

Characteristic Slow-Slip Events on the Superstition Hills Fault, Southern California

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Key Points:

- We document a recent spontaneous slow slip event on the Superstition Hills Fault using creepmeter, InSAR, GNSS, and field measurements.
- Over 41 mm of slip occurred from mid-May to mid-July 2023, with moment release corresponding to a M_w 5.0 earthquake.
- The kinematics of the 2023 event are remarkably similar to several previous slow slip events, suggesting a characteristic rupture process.

Abstract

The Superstition Hills Fault (SHF) exhibits a rich spectrum of slip modes, including M 6+ earthquakes, afterslip, quasi-steady creep, and both triggered and spontaneous slow slip events (SSEs). Following 13 years of quiescence, creepmeters recorded 25 mm of slip during 16-19 May 2023. Additional sub-events brought the total slip to 41 mm. The event nucleated on the northern SHF in early-May and propagated bi-laterally at rates on the order of kilometers per day. Surface offsets reveal a bi-modal slip distribution, with slip on the northern section of the fault being less localized and lower amplitude compared to the southern section. Kinematic slip models confirm systematic variations in the slip distribution along-strike and with depth and suggest that slip is largely confined to the shallow sedimentary layer. Observations and models of the 2023 SSE bear a strong similarity to previous slip episodes in 1999, 2006, and 2010, suggesting a characteristic behavior.

Plain Language Summary

Studying the mechanical properties and behavior of faults is essential for understanding earthquake ruptures. In this study, we investigate a recent slip event on the Superstition Hills Fault (SHF), which has a well-documented record of slip. A notable aspect of the SHF is that it periodically undergoes "slow slip events" (SSEs), where the fault slips and releases energy without any accompanied ground shaking. During May-July 2023, the SHF experienced a major SSE for the first time in 13 years. Our analysis shows that it was the largest documented SSE on the SHF and released equivalent energy to a magnitude 5 earthquake. We also find that the spatial pattern of fault slip is very similar to several previous slip events in 1999, 2006, and 2010, suggesting that the SHF has a tendency to slip in a characteristic manner.

1 Introduction

The Superstition Hills Fault (SHF) is located at the southern end of the San Jacinto Fault Zone (SJFZ), 35 km north of the United States-Mexico border in Southern California (e.g., Sharp, 1967; Hudnut & Sieh, 1989; Tymofeyeva & Fialko, 2018). The SHF has a well-documented record of time-dependent slip, spanning the coseismic, post-seismic, and interseismic phases of the earthquake cycle. Early observations dating back to 1960s detected surface creep along the SHF at an average rate of 0.5 mm/yr (Louie

48 et al., 1985), as well as episodes of accelerated slip triggered by local earthquakes (Allen
49 et al., 1972; Fuis, 1982; Sharp et al., 1986).

50 On 24 Nov 1987, the SHF ruptured in a M_S 6.6 earthquake with 1 m of average
51 coseismic slip below 5 km depth (Wald et al., 1990). Significant surface slip was delayed
52 by minutes or hours, but within a day was quantified as rapidly developing afterslip (Sharp
53 et al., 1986; Williams & Magistrale, 1989), that in the following 3 years decayed to low
54 rates, cumulatively matching coseismic slip at depth (Bilham et al., 2016). The rate of
55 decay of afterslip was interpreted in terms of velocity-strengthening behavior of the up-
56 permost 5 km of the fault (Marone et al., 1991; Barbot et al., 2009). Several years later,
57 the 1992 M_w 7.3 Landers and M_w 6.2 Big Bear earthquakes triggered 8+ mm of slip at
58 the site of a creepmeter operated by CU Boulder, and up to 20 mm elsewhere (Bodin
59 et al., 1994; Rymer, 2000). The 1999 M_w 7.1 Hector Mine earthquake triggered surface
60 slip of up to 18 mm along at least 9 km of the SHF (Rymer et al., 2002).

61 Most of the observed shallow creep events on the SHF appear to be dynamically
62 triggered by regional (e.g. Allen et al., 1972; Louie et al., 1985; Hauksson et al., 2013;
63 Wei et al., 2011) or teleseismic (Heflin et al., 2020) earthquakes. This is similar to the
64 behavior observed on other major faults in the area that exhibit shallow creep, in par-
65 ticular the Southern San Andreas Fault (e.g., Bodin et al., 1994; Fialko, 2006; Tymo-
66 fyeyeva et al., 2019). However, some shallow creep events on the SHF occur spontaneously
67 (Wei et al., 2009), analogous to Slow Slip Events (SSE) observed on megathrusts in sub-
68 duction zones (e.g., Dragert et al., 2001; LaBonte et al., 2009; Wallace, 2020).

69 The first reported spontaneous SSE on the SHF occurred in 2006 and produced \sim 30
70 mm of surface slip over a time period of two weeks, with most of the slip occurring in
71 the first three days (Wei et al., 2009). Inversions of the ENVISAT Interferometric Syn-
72 thetic Aperture Radar (InSAR) data capturing the 2006 event showed that the latter
73 was equivalent to a M_w 4.7 earthquake and that slip was largely confined to shallowest
74 2-3 km of the crust, consistent with the inferred depth of sediments (Kohler & Fuis, 1986;
75 Williams & Magistrale, 1989; Wei et al., 2009). A comparable-size SSE with a similar
76 slip pattern was triggered by the 2010 M_w 7.2 El Mayor-Cucapah earthquake (Wei et
77 al., 2011; Donnellan et al., 2014). Wei et al. (2015) examined ERS-1/2 InSAR data span-
78 ning 1992-2004 (during which no creepmeter measurements were made), and detected
79 at least four more events. The first and second events occurred between November 1993-

80 July 1995, and October-December 1996, respectively, and each produced about 20 mm
81 of slip. The third and fourth events occurred in 1997 and 1998, respectively, but were
82 limited to the northern half of the fault. Additional minor slip on the SHF was triggered
83 by a pair of M_w 5+ earthquakes in the 2012 Brawley Swarm, as well as the teleseismic
84 2017 M_w 8.2 Chiapas (Mexico) earthquake (Hauksson et al., 2013; Heflin et al., 2020).

85 In this study, we present observations and models of a new spontaneous SSE which
86 began in May 2023. We show that the latest SSE is the largest observed shallow slip event
87 yet recorded on the SHF, and that it bears a strong resemblance to previous events (in
88 particular, the spontaneous 2006, as well as the triggered 1999 and 2010 events), sug-
89 gesting a characteristic rupture pattern.

90 **2 Data and Methods**

91 The 2023 SSE was initially detected by two creepmeters installed on the southern
92 SHF, 700 m northwest of Imler Road (Figure 3). The Colorado (COL) creepmeter records
93 slip at 1-minute intervals and consists of a 6-m-long, 4-mm-diameter pultruded carbon
94 rod anchored ± 1.5 m from the fault trace (Bilham & Castillo, 2020). The TM71 creep-
95 meter consists of two Moiré-fringe optical sensors arranged to measure strike-slip, dip-
96 slip, and dilation, from which the total displacement vector can be calculated (Košťák,
97 1969; Klimeš et al., 2012; Martí et al., 2013). TM71 samples at daily intervals and is an-
98 chored ± 0.5 m on either side of the fault trace. Both instruments recorded an abrupt
99 onset of a slip event on 16 May 2023 (Figure 2A). Additional details on the creepmeters
100 are provided in the Supporting Information.

101 Similar, albeit smaller-amplitude, slip was registered by continuously-operating Global
102 Navigation Satellite System (GNSS) station P503, located ~ 3 km northwest of the creep-
103 meters and ~ 300 m east from the fault trace (Figure 1). To remove noise due to common-
104 mode regional signals, we computed the change in fault-parallel baseline between sta-
105 tion P503 and station P493 (Figures 1 & 2).

