A Silent Mw 4.7 Slip Event of October 2006, on the Superstition Hills Fault, Southern California.

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Abstract

During October of 2006, the 20-km long Superstition Hills fault (SHF) in the Salton Trough, Southern California, slipped aseismically producing a maximum offset of 27 mm as recorded by a creepmeter. We investigate this creep event as well as the spatial and temporal variations in slip history since 1992 using ERS and ENVISAT Satellite data. During a 15-year period, shallow creep is punctuated by at least three events. The first two events were dynamically triggered by the 1992 Landers and 1999 Hector Mine earthquakes. In contrast, there is no obvious triggering mechanism for the October 2006 event. Field measurements of fault offset after the 1999 and 2006 events are in good agreement with the InSAR data indicating that creep occurred along 20 km-long fault above 4 km depth with most of the slip occurring at the surface. The moment released during this event is equivalent to a $M_w$ 4.7 earthquake. This event produced no detectable aftershocks and was not recorded by the continuous GPS stations that were 9 km away. Modeling of the long-term 1992 to 2007 creep using stacked ERS interferograms also shows a maximum creep depth of 2-4 km with slip maximum occurred at the surface. Considering the sediment thickness varies between 3 km and 5 km along the SHF, our results are consistent with previous studies suggesting that the shallow creep is controlled by sediment depth, at least indirectly.
1. Introduction

Aseismic creep refers to fault slip that does not produce significant seismic radiation. Both geological and geodetic observations document evidence of creep along many fault segments in California [Burford and Harsh, 1980; Prescott et al., 1981; Schulz et al., 1982; Burgmann et al., 2000; Lyons et al., 2002; Lyons and Sandwell, 2003a]. Fault creep releases elastic strain and reduces the hazard from future earthquakes [Mavko, 1982; Burgmann et al., 2000; Toda and Stein, 2002; Schmidt et al., 2005; Fialko, 2006; Lienkaemper et al., 2006], making it an important part of seismic hazard estimation.

The Superstition Hills Fault (SHF) is located on the southern extent of the San Jacinto fault zone (Figure 1). This fault has a well documented history of surface creep, most of which is triggered by nearby earthquakes as seen in 1951, 1968, 1987, 1989, 1992 and 1999 [Allen et al., 1972; Hudnut and Sieh, 1989; Bodin et al., 1994; Rymer et al., 2002]. The 1987 M$_s$ 6.6 earthquake was the largest event on this segment in 300 years and was extensively investigated in a number of seismic and geodetic studies [Bilham, 1989; Boatwright et al., 1989; Hudnut and Clark, 1989; Hudnut et al., 1989a; Hudnut et al., 1989b; Hudnut and Sieh, 1989; Klinger and Rockwell, 1989; Lindvall et al., 1989; McGill et al., 1989; Sharp, 1989; Sharp et al., 1989; Sharp and Saxton, 1989; Williams and Magistrale, 1989]. During the 11 years before the 1987 earthquake, the average rate of surface creep was 0.5 mm/yr [Louie et al., 1985]. A creepmeter installed after the 1987 earthquake [Bilham and Behr, 1992] showed afterslip at an average rate of 28 mm/yr consisting of episodic creep events super-imposed on a slow quasi-steady slip of 2.4 mm/yr through 1991. No creepmeter data are available between 1991 and 2004. A
new creepmeter was installed in March 2004 and recorded steady creep at a rate of 1.35 mm/year through October 2006. Dextral creep events occurred on 11 Aug 2005 with an amplitude of 0.5 mm, on 20 January 2006 with an amplitude of 0.35 mm, and starting on 3 October 2006 with an amplitude of more than 27 mm over the next 14 days, with 85% of the amplitude manifested in the first 3 days (Figure 2). For the 2006 creep event there was no obvious triggering event. The 2006 creep event was not detected seismically nor was it observed on the closest continuous GPS station 9 km from the fault. A better understanding of the poorly recorded creep history of the SHF has implications not only for the earthquake hazard assessment in the Imperial Valley area, but also for the general understanding of the physical mechanisms of fault slip and the depth-dependent transition from velocity-strengthening to velocity-weakening in the shallow part of the seismogenic zone [Marone and Scholz, 1988].

