

Electronic Supplement 1:
Appendices 1 and 2 and Table A1
for

Recent and Long-Term Behavior of the Brawley Fault Zone,
Imperial Valley, California: An Escalation in Slip Rate?

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APPENDIX 1

HISTORICAL OBSERVATIONS OF SLIP ACROSS THE BFZ AT HARRIS ROAD

A temporally and spatially complex history of aseismic creep, coseismic slip, and postseismic deformation has been documented in the BFZ since the 18 May 1940 Imperial Valley earthquake, although the quality and quantity of the documentation has varied tremendously in those 66 years. Specifically, very little is known about creep prior to August 1970. A summary of the observations of or inferences about creep and slip across the BFZ at Harris Road since 1940 is presented below, and the information is listed more succinctly in Table 4. The discussion below is divided into three parts: aseismic creep, coseismic slip, and postseismic tilting observed prior to and associated with the 1979 earthquake; tilting (indicative of deeper slip) observed between 1980 and 1999; and a shallow creep episode documented in late 2002. The amount of movement documented historically should only be construed as minimum slip during those periods, even since 1970.

SLIP AT HARRIS ROAD, 1940–1979

At least 5 km of the BFZ, from Ralph Road to Keystone Road, ruptured along with the Imperial fault in the 1940 earthquake. Although at least one of the strands crossing Harris Road apparently was involved, details of the rupture and of offsets were not documented (Sharp, 1982b). Recollections by local resident Mr. Richard Hansen (later a superintendent of roads with the Imperial County Department of Public Works) suggest that an abrupt east-side-up (ESU) scarp, perhaps 10 cm high, formed across the then-unpaved Keystone Road, 3.6 km north of Harris Road (Sharp, 1976); this is comparable to the displacement at Keystone Road in 1979.

Additional ESU uplift across Keystone Road after 1940 but before 1960 was noticed by a local rancher and pointed out to the county Department of Public Works prior to the regrading and paving of Keystone Road in 1960 or 1961 (Sharp, 1976). Nothing is known about slip at Harris Road during this period, but presumably creep occurred there as well.

Surface ruptures formed along a 10.4-km long segment of the BFZ during an earthquake swarm in late January and early February 1975; most of the displacement occurred at about the time of the largest shock (M_L 4.8), on 23 January (Sharp, 1976). A scarp height of 8 cm (ESU) was measured on 5 February 1975 by leveling across F1w on Harris Road, but the pre-swarm elevation profile of the road is unknown, so the scarp height indicates only the total slip since August 1970, when Harris Road was regraded and paved (Sharp, 1976). No horizontal component of slip was observed at any location along the fault in 1975 (Sharp, 1976).

The BFZ appeared fairly quiescent from March 1975 to April 1979 except for one small displacement at Harris Road. Between October 1977 and January 1979, a vertical step-like displacement of ~ 0.8 cm (ESU) occurred at F1w (Sharp and Lienkaemper, 1982). Leveling data over that time interval also show a subtle step in the road surface across F1e, although cracking was never detected there before the October 1979 earthquake; the leveling data indicate that the post-1979 small scarp at F1e was almost entirely due to the 1979 earthquake (Sharp and Lienkaemper, 1982; Sharp, 1982b). Fault F2 was not yet known, but cracking and a step in the paved road almost certainly would have been noticed. Hence, appreciable movement across F2 from October 1977 to January 1979 (or for that matter, from August 1970 to April 1979) is unlikely.

Cumulative offsets at Harris Road between successive leveling measurements on 19 April 1979 and 17 October 1979—a time period which included the 15 October 1979 mainshock—were determined from the ongoing leveling measurements and from an offset concrete irrigation canal. Reported offsets were: 5.1 cm ESU and 7.3 cm right-lateral (RL) across F1w; 2.5 cm ESU and negligible RL across F1e; and ~ 7 cm ESU and negligible RL across F2 (Sharp *et al.*, 1982; Sharp and Lienkaemper, 1982). The creepmeter across fault F1w at Harris Road indicated that the coseismic and immediate postseismic displacement grew to its full dimension over more than 12 hours (Cohn *et al.*, 1982). Most of the displacement is assumed to have occurred coseismically and/or in the 12-hour period following the earthquake, but unequivocal evidence precluding slip between 19 April and the

