ABSTRACT

Four new latest Pleistocene slip rates from two sites along the northwestern half of the San Bernardino strand of the San Andreas fault suggest the slip rate decreases southeastward as slip transfers from the Mojave section of the San Andreas fault onto the northern San Jacinto fault zone. At Badger Canyon, offsets coupled with radiocarbon and optically stimulated luminescence (OSL) ages provide three independent slip rates (with 95% confidence intervals): (1) the apex of the oldest dated alluvial fan (ca. 30–28 ka) is right-laterally offset ~300–400 m yielding a slip rate of 13.5 ±3.5 mm/yr; (2) a terrace riser incised into the northwestern side of this alluvial fan is offset ~280–290 m and was abandoned ca. 23 ka, yielding a slip rate of 11.9 ±1.9 mm/yr; and (3) a younger alluvial fan (13–15 ka) has been offset 120–200 m from the same source canyon, yielding a slip rate of 11.8 ±1.8 mm/yr. These rates are all consistent and result in a preferred, time-averaged rate for the past ~28 k.y. of 12.8 ±2.2 mm/yr (95% confidence interval), with an 84% confidence interval of 10–16 mm/yr. At Matthews Ranch, in Pitman Canyon, ~13 km northwest of Badger Canyon, a landslide offset ~650 m with a 26Be age of ca. 47 ka yields a slip rate of 14.5 ±4.5 mm/yr (95% confidence interval). All of these slip rates for the San Bernardino strand are significantly slower than a previously published rate of 24.5 ± 3.5 mm/yr at the southern end of the Mojave section of the San Andreas fault (Weldon and Sieh, 1985), suggesting that ~12 mm/yr of slip transfers from the Mojave section of the San Andreas fault to the northern San Jacinto fault zone (and other faults) between Lone Pine Canyon and Badger Canyon, with most (if not all) of this slip transfer happening near Cajon Creek. This has been a consistent behavior of the fault for at least the past ~47 k.y.

INTRODUCTION

The partitioning of slip rate between faults within the southern San Andreas fault system is still poorly understood. Elastic modeling of geodetic data suggests that a substantial portion of the slip on the Coachella Valley section of the San Andreas fault passes northward into the Eastern California shear zone, rather than remaining on the San Andreas fault (Fig. 1) (Becker et al., 2005; Meade and Hager, 2005; Spinder et al., 2010; Loveless and Meade, 2011; McGill et al., 2015). Likewise, a substantial portion of the slip on the Mojave section of the San Andreas fault appears, in these models, to extend southward onto the San Jacinto fault, leaving a relatively low strain accumulation rate on the San Bernardino and San Gorgonio Pass sections of the fault. Most of these models infer slip-deficit rates (also known as “geodetic slip rates”) of 0–8 mm/yr for the San Bernardino and San Gorgonio Pass sections of the San Andreas fault.

Initially, this model of slip partitioning appeared to contrast dramatically with geologic estimates of the slip rate of 24 ± 3.5 mm/yr near Cajon Creek (Weldon and Sieh, 1985), 14–25 mm/yr at Wilson Creek, in Yucaipa (Harden and Matti, 1989), and 14–17 mm/yr at Biskra Palms (Behr et al., 2010 and Fletcher et al. 2010, following upon earlier work by Keller et al., 1982, and van der Woerd et al., 2006; site locations are shown in Fig. 1). However, several recent investigations have resulted in additional Holocene and late Pleistocene slip rates at sites located southeast of Cajon Creek and northwest of Biskra Palms, which confirm that the San Bernardino and San Gorgonio Pass sections of the San Andreas fault slip more slowly than any other section of the fault zone, with rates of 7–16 mm/yr at Plunge Creek (McGill et al., 2013), 8 ± 4 mm/yr at Burro Flats (Orozco and Yule, 2003; Orozco, 2004; Yule and Spota, 2010; see also Yule, 2009), 5.7 ± 1.9 mm/yr at Millard Canyon (Heermann and Yule, 2017), >5.7 ± 0.8 mm/yr at Cabazon (Yule et al., 2001), and 4–5 mm/yr at Painted Hill, near Whitewater (Gold et al., 2015). In this paper, we report similarly slow rates for two sites near the northwestern end of the San Bernardino strand of the San Andreas fault.
Figure 1. Major faults and fault sections discussed in text, color coded according to recency of movement (U.S. Geological Survey and California Geological Survey, 2018). White circles show locations of latest Pleistocene and Holocene slip-rate sites for the San Andreas and San Jacinto faults, with slip-rate estimates in mm/yr. Smaller white circles show slip-rate sites on the Mill Creek strand of the San Andreas fault. Inset map shows location of Figure 1 within southern California. Box shows location of Figure 2. AW—Ash Wash (Le et al., 2008); Az1—Anza (Rockwell et al., 1990); Az2—Anza (Blisniuk et al., 2013); Az3—Anza (Merifield et al., 1991); BC—Badger Canyon (this study); BF—Burro Flats (Orozco and Yule, 2003; Orozco, 2004; Yule and Spottila, 2010); BP—Biskra Palms (Behr et al., 2010; Fletcher et al., 2010); C—Colton (Wesnousky et al., 1991); Cb—Cabazon (Yule et al., 2001); CC—Cajon Creek (Weldon and Sieh, 1985); Cy—City Creek (1.2 mm/yr: Sieh et al., 1994); DC—Day Canyon (Horner et al., 2007); GT—Grand Terrace (Prentice et al., 1986); IH—Indio Hills (Blisniuk et al., 2021); LC—Lytle Creek (Weldon et al., 2008); MC—Millard Canyon (Heermann and Yule, 2017); NSTB—Northern San Timoteo badlands (Morton et al., 1986; Kendrick et al., 2002; McGill et al., 2012; Onderdonk et al., 2015); Pa—Pallett Creek (Salyards et al., 1992); PI—Plunge Creek (McGill et al., 2013); Pt—Pitman Canyon (this study); PW—Pushawalla Canyon (Blisniuk et al., 2021); RH—Rockhouse Canyon (Blisniuk et al., 2010); SA—Santa Ana River (2 mm/yr: Weldon, 2010); SBM—San Bernardino Mountains; SGM—San Gabriel Mountains; SG Pass—San Gorgonio Pass; SSR—southern Santa Rosa Mountains (Blisniuk et al., 2010); WC—Wallace Creek [inset] (Sieh and Jahn, 1984); WC—Wilson Creek (Harden and Matti, 1989); PH—Painted Hill (Gold et al., 2015).
■ REGIONAL TECTONIC SETTING

The Badger Canyon and Matthews Ranch/Pitman Canyon slip-rate sites are on the northwestern half of the San Bernardino Mountains section of the San Andreas fault zone (Fig. 1). Within the San Bernardino region, four major strands of the right-lateral San Andreas fault zone have been active at various times, along with numerous other fault splays (Matti and Morton, 1993). The two oldest strands—the Wilson Creek and Mission Creek strands—have not been active during the time period for which our slip-rate estimates are valid (Matti and Morton, 1993). Only the San Bernardino and Mill Creek strands are expressed geomorphically in our study area, along with several other fault strands and splays of shorter length (Fig. 2). The slip rates reported in this paper are for the San Bernardino strand, which is the strand with the strongest geomorphic evidence for Holocene activity (Matti and Morton, 1993).

The northern end of the San Jacinto fault zone closely approaches the San Bernardino strand of the San Andreas fault and comprises three strands with evidence for Holocene activity (Fig. 2). The Glen Helen fault is the northeasternmost mapped strand of the San Jacinto fault zone and is located ~2.0 km southwest of the San Bernardino strand at Pitman Canyon (Fig. 2). The San Jacinto fault proper and the Lytle Creek fault (another strand within the San Jacinto fault zone) are located ~4.1 and 5.6 km southwest of the San Bernardino strand at Pitman Canyon, respectively.

Two additional faults have been mapped between the San Jacinto and San Andreas fault zones within the region of their closest approach (Fig. 2; Weldon, 1986). The Peters fault strikes east-west and connects the San Bernardino strand southeast of Pitman Canyon to the Glen Helen fault. Between Pitman Canyon and Devore, the Tokay Hill fault diverges southward from the San Bernardino strand for a length of 2 km, where it ends or is buried beneath young alluvium. These two structures (and possibly others that may be buried under active alluvium between them and the Glen Helen fault) may serve to transfer slip between the San Andreas and San Jacinto fault zones.