While creepmeters can provide excellent temporal coverage of fault slip [Bilham et al., 2004], they do not reveal the spatial variations in displacement that are needed to infer the along-strike and down-dip variations in slip. Field measurements of the surface offset can provide information on along-strike variations due to creep events [Rymer et al., 2002] although they are not always performed or are often incomplete. It is possible that the ground cracking can be distributed across a fault zone so that a portion of slip can be overlooked. Moreover, neither field measurements nor sparse GPS measurements can record the variations in cross-fault displacement that are needed to infer the slip distribution with depth [Lorenzetti and Tullis, 1989; Thatcher, 1990; Savage and Lisowski, 1993; Fialko et al., 2001; Simpson et al., 2001; Wyss, 2001; Malservisi et al., 2005; Schmidt et al., 2005; Funning et al., 2007]. Repeat-pass radar interferometry
[Massonnet and Feigl, 1998] is a valuable tool for measuring spatial variations in fault slip at length scales greater than about 50 m. The main limitations of InSAR are the poor temporal coverage (e.g. given large repeat interval) and lack of phase correlation in vegetated areas [Rosen et al., 1996]. Fortunately, a large section of the SHF is located in arid desert and hence well correlated in the interferometric images (Figure 1). To our knowledge, this is the first time that both extensive field measurements and InSAR interferograms are available for multiple creep events in this area.

There are three goals of this paper. The first is to estimate the magnitude and depth of creep along the SHF associated with the October 2006 creep event. The creepmeter measurement provides excellent temporal coverage of the 2006 event at a single point. To extend the spatial coverage, we use stacks of ascending and descending ENVISAT InSAR imagery. This combination of data is used (i) to demonstrate that the creep is localized on a narrow fault trace, (ii) to measure the along-strike variations in fault creep, and (iii) to invert for creep depth. The amount of moment released by aseismic creep can be used for seismic hazard assessment of the SHF and understanding of the relation between creep and earthquakes.

The second goal is to document the slip history of the SHF over a longer time interval spanning 1992 to 2007 and compare these InSAR measurements with field measurements as well as the long-term creep rate. A similar analysis has been performed by Van Zandt and Mellors [manuscript in preparation, 2008]. In addition, the magnitude and depth of the accumulated shallow creep is estimated and compared with the 2006 event.
The third goal is to test the two-layer creep model for aseismic slip on the SHF proposed by Bilham and Behr [1992]. Creepmeter measurements following the Ms 6.6 1987 earthquake demonstrate that the time averaged slip rate decreases as a power law [Bilham and Behr, 1992]. The 3-year average creep rate between 1989 and 1991 was 28 mm/yr while the average creep rate is about 6.8 mm/yr between 2004-2006 based on creepmeter data. The creepmeter data show that long-term shallow creep consists of slow steady creep punctuated by accelerated creep events. Between 1989 and 1991 the creep rate during the events was about 10 times greater than the average creep rate between events. Based on this 10-1 ratio, Bilham and Behr [1992] proposed a two-layer model for aseismic slip on the SHF. During periods of the long-term shallow steady creep, the slip extends from the surface to a depth of about 300 m. During the creep events the slip extends 10 times deeper to a depth of about 3 km. The estimate of 3 km for the depth of the creep events was based on the abrupt increase in aftershock seismicity below approximately 3 km depth which also corresponds to the base of the sediments in the region [Kohler and Fuis, 1986]. Bilham and Behr speculated that the transition depth is sensitive to applied fault-normal stresses and suggest that the ratio of stable-sliding to episodic-slip velocities may provide an indication of secular variations in tectonic stress.

Using InSAR data we attempt to test the hypothesis that the depth of the long-term shallow steady creep is systematically smaller than the depth of the creep events. We find that the average shallow creep depth between 1992 and 2007 is similar to the depth of the 2006 event, both about 2-4 km. If this observation is correct then the slip is dominated by creep events from 1992 to 2007 and we can’t discriminate the depth of the shallow steady creep from the depth of the creep events using InSAR.
2. Data

Following the observation of the SHF creep event starting on October 6, 2006 [Roger Bilham, personal communication], we performed two field surveys: an initial reconnaissance survey on October 8 and a second more detailed survey in collaboration with Rob Mellors and Afton Van Zandt from San Diego State University on October 12, 2006. Because small surface cracks associated with creep can be quickly degraded by wind and especially rain, it was important to make measurements soon after the event [Rymer et al., 2002]. In the retrospect, the cracks were visible on the surface for more than 3 months following the event due to the lack of rain. In this region, the surface is arid and the creep amplitude was substantial (5-27 mm) making the creep easy to trace for 8 km (Figure 3). The southernmost end of the rupture was located. But the northern end was not completely mapped because of time limitations. A typical surface offset is shown in Figure 3d. Strike-slip displacement was measured along the trace of the rupture at approximately 100 m intervals. Extensional stepovers were identified and a ruler was placed over the crack and aligned in the direction of the overall fault trace (302 degrees clockwise from North). Then the distance between conjugate piercing points was measured at 2-3 locations on each crack (Table 1). The averaged fault offsets are shown in Figure 3c.

