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<th>Title</th>
<th>Prehistoric large earthquakes produced by slip on the San Andreas fault at Pallett Creek, California</th>
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<tbody>
<tr>
<td>Author(s)</td>
<td>Sieh, Kerry</td>
</tr>
<tr>
<td>Citation</td>
<td>Sieh, K. (1978). Prehistoric large earthquakes produced by slip on the San Andreas fault at Pallett Creek, California. Journal of Geophysical Research, 83(B8), 3907-3939.</td>
</tr>
<tr>
<td>Date</td>
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1. INTRODUCTION

Background and Purpose

The geologic record of the recent past provides the best opportunities for study of the long-term behavior of active faults, especially in areas that lack a long historical record of seismicity [Allen, 1975]. Many of the phenomena that accompany earthquakes are preserved in the sedimentary record. These include faults, folds, fissures, soft sediment deformation, and sandblows. A few geologists have attempted to use such features preserved in young sediments to date prehistoric earthquakes and calculate average recurrence intervals. In an excavation across a fault scarp associated with the 1971 San Fernando earthquake, for example, Bonilla [1973] recognized and may have dated an older, buried scarp produced during a previous earthquake, and in excavations of datable prehistoric lake sediments, which were faulted during the 1968 Borrego Mountain earthquake, Clark et al. [1973] recognized evidence of many prehistoric events and were able to infer an average recurrence interval for moderate events. Also, Sims [1973, 1975] has correlated deformed layers of lake deposits with known historical earthquakes.

I studied a section of late Holocene sediments, broken by the San Andreas fault, in an attempt to characterize certain aspects of the late Holocene slip history of one segment of this large strike slip fault. Specifically, I wished to determine when large prehistoric events had occurred, thereby deriving an understanding of the frequencies and irregularities of their occurrence. Such knowledge of the long-term behavior of the San Andreas fault and other faults would provide a better geologic context in which to interpret possible geophysical precursors to large earthquakes.

Setting

During the period of historical record (i.e., the past 100–200 years) the San Andreas fault has exhibited contrasting styles of behavior between its individual reaches. In general, segments that ruptured in 1857 and 1906 (Figure 1) have been seismically very quiet since their respective great earthquakes. The intervening segment, approximately 100 km in length, has been creeping relatively continuously throughout the twentieth century and is characterized by a high level of seismicity [Brown and Wallace, 1968].

Allen [1968] has proposed, on the basis of the rather permanent geological and geometrical characteristics of and contrasts between the creeping and the dormant segments, that the historical behavior is representative of the long-term behavior. This implies that the segments which produced the great 1906 and 1857 earthquakes are characterized by great earthquakes separated by long periods of dormancy. Preliminary examinations of offset channels along the 1857 break seem to support this hypothesis [Sieh, 1977, chapter 2], but further study will be necessary to confirm or deny it.

The site of this study is at least 25 km from the southernmost terminus of the fault rupture associated with the great (Ms = 8+?) 1857 earthquake (Figures 1 and 2) [Sieh, 1978]. Offset stream channels indicate that 1857 displacements in the vicinity were between 3 and 4 m (Figure 2) [Sieh, 1978]. Since 1857 the level of seismicity along the fault near the site has been low. Figure 3 shows earthquakes (M ≥ 6) that have occurred within 80 km of the site. The four smaller events (7, 9, 10, and 11) that have occurred close enough to produce moderate intensities at the site are also plotted. None of the events are believed to have been associated with slip along the trace of the San Andreas fault.

Pallett Creek is an ephemeral stream that flows down the north flank of the San Gabriel mountains and into the Mojave Desert (Figure 4). Near the base of the mountains it flows across the San Andreas fault. Figure 5 illustrates the echelon configuration of the recent fault traces near Pallett Creek.

For centuries, conditions at this crossing have been favorable for the preservation of the geologic features produced in association with earthquakes. The San Andreas fault has ruptured the sediments repeatedly, and their rapid accumulation has produced stratigraphic separation of the faulting events. Long hiatuses in sedimentation have been infrequent, and scour has not eliminated large portions of the record. An abundance of carbonaceous materials allows radiometric dating of events recorded in the layers. Finally, modern incision of the deposits by Pallett Creek has lowered the water table and exposed the previously saturated deposits.
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PREHISTORIC EARTHQUAKES ON SAN ANDREAS FAULT

The San Andreas fault has been the source of two great earthquakes since the arrival of white men in California in 1769. The first occurred in 1857, and the second in 1906. The fault rupture associated with the 1857 earthquake extended more than 250 km to the northwest and at least 25 km to the southeast of Pallett Creek [Sieh, 1978]. LA is Los Angeles, and SF is San Francisco.

Organization of the Paper

I have organized the text into five sections as follows:

1. Introduction. This section sets forth the nature of this study, previous work, and the geographic and seismic setting of the site.

2. Stratigraphy. This section describes the 'environmental' history of the site as revealed by historical records and by the radiometrically dated stratigraphic record.

3. Late Holocene seismic history. This section describes the nature and details of the evidence for large earthquakes at the site.

4. Summary. This section capsulizes the evidence for large seismic events detailed in the previous section.

5. Discussion. This section considers the possible implications of the frequency of large earthquakes at this site in combination with other information on prehistoric and historical behavior of the San Andreas fault.

I suggest that the more casual readers of this paper study only the figures and figure captions in the following rather lengthy sections (2 and 3) and then proceed to the last two sections (4 and 5).

2. Stratigraphy

Near its intersection with the San Andreas fault, Pallett Creek now flows within a 10-m-deep, 50- to 170-m-wide, steep-walled gorge that has been cut into a broad alluvial terrace. Old land-survey records, personal recollections, aerial photographs, and topographic maps offer clear evidence that the initial historic entrenchment of the creek occurred between 1904 and about 1915 and that the water table had been very close to the terrace surface prior to that time. This information, which is summarized in Figure 6, is discussed in detail by Sieh [1977, pp. 79–84].

The entrenchment of Pallett Creek at its crossing of the San Andreas fault resulted in dewatering of an 8-m-thick section of faulted late Holocene peats and clastic sediments. Figure 7 illustrates the excavations at the study site, where the upper 4–5 m (1400 years) of sediment have been examined.

Radiocarbon dates indicate that the average rate of accumulation of the upper 6 m has been about 3.2 mm/yr. Although the oldest accessible materials (i.e., those lying above the 8-m-deep water table) may have been deposited in about 500 B.C., only the sediments deposited after about 500 A.D. have been studied.

Figure 8 is a generalized columnar section of the various deposits. Strata are numbered from 26 to 98, from bottom to top of the section, to facilitate discussion. Numbers that are multiples of 10 indicate groups of strata. Radiocarbon dates are given with a statistical uncertainty of 1 standard deviation (σ) and have been converted from radiocarbon years to absolute years (Table 1) by using the calibration of Damon et al. [1972]. If there is more than one date determination for a stratum, the dates (A, B, ...) and their standard deviations (σ_A, σ_B, ...) have been statistically combined as suggested by Long and Rippeteau [1974] to give an average date:

\[ \text{Date}_{\text{ave}} = \left( \frac{A^2}{\sigma_A^2} + \frac{B^2}{\sigma_B^2} + \cdots \right)^{-1} \left( \frac{1}{\sigma_A^2} + \frac{1}{\sigma_B^2} + \cdots \right)^{-1/2} \]

(1)

\[ \sigma_{\text{ave}} = \left( \frac{1}{\sigma_A^2} + \frac{1}{\sigma_B^2} + \cdots \right)^{-1/2} \]

(2)

Historical Deposits

The uppermost unit in the section (gravel unit 98) must predate 1930 by at least a decade or 2. This can be deduced only the figures and figure captions in the following rather lengthy sections (2 and 3) and then proceed to the last two sections (4 and 5).

Fig. 2. Right lateral offsets along the San Andreas fault associated with the great 1857 earthquake, from Sieh [1978]. Solid lines and heavy dots indicate locations of data points. Light dots indicate interpolated values. Near Pallett Creek, offsets in 1857 ranged between 3 and 4 m.

Fig. 1. The San Andreas fault has been the source of two great earthquakes since the arrival of white men in California in 1769. The first occurred in 1857, and the second in 1906. The fault rupture associated with the 1857 earthquake extended more than 250 km to the northwest and at least 25 km to the southeast of Pallett Creek [Sieh, 1978]. LA is Los Angeles, and SF is San Francisco.
from aerial photographs taken in 1930 and 1940. The 1940 photographs show that the greatest flood on record in the area (March 2, 1938) [Butler et al., 1966, p. 24] removed the large trees shown in the gorge on the 1930 photographs. In addition, the 1940 photographs show fresh 1938 (?) gravels on the gorge floor but none on the top of the terrace. Apparently, then, no deposition occurred on the terrace during the greatest discharge of the past 60 years. The large diameters of many trees in the gorge now and the flood records for neighboring drainages exclude the possibility of any overbank deposition since 1938.

Large trees that are visible in the gorge on the 1930 aerial photographs preclude the possibility that a flood overtopped the gorge during the decade or so prior to 1930. A broken bottle found in unit 98 indicates that the unit must be post-1895, however, because the quality of the glass indicates that the bottle was produced after 1895 (bottle shop owner; Littlerock, California; personal communication; 1976). Thus unit 98 was probably deposited sometime between 1895 and about 1915.

A silty unit underlying unit 98 contains many willow branches, some of which may be in the position in which they grew (all plant identifications are by V. Page, Biology Department, Stanford University). These are probably the buried remnants of the 'willow thicket' noted by the 1904 land surveyor (see Figure 6).

A discontinuous and thin peat mat which occurs at the top of silty unit 88 (Figure 8) is the youngest horizon that could be correlated with the 'swamp' recorded at the site by the 1855 land surveyor (see Figure 6). Unit 81 has a radiocarbon date of 1725 ± 55 A.D. Even if the actual date is 1725 + 2σ (i.e., 1835), the marsh producing the peat of unit 81 probably existed prior to the 1855 marsh. Thus the 1855 marsh deposits are probably present within or at the top of unit 88. This implies that the 1857 event, less than 2 years after the 1855 survey, must have occurred during or at the end of deposition of unit 88. Judging from the historical seismicity the 1857 event is the latest large event associated with fault displacements at Pallett Creek. The nearest moderate historical earthquake (July 22, 1899) occurred about 40 km to the southeast, and its intensity distribution precludes the possibility of major fault rupture at Pallett Creek. Later in this paper the latest seismic disturbances and faulting of the Pallett Creek section are shown to have occurred at the end of deposition of unit 88. An argument can be made, then, that the date of the top of unit 88 is 1857 A.D.

The Peats

The peats in the section are an assortment of freshwater marsh plant remains, as indicated by pollen (J. West, written communication, 1977) in units 26, 33, 38, 47, and 81 and by plant remains in units 26 and 78 (V. Page, written communication, 1977) [Sieh, 1977, Appendix V]. West writes that in the peats there are relatively high values of Cyperaceae [sedge] pollen. These are most likely representative of Scirpis [Bulrush, Tule] and Cyperus [Umbrella Sedge] .... All the [peat] samples have Cyperaceae values sufficiently high to suggest that they are representative of a series of very shallow fresh-water tule-Cyperus marshes. .. the marshes were quite shallow (50-350 mm) when [or if] they did contain standing water .... In unit 26 two charred seeds of Cyperus cf. acuminatus were noted. Cyperus spp. usually like wet places but are not commonly found growing in water.

A detailed description of these plants is given by Munz [1974]. Wood fragments in the section indicate the prehistoric presence of the same willow, pine, cedar, and juniper genera that are present upstream in the Pallet Creek drainage today (V. Page, written communication, 1977).

