fault, 7 39.77N 122 4.36W

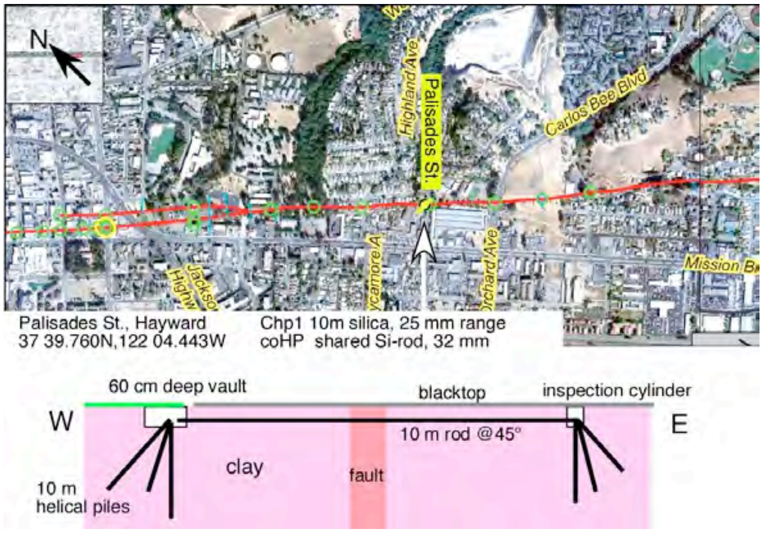


Fig 13. The creep meter is installed under Palisades Road at 45° to the fault. A large welded steel pipe was installed beneath the creep meter length standard in two weeks at the end of Sept. 2006. This offset the instrument mechanically three times by a total of 3 mm before installation was complete. The offsets have been removed by inspection and baseline errors are likely to be less than 0.4 mm.

The data reveal a strong thermoelastic signal. The annual amplitude of this signal is roughly 5 mm, more than the annual creep rate of 4.77 mm/year. Attempts to suppress this signal prior to transmission are rendered difficult due to the phase relationship between maximum measured temperature and maximum thermoelastic signal.

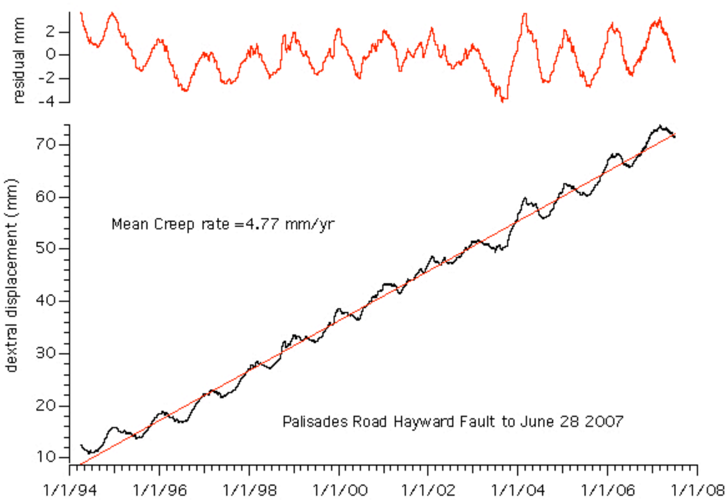


Figure 14 Creep at Palisades Road since installation in early 1994 to 28 June 2007. The mean creep rate is less than the annual thermoelastic signal at this site.

All the Palisades Road data may be downloaded numerically at
http://cires.colorado.edu/~bilham/CREEPDATA/PalisadesCreep.htm

Fremont, Hayward fault 37 31.96 N 121 57.10 E

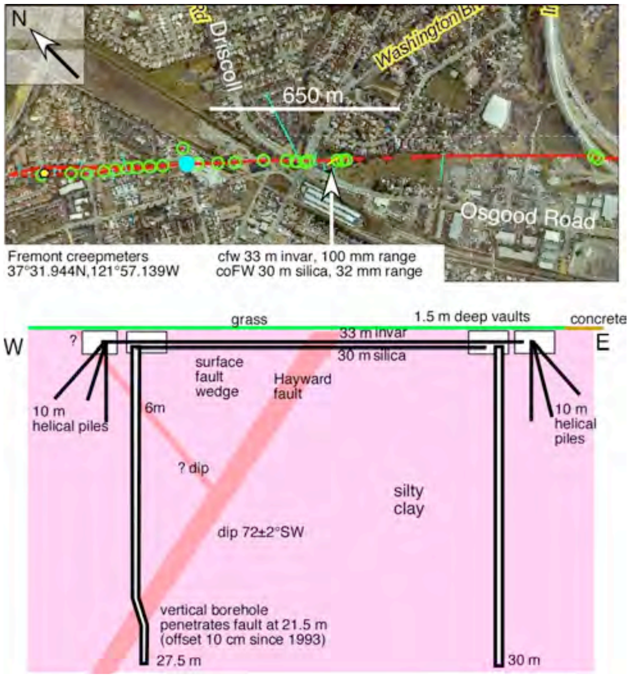


Fig. 14 Map and section for the Fremont Creep meters. Note there are two separate creep meters with different mounts and length standards (invar and silica). The measurements have detected the motion of a surface wedge in the uppermost 22 m of the fault zone. We are unable to make inclinometer measurements to detect tilt of the 30 m deep boreholes because of our request to purchase an inclinometer was declined by the USGS. A new road system is being constructed near the site and the transmissions have been twice vandalized possibly as a result of increased exposure.

Data from December 2003 to June 2007 are shown in Figure 15. They show a mean creep rate in a least-squares sense of 6.9 mm/year interrupted by creep events with amplitudes of 1-2 mm. All or part of the data may be downloaded numerically at http://cires.colorado.edu/~bilham/CREEPDATA/FremontCreepmeter.htm

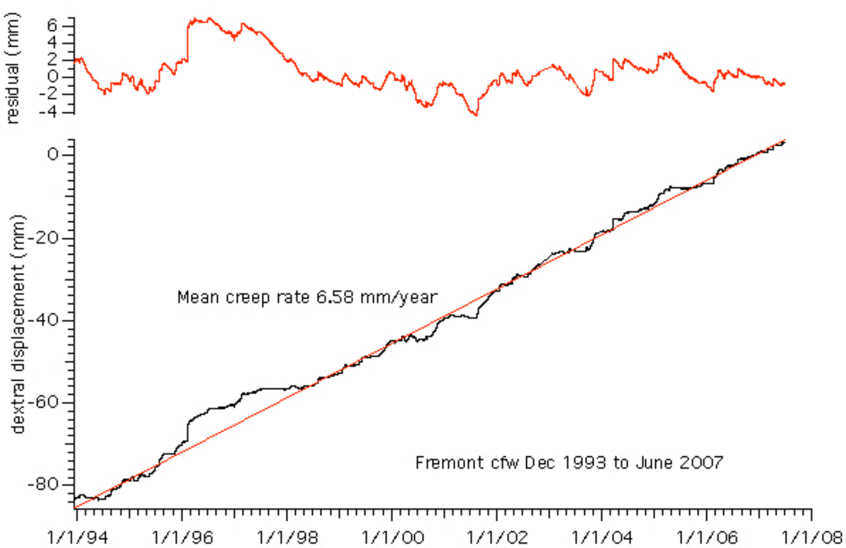


Figure 15 Data from December 2003 to the present show a mean creep rate of 6.6 mm/year. An accelerated rate in 1996 was followed by a retardation of two years. Creep rates in the past two years have been interrupted by relatively small creep events (1 mm).

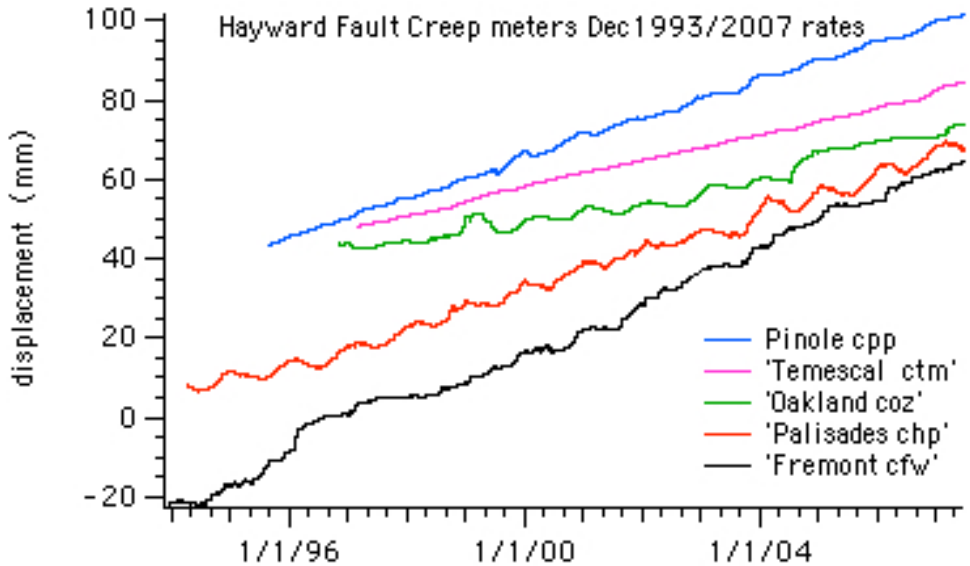


Figure 16A Comparative creep rates on the Hayward fault for 14 years 1993-2007. No clear evidence for propagation of creep accelerations along the fault are discernable although there are clear changes in rate at Fremont.

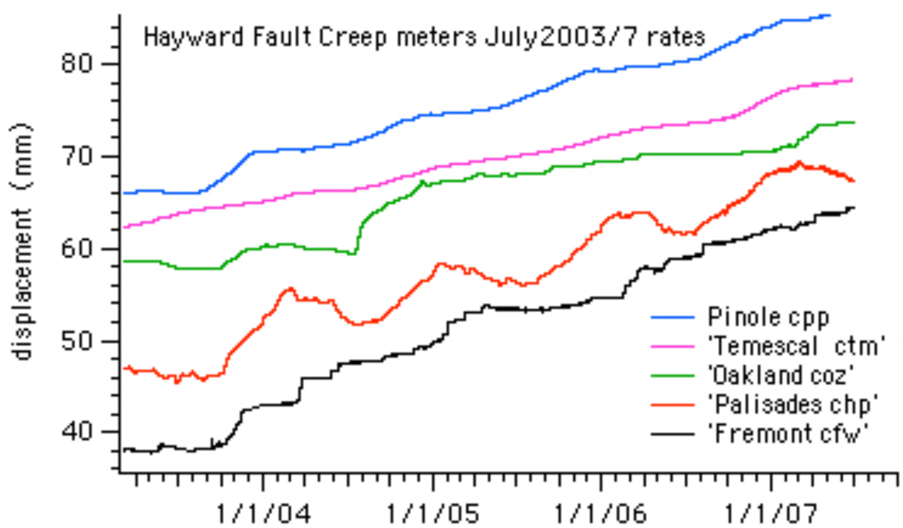


Figure 16B Comparative creep rates on the Hayward fault for the period of this final report Nov 1993-April 2007. No clear evidence for propagation of accelerated or retarded creep along the fault is discernable.

coNR Nyland Ranch 36.8350°N, 121.5463°E

The creepmeter is 8 m long, and is 40° oblique to the San Andreas fault near the entrance to Nyland Ranch, north of San Juan Bautista. It is the most northerly of all the creep meters on the creeping section of San Andreas fault zone in central California, and is close to an instrument originally installed by Nason in the late 1960's.

The creep rate here is 9.3 mm year but its shallow installation results in abrupt reversals in apparent rate due to expansion of the clays in which it is installed during the winter months of each year. The attachment points do not extend more than 1 m into the soil layers, and these seasonal fluctuations regularly exceed 5 mm.