ERS1/2 InSAR data covering a time period of more than 15 years constrain the long-term creep rate of the Superstition Hills fault, and 2 years of ENVISAT data constrain the displacement during the October 2006 event. Both ERS and ENVISAT data along track 356 were collected by the European Space Agency and obtained through the
For the ERS data, we processed two frames, 2925 and 2943, together to better estimate the long wavelength error. ENVISAT data are used to image the 2006 creep event (ascending track 77, frame 657; descending track 356, frame 2943). The InSAR data was processed using SIOSAR software, and SRTM data were used to remove the topographic effect. Deformation along the southern-most end of the SHF was not fully recovered because all interferograms were decorrelated in the agricultural areas of the Imperial Valley.

The field measurements suggest that the fault creep is confined to a very narrow fault zone (< 10 cm). To estimate the deeper slip on the fault down to the base of the seismogenic zone (10-14 km), the deformation measurements must extend sufficiently far from the fault (> 14 km). This wide range of length scales requires both minimal smoothing of the interferograms as well as incorporating long-wavelength constraints from the GPS-derived SCEC V3.0 velocity model [Shen et al., 1996]. We use a remove/restore method along with stacking to minimize the errors [Lyons and Sandwell, 2003b]. Deviations from the standard InSAR processing consisted in the following steps:

1. Compute the line-of-sight (LOS) model phase difference from the SCEC velocity model and map into radar co-ordinates using a topographic phase mapping function.
2. Compute the amplitude dispersion [Ferretti et al., 2001] of all aligned SAR images to use as a weight function for the spatial filtering of the interferograms.
3. Low-pass filter each single-look interferogram using a Gaussian filter with a 0.5 gain at a wavelength of 100 m.
4. Stack the residual phase of the interferograms and remove a planar surface from the stack.
5. Restate the LOS phase from the SCEC velocity model.
3. Displacement along the fault

To begin the analysis we compared the fault slip measured in the descending stacked interferogram covering a time period of 2 years (Figure 3a) with the offsets measured in the field. The LOS displacement is measured by taking the difference of maximum and minimum value within 1 km from the fault after the profile is flattened. In this way, the LOS displacement won’t be underestimated even though the interferograms are smoothed by the Gaussian filter. Atmospheric errors should be less than 3 mm, considering the fact that 7 images are stacked and the horizontal length scale is small [Emardson et al., 2003]. In order to compare the InSAR measurements with the field measurements, pure strike slip is assumed, (as confirmed by data from the ascending orbit and three-dimensional modeling discussed below) and LOS measurements are converted to strike-slip displacements based on satellite and fault geometry. The fault azimuth is 302 degree clockwise from North and the local incidence angle of the satellite is 23 degrees. We use a local incidence angle for the finite fault inversion (3D) and a constant 23 degrees incidence angle for the anti-plane dislocation model (2D).

Results from the creepmeter, InSAR, and field measurements are compared in Figure 3c. All three measurements are consistent at the location of the creepmeter where the displacement is 27 mm. In general there is good agreement between the field measurements and the InSAR data, which confirm that the creep has a negligible (if any) dip-slip component and is confined to a very narrow zone. The InSAR step appears smooth (~50 m) because of the low-pass Gaussian filter that was applied to reduce the phase noise. The dextral horizontal displacement along SHF shows two lobes with a minimum at the along-fault distance of ~13 km (Figure 3c). The along-fault variations in
displacement for the 2006 event are very similar to the field measurements of fault creep made in 1999 just after the Hector Mine earthquake, and the fault offset for both the 2006 and 1999 creep events is similar in magnitude to events in 1968, 1979, and 1987 as compiled by Rymer et al. [2002].

