Creep on the Rodgers Creek fault, northern San Francisco Bay area from a 10 year PS-InSAR dataset

Gareth J. Funning,[1] Roland Bürgmann,[2] Alessandro Ferretti,[3] Fabrizio Novali,[3] and Alfio Fumagalli[3]

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[1] Deformation in the northern San Francisco Bay area is dominated by a series of sub-parallel strike-slip faults. Existing GPS observations provide some constraint on the slip rates of these faults, however these have only limited resolution for resolving shallow fault behavior, such as brittle creep. We use a 30 image Permanent Scatterer InSAR (PS-InSAR) dataset spanning the time interval 1992–2001 to dramatically increase the density of surface deformation observations. We find a discontinuity in observed surface velocities across the Rodgers Creek fault, around Santa Rosa and further north, consistent with shallow creep at rates of up to 6 mm/yr. The creeping segments are located in areas of local transtension, suggesting that lowered normal stresses may play a role in the distribution of creep. The existence of creep could significantly reduce expected moment release in future earthquakes on the Rodgers Creek fault, and thus has implications for seismic hazard assessment. **Citation:** Funning, G. J., R. Bürgmann, A. Ferretti, F. Novali, and A. Fumagalli (2007), Creep on the Rodgers Creek fault, northern San Francisco Bay area from a 10 year PS-InSAR dataset, *Geophys. Res. Lett.*, *34*, L19306, doi:10.1029/2007GL030836.

1. Introduction

[2] Shallow, brittle fault creep is an intermediate fault behavior between the two end member cases of frictional locking and earthquake rupture. In response to tectonic stresses, a creeping fault will move aseismically, either continuously or episodically, with an average rate which is often a significant fraction of its long-term slip rate. Creep on a fault thus has the potential to reduce the magnitude of a future earthquake compared to the case where the fault is fully locked [e.g., *Working Group on California Earthquake Probabilities*, 2003; *Schmidt et al.*, 2005]. The rate and distribution of creep are therefore important parameters when assessing the seismic hazard posed by such faults.

[3] The Rodgers Creek fault, one of the major through-going structures in the northern San Francisco Bay area (hereafter 'North Bay'), links two known active creeping faults – the Hayward fault to the southeast, and the Maacama fault to the northwest [e.g., *Galehouse and Lienkaemper*, 2003, Figure 1a]. It is seismically active – two damaging intermediate magnitude (M_L 5.6 and 5.7) earthquakes occurred on the fault just north of Santa Rosa, the major city in the North Bay, in 1969, and paleoseismic investigations on its southern portion imply that the fault slipped $\sim$2 m in the last major ($M \sim 7$) event on that segment, probably in the 18th Century [*Budding et al.*, 1991; *Hecker et al.*, 2005, Figure 1a]. Whether or not the Rodgers Creek fault creeps like its neighbors has been an open question for some time, and is relevant to current attempts to reestimate earthquake probabilities in California. Existing trilateration and GPS data [e.g., *Lisowski et al.*, 1991; *Prescott et al.*, 2001; *d'Alessio et al.*, 2005] do not require creep, but the density of sites is probably not sufficient near the fault to resolve any such deformation. On the other hand, a recently deployed alignment array, located on the fault at Santa Rosa (site RC1, Figure 1b; http://funnel.sfsu.edu/creep/CreepSites/RogersCreek/RC1.htm), does suggest that creep occurred at that location between 2003 and 2005, but at present no other such data are available.

[4] In this study, we attempt to resolve the question of creep on the Rodgers Creek fault by increasing the spatial density of our observations. By combining existing GPS observations with displacement rates obtained using the Permanent Scatterer Interferometric Synthetic Aperture Radar (PS-InSAR) technique. we believe we can identify and constrain the rate of creep on a $\sim$25 km segment of the fault extending northwest from Santa Rosa.

2. PS-InSAR Observations of Surface Deformation

[5] PS-InSAR is an advanced processing technique for satellite radar data. Using the radar returns from phase-stable targets on the ground, it is possible to generate a time series of surface displacement changes, with atmospheric effects mitigated [*Ferretti et al.*, 2001]. Such stable targets can be identified independently of the stability of their neighbors, a capability that has already been demonstrated to dramatically increase the spatial coverage of observations in areas where there are buildings (which are phase stable) surrounded by vegetation (which is not) when compared to conventional interferometry [e.g., *Ferretti et al.*, 2004].

