Creepmeters on California Faults

USGS 14-08-001-G1876

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We maintain more than a dozen digital creepmeters across active faults in California. The creepmeters can detect motions as small as 10 microns and are located where an earthquake has recently occurred or has a high probability of occurring. Data from the creepmeters are being used to determine the details of fault movement. For example, the Loma Prieta earthquake has evidently resulted in increased strain being applied to the San Andreas fault north of the town of San Juan Bautista. Experiments have revealed that the Superstition Hills fault in southern California can slip smoothly at a rate of less than 1 micron per day, whereas at depths of a few hundred meters the fault will slip episodically by up to 15 mm. At depths greater than 3 km earthquakes account for all the slip on the fault. The same type of behaviour appears typical of other parts of the San Andreas system. We hypothesize that the slow surface fault slip might be a useful indicator of strain applied to the fault, and the ratio of slow surface slip to deeper episodic slip might be an indicator of the stress applied to the fault. Monitoring these parameters may provide a new method of examining faults that are thought to be close to seismic rupture.

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Investigations:

1. We maintain 13 digital creepmeters across active faults in California (Figure 1). The creepmeters are designed to record data once per minute during creep or seismic slip of the fault and once per hour during times of fault inactivity. A decision to retain high data-rates is made if the mean fault slip velocity exceeds 500 μm/hour. The creepmeters have a resolution of 10 microns and a minimum range of 15 cm. Creepmeters in selected seismic gaps, at the southern end of the Parkfield region, and near Anza have ranges up to 1 m. The creepmeters are typically 5-10 m long, but one creepmeter monitors the 110-m-long abutment-separation of Chittenden bridge across the San Andreas fault south of Loma Prieta. The instruments are visited three times each year to collect their recorded data.

2. We have designed experiments to distinguish between soil processes and displacement on surface faults. The experiments are also designed to search for the existence of strain stored close to the fault which may be released during creep events. These experiments use co-linear pairs of identical extensometers, one of which is installed across the fault and one is not. The difference signal, in principle, contains only fault slip.

3. We have examined published accounts of vertical and sinistral creep data from the Xianshuihe fault in eastern Tibet to test the possibility that creep on this fault is similar to steady state creep in central California.

4. We retain four creepmeters in readiness for monitoring afterslip in a future earthquake. Each creepmeter can be installed within 24 hours of an earthquake in California. To facilitate early alert of a California event we have implemented in Boulder the Caltech PDE active display system for earthquakes in southern California.

Results:

1. Episodic afterslip continues on the Superstition Hills fault at approximately 28 mm/year (Figure 2). Creep episodes consist of three or more events with individual slip amplitudes of more than 8 mm and cumulative amplitudes of up to 14 mm (Figure 3). We have recorded creep events on the Imperial fault south of the Mexican Border at Saltillo, on the San Andreas fault 2 km south of Highway 46 near Parkfield, and at Nyland Ranch north of San Juan Bautista. Nyland Ranch fault creep continues at a rate of 20 mm/year which is approximately 3 times higher than the mean creep rate for the past 20 years (Figure 4). No significant cumulative creep has been recorded at Indio or Durmid Hill on the southern San Andreas fault. Creep events with amplitudes >2 mm have been detected on the San Andreas fault south of Highway 46. Although a cumulative dextral offset of 4 mm has occurred since Dec18 1990, we observe two episodes of sinistral slip in March (0.7 mm) and May (1 mm).

2. Slip on the Superstition Hills fault between creep events occurs at a rate of roughly 2.4 mm/year, a factor of ten slower than the annual rate attributable to episodic slip. We suggest that this background slip occurs near the surface, and that deeper parts of the surface fault creep episodically. The ratio of velocities is proportional to the ratio of base depths of these two processes. Thus if episodic creep

extends 3 km from the surface to the top of the coseismic rupture zone, steady state creep is limited in depth to approximately 300 m (Figure 5).
We observe that background creep is a common attribute of many creeping faults. Two properties of our model may prove useful for monitoring time-dependant variations in strain and stress applied to a creeping fault: the background creep signal is a linear measure of strain applied to the fault, and the ratio of the episodic to background creep velocity may depend on, among other variables, the amplitude of in-situ fault normal stress.

We report further that we observe less than 1 μstrain of linear strain release close to the fault zone at the time of creep events with slip more than 1 cm, suggesting block-like motion of the surface fault. We conclude that fault-normal stresses are essentially zero at the surface.