106 The 2023 SSE was also imaged by the European Space Agency’s Sentinel-1A syn-
107 thetic aperture radar satellite. We used data from Sentinel-1A’s descending track 173
108 to map surface deformation associated with the slip episode. Unfortunately, no acqui-
109 sitions were made from the ascending track covering the area of interest. We used the
110 acquisition from 3 May 2023 as reference and processed interferograms using all data col-

111 lected between October 2022–November 2023. To suppress atmospheric contributions,
112 which are the dominant source of noise for measuring small-amplitude deformation (e.g.,
113 Zebker et al., 1997; Pearse & Fialko, 2010; Nof et al., 2012), we used a Common Scene
114 Stacking method (Tymofyeyeva & Fialko, 2015) to estimate atmospheric phase screens
115 (APS) for 3 May and 26 July acquisitions. To do so, we generated all interferometric pairs
116 with the 3 May end date, and the 26 July start date. We chose pairs that minimize the
117 perpendicular baseline, and are least affected by decorrelation. The resulting subsets were
118 averaged to obtain APS for the respective common scenes. We inspected the estimated
119 APS to ensure that no fault slip occurred outside of the 3 May - 26 July 2023 interval,
120 which might bias our deformation measurements, and subtracted the estimated APS from
121 the 3 May - 26 July interferogram (Figure 3). For interferograms that span shorter time
122 periods during the SSE, we only applied the correction for the start date (3–15 May, Fig-
123 ures 2B, S1, & S2; 3 May–8 June, Figures 4 & S3).

124 To evaluate slip along the fault trace, we computed offsets from fault-perpendicular
125 swaths at 250 m intervals along the fault. We also computed the maximum observed sur-
126 face offsets for cases where slip is distributed across a shear zone of finite width, as op-
127 posed to localized on the fault trace (Figures S2 & S3). Further details on the offset es-
128 timation procedures can be found in the Supporting Information. Figure 4B shows the
129 along-fault distribution of surface slip measured by InSAR.

130 We also conducted field surveys to document surface expressions of shallow creep,
131 verify the rupture extent, and measure offsets for comparisons with other datasets. Pre-
132 liminary field investigations on 20 May 2023 revealed evidence of cracking and centimeter-
133 scale offsets along the fault trace near Imler Road and the creepmeters. A more detailed
134 survey on 11 June 2023 mapped surface cracks and measured their offsets (Figures 4A
135 & S4) along much of the SHF. The southern section of the SHF produced a localized sur-
136 face rupture that could be easily traced for several kilometers both north and south of
137 the creepmeters (Figures 1A & 4B). Further to the north, surface expressions of shal-
138 low creep become less obvious, likely due to a distributed nature of surface deformation
139 (Figure S3) and possibly an increased presence of loose sand. Overall, the measured off-
140 sets on the northern SHF are smaller than those on the southern SHF (Figure 4B). A
141 ~ 3 km stretch north of the fault step-over near the GNSS site P503 (Figure 1A) was not
142 mapped due to logistical constraints.

3 Evolution of Fault Slip During the 2023 SSE

High-rate data from the COL creepmeter recorded the onset of the 2023 slip event on 16 May at 18:29 UTC (11:29 PDT, local time) at the location of the creepmeter (see Figure 2A). Retroactive analysis of 12-day Sentinel-1A interferograms reveals that the SSE likely nucleated sometime between 3-15 May 2023 on the northern SHF (Figures 2B, S1, & S2) and propagated to the south. Investigation of both regional and global seismic catalogs does not reveal potential triggers (see Supporting Information for details), suggesting slip initiated spontaneously. The southernmost extent of slip that occurred between 3-15 May 2023 was approximately ~ 10 km from the creepmeters (Figure S1), implying an along-strike rupture velocity on the order of kilometers per day.

Over 20 mm of slip occurred within 24 hours after the slip front reached the creepmeters, and over 80% of slip registered by the creepmeters occurred in first two weeks of the event (Figure 2A & 2C). A 5 mm sub-event on 11 July 2023 brought the total amplitude of the SSE to 41 mm near Imler Road (Figure 2C). InSAR data indicate that slip propagated both northwest and southeast along-strike (Figures S2 & S3), rupturing the entire shallow section of the SHF. The main slip patch is observed within several km of the creepmeters on the southern segment of the SHF, with ~ 45 mm of slip accumulating by mid-June 2023 (Figure 4B). Slip on the northern segment (3-15 km northwest of the creepmeters) was on average ~ 5 mm, with a small peak 7-8 km north of the creepmeters (Figure 4). However, the InSAR data show that slip on the northern section was distributed across a shear zone 400-1300 m wide (Figure S3), so that the maximum fault-parallel displacements occurred away from the fault trace, amounting to 10-20 mm (Figure 4B).

Figure 4B shows a comparison of surface offsets along the SHF measured using different techniques. While the data in general show good agreement, some systematic differences are apparent. In particular, the InSAR-derived offsets are larger compared to the field and creepmeter measurements (the only exception is a ~ 30 mm offset suggested by field observations at ~ 6 km northwest from the creepmeters, see Figure 4B; this data point may be biased due to erosion of surface cracks in soft sediments). Such differences are expected if fault creep is not perfectly localized on a fault trace. All three observations are collocated near Imler Road and the measured slip increases with the observa-

174 tion aperture (centimeters for field measurements, meters for creepmeters, and hundreds
175 of meters for InSAR).

176 InSAR data also indicate that slip on the southern section of the SHF occurs in
177 a zone narrower than ~ 100 m (Figure S3), much more localized compared to slip on the
178 northern section. It was suggested that continuous across-fault variations in surface dis-
179 placements due to fault slip might result from a strong shallow layer resisting the prop-
180 agation of slip to the Earth’s surface, resulting in a “surface locking depth” (Brooks et
181 al., 2017; Parker et al., 2021). However, given the low mechanical strength of near-surface
182 sediments, a more plausible explanation is that the effective width of the shear zone re-
183 flects distributed failure within the fault damage zone with depth comparable to (or greater
184 than) its width (Fialko et al., 2002; Lindsey, Fialko, et al., 2014). Comparisons of sur-
185 face ruptures from InSAR and field surveys for the 2006 and 2010 SSEs reveal a simi-
186 lar pattern (Wei et al., 2009, 2011), suggesting that some fraction of shallow creep may
187 be accommodated by off-fault deformation (Fialko et al., 2005; Jin et al., 2022).

188 To evaluate the subsurface distribution of slip on the SHF due to the 2023 SSE,
189 we performed kinematic inversions of the InSAR line-of-sight displacements (Figure 3)
190 using an elastic halfspace dislocation model (see the Supporting Information for details).
191 Our preferred slip model is shown in Figure 5 and features two primary asperities cor-
192 responding to the northern and southern sections of the SHF. Slip on the southern sec-
193 tion is higher amplitude (>30 mm) and maximum at the surface, while slip on the north-
194 ern section is more subdued (<20 mm) and has a maximum at depth of 1-2 km. The ap-
195 parent “shallow slip deficit” (SSD) on the northern section of the SHF is likely an ar-
196 tifact of a distributed failure (Figure S3) that is not accounted for by our purely elas-
197 tic model (Barbot et al., 2008; Lindsey, Sahakian, et al., 2014). The gap between the two
198 slip patches corresponds to the step-over between the northern and southern SHF seg-
199 ments (Figures 1 & 3). Overall, slip is limited to the depth of sedimentary cover in the
200 Imperial Valley (<4 km; Kohler & Fuis, 1986; Wei et al., 2009; Lindsey & Fialko, 2016).
201 Converting the total slip from our preferred model (Figure 5) to moment magnitude, us-
202 ing shear modulus of 33 GPa, we estimate that the 2023 SSE is equivalent to a M_w 5.0
203 earthquake, making it the largest documented SSE on the SHF to date.

4 Discussion

The growing catalog of aseismic slip events on the SHF enables a comparative analysis of the observed slip distributions. Each of the well-observed 2006, 2010, and 2023 SSEs is characterized by higher slip on the southern segment of the SHF, and lower slip on the northern segment (Figure 5). This spatial pattern was likely similar for the 1999 Hector Mine triggered slip, although the northern SHF was not mapped in-detail (perhaps due to the difficulty in finding surface offsets in zones of distributed shear; Rymer et al., 2002). The respective ratios of slip amplitudes at the southern and northern fault sections are about 2:1 (Figure 3). Given that the entire fault appears to have slipped in the top few km of the crust during the 2006, 2010, and 2023 SSEs (Figure 5; Wei et al., 2009, 2011), the largest SSEs occur as “characteristic” ruptures, with more strain release on the southern section of the SHF. This raises a question about the resulting “strain surplus” on the northern SHF.