The Clastic Deposits

Several thick gravel units (43, 53, 55, 93, and 98) in the section indicate that large floods have buried the marsh on occasion during the past 2000 years. Units 93 and 98 indicate historic floods, and units 53 and 55 indicate floods about 1000 years ago. As might be expected for such deposits, thickness and facies characteristics of these gravels vary considerably at the site. Locally prominent inverse grading suggests that the units were deposited as debris flows, but prominent laminations elsewhere indicate a fluvial origin. None of the gravels or
other fluvial units have cut far into its substrate, so no older units appear to have been eroded out of the section.

Several finer-grained units in places display flow structures. Units 34 and 39 locally contain internal scour and fill and other bed forms indicative of an upper flow regime. Sands of unit 73 contain small climbing ripples, indicative of a low flow regime, and planar lamination.

The wide distribution, uniform grain size, and great uniformity in thickness of several thin silt beds suggest they are aeolian deposits. Unit 71 is perhaps the best example. In almost all exposures this powdery, punky, structureless silt is about 30 mm thick. It mantles scarps and irregular topography without change in thickness. That it accumulated slowly is suggested by the scattered occurrence of a peat stringer about
1 mm thick within the silt. Units that are also aeolian probably include the lower parts of units 34, 39, and 43 and the silts of units 70 and 88 and uppermost unit 50.

A rate of peat deposition (1.4 mm/yr ± 18%) and a rate of silt deposition (1.9 mm/yr ± 32%), which are derived later in the paper, can be used to discern major unconformities within the sedimentary section. The total thickness of peat and silt deposited since about 110 A.D. is about 2.5 m. This represents 1400 (plus or minus several hundred) years, or all but perhaps a few hundred years of the 1800 years represented by the section.

Where might there be major unconformities, then? The most apparent one is the modern surface, which has been inactive for 60-70 years. Others might be (1) between unit 38 and unit 41, where too little silt accumulated to account for the approximately 200 years between deposition of units 38 and 41 and (2) between units 61 and 68. There are few other clues to the stratigraphic locations of other possible unconformities. It is unlikely, however, that any unrecognized unconformities represent as much as a century of nondeposition.

Discussion of these and other phenomena pertinent to the seismic history of the area follows, with the evidence for older events considered first. Evidences for seismic activity have a three-part label on exposures 1-11b. For example, in the label 'F-11-1' the event with which the feature is identified is shown by the letter (F), the exposure in which the feature occurs is shown by the middle number (11), and the individual number of the feature (lower numbers appear nearest the left of the exposure, and higher numbers nearer the right of the exposure) is shown by the last number (1).

Letter designations were assigned to events in the course of field studies, and so, although earlier letters indicate earlier events, letter assignments are not continuous from A to Z. The following detailed discussions of evidence documented in the various exposure maps will be easier to follow if the exposure maps (in pocket at back of journal) are laid out for quick reference in front of the reader.

Event F

Several features in exposures 7, 10, 11, and 11a document the eruption of large sandblows during the time between deposition of units 38 and 41 (see Figure 8). Each of the features includes a pit several tens of centimeters deep and wide excavated into units 34-38. The pit is filled with well-laminated silts and fine sands which generally coarsen gradually upward. These sediments are nearly devoid of recognizable fragments of the surrounding host sediment. The fine sands near the top of the pit are continuous with fine sands overlying a severely disturbed silt (basal unit 39). Some of these sands have structures indicating upper flow regime conditions of deposition, and in two places the sands form constructional cones. Clastic dikes or pipes may connect with the base of all the pits, but this is observed in only one favorably exposed case. These features appear to have resulted from the extrusion of liquefied silt and sand from some depth in the section.

Sandblows. Sandblow deposits are well-known earthquake phenomena. The terms 'sand boil,' 'sand crater' or 'sand craterlet,' and 'sand volcano' also have been used to describe such features. Here 'sandblow' will refer to the active, spouting phenomenon. 'Sandblow deposit' will refer to the sedimentary evidences of the phenomenon. Sandblows and their deposits have been observed after many earthquakes of $M \geq 5$. Recent
Fig. 6. Historical geological changes at the Pallett Creek site. At the time of the first land survey (1855) a swamp occupied the site. Later maps and surveys indicate the presence of springs and a willow thicket at the turn of the century. Floodwaters between then and about 1915 excavated the gorge, which has since been widened considerably as shown by the dot patterns. The creation of the gorge resulted in a lowering of the water table and drying up of the swamp and thicket. Today the gorge itself is full of large cottonwood and willow trees, but the rest of the site supports desert plants.
Fig. 7. Block diagram showing the excavations at the Pallet Creek site. View is toward the northwest from above Pallet Creek gorge at 'site' indicated in Figure 6. Mapped exposures referred to in this paper are numbered 1–11b. All elevations are relative to an arbitrarily chosen point at the site which was assigned an elevation of 100 m. The pair of thick black units shown in the exposures and along the natural wall of the gorge are units 61 and 68.
Fig. 8. Stratigraphic column and legend for the Pallet Creek deposits. The deposits consist of peats deposited in a marsh environment, aeolian silts, and fluvial sands and gravels. Radiocarbon ages determined for many of the peats are to the left, and numbers assigned to distinctive units and groups of units to facilitate reference are to the right of the column. The radiocarbon dates indicate an average rate of deposition of about 0.3 m/century. The legend on the right side of the figure serves as a legend for all exposure maps (in pocket).

The dimensions of sandblow deposits span several orders of magnitude. In San Fernando in 1971, sand forming small (0.1- to 1.0-m diameter) isolated cones was extruded through small cracks several millimeters wide (T. L. Youd, personal communication, 1976). In the Mississippi River Valley in 1811-1812, sandblow cones attained diameters of several tens of meters and were fed by vents more than 2 m wide [Morse, 1941]. Often the features are aligned, suggesting eruption along fissures or faults [e.g., Bolt, 1974, Figure 8]. In some instances, so much sand has been extruded that the entire surface of the ground has been blanketed by a meter or more of sand [e.g., Oldham, 1899, Plate 11]. Large craters in the ground surface...
TABLE 1. Pallett Creek Radiocarbon Samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>Pallett Creek</th>
<th>Laboratory</th>
<th>Stratigraphic Unit</th>
</tr>
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<tbody>
<tr>
<td>PC-2</td>
<td>UW-347</td>
<td>81</td>
<td>1840 ± 80</td>
</tr>
<tr>
<td>PC-56B</td>
<td>USGS-144</td>
<td>81</td>
<td>1760 ± 50</td>
</tr>
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<td>PC-62</td>
<td>USGS-136</td>
<td>72</td>
<td>1490 ± 60</td>
</tr>
<tr>
<td>PC-67</td>
<td>USGS-137</td>
<td>upper 1-2 cm of 68</td>
<td>1630 ± 60</td>
</tr>
<tr>
<td>PC-17</td>
<td>I-9588</td>
<td>upper half of 68</td>
<td>1400 ± 80</td>
</tr>
<tr>
<td>PC-21</td>
<td>I-9591</td>
<td>lower half of 68</td>
<td>1435 ± 80</td>
</tr>
<tr>
<td>PC-6</td>
<td>UW-?</td>
<td>61</td>
<td>1250 ± 90</td>
</tr>
<tr>
<td>PC-18</td>
<td>I-9589</td>
<td>61</td>
<td>1315 ± 80</td>
</tr>
<tr>
<td>PC-10</td>
<td>USGS-84</td>
<td>lower half of 61</td>
<td>1150 ± 60</td>
</tr>
<tr>
<td>PC-28</td>
<td>I-9607</td>
<td>53</td>
<td>840 ± 80</td>
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<td>PC-27</td>
<td>I-9606</td>
<td>51</td>
<td>1115 ± 90</td>
</tr>
<tr>
<td>PC-12</td>
<td>USGS-83</td>
<td>49</td>
<td>820 ± 45</td>
</tr>
<tr>
<td>PC-11</td>
<td>USGS-82</td>
<td>47</td>
<td>930 ± 50</td>
</tr>
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<td>PC-29</td>
<td>I-9608</td>
<td>47</td>
<td>1365 ± 80</td>
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<tr>
<td>PC-64</td>
<td>USGS-138</td>
<td>upper 1 cm of 45</td>
<td>820 ± 65</td>
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<td>PC-5</td>
<td>UW-349</td>
<td>upper 43</td>
<td>665 ± 85</td>
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<tr>
<td>PC-26</td>
<td>I-9605</td>
<td>lower 43</td>
<td>470 ± 80</td>
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<td>PC-25</td>
<td>I-9592</td>
<td>lower 43</td>
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<td>USGS-139</td>
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<td>PC-57</td>
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<td>PC-59</td>
<td>USGS-142</td>
<td>lowest 1 cm of 26</td>
<td>120 ± 50</td>
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<tr>
<td>PC-4</td>
<td>UW-348</td>
<td>4 m below top of terrace</td>
<td>90 ± 90</td>
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|      |      |      | 1770 ± 90         |
|      |      |      | 1700 ± 65         |
|      |      |      | 1465 ± 80         |
|      |      |      | 1465 ± 80         |
|      |      |      | 1590 ± 80         |
|      |      |      | 1430 ± 85         |
|      |      |      | 1420 ± 85         |
|      |      |      | 1250 ± 90         |
|      |      |      | 1310 ± 85         |
|      |      |      | 1225 ± 45         |
|      |      |      | 830 ± 90          |
|      |      |      | 1120 ± 100a       |
|      |      |      | 850 ± 55          |
|      |      |      | 955 ± 60          |
|      |      |      | 1340 ± 85         |
|      |      |      | 845 ± 75          |
|      |      |      | 695 ± 90          |
|      |      |      | 510 ± 80a         |
|      |      |      | 320 ± 90a         |
|      |      |      | 820 ± 70          |
|      |      |      | 600 ± 80          |
|      |      |      | 900 ± 85a         |
|      |      |      | 600 ± 80          |
|      |      |      | 510 ± 75          |
|      |      |      | 565 ± 55          |
|      |      |      | 110 ± 60          |
|      |      |      | 80 ± 100          |

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<th>Best Estimate or Averaged</th>
<th>Comments</th>
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<tr>
<td>1725 ± 55</td>
<td>Peat</td>
</tr>
<tr>
<td>1470 ± 50</td>
<td>Peat; PC-67 separated from main body of unit 68 by silt several centimeters thick</td>
</tr>
<tr>
<td>1225 ± 45</td>
<td>Peat</td>
</tr>
<tr>
<td>80 ± 90</td>
<td>Small wood fragments, some possibly bark</td>
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<tr>
<td>1120 ± 100a</td>
<td>Charcoal</td>
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<tr>
<td>850 ± 55</td>
<td>Peat</td>
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<tr>
<td>955 ± 60</td>
<td>Peat</td>
</tr>
<tr>
<td>1340 ± 85</td>
<td>Peat</td>
</tr>
<tr>
<td>845 ± 75</td>
<td>Peat</td>
</tr>
<tr>
<td>695 ± 90</td>
<td>Pinus (lambertiana?) wood from large trunk or branch</td>
</tr>
<tr>
<td>510 ± 80a</td>
<td>Small wood fragments</td>
</tr>
<tr>
<td>320 ± 90a</td>
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<td>565 ± 55</td>
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<tr>
<td>110 ± 60</td>
<td>Peat</td>
</tr>
<tr>
<td>80 ± 100</td>
<td>Cedar or juniperf branch (~8 cm in diameter)</td>
</tr>
</tbody>
</table>

*USGS is the U.S. Geological Survey, Menlo Park, California. UW is the University of Washington, Department of Chemistry, Seattle, Washington. I is Teledyne Isotopes, Westwood, New Jersey.

