Holocene activity of the San Andreas fault at Wallace Creek, California

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ABSTRACT

Wallace Creek is an ephemeral stream in central California, the present channel of which displays an offset of 128 m along the San Andreas fault. Geological investigations have elucidated the relatively simple evolution of this channel and related landforms and deposits. This history requires that the average rate of slip along the San Andreas fault has been 33.9 ± 2.9 mm/yr for the past 3,700 yr and 35.8 + 5.4/-4.1 mm/yr for the past 13,250 yr. Small gullies near Wallace Creek record evidence for the amount of dextral slip during the past three great earthquakes. Slip during these great earthquakes ranged from ~9.5 to 12.3 m. Using these values and the average rate of slip during the late Holocene, we estimate that the period of dormancy preceding each of the past 3 great earthquakes was between 240 and 450 yr. This is in marked contrast to the shorter intervals (~150 yr) documented at sites 100 to 300 km to the southeast. These lengthy intervals suggest that a major portion of the San Andreas fault represented by the Wallace Creek site will not generate a great earthquake for at least another 100 yr. The slip rate determined at Wallace Creek enables us to argue, however, that rupture of a 90-km-long segment northwest of Wallace Creek, which sustained as much as 3.5 m of slip in 1857, is likely to generate a major earthquake by the turn of the century.

In addition, we note that the long-term rates of slip at Wallace Creek are indistinguishable from maximum fault-slip rates estimated from geodetic data along the creeping segment of the fault farther north. These historical rates of slip along the creeping reach thus do represent the long-term—that is, millennial—average, and no appreciable elastic strain is accumulating there.

Finally, we note that the Wallace Creek slip rate is appreciably lower than the average rate of slip (56 mm/yr) between the Pacific and North American plates determined for the interval of the past 3 m.y. The discrepancy is due principally to slippage along faults other than the San Andreas, but a slightly lower rate of plate motion during the Holocene epoch cannot be ruled out.

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INTRODUCTION

California has experienced many episodes of tectonic activity during the past 200 m.y. During the past 15 m.y. horizontal deformations due to the relative motion of the Pacific and North American plates have been dominant. On land, the major actor in this most recent plate-tectonic drama has been the San Andreas fault, across which ~300 km of right-lateral dislocation has accumulated since the middle Miocene (Hill and Dibblee, 1953; Crowell, 1962, 1981; Nilsen and Link, 1975).

The San Andreas fault traverses most of coastal California, running close to the populous Los Angeles and San Francisco Bay regions (Fig. 1a). Its historical record of occasional great earthquakes (Lawson and others, 1908; Agnew and Sieh, 1978) amply demonstrates that it poses a major natural hazard to inhabitants of these regions. The future behavior of the San Andreas fault thus has long been a topic of great interest to Californians. Interpretations of historical, geodetic, and geologic data have yielded estimates of one century to several centuries for the time between great earthquakes along the fault in the San Francisco Bay region (Reid, 1910; Thatcher, 1975). Geologic data indicate that similar recurrence intervals apply in southern California (Sieh, 1978b, and in press).

The behavior of the San Andreas fault during the past few thousands of years is one of the best clues to its future behavior. Useful forecasts concerning the likelihood or imminence of a great earthquake along the fault will be much more difficult without greater understanding of its behavior during the past several millennia.

In this paper, we present and discuss the geologic history of Wallace Creek, a locality about halfway between San Francisco and Los Angeles that contains much information about the Holocene behavior of the San Andreas fault (Fig. 1a). For the purpose of determining rates of slip in Holocene time, the channel of Wallace Creek offers excellent possibilities. The channel crosses and is offset along a well-defined, linear trace of the San Andreas fault in the Carrizo Plain of central California (Fig. 1b). It is relatively isolated from other large drainages, and, therefore, its history is not complicated by involvement with remnants of other drainages that have been brought into juxtaposition.

The simple geometry of Wallace Creek suggests a simple history of development. Arnold and Johnson (1909) inferred 120 m of offset on the San Andreas fault, because the modern channel of the creek runs along the fault for about that distance. Wallace (1968) also inferred a simple history of offset involving incision of a channel into an alluvial plain, offset of ~250 m, then channel filling and new incision across the fault. The latest dextral offset of 128 m then accumulated. These interpretations are verified and quantified by us in this paper.

STRATIGRAPHY AND GEOMORPHOLOGY

Figure 2 is a geologic map of the Wallace Creek area that is based upon surficial mapping and study of sediments encountered in numerous excavations. The map shows four main geologic units: older fan alluvium (uncolored), younger fan alluvium (green), high-channel alluvium (dark orange), and low-channel alluvium (light orange). A mantle of slope wash and local alluvium, which is extensively burrowed by rodents, overlies most of the deposits. This unit has been mapped (brown) only where it is thicker than ~1 m and does not cover units and relationships that need to be shown on the map.

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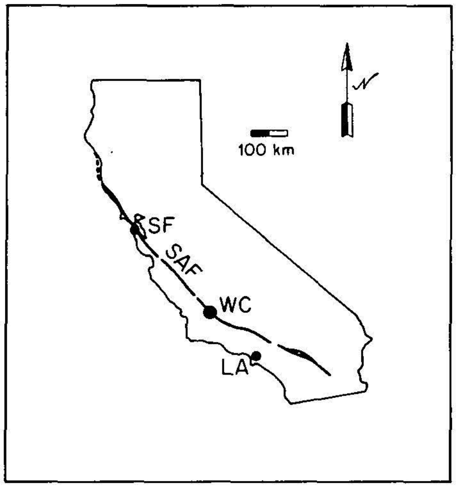
Figure 1. a. Wallace Creek (WC) is along the San Andreas fault (SAF) between Los Angeles (LA) and San Francisco (SF), in the Carrizo Plain of central California. b. This oblique aerial photograph shows the modern channel, which has been offset ~130 m, and an abandoned channel that has been offset ~380 m. An older abandoned channel, indicated by white arrow at left, has been offset ~475 m. Photograph by R. E. Wallace, 17 September 1974. View is northeastward.



a

b

Older Fan Alluvium

Underlying all other units exposed at the site, there is a late Pleistocene alluvial fan deposit derived from the Temblor Range to the northeast. This deposit, here termed the "older fan alluvium," consists of thin sheets, lenses, and stringers of indurate silty clay, pebbly sandy clay, and sandy gravel. Most of the trenches (Figs. 2 and 3) exposed this unit. Southwest of the fault, the older fan alluvium is covered by various deposits, but northeast of the fault, the deformed fan surface is incised.

Charcoal disseminated within the older fan alluvium 4 m below the surface of the fan in trench 5 (Fig. 3), yielded an age of 19,340 ± 1,000 yr B.P. (Table 1). The lack of major unconformities and paleosols in the older fan alluvium below or above this dated horizon implies that all of the exposed 13 m of the unit formed during the late Pleistocene epoch. Evidence discussed below supports a conclusion that the fan surface on the northeast side of the fault had become inactive by about 13,000 yr B.P.

FIGURE 2 EXPLANATION

UNITS

Hl — Low-channel alluvium

Hh — High-channel alluvium

Hs — Slope wash (mantles most of area, but mapped only where boundaries are d stinct)

Py — Younger-fan alluvium (dots indicate edges of individual lobes)

Po — Older-fan alluvium

SYMBOLS

Contacts (solid where geomorphically apparent or exposed in trench, dotted where buried, dashed where inferred

0.3' — Faults (as above; hachures on downthrown side; numbers indicate height of scarp)