One possibility is that the systematic along-strike variations in surface slip (Figure 3) result from variations in the sediment thickness (Wei et al., 2009). Assuming that shallow creep is limited to the sedimentary layer, the magnitude of surface slip is expected to scale with the sediment depth (e.g., Kaneko et al., 2013). In this case, lower slip during the interseismic period should be compensated by higher coseismic slip. However, the observed surface slip due to the 1989 Superstition Hills earthquake was essentially the same on the northern and southern sections of the SHF (Sharp et al., 1989). Another possibility is that the observed smaller slip on the northern SHF during “system-size” SSEs (Figures 3 & 5) is compensated by smaller SSEs that rupture only the northern SHF. There is some evidence for such events from the InSAR observations (Wei et al., 2015). The available data may not be sufficient to determine the average slip balance during the interseismic period, but it is clear that shallow creep on the SHF exhibits substantial spatio-temporal complexity, with both fault-wide and partial ruptures in the uppermost crust, heterogeneous slip distributions, variable near-surface slip localization, and rapid variations in slip rate (Figure 2). Moreover, unlike the two most recent spontaneous creep events (2006 and 2023) that were associated with slip durations of weeks, slip triggered by the El Major-Cucapah earthquake in 2010 was complete between two five-minute samples of the creepmeter. These features are not predicted by classic models of rate-state faults with the velocity-strengthening shallow layer (e.g., Li & Rice, 1987; Kaneko et al., 2013).

237 The interval between episodic creep events following the 1987 earthquake has steadily
238 increased from months to several years. These intervals are apparently shortened by the
239 premature release of an accumulating SSD by shaking during major nearby earthquakes.
240 For example, it is probable that the atypically abrupt surface slip induced by the 2010
241 El Major-Cucapah earthquake efficiently released a SSD that would otherwise have been
242 accumulated and released within several years as a spontaneous creep event. The tran-
243 sition from rapid afterslip process to an episodic creep appears to have occurred start-
244 ing 1995 ± 3 years, since when 15 cm of slip has been released in six creep events. After-
245 slip presumably continues to contribute to surface slip because the intervals between episodic
246 events increases during these 28 years (i.e. shallow slip is not yet entirely attributable
247 to the release of antiplane shear strain arising from interseismic deformation).

248 From 2004-May 2023, the averaged creep rate was 3.2 mm/yr (~ 5 mm/yr if includ-
249 ing the 2023 event). The rate would be 3.2 mm/yr if we suppose that no spontaneous
250 creep event occurs for a further decade, and 4.7 mm/yr should a ~ 40 mm event occur
251 after this interval. These estimates are lower than the maximum long term geological
252 slip rate of 6 mm/yr adopted by Field et al. (2015), based largely on a 660 year geolog-
253 ical slip rate of 2-6 mm/yr determined by Hudnut and Sieh (1989). However, the aver-
254 age shallow creep rate should be a small fraction of the geologic slip rate, depending on
255 the locking depths at the top and bottom of the seismogenic layer (e.g., Lindsey & Fi-
256 alko, 2016). This implies a geologic slip rate on the SHF in excess of 10 mm/yr, higher
257 than that assumed in the Uniform California Earthquake Rupture Forecast v.3 (UCERF3;
258 Field et al., 2014), but consistent with the suggestion that the SHF is a continuation of
259 the main strand of the San Jacinto fault with a slip rate of ~ 15 mm/yr (Tymofyeyeva
260 & Fialko, 2018; Vavra et al., 2023).

261 **5 Conclusions**

262 We document the occurrence of a slow slip event (SSE) on the Superstition Hills
263 Fault (SHF) which began in May 2023 and incremented in ≤ 5 mm slip events, at un-
264 even but increasing intervals for the following 60 days. InSAR measurements indicate
265 the SSE likely initiated near the northern end of the fault and propagated ~ 15 km to
266 the south over the course of several days. Creepmeters on the southern SHF recorded
267 up to 25 mm of dextral slip over the course of 3 days, with slip eventually attaining 41
268 mm by mid-July 2023. Fault offsets computed from InSAR data suggest maximum sur-

269 face slip of 45+ mm. While slip is highly localized along a region of high slip on the south-
270 ern end of the rupture, surface deformation along the northern ~ 12 km of the fault is
271 characterized by distributed shear over 400-1300 m. Finite fault models derived from In-
272 SAR data indicate that the fault slip during the SSE was largest on the southern SHF.
273 On the northern SHF, the average slip amplitude was lower by about a factor of two.
274 Finite fault models also show that slip is largely confined to the shallowest 4 km of the
275 fault, consistent with the depth of sediments and results inferred from previous SHF events.
276 The moment release throughout the entire SSE sequence was equivalent to a $M_w \sim 5.0$
277 earthquake. The similarity of the 2023 SSE to previous events dating back to at least
278 2006 suggests spontaneous SSEs on the SHF have ruptured largely the same fault patches
279 in a characteristic manner. Triggered slip induced by strong shaking from nearby earth-
280 quakes can both advance the timing of the release of an accumulating shallow slip deficit
281 and reduce the duration of this slip from days to minutes.

282 **Open Research**

283 Raw Sentinel-1 data used in generating InSAR time series and velocity maps are
284 openly available from Alaska Satellite Facility via <https://search.asf.alaska.edu> (ASF,
285 2022). GNSS data are from the the Earthscope Geodetic Facility for the Advancement
286 of Geoscience Data Center via <https://www.unavco.org/data/gps-gnss/gps-gnss.html>
287 (EarthScope, 2022). Processed geodetic and field data used in this study are available
288 via Zenodo (<https://zenodo.org/records/10211682>). The seismicity catalogs are avail-
289 able from the Southern California Earthquake Center via [https://scedc.caltech.edu/](https://scedc.caltech.edu/data)
290 data (SCEDC, 2013).

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296 tenance.

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Contributions

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EV wrote the initial manuscript. All authors contributed to the preparation and revision of the final manuscript. RB processed data from the Colorado creepmeter. PS, JaS, PT, and JoS designed, installed, and maintained the Prague creepmeter and conducted the ERT survey. YF processed the InSAR data. EV analyzed the InSAR data and performed fault inversions. EV, YF, TR, PS, and JoS participated in field work. EV and TR mapped the fault rupture.

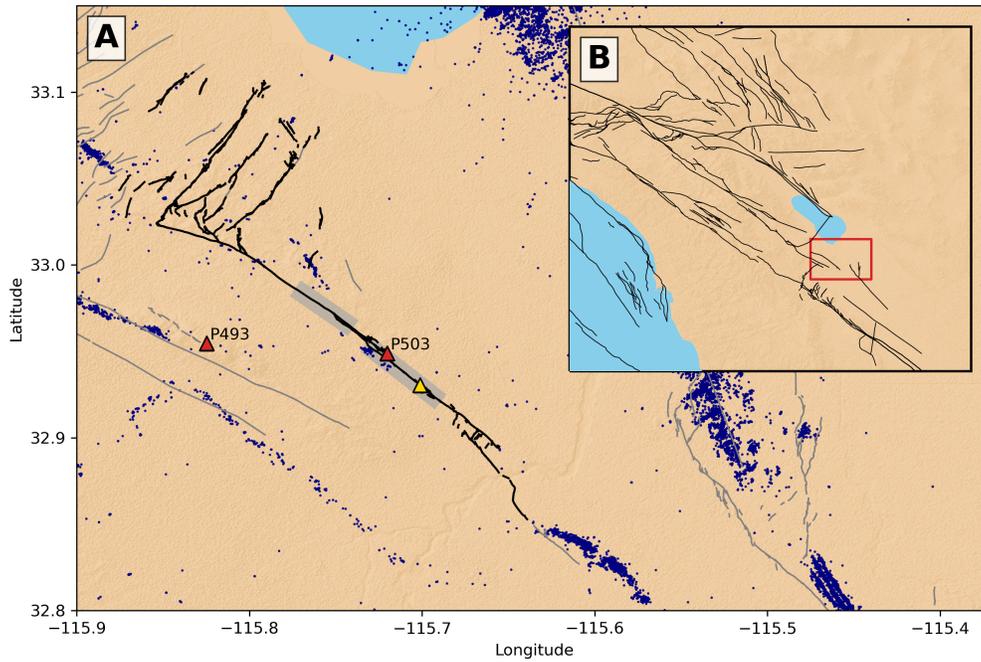
Figures

Figure 1. (A) Regional map of the Superstition Hills Fault (SHF). Quaternary faults are shown in gray (USGS, 2020) with the 1987 SHF surface rupture shown in black. The location of the creepmeters is shown with a yellow triangle. GNSS stations P503 and P493 are shown as red triangles. Gray shading indicates the extent of the field survey. Seismicity from 2008-2017 is shown as blue dots (Ross et al., 2019). (B) Regional tectonic setting of the SHF. Major fault traces are plotted in black (Shaw et al., 2015). The area of (A) is shown in red.