In addition, we estimate the along-strike slip variation from 1992 to 2007 using both individual and stacked interferograms. The slip that accumulated between 1992 and 2007 is compared with the slip measured by Rymer et al. [2002] for the slip events (Figure 5). The InSAR result is consistent with field measurement for slip events in 1999 and 2006, which lends support to the validity of the method. The slip during 1993-1996 is substantial, with a maximum slip rate of 10 mm/yr, which exceeds the steady background slip rate between 1989 and 1992 [Bilham and Behr, 1992] derived from creepmeter data. We hypothesize that one or more creep events occurred between 1993 and 1996. Similarly the average slip between 1992 and 2007 is higher than the background slip rate and the slip is relatively uniform along the fault; both observations suggest slip occurred in multiple events and the stable creep and episodic creep events have a different spatial distribution along the fault. Next, we examine slip variations with distance from the fault to estimate slip distribution with depth.

4. Estimates of slip versus depth using finite fault model

Solutions for surface displacements due to dislocations in elastic half-space are readily available for both homogeneous [Okada, 1985] and layered media [Wang et al., 2003]. To model the displacement for the 2006 creep event, we use the finite fault homogeneous Greens function [Okada, 1985]. This finite fault model is appropriate for a
short-term event because as we demonstrate below, most of slip occurred in the shallow crust. However, to model the long-term slip from 1992 – 2007, we expect a contribution from the interseismic deformation. Expecting less variation of slip along the fault during the interseismic period and trying to simplify the modeling of the interseismic slip, we use the Green’s function for an anti-plane dislocation model for the long-term slip [Savage et al., 1981]. Although the Superstition Hills fault has a thick sediments of several kilometers over bed rock [Fuis and Kohler, 1986], the principal effect of increases in rock rigidity with depth is a small bias in the inferred slip distribution toward shallower depth [Cohen, 1999; Fialko, 2004], so we ignore the effects of layering in our analysis. In order to do a direct comparison of the slip depth between the 2006 creep event and the long-term slip, we model the 2006 creep event using the anti-plane dislocation model as well.

Slip inversions using co-seismic and post-seismic deformation data are well established techniques [Nielsen et al., 1995; Murray and Segall, 2002; Fialko et al., 2005]. A homogeneous half-space elastic model is used to estimate the strike-slip and dip-slip components at depth by least-square fitting the surface deformation data (Figure 6,7,8). The detailed procedure and data reduction method can be found in Fialko [2004].

To stabilize the inversions in the presence of long-wavelength noise (mainly atmospheric noise), we perform an inhomogeneous sampling with the sampling rate based on the distance from the fault (Figure 7). Since the displacement signal is near-field and low amplitude, it is crucial to describe the surface trace of the fault as accurately as possible. We use 26 segments, based on the USGS regional fault map and B4 Laser altimetry data [Hudnut et al., 2005] to model the 20-km-long SHF. Since the inversions are inherently
non-unique, additional constraints are added to regularize the inversion. We prohibited
sinistral slip by using a Coleman algorithm, which is the default in MATLAB function
“lsqin” [Coleman and Li, 1996]. Wild spatial variations in slip were suppressed by using
a Laplacian smoothness constraint. The smoothness weighting parameter controls the
smoothness of the slip model. The Root Mean Square (RMS) misfit of the model is
inversely related to the smoothness weighting parameter, which is a classic tradeoff, as
shown in Figure 6. We use this tradeoff to seek the “smoothest” slip distribution with the
lowest RMS misfit. RMS misfit is defined as
$$\chi = \sqrt{\frac{\sum_{i=1}^{N} (d_i - d_i^m)^2}{N}}$$
where $d_i$ is the LOS displacement on sampled InSAR data points (both ascending and descending), $d_i^m$ is the
modeled LOS displacement on the sampled points, and $N$ is the total number of the
sampled points.

The data and model interferograms are illustrated in Figure 7 for both descending
and ascending LOS directions. The misfit is 1.0 mm LOS for ascending data and 0.9 mm
LOS for descending data. The relatively large anomaly at the very southern end of the
fault in the descending residual might be due to creep on a sub-fault in the irrigation area.
Because it is only an edge effect for our inversion and no useful ascending data cover that
sub-fault, we didn’t include it in our model. The slip versus depth distribution shown in
Figure 8 indicates that most slip is confined to depths less than 3 km and maximum slip
occurs at the surface. The model has only a small component of vertical fault slip
(<10%), which validates our assumption of pure horizontal slip. There are two patches of
high slip along the fault. The north segment slips less than the south segment, with an
average dextral slip of about 9 mm and 13 mm respectively, which is consistent with the
fault offset observed in the field (Figure 3). Using a “nominal” value of the shear modulus of 33 GPa [Becker et al., 2005], the moment of this slip event is $1.3 \times 10^{23}$ dyne-cm. This corresponds to a moment magnitude of $M_w 4.7$ earthquake [Kanamori, 1977].