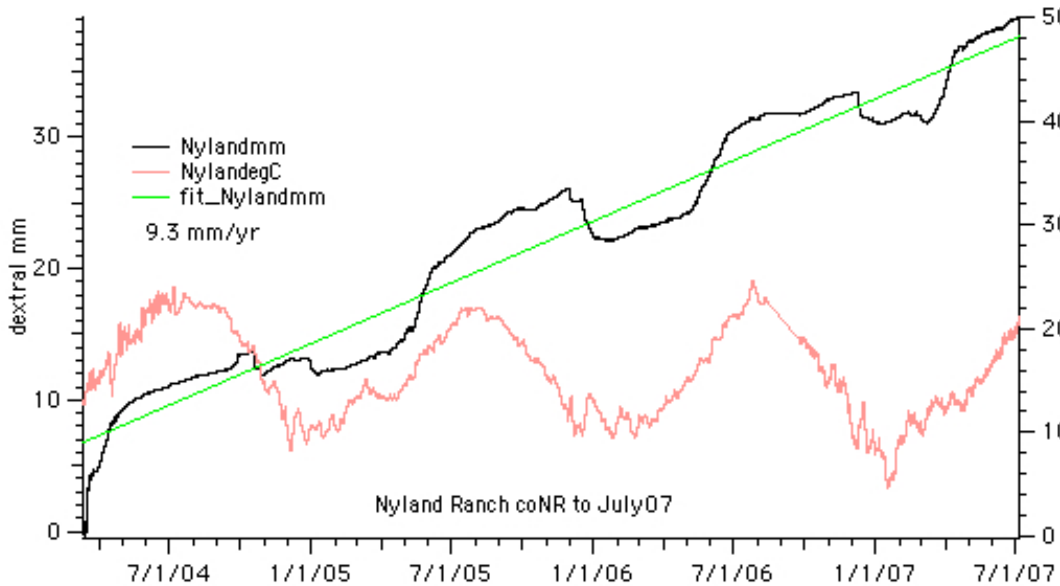


Figure 17A Data fom early 2004 to 2007 from Nyland Ranch north of San Juan Bautista.

Telemetry was added to the site in late 2006 and calibrated desxtral slip data may now be downloaded on line *https://datagarrison.com/users/1101128/5083010240/plots.php* enter *geo* as user name, and *hobo* as password. The data are available as space-delimeted text files in three columns, mm/dd/yy hh:mm:ss, dextral slip, and degC. Only the first two decimal places are significant.

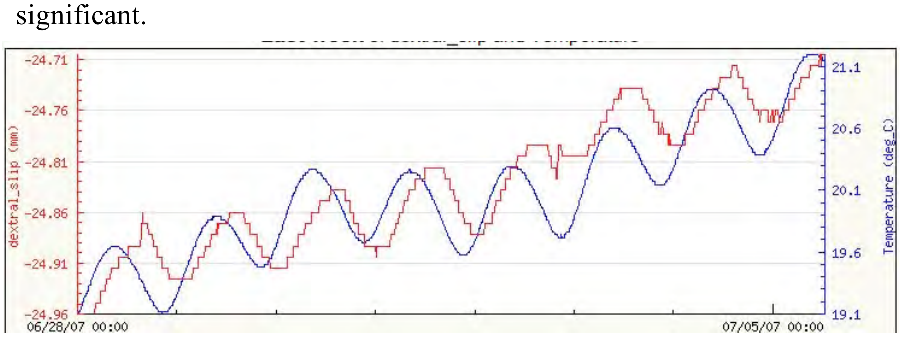


Fig. 17B A week of data from Nyland Ranch shows a diurnal thermoelastic sensitivity of ≈ 0.1mm/°C

Parkfield 28 Sept 2004

The Mw=6 Parkfield earthquake at 11:15 local time, 28 September 2004 dealt a fatal blow to the notion that significant surface slip precedes earthquakes. In 1966, anecdotal reports of surface fissures along the fault zone had been reported in the preceding week, and a water pipe fractured 11.6 hours before the mainshock. This offered hope that substantial surface slip may have occurred had displacement sensors been in place to measure it. In the days, hours and minutes prior to the 2004 Parkfield mainshock, displacement sensors were in place, and nothing happened. According to data from eight creep-meters crossing the fault, the fault remained effectively locked at the detection level of each sensor (6-20µm) (Langbein et al. 2006). This absence of surface slip was accompanied by an absence of significant strain on the borehole dilatometer and shear-strain-meter array in the region, and by the absence of any unusual displacements on the GPS array embracing the 2004 epicenter. Although pre-seismic strain signals seen on some borehole strain-meters suggest that epicentral strain was not completely indifferent to the pending earthquake, the signals are close to instrumental noise levels, and pose new challenges for their reliable future detection.

In contrast to the absence of pre-seismic fault displacement, the creep-meters all recorded an abrupt co-seismic dextral offset at the time of the mainshock. The step corresponds to dextral shear of the fault zone, but in the absence of surface rupture, the creep-meters during early afterslip acted as extensometers, measuring strain rather than fault creep. The serendipitous location of creep-meters at Work Ranch both across and eccentric to the fault zone has provided insight into the development of surface faulting. This showed very clearly that the first few days were accompanied by no surface cracking, and that the surface cracks appeared after 3 days gradually increased in size to form an irregular en-echelon step. Two of the creep meters were discontinued after the earthquake either due to data redundancy or because of an absence of slip. Only the creep meter south of Highway 46 now continues to operate (at USGS's request).

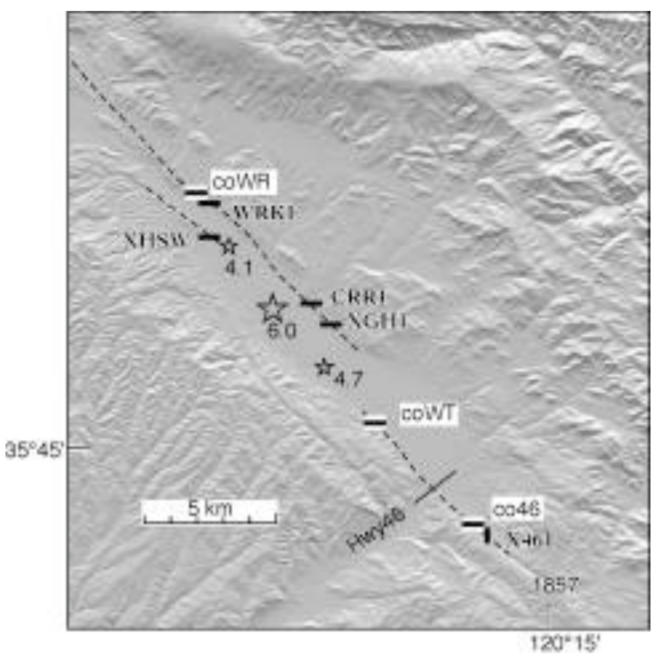


Fig 18. Southern half of the 2004 Parkfield rupture (epicenter=star) showing the approximate location of surface slip in 1966, and named creep-meters discussed in the text, (Azimuths of creep-meters indicated by black bars.) In 2004, surface slip again occurred near coWR, but as of 28 October 04, not between coWT and co46. USGS creep-meters are indicated by solid black bars.

Creep-meters and data processing

The USGS have maintained a creep-meter array in Parkfield since the 1966 earthquake, increasing the number of sensors over the years to thirteen (Schultz, 1989; Schultz et al.,1990; Yamashita and Burford,1973). Data from these instruments indicate that interseismic creep reduces in rate from more than 20 mm/year north of Middle Mountain to zero South of Highway 46 (Langbein et al, 1990). Ten of these now record afterslip with a displacement resolution of approximately 20 µm. The three

University of Colorado (UC) extensometers discussed in this article were installed to capture coseismic slip and afterslip at Parkfield, but were abandoned a decade ago due to funding difficulties. With the resumption of USGS funding in 2003, one was re-activated in April 2004, and two others shortly after the Parkfield earthquake. They measure linear displacements 30-60 cm below the surface between attachment piers on the flanks of the fault. Each attachment pier consists of steel-rods driven to refusal in the form of a buried tripod with a maximum depth of 2 m. The length standards of these original extensometers are solid 1-cm-diameter invar rods that slide within buried telescopic PVC pipes, although new instruments use 6-mm diameter graphite rods. The rods are fastened rigidly to a buried pier at one end. The rod crosses the fault obliquely at ≈30° and motions of its free end relative to the opposing pier are measured with a linear-variable-differential-transformer (LVDT). All three Parkfield systems were equipped with 1" range Schaevitz DCSE 1000 transducers and 12-bit Onset Microstation data loggers that can operate autonomously from AA alkaline batteries for a year (Bilham et al. 2004). The locations, and specifications of the extensometers are shown in Figure 18 and Table 2.

Table 1 Specifications of creep-meters discussed in the text.

site	lat°N	long°W	length	obliquity	azimuth	start
coWR	35.8587	120.3924	14 m	30°	N76E	15-Apr-04
coWRW	35.8587	120.3924	2.5 m	30°	N76E	10-Oct-04
coWRW	35.8587	120.3924	10 m	30°	N76E	28-Oct-04
WKR1	35.8587	120.3924	21m	40-45°	N85E	1978
coWT	35.7580	120.3003	6 m	30°	N76E	2-Oct-04
coWTW	35.7580	120.3003	5 m	30°	N76E	2-Oct-o4
co46	35.7249	120.2818	14 m	30°	N84E	28-Sep-04
coNR	36.8350	121.5463	8 m	40°	N80E	Mar-04

The east component of coWR operated throughout the earthquake. Following the development of surface fissures its length was increased westward by 2 m 10-28 October, and to 10 m subsequently. The obliquity of Work Ranch was measured at 40° but is recorded in USGS archives as 45°, possibly assuming a different local strike for the fault.

Data were downloaded in the field as text files of voltage and temperature, with a timing accuracy of ±3 s. The voltages, which include a non-linear extension of the LVDT range from 25.4 to 39 mm, were first linearized to displacements using 6th order polynomials from laboratory calibration data. Dextral slip is obtained by dividing the displacement data by the cosine of the fault-crossing obliquity assuming no distortion of the rod where it crosses the fault zone. The resulting precision and accuracy in the data is 10 µm. Few spurious data exist in the raw time series, but mechanical adjustments to transducer positions have been removed. No temperature corrections have been made to the data. The diurnal peak-to-peak amplitude in each creep record is less than 80 µm. The processed and raw data are available as numerical listings at the following URL: http://cires.colorado.edu/~bilham/WorkRanchSite.htm

Strain and displacement measured at coWR, Work Ranch

Creep-meter coWR supplements data from a USGS/Caltech telemetered system (WKR1) installed in 1976, which has operated continuously since installation with a sample rate of 10 minutes. Although WKR1 malfunctioned a few days before the earthquake, it was repaired a few days later. The Colorado creep-meter (coWR) was activated in April 2004 to test two new sensors described in Bilham et al. (2004): one with a high-resolution (6 µm) and 39 mm range, and another with low resolution (1.5 mm) and 3 m range. Both the UC sensors recorded surface strain at the time of the Parkfield mainshock, and its subsequent development (Figure 20). The recording rate on the high-resolution creep-meter was unfortunately reduced from 60s to 300s sampling two days before the earthquake, although this 5 minute sample rate remains double the rate of other creep-meters in Parkfield. Following the earthquake its sample rate was increased to 30 s, a rate that recorded triggered displacements at the time of the larger aftershocks. The low-resolution creep-meter operated throughout the earthquake with a 600 s sampling interval.