■ METHODS

We conducted geologic mapping at Badger Canyon and at the Matthews Ranch landslide in Pitman Canyon, as described in more detail in the

Figure 2. Regional tectonic setting of this study. Yellow circles show slip-rate sites present in this study: BC—Badger Canyon site; Pt—Pitman Canyon (Matthews Ranch) site. White circles show other slip-rate sites: CC—Cajon Creek site (Weldon and Sieh, 1985); Pl—Plunge Creek site (McGill et al., 2013); WC—Wilson Creek site (Harden and Matti, 1989). Fault abbreviations: GHF—Glen Helen fault; LCF—Lytle Creek fault; PF—Peters fault; THF—Tokay Hill fault. Other geographic locations mentioned in text: LPC—Lone Pine Canyon; WmC—Waterman Canyon. Faults from U.S. Geological Survey and California Geological Survey (2018).
Supplemental Material. Additional details on methods for radiocarbon and optical stimulated luminescence dating, and methods used to calculate dose rates explained in the footnotes to that table. Table S2 provides latitude, longitude, and depth of each OSL sample. We documented soil development for pedons associated with Q1, Q2t-w, Q2a, and Q3b at Badger Canyon (Table S3). Details are described in the Supplemental Material (text, section S1.2).

We collected samples for 10Be exposure surface dating from ten boulder tops on alluvial fan surfaces at Badger Canyon and from the tops of six blocks on the Matthews Ranch landslide near Pitman Canyon. Details of sample selection, processing, and laboratory analysis are described in the Supplemental Material (section S1.2, see footnote 1). Field and laboratory measurements are reported in Table S4. 10Be exposure ages for boulders were calculated using Martin et al. (2017), and ages obtained using a variety of other models are reported in Table S5. For discussion and analysis, we use the Lal (1991) and/or Stone (2000) time-dependent model with a local production rate scaled from four sites in the Sierra Nevada (Baboon Lakes Moraine, Mount Starr, Greenstone Lake, and Twin Lakes; Martin et al., 2017).

To calculate slip rates, we construct probability density functions (PDFs) for the offset (O) and age (A) of each geologic feature. These PDFs are constrained by quantitative measurements and shaped by our understanding of the geologic history of the site. We then construct a joint probability density function for offset and age of each feature, following McGill et al. (2009). Each cell in the two-dimensional joint PDF contains the probability that the offset and age both fall within the range of offsets and ages spanned by that cell. This probability is calculated using the following equation:

\[
p(O, A) = p(O) dO p(A | dA, \quad (1)
\]

### TABLE 1. RADIOCARBON AGES FROM THE BADGER CANYON SITE

| Lab no. | Sample name | Δδ13C (permil) | Fraction modern | ΔΔ13C | Δ13C age† | †13C age† (yrs B.P.)* | Mean (cal. yrs B.P.) | 95.4% cont. interval | Context |
|---------|-------------|----------------|----------------|-------|-----------|------------------------|---------------------|----------------------|---------|
| 127368  | BC-15       | 0.8618         | 0.0031         | 138.2 | 3.1       | 1195                   | 1120                | 1010–1230            | Young fill (Qa4) over Qls2 in WT-1A |
| 127369  | BC-24       | 0.2104         | 0.0009         | 789.6 | 0.9       | 12525                  | 14,800              | 14,450–15,100        | Base of colluvium over Qts3 in WT-2 |
| 127370  | BC-22       | 0.1988         | 0.0081         | 802.8 | 0.8       | 12,975                 | 15,510              | 15,310–15,710        | Qts3 gravel from WT-1B |
| 127371  | BC-42       | 0.2097         | 0.0009         | 790.3 | 0.9       | 12,545                 | 14,860              | 14,580–15,120        | Qts3 in WT-1A, just south of fault |
| 127372  | BC-17       | 0.0900         | 0.0039         | 910.0 | 3.9       | 19,340                 | 23,320              | 22,490–24,120        | Qts2 in WT-1A, north of fault, above Qls2 |
| 127373  | BC-11       | 0.0911         | 0.0006         | 908.9 | 0.6       | 19,250                 | 23,200              | 22,950–23,450        | Qcc in WT-1A, north of fault, below Qls2 |
| 127374  | BC-20       | 0.0812         | 0.0006         | 918.8 | 0.6       | 20,170                 | 24,240              | 24,020–24,450        | ET-C2 (east of Badger Canyon) |
| 127375  | BC-8        | 0.0481         | 0.0007         | 951.9 | 0.7       | 24,380                 | 28,420              | 28,100–28,720        | Near apex of Qts2, in WT-3C |
| 127376  | BC-12       | 0.0365         | 0.0005         | 963.5 | 0.7       | 26,600                 | 30,730              | 30,020–31,090        | Qtf3a in WT-1A, north of fault, below Qc2 |
| 127377  | BC-13       | 0.0365         | 0.0005         | 963.5 | 1.5       | 23,320                 | 30,730              | 30,020–31,280        | Qtf2a in WT-1A, north of fault, below Qc2 |

*All samples were dated at Center for Accelerator Mass Spectrometry (CAMS), Lawrence Livermore National Laboratory.

†All Δδ13C values are assumed, with the exception of sample BC-51, for which the Δδ13C value was measured.

‡The quoted age is in radiocarbon years using the Libby half-life of 5568 years and following the conventions of Stuiver and Polach (1977).

§Radiocarbon ages were calibrated with OxCal 4.2 (Bronk Ramsey, 2009) using calibration curve intCal13 (Reimer et al., 2013).

*Cal. B.P. indicates (calibrated) calendar years before A.D. 1950.

**yrs B.P. indicates radiocarbon years before A.D. 1950.
where \( p(O,A) \) is the joint probability that the offset (O) and the age (A) are within a particular offset increment \( dO \) and a particular age increment \( dA \), given that \( p(O) \) and \( p(A) \) are the probability density functions for offset and age and are assumed to be independent of each other. We then sum the probabilities contained in all the cells in the joint PDF to have offsets and ages that contribute to a particular range of slip-rate values \( R \), using the relationship

\[
R = O/A,
\]

(2)

to obtain the probability that the slip rate falls within that range. This allows us to calculate a PDF and cumulative probability distribution for the slip rate, from which we can obtain the mean and 95% confidence intervals for the slip rate.

### DESCRIBATIONS AND AGES OF OFFSET DEPOSITS AND LANDFORMS USED TO CALCULATE SLIP RATES

The Badger Canyon study area is located at and west of where Badger Canyon crosses the San Bernardino strand of the San Andreas fault zone (34.191°N/117.313°W). The San Bernardino strand displaces several alluvial fan units from the mouth of Badger Canyon (Fig. 3), forming the basis for three slip-rate estimates. In this section, we briefly describe the geologic units that are relevant to understanding the slip-rate estimates. A more complete description of these and other geologic units and landforms can be found in the Supplemental Material (text, section S2, see footnote 1).

On the southwest side of the San Bernardino strand, a series of three latest Pleistocene alluvial fans (Qf1, Qf2, and Qf3) and one late Holocene alluvial fan (Qf4) are present. All of the alluvial fans are composed of sandy gravel, with abundant cobbles and common small boulders of felsic and intermediate plutonic rock and gneiss, with lesser amounts of other rock types (pegmatite, marble, dolomitic marble, aplite, sandstone, biotite schistose rock, and epidote). Both clast sizes and lithologies are consistent with Badger Canyon being the source of all four alluvial fans. Sediment transported within smaller drainages northwest of Badger Canyon is finer grained (mostly sand) and is richer in marble, dolomitic marble, and aplite clasts than deposits within Badger Canyon or in the four alluvial fans.

The older alluvial fans are offset from the source region (Badger Canyon) by progressively larger amounts than the younger alluvial fans. Reliable age control is lacking for Qf1 (see discussion of available ages in section S2.3.1 of the Supplemental Material [footnote 1]), and human disturbance prevents reliable estimation of the offset of Qf4. Our three slip-rate estimates are thus derived from Qf2 and Qf3.

#### Qf2 and Qf2a

Qf2 is a broad alluvial fan with a slightly lower terrace (Qf2-w) cut into its western side. The topographic contours on the central and eastern portions of the alluvial fan (Fig. 3) are consistent with the typical shape of a single, broad alluvial fan. However, topographic contours, profiles (e.g., Fig. 4), and field observations reveal a ~2.5-m-high terrace riser separating the lower, western portion of the Qf2 alluvial fan (Qf2-w) from the remainder of the alluvial fan. We interpret Qf2-w as an erosional geomorphic surface cut into Qf2 when the active channel migrated to the western side of the alluvial fan after Qf2 was deposited.
The riser between Qf2 and Qt2-w is important because it forms the basis for one of our slip-rate estimates. Although the riser has been modified by a younger, modern channel that flows along it for most of its length, the riser itself and the two surfaces that it separates (the preserved geomorphic surface at the top of Qf2 and Qt2-w) are clearly visible for the first 35–40 m southwest of the fault.

We propose that the alluvial remnant Qf2a on the northeast side of the fault is correlative with the broad Qf2 alluvial fan on the southwest side of the fault. Each of these units is the most prominent alluvial unit on their respective sides of the fault, and alternative correlations that we considered led to untenable reconstructions of the geologic history.

Age estimates for Qf2 and Qf2a range from 18 to 31 ka, with OSL ages being systematically younger than radiocarbon ages from the same layer. Within Qf2, a detrital charcoal sample from a ~10-cm-thick sand layer near the base of trench WT-3C has a \(^{14}C\) age of 28.4 ± 0.3 ka (sample BC-8 in Table 1). This sample was located near the apex of the Qf2 fan on the southwest side of the fault at a depth of ~2.8 m below the surface. Figure S3 in the Supplemental Material (section S2.3.2, see footnote 1) has a photograph of the sample location within trench.