Since the fault slipped slowly over a period of 9 days, no seismic waves were generated. No aftershocks were detected by the regional seismic arrays or local potable seismometers.

5. **Anti-plane dislocation model (2D) for both the creep event and the long-term slip**

Modeling the long-term slip requires consideration of the entire depth range from the surface well below the brittle-ductile transition. The deep slip is most easily parameterized by an anti-plane dislocation extending from the locking depth to infinity. To compare the 2006 creep event to the long-term slip we repeat the event analysis using an anti-plane dislocation model. A discrete slip model has been used to compute the surface profile. However, the shallow locking depth estimated from the discrete slip model is not realistic and shouldn’t be regarded as the true locking depth [Savage, 2006]. Therefore we use a model assuming piecewise constant variations in fault slip with depth based on the anti-plane dislocation model consists of a dextral strike-slip dislocation in an elastic half space [Weertman, 1958; Cohen, 1999]. The surface displacement $v(x)$ is given by

$$v(x) = \int_{-a}^{0} \frac{x}{x^2 + z^2} m(z) \, dz$$  \hspace{1cm} (3)
where $x$ is the distance from the fault trace, $z$ is the depth and $m(z)$ is the slip distribution versus depth.

The model is parameterized in layers with uniform slip in each layer. In this case, the slip distribution $m(z)$ in equation (1) can be set up as a linear programming problem with a smoothness constraint in the form of Laplacian operator $\nabla^2$,

\[
\min \| (Am - b) / \sigma \|^2 + \lambda \| \nabla^2 m \|
\text{subject to } m > 0
\]

where $b$ is the observed surface displacement as a function of distance from the fault trace, $\sigma$ is the uncertainty in the observation, $m$ is fault slip versus depth, $\lambda$ is the weighting factor of smoothness, and $A$ is a Matrix of the Green’s function,

\[
A_{ij} = \int_{z_j}^{z_{j-1}} \frac{x_i}{x_i^2 + z^2} \, dz
\]

\[
= \int_0^{z_{j-1}} \frac{x_i}{x_i^2 + z^2} \, dz - \int_0^0 \frac{x_i}{x_i^2 + z^2} \, dz
\]

\[
= \tan^{-1} \frac{x_i}{z_j} - \tan^{-1} \frac{x_i}{z_{j-1}}
\]

where $x_i$ is the distance from the fault, $z_j$ is the depth of the top of a layer and $z_{j-1}$ is the depth of the bottom of a layer.

The inversion is more sensitive to the shallow slip than to the deep slip so the layer thickness was adjusted to increase with depth from 200 m to 1800 m. The last layer extends from the maximum depth of seismicity in the region (14 km) to infinity. As a
consequence, the entry in the matrix $A$ that corresponds to the last layer is calculated with a single arctangent function. The 100-m wavelength spatial Gaussian filter that was applied to the interferogram was also applied to the Greens functions in the matrix $A$ to make the model smoothness match the data smoothness.

Sixteen fault-perpendicular profiles were extracted from interferograms in rectangular boxes 400 m wide and up to 40 km long. Data near the ends of the fault were not used to avoid the 3-D edge effects. Profiles were binned at an even 100 meters spacing away from the fault [Parker, 1977; Parker and Song, 2005]. The smoothness parameter was selected as a tradeoff between model smoothness and RMS misfit. Because the east side of the SHF is close to farm land, where InSAR data is decorrelated, there is only 5 km of data on the east side of each profile, while data to the west of fault provides much better coverage (> 30km). The model successfully reproduced the surface deformation for all 16 profiles, and the average root mean square (RMS) misfit is 6 mm (Figure 9). The sharp step near the fault is caused by the shallow slip. The magnitude of the slip varies along the fault (as seen from variations between different profiles). However, the decay pattern with depth is similar for all profiles. The far-field deformation vanishes away from the fault, suggesting there is no deep slip for the 2006 creep event. In all cases, the slip has a maximum at the surface and then decays rapidly to zero slip at 2-4 km depth. Many of the profiles show a high noise area about 1 km to the west of the fault. This is likely to be a consequence of stacking several interferograms with similar atmospheric error and less than optimal correlation. To the north of the SHF (Figure 1), a large range change in LOS is observed and is likely
explained by ground subsidence due to the groundwater extraction [Mellors and Boisvert, 2003].