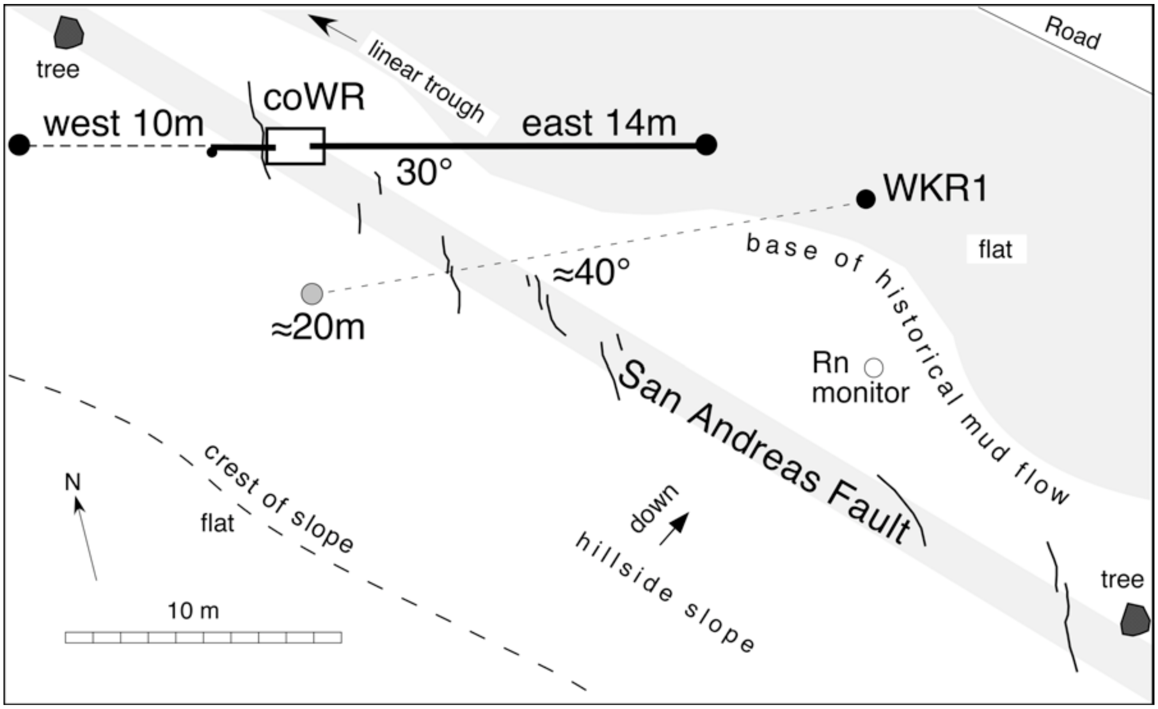


Figure 19. Locations of Work Ranch extensometers relative to 5 mm to 2 cm wide cracks mapped 21 Oct 2004. The cracks were not evident on 2 October. The 2.5 m west extension was constructed 10 October and recorded by an independent data logger after the fault announced its location. On 28 October when cracks clearly established that the fault passed through the center of the coWR inspection vault the length was increased to 24 m.

No cracks were evident in the ground when the Work Ranch creep-meters were visited 5 hours after the earthquake and again 4 days later, but irregular cracks at 3-5 m intervals developed subsequently within a 40-m-long, 3-m-wide, swath near the creep-meters (Figure 19). The N58°W mean strike of the fault followed by these en-echelon cracks revealed that the coWR extensometer embraced (embarrassingly) only half the fault zone. A clear fault zone at this location is not apparent because it is obscured by what is interpreted to be a small scale historic mudflow. By 10 Oct an 18-mm-wide, 3-m-long N5W-trending irregular crack had developed parallel to the western edge of the fiber-glass vault marking the western extremity of the 14-m-long instrument. This crack tapered to a hairline 50 cm to the south of the vault, and 1.5 m to its north (Figure 19). Fault zone fissures were clear in the 40 m zone mapped in Figure 19, but fissures in the contiguous 100 m to the SE and NW were sparse, an observation supported by geological mapping of the region reported by Langbein et al. (2006). The maximum width of opening of the en-echelon fissures was noted to be approximately proportional their separation and to their length. The easternmost and longest fissure had the widest opening and the furthest distance from the next fissure.

On 10 October the coWR creep-meter was extended 2.5 m westwards using a 30-cm-deep graphite rod, and an existing vertical steel pipe as an anchor. On 28 October this temporary arrangement was replaced with a 10-m-long, 60-cm-deep graphite rod, attached to a 2-m-deep buried steel/concrete pier west of the inspection vault. A 10-cm-range sensor now records afterslip embraced by the combined 24-m-long graphite/invar rod system.

That the original UC extensometer incompletely crossed the fault was suspected before surface fractures were manifest. By 2 October, 10.2 mm of afterslip had been recorded by coWR, compared to 23.6 mm on WKR1 (Langbein, personal communication, 2004). The initial efficiency of creep-meter coWR (43%) had reduced to 30% by 10 October (14.8 mm vs. 48.5 mm) with an average afterslip velocity half that of the USGS creep-meter. Even with the addition of the westward extension, the measured dextral slip signal 10-21 October remained 40% smaller than the WKR1 creep-meter (Figure 20B), requiring the creep-meter to be extended to 10 m.

An attempt has been made to infer the relative slip recorded by the west and east-facing creep-meters (Figure 20B). Three assumptions are required. The first is that the WKR1 dextral displacement signal represents the cumulative dextral shear at this point, as inferred from post-seismic mechanical adjustments (by John Langbein) needed to bring the instrument on-line. The second is that the shear strain above a subsurface dislocation is approximately linear on the surface. This assumption is invalid as the subsurface dislocation approaches the surface and the strain-field narrows to dimensions comparable to the lengths of the extensometers. It is approximately correct for the early part of the record. An additional assumption is that creep-meter WKR1 remains straight and 45° to the fault, an assumption that may be incorrect if a sigmoidal kink in the fault zone (Bilham, 1989) has reduced the obliquity of the WKR1 where it passes through the shear zone. Twenty-two cm of creep has occurred at Work Ranch in the past 28 years. The manipulation of these data in this way (explained in the caption to Figure 20B) subject to these various assumptions yields an inexact measure of the missing slip. However, the reduction in estimated partitioning, from 40% to less than 30%, is consistent with the absence of surface cracks in the early part of the record, and with the location of the measurement vault approximately two thirds of the way across the surface shear zone, after these cracks were manifest (Figure18).

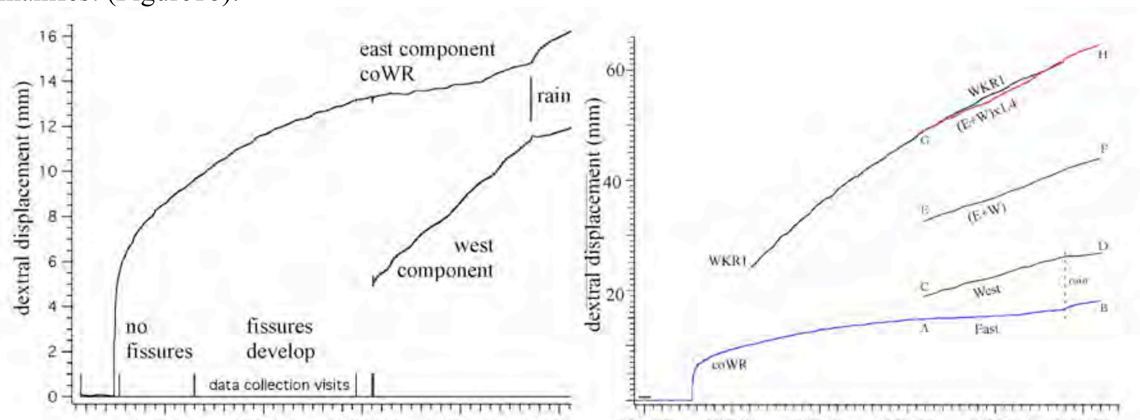


Fig 20A (left) Extensometer data from coWR, east and west. The east component is shown as dextral displacement and strain. The west component has an arbitrary offset and starts 11 October. Figure 20B (right) Comparison with Caltech/USGS creep-meter WKR1 data (from John Langbein). The absolute amount of slip that occurred on the east creep-meter is known but that for the west creep-meter is not, although it can be estimated approximately from observed velocities (line slopes). The period of overlap AB (east) is added to CD (west) to obtain the total *fault zone shear velocity, EF, for the 16.5-m-long combined extensometer. The slope of GH measured by WRK1 remains 1.4 times greater than the slope of EF, hence the estimated displacement of point F must be H/1.4. This then determines the absolute displacement of point D. Dashed lines indicate inferred displacements.*

Rain occurred in the last few days of the record (Figure 21) causing a reduction in the rate of opening of the cracks west of the creep-meter and a corresponding increase in the apparent rate of creep in the east-going creep-meter. The sum of the two signals is almost unperturbed by these changes, so that rain appears to have caused a displacement of the vault position, presumably due to water entering the surface crack at its western edge. Excavations showed that the soil moistening elsewhere was confined to the uppermost 10 cm of the soil layer. Below this depth the soil remained dusty.

Creep south-east of the mainshock, coWT & co46

Two creep-meters were activated after the earthquake southeast of the mainshock. They operated on the SE branch of the San Andreas fault that slipped in 1966 but where no 2004 fissures had yet appeared by 2007. The most southerly of these creep-meters is 100 m north of the USGS creep-meter X461, approximately 1.2 km SE of Highway 46, near an offset drainage whose probable 1857 offset is discussed by Lienkaemper (2001). The northerly one is a restored creep-meter site ("Water Tank"), abandoned due to frequent flooding, approximately 2 km NE of Highway 46 in a featureless location in the floor of the Cholame valley. In the first month of afterslip both creep-meters recorded creep events with 1-3 mm amplitude and 3-8 day duration. The afterslip decay rate causes the intervals between creep events to increase with time. Despite the differences in creep-event amplitude and duration, the afterslip rate at each of these locations is similar, at approximately 0.3 mm/day.

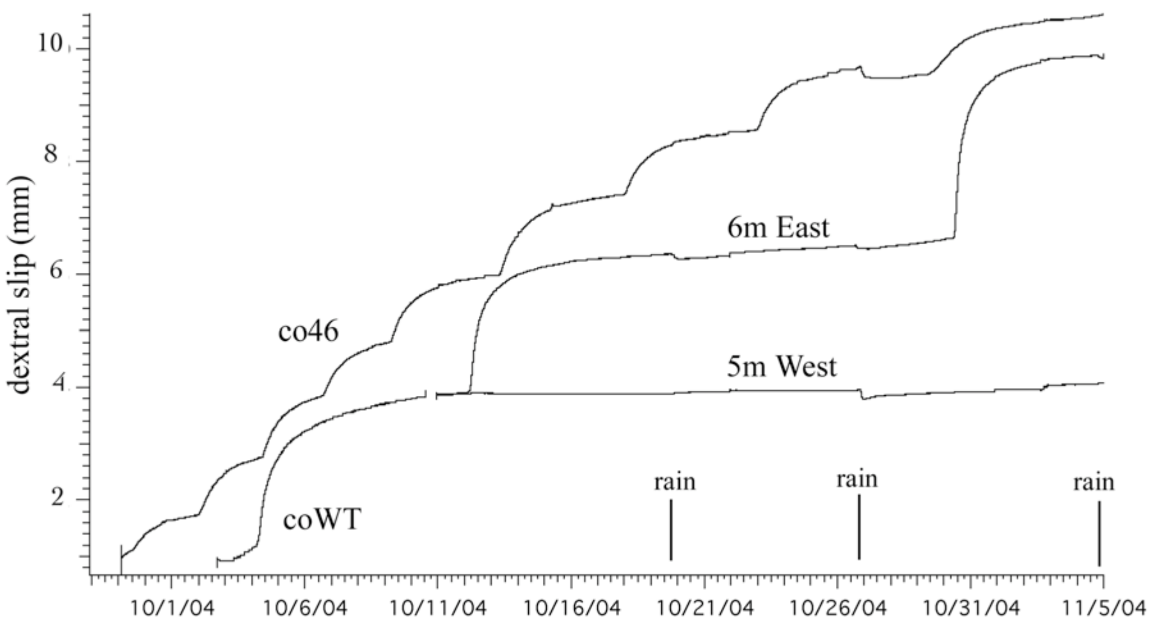


Figure 21 Extensometer data from two locations on the San Andreas Fault segment SE of the epicenter. Both extensometers were activated after the earthquake and hence absolute coseismic displacements are not known. A 23.47 mm extension of coWT may have occurred coseismically, as recorded by clean, rust-free surface on an otherwise rusty sensor clamped a decade ago. The west coWT extensometer is co-linear and contiguous with creep-meter coWT and records no change in strain at the time of creep events on the fault.