15 October mainshock is lacking. [Records from the Harris Road creepmeter are difficult to interpret for at least two reasons: (1) dextral slip would reduce the distance between piers while subsidence to the west of the fault would increase it, owing to the “backwards” orientation of the Harris Road creepmeter; and (2) vertical motion would be recorded at very low gain, owing to the near-90° angle between the fault and the wire for the vertical component of slip (Cohn *et al.*, 1982; Louie *et al.*, 1985). Consequently, vertical slip cannot be distinguished from lateral slip on the creepmeter recordings, and a creep event with a predominantly (or exclusively) dip component of slip might not be resolvable on the creepmeter. Thus, it appears that available data cannot further constrain the timing of the April to October 1979 slip.] At Keystone Road, the offset across the single strand was determined to be ~9.5 cm vertical (ESU) and 7.3 cm RL (Sharp *et al.*, 1982; Sharp and Lienkaemper, 1982).

Following the 15 October 1979 mainshock, minor postseismic westward tilting of the ground surface without vertical movement at the fault traces was recorded; by 30 December 1979, the east end of the leveling line across F1w and F1e had risen ~1 cm with respect to the west end. However, the large amount of afterslip that was observed on the Imperial fault following the 1979 earthquake (in many cases, the amount of afterslip approximately equaled the amount of coseismic slip) generally was not observed on the BFZ (Sharp and Lienkaemper, 1982).

SLIP AT HARRIS ROAD, 1980–1999

After 1979, additional leveling profiles were surveyed, but data for only selected time intervals have been published, and regrettably, a thorough search by the primary author (A.J.M.) and M.J. Rymer through the records of R.V. Sharp did not bring to light any additional useable data. The only time intervals for which the vertical slip history of the BFZ at Harris Road is known cover a brief period in early 1981 and a continuous period from February 1984 to April 1988. No shallow slip apparently occurred across any of the surface traces of the BFZ at Harris Road during those intervals, but broad tilting of the profiles that

is consistent with deep slip was observed (*e.g.*, Sharp, 1989). Additional details are presented in Table 4.

In addition to the leveling profile re-surveys, the BFZ was inspected for triggered slip following a number of significant earthquakes in southern California in the 1980s and 1990s, but no clear evidence of such slip was ever found (*e.g.*, Sharp *et al.*, 1986; Sharp, 1989; McGill *et al.*, 1989; Rymer *et al.*, 2002).

A CREEP EVENT AT HARRIS ROAD IN 2002

Although regular monitoring of creep was largely discontinued by 1988, it is evident that creep still occurs along the BFZ more than two decades after the 1979 earthquake. Over time, cracks in paved roads and concrete irrigation canals (some with measurable displacement) have grown and widened, and in November 2002, a localized strain event developed along the BFZ while our trench was open. The exact timing of the event and the geographic extent of creep are not well constrained, but the event produced ~6 mm of vertical (ESU) and ~4 mm of RL displacement across fault F1w, cleanly offsetting the etched walls of the trench on the south shoulder of Harris Road. No other creep was observed in the nine months that trenches were open at this site.

That creep had occurred at the trench site (BFH1) was first recognized when one of the authors (A.J.M.) and a field assistant (D. M. Verdugo, San Diego State University) arrived at the site on the afternoon of 21 November 2002, after being away from the trench for three weeks. The trench had already been open for several months, and the walls of the trench had been flattened, etched, photographed, and logged during previous visits. That day, a fresh crack was plainly visible in the walls of the trench, and it cleanly cut across the spoils pile adjacent to the trench. The crack continued on the ground surface for tens of meters in either direction from the trench, following the fault trace, until it went into agricultural fields; there, any evidence of movement would have been difficult or impossible to recognize, owing to the dense crops growing in the fields.

On the ground surface, the crack appeared to be characterized primarily by extension of several millimeters; if there was any displacement at the ground surface, it was masked by the tensile opening. At the base of the trench, 2 m below the ground surface, the crack was also dominated by extension; however, given the smooth, planar nature of the flattened trench walls prior to the creep event, A.J.M. and D.M.V. were able to resolve 1-2 mm of RL slip at the base of the trench, with that value generally decreasing to less than a resolvable threshold as the cracks rose to the ground surface. If there was any dip component of slip, it was also below resolution.