øHalf-life (t/) is 5570 years.

cCalculated from tables of Damon et al. [1972]; all dates rounded to nearest 5 years.

dCalculated from (1) and (2).

eThere is no stratigraphic indication of a long hiatus between the deposition of unit 49 and unit 51. Also, contrary to the implication of the date, there is a stratigraphic suggestion of a long period of time between the deposition of unit 51 and unit 61. Therefore the date is suspect.

fThis date conflicts with all surrounding dates and is therefore suspect.

*gSee Sieh [1977, Appendix V].

*hThese dates are older than surrounding dates and are therefore suspect. If they were derived from old trees, they may be good dates, but they may be older than the stratum in which they were deposited.

unaccompanied by large volumes of extruded sand and a constructional cone also have occurred [e.g., Morton and Campbell, 1973].

Typically, the eruption of the sandblow occurs a minute or more after the seismic shaking begins [Scott and Zuckerman, 1973]. The eruption is characterized by a fountain of water and sand playing for minutes or hours over the vent or fissure from which it is issuing. Usually, sandblows occur in regions of near-surface water tables and recent sedimentation. The experiments of Scott and Zuckerman [1973] indicate that the formation of sandblows involves the liquefaction of a subsurface layer. The overpressured fluid reaches the ground surface by mechanical assimilation of the overlying sediments.

The following detailed descriptions of sandblow features at Pallett Creek are critical for an understanding of the processes involved in their formation.

In exposure 7 a body of micaceous sand rimmed with silt and clay interrupts units 34-38 (F-7-1). The sand forms a cone above these older units. A cross-bedded fine sand unit overlies the northeast flank of the cone above these older units. A cross-bedded fine sand unit overlies the northeast flank of the cone and thins to its terminus 2 m northeast of the center of the cone (the slip after deposition of unit 41 along two faults can be restored and ignored for this discussion). A coarser, locally pebbly sand blankets the entire section, thinning to a feather edge 3 m northeast of the cone. The great extent of this...
Fig. 9. Fence diagram of Pallett Creek exposures 1, 2, 5, 7, 10, and 11 reveals the major features encountered at the site as well as a host of smaller, more localized features. The exposure maps (in pocket) show much more detail than is shown here.
coarser unit in other excavations suggests that it was fluvially derived. In the plane of excavation 7 the three units compose a wedge 3 m long and more than ½ m thick over the vent.

The circular vent 100 mm in diameter from which the sand was extruded is bisected by the plane of exposure 7. Excavation of the loose sand within the pit revealed that the vent has a main trunk with several very short, narrower blunt-nosed pipes penetrating horizontally into the silt and clay of the lower portion of the pit. This may indicate that as the liquefied materials mechanically assimilated a path through the overlying sediments, several pathways were actively eroded toward the ground surface. When one broke through the ground surface, the other pathways may have become inactive, and the rapid removal of sand may have widened the pipe which had reached the surface.

Further excavation of exposure 7 revealed the geometry of the sandblow deposit in three dimensions. Perpendicular to the plane of exposure 7, the pit in units 34, 36, and 38 diminishes in depth. One-half meter to the northwest (behind the face of exposure 7), the pit is about as deep as it is in exposure 7 but has no vent piercing its base or sides (Figure 10). Notice the gradual upward coarsening of the dark organic silts into light, fine micaceous sand. Nearly 1 m behind the face of exposure 7 the pit is only half as deep. The three-dimensional pit shape can be imagined as a canoe 3 m long oriented nearly perpendicular to the exposure; it is deepest at the vent and higher on the left than on the right. The sand composing the cone exposed in excavation 7 was extruded along a fault formed just prior to eruption. This fault is indicated by a difference of about 300 mm in elevation of the unit 38 peat across the sand body after one makes a mental restoration of post-unit-41 faulting (see exposure 7). The fault plane in the exposure was destroyed by the excavation of the sandblow pit immediately below the cone. Thus the faulting preceded the pit formation, although perhaps by no more than a few minutes, and the downthrown block received most of the extruded sand.

Between the extruded sand that composes upper unit 39 and the peat of unit 38 in exposure 7 is a contorted silt layer. Although the silt is locally well laminated, it generally displays disturbed structure. Small open and closed folds and flamelike structures are common. Similar structures have developed in unconsolidated saturated lake sediments subjected to seismic shaking [Sims, 1973, 1975]. Thus seismic shaking may have preceded the ejection of the sandblow deposit.

The relationships of various facies within the sandblow deposit are important in understanding the evolution of this sandblow. In the exposure 7 record the fine micaceous sand composing the cone and filling most of the pit surrounds an angular body of silt. Similar silt and clay form a liner, a few tens of millimeters thick on the edges of the pit and thicker at the base of the pit. This silt and clay unit is pierced by the sand-filled vent. Behind the mapped exposure the well-laminated silt and clayey silt that interrupts units 34–38, (2) a large wedge of sand that shows dune or antidune bed forms and thins and flows southward away from a vent above the plug, and (3) a thinner body of sand north of the plug. The plug disappears only ½ m behind (southeast of) exposure 7, is deepest in exposure 11a, and is very nearly parallel to a major fault. As at F-7-1, there is evidence for faulting and seismic shaking just prior to sandblow deposition, and there is additional evidence bearing on the nature of emplacement of the pit sediments.

Another feature that may be related to the extrusion of liquefied materials occurs in exposures 11 and 11a. F-11-1 and F-11a-1 are about 1 m apart on opposite walls of trench 11. Essentially, they are transverse cross sections through a body similar in general form to the F-7-1 sandblow feature. In general, this feature consists of (1) an inclined tabular plug of laminated silt and clayey silt that interrupts units 34–38, (2) a large wedge of sand that shows dune or antidune bed forms and thins and flows southward away from a vent above the plug, and (3) a thinner body of sand north of the plug. The plug disappears only ½ m behind (southeast of) exposure 11, is deepest in exposure 11a, and is very nearly parallel to a major fault. As at F-7-1, there is evidence for faulting and seismic shaking just prior to sandblow deposition, and there is additional evidence bearing on the nature of emplacement of the pit sediments.

In exposure 11, unit 38 has a vertical separation of about 500 mm. Unit 41, overlying the sandblow deposit, has a vertical separation of only about 300 mm. This difference cannot be explained by lateral offset of units with different dips, since both units have an apparent dip of about 1° parallel to the fault in trench 11. Thus slip apparently occurred between the deposition of units 38 and 41.
Relationships in F-11-1 supply additional evidence for fault slip just before or during sandblow deposition. In the cross section of exposure 11, two blocks of units 36–38 occur between the pit and the main fault trace. The block nearest the pit appears to have slid into the pit sometime after the lower-most 50–100 mm of the pit had been filled with silty clay, clayey peat-rich silt, and charcoal-rich silt. This suggests that a fresh, unstable fault scarp existed during deposition of materials within the pit.

Vents. The source of the sandblow deposit in exposures 11 and 11b is not obvious. A sand-filled crack 10 mm wide bisecting the F-11-1 body (see exposure 11) may have been filled from above after deposition of the sandblow materials. The wide sand-filled crack overlying the plug and interrupting the laminated sands of F-11a-1, however, almost certainly is a sandblow vent. It has irregular vertical laminations in the sand filling the crack, nonmatching crack walls, and a circular plan view. Nevertheless, the vent could not be traced downward into the plug of silts and clayey silts. Perhaps the lower portion of the vent was destroyed during excavation of the trench.

F-11a-3 is another sandblow feature. The plug of silt and clayey silt widens into the wall of the exposure, suggesting that the pit was a circular feature. Only the edge was intersected by the excavation. No obvious vent was found to penetrate the plug, yet it appears that a cone of extruded sand rests over the plug.

The silt plug. The geometries and relationships of various facies within the sandblow deposit F-11-1/F-11a-1 are puzzling but must be considered in the discussion of the creation of the deposit. F-11-1 has a partial lining of chaotic deposits in its base (exposure 11 and Figure 11). These may be fragments of the eroded host material. As in F-7-1, however, the silts and sands filling the pits have no recognizable fragments of the intruded material. The F-11-1/F-11a-1 pit is steeply inclined and at least 1½ m long, yet the unconsolidated water-saturated slab of overlying sediments did not collapse into the pit before it was filled. In fact, exposure 11 shows that the peat of unit 39 and the overlying silt of unit 39 were undermined about 250 mm, yet these thin overhanging units did not collapse into the pit. This also occurred in pit F-11a-3 at point F-11a-4. F-11a-3 and F-11a-4 show tongues of clayey silt and silt probing into the host materials yet without incorporation of recognizable fragments of the host materials. Also the basal silt of unit 39 and the unit 38 peat appear to be intricately intercalated with the deposits of F-11-1 (Figure 11), F-11a-1, and F-11a-3.

The features shaped like kettle drums labeled F-10-1 and F-10-2 are two more sandblow phenomena. Unlike the features just discussed, F-10-1 and F-10-2 are not associated with a constructional cone. In fact, unit 41 is depressed over the two features. Apparently, too little material was extruded to construct a cone over these large pits or bowing of the ground surface at the time of event F allowed extruded sand to be deposited away from the vent area. Units 34–38 are continuous on the opposite ( unmapped) wall of the excavation about 1 m to the northwest. Likewise, these units were found to be continuous only ½ m southeast of exposure 10. Thus the two pits are roughly circular in plan view, with diameters of about 1 m. Although no vent pierces the silt to sandy fill of either pit in the plane of the exposure, the wall of the exposure may be one side of the vents. These two pits are also filled with well-laminated silts and sand that coarsen upward. A broken peaty unit between the pits is undercut by the northeastern pit.

Creation and filling of the pits. Several observations are pertinent to discussion of the processes of formation of the pits that have been described:

1. The sediments coarsen upward, generally from dark brown peat- and charcoal-rich clayey silt through fine sandy silt and silty fine sand into fine sand. Where the coarsening is gradual, it suggests rather continuous deposition of gradually coarsening materials; where it is relatively abrupt, a two-stage depositional process might be invoked.

2. The silts, clayey silts, and sandy silts filling the pits constitute a relatively small percentage of the total volume of extruded materials.

3. Two of the pits are tabular and aligned along fault planes. It is hard to conceive of pits of such shape being explosively excavated by forces concentrated at the top of a vent 100–200 mm in diameter.

4. Pit boundaries are very sharp, although locally, they are very irregular and extend into the host materials as wedges and tongues. Although in large part the pits may have been explosively excavated, substantial additional erosion by the turbulent movement of water and liquefied materials within the pit after the explosive excavation is probably responsible for the clean but irregular boundaries.

5. Few fragments of the surrounding materials are incorporated within the pit sediments. Most host material must have been either removed from the pit or so thoroughly disarticulated and homogenized as to be unrecognizable in the pit sediments. Although the lowest parts of the pits contain peat and charcoal fragments probably derived from host or underlying materials, the complete absence of any pebbles from unit 34 implies that the former explanation may be correct.

6. The silty sand and sandy silts of the pits in exposures 11 and 11a are intercalated with unit 39 and basal unit 39 at the lip of the pit (Figure 11). The laminae of sand and silt interleave or intrude the irregular laminae of the deposits of units 38 and 39.

7. Thin slabs of unit 38 and basal unit 39 overhang the pits at a few sites. These un lithified water-saturated sediments probably would not have had sufficient coherence or strength to maintain such positions if the pits had been filled merely with air or water prior to pit sedimentation. Perhaps then the pit sediments were emplaced as slurries immediately after excavation of the pits. However, it is difficult to envision lamina-
tion and sorting of sand and silt under such conditions of deposition.

8. The silt and sand laminae are regular, nowhere convoluted or irregular, and typically terminate abruptly at the pit walls. This might argue against deposition as slurries and in favor of deposition in quiet water. Such a history would require two large seismic events, the first resulting in creation of the pits and followed by hours, days, or months of quiet deposition of silt and clayey silt. The second seismic event would have resulted in deposition of the sandy portions of the sandblow deposits.