Since no nearby geodesy is available to constrain the absolute amplitude of post-seismic slip at these locations, the displacement datum in Figure 4 is arbitrary. Extrapolating the data back to the time of the mainshock suggests that recording at each site may have started at the end of an earlier creep event of similar magnitude and duration to the ones that followed. If this indeed occurred the cumulative afterslip to 21 October is 9-10 mm at each location. However, a coseismic step in the signal may have occurred at each site, either due to static-strain or to inertial shaking effects. During installation of coWT its transducer (abandoned in 1993) was found to retain signs that it had been pulled apart from its attachment to its invar rod relatively recently. The fresh rust-free surface had parted 23.47 mm from its retaining clamp, presumably during the mainshock, but it is not certain how long this fresh surface could have been exposed underground without rusting.

The coWT creep-meter has two rods, one extending east and the other west from a central recording system. Between 2 Oct and 10 Oct a single transducer recorded their combined signal, but after 10 October the west component was recorded separately to learn something of the spatial distribution of surface shear. In the ten days of data available for present analysis we conclude that the western arm does not cross any part of the active fault. The west component, however, does respond to soil moisture changes (rain 18-19 Oct) in the opposite sense to the fault-crossing east creep-meter.

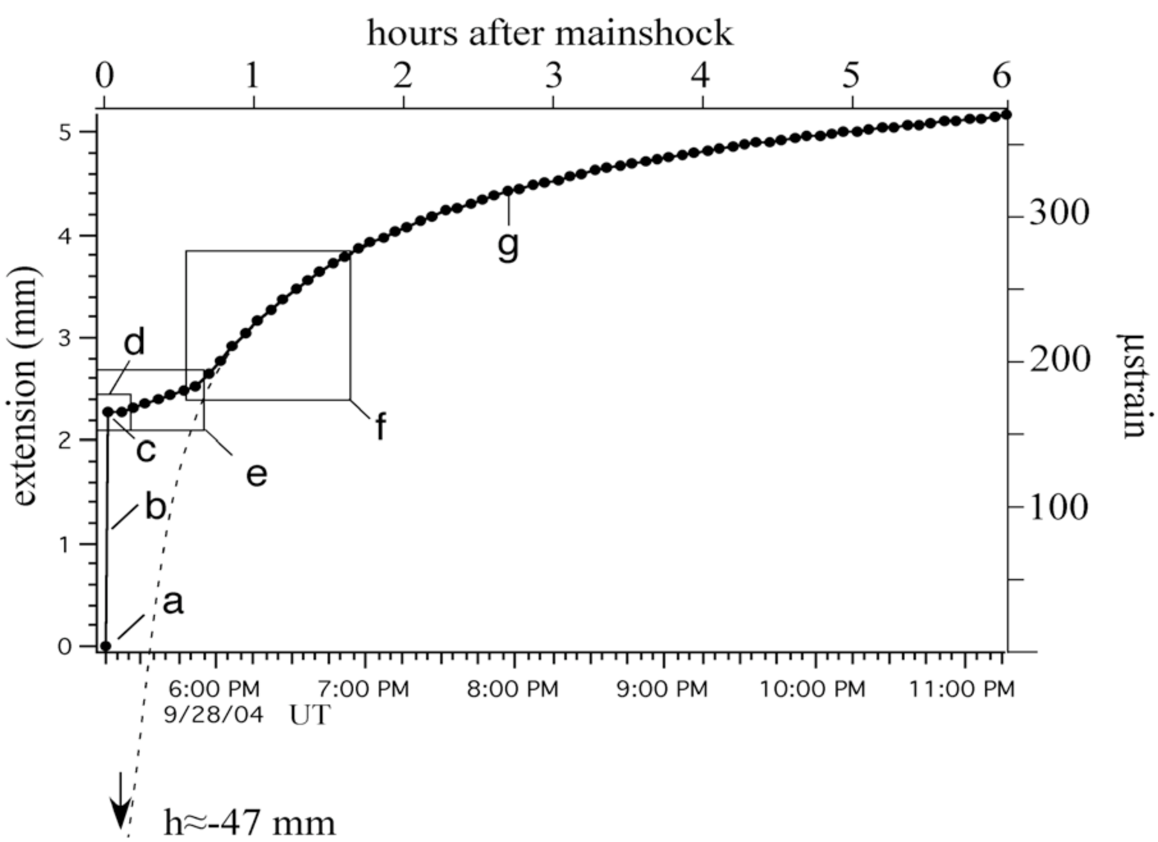


Figure 22 Five-minute samples from creep-meter coWR from before the mainshock to six hours following the mainshock. The axes are axial-displacement (not dextral fault slip), and linear strain at azimuth N94°W. Labeled features identified on the record are (a) data point 3 minutes before mainshock, (b) coseismic extension of 2.28 mm , (c) data point two minutes after mainshock, (d) first two post-seismic data points may correspond to instrument overshoot or backlash, (e) a linear ramp at 60 µm/s for ≈40 minutes followed by (f) a transitional acceleration

to (g), an exponentially decaying afterslip process. The exponents in the first hour of this decay process change significantly suggesting that although the transitional acceleration (f) appears to be only 15 minutes, it may have a duration of up to an hour. Data between 2-6 hours following the mainshock fit an exponential decay curve to within 0.1 mm permitting the curve to be extrapolated back to the time of the mainshock (h). At the time of arrival of s-waves from the hypocenter the extrapolated displacement applied to the creep-meter corresponds to ≈47 mm.

Coseismic fault strain above the Parkfield rupture

Creep-meters frequently record a process known as triggered slip whereby a surface fault slips during the passage of strong seismic waves from a remote earthquake (e.g. Schultz et al., 1990, Bodin et al., 1994). The data discussed here differ from these observations in that they represent a coseismic step in the plane of the mainshock-rupture, and close to the hypocenter. Slip on the surface fault has developed unevenly in time and space in the days following the mainshock (Langbein et al. 2006), and the Work Ranch site is near the southern end of the region of maximum surface slip. The following discussion concerns postseismic strain changes whose details are thus probably specific to the Work Ranch site.

The five-minute sampled record from Work Ranch increments by 2.279±0.006 mm between the two samples that bracket the mainshock (Figure 21). The absence of recognizable post-seismic surface rupture in the subsequent several days is interpreted to signify that the early creep signal does not measure dextral displacement, nor even fault zone shear. Instead it measures strain, and, to a first approximation, the strain is equivalent to homogeneous strain in an elastic half-space. The length of the creep-meter is 14.25±.25 m, and assuming that large accelerations in the earthquake caused no shift in the attachment piers (see discussion below), this corresponds to a strain change of 160±3.5 µstrain at azimuth N76W.

Thus, the initial step in the data represents surface-strain imposed by the M=6.0 rupture at depth, and the subsequent signal represents the increase in local strain arising from the approach of the shallow rupture towards the surface, at a rate moderated by presumably velocity-strengthening rheologies (Marone et al, 1993). Thus, before the development of recognizable surface fractures four days after the earthquake, the creep-meter acted as a strain-meter (Figure 5). After their development the extensometer continues to record strain since the fissures do not form a continuous linear rupture on which displacements can be observed. The distinction is more than semantic because in the absence of a surface offset there remains some doubt about the width of the extensometer required to capture the entire subsurface slip velocity.

Although surface strain had more than doubled (from 160 µstrain to 360 µstrain) 5 hours after the mainshock, no cracks or fissures were evident. The mean spacing between *en-echelon* fissures that eventually developed near the creep-meter (Figure 19) is 4-5 m suggesting that the maximum crack that could have developed at the end of 5 hours would have been 1.8 mm. The absence of coherent crack formation at this time suggests that the failure strain of surface soils exceeds 300 µstrain, or that surface strain at this time was accommodated in a broad area populated by randomly oriented desiccation cracks.

Of interest to this study is that no abrupt deceleration in measured displacement-rate is recorded by coWR that can be ascribed to the sudden growth of surface cracks. The development of a vertical crack near a horizontal strain-meter should reduce measured strain, if the crack is produced by elastic failure. Strain will reduce to zero if the crack is long and deep, but will be reduced significantly if the crack is comparable in dimensions to the length of the strain-meter. No reduction is slip is observed in the coWR data signifying that crack development was not associated with local strain release, but was driven by additional strain focused in the region by the afterslip process. Incipient cracks may have been present very early in the afterslip process with a wall separation too small to be visible, but it is more likely that the cracks propagated steadily to the surface through a fault zone of low tensile strength.

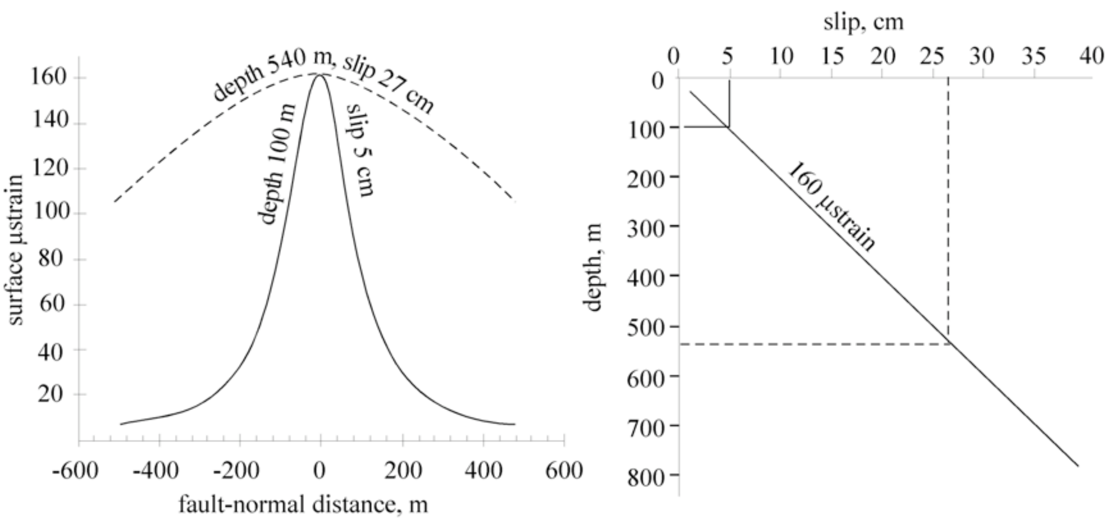


Fig. 23. Strain above a 2-D planar, buried dislocation extending to 12 km depth. Two illustrative curves (of many) are shown that yield a maximum strain of 160 μstrain at the surface fault. The dashed line indicates the deepest upper surface of a uniform dislocation that slips 27 cm, the mean slip inferred for the Parkfield 2004 earthquake.

That no decrease in strain occurred in the east coWR record after cracks were manifest requires that crack growth was driven by additional strain. This additional strain can be estimated to be of the order of 200-500 μstrain from the growth of strain recorded by the nearby WKR1 creep-meter, and the western extension to coWR.

I next estimate the size of strain changes anticipated from an upward propagating shear dislocation embedded in an uniform half-space. The strain at the surface above a buried planar strike-slip dislocation is a maximum at the future fault rupture (Figure 23). Using the 160 μstrain strain-step observed at Work Ranch and the average slip on the fault during the earthquake (27 cm) as constraints, the closest approach of the Parkfield rupture to the surface can be calculated. Uniform, planar, 2-D slip between 12 km and the shallow subsurface is an unreasonable constraint, but it reveals that the upper edge of such a dislocation would need approach within 540 m of the surface. However, the same surface-strain can be produced by smaller amounts of buried slip at shallower depths. For example, 1 cm of planar slip at 19 m will also produce 160 μstrain of surface strain. Slip presumably tapered towards the surface and a more realistic model will eventually be possible using additional strain and displacement constraints.