Figure 3. (A) Simplified geologic map of the Badger Canyon site including trench, soil profile and sample locations. See section (C) of the figure for explanation of map units and symbols. Sample numbers are only shown for samples not shown in Figures 5 or 8. Optically stimulated luminescence dating sample numbers are labeled with white text; all other sample numbers and soil profile labels are in black text. Short black lines crossing trenches mark locations of faults that were observed in trenches but could not be mapped at the surface. Boxes with solid outlines mark locations of enlarged map figures. Contour interval is 10 m. SAF — San Andreas fault. (Continued on following two pages.)
An OSL sample from the same sand layer yields an age of 20.6 ± 3.0 ka (sample BC2 in Table 2). On the northeast side of the fault, Qf2a, has similar ages. Two charcoal samples from a sand lens exposed in trench WT-1A, have radiocarbon ages of 30.7 ± 0.7 and 30.8 ± 0.3 ka (samples BC-13 and BC-46 in Table 1 and Fig. 5). These ages are slightly older than the radiocarbon age from Qf2 on the southwest side of the fault (28.4 ± 0.3 ka) but are consistent with that age, given that the fan was likely deposited over a period of time. This supports our correlation of Qf2 and Qf2a across the fault. An OSL sample from the same sand lens within Qf2a, has an age of 22.2 ± 3.8 ka (BC6 in Table 2 and Fig. 5), slightly older than, but consistent with the OSL age from Qf2 on the southwest side of the fault (20.6 ± 3.0 ka), again supporting the correlation of Qf2a with Qf2.

Self-consistent results within each dating technique suggest one of these methods provides a reliable age, but not both. Either dating technique could provide ages that are either too old (e.g., incomplete bleaching of luminescence samples; delays between the growth of wood and its deposition within a sedimentary layer as detrital charcoal), or too young (e.g., incorporation of detrital charcoal into an older sedimentary layer via bioturbation, or mixing of younger grains into an OSL sample from an older layer via bioturbation). All of the charcoal and OSL samples from Qf2 and Qf2a were collected from ~10-cm-thick, moderately well sorted
sand layers, in which any burrows intersected by the trench wall would have been easily visible and avoided. Of course, we cannot rule out the possibility that the OSL sample tubes may have intersected a burrow behind the trench wall.

We favor the radiocarbon ages for several reasons. (1) The systematics of radiocarbon dating are better understood than for OSL dating. (2) If we accept the two OSL ages from Qf2 and Qf2a, then we must interpret the three aforementioned 14C ages, as well as two 14C ages from younger units (Qc2 and Qf2b, described below) as being thousands of years older than the deposits from which they were collected. (3) The two OSL ages from Qf1 also appear to be anomalously young (see discussion of Qf1 below). (4) Other investigators have reported anomalously young OSL ages on quartz from southern California (Lawson et al., 2012; Roder et al., 2012). Although we favor the 14C ages, we calculate separate slip rates using the 14C and OSL ages from Qf2 and report both results.

Qt2-w

The Qt2-w geomorphic surface is a cut terrace incised into, and therefore younger than, the Qf2 alluvial fan. Surface exposure ages from 10Be concentrations in the tops of four boulders on Qt2-w (Fig. 3) range from 11 to 43 ka (samples BC5, BC6, BC7, and BC8 in Tables S2 and S3). We have no radiocarbon or OSL ages from the deposits that underlie Qt2-w. The soil development associated with the Qt2-w surface (described in trench WT-7B) is characterized by rubification, development of strong subangular structure, and few, thin clay films (Table S3). This degree of soil development is comparable to nearby surfaces in the San Timoteo Badlands chronosequence independently dated as latest Pleistocene (Kendrick et al., 2002). On the northeast side of the fault, Qf2a (correlated with Qf2) has been incised on its northwest

Figure 3 (continued). (C) Explanation of map units and symbols used in (A).
side, resulting in a terrace riser stepping down from Qf2a to a strath terrace incised into bedrock (Kmg-u and Tc) and later buried by a thin veneer of Qa4. We correlate the riser between Qf2a and the strath terrace below it on the northeast side of the fault, with the riser between Qf2 and the cut-terrace below it (Qt2w) on the southwest side of the fault. These two risers have similar heights and orientations, and both are incised into Qf2 or its equivalent (Qf2a) (Figs. 3 and 4).

Qc2

Within trench WT-1A (Figs. 3 and 5), on the northeast side of the fault, gravel deposits of Qf2a are overlain by moderately to poorly sorted, mostly massive, sandy colluvium with a pinkish tan color, designated Qc2 (Fig. 5). Lenses of gravel are present within Qc2, indicating an interfingering relationship with Qf2a. One charcoal sample from Qc2 has a radiocarbon age of 23.2 ± 0.25 ka (BC-11 in Table 1). The soil developed within Qc2 exhibits a 141-cm-thick argillic horizon with 7.5 YR colors, with very few moderately thick and few thin clay films (Table S3). The degree of soil development suggests an estimated age of ca. 30 ka.

Qls2

We mapped a landslide deposit (Qls2) that plays an important role in understanding the history of deposition of the Qf2 alluvial fan and in constraining the age of the piercing line used for one of our slip-rate measurements. We describe the landslide deposit here and provide additional details and discuss alternative interpretations in the Supplemental Material (text, section S2.3.4, see footnote 1). At 230 m in trench WT-1A (Fig. 5), a sheared contact striking 270° and dipping 37°N separates Qc2 on the south from granitic rock with blocky fracture on the north (Fig. 6). We interpret this contact as the basal shear of a landslide deposit, as did J. McKeown (written communication, 2006). A north-dipping, sheared contact is also visible in a natural exposure ~20 m west of WT-1A (at N34.19238, W117.31330), where similar granitic rocks with blocky fracture overlie Potato Sandstone (Tc). This location is at the north end of the narrow outcrop of Tc just west of WT-1A in Figure 3. This contact between fractured granitic rock on the north and Potato Sandstone on the south extends westward along a south-facing slope that we interpret as the toe of a landslide (see blue contact in Fig. 3). This south-facing slope was intersected by trench WT-4, and two shallowly north-dipping shear zones were exposed, separating fractured granitic rock above from sandstone below (J. McKeown, written communication, 2006).

We agree with McKeown’s interpretation of the shallowly north-dipping shear planes exposed in WT-4 and WT-1A as the basal slip surface at the toe of a landslide. This is supported by the hummocky topography of the region north of the north-dipping shear planes, which we interpret as a landslide deposit (Fig. 7). A possible head scarp is outlined in Figure 7, demarcating the landslide source region as an area with more intense gully development. Lithologies within the landslide deposit are felsic plutonic rocks that are similar to Kmg in the proposed source region for the landslide.

The age of the Qls2 landslide is determined by the ages of one detrital charcoal sample from Qc2 (23.2 ± 0.3 ka) below the landslide and one detrital charcoal sample from Qf2b (23.3 ± 0.8 ka) above the landslide (samples BC-11 and BC-17 in Table 1 and Fig. 5). The two ages are nearly identical, tightly bracketing the age of the landslide to 23.1 ± 0.4 ka, using the sequence modeling function of OxCal.
Figure 5. Logs of trenches WT-1C and of the central portion of WT-1A, from 20 m southwest of the San Bernardino strand of the San Andreas fault (SAF) to 240 m northeast of that strand. Dashed box in Figure 3B outlines the portion of WT-1A that is shown here. The southernmost portion of WT-1A is shown in Figure 8. The northermmost portion of WT-1A is not shown and is not essential to the slip-rate estimates. Thick black lines mark the locations of fault strands. Blue lines mark the basal shear plane of the Qls2 landslide. See Figure 7 for an enlarged view of the landslide. See Figure 3 for explanation of other symbols. Two facies of Qls2 are distinguished: Qls2-w is composed of fine-grained granitoid rock composed of white feldspar and quartz with a few percent biotite, and Qls2-s is composed of fine-grained plutonic rock pervasively fractured into pebble-sized angular blocks (with no matrix between blocks) and with most fracture surfaces stained dark brown. Box shows location of Figure 6. Darker-colored top of Qf2b in WT-1A (220–260 m) and WT-1C (0–50 m) marks location of redder-colored deposits, presumed to be derived from nearby exposures of Qf1, which has a strong red soil. Thin, grayish-brown unit on top of Qc2 and Qa4 in WT-1A (220–240 m, 280–330 m, and 350–410 m) and on top of Qf2b in WT-1C (38–46 m) is an organic-rich soil (A-horizon). Numbers below faults and landslide toe indicate orientations of these semi-planar features (strike, dip, using right-hand rule). Note that Qls2 has overridden Qc2 and has in turn been buried by Qf2b. Uncolored material within the fault zone includes fault scarp colluvium in upper half of trench and undifferentiated sheared alluvial units in lower half.
(Bronk-Ramsey, 2009) to calculate the 95.4% confidence interval on the age of the boundary between Qc2 and Qf2b based on the bounding 14C samples. The dissected character of the landslide is consistent with a late Pleistocene age.