3. Although recent creep data from the Xianshuihe fault suggest steady-state sinistral creep, an alternative and more likely interpretation is that surface creep was initiated as afterslip following the 1973 Luhuo earthquake and is currently decaying slowly. Supporting this view we observe that creep measurements prior to the earthquake do not exist, and that creep is restricted to parts of the fault that have slipped recently during earthquakes. The sinistral creep data, unlike the dip-slip data, were not recorded for the first four years following the Luhuo earthquake. However, we found that the horizontal and vertical slip signals are related by a linear ≈8.3 scaling factor for the eleven years for which they are available simultaneously (Figure 6). By assuming that this correlation holds for the missing early years of sinistral slip we infer that up to 24 cm of slip may have occurred on the fault since the Luhuo earthquake (more than doubling previous estimates), and that this slip is a manifestation of afterslip. The absence of steady-state creep on the Xianshuihe Fault leaves the San Andreas system a unique location for this style of aseismic slip.

4. A display of southern California earthquakes is currently operating on an IBM compatible system under control of software developed by Caltech and loaned to us by Egill Hauksson. The data are forwarded to us from Caltech using an E-mail scheme into which address we also receive worldwide PDE data from the Global Seismology branch of USGS Denver. We envisage developing a future display that will alternate between a world map and a California map showing significant earthquakes within minutes of a PDE availability. We wish to thank Egill Hauksson and Waverly Person for their assistance in facilitating these displays.

Publications:

Behr, J., R. Bilham, P. Bodin, R. Burgmann and R. O. Burford (1990). Aseismic slip on the San Andreas fault south of Loma Prieta,*Geophys. Res. Lett.* **17**, 9, 1445-1448.

Behr, J. and R. Bilham (1991). A two layer model for fault creep; Background Creep Velocity as a measure of local stress and strain. *Eos Trans. Amer. Geophys. Un.* **72**, 44, 444

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Bilham, R and J. Behr (1991). A two layer model for aseismic slip on the Superstition Hills fault, submitted to*Bull. Seism. Soc. Amer.*

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Marone, C. J., C. H. Scholz, and R. Bilham (1991). On the mechanics of earthquake afterslip, *J. Geophys. Res.*, **96**, 8441-8452.

Sylvester A., S. Barrientos, R Bilham, and M Jackson (1991). Shear, Uplift and Shortening across Durmid Hill: Interseismic Transpression on the Southern San Andreas Fault, California. *Eos Trans. Amer. Geophys. Un.* **72**, 44, 497

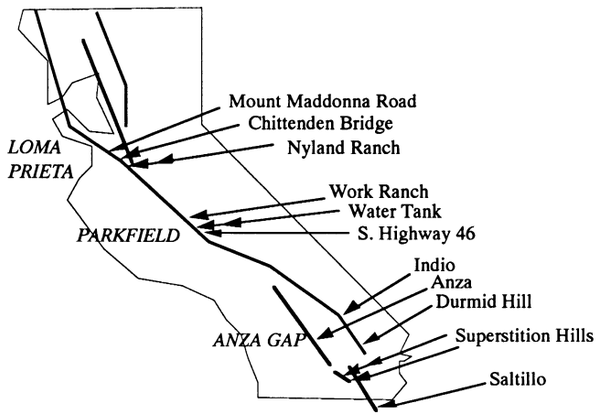

Figure 1 Locations of digital creepmeters. Three instruments currently operate on the Superstition Hills fault, three on the San Andreas fault south of Loma Prieta, three on the southern part of the Parkfield region, two on the southern San Andreas fault and one each on the southern Imperial and the San Jacinto fault. Pairs of creepmeters indicated by double arrows.

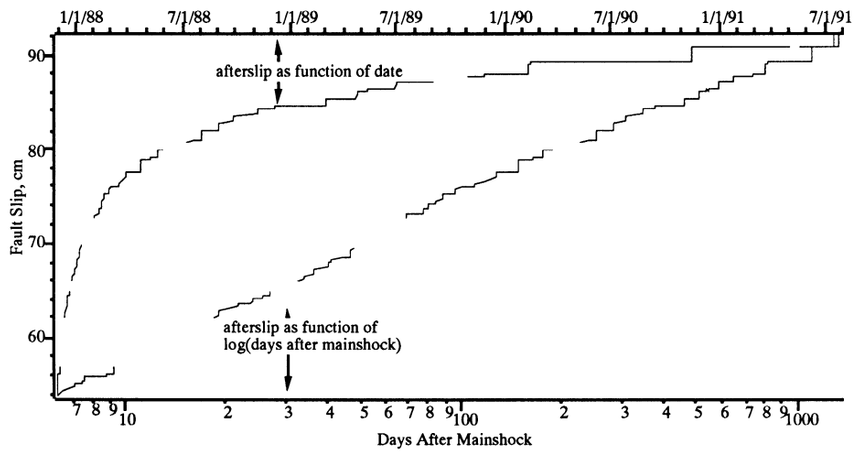

Fig. 2. Afterslip data from Site 1 near Imler Road on the Superstition Hills fault for 3.6 years after the mainshock. Afterslip remains a factor of two higher than the mean slip rate in the 30 years prior to the mainshock.