One of the least implausible explanations for the observed features and relationships has the action starting with a strong earthquake accompanied by surface faulting. Basal unit 39, lying at the surface of the marsh, undergoes soft sediment deformation. A fine sandy layer at some depth liquefied after the onset of heavy shaking. Overpressured water in the liquefied sand layer begins to assimilate mechanically or to fracture overlying silty and peaty materials hydraulically, and a pipe or sheet of fluidized materials grows upward along the fault plane; the materials in the pipe or sheet are predominantly assimilated silts and peats secondarily liquefied by the rising overpressured water. Upon reaching a point about 1 m below the marsh surface, the overpressured water overcomes the overburden pressure, and a crater is explosively excavated in the ground surface. The fluidized materials high in the pipe or sheet are the assimilated peats and silts. The circulating slurry of these materials (1) rapidly erodes the greater part of the pit, removing most of the host materials, and (2) is then deposited in the excavated pit. The liquefied fine sands follow the finer materials up the vent and works through the finer pit deposits, eroding onto the ground surface. Bed forms of the upper flow regime suggest that the sand is ejected with large volumes of water. A fountain spouts over the vent for several minutes or hours before gradually ceasing to flow.

**Evidence for fault slip synchronous with the sandblows.** Several localities show evidence of fault slip synchronous with the sandblow activity. Dip-slip movement on a fault synchronous with the formation of F-11-1 has been described above. Several minor faults appear to have slipped at this time also. Units 34–39 are separated more than unit 41 along F-7-2. Unless the difference is due to offset of beds of different orientation, this indicates slip subsequent to the extrusion of sandblow F-7-1, perhaps in response to the evacuation of subsurface material in order to create the sandblow. Fault F-10-3 appears to have slipped after deposition of unit 38 and the basal silt of unit 39. It does not offset the sand of unit 39, F-5-1 is a complicated fault zone which disrupts all units below unit 39 but disturbs none from unit 39 up. Unit 38 is thrust over itself, and an older peat is tightly folded on top of unit 38. Complications seen in this fault zone at and below the 94-m level are related to a 1-m-diameter plug of sand and sandblow cone a few hundred millimeters behind the plane of the mapped exposure. The massive oval body in the exposure record is a part of the silt shell surrounding that unexposed body that was produced during event F.

Substantial slip on the main fault probably occurred during event F (that is, between deposition of units 38 and 41). The relationship of unit 38 to overlying units 41–47 in exposure 5 (F-5-2) establishes this. Unit 38 displays a large dip away from the main fault zone. Units 45 and 47 show only a slight dip. Units 41–47 merge toward the main zone with unit 38. This appears to reflect local warping of the ground surface near the fault between the time of deposition of units 38 and 41. This warping is probably indicative of movement on the main fault during event F.

**Event D**

Although exposures of materials older than unit 38 are relatively limited, the northern half of exposures 11 and 10 display enough older stratigraphy to reveal at least one event that occurred prior to event F. This will be called event D. Several small faults related to event D occur in exposure 10 below unit 34. D-10-1 displaces all units exposed below unit 34 about 50 mm and terminates upward at a degraded scarp at the top of unit 34. D-10-2 and D-10-3 displace older units as much as 200 mm but cannot be traced through unit 34. D-10-6 is a group of faults clearly offsetting all units exposed below unit 34 but not affecting the younger craters of event F above. Together the apparent vertical slip on these faults is less than 1 m. Perhaps the 300-mm change in thickness of unit 34 across the F-10-6 fault zone in exposure 10 is an indication of the apparent vertical slip.

Near the faults in exposure 10 is evidence that unit 34 is a sandblow deposit. Two silty plugs (D-10-5) pierce unit 33 and lower unit 34. They are part of a pit through which unit 34 apparently was extruded. D-10-4 is a silty clayey flare originating in D-10-5 and penetrating the sand of unit 34. Immediately to the left are nearly vertical laminations in unit 34. The steep laminations of D-10-4 and D-10-5 indicate nearly vertical movement of materials.

**Event I**

Unit 46 appears to be a sandblow deposit extruded during an event hereinafter termed event I. The unit occurs locally as lenses, wedges, and irregular bodies of silty fine sand (exposures 10, 10a, 11, and 11b) between units 45 and 47. I-10-1 is the largest body of unit 46. Silt near the main fault trace with vertical laminations (Figure 12) suggests a vent nearby. A small crack in unit 45 only about 100 mm southwest of the fault appears to have been a minor route of evacuation. The sand and silt body thins to a feather edge about 4 m southwest of the fault. About 1 m from the vent it was deposited over a small fault in unit 45 (I-10-2); I-2 to 2 m from the vent it buried the highly deformed surface of unit 45 (I-10-3). This deformation may indicate seismic shaking of at least Modified Mercalli intensity V or VI [Sims, 1973, p. 63]. About 3 m from the vent the extruded sand buried a 150-mm-high fault scarp (I-10-4). The fact that the fault displaces all older deposits by the same amount indicates that slip occurred either during or just before the sandblow occurred. A few more tens of millimeters of slip occurred soon after burial of the fault by unit 47 or 49.

Units 45–47 in exposures 11 and 11b display stratigraphic and structural complexity. The soft upper surface of unit 45 is deformed in three places (I-11-3, I-11-6, and I-11-7). Several minor breaks in unit 45 do not extend upward into unit 47 (I-11-5, I-11-7, and I-11-9). Many small pods and lenses of fine sand occur between units 45 and 47. These lenses and pods are discontinuous not only in the direction of the exposure but also perpendicular to the exposure, since very few are on the opposite side of the trench. The large sand body (unit 46) southwest of the fault in exposure 11b, for example, is but a small sliver across the trench in exposure 11. It is difficult to conceive of fluvial or aeolian deposits with these geometric relationships. The stratigraphic association of these pod- or wedge-shaped bodies with soft sediment deformation, minor
faults, and the large sandblow wedge (I-10-1) suggests that they might be sandblow deposits.

The sandblow deposits of event F (unit 39) may be the source for at least some of the sandblow deposits of event I. I-10-5, which appears to originate in unit 39, the event F sandblow deposit, may be representative of fissures through which the small deposits were extruded. In exposure 10, unit 39 is thinnest directly below the thickest portions of I-10-1. The volume needed to restore unit 39 to its 'normal' thickness is approximately equal to the volume of I-10-1. Although this may be a mere coincidence, the temptation is to conclude that unit 39 was liquefied again during event I and was redeposited as I-10-1.

Movement on a main fault trace during event I cannot be unequivocally demonstrated, but two lines of evidence suggest such movement:

1. Vertical separation of unit 45 at I-10-1 is greater than the vertical separation of unit 47. This suggests that at least one more increment of slip has been experienced by unit 45 than by unit 47. Alternatively, this apparent slip difference might be due to horizontal slip juxtaposing a section in which unit 46 was deposited against a section in which it was not deposited (Figure 13a), or the extrusion of unit 39 onto the surface might have caused nontectonic slip on the main fault (Figure 13b).

2. I-10a-2 suggests that a scarp may have existed on the main fault trace when unit 47, but not unit 45, was deposited. The top of unit 46 swings sharply upward at the fault, and unit 47 seems to have been deposited upon unit 46 in response to this condition. By the time of deposition of basal unit 50, this scarp was buried, and units were being deposited horizontally across the scarp. It is important to emphasize that in this particular case the evacuation of the liquefied subsurface unit might have produced nontectonic slip on the main trace of the fault (Figure 13b).

Event N

Indications of a large deformation near the fault in exposure I strongly suggest movement on the main trace of the fault after deposition of unit 52. Units 45–53 southwest of the fault tilt steeply away from the fault (N-1-5). Because the overlying portions of unit 50 thin toward the fault, it can be concluded that the deformation took place before their deposition. This effect and accompanying effects indicate event N.

A wedge of rubble overlies unit 52 southwest of the main fault (N-1-6). The rubble inter fingers with gravel of units 53 and 55, suggesting that it was deposited gradually after deposition of unit 52. Burrows suggest that the rubble may be part of a ground squirrel mound. Alternatively, the rubble unit may be a breccia formed at the base of an event N fault scarp. If so, it is not extensive along the fault. Less than 1 m to the northwest, in exposure 3, the rubble (N-3-1) occupies the same stratigraphic position but is only 100 mm thick, is not pebbly, and grades imperceptibly into the pebbly gravel of unit 53. Because the rubble overlies a major break within the main fault zone (exposure 3) and is associated with a large warp near the fault (N-1-5), event N probably represents major slip along the San Andreas fault at this locality.

Supporting data for an event N are numerous minor faults and fractures in exposures 1, 3, and 11 (N-1-2, N-1-3, N-3-2, N-3-3, N-11-1, N-11-2, and N-11-3) that break units 52 and below but are overlain by the gravel of unit 53. Soft sediment...
deformation also is associated with event N. N-11-4 and N-11-5 are flexures in unit 52 that developed before deposition of unit 53. More impressive are unmapped sinusoidal folds in units 45–52 exposed in the gorge wall at the southwest end of trench 11 (Figure 7 shows the location of the gorge wall). These extend nearly parallel to the fault for about 10 m along the gorge wall. Their amplitudes are about 100 mm, and their wavelengths are about 400 mm. They are overlain by apparently undisturbed gravel of unit 53.

**Event R**

Event R is based upon three exposures which contain evidence that strike-slip faulting occurred prior to deposition of peat unit 61. At all three localities a 150- to 300-mm southwest trench l (Figure 7 shows the location of the gorge wall). Characteristics has occurred. At location R-11-1, near the northern end of exposure 11, a major fault terminates upward in a hard clayey silt. Different facies across the fault there show significant lateral slip on the fault (for example, units above 55 and units 45–49).

A 230-mm scarp formed just prior to deposition of unit 61 at exposure 7 (refer to Figure 9). Lateral offset created facies differences across the fault. The silt of uppermost unit 50, displaced downward on the southwest side of the fault, has no equivalent across the fault. This suggests that it was eroded from the upthrown block before deposition of unit 61. Unit 61 was deposited over a very broad scarp remaining from event R. This is not apparent unless one views unit 61 parallel to the plane of the exposure.

Another fault, visible in the bulldozer cut (Figure 14), also moved during event R. All exposed units below unit 61 are offset about 300 mm along this fault, which implies that the fault moved only once. As in exposure 7, unit 61 was deposited across the very broad eroded scarp of this fault.

**Event T**

Disruption along the main fault trace and evidence of liquefaction are the principal indicators of event T, which occurred just after deposition of the peat of unit 61. T-2-1 is a fissure that opened along the main fault during event T and was later filled. The northeastern boundary of the fissure is the plane of the main fault trace and thus has slipped again since the fissure formed. The southwestern edge of the fissure, which has not been disturbed since its burial, terminates at the top of unit 61. The fissure is less than 3 m long. It continues only about 1 m to the northwest and continues no more than about 1 m to the southeast, because it does not appear in exposure 3. The lower half of the fissure is choked with peaty silt, rubbly pebbly sand, two fragments of peat, and a fragment of silt. The fragments of peat meet unit 61 in texture and general appearance. These materials probably fell into the fissure shortly after or during its formation. A well-laminated silty sand with festooned cross beds fills the upper half of the fissure and overlies unit 61 to the southwest. Whether this is a fluvial or a sandblow deposit is not known. However, it is too poorly sorted to be aeolian.