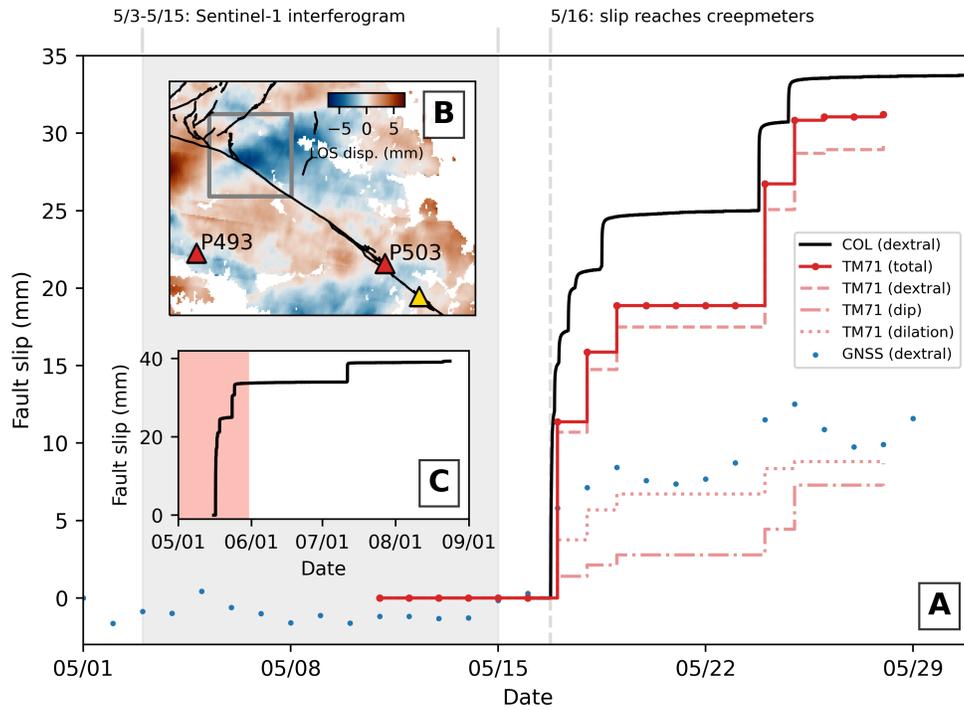


Figure 2. (A) Fault slip during May 2023. Dextral slip measured by COL is shown in black. Red lines show dextral slip (dashed), dip slip (dot-dashed), dilation (dotted), and total fault displacement (solid) from TM71 (circles). Blue dots show the fault-parallel baseline change between stations P503 and P493. Gray shading indicates the epoch of the 3-15 May Sentinel-1 interferogram. (B) 3-15 May Sentinel-1 interferogram showing initial slip on the northern SHF (gray box). (C) Time series of fault slip through August 2023 from COL. Red shading indicates the time span of (A).

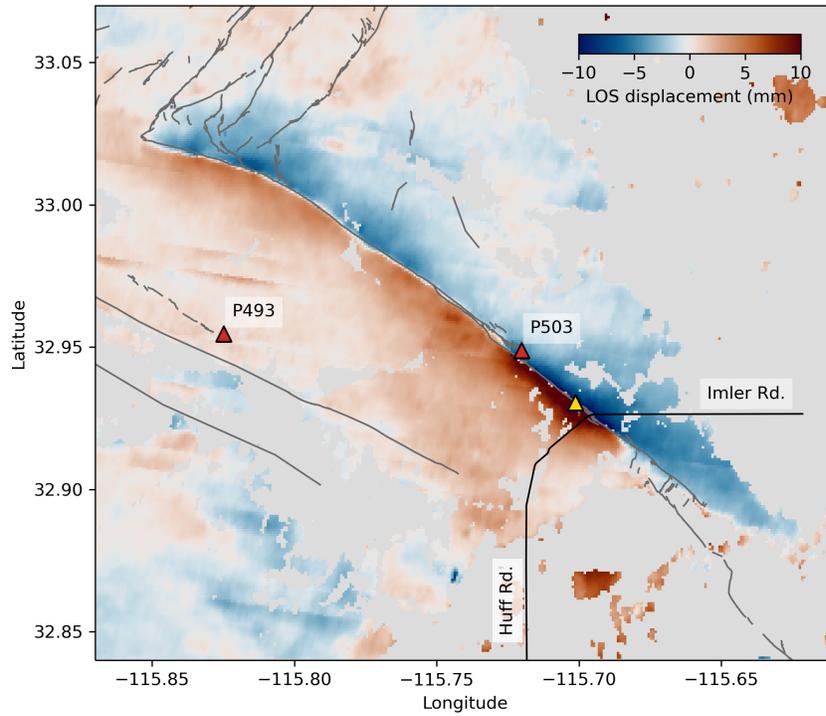


Figure 3. Surface displacements due to 2023 slow slip on the Superstition Hills Fault from Sentinel-1 InSAR analysis. Positive values (red) correspond to motion away from the satellite. Quaternary faults are shown in gray (USGS, 2020). The locations of the creepmeters (yellow triangle) and GNSS stations (red triangles) are also shown.

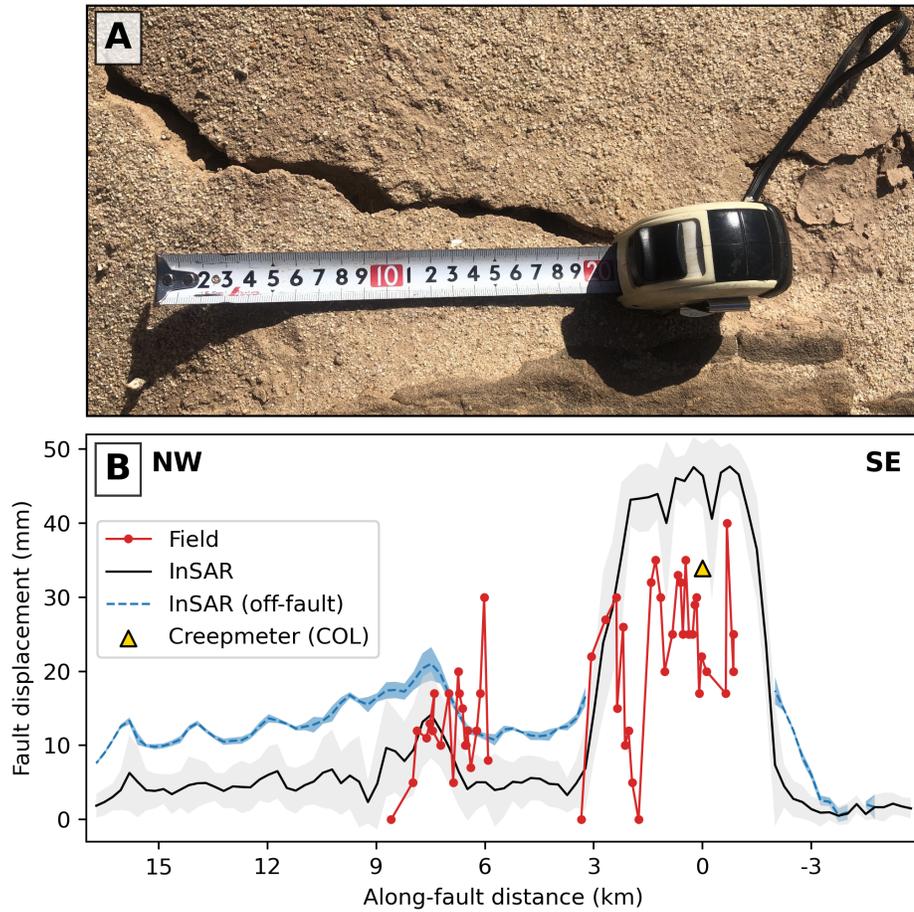


Figure 4. (A) An example surface crack observed during the 11 June 2023 field survey. The measuring tape is in centimeters and is aligned with the local strike. (B) 2023 Surface rupture along the Superstition Hills Fault. Estimated on-fault and maximum off-fault offsets from InSAR are shown with associated shading indicating uncertainty estimates. Red lines indicate the extent of field mapping. The COL creepmeter measurement is from 11 June, while InSAR displacements span 3 May to 8 June. Distances are referenced to the location of the creepmeters.