Selected small gullies offset ~9m in 1857

5, 10 — Trenches {backhoe, bulldozer}

Crests of small fans and source gullies offset ~9m in 1857

0.3' — Landslide, showing headscarp, scarp height, and direction of movement

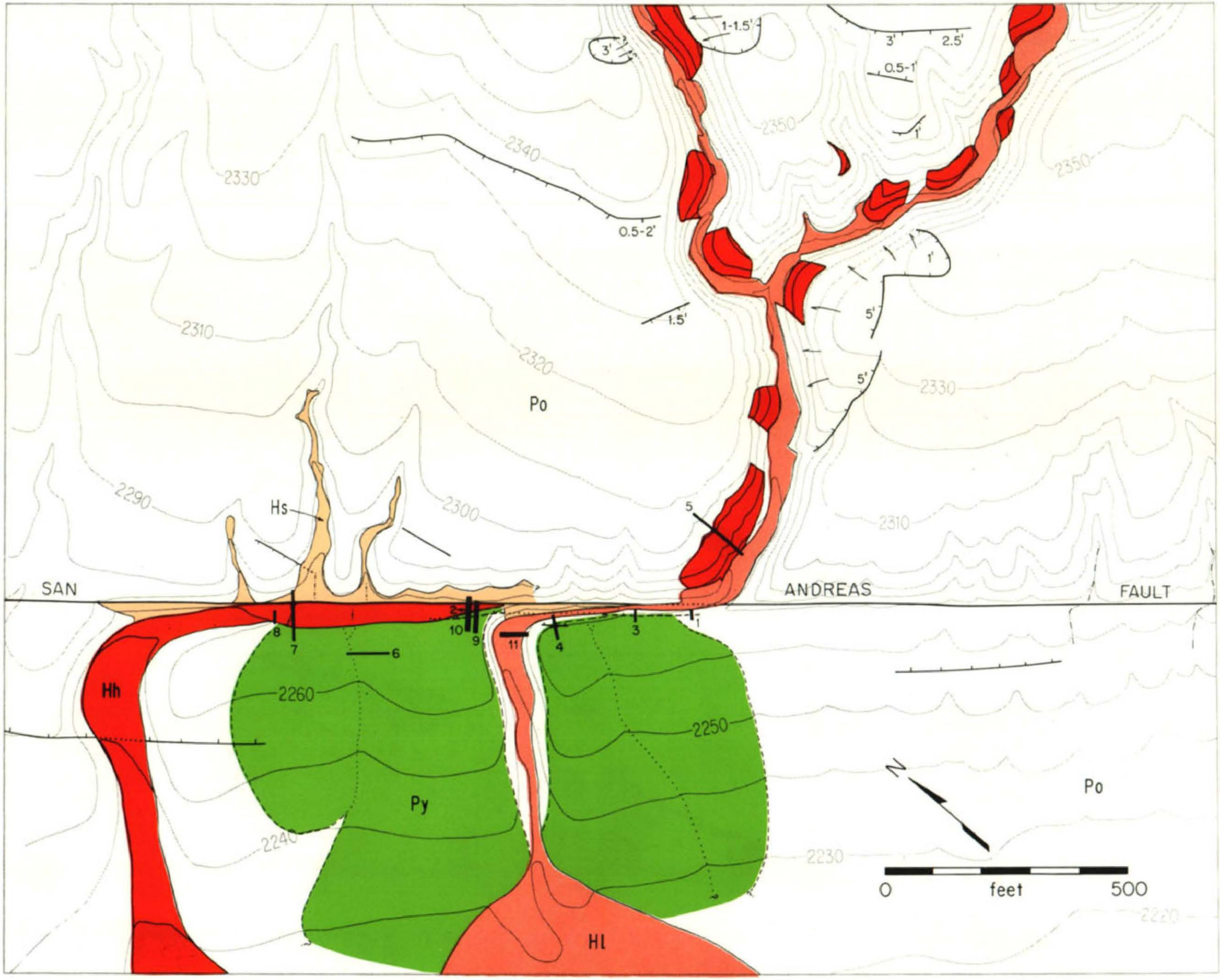


Figure 2. Geologic map of Wallace Creek. Contours of topographic base map show elevation (in feet) above sea level.

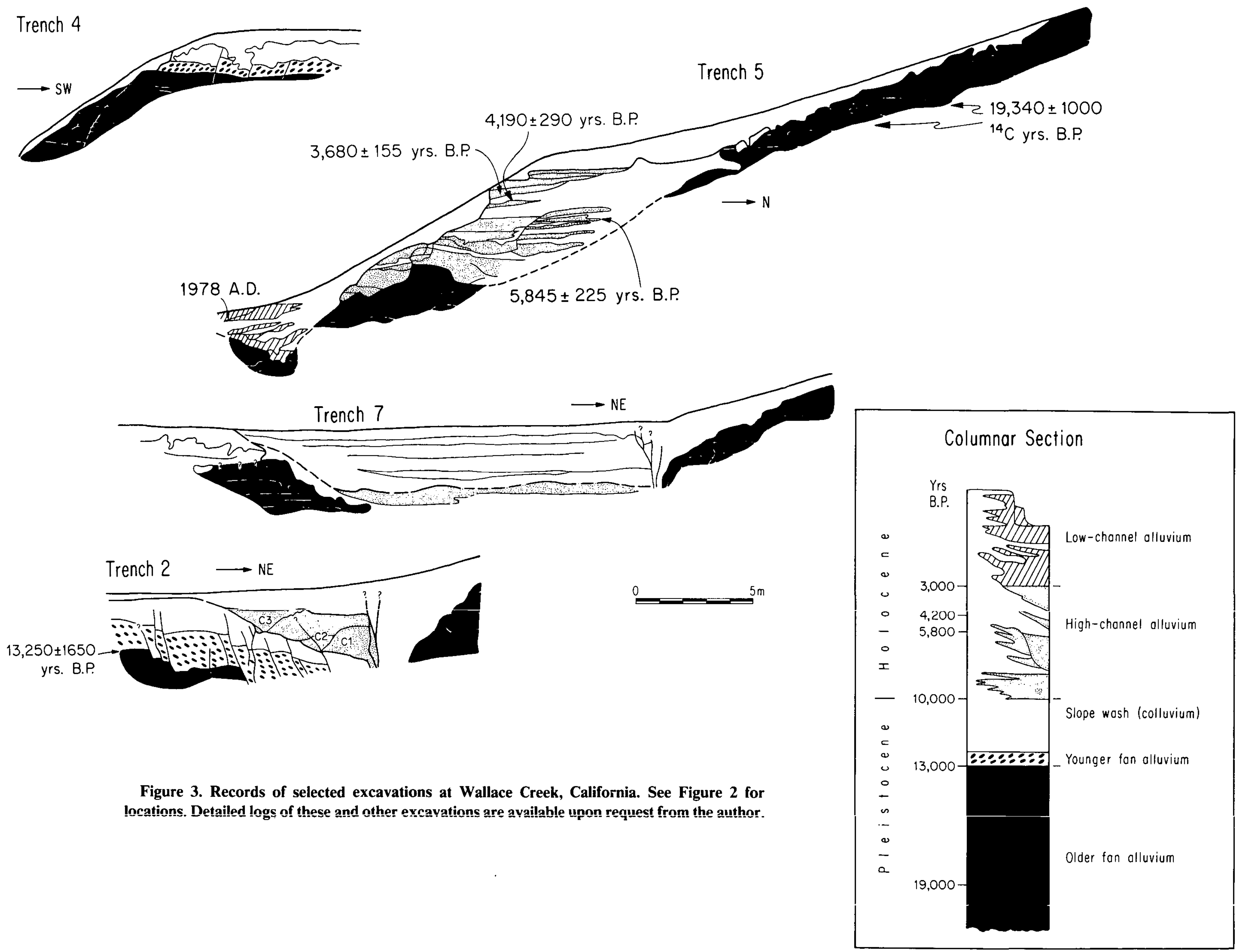


Figure 3. Records of selected excavations at Wallace Creek, California. See Figure 2 for locations. Detailed logs of these and other excavations are available upon request from the author.

TABLE 1. RADIOCARBON ANALYSES

Sample no. Caltech	Sample no. Univ. Wash.	Conventional ^{14}C age† (yr B.P.)	$\delta^{13}C$	Reservoir corrected age§	Calendric age (yr B.P.)
WC-5	UW-567	18,750 ± 450	−22.37	18,782 ± 450	19,340 ± 1000**
WC-2	UW-572	12,865 ± 1650	..	..	13,250 ± 1650**
WC-6	UW-564	5,040 ± 180	−21.51	5,096	5,845 ± 225††
WC-7	UW-565	3,730 ± 170	−22.40	3,772	4,190 ± 290††
WC-9-2	UW-744	3,720 ± 140	−10.5	3,956	4,480 ± 270††
WC-3	UW-563	3,495 ± 110	−19.71	3,580	3,680 ± 155††
WC-3	UW-563b	3,285 ± 100	−19.71	3,370	
McKS-1	UW-355	3,340 ± 120	..	..	..
WC-10-1	UW-742	3,320 ± 100	−15.4	3,476	3,780 ± 155††
WC-11-1	UW-745	1,110 ± 180	−10.8	1,341	1,035 ± 235§§

Note: all date uncertainties in the table are at 95% confidence level.
†As defined by Stuiver and Polach (1977, p. 356).
§As explained in Stuiver and Polach (1977), conventional ages must be corrected for isotopic fractionation.
**Corrected using half-life of 5,730 yr; uncertainty estimated following suggestion of Klein and others (1982, p. 117).
††From Klein and others (1982, Table 2).
§§From Stuiver, 1982.

Younger Fan Alluvium

Southwest of the fault (Fig. 2), there is a lobate deposit that we have termed the "younger fan alluvium." This deposit overlies and is less indurated than the older fan alluvium. It is a well-sorted gravelly sand with a distinctive imbrication of pebbles that indicates southwestward current flow. The unit is thickest near trenches 2, 9, and 10 and thins to the northwest, southeast, and southwest. The boundary of this composite alluvial fan is inferred from the topography and the trench exposures. A radiocarbon date from charcoal in the upper centimetre of the older fan alluvium (trench 2) indicates that the younger fan alluvium began to accumulate 13,250 ± 1,650 yr B.P. (Table 1).

High-Channel Alluvium

Nestled within the channel of Wallace Creek above the modern stream bed, there are numerous remnants of an ancient terrace (Fig. 2). This surface is referred to as the "high terrace," and it is underlain by sand and gravel beds characterized by scour-and-fill structures, which we refer to as the "high-channel alluvium" (trench 5 in Fig. 3). The massive and poorly sorted nature of some of these "high-channel" beds indicates that they are debris-flow deposits. Other beds that are well sorted and laminated must have been transported as bedload in the waters of Wallace Creek.

Radiocarbon analyses (3) of charcoal from within the high-channel deposits in trench 5 demonstrate that these beds were accumulating through a period from 5845 ± 225 yr B.P. to 3680 ± 155 yr B.P. (samples WC-3, WC-6, and WC-7 in Table 1).

Southwest of the San Andreas fault, the high-channel deposits occur in the abandoned channel of Wallace Creek (Figs. 1 and 2). Trenches 2, 7, and 8 (Fig. 3) and 9 and 10 (Fig. 4) show these sands and gravels residing in a 3- to 4-m-deep channel cut into colluvium. Like their correlatives northeast of the fault, these beds exhibit major episodes of scour and fill. A radiocarbon analysis of organic matter from trench 10 yielded an age of 3,780 ± 155 yr B.P. This sample was collected from a colluvial wedge in the middle of the deposits in the abandoned channel, and its age indicates that the abandoned-channel deposits are contemporaneous with the high-channel deposits across the fault and upstream.

Figure 5 includes a profile of the high terrace. The height of the high terrace above the modern channel is greatest at the fault; the terrace merges with a low terrace ~1 km upstream from the fault. Judging from the elevation difference of the high terrace across the fault, vertical slip during the past 3,800 yr is 3 m, which is a mere 2.3% of the horizontal slip during that time period. It is worth noting that within 1 km to the northwest and to the southeast, this vertical slip diminishes to zero and reverses sense.

Modern-Channel Alluvium

Younger sand and gravel beds very similar to the high-channel alluvium have been deposited in the modern channel of Wallace Creek (Fig. 2, and trench 5 in Fig. 3). Like the high-channel alluvium, this "modern-channel alluvium" also exhibits scour-and-fill structures and interfingers with debris derived from the channel walls.