Fissures can form along faults unaccompanied by seismic activity. Clark [1972] carefully documented the development of collapse fissures along the Coyote Creek fault well after the fault had experienced seismic slip. Rainwater running into the tectonic fractures at the ground surface eroded large chasms by carrying material downward along the tectonic fractures to the water table tens of meters below. I have found clear evidence of the same process along the San Andreas fault in the Carrizo Plain 200 km northwest of Pallet Creek after heavy rains. There also a deep water table enables downward flow of rainwater along tectonic fractures. The peat of unit 61 at Pallet Creek indicates a water table very near, if not at, the ground surface immediately prior to event T [Sieh, 1977, Appendix V]. Hence it is quite unlikely that piping by water flowing into a tectonic fracture could have produced the fissures observed in the section. Thus the existence of the fissure, T-2-1, suggests that slip on the main trace of the fault occurred at the time of event T.

A small silt- and clay-filled crevasse (T-10-3 and T-10a-1) may also derive from a crack that formed along the fault during event T. The crevasse is overlain by peat. The usual units 61-65-68 sequence is not present at this locality, and it is uncertain whether the peat overlying the crack belongs to unit 61, unit 68, or both. Thus it is not clear whether the crack formed just before deposition of unit 61 or before deposition of unit 68. In any case, its formation would correlate either with event T (before unit 68) or with event R (before unit 61). For two reasons the overlying peat probably belongs to unit 68, and so the crack probably formed during event T: (1) The orange silt and clay filling the crevasse is similar to orange silt and clay mapped elsewhere in exposure 10 under or within unit...
occluded during event T (Figure 16). Erosion of the scarp then occurred. Unit 65 was then deposited upon the remnant of the scarp. During deposition of lower unit 68, an additional 70 mm of slip occurred. This slip after event T may indicate slumping toward the main fault trace rather than tectonic activity.

Several lenses of silt between units 61 and 68 in exposures 1 and 11 may be sandblow deposits of event T (T-1-1, T-1-3, T-1-4, and T-11-1). One lens (T-1-1) is connected to a clastic dike which originates within unit 50. Unit 61 is offset along this dike, but unit 68 is not. In general, unit 61 in exposure 1 is more disturbed by faulting than unit 68, which suggests the occurrence of event T.

**Event V**

The largest vertical separation of any unit ascribable to one seismic event appears in trench 11. About 400 mm of separation occurred on a fault within the main fault zone during event V, between the deposition of units 68 and 71 (V-11-1). In exposure 11b the faulting (V-11b-3) was accompanied by a large amount of warping. That this fault has not been reactivated since event V is evidenced by the unbroken sediments that blanket the fault (Figure 17). A thin blanket of silt (unit 71) covers unit 68 and drapes the fault scarp of event V. This silt is aeolian, judging from its uniform thickness over an irregular topography. Large differences in facies and thickness of subunits of units 40, 50, and 60 across the fault indicate a large amount of horizontal slip on the fault.

The other principal fault break, about 1 m southwest of the fault just described, also slipped during event V. This is implied by the adjacent disruption of unit 68 (V-11-2). In addition, units 71 and 72 were deposited over the scarp of this fault. Materials of both units appear to have slid off the scarp to form a jumbled mass at V-11b-1.

Fissuring in the marsh occurred during event V. V-10-1 is a cross section of an event V fissure into which some of units 61 and 68 and upper unit 50 have dropped. Units 71 and 72 blanket the fissure. The fissure is also visible in the wall of the trench opposite V-10-1 (Figure 18). There, however, no fractured materials fell into the fissure. Instead, silt that coarsens upward completely fills the crack. Silt in the upper half of the
During event V, slip on this fault in exposure 11 broke units 61 and 68 and older units. Younger aeolian and fluvial sediments (71, 73, etc.) and peat subsequently buried the 400-mm-high fault scarp. Another principal trace of the San Andreas fault, which was active during later events, is concealed behind one of the braces used to prevent collapse of the trench.

Sedimentation After Event V and Evidence for Lack of Faulting Between Events V and X

Exposure 11 shows that scarps of event V were buried by younger sediments. After deposition of unit 78 the scarps and depression formed during event V were almost undetectable on the surface.

Figure 19 clarifies the nature of the sedimentation that occurred after event V by subtracting from the exposure 11 record all fault slip which occurred after event V. Units 71, 72, and 73 display the strongest response to the topography created by event V. Clearly, unit 73 is thickest on the downthrown blocks in the vicinity of the faults, and units 71 and 72 were deposited directly on the scarp as evidenced by their dips. Younger sediments reflect the underlying scarp very little. The peat of unit 81 shows very little or no depositional response to the scarp.

In addition, units 72-78 are offset the same amount (470 ± 20 mm) by later events. This strongly implies that no scarp was formed anytime between the deposition of units 73 and 78.

Event X

A complex sedimentation and faulting history suggests that two major seismic events took place after unit 78 was deposited. The first of these was event X.

The clearest indication of event X is a small sandblow cone and clastic dike (X-10-2). The cone was erupted directly onto the peat of unit 81. The undisturbed nature of the thin peats and silt overlying the cone indicates that it was not intruded between units 81 and 88. Unlike the clastic dike through which the sand was extruded, the cone appears only on one wall of the trench. On the opposite (northwestern) wall the dike does not pierce unit 81. The dike is not traceable below upper unit 50, and thus the sand may have originated in that unit.

A secondary fault (X-10-1 and X-10a-2) that offsets unit 81 and older units is additional evidence of event X. In exposure 10 all units older than unit 88 are offset 210 ± 20 mm, and the top of unit 88 is not affected by the fault. This suggests that the fault moved only after deposition of unit 81. Relationships in exposure 10a, however, seem to indicate a different history for this fault. Here, only 1 m northwest of exposure 10 the fault offsets upper unit 50 through unit 72 about 210 mm, as in exposure 10, but younger units are offset less. Upper unit 73 is offset only 170 mm, unit 78 only 110 mm, and lower unit 81 only 80 mm; upper unit 81 is not offset. Thus it appears from offsets in exposure 10a that the fault began to move after unit 72 was deposited and slipped many times before unit 81 was deposited. This would suggest, however, the presence of a scarp throughout the period of deposition of unit 70. The seeming lack of response of any unit 70 peats, sands, or silts to the suggested scarp suggests the solution to the apparently different fault histories in exposures 10 and 10a. The fault strike indicates that it merges with the main trace to the northwest (Figure 20). In exposure 10a the fault may be very close to its terminus; that is, it may be near a point just to the northwest, where the fault did not break. The decrease in slip from unit 72 to 81 may indicate the dying out of the fault (Figure 20) rather than repeated slip events. Thus the favored interpretation of the record of this secondary fault is that it slipped only once: during event X, that is, after deposition of unit 81 and before deposition of unit 88.
Evidence for event X at the main fault is present, but it is difficult to interpret. Unit 78 is not abruptly truncated by the fault at X-11-1, unlike lower subunits of unit 70, which appear to have been simply sheared after deposition and burial. Rather, the upper surface of unit 78 slopes 35° toward the fault on the northeast side of the fault. Unit 81 rests upon this slope. The contact of units 78 and 81 along the slope may be either depositional or faulted. If it is a faulted contact, it must have developed soon after unit 81 formed, because no units above unit 81 are broken by this fault. If it is a depositional contact, it must indicate formation of a scarp just after deposition of unit 78. For reasons that are made apparent below, the evidence seems best to fit the history illustrated below (Figure 21, sequence 21a-21b-21c).

Exposure 10a appears to display evidence of a history similar to that just suggested for exposure 11. In exposure 10a the base of unit 78 seems to have been deposited almost horizontally across the buried fault. Thus it can be inferred that no fault scarp was present at the time of deposition of unit 78. Upper unit 78, however, slopes at the fault as in exposure 11. Unit 81 is very thin over this slope (X-10a-1). Figure 21 (sequence 21a-21b-21c) illustrates the favored interpretation for the development of these relationships. A thin lamina of peat appears to have formed just after event X. This peat drapes the degraded scarp slope of unit 78. Perhaps this is the same peat which drapes the sandblow X-10-2. Judging from the slope height of X-10a-1 and X-11-1 the scarp that formed during event X was 200-300 mm high.

Sedimentation After Event X

The occurrence of event X can be indirectly verified from the nature of unit 88 deposits, which were formed after event X. Recalling that in exposures 11 and 10a, all or nearly all scarps and irregular topography associated with event V are buried under deposits of unit 70, note that unit 88 shows a marked response to an irregular topography. Unit 88 is thicker and has more subunits southwest of the fault than northeast. This demands the existence of a 200-mm-high event X scarp during unit 88 deposition.

In exposure 11 the thickness of unit 88 immediately southwest of the fault is 370-400 mm, tapering to less than 100 mm 7-8 m southwest of the fault. On the higher block, northeast of...
and near the fault, thicknesses of unit 88 are 160–200 mm. The difference between the thicknesses of unit 88 on the two sides of the fault scarp which formed during event X gives a clue as to what degree the scarp was obscured by deposition of unit 88. The difference is about 200 mm. Since this is very similar to the inferred height of the scarp which formed during event X, it is reasonable to conclude that the scarp was not evident at the surface after unit 88 had been deposited. Similar analyses of exposures 10, 10a, and 11b support this conclusion that unit 88 buried the scarps of event X.

Event Z

The latest seismic event recorded in the Pallett Creek section occurred just after deposition of unit 88. The great disturbances of unit 88 are the most striking evidence of this event. In places, unit 81 penetrates into unit 88 as peat diapirs (Z-10-1, Z-10-3, and Z-11-5). At one locality, near Z-10-3, peat of unit 81 actually rests at the top of unit 88. Throughout exposure 10 is evidence of internal contortion of unit 88, involving sandy and silty loops and wisps within the unit and an irregular or undulatory upper surface. Exposure 11 also displays a great deal of irregularity in the upper surface of unit 88 but only a few expressions of soft sediment deformation (Z-11-3 and Z-11-6) or peat diapirs (Z-11-4 and Z-11-5) as pronounced as those in exposure 10. None of these disturbances involve unit 93. Where the top surface of unit 88 is undulatory, undisturbed gravel of unit 93 fills the troughs. Thus the shaking occurred between the times of deposition of unit 88 and unit 93.

Evidence of fault slip during event Z exists but is puzzling. If the previous argument that no appreciable scarp existed just after deposition of unit 88 were valid, then the scarp height for event Z would be simply the difference in the elevation of the top of unit 88 across the fault zone. The scarp thus determined is ≤ 130 mm in exposures 10 and 10a and about 300 mm in exposures 11 and 11b. The thoroughly homogenized nature of unit 88 in exposures 10 and 10a suggests that it probably liquefied during event Z and thus did not encourage formation of a scarp at the top of unit 88. The 300-mm height of the scarp in exposures 11 and 11b would therefore be a more representative figure.

The fault plane along which event Z slip occurred is elusive. Only in exposure 10 is it well defined (Z-10-2). There it effects a 300-mm vertical separation of unit 81. This slip cannot have occurred during event X, because unit 88, a unit deposited after event X, is faulted against unit 78. Exposure 11b shows clear evidence for disruption of well-laminated silts and sand layers of unit 88 over a 500-mm-wide zone above the fault, but no clear break is evident. Apparently, the fault ruptures of event X and event Z at this locality are characterized more as monoclinal warps than as a discrete fault plane.

Exposures 11 and 10a display no clear evidence for major fault slip in unit 88. Two faults which appear to be minor are evident in exposure 11 at the main fault. One (Z-11-1) vertically separates subunits of unit 88 about 30 mm. The excellent match of all subunits across this break argues strongly that no major horizontal slip occurred along it. An open fracture (Z-11-2) is located in unit 88 just above the main fault trace. No appreciable slip is detectable across this feature in exposure 11. The only suggestion of major slip is the chaotic lamination of the silty sandy units between Z-11-1 and Z-11-2. However, about 60 mm southeast of (behind) the mapped exposure the sediments southwest of Z-11-1 dip vertically. Evidently, fault slip during event Z occurred between the two fractures.