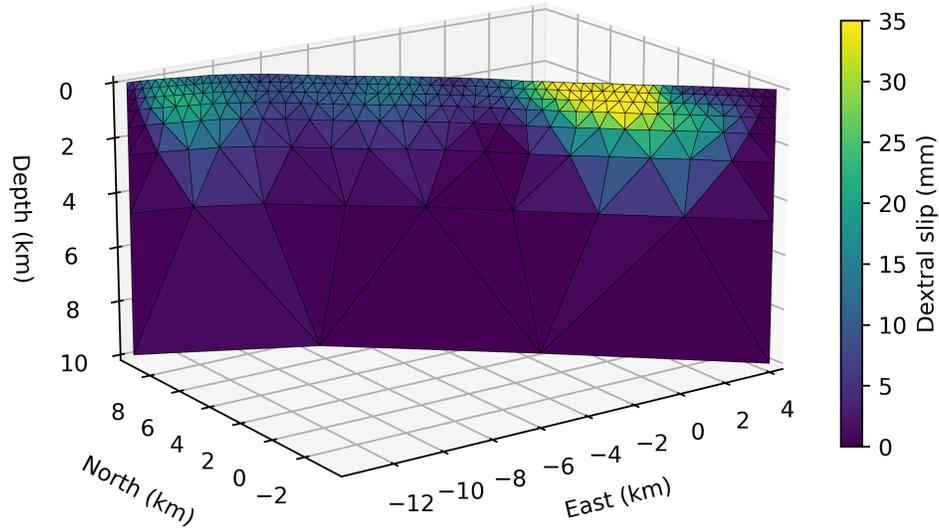


Figure 5. Three-dimensional kinematic model of slip along the Superstition Hills Fault during the 2023 slow-slip event. Fault patch colors correspond to the amplitude of dextral slip. The coordinates are centered at the location of the creepmeters. The moment release associated with this model corresponds to a M_w 5.0 earthquake.

305 **References**

- 306 Allen, C. R., Wyss, M., Brune, J. N., Grantz, A., & Wallace, R. E. (1972). *Displace-*
 307 *ments on the Imperial, Superstition Hills, and San Andreas Faults Triggered by*
 308 *teh Borrego Mountain Earthquake.* (Tech. Rep.).
- 309 ASF. (2022). *European Space Agency Copernicus Sentinel data [dataset].* Alaska
 310 Satellite Facility Distributed Active Archive Center. Retrieved from [https://](https://search.asf.alaska.edu/)
 311 search.asf.alaska.edu/
- 312 Barbot, S., Fialko, Y., & Bock, Y. (2009). Postseismic deformation due to the M
 313 w 6.0 2004 Parkfield earthquake: Stress-driven creep on a fault with spatially
 314 variable rate-and-state friction parameters. *Journal of Geophysical Research,*
 315 *114*(B7), B07405.
- 316 Barbot, S., Fialko, Y., & Sandwell, D. (2008). Effect of a compliant fault zone on
 317 the inferred earthquake slip distribution. *Journal of Geophysical Research,*
 318 *113*(B6), B06404.
- 319 Bilham, R., & Castillo, B. (2020). The July 2019 Ridgecrest, California, Earthquake
 320 Sequence Recorded by Creepmeters: Negligible Epicentral Afterslip and Pro-
 321 longed Triggered Slip at Teleseismic Distances. *Seismological Research Letters,*
 322 *91*(2A), 707–720.
- 323 Bilham, R., Ozener, H., Mencin, D., Dogru, A., Ergintav, S., Cakir, Z., ... others
 324 (2016). Surface creep on the North Anatolian fault at Ismetpasa, Turkey,
 325 1944–2016. *J. Geophys. Res., 121*(10), 7409–7431.
- 326 Bodin, P., Bilham, R., Behr, J., Gomberg, J., & Hudnut, K. W. (1994). Slip trig-
 327 gered on southern California faults by the 1992 Joshua Tree, Landers, and Big
 328 Bear earthquakes. *Bulletin of the Seismological Society of America, 84*(3),
 329 806–816.
- 330 Brooks, B. A., Minson, S. E., Glennie, C. L., Nevitt, J. M., Dawson, T., Rubin, R.,
 331 ... others (2017). Buried shallow fault slip from the South Napa earthquake
 332 revealed by near-field geodesy. *Science advances, 3*, e1700525.
- 333 Donnellan, A., Parker, J., Hensley, S., Pierce, M., Wang, J., & Rundle, J. (2014).
 334 UAVSAR observations of triggered slip on the Imperial, Superstition Hills, and
 335 East Elmore Ranch Faults associated with the 2010 M 7.2 El Mayor-Cucapah
 336 earthquake. *Geochemistry, Geophysics, Geosystems, 15*(3), 815–829.
- 337 Dragert, H., Wang, K., & James, T. S. (2001). A Silent Slip Event on the Deeper

- 338 Cascadia Subduction Interface. *Science*, 292(5521), 1525–1528.
- 339 EarthScope. (2022). *Global navigation satellite system position solutions [dataset]*.
 340 Geodetic Facility for the Advancement of Geoscience. Retrieved from
 341 <https://www.unavco.org/data/gps-gnss/gps-gnss.html>
- 342 Fialko, Y. (2006). Interseismic strain accumulation and the earthquake potential on
 343 the southern San Andreas fault system. *Nature*, 441(7096), 968–971.
- 344 Fialko, Y., Sandwell, D., Agnew, D., Simons, M., Shearer, P., & Minster, B. (2002).
 345 Deformation on Nearby Faults Induced by the 1999 Hector Mine Earthquake.
 346 *Science*, 297(5588), 1858–1862.
- 347 Fialko, Y., Sandwell, D., Simons, M., & Rosen, P. (2005). Three-dimensional de-
 348 formation caused by the Bam, Iran, earthquake and the origin of shallow slip
 349 deficit. *Nature*, 435(7040), 295–299.
- 350 Field, E. H., Arrowsmith, R. J., Biasi, G. P., Bird, P., Dawson, T. E., Felzer, K. R.,
 351 ... others (2014). Uniform California Earthquake Rupture Forecast, version
 352 3 (UCERF3) The time-independent model. *Bull. Seism. Soc. Am.*, 104,
 353 1122–1180.
- 354 Field, E. H., Biasi, G. P., Bird, P., Dawson, T. E., Felzer, K. R., Jackson, D. D.,
 355 ... Zeng, Y. (2015). Long-Term Time-Dependent Probabilities for the Third
 356 Uniform California Earthquake Rupture Forecast (UCERF3). *Bulletin of the*
 357 *Seismological Society of America*, 105(2A), 511–543.
- 358 Fuis, G. S. (1982). Displacement on the Superstition Hills fault triggered by the
 359 earthquake. *U.S. Geologic Survey Professional Paper*, 1254, 145–154.
- 360 Hauksson, E., Stock, J., Bilham, R., Boese, M., Chen, X., Fielding, E. J., ... Yang,
 361 W. (2013). Report on the August 2012 Brawley Earthquake Swarm in Imperial
 362 Valley, Southern California. *Seismological Research Letters*, 84(2), 177–189.
- 363 Heflin, M., Donnellan, A., Parker, J., Lyzenga, G., Moore, A., Ludwig, L. G., ...
 364 Pierce, M. (2020). Automated Estimation and Tools to Extract Positions,
 365 Velocities, Breaks, and Seasonal Terms From Daily GNSS Measurements: Il-
 366 luminating Nonlinear Salton Trough Deformation. *Earth and Space Science*,
 367 7(7), e2019EA000644.
- 368 Hudnut, K. W., & Sieh, K. E. (1989). Behavior of the Superstition Hills fault dur-
 369 ing the past 330 years. *Bulletin of the Seismological Society of America*, 79(2),
 370 304–329.