In trench 5, the base of the modern-channel alluvium is ~2.5 m beneath the creek bed, and along the entire channel, there is a low terrace that occurs 1.5 m above the modern creek bed (Fig. 5). This terrace represents the highest level reached by the modern-channel deposits; it formed and was incised within the past 1,000 yr, as indicated by the radiocarbon date of 1035 ± 235 yr B.P. on charcoal 2.5 m below the terrace surface in trench 11 (Fig. 6). An early photograph of the channel shows that the low terrace was incised by the creek prior to A.D. 1908 (Sieh, 1977, p. 61).

GEOLOGIC HISTORY

The evolution of Wallace Creek has been rather simple. It is divisible into four periods, each of which ends in a sudden change of channel configuration.

Accumulation of Older Fan Alluvium and Initial Entrenchment of a Channel

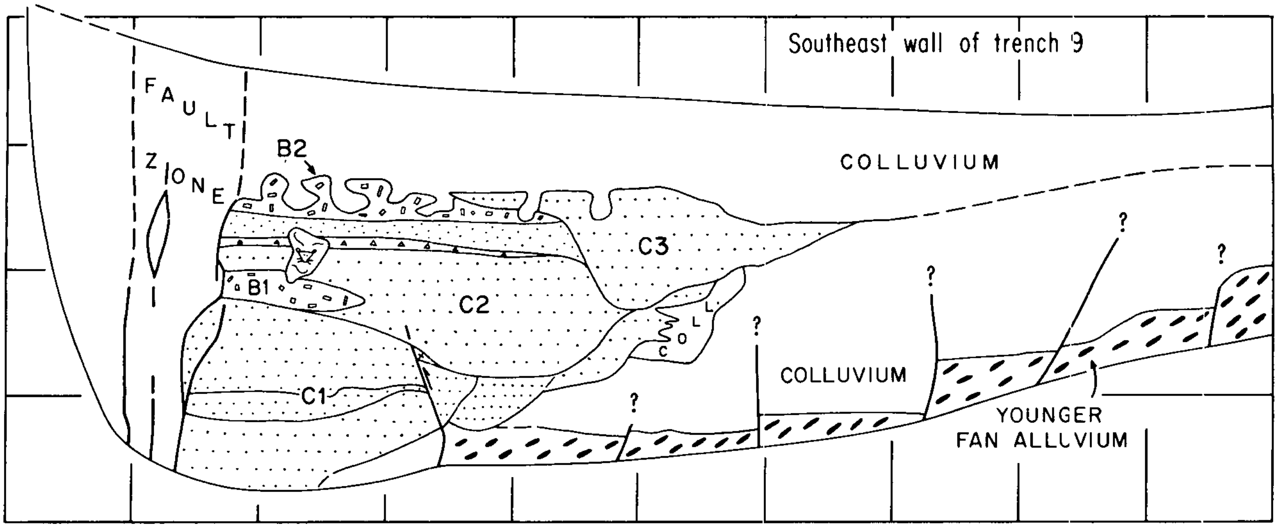
Prior to initial incision of Wallace Creek, during the late Pleistocene epoch, the older fan alluvium gradually accumulated as broad, thin beds on an alluvial fan or apron that extended southwestward from the Temblor Range across the San Andreas fault (Fig. 7a). The lack of small channels within the older fan alluvium indicates either that any scarps that formed along the fault during this interval were buried before they accumulated even 1 m of height, or that they faced mountainward and served to pond the older fan alluvium on the upstream side of the fault. About 13,000 yr B.P., the first major entrenchment of the older fan alluvium occurred (Fig. 7b). Several small gullies were eroded into the fault scarp, and their debris, the younger fan alluvium shown in Figure 2, was deposited at the foot of the scarp. At about the same time, the initial entrenchment of Wallace Creek occurred. The downstream segment of this initial channel now lies outside the mapped area, ~475 m northwest of Wallace Creek (beneath the white arrow at left margin of Fig. 1b).

Initial Offset of Wallace Creek and Re-entrenchment

After ~100 m of right-lateral slip had been registered by the features formed ~13,000 yr B.P., the initial downstream segment of Wallace Creek was abandoned, and a new segment was cut, so that a straight-channel configuration was restored across the fault (Fig. 7c). This new segment is the one labeled "abandoned channel" in Figure 1.

More Offset and Re-entrenchment of the Channel

For several millennia the newly re-entrenched Wallace Creek served as a narrow conduit for materials being transported fluvially out of the nearby Temblor Range. The depth of initial incision of this channel is poorly constrained, but it cannot have been more than 12 m, which is the depth of the base of the high-channel deposits below the surface of the old alluvium in trench 5. As slip accumulated along the San



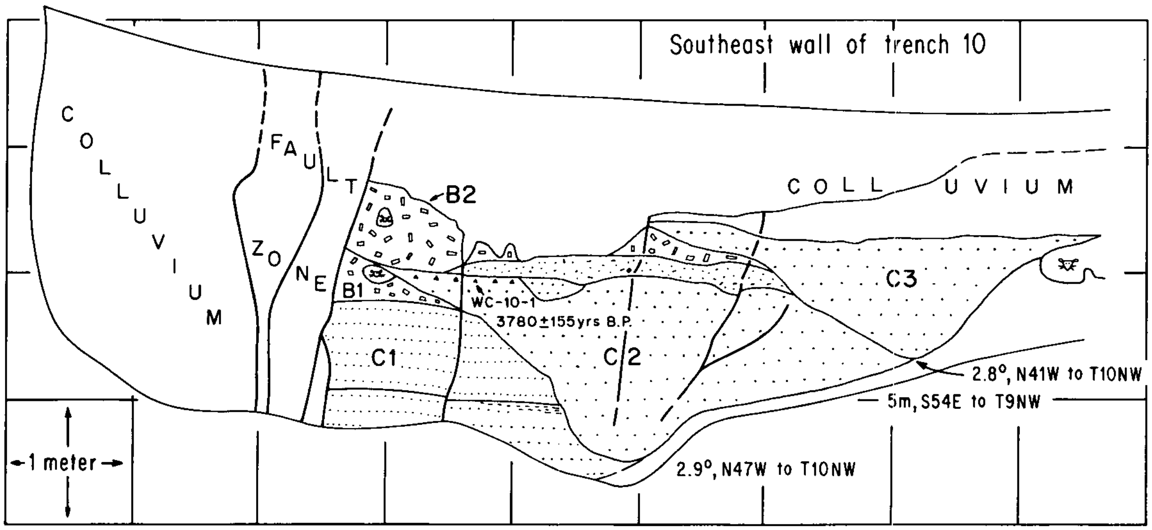


Figure 4. Trenches 9 and 10 reveal the various deposits of the abandoned channel. B_1 and B_2 are scarp-derived breccias. C_1, C_2, and C_3 are fluvial sands and gravels. Solid triangles indicate location of charcoal that yielded date for channel deposits.

Andreas fault early during the Holocene epoch, Wallace Creek developed a bend along the fault that reflected the offset accumulated since entrenchment (Fig. 7d). Water and debris flowing within the channel were diverted to the right at the fault, flowed along the fault for a distance equal to the accumulated offset, and then were diverted left and away from the fault. These two bends in the channel will be referred to hereinafter as the right bend and the left bend.

Trench 5 indicates that by ~6000 yr B.P., 3.0 to 3.3 m of sediment had been deposited within the channel at the right bend. Trench 5 also shows that, locally, at least 1.5 and perhaps 3.3 m of these high-channel deposits subsequently was eroded away. About 3800 yr B.P., after the channel had been offset ~240 m, critical changes began to occur within the channel. For reasons that we do not understand, debris began to accumulate in the channel to greater thicknesses than ever before (Fig. 7e). Trench 5 reveals that at the right bend, the accumulation was at least 5.5 m deep. Trenches 2, 9, and 10 show that this accumulation all but filled the channel at the right bend. This filling set the stage for abandonment of the channel downstream from the right bend and re-entrenchment of Wallace Creek straight across the fault (Fig. 7e). The new channel was cut no more than 8.5 m below the level of the old channel, as the maximum depth of the new channel is only 8.5 m below the top of the high terrace in trench 5.

Offset and Future Re-entrenchment of the New Channel

The new channel has been offset ~130 m subsequent to its creation about 3800 yr B.P. (Fig. 7f). The modern-channel deposits have accumulated in the new channel during this period of time. They are now ~2.5 m thick at the right bend and more than 2.5 m thick at the left bend.

Although the active channel floor is now ~3 m below the crest of the channel bank at the