The same anti-plane dislocation inversions were performed on 16 profiles extracted from the long-term stack (1992-2007). These profiles generally have a lower noise level because more data are available for stacking. The anti-plane dislocation model also shows a good fit to all the profiles with an average RMS misfit of 1.1 mm/yr (Figure 10). The slip versus depth models show shallow and deep slipping zones separated by a locked zone from 3-7 km deep. The shallow slip has a peak at the surface and decays rapidly to zero at 2-4 km depth. This is very similar to the slip versus depth distribution derived from the interferograms spanning the 2006 event. In addition, the long-term models all have a deep-slip component that matches the nearly linear trend in the profiles far from the fault. As discussed above, this trend is constrained by the SCEC velocity model, which is based on GPS measurements. We find there is a trade off between the locking depth and the deep slip rate. Based on the maximum depth of the aftershocks following the 1987 earthquake, we chose the upper edge of the deepest layer to be 14 km [Lin et al., 2007]. In the inversion, a deep slip rate of about 30 mm/yr from 1992 to 2007 is preferred. However, as discussed below, an unknown fraction of the linear trend could be due to interseismic slip on nearby faults such as the San Andreas/Brawley Seismic Zone, Superstition Mountain, or Imperial faults. Therefore, we cannot constrain the deep slip rate using the InSAR data.

To estimate how deep slip from nearby faults might contribute to our inversion (without constructing a complete interseismic model for the region), we re-ran the inversion on a representative profile (#11) and removed a linear trend from the data. As a
consequence, the deep slip rate decreases as more linear trend is removed. When a linear trend of 0.2-0.3 mm/yr/km is removed, the deep slip rate is consistent with the best estimate for long-term slip rate on this fault, which ranges from 1.7 to 5.5 mm/yr, based on paleoseismic evidence [Hudnut and Sieh, 1989]. Despite the amount of linear trend that is removed all the inversions show similar patterns of shallow slip between 0 and 4 km deep (Figure 11); there is a maximum in slip rate at the surface that decreases to zero slip at 4 km depth. At depths greater than 5 km the estimates of slip rate are highly dependent on the removed linear trend. High linear trend removed (> 0.2 mm/yr/km ) result in no slip in the seismogenic layer (at depths between 4 and 9 km). In contrast, low linear trend removed (< 0.2 mm/yr) result in low slip rate between 4 and 9 km. A robust feature of the analysis is that the slip rate versus depth function has a peak at the surface and decreases rapidly to 0 at about 4 km depth. This decrease in slip rate to a locked zone with the top at ~4 km depth, common in all the models, is required to fit the sharp curvature in the horizontal displacement between 0 and 4 km from the fault on both sides. Understanding the slip rate at greater depths will require a more complete regional analysis that includes a 3D finite fault interseismic model of all major faults of the southern San Andreas system and the cross-faults which parallel to the Elmore Ranch fault.