Qf2b

In both trenches WT-1A and WT-1C, the granitic landslide deposits of Qls2 are overlain by alluvial gravel derived from Badger Canyon (Figs. 3 and 5). We refer to the alluvial deposits on top of the Qls2 landslide as Qf2b. Detrital charcoal sample BC-17, with an age of 23.3 ± 0.8 ka (Table 1), is from this unit (Fig. 5).

Presumably the Qf2b alluvial deposits extended southward across the fault. They may have formed a thin (unmapped) veneer of sediment on top of the eastern portion of the Qf2 alluvial fan, but any such veneer would have to be quite thin because the topographic contours on the eastern side of the Qf2 alluvial fan still reflect the shape of the original, broad alluvial fan beneath any hypothetical veneer. Alternatively, the downstream continuation of these deposits may form the western one-third of the Qf3 alluvial fan (the part mapped as Qf3a), or they may be buried beneath Qf3a. We favor the last of these interpretations, but the uncertainty in the location of any deposits southwest of the fault that may be correlated with Qf2b does not affect any of the slip-rate estimates that we obtain from the Badger Canyon site.

Figure 6. View of part of trench WT-1A at 230 m showing north-dipping shear zone (blue line) beneath toe of landslide deposit composed of fractured, white, granitic rock (Qls2). Landslide mass (Qls2) has overridden colluvium (Qc2). Each tier of the trench is ~1.3 m high. See Figure 5 for location of photograph.

Qf3

Qf3 comprises alluvial gravel derived from Badger Canyon. An inflection in the topographic contour lines suggests a possible distinction between the western and eastern portions of Qf3 (labeled Qf3a and Qf3b, respectively, on Fig. 3), with topographic contours on Qf3b having a tighter radius of curvature than those on Qf3a. No age estimates are available directly from Qf3a, but one radiocarbon sample from the base of colluvium that buries Qf3a is similar to available ages from Qf3b (see below), so we interpret the two units as part of the same alluvial fan. We interpret the tighter radius of curvature of topographic contours on Qf3b compared to Qf3a as either (1) reflecting the shape of the final pulse of deposition on Qf3b, and/or (2) as a result of incision of the eastern edge of Qf3b, resulting in truncation of contours that once had a broader radius of curvature. The topographic contours on the surface of both Qf3a and Qf3b indicate that these deposits are not part of the Qf2 fan (Fig. 3), and the ages discussed below also confirm this. The slope on the eastern side of Qf3b, where Qf3

Figure 7. (A) Light detection and ranging (Lidar) image showing landslide Qls2 and its head scarp, and (B) geologic map of same area showing relations among the Qls2 landslide deposit and Qf2b, whose ages are used to define the slip rate for the past ~23 k.y. See Figure 5 for cross-section view of these relationships. See Figure 3C for explanation of map patterns and symbols.
abuts Qa4, may be the depositional edge of Qf3, although it seems rather steep for this. Alternatively, this slope may be a degraded terrace riser incised into the eastern edge of Qf3.

Trench WT-1A reveals further complexity in that Qf3b buries a remnant of much older alluvium with strong soil development (“Qvof2” in Fig. 8). Between this shutter ridge and the fault, deposits of Qf3b fill a channel, the western wall of which strikes SSE between the two walls of Trench WT-1A. This suggests that at some point in time, Badger Creek incised a channel around the eastern edge of the shutter ridge. Whether or not flow from Badger Creek had previously been diverted northwestward along the fault by the shutter ridge is unknown. The presence of Qf3b overlying “Qvof2” in Trench WT–1A (Fig. 8) indicates that in the late stages of aggradation, Qf3b completely overtopped the shutter ridge. These uncertainties in the history of the Qf3 alluvial fan are included in the uncertainties of our slip-rate estimate that is based on Qf3.

Age estimates from multiple techniques are available for Qf3b. Two radiocarbon ages on detrital charcoal range from 14.6 to 15.7 ka (Table 1). One of the samples (BC–42, from trench WT-1A; Fig. 8) comes from the portion of Qf3b that lies within the channel between the buried ridge of older alluvium and the fault, and the other comes from a more distal region of Qf3b (sample BC–22 from WT-1B, Fig. 3 and Fig. S4). Three OSL dates from Qf3b, from both sides of the buried ridge of older alluvium, range from 10.2 to 15.9 ka (samples BC3, BC4, and BC5 in Table 2 and Fig. 8). We have no direct radiocarbon ages from Qf3a, but sample BC–24, from the base of the colluvium that buries Qf3a (WT-2; Fig. 8), has an age of 14.5–15.1 ka (Table 1). This is similar to the ages from Qf3b, suggesting that Qf3a was beginning to be buried by colluvium while the final stage of deposition of Qf3b was continuing. Two 10 Be surface exposure ages from boulder tops on Qf3a range from 15.2 to 21.3 ka (samples BC9 and BC10-top in Tables S2 and S3 and Fig. 3).

The soil developed on Qf3b within WT–1A exhibits a cambic B horizon with 7.5 YR colors (Table S3), with a soil profile index that suggests an age of ca. 4–5 ka, significantly younger than all of the quantitative dating techniques.

### RECONSTRUCTION OF THE HISTORY OF OFFSET FANS AT BADGER CANYON

Figure 9 shows our interpretative reconstruction of the alluvial fans offset from Badger Canyon. Uncertainties in the amount of slip needed to restore different parts of the alluvial fans are discussed in the upcoming sections in which slip-rate estimates are presented. The deposits of fan Qf1 have been offset ~700 m from Badger Canyon (Fig. 9A). Unfortunately, we have no reliable, quantitative age estimate for these deposits. Reconstruction of ~350 m of right-lateral slip restores the Qf2 alluvial fan in its entirety (including the Qf2 deposits...
Figure 9. Reconstructions showing inferred history of fault offset and alluvial fan deposition and incision at the Badger Canyon site. See Figure 3 for explanation of symbols. Semi-transparent colors (with light detection and ranging hillshade map showing through and topographic contour lines plotted) are mapped units that exist today and existed during the time frame shown in the figure (except in the southeastern corner of the map where a sparse dotted pattern has been added to mark units that exist today but had not yet been deposited at the time frame shown in the figure). Opaque colors with no contour lines are used for units that are inferred to have existed at the time shown in the reconstruction, in order to construct a reasonable geologic history, but may have been eroded or buried after that. (Continued on following page.)
beneath the Qt2-w cut-terrace) to the broad mouth of Badger Canyon (Fig. 9B). Sometime after deposition of Qf2, incision occurred on the west side of the alluvial fan, forming the terrace riser between Qf2 and Qt2-w, southwest of the fault, and between Qf2a and bedrock (Tc and Kmg-w), northeast of the fault. Reconstruction of 290 m of right-lateral slip aligns these two terrace risers across the fault (Fig. 9C).

We interpret the sandy colluvium (Qc2) that buries Qf2a in WT-1A to be a colluvial wedge that built out from the eastern side of Badger Canyon while the locus of fluvial erosion, transport and deposition was concentrated on Qt2-w (Fig. 9C). This interpretation implies that Qt2-w and Qc2 should be about the same age. However, the soil within Qc2 is better developed than that observed within Qt2-w, and is closer to, though less developed than, that on Qf1 (see Table S3 and Supplemental Material, text, section S2.3.1 [footnote 1]). We considered an alternate interpretation in which Qc2 and the underlying Qf2a alluvial deposits northeast of the fault would correlate with the Qf1 alluvial fan southwest of the fault, but found this to be untenable because (1) Qf1 is more strongly dissected and more steeply sloping than Qf2a and the overlying Qc2, and (2) this would leave no deposits northeast of the fault that could correlate with Qf1, which is the most prominent alluvial fan southwest of the fault, and no deposits southwest of the fault that could correlate with the Qf1 remnant north of the fault. The apparently stronger soil development on Qc2 than on Qt2-w may possibly be due to detrital clay eroded from the Qf1 remnant north of the fault and incorporated into the parent material of Qc2, or might reflect a localized difference in the mineralogy of the parent materials at this location.

We infer that stream flow on Qt2-w halted when a landslide (Qls2) blocked the western side of Badger Canyon (Fig. 9D). Transport and deposition within Badger Canyon immediately shifted back to the eastern side of the canyon, and a thin veneer of alluvium (Qf2b) covered the eastern edge of the landslide deposit (Fig. 5). The Qf2b alluvial gravel presumably extended southward across the fault. Figure 9E shows our preferred interpretation, in which the deposits southwest of the fault that correlate with Qf2b lie beneath Qf3a.