Sedimentation After Event Z

Exposure 11b best shows the wholly undisturbed nature of the sands and gravels deposited over unit 88 after event Z. The zone of disruption of unit 88 does not continue into the well-laminated sands of unit 93. Unit 93 also lies undisturbed over faulted unit 88 in exposures 11, 10, and 10a and shows a sedimentary response to the event Z scarp. This is especially clear in exposure 11, where the unit is about 200 mm thicker and has several more subunits on the lower block than on the higher block.

Despite burial of the fault by unit 90 the fault in exposures 11 and 11b is expressed as a broad 160- to 200-mm-high scarp over the buried fault. The shallower surface expression over 10 and 10a probably reflects the small scarp that developed there during event Z because of liquefaction of unit 88.

Suggestions of Other Events

Are other events recorded in the Pallett Creek section? The answer to this question is not clear. Because each major new excavation has led to the discovery of at least one previously unknown or unconfirmed event, one might expect that other significant seismic events are recorded elsewhere in units 30–90 of the Pallett Creek deposits. Alternatively, because evidence for all but two of the nine established events exists in two or more excavations, the presence of evidence for other events elsewhere at the site may be considered unlikely.

Several of the nine established events were first suspected from ambiguous and suggestive relationships. Event V, for example, was first suspected from evidence of a fissure in trench 10. With this lead, trench 11 was excavated in search of unequivocal evidence for event V. Keeping this in mind, the following paragraphs describe suggestive evidence for events that remain unconfirmed.

Faulting at the base of unit 33 and above unit 29 in exposure...
5 (near the southwest end of the exposure) may indicate an event previous to event D. Small faults at about the 95-m level just northeast of the main fault in exposure 1 also suggest this event. Exposures of this portion of the section are too limited, however, to support any conclusions regarding this (these) possible event(s).

Two small faults break unit 43 but are capped by unit 45 (H-10-1 and H-10-2). One (H-10-1) has a scarp at the top of unit 45. These faults may be due to settling of unit 39, especially if unit 39 liquefied to produce unit 46 during event I.

The upper surface of unit 47 is very irregular at two localities (J-2-1 and J-3-1). This suggests either seismically induced post-unit-47 soft sediment deformation after deposition of unit 47 or deposition of unit 47 over a section of unit 45 disturbed by event I. No other exposures corroborate an event after deposition of unit 47 by providing other features ascribable to seismic activity or fault slip.

At several localities (for example, L-2-1 and L-3-1), small faults terminate in upper unit 51. Perhaps more significant is the suggestion of a fault and a sedimentary disturbance in upper unit 51 (L-11b-1) capped by unit 52. Because this disturbance is so near the main fault (100 mm), where very large displacements have taken place, it may be related in some unseen way to an established event on that fault. A fissure in units 45-49 filled with unit 51 (L-11b-2) also suggests the possibility of an event I. It is not inconceivable, however, that this feature was produced by later faulting, perhaps during event V.

Several disturbances near the level of unit 55 in exposures 1 and 2 hint at the possibility of an event P. Terminating within unit 55 is a minor fault, P-1-3. This suggests slip during an event P. A sandblow pit 300 mm in diameter (P-1-1) and related small faults (P-1-2) might represent such an event were it not that the sandblow cone usually associated with such a feature is not present. The fine micaceous sand filling the pit and the feeder dike is not similar to the fine to coarse sand of unit 55. It is identical, however, to sand in several dikes cutting unit 50. One of these is the feeder to a small event T sandblow deposit (T-1-1). Two small bodies of the fine micaceous sand do occur in unit 55 just north of the pit. However, it is unlikely that these fragile bodies were picked up from a nearby sandblow cone and deposited within unit 55 here. Perhaps the sand was liquefied by event R, T, V, X, or Z shaking. The sand and water began to move upward through dikes at the site, but upon reaching the surface at a different locality, the liquefied unit was able to dissipate its high water pressures quickly and thereby cease to be active. The nearby faults (P-1-2) might be products of the final assimilating activity of the upward moving fluidized sand. Taken together, these features do not constitute compelling evidence for seismic shaking of fault slip during an event P.

A conservative appraisal would allow for the possibility that events H, J, K, and P are significant but as yet undiscovered events recorded in the Pallett Creek deposits. Moreover, it is not altogether impossible that features of some other significant event, not yet even suggested, may lie at some unexplored location at the site. The existence of any undiscovered event more recent than event T is very unlikely, however, judging from the sediment/fault relationship described previously (see discussion of Figure 19). In my opinion it is unlikely that more than two large events remain undiscovered in the record of the past 1400 years at Pallett Creek, and it is entirely possible that the nine established events are the only ones that occurred during that time period.

Sizes of the Seismic Events

Estimation of the 'sizes' of the nine established seismic events is necessary if the Pallett Creek record is to aid in understanding the patterns and periodicities of major or great earthquakes affecting southern California. Ideally, each event identified at Pallett Creek would be related to a specific, measured amount of right lateral slip and correlated with events identified at similar study sites along the fault. A crude knowledge of the rupture lengths and displacements gained in this manner enables estimation of their seismic moments or magnitudes.

Unfortunately, sites other than Pallett Creek, where prehistoric events might be dated, remain undiscovered; and studies of offset surficial features near Pallett Creek have not yet established right lateral offsets for the prehistoric events. At this time the Pallett Creek section yields the only data available for assigning sizes to the eight prehistoric events. The following discussion concerns data from Pallett Creek pertinent to assessing the sizes of these events.

Using the 1857 event as a calibration. The horizontal slip associated with the eight prehistoric events at Pallett Creek can be inferred by comparison of their effects with the effects of the 1857 event, for which the horizontal slip is known. Offset gullies and other reference features indicate that the latest large slip event in the vicinity of Pallett Creek is associated with 3-4 m of right lateral slip (Figure 2) [Sieh, 1978]. Knowledge of the historical seismicity of the area (Figure 3 and previous discussion) leaves little doubt that this latest slip event produced the great earthquake of 1857. Hence the 1857 event correlates with the youngest disturbance in the Pallett Creek deposits: event Z.

Substantial vertical deformation accompanied the 1857 event. The nature of the deformation can be determined in the following manner. Recall that previous discussion of exposure 11 shows that sedimentation after event X buried the fault scarp and other disturbances created by that event. Thus the surface of the marsh was fairly regular or flat just prior to the 1857 event (event Z). Therefore irregularities now visible in the buried 1857 surface (i.e., the top of unit 88) are the result of the 1857 event.

The configuration of the 1857 surface in exposure 11 is shown as profile Z in Figure 22. Apparently, the creation of a trough 300 mm deep and 6 m wide accompanied the 3-4 m of right lateral slip. The 300-mm-high scarp bounding the trough on the northeast is due, at least in part, to horizontal offset of the gently dipping Pallett Creek deposits. I address this in detail further on in the paper.

Event X. Sedimentation during the years prior to event X buried the topographic features produced by the previous event (event V). The marsh therefore presented a relatively flat surface to the deforming action of event X. In exposure 11, however, that surface (the top of unit 81) is moderately deformed. This deformation must have resulted from events X and Z. Subtraction of the deformation produced during event Z (i.e., profile Z) from the profile of unit 81 yields the deformation produced by event X (profile X, Figure 22). Near the fault trace, profile X is based upon the evidence for a 200-mm-high event X scarp, which is discussed in the previous segment of this paper. Although the style of deformation during event X is somewhat different, the magnitude of vertical deformation is very similar to the magnitude of 1857 deformation: a south-west facing fault scarp 200 mm high forms the northeastern boundary of a trough 200 mm deep. In addition to the scarp
Fig. 22. Reconstructions of the ground surface immediately after each event (profiles F–Z), based on interpretations of exposure 11, suggest that vertical deformations associated with all events except perhaps I and R are similar in style and magnitude to the deformations associated with the 1857 event (profile Z). If vertical deformations are proportional to right lateral fault slip, all except perhaps events I and R are associated with right lateral fault slip as great as that of the 1857 event, that is, several meters.
and trough, a 15° tilt to the northeast may have accompanied the event. If style and magnitude of deformation in the vertical plane are proportional to the magnitude of horizontal fault slip, the horizontal slip accompanying event X was similar to that of 1857, i.e., several meters. This assumption is similar to that made by Clark et al. [1972] in establishing an average recurrence period for moderate earthquakes on the Coyote Creek fault in southern California.

Event V. If sedimentation after event T (top of unit 61) had buried the irregular topography produced by event T, the deformation accompanying event V could be found by subtracting 1857 and event X deformation from the top of unit 68. Unfortunately, only a thin gravel (unit 65) and peat (unit 68) blanketed event V topography at the time of event V. Although it is clear from the abnormal thickness of the peat of unit 68 just southwest of the fault in exposures 10 and 11 that some masking of the event V scarps occurred, it is also clear that event V topography still existed at the time of event V (e.g., note the broad depression of the top of unit 68 over T-10-1). So, subtracting 1857 and event X deformations from the event V surface yields event V deformations plus some broad event T deformation.

The profile of the ground surface just after event V (profile V, Figure 22) is very similar to the event X and 1857 profiles: a trough 5 m wide and 400 mm deep bounded on the northeast by a fault scarp 300 mm high. Unlike the deformations associated with event X and the 1857 event, however, an anticlinal warp occurred southwest of the fault during event V. Because a 300-mm-high scarp formed during event V (see discussion in previous section or Figure 17), it is fairly certain that most of the 400-mm-deep trough formed during event V. Event V deformations then are remarkably similar in form and magnitude to those of 1857 and event V. Hence the amount of right lateral slip during event V was comparable to that of the 1857 event and event X.

Event T. The relatively uniform thickness of unit 61 and nearly complete burial of two observed event R scarps (R-11-1 and R-11-3) suggests that the marsh surface was fairly regular or flat just before event T occurred. Therefore profile T (Figure 22) should be a reliable representation of event T deformation. It is a profile of unit 61 minus profiles V, X, and Z. The profile is a minimum event T deformation, however, since some event T deformation is contained in profile V. Again the familiar fault-bounded trough is present.

Clay-, sand-, and silt-filled fissures up to 500 mm in width, which formed along the fault during event T (see previous discussion), suggest that T was a substantial event. Together with profile T they suggest that right lateral slip associated with event T was similar in size to the slip associated with the 1857 event.

Event R. Event R deformations are well represented by profile R (Figure 22) because event R occurred after deposition of a thick blanket of gravels, sands, and silts which buried the deformations resulting from event N. Profile R is the profile of the base of the hard, clayey silt near the top of unit 50 minus profiles T, V, X, and Z (i.e., minus deformations of events T, V, X, and Z).

The principal vertical deformation occurred on a fault at the northeast end of exposure 11 (R-11-1). Other than this, very little warping appears in the profile. Fault slip on the main fault cannot be convincingly demonstrated or ruled out in trenches 11, 10, 2, or 1.

Two southwest facing fault scarps, in addition to R-11-1 in exposure 11, were formed during event R. A scarp 300 mm high is visible in the wall of the bulldozer cut (see Figure 14), and a scarp 200 mm high is apparent in cut 7 (see Figures 7 and 9). The three faults are not connected to one another. Facies changes across all three faults formed during event R imply at least 100 or 200 mm of horizontal slip on each of the three independent faults.

Effects of event R on the Pallet Creek differ noticeably from the effects of events T, V, X, and the 1857 event. No pronounced warping of the ground surface southwest of the fault occurred, and no slip on the main fault is recognized. Three separate faults northeast of the main fault produced southwest facing scarps and show evidence of horizontal slip totaling at least several hundreds of millimeters. These differences may indicate that event R was smaller than events T, V, and X and the event of 1857. Nevertheless, horizontal slip of at least several hundred millimeters suggests at least a moderate event (i.e., $M \geq 6$).