- 371 Jin, Z., Fialko, Y., Zubovich, A., & Schöne, T. (2022). Lithospheric Deformation
 372 Due To the 2015 M7.2 Sarez (Pamir) Earthquake Constrained by 5 years of
 373 Space Geodetic Observations. *Journal of Geophysical Research: Solid Earth*,
 374 *127*(4), e2021JB022461.
- 375 Kaneko, Y., Fialko, Y., Sandwell, D. T., Tong, X., & Furuya, M. (2013). Inter-
 376 seismic deformation and creep along the central section of the North Anato-
 377 lian Fault (Turkey): InSAR observations and implications for rate-and-state
 378 friction properties. *Journal of Geophysical Research: Solid Earth*, *118*(1),
 379 316–331.
- 380 Klimeš, J., Rowberry, M. D., Blahůt, J., Briestenský, M., Hartvich, F., Košťák, B.,
 381 ... Štěpančíková, P. (2012). The monitoring of slow-moving landslides and
 382 assessment of stabilisation measures using an optical–mechanical crack gauge.
 383 *Landslides*, *9*(3), 407–415.
- 384 Kohler, W. M., & Fuis, G. S. (1986). Travel-time, time-term, and basement depth
 385 maps for the Imperial Valley region, California, from explosions. *Bulletin of the*
 386 *Seismological Society of America*, *76*(5), 1289–1303.
- 387 Košťák, B. (1969). A new device for in-situ movement detection and measurement.
 388 *Experimental Mechanics*, *9*(8), 374–379.
- 389 LaBonte, A., Brown, K., & Fialko, Y. (2009). Hydrogeologic detection and finite-
 390 element modeling of a slow-slip event in the Costa Rica prism toe. *J. Geophys.*
 391 *Res.*, *114*, B00A02.
- 392 Li, V. C., & Rice, J. (1987). Crustal Deformation in Great California Earthquake
 393 Cycles. *J. Geophys. Res.*, *92*, 11533–11551.
- 394 Lindsey, E. O., & Fialko, Y. (2016). Geodetic constraints on frictional properties
 395 and earthquake hazard in the Imperial Valley, Southern California. *Journal of*
 396 *Geophysical Research: Solid Earth*, *121*(2), 1097–1113.
- 397 Lindsey, E. O., Fialko, Y., Bock, Y., Sandwell, D. T., & Bilham, R. (2014). Lo-
 398 calized and distributed creep along the southern San Andreas Fault. *Journal of*
 399 *Geophysical Research: Solid Earth*, *119*(10), 7909–7922.
- 400 Lindsey, E. O., Sahakian, V. J., Fialko, Y., Bock, Y., Barbot, S., & Rockwell, T. K.
 401 (2014). Interseismic Strain Localization in the San Jacinto Fault Zone. *Pure*
 402 *and Applied Geophysics*, *171*(11), 2937–2954.
- 403 Louie, J. N., Johnson, D. C., Haase, P. C., & Cohn, S. N. (1985). Fault Slip in

- 404 Southern California. *Bulletin of the Seismological Society of America*, 75(3),
405 811–833.
- 406 Marone, C. J., Scholtz, C. H., & Bilham, R. (1991). On the mechanics of earthquake
407 afterslip. *Journal of Geophysical Research: Solid Earth*, 96(B5), 8441–8452.
- 408 Martí, X., Rowberry, M. D., & Blahút, J. (2013). A MATLAB® code for counting
409 the moiré interference fringes recorded by the optical-mechanical crack gauge
410 TM-71. *Computers & Geosciences*, 52, 164–167.
- 411 Nof, R. N., Ziv, A., Doin, M.-P., Baer, G., Fialko, Y., Wdowinski, S., . . . Bock, Y.
412 (2012). Rising of the lowest place on Earth due to Dead Sea water-level drop:
413 Evidence from SAR interferometry and GPS. *J. Geophys. Res.*, 117(B5).
- 414 Parker, J., Donnellan, A., Bilham, R., Ludwig, L. G., Wang, J., Pierce, M., . . .
415 Jänecke, S. (2021). Buried Aseismic Slip and Off-Fault Deformation on the
416 Southernmost San Andreas Fault Triggered by the 2010 El Mayor Cucapah
417 Earthquake Revealed by UAVSAR. *Earth and Space Science*, 8(8).
- 418 Pearce, J., & Fialko, Y. (2010). Mechanics of active magmatic intraplate in the
419 Rio Grande Rift near Socorro, New Mexico. *J. Geophys. Res.*, 115, B07413.
- 420 Ross, Z. E., Trugman, D. T., Hauksson, E., & Shearer, P. M. (2019). Searching for
421 hidden earthquakes in Southern California. *Science*, 364, 767–771.
- 422 Rymer, M. J. (2000). Triggered Surface Slips in the Coachella Valley Area Associ-
423 ated with the 1992 Joshua Tree and Landers, California, Earthquakes. *Bulletin*
424 *of the Seismological Society of America*, 90(4), 832–848.
- 425 Rymer, M. J., Boatwright, J., Seekins, L. C., Yule, D., & Liu, J. (2002). Triggered
426 Surface Slips in the Salton Trough Associated with the 1999 Hector Mine, Cal-
427 ifornia, Earthquake. *Bulletin of the Seismological Society of America*, 92(4),
428 1300–1317.
- 429 SCEDC. (2013). *Southern California Earthquake Data Center [dataset]*. Caltech.
430 doi: <https://doi.org/10.7909/C3WD3XH1>
- 431 Sharp, R. V. (1967). San Jacinto fault zone in the Peninsular Ranges of southern
432 California. *Geol. Soc. Am. Bull.*, 78, 705–730.
- 433 Sharp, R. V., Budding, K. E., Boatwright, J., Ader, M. J., Bonilla, M. G., Clark,
434 M. M., . . . Sims, J. D. (1989). Surface faulting along the Superstition Hills
435 fault zone and nearby faults associated with the earthquakes of 24 November
436 1987. *Bulletin of the Seismological Society of America*, 79(2), 252–281.