A second estimate of the shallowest depth of coseismic rupture follows from the observation that no cracks were visible at the surface up to 4 days after the earthquake, during which time linear strain increased from 160 μstrain to more than 500 μstrain. The precise moment that cracks appeared is not known, but because the strain increased slowly after the first day I assume that incipient crack formation occurred when approximately 400 μstrain had been recorded by coWR. The half-width of synthetic maximum strain is approximately equal to half the depth to the top of the dislocation (Figure 23), hence the maximum width of the zone of en-echelon cracks that eventually developed (4 m) suggests that the dislocation may have approached closer than 2 m to the surface. A slip of ≈5 mm will produce 400 μstrain of surface strain from such a shallow dislocation, however, the half-width of the strain-field from such a shallow dislocation, is much smaller than the length of the creep-meter, so that slip estimated in this calculation is too small by a factor of 2-3, i.e. an acceptable solution is for 8-14 mm of slip at approximately 5-10 m depth. The 10-18 mm maximum crack widths that had developed by 10 Oct at Work Ranch are approximately consistent with these estimates for shallow slip amplitudes.

Alternative explanations for a coseismic step

The coseismic signal recorded by creep-meter coWR has been assumed to correspond to separation between its attachment piers, resulting from tensile soil strain, or dextral fault slip. However, a defect of most soil-embedded objects, unless they are of identical modulus and density to surrounding soils, is that they tend to shift relative to their surroundings during high accelerations. Could an imperfection in the creep-meter have induced co-seismic rod contraction, or mount-settlement?

Since the accelerations during the earthquake are estimated to be 0.2-0.45 g near Work Ranch (Langbein et al., 2006), axial forces of up to 36 N were induced briefly on the eastern attachment point by the 8 kg mass of the invar rods. Forced displacement of this mount, or transient buckling of the rod, could thus be responsible for the observed coseismic signal. The diameter of the telescopic PVC tube is 4 cm, and hence a 2.6 mm shortening in rod length due to buckling would require a saw-tooth buckle with an amplitude 34 mm and quarter-wavelength of 2 m. This is considered unlikely because a spring between the free-end of the rod and the nearby mount maintains the rod in tension, and shaking would tend to straighten the rod rather than shorten it. Static loading of the mount by 55 N, causes fewer than 12 μm of displacement, but the effects of high-frequency prolonged 3-D dynamic shaking on soils surrounding the low-density vaults are essentially unpredictable. Accelerations at coWT, where a 23.5 mm coseismic displacement may have occurred, were in the range 0.65-1.3 g, causing nearby liquefaction in the valley floor (Langbein et al., 2004)

Some of the creep-meters operating in Parkfield use wires in tension, so that dynamic forces on the end-attachment points from these length-standards are essentially negligible. Yet the sense of co-seismic strain recorded by these creep-meters is also tensile (the direction of dextral slip), including data from the somewhat noisy creep-meter x461, which is installed at an azimuth where dextral slip results in approach of its two attachment piers. Coseismic shaking stimulates a "bow-string" mode and a pendulum mode in suspended wires, both of which result in apparent shortening of the length-standard, i.e. ground extension. This would have been transient and probably damped after a few minutes. Unpredictable settlement of these creep-meter vaults and attachment piers during the dynamic shaking of surrounding soils presumably means that the precise amplitudes of these coseismic strain increments are also subject to uncertainty.

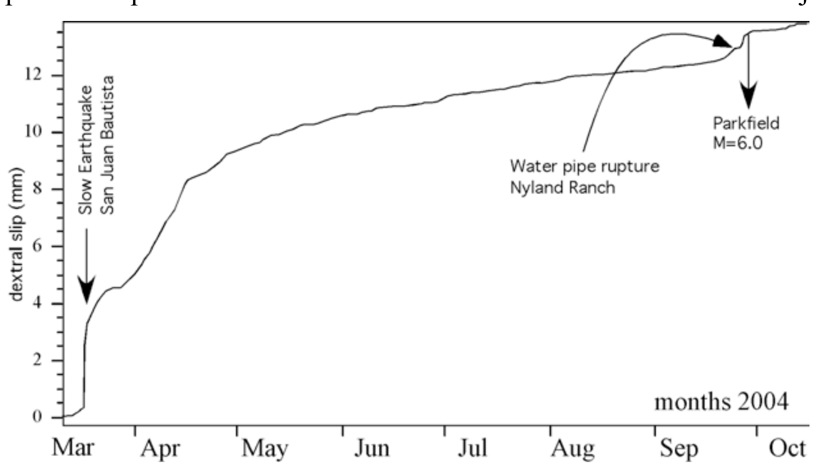


Figure 24 Creep data from Nyland Ranch, north of San Juan Bautista, showing the fracture of a water pipe caused by a small creep event three days before the Parkfield earthquake. Although the creep rate here has averaged 7 mm/year for the past three decades, surface creep following a

slow earthquake occurred in March 2004 that almost doubled the annual slip in just 6 months. The effects of the slow earthquake were confined to the northernmost 10 km of the 125-kim-long creeping zone.

Rupture of water pipes before Parkfield earthquakes

Despite its intriguing predictive possibilities, the observation of a ruptured water pipe prior to the 1966 mainshock was considered by most scientists to be a random occurrence, the result of slow stressing following decades of cumulative creep on the surface fault. The absence of preseismic acceleration on the fault in 2004 confirms this supposition.

However, a pipe did indeed shatter 3 days before the 2004 Parkfield earthquake (Figure 24). The coincidence occurred on 26 Sept 2004 some 125 km north of Parkfield where a pipe crosses the northern end of the creeping zone near San Juan Bautista. Obviously, there is no link between this pipe-break, and the recent earthquake, and fortunately we possess a quantitative creep record from a creep-meter fewer than 2 m from the water pipe that records its recent approach to failure. (Figure 24). Creep on the fault here has proceeded at a rate of 7 mm/year for many decades (Sylvester,2004), interrupted by retardations and accelerations linked to slow earthquakes in the subsurface (Linde et al., 1992). A slow earthquake near Nyland Ranch in March 2004 was followed by 13 mm of surface fault-slip. The pipe finally failed during a 1 mm creep event on 25 September at Nyland ranch.

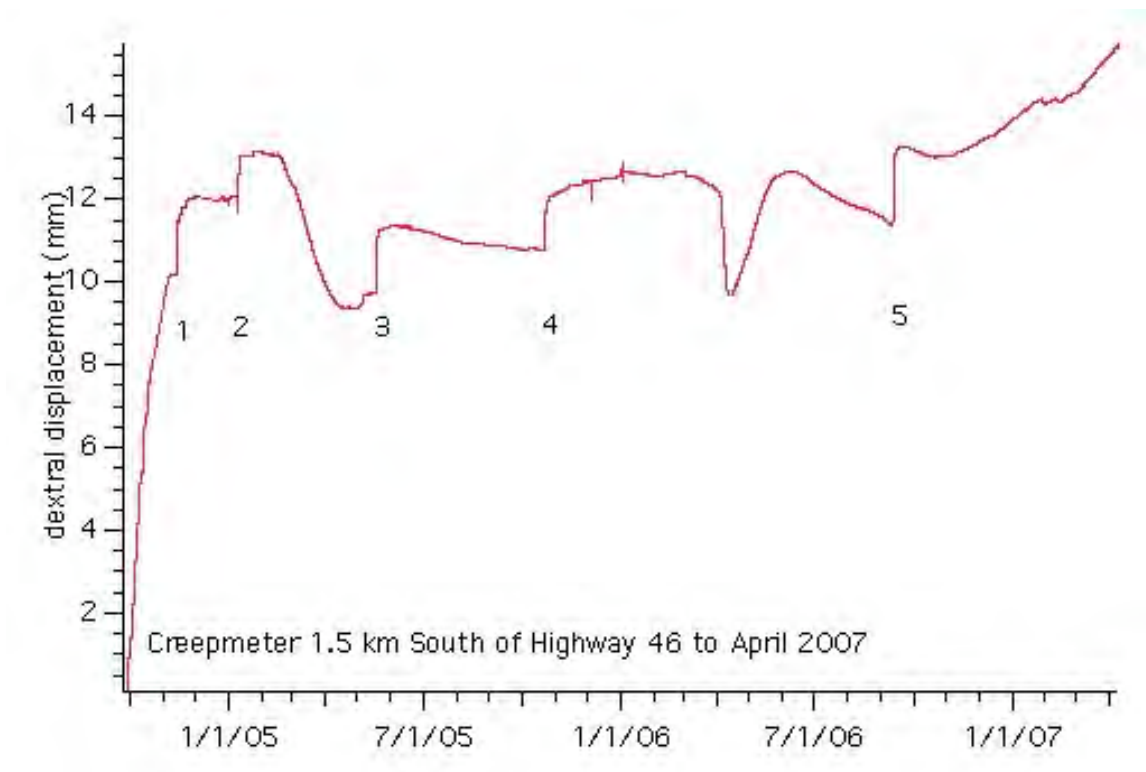


Figure 25A Two years of Parkfield afterslip south of Highway 46. Most of the afterslip occurred within a few months of the earthquake in a sequence of 1 mm creep events (Fig. 20.) These continued with decreasing frequency until late 2006. Another event may occur in 2008. Five 1-mm-amplitude creep events occur as impulsive dextral slip events (see figure 25B) Apparent sinestral slip between these events is caused by soil expansion following times of wet weather.

Co46 Parkfield Multiple creep events occurred in 2005 and one in 2006 with a total surface slip of 14 mm since the Parkfield mainshock. Figure 25A illustrates that the signal between creep events should be ignored since reversals in trend are caused by soil moisture changes that result in slow interevent strain changes. In contrast, the creep events are abrupt. The most recent five are numbered on Figure 25A.

Three 2005 creep events from co46 (1, 3 and 4) are shown to illustrate their repeatability in amplitude (≈1.2 mm) and duration (<12 hours). Their similarity suggests they are driven by subsurface stresses independent of soil conditions, but their small amplitude suggests that they are occurring at shallow depth (<<1 km). The increasing intervals between these events is related to the decreasing rate of subsurface slip following the Parkfield mainshock.

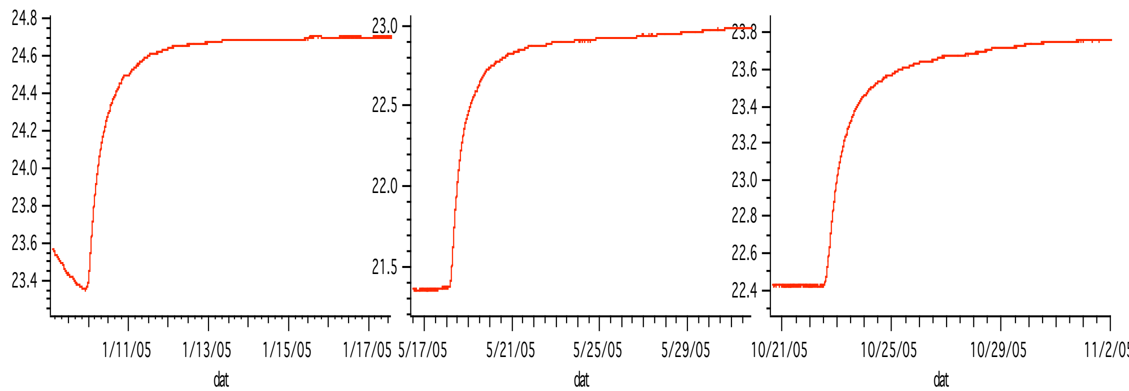
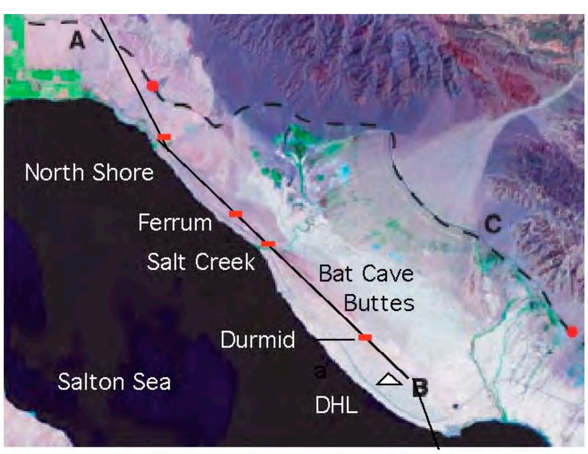


Figure 25B shows the similarity in duration and amplitude of creep events that have occurred south of Highway 46 (Events 1, 3 and 4 from Figure 25A). Time intervals increasing between these events suggest that the next one is not due until 2008.