[6] For this study we use data acquired by the European Space Agency satellites ERS-1 and ERS-2 between 1992 and 2001. The North Bay region is covered in its entirety by a single descending track scene (track 342, frame 2835), and in total 30 useable images were acquired over this frame in

[1]Department of Earth Sciences, University of California, Riverside, California, USA.
[2]Berkeley Seismological Laboratory, University of California, Berkeley, California, USA.
[3]Tele-Rilevamento Europa, Milan, Italy.

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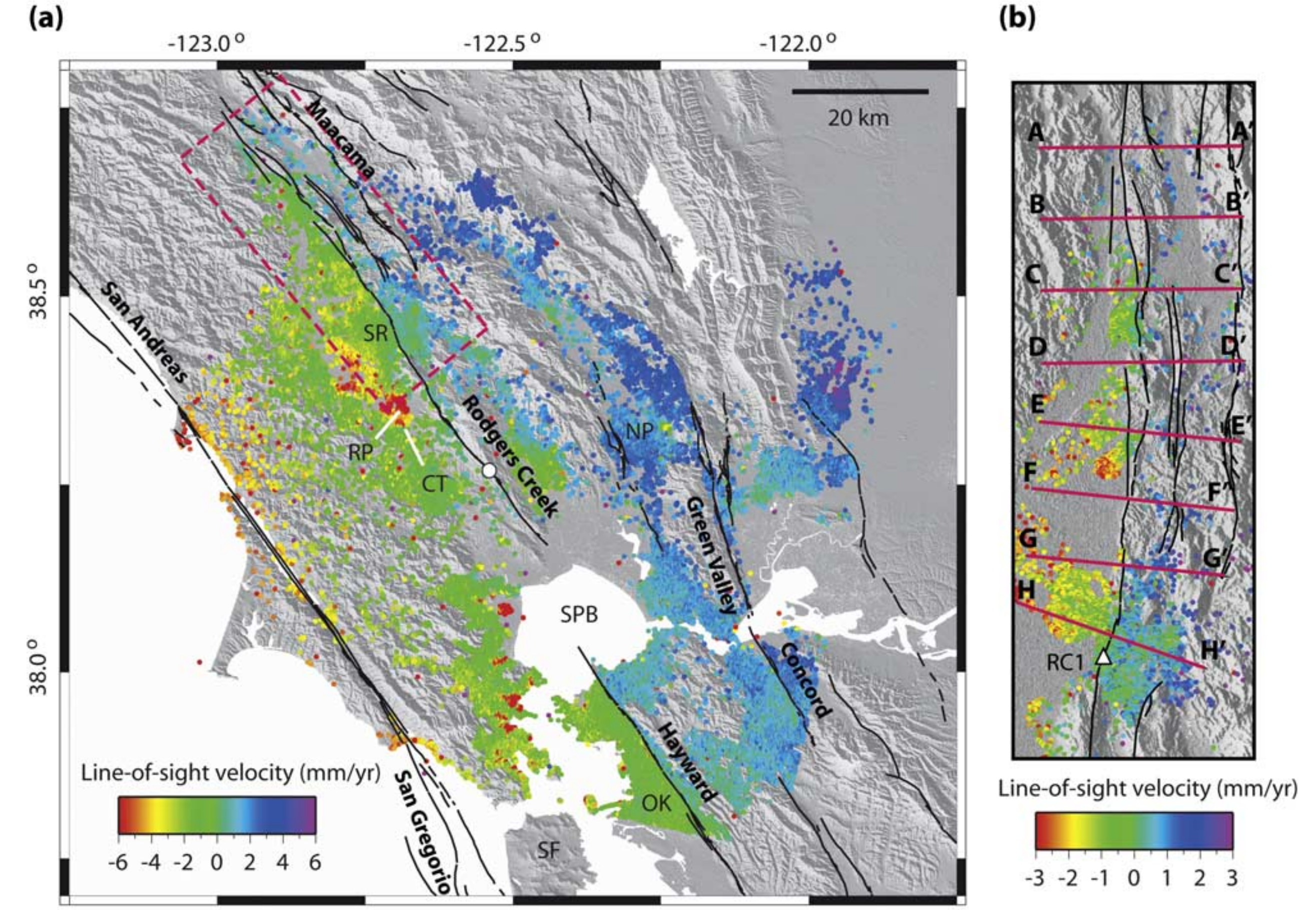