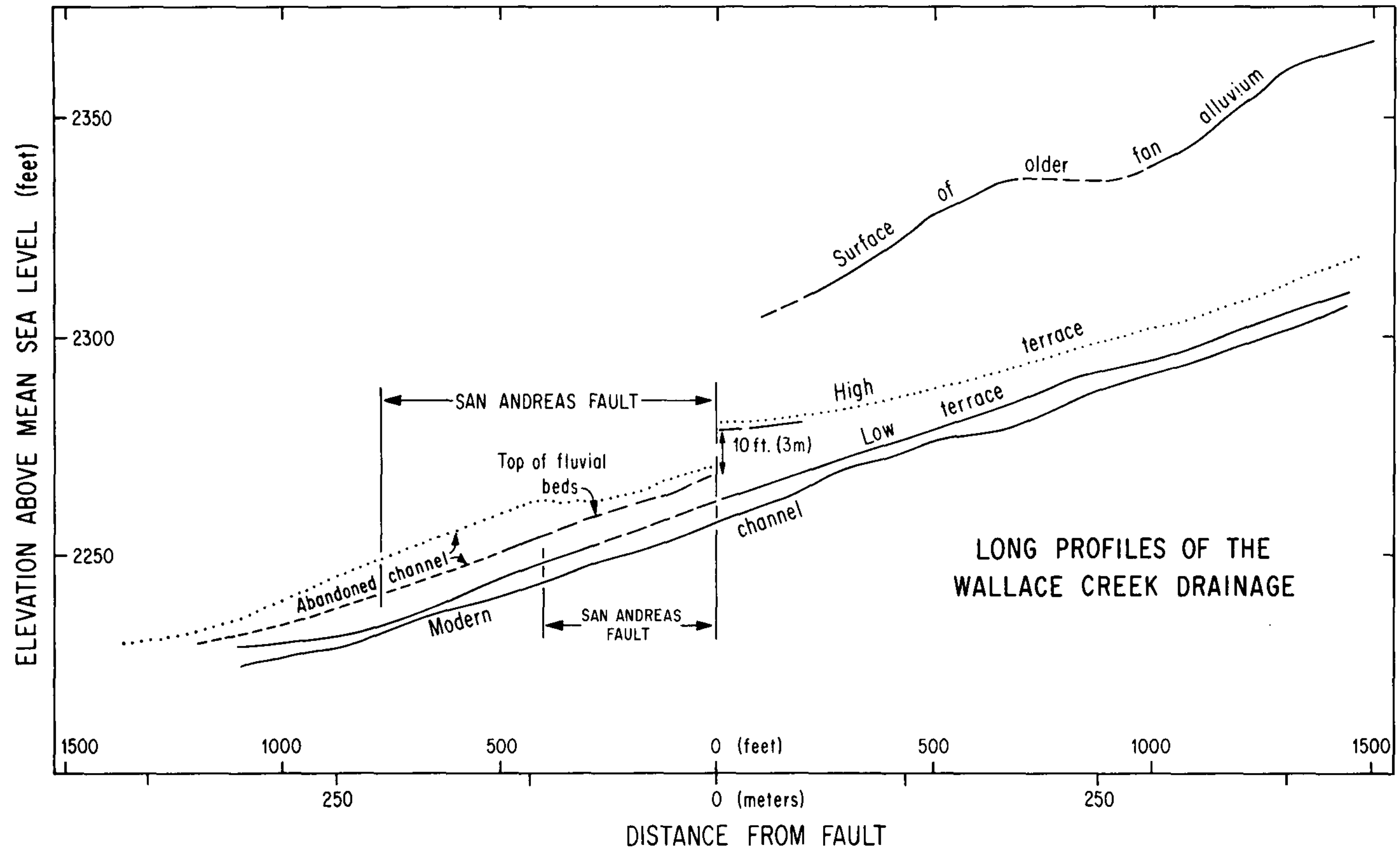


Figure 5. Stream profiles of the modern and the abandoned channels of Wallace Creek. High terrace, indicated by dotted lines, and top of high-channel alluvium, indicated by solid and dashed lines, are offset ~3 m vertically.

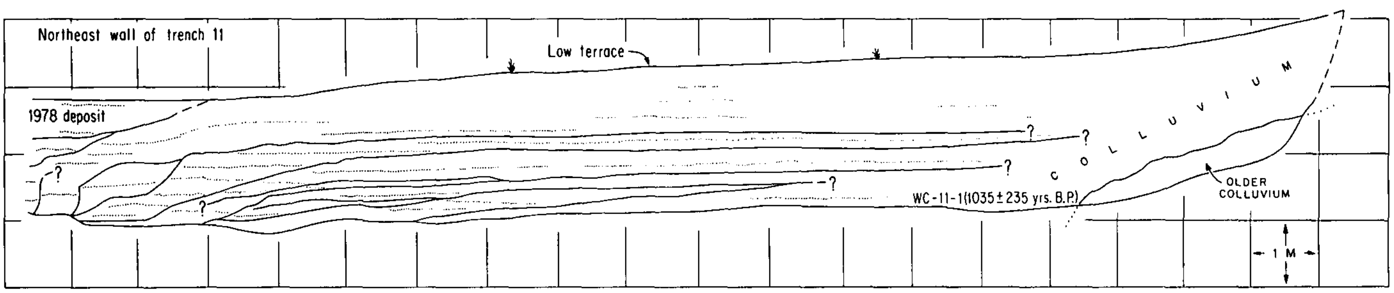


Figure 6. Trench 11 exposes the upper 2.5 m of low-channel deposits in the modern channel. Solid lines are contacts of individual fluvial beds. Dotted lines represent locally visible layering within these beds.

right bend, older modern-channel deposits form a low terrace surface that is only 1 m below the crest of the bank there. Mr. Ray Cavanaugh, who farms at Wallace Creek, reported to us that water actually spilled over the edge at the right bend in the winter of 1971–1972 or 1972–1973. It is not hard to envision a third entrenchment of Wallace Creek (Fig. 7g), given another metre or two of channel filling and a moderately high discharge. Such a re-entrenchment would establish the creek once again straight across the fault.

SLIP RATE OF THE SAN ANDREAS FAULT

Slip Rate during the Late Holocene

Knowing the date of the most recent entrenchment of Wallace Creek and the offset that has accumulated since that entrenchment, one can calculate rather precisely the rate of slip for the San Andreas fault. That rate is 33.9 ± 2.9 mm/yr, and its derivation is explained in detail below.

The offset of the modern channel of Wallace Creek is 128 ± 1 m. This figure is obtained by extrapolating the southwestern edge of the abandoned channel (labeled 1 in Fig. 8) to its

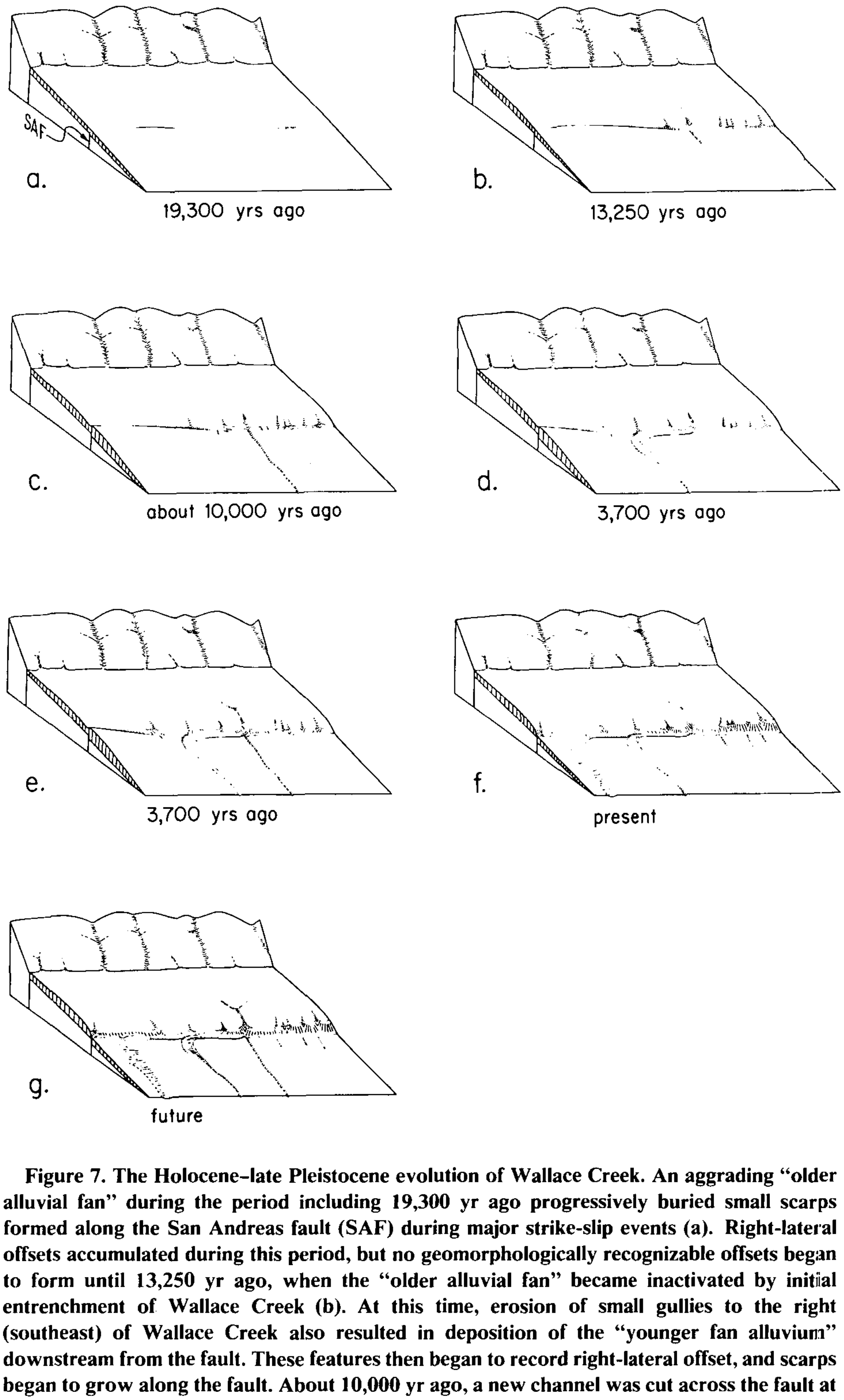


Figure 7. The Holocene–late Pleistocene evolution of Wallace Creek. An aggrading "older alluvial fan" during the period including 19,300 yr ago progressively buried small scarps formed along the San Andreas fault (SAF) during major strike-slip events (a). Right-lateral offsets accumulated during this period, but no geomorphologically recognizable offsets began to form until 13,250 yr ago, when the "older alluvial fan" became inactivated by initial entrenchment of Wallace Creek (b). At this time, erosion of small gullies to the right (southeast) of Wallace Creek also resulted in deposition of the "younger fan alluvium" downstream from the fault. These features then began to record right-lateral offset, and scarps began to grow along the fault. About 10,000 yr ago, a new channel was cut across the fault at Wallace Creek, and the initial channel, downstream from the fault, was abandoned (c). The new channel remained the active channel of Wallace Creek during the early and middle Holocene, during which ~250 m of slip accumulated (d). This channel filled with "high-channel alluvium" 3,700 yr ago, and Wallace Creek cut a new channel straight across the fault (e). Between 3,700 yr ago and the present, this youngest channel has registered 128 m of right-lateral offset (f). Aggradation of this channel, accompanied by continued offset, will probably lead to its abandonment and the creation of a new channel, cut straight across the fault (g).

intersection with the fault and then measuring the distance from that intersection to the intersection of the modern channel edge (labeled 2 in Fig. 8) with the fault. The same value is obtained if one measures the distance between the offset segments of the modern channel (labeled 3 and 4 in Fig. 8). In making the latter measurement of offset, it is important to realize that the outside edge of the left bend has been eroded by flood waters that have swept against it as they have passed around the left bend. The right bend has not been eroded in this manner, because it is refreshened each time the fault slips.