Qf2b was abandoned when the channel of Badger Creek incised on the east side of Badger Canyon and Qf3a was deposited (Fig. 9F). Deposition of Qf3a and/or Qf3b may have been diverted northwestward around a shutter ridge of very old alluvium (“Qvof2” in WT-1A, Fig. 8) at some point in time (Fig. 9G). However, the shutter ridge was eventually breached by a channel that flowed around its east edge (Fig. 9G) and finally was overtopped by the last stage of Qf3b deposition (Fig. 8). On the northeast side of the fault, no remnants of Qf3 are preserved. They were likely eroded when Badger Creek incised on the east side, followed by deposition of Qa4 and Qf4.

Restoring 85 m of slip places the terrace riser between Qf3b and Qf4 (south of the fault) adjacent to the riser between Qf2a,b and Qa4 (north of the fault) (Fig. 9H). This may have been the geometry at the time that this riser was last refreshed.

OFFSET MEASUREMENTS AND SLIP-RATE CALCULATIONS AT BADGER CANYON

Offset geologic features at the Badger Canyon site with reliable age estimates include: (1) the apex of alluvial fan Qf2; (2) the terrace riser between Qf2 and Qt2-w; and (3) the Qf3 alluvial fan.

Slip Rate Estimated from Qf2

We create probability density functions (PDFs) to represent the range of possible values and find the most likely values for both the offset and the age of the Qf2 alluvial fan, and then we use these to construct a PDF for the slip rate, using the method described in McGill et al. (2009). To find the location of the apex of the Qf2 fan, we used a Gold et al. (2015) script that uses the MATLAB function fitcircle to fit circles to the topographic contour lines on Qf2 (excluding Qt2-w). We used the nonlinear fit option (minimizes geometric error), and we...
interpret the centers of the fit circles as representing locations within the source channel of Qf2. In this analysis, we used contours from 476–480 m and 482–502 m above sea level (asl), excluding contours 481 and 503–506 m asl due to disruption of the ground surface by dirt roads and excluding contours 507–518 m asl due to potential vertical warping near the fault. This analysis provides a range of estimates for the location of the apex of the alluvial fan, based on the center of each of the circles that were fit to the contour lines (see purple dots north of the fault on Fig. 10A). We interpret the linear collection of circle centers to represent the location of the source channel, as did Gold et al. (2015) in their study. Reconstructing 370–430 m of right-lateral slip (Figs. 10B and 10C) restores the set of inferred fan apex locations to the west and east edges, respectively, of Badger Canyon. The 430 m restoration (Fig. 10C) places the eastern edge of Qf2 ~85 m east of the eastern edge of Badger Canyon, which is not unreasonable given that alluvial fan sediment can spread out from the mouth of a canyon. The 370 m reconstruction restores the east edge of Qf2 to the east edge of Badger Canyon in addition to restoring the set of inferred fan apices to near the west edge of present-day Badger Canyon, along the contact between Qf2b with Qf1 and with the landslide deposit (Qls2). We consider it equally likely that the offset of Qf2 lies between 370 and 430 m; therefore, our probability density function for the offset, has a flat top between 370 and 430 m (Fig. 11A).

An absolute maximum offset of 460 m for Qf2 comes from restoring the dated samples from Qf2 in WT-3C to the extreme east edge of Badger Canyon, which is the easternmost location at which these samples could have been deposited (Fig. 10D). This reconstruction is unlikely because it places the eastern edge of Qf2 120 m east of the eastern edge.
Figure 11. Probability density functions (PDFs) for the offset (A, D, G, and J), age (B, E, H, and K) and slip rate (C, F, I, and L) for the three offset features at Badger Canyon: Qf2 apex (A–C), riser between Qf2 and Qt2-w (D–F) and Qf3 (G–I), and for the offset landslide at Matthews Ranch in Pitman Canyon (J–L). Vertical, dashed lines in C, F, and I mark the bounds of the 95% confidence interval for each slip-rate PDF.
of Badger Canyon and places most of the inferred fan apex locations within the bedrock east of Badger Canyon. Nonetheless, it represents an upper bound on the offset, and our trapezoidal PDF for the offset therefore tapers to zero at 480 m (Fig. 1A). Offset of the Qf2 alluvial fan apex can be no less than 290 m, because that amount of slip is required to restore the (younger) terrace riser between Qf2 and Qt2-w to its correlative riser northeast of the fault (see next section). Therefore, our PDF for the offset of Qf2 tapers to 0 at 290 m (Fig. 1A).

The age of the sand layer 2.8 m beneath the apex of alluvial fan Qf2 is either 28.4 ± 0.3 ka (if the radiocarbon age of sample BC-8 is representative of the true age; Table 1) or 20.6 ± 3.0 ka (2σ) (if the OSL age, OSL-BC-2, is representative of the true age; Table 2). Combining the PDF for the radiocarbon age (Fig. 11B) with the PDF for offset of the apex of the alluvial fan (Fig. 11A) yields our preferred slip rate of 13.5 mm/yr with a 95% confidence interval of 11.0–15.7 mm/yr (Fig. 11C). If, instead, we use a PDF for the age of Qf2 using the OSL ages (a Gaussian PDF with a mean of 20,600 years B.P. and a standard deviation of 1500 years), this yields a slip rate of 18.6 mm/yr with a 95% confidence interval of 14.7–24 mm/yr. In a previous section (description of Qf2 and Qf2a), we have explained why we have more confidence in the radiocarbon dates from Qf2 and Qf2a than in the OSL ages from that unit. The Qf2 slip rate using the radiocarbon dates is thus our preferred rate.

**Slip Rate Estimated from the Riser between Qf2 and Qt2-w**

Our second slip-rate estimate is based on the offset of the northwest-facing terrace riser between Qf2 and an erosional terrace, Qt2-w, cut into it (southwest of the fault) from a northwest-facing terrace riser on the northwestern edge of Qf2a and a strath terrace cut into bedrock northeast of the fault (Fig. 9E). Although the different substrates below the erosional terraces on the two sides of the fault make this correlation less certain than the correlations used for our other slip-rate estimates, the similar orientation and height of the riser on both sides of the fault, as well as the presence of deposits of similar age on the east side of the riser on both sides of the fault, support this correlation.

If the correlation of the riser across the fault is correct, the following constraints can be placed on the amount of offset of the riser. The offset of the riser is most likely 280–290 m, based on the reconstruction shown in Figure 9E (290 m) and the 280 m distance measured between the red star south of the fault and the white star north of the fault in Figure 12, which mark our preferred projections of the two terrace risers to the fault. An alternate projection of the terrace riser southwest of the fault intersects the fault at the red circle and allows the offset to be as small as 240 m. This projection would require that the fault slipped faster than the stream could keep refreshing the riser straight across the fault, so that at the time the landslide caused flow on Qt2-w to cease, the riser had a fault-parallel segment, along the dashed green projection line southwest of the fault in Figure 12. An alternate projection of the riser on the northeast side of the fault intersects the fault at the white square (Fig. 12). This projection follows a bend in the terrace riser that we suspect is the result of relatively recent erosion, which should therefore be ignored. However, if it existed at the time the riser was abandoned, then the offset of the riser could be as large as 300 m.

Apart from the erosion just mentioned, it is unlikely that the riser has been significantly modified after it was abandoned, because its abandonment was caused by emplacement of the landslide deposit, which forced active flow within Badger Creek to shift to the east side of the canyon. Flow in Badger Creek never returned to the west side of the alluvial fan. On the northeast side of the fault, the bedrock (Tc and Kmg) on the west side of the riser has been buried by a thin (<1 m) veneer of sandy alluvium (Qa4), which was derived from small, local drainages. Flow from these small drainages would not have had the erosive power to have significantly modified the riser.

Figure 12. Geologic map showing preferred (red and white stars) and limiting (red and white squares) locations of piercing points for the terrace riser between Qf2 and Qt2-w on the southwest side of the fault (red star and red circle) and the terrace riser that forms the western edge of Qf2a on the northeast side of the fault (white star and white square). The preferred projection of the risers to the fault yields an offset of 280 m. Red dashed lines show alternate projections that allow the offset to be between 240 and 300 m.
The original riser on the northeast side of the fault might initially have been located farther to northwest and have been laterally eroded by flow along the Qt2-w terrace prior to emplacement of the landslide, but this would not affect our slip-rate estimate because the age control we are using for this estimate is the age of the landslide (bracketed by dates from Qc2 and Qf2b). The emplacement of the landslide ended flow of Badger Creek along this riser. Therefore, we interpret the age of the landslide to be identical with the age of abandonment of the riser. Matching any earlier location of the riser northeast of the fault with the age of termination of the flow of Badger Creek along this riser is not appropriate.

Our PDF for the offset of this riser is trapezoidal, with a flat top between 280 and 290 m, tapering to zero at 240 and 300 m (Fig. 11D). The channel north-west of this riser ceased being an active conduit for flow from Badger Canyon when the Qls2 landslide was deposited. 23.1 ± 0.4 ka. The riser might have been abandoned and started accumulating offset prior to the landslide, while Badger Creek was still flowing on Qt2-w and its correlative strath terrace northwest of the fault. Although we argue this is unlikely, this possibility is included within our uncertainty bounds for the offset, which allow the offset to be as small as 240 m. Using the PDFs shown for the offset and age of abandonment of this riser (Figs. 11D and 11E), we estimate a slip rate of 11.9 ± 1.5 mm/yr (Fig. 11F).