In the trench faces that had already been logged, the fresh crack generally followed a preexisting fault, but the fresh crack extended higher up in the section than we were able to confidently log the fault previously. As a caveat, the uppermost part of the section is artificial fill, and it is not clear whether a fault would have been recognizable in that material if it had moved prior to the opening of the trench. Unfortunately, light ran out on 21 November before other sites in the BFZ could be inspected for creep, and none of us were able to return to the site until 13 December 2002.

We determine the timing of the onset of slip to being prior to our arrival that day and subsequent to our departure on the previous occasion. These limits require that the slip event initiated between approximately 16:00 PST on 2 November 2002 (00:00 GMT on 3 November 2002) and 13:30 PST (21:30 GMT) on 21 November 2002. We searched the Southern California Seismic Network (SCSN) earthquake catalog (available at <http://www.data.scec.org/research.html>) for earthquakes on or near the BFZ or within 20 km of the trench site between 00:00 GMT on 20 October and 00:00 GMT on 22 November 2002. (Note that results of this search would include events up to two weeks prior to the earliest possible onset of creep at Site BFH1, which might be relevant if the creep was a delayed response to coseismic slip at depth.) As it turns out, no events in the catalog fit those criteria, so it appears that this creep event is not associated with any local earthquakes.

When A.J.M., T.K.R., and D.M.V. returned to the trench on 13 December 2002, it was apparent that additional creep had taken place since our prior visit, as the cracks in the

trench were wider, and the displacement across them was greater. On 13 December, using the most reliable piercing points we could find, we estimated that a total of ~6 mm of vertical (ESU) displacement and ~4 mm of RL displacement, in addition to several mm of extension, had occurred across F1w in the lower wall of the trench. As was the case in November, the amount of slip appeared to diminish upward, although an alternate explanation could be that in the uppermost meter or two, the deformation was more diffuse, so that it wouldn't be recognized as discrete slip along a fault surface. We measured a total of ~8 mm of ESU vertical displacement across the road surface in the middle of Harris Road, but the road surface was not completely level prior to November. Hence, the ~8 mm displacement reflects only the total vertical displacement since the road was last patched. (An inquiry in 2004 to Mr. Manuel Provencio, a superintendent of roads with the Imperial County Department of Public Works, reveals that although no records are kept of when specific roads are patched, the crack on Harris Road at F1w has typically been re-patched in winter, once every year or two, at least in recent years. This suggests that additional undocumented creep has occurred at the site repeatedly since 1988.)

On the morning of 14 December, several other sites were inspected for creep. Cracks were observed at Keystone Road and along McConnell Road, 1 km south of Keystone Road, in the same locations as where faulting was observed in the 1979 earthquake (Figure 2; Sharp *et al.*, 1982, plate 1). At these locations, cracks in the pavement (which likely represented the cumulative effect of years of slip) marked the locations of the fault strands; somewhat obscured but nonetheless visible cracks on the adjacent dirt shoulders (which likely were not more than a month or two old) indicated the relative recency of renewed creep. No clear evidence of fresh creep could be found north of Keystone Road; a search was not performed south of Harris Road. Along Harris Road, no evidence for creep was observed along F1e in either November or December, and no evidence was observed along F2, F3, or F4, although the latter faults were not checked in November, and any evidence of creep could have been destroyed by 14 December.

In regard to the timing of the event, one important observation is that, based on the judgment of A.J.M. and D.M.V., the cracks appeared fresh on 21 November 2002; in contrast, when the two returned to the site with T.K.R. on 13 December 2002, the cracks were considerably degraded and in some cases no longer visible. This marked contrast might suggest that the cracks formed very shortly (*i.e.*, within a few days) prior to 21 November. The degradation of the cracks, however, probably has more to do with the weather during that time than with the duration for which the cracks were exposed. Examination of weather records from the National Climatic Data Center (NCDC) (available at <http://www.ncdc.noaa.gov/>) reveals that the only measurable precipitation that occurred between 1 November and 15 December 2002 in any of the nearby towns of Brawley, Imperial, El Centro, or Calexico occurred entirely within a 5-day window between 17:00 PST on 25 November and 09:00 PST on 30 November—after the 21 November visit but prior to the 13 December visit; the rainfall totals at each site during that period were 4.3, 4.6, 6.6, and 4.6 mm, respectively.