The fact that feature 1 and feature 3 (Fig. 8) intersect the fault at almost the same point strongly suggests that the abandonment of the high channel and entrenchment of the modern channel were contemporaneous. This coincidence also indicates that the new channel was cut straight across the fault without any initial nontectonic deflection of the stream along a fault scarp. The absence of any initial, nontectonic deflection is also confirmed by the fact that the modern channel is entrenched through a broad topographic high immediately downstream from the fault (consider contours in Fig. 2). If the channel had been deflected along a fault scarp, one would expect it to have cut through a low point on the downstream side of the fault rather than a high point. The measured separation of 128 m thus is ascribable entirely to tectonic offset.

The youngest date from the deposits of the abandoned high channel (3680 ± 155 yr B.P.) provides a maximum age for the modern channel, because all of the high-channel sediments were deposited before the modern channel was cut. All offset of the modern channel thus occurred between this date and A.D. 1857. The average slip rate, therefore, can be no slower than 35.7 ± 1.9 mm/yr [128 ± 1 m/3,680 ± 155 − 93 yr]. (93 yr is the time between A.D. 1950, which has been designated zero B.P., and A.D. 1857.)

Additional considerations are necessary to provide an upper limit to the slip rate. For this constraint, trenches 9 and 10 (Fig. 4) are useful. The high-channel deposits here consist of three distinct units, labeled C1, C2, and C3, that represent three distinct scourings and fillings. The uppermost sediment of channel C2 in trench 10 contained the radiocarbon sample the age of which is 3780 ± 155 yr B.P. At the time of deposition, C1, C2, and C3 in trenches 9 and 10 must have been at or northwest of the right bend of Wallace Creek. Trench 9 is now 145 m northwest of the right bend, and so no more than 145 m of dextral slip has accumulated since channel C2 was filled 3780 ± 155 yr B.P.

The trend of C2 between trenches 10 and 9 suggests that the edge of C2 actually intersects

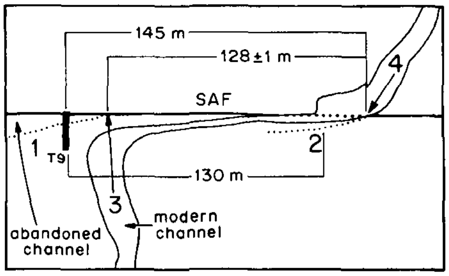


Figure 8. The edge of the abandoned channel (1) intersects the fault 128 ± 1 m northwest of the intersection of the modern channel edge (2) and the fault. The offset of the modern channel (from point 3 to point 4) is also 128 m. These provide the best measure of offset during the past 3,700 yr.

the fault at least 10 m closer to the modern right bend. In support of this, we note that the channel is ~5 m wide and rests entirely southwest of the fault in both trench 9 and trench 10. Sufficient channel width to accommodate a similar deposit southwest of the fault in the modern channel does not exist until at least 15 m downstream from the modern right bend. There, the crest of the channel bank is ~5 m southwest of the fault trace, and, were the channel to fill this year, a 5-m wide deposit analagous to the channel fill in trenches 9 and 10 would be deposited. From trench 9 to this geometrically analagous point in the modern channel (labeled 2 in Fig. 8) is ~130 m. It seems, therefore, that no more than 130 m of dextral slip accumulated between 3780 ± 155 yr B.P. and A.D. 1857. This yields an *upper* limit of 35.3 ± 1.5 mm/yr [130 m/(3,780 ± 155 − 93 yr)] for the slip rate. This maximum limiting rate is indistinguishable from the minimum limiting rate of 35.7 ± 1.9 mm/yr determined previously and independently. The rate must therefore be 35.3 ± 1.5 mm/yr, which includes the highest maximum value (35.3 + 1.5 mm/yr) and the lowest minimum value (35.7 − 1.9 mm/yr).

The calculations thus far have assumed continuous fault displacement between 3680 yr B.P. and A.D. 1857. It is very likely, however, that much, and possibly all, of the slip accumulates sporadically, during large earthquakes, such as that which occurred in 1857. If, as we argue below, this segment of the fault is characterized by coseismic displacements of ~10 m, followed by several centuries of quiet repose, the fault could have been at any point in its earthquake cycle 3680 yr B.P. If, in that year, the region bisected by the fault was in the middle or toward the end of a period of elastic strain accumulation, the rate calculated using this data will be slightly too high, because the 128-m offset accumulated between then and 1857 is in small part due to loading that occurred slightly earlier. Put in a different way, the 3,680-yr date may be any fraction of a recurrence interval younger than the beginning of a strain accumulation cycle. The beginning of the loading cycle corresponding to the earliest increment of the 128-m offset thus may be any time between 3680 yr B.P. and 3680 plus one recurrence interval. As is seen below, the average recurrence interval here is ~310 yr, or 8% of the time between A.D. 1857 and 3680 yr B.P. The actual slip rate thus could be as much as 8% lower than that just calculated, or 32.5 ± 1.5 mm/yr. The late Holocene slip rate thus could be any value between 32.5 ± 1.5 and 35.3 ± 1.5 mm/yr. This range is conveniently expressed as 33.9 ± 2.9 mm/yr.

Slip Rate since 13,250 yr B.P.

An additional determination of slip rate along the San Andreas fault at Wallace Creek comes from the 475-m offset of a 13,250-yr-old alluvial fan from its source gullies. This provides an average slip rate of 35.8 + 5.4/−4.1 mm/yr, which is not appreciably different from the late Holocene rate of 33.9 ± 2.9 mm/yr.

The 13,250-yr-old alluvial fan constitutes the "younger fan alluvium" mapped in Figure 2. The fan radiated from a point that is now located very near the modern left bend of Wallace Creek. Its existence is reflected in the bulging of the 2,240-, 2,250-, and 2,260-ft contours toward the southwest (Fig. 2). Even though it is now buried by 1.5 to 2 m of unmapped slope wash and bioturbated materials, the bulging of the contours and measurements of thickness in trenches 2, 3, 4, and 6 enable construction of the isopach map of the younger fan alluvium shown in Figure 9.

Trench 2 (Fig. 3) exposes the sediments of the fan near its apex. There, the sediments constitute a 1.3-m-thick bed of well-sorted, imbricated sandy gravel. The gravel is composed of tabular pebbles of diatomaceous Tertiary marine mudstone. Imbrication of these tabular pebbles clearly indicates a flow direction toward the southwest. The source of the alluvial fan thus must be on the opposite side of the San Andreas fault. Although the fan is composed of three discrete beds in trench 2 (see detailed log of trenches, available from author), the lack of bioturbation or weathering of the two horizons between these beds suggests that the fan was deposited very rapidly, perhaps in a matter of a few decades or less.

The deposit overlies a massive, poorly sorted sandy loam that represents either a colluvial unit or an alluvial deposit that was extensively bioturbated prior to burial. The unit probably lay at the ground surface for a long time prior to burial by the alluvial fan. The presence of charcoal pebbles and granules in this unit, no more than a centimetre or two beneath the base of the fan, suggests that a range fire occurred just prior to deposition of the fan. The charcoal certainly would have been oxidized if it had not been buried deeply very soon after its formation. Erosion of the fan materials from their source within the burned area may have been a direct result of the fire, which removed protective vegetative cover from the ground surface. The charcoal age of 13,250 ± 1,650 yr B.P. thus represents the age of the basal unit of the overlying alluvial fan.

If the source of the younger fan sediments were Wallace Creek, the fan would be offset a mere 128 m. This would imply that the fault was inactive between about 13,000 yr and about 3700 yr B.P., because we have just shown that 128 m of slip has occurred since about 3700 yr B.P. Such a long period of dormancy along the San Andreas fault seems very unlikely to us, and so we seek a source for the younger fan that is farther to the southeast.

The volume of the fan is ~25,000 m^3. Candidates for the source gully (or gullies) must have total eroded volumes at least as great as this and preferably somewhat larger, because some of the material transported out of the source region must have been carried beyond the alluvial fan as suspended load and bedload.

Given this constraint, only two plausible sources for the fan exist within 1 km of Wallace Creek. The first is a solitary channel ~730 m southeast of the fan apex (E in Fig. 1). This channel originates in the Temblor Range but drains a much smaller area than Wallace Creek. If this is the source, an average slip rate of ~63 mm/yr for the period 13,250 to 3700 yr B.P. is calculated:

$$\frac{(730 - 128)\ \text{m}}{(13{,}250 - 3{,}680)\ \text{yr}} = 63\ \text{mm/yr}.$$

This would indicate fluctuations in slip rate of at least several centimetres per year during the past 13,000 yr, because the average rate for the past 3,800 yr has been ~34 mm/yr.

More likely sources for the alluvial fan are four closely spaced gullies several hundred metres southeast of the fan apex (A, B, C, and D in Fig. 1). In Figure 9, these have been restored to their probable location at the time of formation of the fan. None of these four small gullies, which extend only a few hundred metres back from the fault scarp, could have been the sole provider of enough material to construct the entire fan. The volumes of A, B, and C are only ~13,000 m^3 each, and D is much smaller. In any combination, however, they could have delivered enough material.