As a result of the well-defined location of the terrace riser on both sides of the fault and the tightly bracketed age of the landslide (and thereby the age of abandonment of the riser), this rate has the tightest constraint on the slip rate (10.8–12.8 mm/yr) of any of the rates reported in this paper. However, it is possible that these constraints underestimate the full uncertainty. There is an unquantifiable (but likely small) possibility that the two risers do not correlate across the fault or that the two detrital charcoal samples used to constrain the age of the riser both significantly overestimate the ages of the deposits that pre- and post-date the riser. Nonetheless, even if both detrital charcoal samples are significantly older than the deposits, the landslide clearly terminated deposition on Qt2-w prior to the initiation of deposition of Qf3, which occurred sometime prior to ca. 15 ka. If abandonment of Qt2-w occurred as recently as 15 ka, the slip rate could be as high as 19 mm/yr, but no higher.

**Slip Rate Estimated from Qf3**

To define the slip rate since the time of deposition of Qf3, we use the dated radiocarbon and OSL samples from Qf3b that are located closest to the fault (BC42 and OSL-BC-5; Fig. 8 and Tables 1 and 2) because the offset of this proximal part of the alluvial fan can be constrained more tightly than the offset of more distal portions of the alluvial fan. Samples BC-42 and OSL-BC-5 are from within the top 1.2 m of Qf3b deposits (Fig. 8), indicating that they were deposited during the late stages of Qf3. They also are from the portion of Qf3b that fills a channel that strikes SSE, which we interpret to have breached the buried shutter ridge (Figs. 8 and 9G).

The source channel for Qf3a and Qf3b is constrained to lie between Qf2a,b and the eastern margin of Badger Canyon. We consider it equally likely that the offset since the time of deposition of samples BC-42 and OSL-BC-5 is between ~120 and 200 m. An offset of 120 m (Fig. 13A) restores samples BC-42 and OSL-BC-5 to the west edge of the source channel location. An offset of 200 m (Fig. 13B) restores samples BC-42 and OSL-BC-5 to the east edge of Badger Canyon. Restoration of 120–200 m offset also places the other samples from Qf3b (BC-22, OSL-BC-3, and OSL-BC-4) in a position where they could have been deposited, and sample BC-24 where it could be deposited within the base of fault scarp colluvium that buried Qf3a (Figs. 8 and 13).

To calculate the slip rate and its uncertainty, we construct a PDF for the offset of samples BC-42 and OSL-BC-5 from Qf3b as follows (Fig. 11A). The plateau of this PDF extends from 120 to 200 m, reflecting our judgment that the offset is equally likely within this range, and is very unlikely outside this range. The values of 120 and 200 m were chosen as the limits of this plateau because any offset amount within this range places samples BC-42 and OSL-BC-5 immediately downstream from the location of the 50–60-m-wide source channel for Qf3 (Fig. 13). Because samples BC-42 and OSL-BC-5 are from a channel that trends SSE, it is unlikely that they were deposited by flow of Badger Creek spreading out to the southeast or northwest of the mouth of Badger Canyon, as would be required if their offset was significantly >200 m or <120 m. Because of the extreme unlikelihood of the offset being outside this range, we apply an exponentially decaying tail to both sides of the plateau in the PDF and constrain these two tails such that each contains 5% of the area under the PDF, and 90% of the area lies between 120 and 200 m (Fig. 11A).

We also calculate a PDF for the age of samples BC-42 and OSL-BC-5 (Fig. 11B). This PDF has a plateau between the mean ages of these two samples (13.3 ka for OSL-BC-5 and 14.9 ka for BC-42) and tapers to zero at 11.1 and 15.1 ka (the low and high ends of the 95% confidence intervals for the ages of samples OSL-BC-5 and BC-42, respectively). The resulting PDF for slip rate has a mean of 11.8 mm/yr, yet the broad plateau extending from ~10 to 13.5 mm/yr indicates that the slip rate is equally likely to be anywhere within that range (Fig. 11C). The 95% confidence interval for the slip rate is 8.3–16.0 mm/yr.

**SLIP RATE ESTIMATED FROM THE MATTHEWS RANCH LANDSLIDE IN PITMAN CANYON**

**Geology of the Landslide**

The Matthews Ranch landslide covers ~1 km² across the San Andreas fault and is located in and around Pitman Canyon, 2 km northwest of the town of Devore (Figs. 2, 14, and 15). The landslide consists of two main facies—a coarse, angular blocky mass that apparently failed catastrophically (Qlsp) and a less coarse, more colluvial-appearing deposit (Qlsg) with blocks from 3 to 10 m; the latter deposit appears to be material that subsequently filled the space between the slide and its breakaway scarp and possibly extended across the fault (Fig. 14). The southernmost possible remnant, south of Pitman Canyon (“Qls-o?” in Fig. 14), appears to be made of slightly more weathered material, so is likely to

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be an isolated remnant of an older slide (Qls-o). Geologic units for the Matthews Ranch site are from Weldon (1986).

The volume of Qlsg suggests that the breakaway could have expanded following the main landslide event, especially on the north and east side. The landslide deposit (Qlsp) is extensively eroded, producing some uncertainty in the original extent of the deposit. However, this erosion has locally exposed the base of the landslide, which supports the interpretation that the exposed remnants were once a single landslide mass. Southwest of the fault, the landslide is underlain by Pelona Schist, which is typical basement rock in this region, and by fluvial sediments of Cajon Creek. The primary landslide (Qlsp) and Qlsg include blocks of foliated granitic rock with pendants of marble, demonstrating that the landslide source is north of the fault.

**Offset Estimate**

The San Bernardino strand of the San Andreas fault is the only fault that has offset the landslide laterally. Within the study area, two faults cross the Matthews Ranch landslide ~0.3 and 1.0 km northeast of the San Bernardino strand (Fig. 14). The southern one of these two faults has produced minor normal slip (~10 m) within the landslide deposits, but neither of them contributes any lateral offset to the landslide.

Figure 15 shows a simplified map (A) and several possible reconstructions of the offset landslide (B–D). The likely extent of the slide (Qlsp) on the south side of the fault (green line on Fig 15), is based on (1) the mapped extent on the east and (2) projection of the preserved edge (next to “S” in “Samples” on Fig. 15) to the fault on the west. The maximum extent of the landslide on the south side of fault (pink line in Fig. 15) assumes: (1) landslide material that appears to be older on the east side of Pitman Canyon (pink in Fig. 15; “Qls-o?” in Fig. 14) is part of the slide; (2) the landslide may have once extended to the knob on west side (but was eroded by the stream occupying Perdue Canyon). The east edge of the landslide can be no farther east than this maximum extent, because it is limited by a continuous gully exposure revealing the surface of Qoa-d, which is older than the landslide. Although a small outcrop of what may be Qlsg is present on top of Qoa-d southwest of the fault, the continually preserved surface of Qoa-d indicates that primary landslide deposits (Qlsp) Age (ka) here, for if they had been present and later eroded, the Qoa-d surface would not be preserved.

The likely extent south of the fault fits within the head scarp on the north side of the fault with 650 m of offset reconstructed along the San Bernardino strand in Figure 15. We estimate that the maximum possible offset could be ~950 m, which aligns the landslide masses across the fault except for the easternmost finger of the landslide that could have flowed around the eastern edge of the head scarp. This also assumes that the west edge of the slide did not extend to the head scarp on the north side, or more of the landslide is eroded from the west edge on south side than we infer. We estimate that the minimum possible offset could be ~425 m, which aligns the westernmost outcrop of the landslide (Qls; green on Fig. 15) south of the fault with the top of the head scarp north of the fault.
Figure 14. Geologic map of the Pitman Canyon area (modified from Weldon, 1986) including the offset Matthews Ranch landslide (Qlsp) and associated subsequent debris (Qlsg). Black square shows location of Figure 15. Map shows the distribution of faults and Quaternary deposits immediately southeast of where Cajon Creek crosses the San Andreas fault. See Weldon and Sieh (1985) for more detailed descriptions and ages for the Quaternary units. Only the San Bernardino strand (labeled “SB strand” in the margins) has significant lateral slip since the late Pleistocene.
Figure 15. Plausible reconstructions of the Matthews Ranch landslide in Pitman Canyon. Yellow and purple lines mark the locations of the top and base of the head scarp, respectively. Green line connects the downhill limit of deposits that are definitely part of the offset landslide ("Qls" in Fig. 14) and marks the narrowest limit of offset landslide deposits south of the fault. Pink line marks the broadest limit of offset landslide deposits south of the fault, assuming that the deposits shown in pink above (and labeled "Qls(-o?)" in Fig. 14) are correlative with "Qls." Location of the boulders from which the $^{10}$Be dating samples were collected is marked with an “X” and the word “samples.”
Age of the Landslide

We sampled a geomorphically pristine remnant of the Matthews Ranch landslide on its western edge south of the fault (“X Samples” in Fig. 15). The $^{10}$Be field and lab measurements and ages from six blocks on the surface of the landslide deposit are shown in Tables S4 and S5 and Figure 16. Three of the six blocks (MR2, MR4, and MR6) have ages that cluster ca. 44–47 ka. If we assume that the ages of these three samples represent the age of the landslide and that the other samples are outliers whose ages are affected by inheritance (MR3) or erosion or exhumation (MR1, MR5), then we may combine the PDFs for MR2, MR4, and MR6 by multiplying the values for each age increment and then renormalizing the combined PDF (i.e., the “product” method of Gold et al., 2017, and DuRoss et al., 2011). This results in an age estimate of 45.3 ka with a 95% confidence interval of 42.6–47.9 ka. Including samples MR3 and MR5 in the combination of PDFs using the “product” method, results in a very similar mean age (45.5 ka) with only a small increase in the 95% confidence interval (41.9–47.9 ka), due to the minimal overlap of the PDFs for MR3 and MR5 with those of MR2, MR4 and MR6 (Fig. 16).