Southern California Creep meters



The last part of this report describes data from the creep meters in the Coachella Valley**.** Three are located on the southern San Andreas Fault at Durmid Hill and one on the Superstition Hills fault described above. We have initiated a search for new sites near Indio and the Mecca Hills but have found none that we can reliably instrument without inviting vandalism.

Figure 26 Location of creep meters relative to the long baseline strain meter (DHL) on Durmid Hill.

coFE Ferrum (33.4572°N , 115.8538°W) is the most northerly of three creep meters that operate on Durmid Hill. The instrument is completely buried at 50 cm depth beneath a disused rail track (see front cover of SRL for August 2004). Its ends are cemented to shales and the length standard is a graphite rod. The system was installed in March 2004 and runs on AA cells for a year. Since September 2006 its data have been transmitted for public access using a solar panel system and a satellite transmitter.

The creep rate averages 2.6 mm/year with retardation evident in the winter months of 2005 and 2007 presumably related to seasonal cooling or desiccation. A pair of ≈1 mm amplitude creep events occurred in December 2005. No triggered slip accompanied the local M4.2 earthquake in the first few days of June 2007 at Indio (this record ends 1 July 2007)

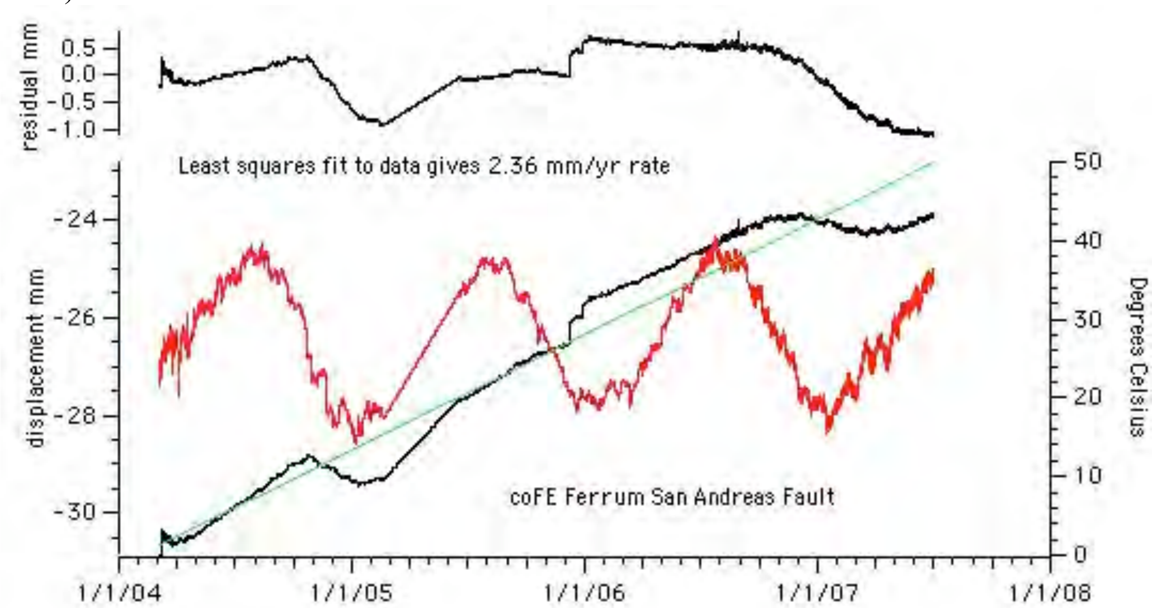


Figure 27 Data from Ferrum on the southern San Andreas Fault. Red trace is temperature at 50 cm depth.

coSC Salt Creek (33.44855 N 115.8437 W) The March 2004 instrument is a retrofit to the 1970's Caltech instrument that had fallen into disuse. After a number of trial geometries the retrofit consists of a transducer bolted directly between the original stainless steel wire and the underground pipe where it is welded to the access culvert. The obliquity of the wire to the fault is ambiguous since the location of its buried eastern end is unknown. Trains cause the beam balance that holds the wire in tension to resonate and there is a strong thermal signal from the stainless steel. The data are first corrected for temperature effects by obtain a regression between the displacement in mm and the measured temperature in the wire. The regression coefficient is then used to subtract the temperature correlated component. A residual drift of less than 1 mm year is evident in the data, and since this is contractional the data are detrended to indicate zero slip on the fault for periods of time when no obvious creep events occur. To some extent the resulting figure is misleading since it does not reflect the creep rate on the fault measured at Ferrum or Durmid. The non-thermally corrected data, however, are too noisy to make definite conclusions about long term drift. Vandalism occasionally occurs at this location resulting to damage to external cables and locks, although as yet no data have been lost.

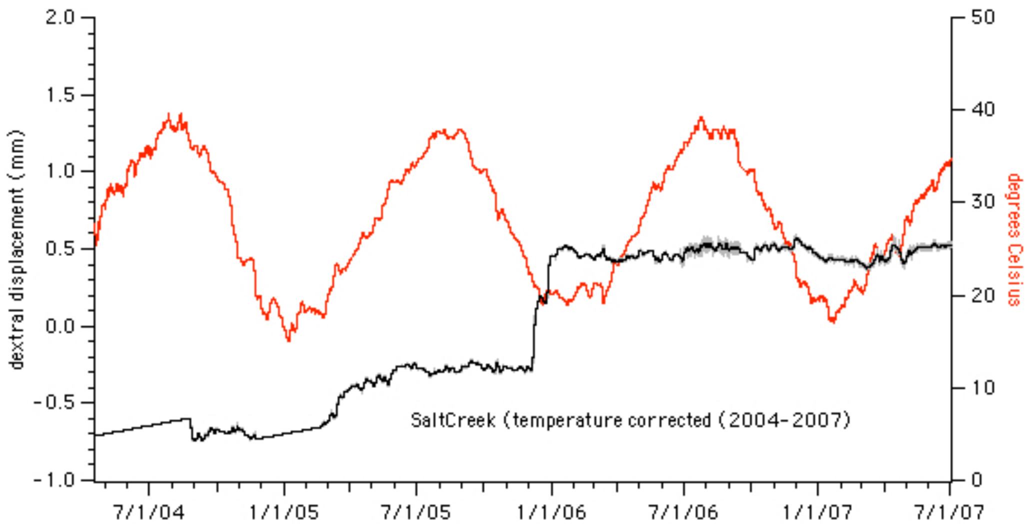


Figure 28 Creep data from Salt Creek corrected for thermal effects. Red trace is temperature at 80 cm depth in length-standard tube.

Since September 2006 data have been transmitted for public access using a solar panel system and a satellite transmitter. (user=geo, password=hobo) https://datagarrison.com/users/1101128/E5NDG1/plots.php?plot=1. The large thermal coefficient of the creep meter wire, which is expressed as an anti-correlation with the system temperature, is obvious in these on-line plots, and it is remarkable that the corrected data show seasonal noise levels of less than 0.2 mm.

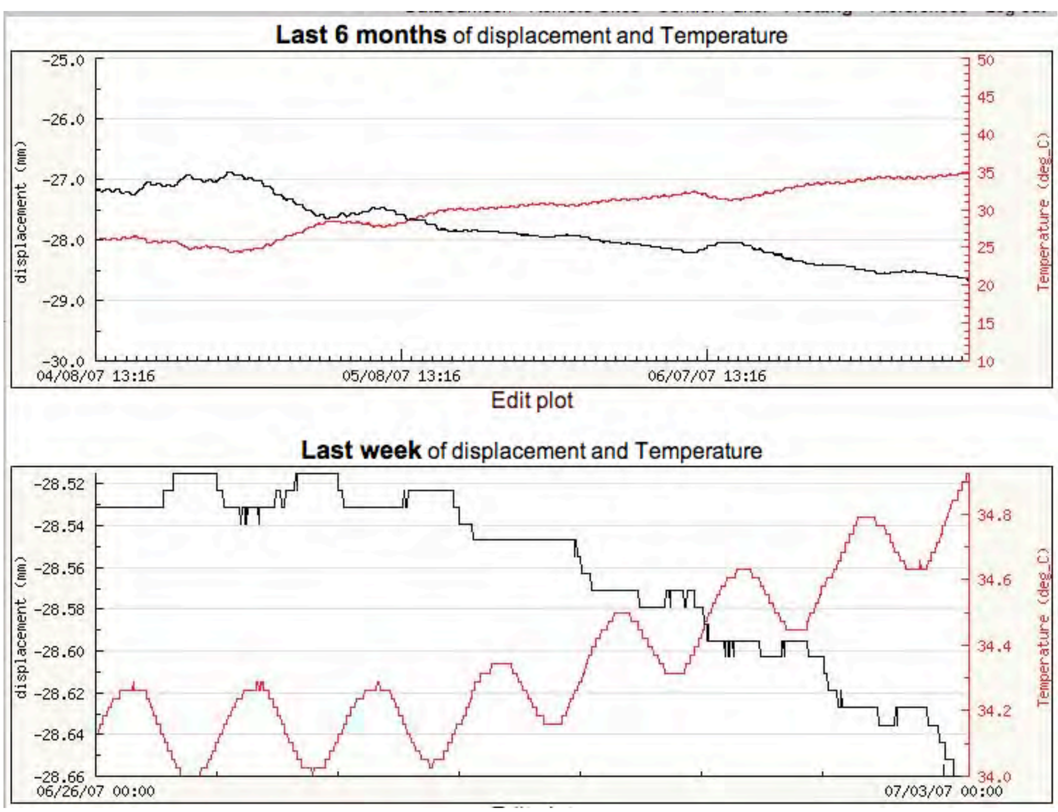


Fig 29 Online data from Salt Creek satellite telemetry showing daily and seasonal variations.

Durmid Hill CoDU 33.4147 N 115.7985 W This instrument is the southernmost creep meter on the San Andreas Fault and is completely buried. It uses a graphite rod, which is largely immune to direct thermal effects. A thermoelastic signal is present with an amplitude of approximately 1 mm.