The proper matching of this multiple source with the younger fan deposit can be determined rather precisely. If the general reconstruction shown in Figure 9 is correct, the southeastern

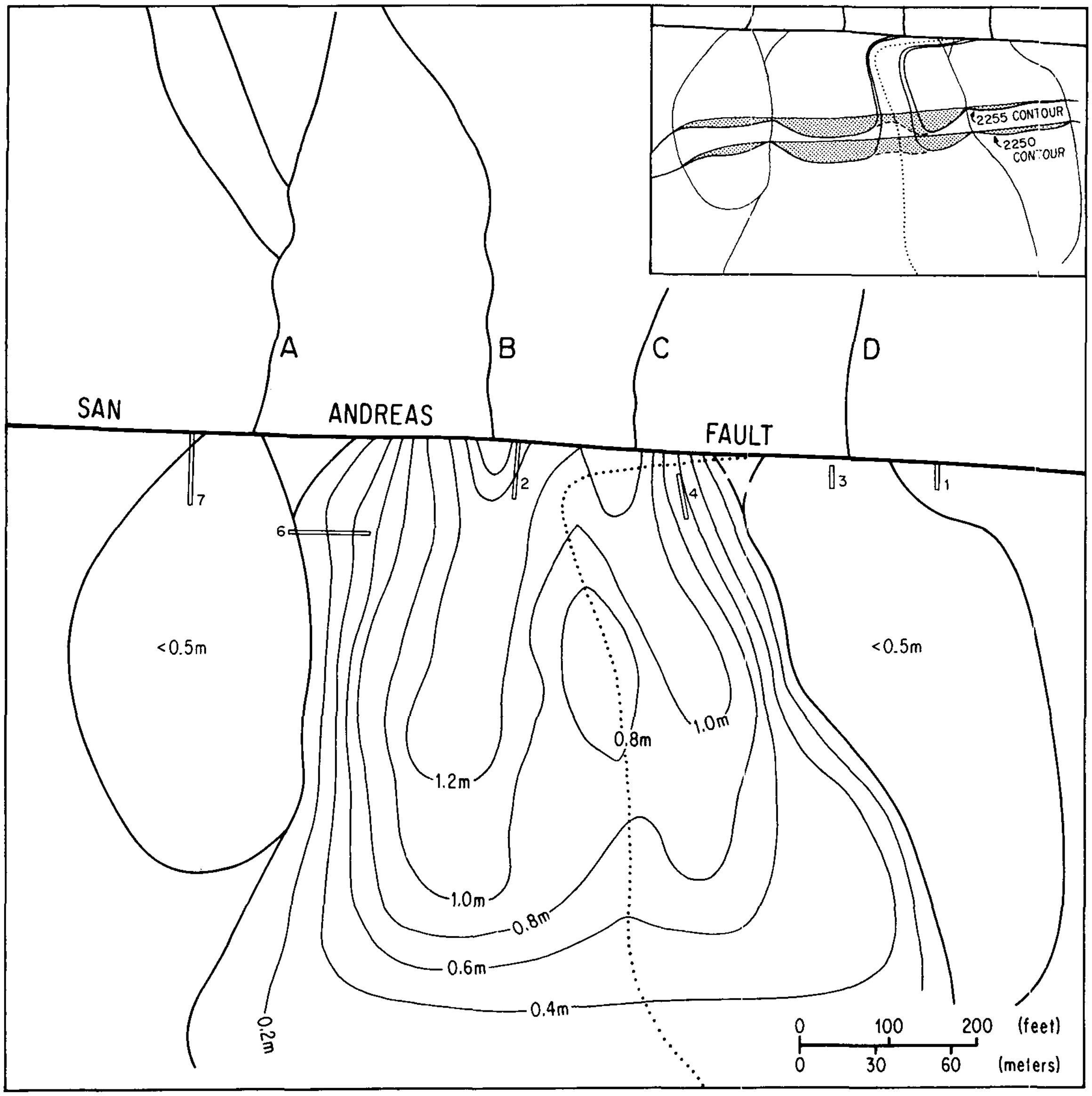


Figure 9. Isopach map of 13,250-yr-old alluvial fan and source gullies B and C. In this figure, the gullies have been restored 475 m to their late Pleistocene position upstream from the fan. The same gullies are indicated by letters B and C in Figure 1b. For reference, dotted line represents location of modern channel of Wallace Creek. Isopach map is based on trench exposures (thick, open bars) and geometry of contours. Insert in upper right illustrates use of topographic contours in constructing isopach map. Lower edge of stippled region is topographic contour. Upper edge is contour prior to deposition of fan. Southwestward bulging of contours indicates presence and thickness of alluvial fan.

flank of the main fan complex had to be southeast of channel C. The offset thus is no less than 472 m. At the same time, the crests of the two distinct lobes of the fan shown in Figure 9 should have had their apexes at the mouths of two of the middle gullies. Only gullies B and C are spaced appropriately to meet this constraint. The mouth of gully B cannot be offset more than 478 m, if B is the source of the northwestern lobe of the fan. It is of interest that the younger fan deposits are offset from gullies A, B, C, and D, only slightly less so than the oldest, beheaded channel of Wallace Creek itself (marked with a white arrow at the left margin of Fig. 1). The creation of gullies A, B, C, and D must, therefore, be nearly contemporaneous with the first entrenchment of Wallace Creek.

These considerations constrain the offset of the younger fan deposits to 475 ± 3 m. In that the younger fan formed 13,250 ± 1650 yr B.P., the average slip rate must be 35.8 + 5.4/−4.1 mm/yr. Within the level of resolution, this cannot be distinguished from the average late Holocene rate of 33.9 ± 2.9 mm/yr.

RECURRENCE INTERVALS BETWEEN PAST LARGE EARTHQUAKES AT WALLACE CREEK

The average Holocene and late Holocene rates of slip at Wallace Creek are important new measurements of strain across the San Andreas

TABLE 2. SMALLEST STREAM OFFSETS NEAR WALLACE CREEK AND PROPOSED INTERVALS BETWEEN GREAT EARTHQUAKES

(1) Stream offsets (m)	(2) Remarks	(3) Produced by	(4) Slip associated with earthquake (m)	(5) Proposed interval between events (yr)
9.5 ± 0.5(± 1σ)	Average of 5 measurements	1857 event	9.5 ± 0.5(± 1σ)	
				240 to 320§
21.8 ± 1.1	Average of 4 measurements**	1857 plus last prehistoric event	12.3 ± 1.2*	
				300 to 440§
32.8 or 33.5 ± 1.9	Average of 3 measurements**	1857 plus latest 2 prehistoric events	11.0 or 11.7 ± 2.2†	240 to 450§

*$21.8 \; 9.5 \pm (0.5^2 + 1.1^2)^{1/2}$.
†$32.8 \; 21.8 \pm (1.1^2 + 1.9^2)^{1/2}$ or $33.5 - 21.8 \pm (1.1^2 + 1.9^2)^{1/2}$.
§Slip during following earthquake in column 4 divided by average late Holocene slip rate (33.9 ± 2.9 mm/yr).
**Offset gullies are all between Wallace Creek and Gully D in Figure 1.

TABLE 3. SMALLEST STREAM OFFSETS NEAR WALLACE CREEK AND PROPOSED DATES AND CORRELATION OF LATEST FOUR GREAT EARTHQUAKES

(1) Stream offsets (m)	(2) Time required to accumulate offset as elastic strain using average late Holocene slip rate (years)	(3) Proposed dates for latest earthquakes (A.D.)	(4) Possible correlations with events recognized at Pallett Creek	(5) Possible correlations with events recognized at Mill Potrero by Davis (1983)
		1857	Z(1857)	Z(1857)
9.5 ± 0.5 (± 1σ)	240 to 320			
		1540 to 1630*	V(1550 ± 70)	V(1584 ±70)
21.8 ± 1.1	560 to 740			
		1120 to 1300†	R(1080 ± 65)	
32.8 or 33.5 ± 1.9	840 to 1140			
		720 to 1020§	F(845 ± 75)	

*1857 – (240 to 320 yr).
†1857 – (560 to 740 yr).
§1857 – (840 to 1140 yr).

fault in central California, because they are the first to span more than a fraction of a great earthquake cycle of strain accumulation and relief. These millennial averages can be used in conjunction with other data to infer earthquake recurrence intervals.

For example, the length of the cycle of strain accumulation that preceded and led to the great 1857 earthquake can be calculated. In 1857, the San Andreas fault sustained 9.5 m of right-lateral slip at Wallace Creek. This is indicated by five small offset gullies nearby (A, B, C, D, and E in Fig. 1; Table 2), as well as by small offset gullies at distances of as much as several kilometres to the northwest and southeast. These gullies were incised across the fault prior to the 1857 event, but after the previous large event (see Sieh, 1978c, for a more detailed discussion). If one assumes that the 9.5 m of fault slip associated with the 1857 earthquake relieved elastic strains that had accumulated in the adjacent crustal blocks at an average rate of 34 mm/yr, one calculates that the 1857 earthquake was preceded by a 280-yr period of strain accumulation. This calculation does not assume that annual strain accumulation was uniform during the 280-yr period, but only that the *average* annual rate was equal to the millennial average of 34 mm/yr. Periods of faster or slower accumulation thus could be accommodated within the over-all loading cycle. Table 2 (top of col. 5) displays the actual range of values for the period of strain accumulation if the uncertainties in the 1857 offset value and average slip rate are taken into account. In lieu of a direct dating of the large event that preceded the 1857 event at Wallace Creek, this range (240–320 yr) is probably the best estimate that can be made for the recurrence interval between the 1857 earthquake and its predecessor.

Estimates of the duration of two earlier periods of strain accumulation can also be made, using the average late Holocene slip rate and the amount of fault slip associated with each of the last two prehistoric earthquakes. Table 2 lists the data that suggest these 2 events were associated with ~12.3 and 11.5 m of fault slip at Wallace Creek. At 34 mm/yr, these values would have accumulated in 360 and 340 yr, respectively. The actual range in value for both of these recurrence intervals, calculated using the ranges in value for the slip rate and the offsets, is displayed in column 5 of Table 2. From the table, one can see that the latest 3 recurrence intervals are estimated to be within the range of 240 to 450 yr.