Event N. Sediments deposited prior to event N appear to have buried surface irregularities created during event I. Beds are very regular in exposure 11 even where they cover large event I irregularities (e.g., consider unit 52 over I-11-1). It seems reasonable to believe that a once flat pre-event-N surface was deformed by event N and subsequent events. Subtracting the deformations of events R, T, V, X, and Z from the pre-event-N surface in exposure 11 yields the deformation associated with event N (profile N, Figure 22). The deformation is very similar to deformations associated with events T, V, X, and Z. It bears an especially close resemblance to the disturbance associated with event V. The surface southwest of the main trace has a 400-mm-high arch. Except for possibly about 100 mm of slip on the fault at the northeast end of the profile, the profile northeast of the main fault, like profiles T, V, and Z, is not appreciably warped. A 400-mm-deep trough is indicated southwest of the main fault. Gravels deposited after event N seem to have been deposited in response to this trough, the coarsest facies having been deposited in the deepest part of the trough.

Other evidence suggests that N was a large event. During event N a homoclinal warp 800 mm high developed on the southwest side of the main fault trace in exposure I. In addition, an oblique-slip fault (N-I-1) at the southwest edge of exposure I produced a scarp 250 mm high probably during event N.

All the evidence described above leads to the conclusion that displacements associated with event N were at least as large as those of 1857.

Event I. After event F, as much as a meter of coarse sand and gravel buried the topographic evidence for that event. The apparent result was that just prior to event I the marsh surface was relatively flat. The fairly regular thickness of the unit 45 clays, silts, and peats, which were deposited before event I, supports this view. Profile I (Figure 22) then fairly well represents the deformation of that flat surface during event I. This is the profile of the top of unit 45 minus profiles N-Z.

A scarp perhaps 100 mm high appears at the northeast edge of the profile. The contrast in sandblow thickness across the fault is a reminder that variations in thickness of a unit parallel to the fault can result in an apparent rather than a real offset. This may be the explanation for the scarp at the main fault in profile I (Figure 22). Neglecting sandblow deposits and soft sediment deformation, substantial warps developed during this event. The reality of the southwest dipping, 300-mm-deep warp southwest of the main fault may be indicated by more substantial peat and sand deposits on the lower parts of the
slope after event I. That is, the existence of the warp may be
verified by the response of later sedimentation to it.

There is no convincing evidence that major tectonic fault
slip occurred during event I. The extensive array of sandblow
deposits, numerous small secondary faults, and soft sediment
defor mation does not require an event with a magnitude of
larger than 5.5–6.0. Although the warping is as great as that
for the 1857 event, its different style cautions against using the
evidence to conclude that event I displacements were as great
as those of 1857. Therefore I consider event I to be a moderate
or large event.

Event F. Several lines of evidence lead to the conclusion that
event F was comparable in size to the 1857 event:
1. Six sandblows occur in the several tens of meters of
event F horizon exposed in the excavations. This density of
sandblows suggests a scene at Pallett Creek during event F
reminiscent of one related by an observer of effects of the
Indian earthquake of 1934 (Ms = 8.3) [Geological Survey of
India, 1939, p. 34]:

...As the rocking ceased ... water spouts, hundreds of them
throwing up water and sand, were to be observed on the whole
face of the country, the sand forming miniature volcanoes, whilst
the water spouted out of the craters, some of the spouts were quite
5 feet high. In a few minutes—as far as the eye could see—was
vast expanse of sand and water, water and sand. The road
spouted water, and wide openings were to be seen across it ahead
of me, then under me, and my car sank, while the water and sand
bubbled and spat, and sucked, till my axles were covered. 'Aban-
don ship' was quickly obeyed, and my man and I stepped into
knee deep water and sand and made for shore.

Whether the spectacular display of sandblow fountains during
event F required a very large number of loading cycles (i.e., a
great earthquake) or relatively few is not known.

2. Secondary faulting occurred prior to the evacuation of
the sandblow material. This has been discussed in the previous
section on event F disturbances.

3. The most compelling evidence that event F was a large
event is the large-scale warping visible in exposure 5 southwest
of the main fault. If unit 45 (deposited after event F) is re-
stored to horizontality, units deposited prior to event F still
dip about 7° away from the fault. Whether this indicates
development of a 400-mm-deep trough southwest of the fault
or a 400-mm-high mound along the fault is unknown. In either
case this deformation is no less than that associated with the
1857 event at Pallett Creek.

4. A high-amplitude warp also is evident in exposure 10. If
unit 45 northeast of the main fault is restored to horizontality
there, unit 38, which was deposited prior to event F, retains a
300-mm-high anticlinal arch centered on the two large event F
sandblow pits. This magnitude of deformation is comparable
to that of 1857. All available evidence points to the assignment
of a large size to event F.

Event D. The event D horizon (i.e., unit 33) is exposed in
relatively few places, so there is little opportunity to view
defor mations associated with event D. Deformation in ex-
posure 10, one of only two long exposures of unit 33, suggests
that event D may have been large. There, northeast of the
main fault, slip along several event D faults produced a 300-
mm-high southwest facing scarp (see previous discussion of
event D). If unit 34, which buried the scarp, is a sandblow
deposit, very large volumes of sand were extruded during or
immediately after event D. This might have produced surface
defor mations similar in size to those of 1857, even if event D
was a smaller event. Nonetheless, in view of substantial defor-
mation and liquefaction effects similar to event F liquefaction
effects, event D is tentatively considered to be a large event.

Apparent offsets along the main fault and other structural
developments. In general, the Pallett Creek deposits slope 1°–2°
to the southeast, parallel to the main fault. Thus the total
horizontal slip L that occurred since deposition of a bed would
be proportional to the vertical separation of the bed (see Figure 23).
In this way, successive episodes of horizontal slip
would result in greater vertical separation of older units than
younger units (Figure 24).

The exposure records and the deformation profiles pro-
duced from exposure 11 (Figure 22) show that the relation-
ships are more complex than this. Consider the deformation
profile of the 1857 event (profile Z, Figure 22). Theoretically, a
4-m lateral offset of a 1°–2° slope would have produced the
profile drawn with a solid line in Figure 25. Instead, the profile
drawn with a dashed line was produced. This discrepancy
demonstrates that a small syncline and anticline developed
southwest of the fault in 1857.

Deformation profiles F, N, T, V, and X (Figure 22) indicate
that this structure has been developing for at least the past
1400 years. Only events I and R do not seem to have contrib-
uted to its development. The welt and trough also are present
southwest of the fault in exposure 10, although the details are
somewhat different. In exposures I and 2 the structure is not
apparent. Perhaps the growth of the welt has been responsible
for the deflection of Pallett Creek along the fault (Figure 26).

In exposure 10, vertical separation on the main fault in-
creased fairly regularly with increasing unit age, suggesting
fault activity from event F to the 1857 event. In exposure 11,
units 61–88 show increased vertical separation at the times of
events T, V, and X and the 1857 event, but older units display
a nearly uniform vertical separation of about 1 m. The fault at
the northeast end of the exposure, however, displays vertical
separations which are greater for older units. Does this imply
that the main trace in exposure 11 was active only after event T
and that the northeastern trace was the principal trace during
earlier events? The following discussion demonstrates why one
should be cautious about such an interpretation of data on
increasing vertical separation.

The apparent offset of a 1° slope (the average slope of unit
38 is 1°) produced by right lateral slip of 41 m is 80 mm. If one
assumes that all large events at the site since event F have been
associated with 41 m of right lateral slip, the total lateral offset
of unit 38 deposited prior to event F ought to be 27 m (six
events (F, N, T, V, X, and Z) × 41 m = 27 m). The vertical
separation due to right lateral slip ought to be 480 mm. The
observed vertical separation, shown in the tabulation below,
ranges from 970 to 1260 mm:

Fig. 23. A simple model demonstrates that right lateral offset L of
a surface with a slope angle θ parallel to the fault produces a vertical
separation or apparent vertical offset D. At Pallett Creek, where the
deposits slope generally 1°–2° to the southeast, parallel to the fault,
right lateral movement is, at least in part, responsible for the vertical
separation of units seen in the exposures.
Consider now the magnitude of local disturbances along the fault. In exposure 10, unit 38 varies in elevation by some 600 mm northeast of the fault and by a similar amount southeast of the fault. These variations occur over distances of only 2-3 m. In exposure 11, unit 38 has been offset 500 mm on another fault northeast of the main fault. If local deformations parallel to the fault are as great as these deformations transverse to the fault, it is small wonder that vertical separations of unit 38 vary by 200 mm. Comparing absolute elevations of unit 38 to the fault are as great as these deformations transverse to the vertical separations than the younger layers.

Events (I and R) are associated with displacements and effects. Just northeast of the fault between exposures 10 and 11, unit 38 slopes 1.4° to the northwest, whereas its average dip at Pallet Creek is 1.0° southeast. A future 4-m right lateral offset would reduce the 970-mm vertical separation of unit 38 now seen in exposure 11 to only 850 mm. Unit 45, which dips about 0° between exposures 10 and 11 and now has a vertical separation of 1.08 m, would maintain that separation were 4 m of right lateral slip to occur.

Attempts to calculate the height of scarps produced by individual events from apparent vertical offsets have been futile for events previous to R, because of these irregularities. For this reason, scarps heights shown in profiles F, I, N, and R (Figure 22) for events F, I, N, and R are not meaningful.

The younger units 61-98 have relatively regular slopes at the site, and scarp heights observed at various exposures are more consistent (Table 2); 1857 scarp heights are about 300 mm. Event X, V, and T scarps are about 200 mm. This agrees with the deformation profile data in suggesting that these past four events have been of similar size.

Analysis of the effects of the nine established events leads to the conclusion that the magnitude of right lateral slip associated with at least six of the eight prehistoric events at Pallet Creek is similar to that of the 1857 earthquake. Two of the events (I and R) are associated with displacements and effects indicating at least a moderate size.

Dating the Events

The many radiocarbon dates determined for various strata in the Pallet Creek section provide a basic time framework for the nine events. Rates of deposition and other stratigraphic considerations allow more refined assignment of event dates within this framework.

Table 3 summarizes the data used in assigning each event a date. The second column indicates the stratigraphic units deposited just before and just after each event. The third column shows the radiocarbon and/or historic dates bracketing the event. In the fourth column are comments and stratigraphic considerations pertinent to estimating the dates of occurrence shown in the last column.

**Rates of sediment deposition.** The determination of reasonable rates of sediment deposition is critical in refining the dates of the prehistoric events. Sedimentation rates determined in this section enable interpolation of dates for events which occurred between the deposition of two radiometrically dated layers.

First, I calculate a rate of peat and clay deposition, using the two radiocarbon dates which bracket the formation of peat-rich units 29-33 (see exposure 11). The majority of material constituting units 29-33 is peat and clay. The measured thickness of the peat and clay (T_p) is 615 mm. The average rate of deposition of the peats and clays (R_p) equals their thickness (T_p) divided by the length of time during which they accumulated (t_p):

$$R_p = T_p / t_p$$  \(\text{(3)}\)

It is assumed that each of the four sand beds between units 29 and 33 accumulated instantaneously. Hence their thicknesses are not included in T_p.

The time required for deposition, t_p, equals the difference, |A - B|, of the radiocarbon dates of unit 33 (A = 565 A.D.) and unit 29 (B = 110 A.D.): 455 years. The statistical uncertainty σ in t_p is a function of the uncertainty in these radiocarbon dates (σ_A = 55 years, and σ_B = 60 years) [Beers, 1962, p. 33]:

$$\sigma = (\sigma_A^2 + \sigma_B^2)^{1/2}$$  \(\text{(4)}\)

In this case, \(t_p = 455 \pm 81\) years. Before \(t_p\) can be divided into \(T_p\) to derive \(R_p\), the uncertainty in \(t_p\) must be expressed in percent of \(t_p\), that is, 455 ± 18%. To determine the uncertainty in \(R_p\), this uncertainty is combined with the uncertainty in \(T_p\) (which in this case is zero) in the same fashion as \(σ_A\) and \(σ_B\) were combined in (4) [Beers, 1962, p. 34]. Thus \(R_p = 1.4\) mm/yr ± 18%.