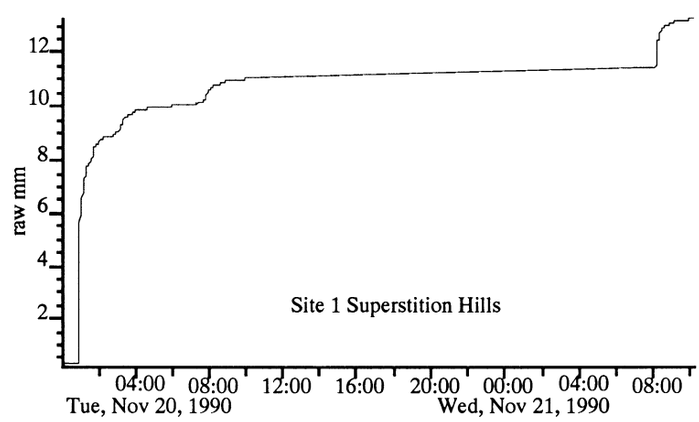

Figure 3 The largest creep sequence on the Superstition Hills fault was recorded on 21/22 Nov 1990. Dextral slip is obtained by muliplying the above values by 1.26. This creep event and the following 9 Feb event consisted of four subevents. Maximum fault slip velocity occurred in the second minute of the 21 Nov event and was not preceeded by any slow acceleration in creep or by the release of strain on an adjoining extensometer. The preceeding interval was the largest interval between events in the afterslip process. Sharp (personal communication, 1991) reports that slip in November propagated the entire length of the Superstition Hills fault.

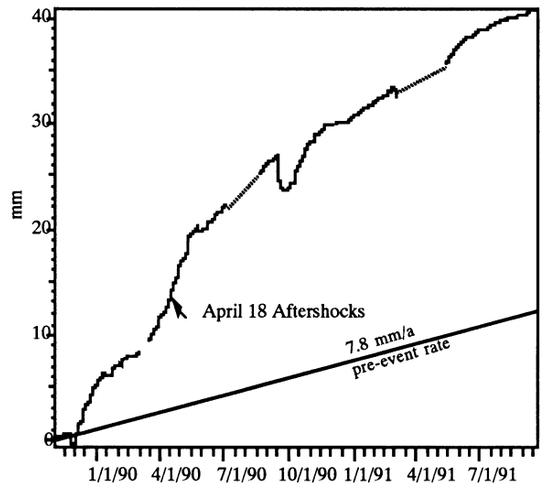

Figure 4 Data from Nyland Ranch after the Loma Prieta earthquake show continued creep at rates several times higher than that observed in the preceeding thirty years. Creep did not commence at Nyland ranch for more than a week following the mainshock. Mt. Madonna Road creep is insignificant after an initial settlement in the week following the event

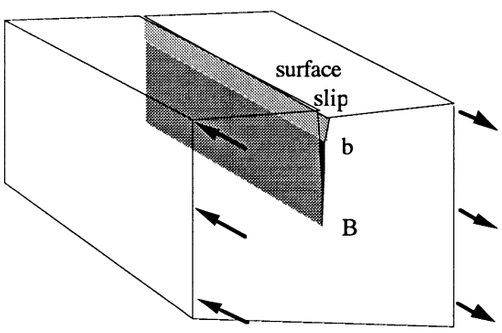

Fig. 5. Proposed two depth model for aseismic surface slip. Slip proceeds steadily on the surface in response to applied antisymmetric strain. Although the displacement rate is low, its measurement as across-fault strain offers an amplified signal compared to strain in the adjacent materials. Episodic slip occurs below a transition depth, b. The transition depth is presumably partly controlled by fault normal stress, hence, variations in the ratio of background creep to episodic creep may reveal changes in in-situ stress.

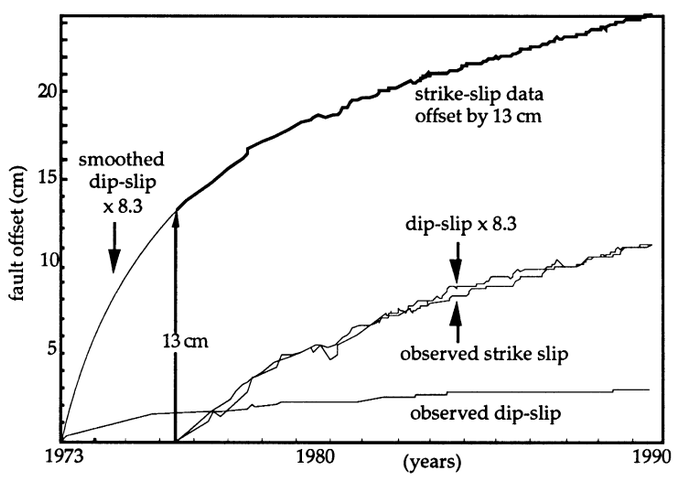

Fig. 6 Proposed reconstruction of the first four years of afterslip on the Xianshuihe fault at Xialatuo based on an observed linear scaling relationship between sinistral and dip-slip fault creep between 1976 and 1990.