The search of the SCSN earthquake catalog was extended through 00:00 GMT on 14 December 2002, to check if the additional creep (subsequent to 21 November) could be attributed to any earthquakes. Four events appear in the catalog that occurred within 20 km of Site BFH1 (see Table A1), but none of them were particularly close to the BFZ, none were larger than M 2.5, and all four events occurred *after* the rain event of 25–30 November and within 10 days of the 13 December visit, which would be inconsistent with the uniformly degraded appearance of the cracks by 13–14 December 2002. Hence, we once again argue that the creep was completely aseismic and not associated with any local earthquakes.

APPENDIX 2

DISCUSSION OF POSSIBLE FAULT STRAND F4

At Site BFH4, we identified a possible fault (F4) based partly on an apparent east-side-up step of ~10 cm in the base of Unit 100 in the wall of Mesquite Drain 2. In the agricultural field due south of this point, we observed a vegetation boundary, hereafter referred to as the “F4 vegetation boundary” (see Figures 4 g–h). We herein comment on the potential significance of the F4 vegetation boundary. West of this boundary, alfalfa has been planted, but east of the boundary within the same field, Bermuda grass is growing. It is not common in the Imperial Valley to find different crops growing together in the same field as they do here, but this uncommon relationship also exists in the field immediately to the west; in the field to the west, the vegetation boundary is roughly coincident with fault F1w, with alfalfa to the west and Bermuda grass to the east. (We will hereafter refer to this as the “F1w vegetation boundary.”) According to Mr. Mark Osterkamp, a land owner and farmer in the Imperial Valley, Bermuda grass will grow in highly saline soil, whereas alfalfa will not. Mr. Osterkamp owns the field immediately north of Harris Road that straddles fault F1w and is familiar with the F1w vegetation boundary: when the original farmers graded their fields across F1w and removed the excess material from the upthrown side of F1w, they discovered that the soil that remained east of the fault was too saline to grow alfalfa; even today, only Bermuda grass will grow there. Although Mr. Osterkamp is not familiar with the F4 vegetation boundary, we can speculate from the presence of the Bermuda grass that the soil east of the F4 vegetation boundary is more saline than the soil immediately to the west. It remains inconclusive, however, whether the F4 vegetation boundary is controlled by a fault. The field containing the F4 vegetation boundary is topographically lower than the adjacent field to the east. (Fault F2 lies near the boundary of the two fields.) From Mr. Osterkamp’s experience, where there is an elevation difference between two adjacent fields, some salt can leach down from the higher field into the lower field simply from the gravity-driven downward flow of water; to his knowledge, this leaching occurs independently of the location of faults. Hence, although we may reasonably assume that the soil immediately east

of the F4 vegetation boundary is saltier than the soil immediately to the west, the higher salinity to the east does not necessarily imply the existence of a fault at the F4 vegetation boundary, nor does it imply that any material has been removed from the area immediately to the east of that boundary. The existence of fault F4, therefore, remains questionable.

Table A1: Earthquakes within 20 km of Site BFH1, 20 Oct to 13 Dec 2002

Search Parameters:

Start Date:	2002/10/20 00:00:00 (UTC)	[2002/10/19 16:00:00 PST]
End Date:	2002/12/14 00:00:00 (UTC)	[2002/12/13 16:00:00 PST]
Minimum Mag:	0.0	
Minimum Depth:	0.0	
Location:	within a 20 km radius of 32.8828° N, 115.4794° W	
Catalog:	SCSN	

Network-located earthquakes within search parameters:

Date (Y/M/D)	Time	Mag	Lat	Lon	Depth	Location
2002/12/04	22:47:34.18	1.50	33.025	-115.556	5.5	6 km ESE of Westmorland, CA
2002/12/08	13:41:50.77	1.69	32.728	-115.483	15.7	7 km N of Calexico, CA
2002/12/10	05:51:31.00	1.31	32.770	-115.434	10.0	11 km ESE of El Centro, CA
2002/12/13	01:23:27.12	2.52	32.970	-115.527	15.9	1 km NE of Brawley, CA

Date and time in UTC; 'mag' is local magnitude; latitude and longitude in decimal degrees; depth in km.

Source: Southern California Earthquake Data Center (2004). 1932–present earthquake catalog, http://www.data.scec.org/catalog_search/radius.php. (Data downloaded 2 May 2004.)