Figure 1. Fault summary map and PS-InSAR data for the northern San Francisco Bay area. Red colors indicate motion away from the satellite (range increase); blue, motion towards. (a) Regional surface velocity field. Solid lines show mapped active faults (U.S. Geological Survey and California Geological Survey, Quaternary fault and fold database for the United States, http://earthquake.usgs.gov/regional/qfaults/, 2007). Dashed box shows location of Figure 1b. White circle shows location of paleoseismic trench sites [*Budding et al.*, 1991; *Hecker et al.*, 2005]. SR, Santa Rosa; RP, Rohnert Park; CT, Cotati; NP, Napa; SF, San Francisco; OK, Oakland; SPB, San Pablo Bay. (b) Detail of velocities in the Santa Rosa area, after removal of points on weak substrate and thick sediment. Note that the color palette has been adjusted to highlight the velocity offset at the Rodgers Creek fault. Locations of 15 km-long fault-perpendicular profiles in Figure 2 are shown. White triangle indicates location of alignment array RC1. More details in the main text.

the study interval (Table S1 of the auxiliary material).[1] Permanent scatterers (PS) were identified using the method of *Ferretti et al.* [2001], and a best linear line-of-sight (LOS) velocity estimated for each. Uncertainty estimates for these were made by assessing the misfit of each linear velocity to each displacement time series. In total, 71000 PS were identified (Figure 1a). Data coverage is generally good, with a reasonable distribution of observation points across the region, especially considering the amount of forested and agricultural land in the North Bay. As might be expected, coverage is better in the more developed areas in the scene – surrounding San Francisco and San Pablo Bays and the areas around Santa Rosa and Napa.

[7] On a regional scale, the velocity field obtained by PS-InSAR shows the deformation due to accumulation of strain on the major strike-slip faults. In Figure 1a this is represented by a color change from red to blue from west to east, signifying an eastward increase in velocity of $\sim$10 mm/yr towards the satellite. Assuming that the deformation in the area is predominantly horizontal, this is consistent with right-lateral shear across the fault system [e.g., *Bürgmann et al.*, 2006]. More locally, steps in LOS velocity across faults represent shallow creep on those structures. We can identify such features for the Hayward and, we argue below, Rodgers Creek faults.

[8] The largest amplitude signals we observe generally have nontectonic origins. Several areas fringing San Pablo Bay, for instance, show large negative (away from the satellite) velocities compared with inland areas. This implies subsidence of the coastal areas, from consolidation and/or settling of the mud-rich sediments and fill beneath them, as seen at Treasure Island [*Ferretti et al.*, 2004]. To prevent such observations from biasing our models, we use maps of

[1]Auxiliary material data sets are available at ftp://ftp.agu.org/apend/gl/2007gl030836. Other auxiliary material files are in the HTML.