On the other hand, if we treat only MR1 as an outlier and consider that any of the other five samples is equally likely to represent the age of the landslide, then it is more appropriate to combine the five PDFs by summing the values for each age increment and then renormalizing (i.e., the “sum” method of Gold et al., 2017, and DuRoss et al., 2011). This more conservative method results in the PDF shown in Figure 11K, with a mean of 47.2 ka and a 95% confidence interval of 30.1–71.1 ka, which is used in our slip-rate estimate.

Slip-Rate Calculation

We use a triangular PDF for the offset of the landslide with a peak at 650 m, tapering to zero at 425 and 950 m (Fig. 11J). Combining this with the PDF for the ages of samples MR2–MR6 combined by the sum method (Fig. 11K) yields a slip rate of 14.5 mm/yr, with a 95% confidence interval of 8.3–24.4 mm/yr (Fig. 11L), and a 68% confidence interval of 11.0–18.8 mm/yr.

DISCUSSION

Possible Slip-Rate Contributions from Other Strands of the San Andreas Fault

Our slip-rate estimates for the Badger Canyon site apply to the San Bernardino strand (Fig. 3). The Mill Creek strand traverses the Badger Canyon study area and merges with the San Bernardino strand within the northwestern quarter of Figure 3, ~0.6 km northwest of Badger Canyon (Miller et al., 2001). The Mill Creek strand is estimated to have initiated in the latter part of the middle Pleistocene (Matti and Morton, 1993) and may exhibit Holocene displacement locally (McGill et al., 1999). Kendrick et al. (2015) argue that total displacement along the Mill Creek strand in the San Gorgonio Pass region is 7.1–8.7 km over the past ~100 k.y.

On the east side of Badger Canyon, the Mill Creek strand separates Cretaceous biotite monzogranite (Kmg) from Miocene (?) conglomeratic sandstone (Tc) (Miller et al., 2001) informally known as the Potato Sandstone. We mapped subtle fault scarps within very old alluvium (Qvoc2) along the Mill Creek strand on the east side of Badger Canyon but found no clear lateral offsets of drainages incised into Qvoc2 nor scarps within younger units within the map area (Fig. 3). On the west side of Badger Canyon, the contact between crystalline rock and Potato Sandstone appears to be the basal plane of a bedrock landslide (contact visible where a very narrow strip of Potato Sandstone is exposed and overridden by the landslide, west of trench WT-1A); so the Mill Creek strand is likely buried beneath both the landslide (Qls2) and the latest Pleistocene alluvium that buries the landslide (Qf2b). Based on these relationships, we conclude that the Mill Creek strand does not contribute significantly to the latest Pleistocene right-lateral slip on the San Andreas fault zone at Badger Canyon since the time of Qf2.
Right-lateral offsets are present farther southeast along the Mill Creek strand, however. At City Creek, ~12.5 km southeast of Badger Canyon, the Mill Creek strand may accommodate ~10% of the slip rate across the San Andreas fault zone, for late Pleistocene deposits (Sieh et al., 1994). Similarly, Weldon (2010) estimates a latest Quaternary rate of 2 mm/yr for the Mill Creek strand where it crosses the Santa Ana River, 22 km southeast of Badger Canyon. We infer that the slip rate of the Mill Creek strand decreases between the Santa Ana River and Badger Canyon.

Several other late Quaternary fault strands are also present within the study area. Subparallel to and 0.3–1.0 km northeast of the Mill Creek strand at Badger Canyon is a 6-km-long fault that is unnamed on most maps. In the U.S. Geological Survey (USGS) Quaternary fault and fold database (U.S. Geological Survey and California Geological Survey, 2018) this fault is considered to be a secondary strand of the Mill Creek strand, but to avoid confusion between these two fault strands, we prefer the name Arrowhead Springs fault for this northeastern strand, as it was referred to in reports generated for the Metropolitan Water District's Arrowhead Tunneling Project (e.g., Sholley et al., 2011). This fault is not to be confused with the early to middle Quaternary Arrowhead fault (U.S. Geological Survey and California Geological Survey, 2018), located just east of and outside of our study area. The Arrowhead Springs fault projects toward the San Bernardino strand of the San Andreas fault zone near Devil Canyon, ~2.3 km northwest of Badger Canyon, and separates Mesozoic gneiss of Devil Canyon (Mzdc) on the northeast from Cretaceous monzogranite (Kmg) on the southwest (Miller et al., 2001). Aligned patches of vegetation, saddles, and fault-line scarps with south-side-up separation mark the fault trace. The fault truncates early or mid-Pleistocene sediments (Miller et al., 2001) but does not offset late Holocene deposits in Badger Canyon (Qa4; Fig. 3). There is no observable lateral offset of the margins of Badger Canyon at this fault, but 3.5 km to the east, the western margin of Waterman Canyon (Fig. 2) is right-laterally deflected by 100–150 m at the northernmost strand of the Arrowhead Springs fault. We infer that the contribution of the Arrowhead Springs fault to the late Pleistocene right-lateral slip rate across the San Andreas fault zone at Badger Canyon is no more than a few tenths of one mm/yr.

Slip Rate as a Function of Time

Latest Pleistocene slip rates for the San Bernardino strand of the San Andreas fault at Badger Canyon are very similar over three different time scales: (1) 13.5–12.2–9.5 mm/yr for the past 28 k.y.; (2) 11.9–9.5–9.0 mm/yr for the past 23 k.y.; and (3) 12.0–10.0–5.5 mm/yr for the past 11–15 k.y. This suggests a relatively steady rate of strain release in earthquake slip between 28 ka and 11 ka (Fig. 17A).

To obtain our preferred, time-averaged slip rate at the Badger Canyon site, we sum and renormalize the PDFs for our three slip-rate estimates at that site. The resulting PDF (Fig. 17B) has a mean of 12.8 mm/yr, a 67% confidence interval of 11.1–14.8 mm/yr and a 95% confidence interval of 8.1–18.4 mm/yr. The PDF is irregular, with obvious changes in slope at 10 and 16 mm/yr, with 84% of the area under the curve contained within those limits. We thus report a preferred, time-averaged rate for the past 28 k.y. rate of 12.8 mm/yr with an 84% confidence interval of 10–16 mm/yr.

Distribution of Slip between the San Ande

The offset and age of the Matthews Ranch landslide is consistent with the time-averaged slip rate obtained from Badger Canyon (Fig. 17A). All of these slip-rate estimates are also very similar to the 7–16 mm/yr slip rate at Plunge Creek, ~18 km farther southeast along the San Andreas fault (McGill et al., 2013). However, these slip-rate estimates from the San Bernardino strand of the SAF are notably slower than the San Andreas fault slip rate at Cajon Creek and Badger Canyon (~12.8 mm/yr; Weldon and Sieh, 1985). The decrease in San Andreas fault slip rate between Cajon Creek and Badger Canyon suggests that ~1 ± 0.5 cm/yr of slip transfers from the Mojave section of the San Andreas fault to the San Jacinto fault within the 16 km stretch between Cajon Creek and Badger Canyon (Fig. 18A). While the Cajon Creek and Matthews Ranch rates overlap, the best estimate of the slip rate at the Matthews Ranch site is only a couple of mm/yr higher than at Badger Canyon, suggesting that much of this ~1 ± 0.5 cm/yr of slip transfer may occur within the 3 km between Cajon Creek and Pitman Canyon (Fig. 18A). It is possible that the Peters fault and/or the Tokay Hill fault (Fig. 2) accommodate a minor amount of slip transfer from the San Andreas fault to the San Jacinto fault between Pitman Canyon and Badger Canyon. This slip transfer is consistent with the results of mechanical modeling of the San Andreas fault system (e.g., Herbert et al., 2014) as well as with modeling of geodetic data (e.g., Becker et al., 2005; McCaffrey, 2005; Meade and Hager, 2005; Loveless and Meade, 2011; McGill et al., 2015).