Of course, it is possible that the 4,000-yr and 13,000-yr average slip rates do not represent the average rate of strain accumulation during the periods of fault dormancy prior to 1857 and the 2 previous great earthquakes. For example, the rate of accumulation actually could have been much higher during the past millennium and much slower during the previous 4,000-yr interval. If so, the recurrence intervals between the latest few earthquakes would be much shorter than those calculated above. Perhaps a future study of a currently undiscovered 1,000-yr-old feature near Wallace Creek will resolve this issue by providing a 1,000-yr average rate. Alternatively, the past several earthquakes may be dated directly, as has been done at Pallett Creek (Sieh, 1978b, in press). In the meantime, the validity of using the 3,700-yr average slip rate in calculating recurrence intervals of recent and future great earthquakes must be assessed in other ways.

First, the slip rate averaged over the past 3,700 yr (33.9 ± 2.9 mm/yr) does not differ appreciably from the 13,000-yr average (35.8 + 5.4/−4.1 mm/yr), although the 13,000-yr average conceivably could be as much as 10 mm/yr (~30%) faster than the late Holocene average, given the imprecision of the 2 determinations.

Second, geodetic data on modern rates of strain accumulation across the fault are available from the "Carrizo" net, which spans the fault and 80 km of adjacent territory at the latitude of Wallace Creek (Savage, 1983, and 1982, written commun.). These data are available, however, only for the period 1977.6 to 1981.5. The deformation observed during this period averages 0.29 ± 0.06 μstrain/yr (extension) N89° ± 4°W and −0.09 ± 0.06 μstrain/yr (contraction) north-south. Numerous models of lithospheric deformation can produce this observed surficial deformation. One class of model involves the assumption that the observed deformations are the result of aseismic right-lateral slip on the San Andreas fault beneath its locked, brittle upper 10 or 20 km. In this case, the observed deformations of the Carrizo net are resolved as right-lateral shear strains parallel to the San Andreas fault. The average shear strain over the entire 80-km-wide network is 0.38 ± 0.04 μrad/yr. This translates into a deep slip rate on the fault of 30.4 ± 3.2 mm/yr, if one assumes that the network spans the entire zone of deformation due to slip on the fault. If it does not span the entire zone, the rate of deep slip on the fault must be higher. Like the 13,000-yr average rate, the geodetically determined modern rate does not differ significantly from the 3,700-yr average.

The similarity of the 13,000-yr, 3,700-yr, and 4-yr averages suggests that strain accumulation across the fault may be fairly uniform. Of course, numerous histories could be invented that include these three data points and yet involve large fluctuations in the strain accumulation rate between earthquake cycles or recurrence intervals. To date, however, no known data support large fluctuations. A reasonable assumption, thus, is that the late Holocene average slip rate represents the average rate of strain accumulation between large earthquakes. The recurrence intervals displayed in Table 2 may, therefore, be realistic estimates of the dormant intervals that preceded the past three great earthquakes.

In the next section, we attempt to assess when the current earthquake cycle will end at Wallace Creek; that is, when the next great earthquake, accompanied by rupture at Wallace Creek, will occur. We also attempt to use the 3,700-yr average slip rate to assess the likelihood of large earthquakes elsewhere along the San Andreas fault.

FORECASTS OF THE BEHAVIOR OF THE SAN ANDREAS FAULT

Along the South-Central (1857) Segment

If the crust adjacent to the San Andreas fault has been accumulating strain at 34 mm/yr since 1857, as much as 4.3 m of potential slip has now been stored and conceivably could be released along all or part of the 1857 rupture. Geomorphologic data, however, suggest that this is likely only along two portions of the 1857 rupture. Wallace Creek is not within either of these portions.

Figure 10 displays offsets measured along the south-central segment of the San Andreas fault. The 1857 segment is divisible into at least three parts, based on slippage during the 1857 earthquake and one to four previous large earthquakes. The southeastern part is ~90 km long and seems to have been characterized by 3- to 4.5-m slip events. The central 160 km, including Wallace Creek, has experienced 7 to 12.3 m of slip during the most recent 3 great earthquakes. The lower values along this central portion occur along the reach between km 90 and km 200, where several other active faults to the north and northeast exist, and so the lower values may reflect distributed deformation, away from the San Andreas fault. A 30-km segment northwest of Wallace Creek experienced 3 to 4 m of slip in 1857 and probably 1 or 2 during previous large earthquakes, as well.

These data suggest that each part of the fault has experienced a characteristic amount of slippage during the past three to four large earthquakes. Although, of course, so few data do not provide a statistically sound basis for predicting all previous and future events, we are confident that this pattern offers some insight into the long-term behavior of the fault.

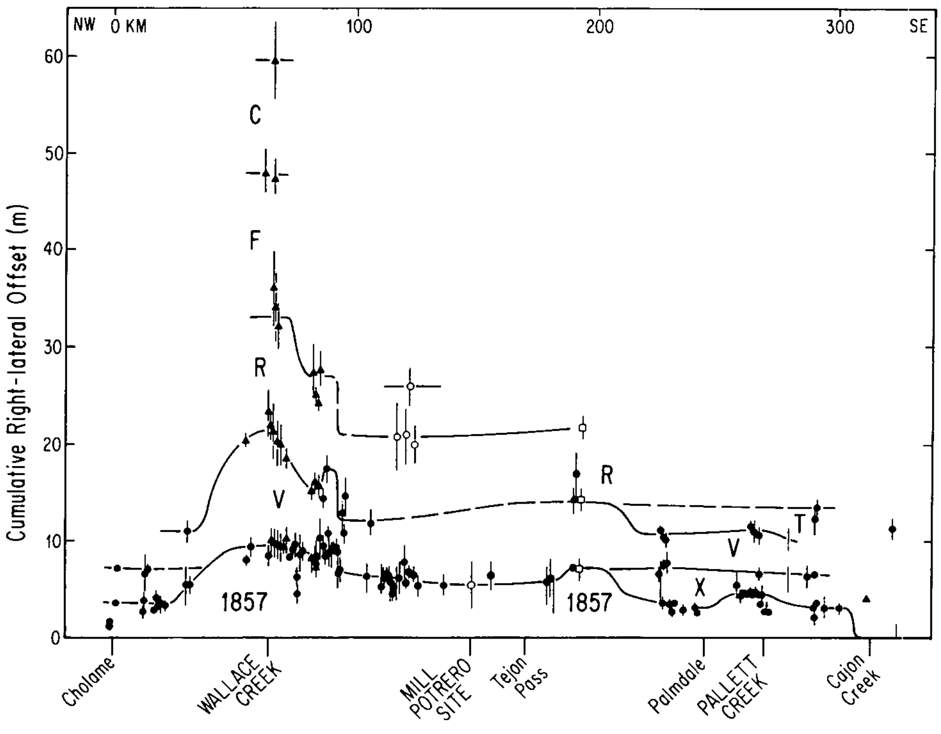


Figure 10. Right-lateral offsets measured along the south-central (1857) segment of the San Andreas fault suggest that slip at each locality is characterized by a particular value. Solid circles are data from Sieh (1978c), with poor-quality data deleted. Open circles are data from Davis (1983). Triangles are new data and remeasurements at sites reported by Sieh (1978c). Open squares are new data. Vertical bars indicate magnitude of imprecision in measurement.

At least two explanations are worth considering. First, we consider the possibility that the northwestern 40 km and southeastern 90 km are loaded more slowly, and, therefore, when the earthquake occurs, they experience lesser amounts of slip than does the central 160-km-long part. This is unlikely, because the average Holocene slip rate along these two parts must be nearly equal to the rate determined at Wallace Creek. Just beyond the south-central segment, at Cajon Creek (Fig. 10), the San Andreas has average Holocene and late Holocene slip rates of 25 ± 3 mm/yr (Weldon and Sieh, 1981). The nearby San Jacinto and related subparallel faults probably carry ~10 mm/yr at this latitude (based on data of Sharp, 1981, and Metzger, 1982). These fault systems end and nearly merge with the San Andreas fault just northwest of Cajon Creek. Farther northwest, the San Andreas fault is the only major active structure, and so northwest of Cajon Creek, it must have a slip rate of ~35 mm/yr. In addition, the average recurrence interval for large earthquakes at Pallett Creek (location in Fig. 10) is in the range of 145 to 200 yr, which is appreciably shorter than the 240- to 450-yr range at Wallace Creek. For this reason, some of the slip events shown in Figure 10 in the Palmdale–Pallett Creek region must have their northwestern rupture tip southeast of Wallace Creek, and 1857-like events cannot be the only type of slip event along this part of the south-central segment.

The northwestern 30 km of the south-central segment (Fig. 10) must also share the long-term average slip rate of Wallace Creek. No diversion of a large fraction of the Wallace Creek rate along other structures is plausible. The only known major active(?) fault nearby is the San Juan Hill fault, which runs 3 to 14 km west of and subparallel to the San Andreas from about Cholame to Wallace Creek (Jennings and others, 1975). Its rate of slip is probably no more than a few millimetres per year.

A second explanation for the different behavior of the three parts of the south-central segment is based on the hypothesis that each part is imbued with a different strength. If, for reasons of geometry or rock properties, the central 160 km of the segment were 2 or 3 times stronger than the 2 other parts, 2 or 3 times as much elastic loading of the adjacent crustal blocks would be necessary before failure occurred.

Each failure thus would result in two to three times as much slippage as on the two adjacent parts. Such an explanation is compatible with our judgments that (1) slip rate does not vary greatly along the south-central segment, and (2) large earthquakes are more frequent at Pallett Creek than at Wallace Creek.

Table 3 lists our best estimates of the dates of large earthquakes at Wallace Creek and proposed correlations with large earthquakes that have been directly dated at Pallett Creek (Sieh, in press) and at Mill Potrero (Davis, 1983). The capital letters in Figure 10 reflect our best judgment regarding correlation of the latest events at Wallace Creek, Pallett Creek, and Mill Potrero. Event X at Pallett Creek (A.D. 1720 ± 50) has no correlative at Wallace Creek, although Davis (1983) discovered evidence for and dated a relatively small slip event at Mill Potrero that may well be event X. Event V at Pallett Creek occurred about A.D. 1550, which is about the time we estimate that the last prehistoric event at Wallace Creek occurred, and also about the time of a large slip event that Davis (1983) discovered at Mill Potrero. Similarly, events R and F at Pallett Creek occurred at about the time we estimate that the third and fourth events occurred at Wallace Creek.