- 437 Sharp, R. V., Rymer, M. J., & Lienkaemper, J. J. (1986). Surface displacement
 438 on the Imperial and Superstition Hills faults triggered by the Westmorland,
 439 California, earthquake of 26 April 1981. *Bulletin of the Seismological Society of*
 440 *America*, *76*(4), 949–965.
- 441 Shaw, J. H., Plesch, A., Tape, C., Suess, M. P., Jordan, T. H., Ely, G., . . . Munster,
 442 J. (2015). Unified Structural Representation of the southern California crust
 443 and upper mantle. *Earth and Planetary Science Letters*, *415*, 1–15.
- 444 Tymofyeyeva, E., & Fialko, Y. (2015). Mitigation of atmospheric phase delays in
 445 InSAR data, with application to the eastern California shear zone. *Journal of*
 446 *Geophysical Research: Solid Earth*, *120*(8), 5952–5963.
- 447 Tymofyeyeva, E., & Fialko, Y. (2018). Geodetic Evidence for a Blind Fault Segment
 448 at the Southern End of the San Jacinto Fault Zone. *Journal of Geophysical Re-*
 449 *search: Solid Earth*, *123*(1), 878–891.
- 450 Tymofyeyeva, E., Fialko, Y., Jiang, J., Xu, X., Sandwell, D., Bilham, R., . . .
 451 Moafipoor, S. (2019). Slow Slip Event On the Southern San Andreas Fault
 452 Triggered by the 2017 Mw 8.2 Chiapas (Mexico) Earthquake. *Journal of*
 453 *Geophysical Research: Solid Earth*, *124*(9), 9956–9975.
- 454 USGS. (2020). *Quaternary Fault and Fold Database for the Nation*.
- 455 Vavra, E. J., Qiu, H., Chi, B., Share, P.-E., Allam, A., Morzfeld, M., . . . Fialko, Y.
 456 (2023). Active dipping interface of the southern San Andreas fault revealed by
 457 space geodetic and seismic imaging. *Journal of Geophysical Research: Solid*
 458 *Earth*, *128*(11), e2023JB026811.
- 459 Wald, D. J., Helmberger, D. V., & Hartzell, S. H. (1990). Rupture process of the
 460 1987 superstition hills earthquake from the inversion of strong-motion data.
 461 *Bulletin of the Seismological Society of America*, *80*(5), 1079–1098.
- 462 Wallace, L. M. (2020). Slow Slip Events in New Zealand. *Annual Review of Earth*
 463 *and Planetary Sciences*, *48*(1), 175–203.
- 464 Wei, M., Liu, Y., Kaneko, Y., McGuire, J. J., & Bilham, R. (2015). Dynamic trig-
 465 gering of creep events in the Salton Trough, Southern California by regional
 466 M 5.4 earthquakes constrained by geodetic observations and numerical simula-
 467 tions. *Earth and Planetary Science Letters*, *427*, 1–10.
- 468 Wei, M., Sandwell, D., & Fialko, Y. (2009). A silent M_w 4.7 slip event of October
 469 2006 on the Superstition Hills fault, southern California. *Journal of Geophysi-*

- 470 *cal Research*, 114(B7), B07402.
- 471 Wei, M., Sandwell, D., Fialko, Y., & Bilham, R. (2011). Slip on faults in the Im-
472 perial Valley triggered by the 4 April 2010 Mw 7.2 El Mayor-Cucapah earth-
473 quake revealed by InSAR. *Geophysical Research Letters*, 38(1).
- 474 Williams, P. L., & Magistrale, H. W. (1989). Slip along the Superstition Hills fault
475 associated with the 24 November 1987 Superstition Hills, California, earth-
476 quake. *Bulletin of the Seismological Society of America*, 79(2), 390–410.
- 477 Zebker, H. A., Rosen, P. A., & Hensley, S. (1997). Atmospheric effects in interfer-
478 ometric synthetic aperture radar surface deformation and topographic maps.
479 *Journal of Geophysical Research: Solid Earth*, 102(B4), 7547–7563.

Figure 1.

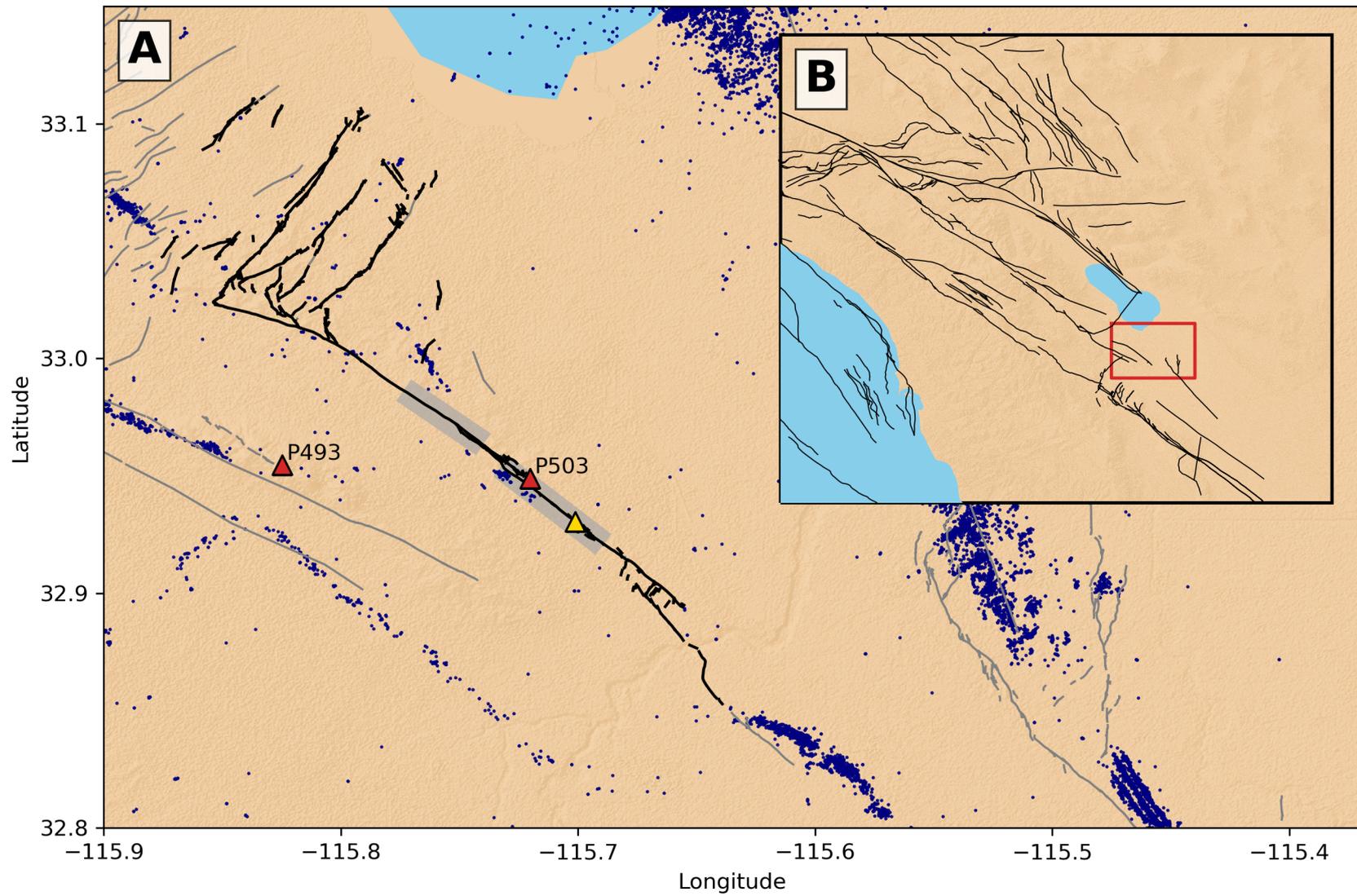


Figure 2.