Northwest of Cajon Creek, best estimates of Holocene slip rates for the Mojave and Carrizo segments of the San Andreas fault are ~35–37 mm/yr (Sieh and Jahns, 1984; Salyards et al., 1992; Weldon et al., 2008), but with large uncertainties (see Figs. 1 and 18B). Using the best-estimate of 34 mm/yr (range 25–40 mm/yr) for the slip rate of the Mojave South section of the San Andreas fault from the Uniform California Earthquake Rupture Forecast version 3 (UCERF3) (Dawson and Weldon, 2013), an additional ~1 ± 1 cm/yr of slip may transfer from the Mojave section of the San Andreas fault onto the San Jacinto fault (north of Cajon Creek) and/or onto other faults. Overall, the San Andreas fault slip rate decreases by ~2 ± 1 cm/yr between the southern Mojave section (34 mm/yr; Dawson and Weldon, 2013) and Badger Canyon (~12.8 mm/yr, this paper), and this slip must be transferred onto the San Jacinto and other faults of the San Andreas system.

In the Uniform California Earthquake Rupture Forecast (UCERF) models 2 and 3 (Wills et al., 2008; Dawson and Weldon, 2013), the San Bernardino strand of the San Andreas fault was divided into a North San Bernardino strand and a South San Bernardino strand based on early slip-rate estimates for the Badger Canyon and Matthews Ranch/Pitman Canyon sites, published in abstract form, which
Figure 17. (A) Offsets and ages used to constrain the four slip rates presented in this paper. Black dots mark the means of the probability density functions (PDFs) for offset and age shown in Figure 11. Boxes outlined by black lines show the 95% confidence intervals on the offset and age estimates. Smaller box with red outline for QF3 shows the parameter space that falls beneath the plateaus that form the tops of the trapezoidal PDFs for offset and age of QF3. This represents the most likely offsets and ages (and equally likely anywhere within the box). Vertical red bar for QF2 marks the range of offsets that we deem most likely (and equally likely anywhere along that bar). Thick, horizontal, red bar for the Matthews Ranch (MR) landslide marks the 95% confidence interval for the age of the landslide if the “product method” is used to combine the PDFs for the five boulder ages. Thinner red bar marks the 68% confidence interval for the age landslide if the sum method is used. (The width of the large black box represents the 95% confidence interval for the age of the Matthews Ranch landslide when the “sum method” is used). Sloping line labeled 12.8 mm/yr marks the mean of the combined (via the “sum method”) PDF for the three slip-rate estimates from Badger Canyon (shown in B). The 68% confidence interval for this rate is 11.1–14.8 mm/yr. The age and offset for the Matthews Ranch (MR) landslide are only broadly constrained (see large black box) but are consistent with the rates from Badger Canyon. (B) Black curve shows the PDF for the three slip rates from Badger Canyon combined by the sum method. Gray curve shows the PDF for those three rates combined via the “product method.” Vertical dashed lines show the 67% confidence interval for the combined PDF obtained by the sum method.
showed a higher slip rate at the latter site (McGill et al., 2010). In the final slip rates presented here, the slip rate for the Matthews Ranch/Pitman Canyon site is lower than the previously estimated rate, largely due to a change in the estimated $^{10}$Be production rate. Thus, the division of the San Bernardino strand into two sections is no longer necessary.

Slip-rate estimates for the central San Jacinto fault near Anza are constrained to 9.5–15.5 mm/yr (Blisniuk et al., 2013), with similar rates reported by Rockwell et al. (1990). Farther north on the San Jacinto fault, slip-rate estimates vary widely including 6–13 mm/yr (Prentice et al., 1986), >20 mm/yr (Kendrick et al., 2002), 5–18 mm/yr (McGill et al., 2012), and 12.8–18.3 mm/yr (Onderdonk et al., 2015). These rates for the San Jacinto fault suggest that much, but not all, of the slip that transfers off of the San Andreas fault between Pallet Creek and Badger Canyon transfers onto the San Jacinto fault. A significant amount of slip (~3–8 mm/yr), however, likely transfers onto other faults, such as the Cucamonga fault, North Frontal fault, the Mill Creek strand of the San Andreas fault, and other faults within the San Bernardino Mountains (Figs. 1 and 2), or is accommodated by off-fault deformation in the region; see McGill et al. (2013) for further discussion.

Holocene and latest Pleistocene slip rates are relatively low along the San Andreas fault through San Bernardino Valley and San Gorgonio Pass, with rates of 8 ± 4 mm/yr on the San Bernardino strand near Burro Flats (Orozco and Yule, 2003; Orozco, 2004; Yule and Spotila, 2010; Cabazon (Yule et al., 2001); Painted Hill (Gold et al., 2015). (B) Slip rate of the San Andreas fault zone as a function of distance along strike from central California to the Coachella Valley. Wa—Wallace Creek (Sieh and Jahns, 1984); LC-Pa—Little Rock and Pallett Creek (Matmon et al., 2005; Weldon et al., 2008; Salyards et al., 1992); CC—Cajon Creek; Pt—Pitman Canyon; BC—Badger Canyon; Pl—Plunge Creek; Wi—Wilson Creek; BF—Burro Flats; SGP—San Gorgonio Pass; Ca—Cabazon; PH—Painted Hill; BP—Biskra Palms Oasis; PW—Pushwalla Canyon (Behr et al., 2010; Fletcher et al., 2010).
Paleoseismic Implications

The low rates of slip on the San Andreas fault zone through San Bernardino Valley and San Gorgonio Pass compared to the higher rate for the Mojave section of the fault suggest that some ruptures on the Mojave section of the San Andreas fault must either (1) stop at the intersection with the San Jacinto fault or (2) rupture with a reduced amount of slip on the San Bernardino section of the fault, and/or (3) rupture simultaneously with the northern San Jacinto fault zone. The possibility of through-going earthquake ruptures jumping the step-over between the Mojave section of the San Andreas fault and the northern San Jacinto fault has been discussed by Lozos (2016).

The dramatic drop in slip rate of the San Andreas fault between Pallett Creek and Pitman Canyon, with the best estimate of the rate at Pitman Canyon being ~40% of the best estimate of the rate at Pallett Creek (Salyards et al., 1992), suggests that the frequency and/or slip amounts of prehistoric earthquakes at Pitman Canyon (Seitz and Weldon, 1994) should be less than half of what they are at Pallett Creek (Sieh, 1978, 1984; Sieh et al., 1989; Scharer et al., 2011) and Wrightwood (Fumal et al., 2002; Scharer et al., 2010). The southeastward termination of the 1857 earthquake rupture in Cajon Pass is consistent with the reduced slip rate in the vicinity of Cajon Pass. However, the frequency of earthquakes at Pitman Canyon during the past 1000 years is comparable to that at Wrightwood and Pallett Creek, with seven surface-rupturing earthquakes at Pitman Canyon in the past 1000 years (Seitz and Weldon, 1994), eight earthquakes at Wrightwood (Scharer et al., 2010), and six at Pallett Creek (Scharer et al., 2011) during that same time period. Slip per event at Pitman Canyon is thought to be 3–4 m for the most recent two events (Seitz and Weldon, 1994), comparable to the 2–4 m of slip per event documented over the past 1600 years at Wrightwood (Weldon et al., 2002). These studies suggest that the late Holocene slip rate of the San Bernardino strand at Pitman Canyon may be faster than the late Pleistocene rate of 14.5 ±3.9 _/−_4.2 mm/yr reported here, or that the late Pleistocene slip rate at Pitman Canyon is closer to the upper end of that range. The possibility of complementary temporal fluctuations in slip rate between the San Andreas and San Jacinto faults has been raised by Bennett et al. (2004). Better constraints on the slip rate of the northernmost San Jacinto fault, including the Glen Helen strand, would help to resolve these questions.

CONCLUSIONS

Three late Pleistocene slip-rate estimates for the San Bernardino strand of the San Andreas fault at Badger Canyon indicate the average slip rate for the past 28 k.y. was 12.8 ±3.2 _/−_4.3 mm/yr (95% confidence interval) and was most likely between 10 and 16 mm/yr (84% confidence interval). The slip rate of the San Andreas fault drops to the southeast from ~24.5 ± 3.5 mm/yr at Cajon Pass (Weldon and Sieh, 1985) to 14.5 ±3.2 _/−_4.2 mm/yr at Matthews Ranch in Pitman Canyon and to 12.8 ±3.9 _/−_4.2 mm/yr at Badger Canyon. Previously published slip rates farther southeast along the fault through San Bernardino Valley and San Gorgonio Pass are similarly low. This suggests that more than half of the slip on the Mojave section of the San Andreas fault may transfer to the San Jacinto fault and other faults within the vicinity of Cajon Pass. Additional slip-rate estimates from the northernmost strands of the San Jacinto fault as well as from the Peters and Tokay Hill faults will help to further clarify the transfer of slip in this complex region.

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