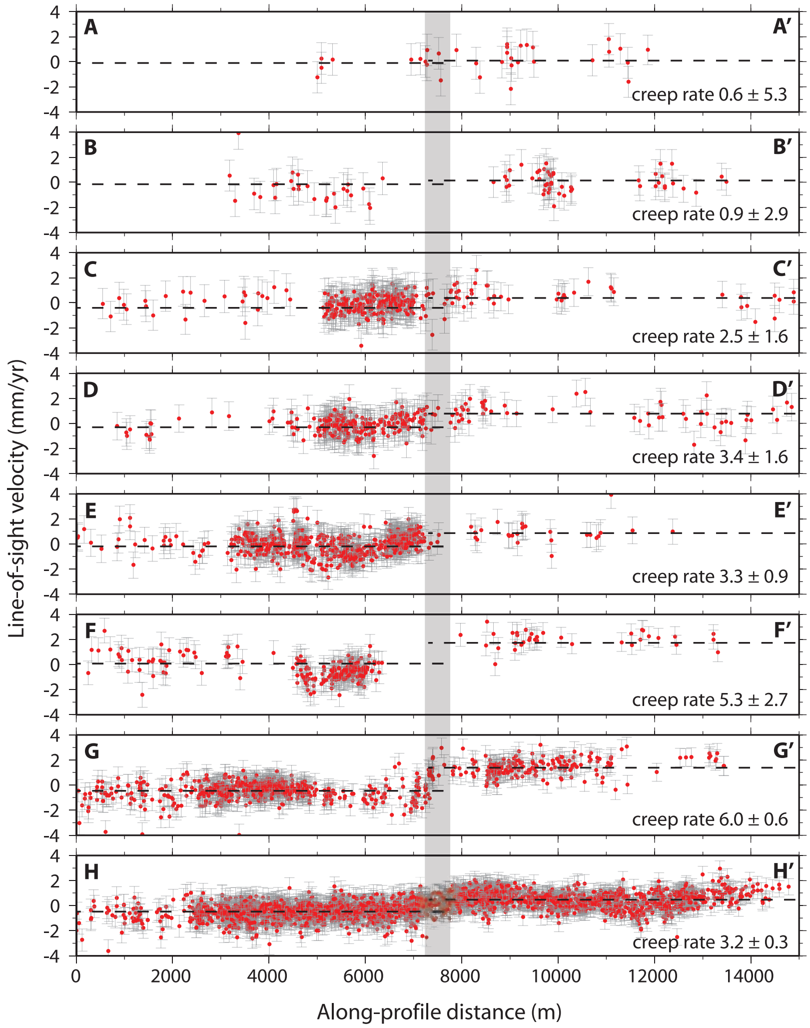

Figure 2. Profiles of PS-InSAR data across the Rodgers Creek fault near Santa Rosa. Red points signify PS velocity measurements within 2.5 km of the profile line; error bars indicate 1σ uncertainties. Velocities have been detrended by subtracting a best-fitting linear gradient. Black dashed line indicates the best average linear fit to velocities from a range of windows either side of the fault. Gray box indicates the approximate location of the fault. For a detailed description, see the main text; profile locations are in Figure 1b.

liquefaction risk [*Knudsen et al.*, 2000] to exclude datapoints on Holocene and/or weak fine-grained substrate.

3. Creep and Subsidence Around Santa Rosa

[9] Santa Rosa is located in a releasing bend of the Rodgers Creek fault (Figure 1). To the southwest lies a flat plain ~10 km wide, within which a prominent double-lobed negative line-of-sight velocity feature can be observed, corresponding to the settlements of Rohnert Park and Cotati (Figure 1a). Geophysical investigations of the area suggest that the plain is underlain by up to 2 km of Cenozoic/Quaternary sediment, including water-bearing aquifers that are currently being exploited [*Langenheim et al.*, 2006; *McPhee et al.*, 2007]. The observed deformation here is consistent with land subsidence due to groundwater extraction, perhaps enhanced by the weak fine-grained floodplain sediments upon which Rohnert Park is built. We attempt to remove these subsiding areas from our dataset, relying on data on the basement cover thickness [*Langenheim et al.*, 2006]. Only data from areas where the sediment thickness is known to be 750 m or less are used. This eliminates the majority of the subsiding datapoints (e.g., Figure 1b), with the exception of the basin fringe to the northwest.

[10] After the subsidence signals, the most prominent feature in the deformation field around Santa Rosa is a step in velocity across the Rodgers Creek fault. We investigate this feature, which we interpret as representing surface fault creep, by plotting cross-fault profiles through our reduced PS-InSAR dataset at 5 km intervals (Figure 2). To estimate fault offset rates, we fit parallel straight lines to windows of datapoints either side of the fault, and calculate the separation between them. The gradients of the lines reflect the regional component of deformation, along with any residual error in satellite orbital position, and are used to detrend the profiles. Assuming pure right-lateral strike-slip motion, we then convert the LOS velocities to creep rates by considering the contribution of unit velocity in the fault-parallel direction to measured LOS velocity, propagating the uncertainties of the measurements through the calculation to obtain formal error estimates. We obtain rates which peak at 6.0 ± 0.6 mm/yr immediately north of Santa Rosa (profile