6. Discussion

Previously published data from creepmeter measurements have demonstrated that creep on the SHF consists of a secular background creep and a decaying post-seismic transient that are punctuated by episodic creep events [Bilham and Behr, 1992]. The
quasi-steady creep was fastest just after the 1987 earthquake (28 mm/yr) and slowed to 2.4 mm/yr between May 1989 and July 1991. Creepmeter data were unavailable from 1992 to 2004. One question is whether the post-seismic transient still affects the present-day deformation. We divided the average slip along the SHF fault for each interferogram by the time interval of the interferogram (Figure 12). To make sure that the result represents average slip, we excluded interferograms with time interval shorter than 2 years. Usually one needs to stack several interferograms to reduce the atmospheric error. However, for our purpose, atmospheric error is negligible because the creep signal is localized within 1 km of the fault and changes in the atmospheric contribution are typically not large over this length scale. In the context of afterslip of the 1987 SHF earthquake, we compare our data with two afterslip models, both stemming from the rate and state friction formulation but in different ways. The first model (Figure 12, solid curve) is \[ S(t) = b \frac{1}{1 + t / \left(\frac{a}{b}\right)} \], where \( S(t) \) is the slip rate, \( t \) is time after the earthquake, \( a \) and \( b \) are constants estimated from creepmeter data on the SHF between 1987-1992 \( (a = 53.45 \text{ and } b = 302.2 \text{ in Figure 12}) \) [Marone et al. 1991; Wennerberg and Sharp, 1997]. The second model (Figure 12, dashed curve) is \[ S(t) = A \frac{\coth(k/2)e^{kt}/t_0}{1 - \left[\coth(k/2)e^{kt}/t_0\right]^2} + c \], where \( A, k, t_0 \) and \( c \) are constants \( (A=-20, k=5, t_0=25 \text{ and } c=0.5 \text{ in Figure 12}) \) [Barbot et al. 2008, under review]. Both models have decaying velocity with time but have different asymptotic behavior; the second model reaches a steady slip rate sooner than the first model. The similarity between the two models as well as the large uncertainty in the InSAR data does not allow us to discriminate between them. Also we cannot conclude
that the slip rate is decaying during 1992-2008 time interval. However, in the 11 years
prior to the 1987 earthquake, the shallow creep rate was only 0.5 mm/yr [Louie et al.,
1985] is much lower than any of the post earthquake measurements. This suggests that
the post-seismic transient from the 1987 earthquake might be still occurring.

*Allen et al. [1972] first noted that the aspect ratio between the amplitude of the
displacement and the fault length for a creep event is smaller than that for earthquakes. In
our case, the 2006 creep event has a displacement of 1-3 cm and fault length of 20 km,
which is consistent with *Allen’s* observation. Sieh and *Williams* [1990] estimated the
depth (0.6 – 2.7 km) of shallow creep and compared it with the sediment depth (1.3-3
km) of the Coachella Valley segment of the San Andreas Fault. They concluded that the
high pore pressures in the sediments could produce a weak zone in the upper 1 or 2 km of
the fault, and the shallow creep is controlled by sediment depth, at least indirectly. Our
study of the SHF is consistent with their conclusion. We find a maximum creep depth of
2-4 km where the sediment thickness varies between 3 km and 5 km [Kohler and Fuis,
1986].

Our results from the interseismic modeling show both shallow and deep aseismic
slip with a locked zone at depths between 4 and 6 km. This interseismic distribution of
slip with depth is nearly a mirror image of the co-seismic moment release versus depth
inferred from several major strike-slip earthquakes (Landers, Mw 7.3, Hector Mine, Mw
7.1, Izmit Mw 7.6 and Bam Mw 6.5) for which high-quality geodetic data are available
[Fialko et al., 2005]. All four earthquakes show shallow coseismic slip deficit. If the
shallow coseismic slip deficit is a common feature of strike-slip faults, it must be
compensated by post-seismic afterslip, episodic slip events, continuous interseismic
creep, or off-fault yielding [Bodin and Bilham, 1994; Fialko et al., 2005]. The Superstition Hills fault displays all three types of localized shallow slip.

We note that no seismic signal was detected by seismometers of the existing network during the 2006 creep event or by a seismometer installed on the fault after the creep event (E. Cochran, Personal communication). The closest operating seismometer, SWS of the Caltech/USGS regional seismic network, was about 5 km away from the SHF trace (Southern California Earthquake Center). These observations suggest that the 2006 creep event was a spontaneous slip event that was neither triggered by, nor produced any seismic activity. This event was also not detected by the existing continuous GPS network. The closest available continuous GPS station, CRRS in the SOPAC network, is 9.3 km to the northeast. The precision of the GPS station is 1.1 mm in north, 1.3 mm in east, and 3.0 mm in up component, and the sampling rate is 1 Hz. Based on our finite fault slip model, the expected signal from the 2006 creep event is 0.9 mm north and 0.6 mm east. We checked the data in the CRRS station and found no obvious signal around the time of the creep event. The lack of a resolvable signal at the closest GPS site confirms our inference that the creep occurred at a fairly shallow depth. It also illustrates difficulties associated with detection of shallow transient deformation using relatively sparse GPS arrays.