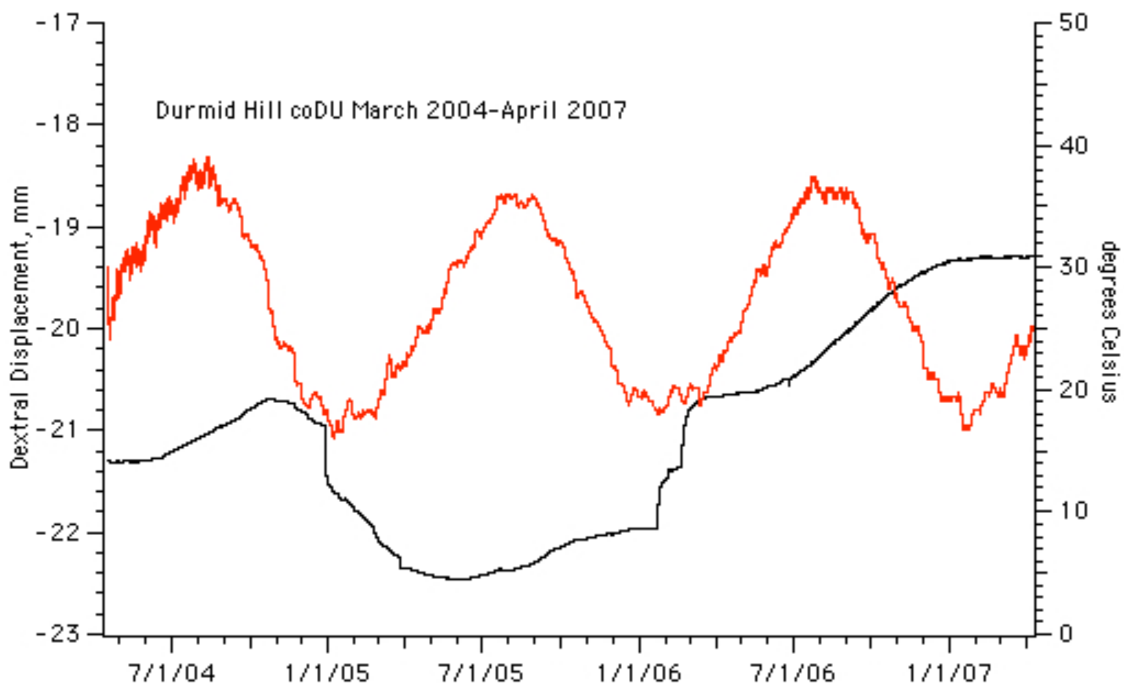


Fig 30 Data from the autonomous creep meter at Durmid Hill. Red is seasonal temperature variation

An unusual, but small (0.5 mm) left-lateral creep event creep event occurred in the days following the Sumatra Mw9.15 earthquake which initiated left lateral slip for the following 6 months. Curiously the left lateral offset from this event and is aftermath was almost precisely matched by the right lateral offset in two dextral creep events that occurred more than a year later.

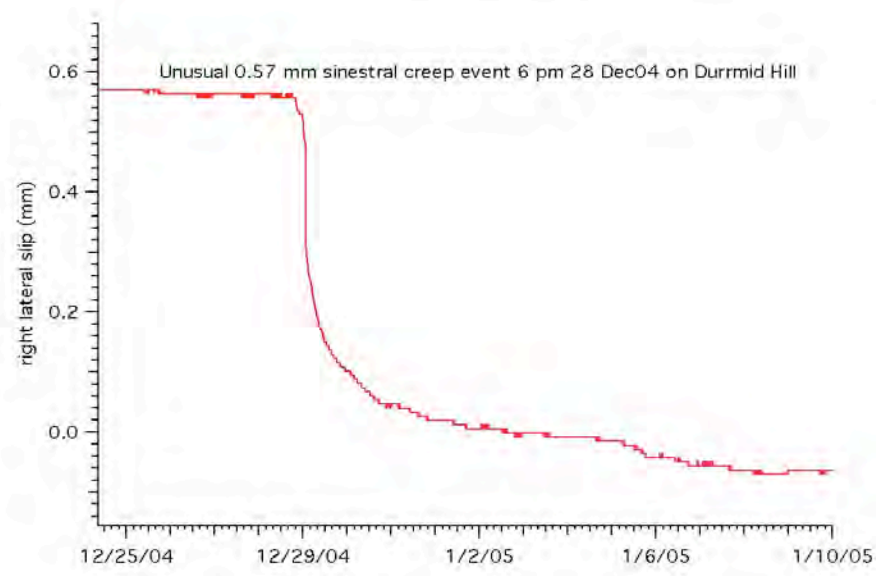


Figure 31 Left lateral creep event on Durmid Hill following the Sumatra earthquake

Figure 31. Location of the Superstition Hills Creep meter coSH

Superstition Hills Fault 33.72824°N, 116.23171°W Imler Road, Coachella Valley.
A most unusual 27 mm amplitude creep started on 3 October 2006 and continued with decreasing vigor until December. The character of this event is clearly expressed in Fig.3. Small creep events (<0.5 mm amplitude, 2 day duration) on the Superstition Hills fault occurred 10 August 2005, and 19 Jan 2006, which together with a background creep rate of 1.33 mm/year had established a mean creep rate from March 2003 to September 2007 of 1.35 mm/yr. This rate was interrupted by 27 mm of incremental slip that occurred mostly over a period of two days but continued as small events for the next two months, before settling down in January 2007 to an almost linear rate of 3.22 mm/yr.

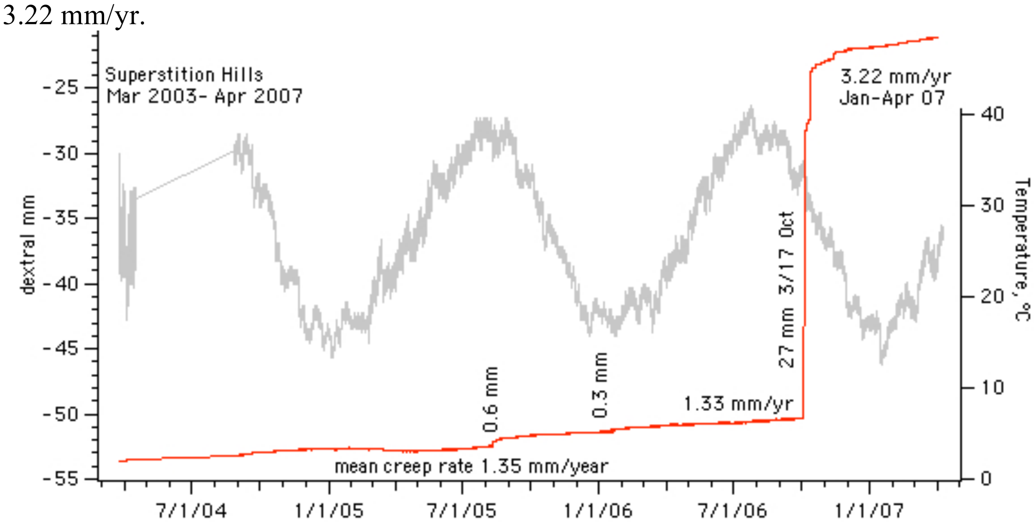


Figure 32 Between 3 and 17 October 2006 an unique 27 mm amplitude multiple creep event occurred that by January 2007 had established a new creep rate on the fault of 3.23 mm/yr, more than twice its previous creep rate. The creep event caused >20 mm of discontinuous dextral

cracking on the surface for a distance of at least 10 km. The details of the individual slip episodes that formed this multiple creep event are shown in Figure 33 & 34.

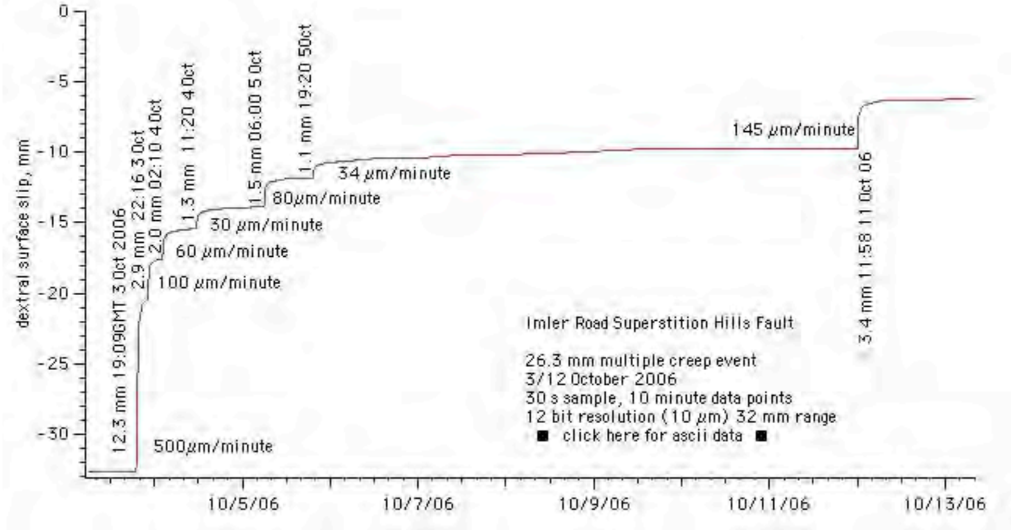


Figure 33 The October 2006 creep event on the Superstition Hills Fault consisted of at least seven* events whose occurrence interval decayed exponentially in time until 11 December. The large event in the first hour may have been formed from 3-4 subevents (See Figure 34). The graph is a facsimile of the web page from which numerical data may be downloaded. *The time history suggests that at least 3 more are aliased in the first hour (see fig. 34)

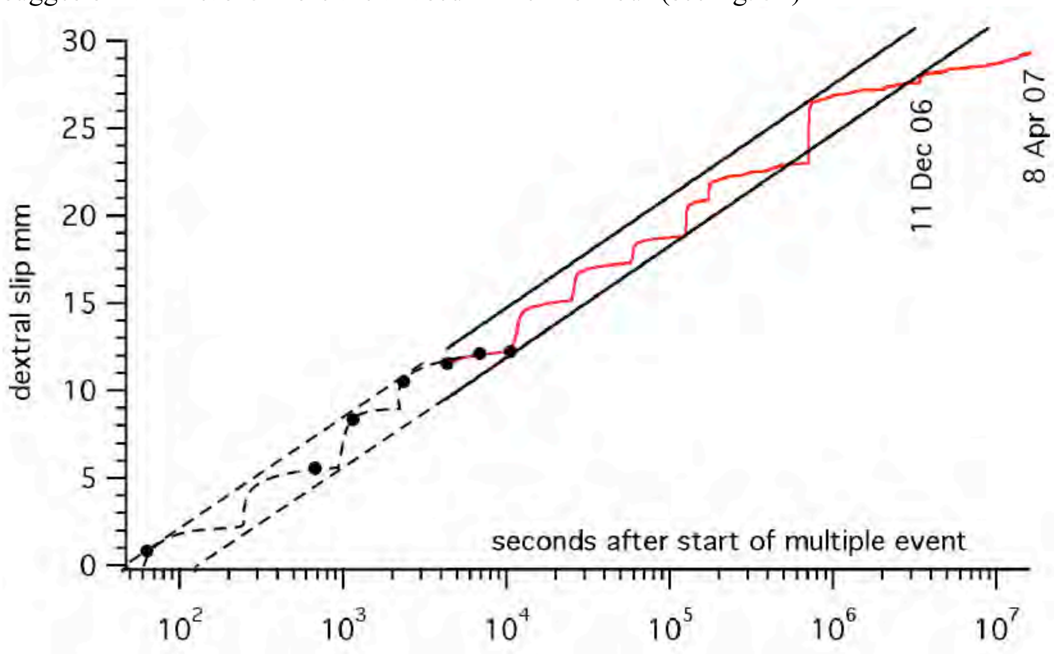


Figure 34 A log/lin plot of the creep sequence 3 Oct to 17 April 2007 extrapolated towards the start of the sequence (dashed lines). It appears very probable that at least three early sub-events were sampled incompletely by the 10 minute sampling of the data logger.

The well-behaved exponential increase in time between individual events within a ±1.5 mm displacement band between 3 Oct to 11 Dec 06 suggests that at least three earlier events were aliased by the 10 minute recording interval in the first hour of the slip sequence (dashed in fig. 34). The lower line in Fig. 34 indicates the approximate displacement/time limit before which a creep event must occur and the line 3.5 mm above it represents the approximate slip limit (a proxy for strain release) for individual events. The seven dots indicate measured displacement from the pre-event datum; thereafter the data are shown as a continuous line. The samples are all at ten minute intervals but the origin time of the event has been approximated to be 15 seconds before the first data point. Four ≈3 mm events are shown as a dashed curve, although other scenarios are possible.