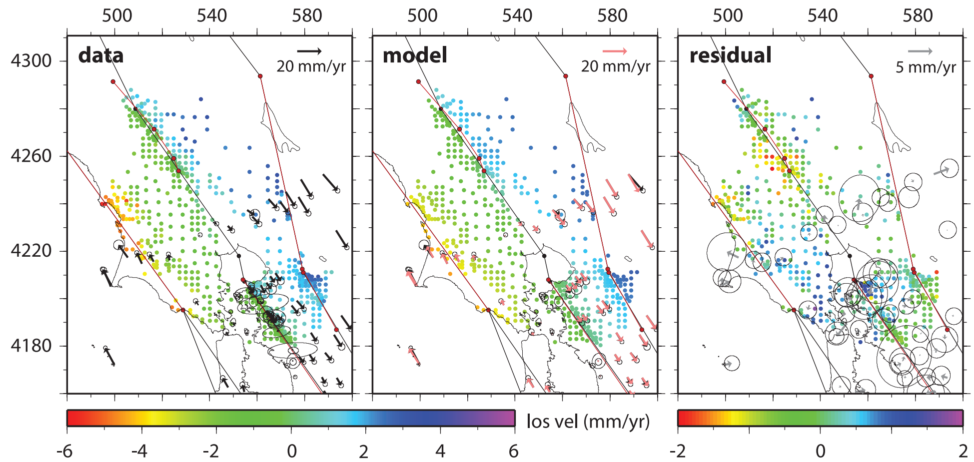

Figure 3. Dislocation modeling of the PS-InSAR and GPS data. (left) Subsampled PS-InSAR data (colored circles) and GPS data (black arrows) used in the inversion. (center) Preferred model velocities (GPS model velocities in pink). (right) Residual velocities. The fit to the GPS data is generally within error; misfit to the PS-InSAR data is at most ±2 mm/yr. Further description is given in the text. Black solid lines, modeled deep dislocations; red solid lines, modeled shallow dislocations; GPS error ellipses indicate 95% confidence limits. Coordinates are given in UTM km, zone 10.

G–G′), and die off to the north and south. It is possible that the southernmost profile (H–H′) appears less steplike than when plotted in plan view (Figure 1b) due to the fault bend at Santa Rosa. These rates, which represent the averages over an 10 year interval, are comparable with the estimate of 4.3 mm/yr recently obtained from alignment array measurements at site RC1 (Figure 1b) which do not overlap in time with our measurements.

4. Dislocation Modeling of the Deformation Field

[11] We use elastic dislocation modeling [e.g., *Simpson et al.*, 2001; *Schmidt et al.*, 2005] to estimate the lateral and depth extents of creep on the major faults in the North Bay. Vertical rectangular dislocations in an elastic half space are assumed [e.g., *Okada*, 1985], with Lamé parameters $\lambda = \mu =$ 30 GPa. Both the PS-InSAR data and 61 regional GPS velocities (Figure S1) from the BAVU compilation [*d'Alessio et al.*, 2005] are modeled. Deep dislocations, starting at the base of the seismogenic crust and extending to depth and representing steady aseismic shear at depth are used to reproduce the regional strain field; shallow dislocations, extending from the surface to a few kilometers' depth, represent the portion of the fault undergoing brittle creep. The modeled dislocations approximately follow the mapped surface traces of the major fault systems within the area of interest. Discontinuities at the surface, e.g. the stepover between the Hayward and Rodgers Creek faults, are represented by steps in the shallow dislocations, and by continuous, connecting structures at depth. (Full details of model fault locations are given in Table S2.)

[12] In order to reduce computation time and remove potential biases due to clustering of data points in urban areas, the PS-InSAR data, with unreliable data masked out as described above, are downsampled by considering where we would require data coverage to resolve creep on the three major North Bay faults. Such model design-based methods are efficient when modeling conventional interferograms [*Lohman and Simons*, 2005]; however no such methods currently exist for irregularly gridded data, such as PS velocities. We develop a new sampling scheme, applying a curvature-based quadtree decomposition [e.g., *Simons et al.*, 2002] to a forward model of creep on the upper 6 km of those faults, and generating a set of square cells of approximately constant model velocity (Figure S2). The median of the PS-InSAR velocities located spatially within each cell is used as a datapoint in the inversion (Figure 3). In addition, data within 500 m of the model fault traces are excluded to account for any mismatch between the simplified fault model and the complex mapped trace.

[13] We invert for the slip rates of these structures in a least-squares sense, searching over a range of integer increments of creep depth for a minimum misfit – a method that, we find, reduces tradeoffs in slip rate and creep depth between neighboring faults. Deep dislocation locking depths are fixed to the favored values obtained by *d'Alessio et al.* [2005]. Nuisance parameters, such as a static shifts in all velocities and linear ramps across the PS-InSAR scene to simulate residual orbital error, are solved for simultaneously. To weight our observations and estimate formal model parameter uncertainties we construct a full covariance matrix for the PS-InSAR data, assuming a negative exponential covariance-distance relation with an e-folding length scale of 10 km; for the GPS data we use formal uncertainties, including correlations between components.