7. Conclusions

The InSAR data, field measurements, and creepmeter data well document the surface deformation due to the 2006 creep event on the SHF (Figure 3). The maximum slip occurred along the southern end of the fault. The slip distribution along the fault is
similar to the surface slip of the triggered event in 1999. Using InSAR, we detect at least
three creep events. The creep event in 1992 is triggered by the Landers earthquake, the
event in 1999 is triggered by the Hector Mine earthquake, and the 2006 event has no
obvious triggering mechanism. The maximum shallow slip rate in the SHF is about 10
mm/yr between 1992 and 2007, and the maximum surface displacement due to the 2006
event is about 27 mm. Both the 2006 creep event and the long-term slip, which includes
several creep events, have maximum slip at the surface and decay to zero at depth of 2-4
km where the sediment thickness varies between 3 km and 5 km. Our results lead
support to previous suggestions that the shallow creep is controlled by sediment depth,
at least indirectly.

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Consortium. This research was supported by the National Science Foundation (EAR
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References:


Coleman, T. F., and Y. Y. Li (1996), A reflective Newton method for minimizing a quadratic function subject to bounds on some of the variables, Siam Journal on Optimization, 6(4), 1040-1058.


Fialko, Y., et al. (2001), The complete (3-D) surface displacement field in the epicentral area of the 1999 M(w)7.1 Hector Mine earthquake, California, from space geodetic


Lyons, S., and D. Sandwell (2003a), Fault creep along the southern San Andreas from interferometric synthetic aperture radar, permanent scatterers, and stacking, *Journal of Geophysical Research-Solid Earth, 108*(B1), -.


Lyons, S. N., et al. (2002), Creep along the imperial fault, southern California, from GPS measurements, *Journal of Geophysical Research-Solid Earth, 107*(B10), -.


Mellors, R. J., and A. Boisvert (2003), Deformation near the Coyote Creek fault, imperial county, california: Tectonic or groundwater-related?, *Geochemistry Geophysics Geosystems, 4*, 1012, doi:10.1029/2001GC000254.


Thatcher, W. (1990), Order and Diversity in the Modes of Circum-Pacific Earthquake 
Recurrence, *Journal of Geophysical Research-Solid Earth and Planets, 95*(B3), 2609- 
2623, doi:10.1029/JB095iB03p02609.

Toda, S., and R. S. Stein (2002), Response of the San Andreas fault to the 1983 Coalinga-
Nunez earthquakes: An application of interaction-based probabilities for Parkfield, 
*Journal of Geophysical Research-Solid Earth, 107*(B6), 2126, 

Wang, R. J., et al. (2003), Computation of deformation induced by earthquakes in a 
multi-layered elastic crust - FORTRAN programs EDGRN/EDCMP, *Computers & 

Physics, 29*(12), 1685-1689.

Wennerberg, L., and R. V. Sharp (1997), Bulk-friction modeling of afterslip and the 
modified Omori law, *Tectonophysics, 277*(1-3), 109-136, doi:10.1016/S0040- 
1951(97)00081-4.

Williams, P. L., and H. W. Magistrale (1989), Slip Along the Superstition Hills Fault 
Associated with the 24 November 1987 Superstition Hills, California, Earthquake, 

Wyss, M. (2001), Locked and creeping patches along the Hayward fault, California, 
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**Figure 9.** Profiles of the 2006 slip event on the SHF and the best fitting anti-plane dislocation models. (a) Profiles and best fitting anti-plane dislocations. The black dots are the InSAR data with boxes 400 m wide and 40 km long, and the red lines are the best fitting models. The y-axis is the relative slip displacement. (b) Slip in depth distribution of the best fitting models for the creep event. Smoothness constraint is chosen from the tradeoff between misfit and smoothness. The result shows that the creeping depth is about 2-4 km for the event. The sharp signal on 10 km left of fault (left Figure) is not aligned with Superstition Hills Mountain fault.

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**Figure 11.** The effect of interseismic deformation on nearby faults on slip inversion. (a) InSAR profile #11 (see Fig.3a) and best fitting models for data with different linear trends removed: (1) No trend removed, 24 mm/yr deep slip rate; (2) 0.1 mm/yr/km, 17 mm/yr deep slip rate; (3) 0.2 mm/yr/km, 5 mm/yr deep slip rate; (4) 0.3 mm/yr/km. Black dots are InSAR data with different trend removed and red
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Table 1. Field measurements of fault offset collected on October 12, 2006 along the SHF.

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