After 11 Dec 06 strain driving surface slip was sufficiently depleted such that an anticipated 3 mm creep event around this time was represented by a 0.5 mm event. After this time the creep rate on the fault diverged from the logarithmic decay characteristic of the October sequence, and a background creep rate took over. This new background creep rate appears to have been established on the log/lin curve before in December 2006. Steady creep on the fault now occurs at roughly 3.22 mm/year, a rate that is more than double its pre-October 2006 rate.

We note that the 28 mm of creep event is equivalent to 9 years of creep at its current rate, or 20 years of creep at its pre-1906 rate. Bob Sharp Jr. is remembered as having reported a similar large creep event on the Superstition Hills fault and associating it with a pressure front passing through the area about ten years ago. We and others have been unable to trace a written record of his observation.

During the time of this unusual episode on the Superstition Hills fault the San Andreas fault showed no change in creep rate and there were no seismic events nearby. The effect is thus purely local and linked to the afterslip process here that started immediately after the 1987 Superstition Hills earthquake. Figures 7 and 33 summarize creep rates from southern California prior to this creep event.

Conclusions

Three findings from the past three years of work conspire to relegate fault creep measurement to a tectonic relevance of less significance than ever before:

1. Surface creep does not precede moderate earthquakes

No surface fault slip, or significant strain preceded the September 2004 Parkfield earthquake. The rupture of a pipe before the 1966 Parkfield earthquake can now be classified, somewhat confidently, as a coincidence resulting from prolonged stressing in the fault zone in the decades prior to 1966. A similar pipe failure occurred at Nyland Ranch, at the northern end of the central California creeping zone three days before the 2004 Parkfield earthquake and in the absence of measurements, this might have become another Parkfield-like precursor legend, but in this case a nearby creep-meter records the decadal development of creep at Nyland Ranch at a rate of 7-8 mm/year. A slow earthquake added an additional 13 mm of slip between March and September 2004. The final millimeter that broke the pipe consisted of a small creep event that was recorded at about the same time on the XSJ2 creep-meter at San Juan Bautista.

2. Surface cracks are delayed by the slow approach of rupture to the surface

Not only was there no surface slip preceding the Parkfield earthquake, there is clear evidence that surface slip was delayed by minutes and days after the mainshock. A coseismic signal present on the creep-meters at the time of the 2004 earthquake, although possibly contaminated by instrument settlement, is interpreted as tensile strain associated with subsurface rupture. Simple elastic models suggest that, at Work Ranch, the subsurface rupture must have approached at least to within 540 m of the surface during mainshock rupture. This conclusion is derived from elastic models of surface strain resulting from 27 cm of uniform slip on a simple planar fault. Closer approach to the surface with smaller amounts of slip is also possible (e.g. slip of 8 to 14 mm at 5 to 10 m depth respectively. Closer approach is likely to have produced surface fractures that were not observed until several days later.

Surface fissures at Work Ranch Parkfield only appeared after measured strain exceeded 400 μstrain. Because no relaxation in the monotonic increase in strain was recorded by the eccentric creep-meter at coWR, at the time of their development, cracks and fissures did not release stored elastic strain when they formed near the surface. Instead their growth appears to have been driven by additional strain presumably propagating towards the surface from below.

3. Surface 28 mm slip-sequence on the Superstition Hills Fault: very late 1987 afterslip

A further blow to the significance of fault creep as an earthquake precursor is that substantial slip can occur without being associated with contemporaneous local seismicity. Surface cracking and slip mostly between 3 and 17 October 2006 on the surface expression of the Superstition Hills fault was very probably caused by the late release of accumulated afterslip from the 1987 earthquake. More than a meter of afterslip had been recorded at this location 19 years previously and the slip in 2006 amounted to less than 3% of the total, equivalent to more than a decade at previous background creep rates. No local earthquakes occurred nearby and the creep rate on the southern San Andreas fault remained unaffected. One interesting effect is that the slip rate following the sequence (3 mm/year) remains more than double its pre-sequence rate suggesting a change in the frictional properties of the fault zone. An alternative intepretation is, of course that slip is faster because of an increment in applied shear, but this appears unlikely giving the absence of other evidence for increased strain rates.

Future Work The findings listed above are not without scientific interest, they are merely without public utility. In my opinion they eliminate fault-creep from consideration for use in short term earthquake prediction. However, despite this somewhat discouraging conclusion, aspects of slip on the Hayward fault suggest that creep processes may be linked to microseismicity, that may provide insights into future seismicity on the fault. Steady Hayward fault creep is interrupted by small creep events at Oakland and Fremont. An unusual 2-3-month-duration creep sequence at Oakland Zoo was associated with local microseismicity in early 2003, and a second larger event 21 July 2004 resulted in 6.5 mm of slip.
http://cires.colorado.edu/~bilham/CREEPDATA/OaklandZooWeb/ZooCreepEvents.htm
This suggests that continued measurements of creep on the Hayward fault are important. In that creep rates are remarkably steady beneath a veneer of seasonal noise, methods to suppress surface hydraulic and thermal noise would be of value, including methods to measure creep at depths of 10 -20 m from the surface using borehole instrumentation. Similarly an improved installaion a Nyland ranch is merited since slow earthquakes are here common. Improved installations were proposed but not funded for the follow-on continuation of the measurements described here.

The largest recorded signal that remains unexplained in the past three years concerns the left lateral slip event on Durmid Hill that occurred within a few days of the 2004 Mw=9.15 Indonesian earthquake. The uniqueness of this 0.5 mm sinestral slip event and its occurrence after this massive earthquake could, however, have been a coincidence.

References

Andrews, D. J., Oppenheimer, D. H., and J. J. Lienkaemper, The Mission link between the Hayward and Calaveras faults, *J. Geophys. Res., 98*, 12083-12095, 1993.

Bakun, W. H., Seismic Activity of the San Francisco Bay Region, *Bull. Seis. Soc. Amer., 89*, 764-784, 1999.

Bilham, R., Surface slip subsequent to the 24 November 1987 Superstition Hills, earthquake,

California, monitored by digital creep-meters, Bull. Seism. Soc. Amer., 79(2), 425-450, 1989.
Bilham, R., Borehole Inclinometer Monument for Millimeter Horizontal Geodetic Control Accuracy, *Geophys. Res. Lett.* 20, 2159-2162, 1993.
Bilham, R., and S. Whitehead. Subsurface Creep on the Hayward Fault, Fremont California, *Geophys. Res. Lett.* **24**, 1307-1310. 1997.
Bilham, R. Co-seismic strain and the Transition to Surface Afterslip recorded by Creep-meters near the 2004 Parkfield epicenter. *Seism. Res. Lett.* 76(1), Jan. 2005
Bilham, R, N. Suszek and S. Pinkney, California Creep-meters, Seism. Res. Lett. 75(4), 481-492. August 2004
Bodin, P., R. Bilham, J. Behr, J. Gomberg, and K Hudnut, Slip Triggered on Southern California Faults by the Landers, Earthquake Sequence. Bull. Seism. Soc. Amer. 84(3), 806-816, 1994.
Bruce A. Bolt and Walter C. Marion Instrumental measurement of slippage on the Hayward fault , *Bull. Seis. Soc Am* (1966), 56(2):305-316
Langbein, J. O., R.O Burford, and L. E. Slater, Variations in fault slip and strain accumulation at Parkfield, California: Initial results using two color geodimeter measurements, 1984-1988, *J. Geophys. Res,* 95, 2533-2552, 1990.
Langbein, J., J. R. Murray, and H. Andrew Snyder Coseismic and initial postseismic deformation from the 2004 Parkfield, California, earthquake, observed by Global Positioning System, electronic distance meter, creep meters, and borehole strainmeters (*in* Special issue on the 2004 Parkfield earthquake and the Parkfield Earthquake Prediction Experiment)*Bull. Seis. Soc Am.* (September 2006), 96(4B):S304-S320
Lienkaemper, J. L., (2001), 1857 Slip on the San Andreas Fault Southeast of Cholame, California, Bull. Seism. Soc. Amer., 91(6) 1659-1572.
Lienkaemper, J. J., Galehouse, J. S., and R. W. Simpson, Long-term monitoring of creep rate along the Hayward fault and evidence for a lasting creep response to 1989 Loma Prieta earthquake, *Geophys. Res. Lett., 28*, 2265-2268, 2001.
Lienkaemper, J. L., (2001), http://pubs.usgs.gov/ds/2006/177/
Lienkaemper, J. L., (2001) Map of Recently Active Traces of the Hayward Fault, Alameda and Contra Costa Counties, California, U.S. Geological Survey Miscellaneous Field Studies Map MF-2196 1992
Linde, A. T., M. T. Gladwin, M. J. S. Johnston, R. L. Gwyther, and R. Bilham, 1996. A Slow Earthquake near San Juan Bautista, California, in December, 1992, Nature., 383, 65-68.
Marone, C.J., C.H. Scholz and R. Bilham, On the Mechanics of earthquake afterslip, J. Geophys. Res., 96, 8441-8452, 1991.
Schultz, S. S. Catalog of creep-meter measurements in California from 1966 through 1988. U.S.G.S. Open File Report 89-650.
Schultz, S., Mavko, G., and Brown, B., 1990, Response of creep-meters on the San Andreas fault to the earthquake, in: The Coalinga, California, Earthquake of May 2, 1983, Rymer, M.J. and Ellsworth, W.L., eds., U.S. G. S. Professional Paper, P1487, 409-417.
Smith, S. W. and M. Wyss, Displacement on the San Andreas fault subsequent to the 1966 Parkfield earthquake, Bull Seism. Soc. Am. 58, 1955-1973, 1968.
Sylvester, A, (2004). http://www.geol.ucsb.edu/projects/geodesy/nail_lines/ X0070_NYLAND _RANCH_NL.html
Waldhauser, F., and W. L. Ellsworth, Fault structure and mechanics of the Hayward fault, California, from double- difference earthquake locations, *J. Geophys. Res., 107*, 10.1029/2000JB000084, 2002.
Yamashita, P. A. and R. O Burford (1973), Catalog of preliminary results from an 18 station creep-meter network along the San Andreas Fault system in central California for the time interval June 1969 to June 1973, U. S. Geol Survey Open File Report.

Non technical Summary (100 words)

The largest aseismic slip measured in recent years on California faults consists of afterslip following the 2004 Parkfield earthquake. Between July and December 2004 a 6 mm creep acceleration event occurred in Oakland on the Hayward fault, and in October 2006 an unusual 28 mm slip event occurred on the Superstition-Hills fault, which has doubled its pre-2006 creep rate. The rate on faults elsewhere is unchanged from previous years. South of Highway 46, the southern end of the 2004 Parkfield rupture now slips at less than 1 mm/year. Creep rates in the Coachella Valley are 1-3 mm/yr.

Reports published

Bilham, R, N. Suszek and S. Pinkney, California Creep meters, *Seism. Res. Lett.* 75(4), 481-492. August 2004.

Bilham, R. Co-seismic strain and the Transition to Surface Afterslip recorded by Creep-meters near the 2004 Parkfield epicenter. *Seism. Res. Lett.* 76(1), Jan. 2005

Availability of data : Three methods are available for unrestricted public access to numerical or graphical data

1. Hayward Creep data are available at the USGS website
http://quake.usgs.gov/research/deformation/monitoring/downloadcreep.html
http://quake.usgs.gov/research/deformation/monitoring/sf.html

2. GMT time-tagged and calibrated creep data are available on the web in graphic or numeric form at

http://cires.colorado.edu/~bilham/
and a clickable table and map is available at
http://cires.colorado.edu/~bilham/CREEPDATA/HaywardCreepmeterAccess.htm

3. Finally today's calibrated data are available directly from a web browser
www.datagarrison.com
enter the user name **'geo'**
enter the password '**hobo**'
click on the instrument of interest and view data, or **download data** in three-column text format: time, temperature and voltage. The data are in °C and calibrated dextral slip and the time in GMT. The header gives the calibration in dextral mm/volt