[14] Our model results and uncertainties are shown in Table 1, the data fit in Figure 3. We find 7.5 mm/yr of creep on the Rodgers Creek fault in the zone north of Santa Rosa, and 4.0 and 3.3 mm/yr at the southern and northern ends of the creeping segment, respectively. These are compatible, within error, with the fault profile estimates and data (Figure S3). We are unable to place firm constraints on the depth of creep; approximately equal misfits are obtained for the depth range 6–10 km, with a tradeoff between creep depth and creep rate. Creep at 4.9 mm/yr on the upper 4 km of the Hayward fault is consistent with existing, more complex models [*Schmidt et al.*, 2005]. No significant creep can be resolved on the San Andreas or Concord faults; a marginal improvement to the data fit is obtained with 4.1 mm/yr of creep on the Green Valley fault, albeit with

Table 1. Modeled Fault Slip and Creep Rates

Fault	Depth, km	Rate, mm/yr[a]
Deep dislocations		
Rodgers Creek	10[b]	13.8 ± 2.3
Rodgers Creek-Hayward stepover	10[b]	2.8 ± 34.5
Hayward	10[b]	8.9 ± 2.6
San Andreas (North)	15[b]	18.4 ± 2.3
San Andreas (Peninsula)	14[b]	18.2 ± 1.7
San Gregorio	13[b]	2.4[c]
Green Valley	12[b]	10.3 ± 1.2
Concord	15[b]	13.1 ± 2.3
Shallow dislocations		
Rodgers Creek (Creeping) North	6[d]	3.3 ± 4.3
Rodgers Creek (Creeping) Central	6[d]	7.5 ± 2.6
Rodgers Creek (Creeping) South	6[d]	4.1 ± 1.1
Hayward	4[d]	4.9 ± 0.5
Concord	2[d]	2.0 ± 2.5
Green Valley	6[d]	4.1 ± 2.0
San Andreas	6[d]	0.6 ± 0.6

[a]Quoted uncertainties are 1σ formal uncertainty estimates.
[b]Fault locking depth from *d'Alessio et al.* [2005].
[c]Fixed to rate obtained by *d'Alessio et al.* [2005].
[d]Preferred depth to base of creeping patch.

large uncertainty. We do not find an improvement by adding a dislocation along the mapped southern Maacama fault, however data coverage there is limited. Overall, the measured velocities are fit well by the model, with the vast majority of GPS velocities fitting within error and the maximum absolute misfit to the PS-InSAR data being <2 mm/yr (Figure 3).

5. Discussion and Conclusions

[15] Average surface velocities taken from a 10 year ERS PS-InSAR dataset indicate that there may be significant shallow creep along the northern Rodgers Creek fault near Santa Rosa. Information on creep rates and depths, combined with geologically determined long-term slip rates, which do not yet exist along this stretch of the fault, will allow in future the estimation of the proportion of potential accumulated moment dissipated by creep. Creep is not observed further south, in our dataset or by other workers, raising the question of the cause of this along-strike change in fault behavior. One potential factor is fault geometry – if slip were transferred eastwards to the Maacama fault, north of Santa Rosa, there would be a $\sim$8 km releasing stepover consistent with an unclamping of the Rodgers Creek fault. Further targeted PS-InSAR and GPS studies may allow us to determine where this slip transfer occurs, and thus to quantify the importance of this effect.

[16] Shallow brittle creep on other faults, in the San Francisco Bay area and further south, is often accompanied by sequences of characteristic repeating earthquakes. The magnitudes and repeat intervals of these events can be related to the creep rate [e.g., *Nadeau and McEvilly*, 1999; *Schmidt et al.*, 2005]. Although, to our knowledge, no such earthquake sequences have been identified along the Rodgers Creek fault, the area has not hitherto been a target for such studies. Certainly, the distribution of earthquakes along the fault, including the locations of the 1969 earthquakes, suggests some link between creep and microseismicity – cataloged seismicity shows that events are concentrated on the portion of the Rodgers Creek fault that we believe to be creeping, whereas the southern, locked, portion is largely aseismic.

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R. Bürgmann, Berkeley Seismological Laboratory, University of California, Berkeley, 215 McCone Hall, Berkeley, CA 94720, USA.
A. Ferretti, A. Fumagalli, and F. Novali, Tele-Rilevamento Europa, Via Vittoria Colonna 7, Milan I-20149, Italy.
G. J. Funning, Department of Earth Sciences, University of California, Riverside, Riverside, CA 92521, USA. (gareth@ucr.edu)