5/3-5/15: Sentinel-1 interferogram

5/16: slip reaches creepmeters

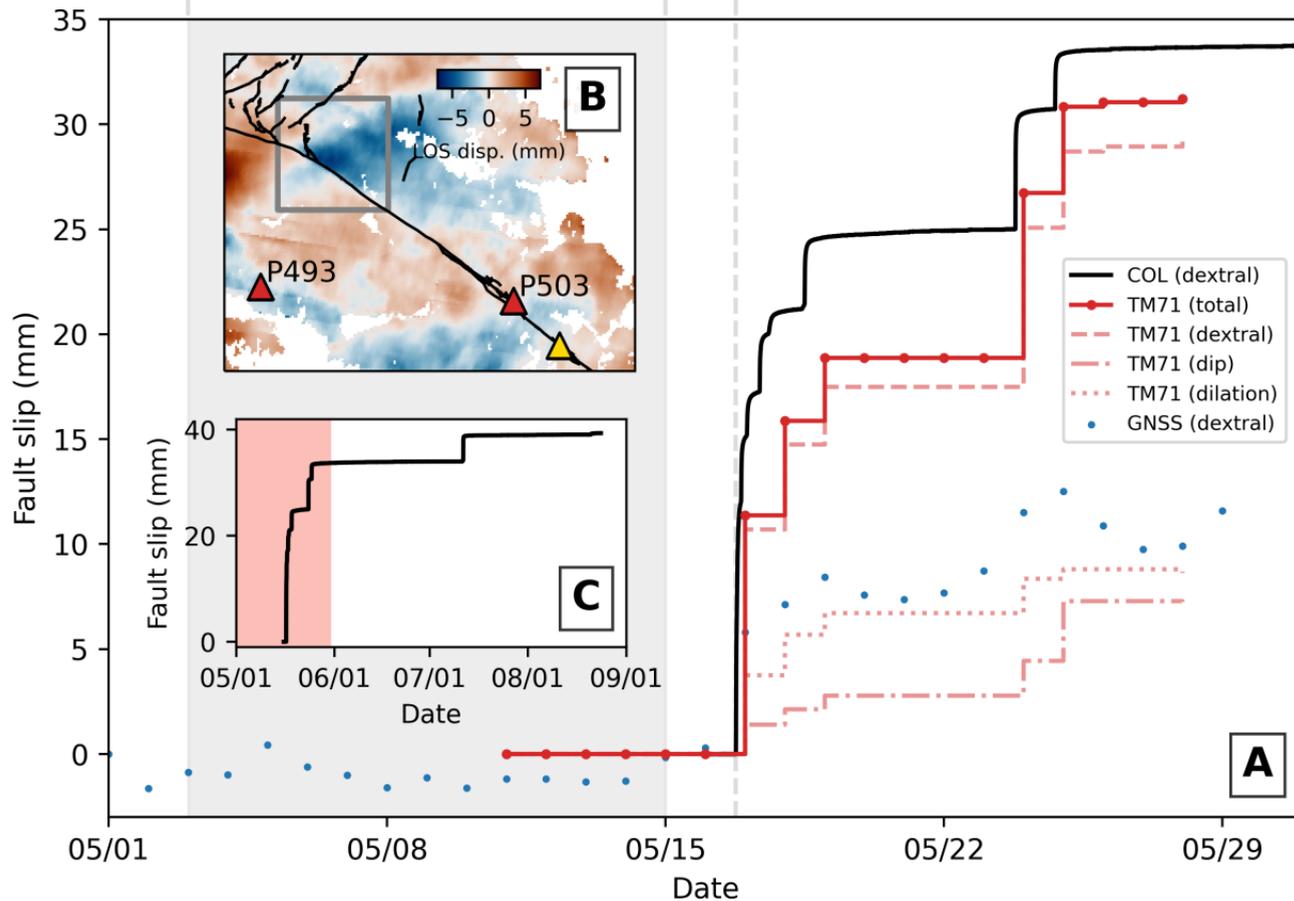


Figure 3.

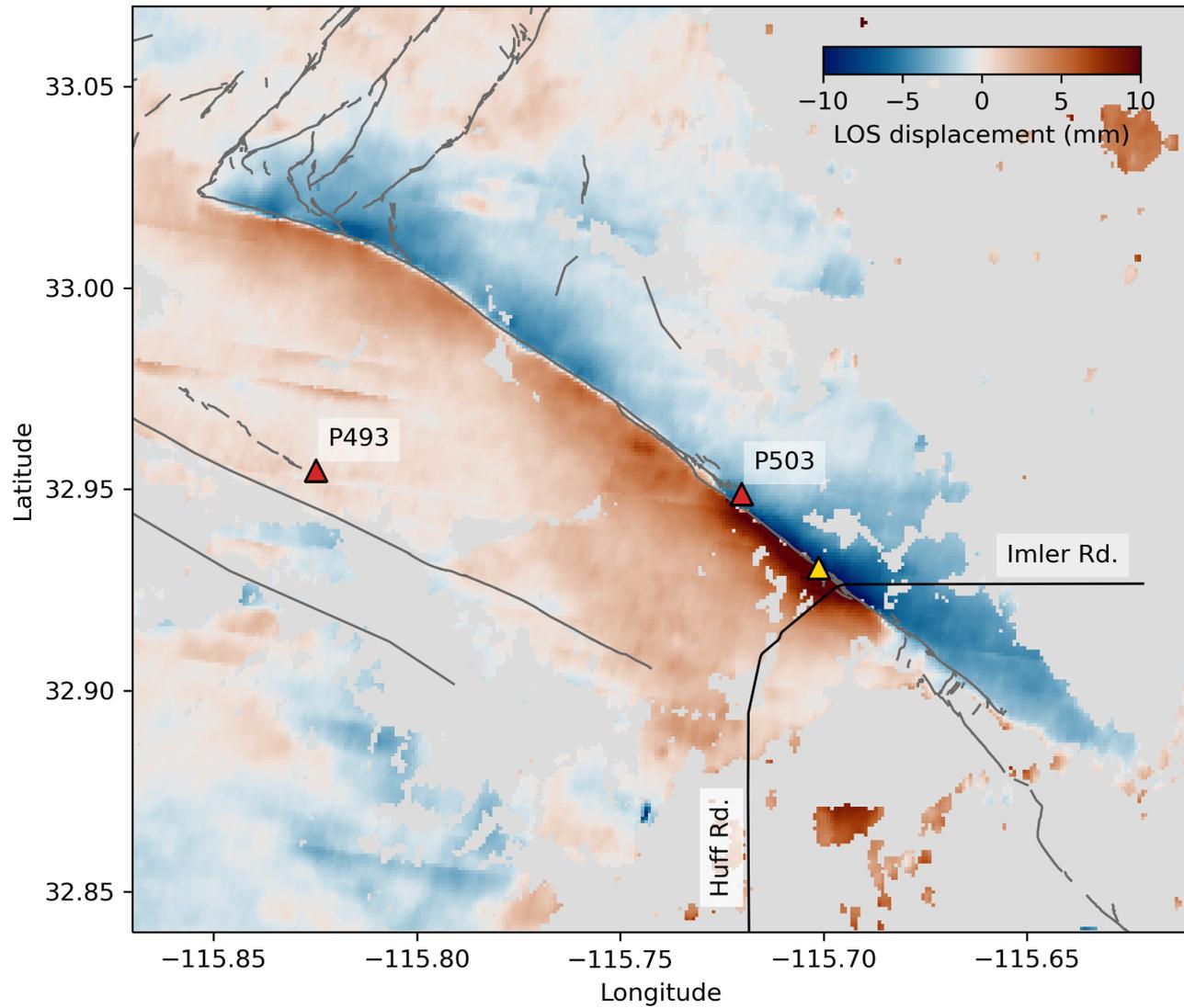


Figure 4.

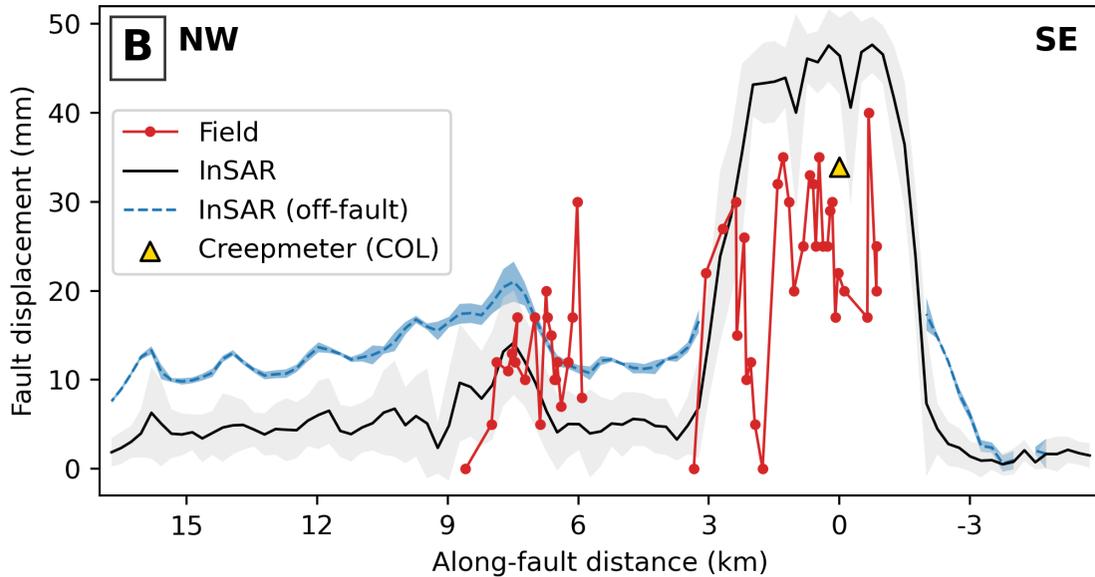


Figure 5.