On the basis of the foregoing discussion, we judge that the central 160 km of the south-central segment of the San Andreas fault is unlikely to generate a great earthquake for at least another 100 yr. Recurrence intervals appear to be in the range of 250 to 450 yr, and yet the time elapsed since the great earthquake of 1857 is only 127 yr. Slip during the latest 3 great earthquakes has been 7 to 12.3 m, and yet we suspect that only a little more than 4 m of potential slip has been stored in the past 127 yr.

The southeastern 90 km and the northwestern 30 km of the south-central segment are good candidates for producing a large earthquake within the next several decades. Geomorphologic measurements seem to indicate that 3 to 4.5 m of slip is characteristic during large events, and >4 m of potential slip may well have been stored in the adjacent crustal blocks since 1857. Based on studies at Pallett Creek, the probability of a great event along the southeastern 90 km of the south-central segment within the next 50 yr is between 26% and 98% (Sieh, in press).

Along the Creeping Segment

The long-term average slip rates determined at Wallace Creek are indistinguishable from the geodetically determined rates of slip at deep levels along the fault from Wallace Creek to Monterey Bay (Savage, 1983; Lisowski and Prescott, 1981). The long-term rates at Wallace Creek are also identical to the historical rate of slip at shallow levels along the central 50 km of the creeping segment (see data compiled by Lisowski and Prescott, 1981, Fig. 6). These similarities could be coincidental, but they suggest that the central 50 km of the creeping segment is creeping annually at its millennial-average rate of slip. If this were true, it would mean that large elastic strains are not accumulating across the central 50 km of the creeping segment, and that this segment will not participate in the generation of the next large earthquakes along the San Andreas fault.

From a geological point of view, it is reasonable to suspect that the long-term slip rate along the San Andreas fault at Wallace Creek should not be different from its long-term rate along the creeping segment, except along its northernmost 50 km, adjacent to which runs the actively creeping Paicines fault (Harsh and Pavoni, 1978). No other large, active structures in the latitudes of the creeping segment can be called upon to absorb a large portion of the slip rate observed farther south at Wallace Creek. Likewise, there are no obvious geological structures near the San Andreas that would lead one to suspect that the long-term slip rate along the creeping segment is appreciably higher than the long-term rate farther south.

Along the 90-km Segment Centered on Cholame

Between the central 50 km of the creeping zone and Wallace Creek, there is a stretch of the San Andreas fault that historically has been a zone of transition between the fully creeping and fully locked portions of the fault. On the basis of available data, this segment is a prime candidate for generating a large earthquake in the near future. In the period of historical record, it has not experienced as much slip as have segments to the northwest or southeast, and it is therefore a "slip gap."

One interpretation of the historical data is illustrated in Figure 11, in which cumulative right-lateral slip for the past two centuries is

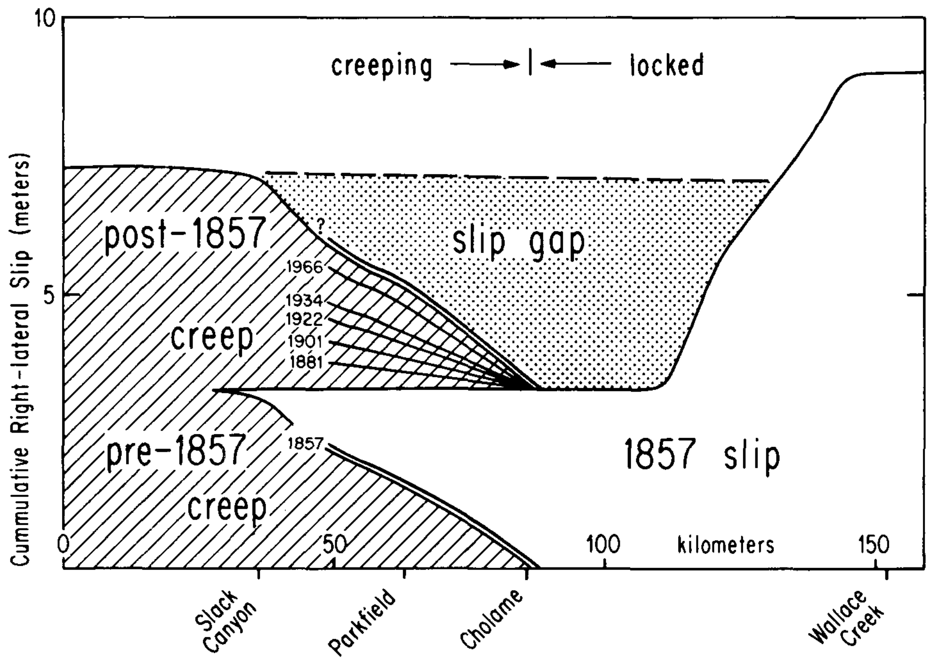


Figure 11. Hypothetical source of future major earthquake along the San Andreas fault includes ~60 km of the currently creeping segment and 30 km of the locked segment. Cumulative right-lateral slip plotted against distance along the fault indicates that this 90-km segment is slip-deficient relative to adjacent stretches of the fault. Slip in 1857 is from Sieh (1978c). Cumulative slip along the creeping segment is extrapolated from alignment array slip rates for period 1968–1979 (Lisowski and Prescott, 1981, Fig. 6). Dates of moderate earthquakes generated by slip along the fault in the Parkfield-Cholame region are shown, because such an event probably triggered the great 1857 rupture and conceivably could trigger the rupture of the slip gap.

plotted as a function of location along the fault. We assume that creep rates northwest of Cholame have been constant for the past few hundred years, so that the alignment array data for the period 1968–1979 are representative of the pre- and post-1857 creep rates. We also assume that Cholame has been the edge of the creep zone throughout this period. In the century preceding 1857, 3 to 3.5 m of slip would have accumulated by creep northwest of Slack Canyon. Less slip would have accumulated by creep, and perhaps during occasional moderate earthquakes, between Slack Canyon and Cholame.

In 1857, ~3.5 m of slip occurred along the 30-km stretch of the fault southeast of Cholame, and 9.5 m of slip occurred in the vicinity of Wallace Creek. The sparse historical accounts are compatible with our inference in Figure 11 that slippage during the earthquake decreased northwestward from Cholame and died out near Slack Canyon (Sieh, 1978c, p. 1423–1424).

Following 1857, creep resumed northwest of Cholame. Northwest of Slack Canyon, ~4.5 m of slip now has accumulated at the full, long-term rate of loading of the fault (that is, 34 mm/yr). The 60-km-long section between Slack Canyon and Cholame, however, has crept at rates that are significantly lower than the loading rate, and strain is being stored in the rocks adjacent to the fault there. Similarly, elastic strains are accumulating in the rocks adjacent to the locked portion of the fault, and the northernmost 30 km of this portion, which seems to fail in 3- to 4-m slip events, may well be loaded nearly to the point of failure.

We suggest that this northernmost part of the locked segment and the southernmost part of the creeping segment might fail in unison and produce a major earthquake. This hypothetical event would be associated with ~90 km of surface rupture and a maximum of ~4.3 m of right-lateral slip.

In discussing this hypothetical event, it is important to note that the great 1857 earthquake seems to have originated in this region. Sieh (1978a) documented that at least 2 moderate foreshocks occurred in this vicinity about 1.5 and 2.5 hr prior to the main shock. Within the past century, 5 moderate (M5.5 to 6) earthquakes have been produced by slippage along the San Andreas fault northwest of Cholame. Sieh (1978a) inferred that the 1857 foreshocks emanated from a source similar to that which produced these historical shocks. If this is true, then the next moderate "Parkfield-Cholame" earthquake might well be a foreshock of the hypothetical major event described above.

ROLE OF THE SAN ANDREAS FAULT IN THE RELATIVE MOTION OF THE NORTH AMERICAN AND PACIFIC PLATES

Minster and Jordan (1978) determined from a circumglobal data set that the relative motion of the Pacific and North American plates has averaged ~56 mm/yr during the past 3 m.y. The geological record at Wallace Creek shows that, at least during the past 13,000 yr, only ~34 mm/yr of this has been accommodated by slip along the San Andreas fault. If one assumes that the 3-m.y. average represents the Holocene average rate across the plate boundary as well, then clearly the San Andreas fault is accommodating only ~60% of the relative plate motion. The remainder of the deformation must be accomplished elsewhere within a broader plate boundary. The San Gregorio–Hosgri fault system, which traverses the coast of central California, may have a late Pleistocene–Holocene slip rate of 6 to 13 mm/yr (Weber and Lajoie, 1977), and the Basin Ranges, to the east of the San Andreas fault, may be opening N35°W on oblique normal faults at a late Pleistocene–Holocene rate of ~7 mm/yr (Thompson and Burke, 1973). Most of the 56 mm/yr plate rate thus may be attributed to the San Andreas, San Gregorio–Hosgri, and Basin Range faults. Long-term slip rates on these three major fault systems are not known precisely enough to preclude or confirm the possibility that the rate of relative plate motion during the Holocene is equal to the 3-m.y. average. No clear basis exists, however, for suggesting that the Holocene rate is less than or more than the longer-term rate.

ACKNOWLEDGMENTS

Wallace Creek is named after Robert Wallace, who elucidated the basic history of the channel more than 15 years ago and provided us with a special topographic base map. N. Timothy Hall drew our attention to the study site. He and Laurie Sieh participated in initial studies. Art Fairfall and John Erickson at the University of Washington provided all of the radiocarbon analyses. Robert Wallace, David Schwartz, David Pollard, Christopher Sanders, and Ray Weldon provided helpful criticisms of earlier manuscripts. This work was supported by the National Earthquake Hazards Reduction Program, U.S. Geological Survey Contract nos. 14-08-0001-15225, 16774, 18385, and 19756.

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