Second, I estimate an average rate of deposition \(R_s\) for silty sand and silt, using the deposits of unit 70. This involves subtracting the time during which peat was accumulating in that section and assumes that the peats of unit 70 accumulated at the same rate as those between units 29 and 33:

$$R_s = T_s / (t - t_p)$$  \(\text{(5)}\)
Fig. 26. Analysis of exposures 10 and 11 indicates that an anticline and syncline have been developing southwest of the fault during at least the past 1400 years. The anticline may have deflected Pallett Creek to the southeast.

TABLE 2. Scarp Height Associated With Pallett Creek Events

<table>
<thead>
<tr>
<th>Source of Calculations</th>
<th>Exposure 2</th>
<th>Exposure 10</th>
<th>Exposure 10a</th>
<th>Exposure 11</th>
<th>Exposure 11b</th>
<th>Comments and Cautions</th>
<th>Best Value, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offset top of unit 88</td>
<td>290-340</td>
<td>130</td>
<td>~10</td>
<td>290</td>
<td>300</td>
<td>Event Z</td>
<td>300</td>
</tr>
<tr>
<td>Unit 78 faulted against unit 88</td>
<td></td>
<td>260</td>
<td>120</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Offset of unit 81 minus height of scarp on unit 78</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Offset of unit 81 minus offset top of unit 88</td>
<td>140-190</td>
<td>140</td>
<td>190</td>
<td>210</td>
<td>Event X</td>
<td>Exposure 10 was complicated by secondary faulting. For exposure 2, values are unreliable, since unit 81 is eroded (?) off one side.</td>
<td>210</td>
</tr>
<tr>
<td>Height of scarp on unit 78</td>
<td></td>
<td></td>
<td></td>
<td>180</td>
<td>240-260</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Offset of unit 68 top minus offset of unit 81</td>
<td>100-150</td>
<td>30</td>
<td>140</td>
<td>470</td>
<td>Event V</td>
<td>Offset difference may include some event T slip where post-event-T sedimentation did not completely bury event T scarp.</td>
<td>200</td>
</tr>
<tr>
<td>Offset of unit 61 minus offset of unit 68 top</td>
<td>280-350</td>
<td>40-270</td>
<td>220</td>
<td>140</td>
<td>Event T</td>
<td>Offset difference may be low where event T scarp was not completely buried by post-event-T, pre-event-V sediments. Exposure 2 was complicated by a secondary fault. Exposure 10 includes slip on a secondary fault with little strike-slip; 90-100 mm of secondary fault slip is post-event-T, and thus 180-250 mm might be a better figure.</td>
<td>210</td>
</tr>
</tbody>
</table>
### TABLE 3. Dates of Occurrence of Events D–Z

<table>
<thead>
<tr>
<th>Event</th>
<th>Overlying Unit</th>
<th>Upper Bounding Date, A.D.</th>
<th>Underlying Unit</th>
<th>Lower Bounding Date, A.D.</th>
<th>Discussion, Comments, and Considerations</th>
<th>Estimated Date of Occurrence, A.D.*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z</td>
<td>93 upper 88</td>
<td></td>
<td></td>
<td></td>
<td>Historically well documented.</td>
<td>Jan. 9, 1857</td>
</tr>
<tr>
<td>X</td>
<td>88 81 1725 ± 55</td>
<td>1857</td>
<td></td>
<td></td>
<td>About 250 mm (145 ± 65 years) of silt accumulated after this event and prior to 1857. Unit 81 peat was being deposited at the time of the event. The date of event X is estimated to be the same as the date of deposition of uppermost unit 81. Historical records preclude post-1769 events.</td>
<td>1745 ± 55</td>
</tr>
<tr>
<td>V</td>
<td>71 1465 ± 80</td>
<td>68 1470 ± 50</td>
<td></td>
<td></td>
<td>Unit 65, between 68 and 61 peats, is in part coseismic and in part post-seismic. It displays abundant evidence of burrowing and/or rooting which does not affect overlying units. This is evidence that event T preceded unit 68 by a fair amount of time. The event appears to have occurred as the last of unit 61 was being deposited. The date of event T is estimated to be the same as the date of deposition of uppermost unit 61.</td>
<td>1470 ± 40</td>
</tr>
<tr>
<td>T</td>
<td>68 1225 ± 45</td>
<td>61 1225 ± 45</td>
<td></td>
<td></td>
<td>Two dates are derived from this event by using the bounding dates and sedimentation rates. Using the 850 ± 55 unit 49 date results in a 922 ± 72 A.D. event N date. Using the 1225 ± 45 unit 61 date produces a 1004 ± 69 A.D. date. These are statistically averaged to yield the final event date.</td>
<td>1245 ± 45</td>
</tr>
<tr>
<td>R</td>
<td>61 1225 ± 45</td>
<td>55+</td>
<td></td>
<td></td>
<td>The date of event R is calculated by subtracting from the event T date the time required to deposit the 50-mm unit 61 peat at 1.4 mm/yr ± 18% and the 40-mm silt under unit 61 at 1.9 mm/yr ± 32%.</td>
<td>1190 ± 45</td>
</tr>
<tr>
<td>N</td>
<td>53 1225 ± 45</td>
<td>52 850 ± 55</td>
<td></td>
<td></td>
<td>Dates for units 45, 47, and 49 are combined with sedimentation rates to calculate three independent event I dates. These three dates are then statistically averaged to yield the final event date.</td>
<td>965 ± 50</td>
</tr>
<tr>
<td>I</td>
<td>47 850 ± 55 and 955 ± 60</td>
<td>45 845 ± 75</td>
<td></td>
<td></td>
<td>The event occurred after deposition of 100 mm of silt upon dated unit 38. The unit 38 date is used to derive the event date. The event occurred after the top of the peat unit was deposited (610 ± 80 A.D.) and after the 100 mm of silt was deposited (610 ± 80 A.D. plus 53 ± 17 years).</td>
<td>860 ± 35</td>
</tr>
<tr>
<td>F</td>
<td>41 820 ± 70</td>
<td>38 600 ± 80</td>
<td></td>
<td></td>
<td>The event followed the deposition of lower unit 34 and was followed by the deposition of unit 35. Radiocarbon dates are averaged to derive estimates of the date of event D.</td>
<td>545 ± 45</td>
</tr>
<tr>
<td>D</td>
<td>35 510 ± 75</td>
<td>34 565 ± 55</td>
<td></td>
<td></td>
<td>The event occurred just after deposition of peaty unit 81. Between the time of event X (after deposition of unit 81) and 1857 (after deposition of unit 88), about 250 mm of planar-laminated silt and about 50 mm of sand were deposited as unit 88. The silt probably accumulated slowly, perhaps at an average rate of only 2.2 mm/yr ± 48%. Thus Rₚ might be considered to be the statistical average of the two Rₚ determinations, 1.9 mm/yr ± 32% (calculated as in (1) and (2)).</td>
<td>510 ± 75</td>
</tr>
</tbody>
</table>

* Radiocarbon dates have been corrected to calendar dates using the calibrations of Damon et al. [1972].

where

\[ T_s = \text{thickness of the silts and sandy silts (measured in exposure 11 and excluding sand unit 78 because it assume that it was deposited instantaneously), equal to 380 mm;} \]

\[ t = \text{date of unit 81 minus date of unit 71 (from Table 1), equal to } 1725 - 1465 = 260 ± 97 \text{ years.} \]

Also in (5),

\[ t_p = \frac{T_p}{R_p} = \frac{50 \text{ mm}}{1.4 \text{ mm/yr ± 18%}} = 36 ± 6 \text{ years} \]

where \( T_p = 50 \text{ mm (measured from exposure 11). Using these values in (5),} \]

\[ R_s = \frac{380 \text{ mm}}{[(260 ± 97) - (36 ± 6) \text{ years}]} = \frac{380 \text{ mm}}{224 \text{ years ± 43%}} = 1.7 \text{ mm/yr ± 43%} \]

An independent \( R_s \) for silt and sandy silt can be estimated by using unit 88 in exposure 11 and its bracketing dates. Again it is assumed that the sand units can be ignored. In this case,

\[ T_s = \text{thickness of unit 88 (measured from exposure 11), equal to 250 mm;} \]

\[ t = \text{time between deposition of top of unit 88 (1857 A.D.) and middle of unit 81 (1725 ± 55 A.D.), equal to 132 ± 55 years;} \]

\[ t_p = \text{time of accumulation of upper half of unit 81, equal to 25 mm/(1.4 \text{ mm/yr ± 18%}), which equals 18 ± 3 years.} \]

Using these values in (5), \( R_s = 2.2 \text{ mm/yr ± 48%} \). Thus \( R_s \) might be considered to be the statistical average of the two \( R_s \) determinations, 1.9 mm/yr ± 32% (calculated as in (1) and (2)).

The sedimentation rates \( R_p \) and \( R_s \) that have been derived above can now be used to estimate the dates of occurrence of the seismic events within the framework of radiocarbon dates. In the sections that follow, each event is separately considered.

**Event X.** Event X occurred just after deposition of peaty unit 81. Between the time of event X (after deposition of unit 81) and 1857 (after deposition of unit 88), about 250 mm of planar-laminated silt and about 50 mm of sand were deposited as unit 88. The silts probably accumulated slowly, perhaps at an average rate of only 2.2 mm/yr ± 48%. This would suggest that a period of about 1 century separates event X and the 1857 event. This is consistent with the stratigraphic evidence placing the date of event X just after the final date of deposition of the unit 81 peat. Since the entire 50-mm thickness of unit 81 was used for the ¹⁴C date determination (1725 ± 55 years), the date of event X seems to have occurred around 1857.
A.D.), the date is an average figure. If the peat took about 36 
± 6 years to accumulate (50 mm at 1.4 mm/yr ± 18%), and if 
the average date, 1725 ± 55 A.D., is assumed to be the date at 
the midpoint in the deposition of the peat, another 18 ± 6 
years should be added (using (4)) to obtain the date of final 
deposition of the peat and event X. Thus event X is assigned 
a date of 1745 ± 55 A.D.

Historical information allows further reduction in uncer-
tainty of the date of event X. Continuous recorded history in 
southern California begins in 1769 with the first expedition to 
establish the missions. The San Gabriel mission (44 km south 
of Pallet Creek) was established in 1771. Had any large earth-
quake been produced by slip on the fault in the vicinity of 
Pallet Creek after establishment of the mission, records of this 
and the more distant missions would mention it. The only 
large historic earthquake that one might attempt to associate 
with the event X effects at Pallet Creek is the 1769 event 
reported by the Portolá expedition [Bancroft, 1884, p. 146; 
Palóu, 1926, p. 129; Portolá, 1909, p. 21]. Portolá's diary, 
however, indicates that although the shaking was violent dur-
ing that event, it lasted only "about half as long as an Ave 
Maria" [Portolá, 1909, p. 21], that is, only a few seconds. This 
suggests that the 1769 earthquake was only a moderate event 
in the Los Angeles region, probably more similar to the 1933 
M_ perplex = 6.3 or 1971 M_ perplex = 6.4 earthquake (Figure 3) than to a 
large event produced by slip on the San Andreas fault.

Event X is assigned a date of 1745 ± 55 A.D. The younger 
date (1745 ± 24 A.D.) is an absolute boundary; the older is a 
1σ limit.

Event Y. Two peats (unit 68 and unit 71) bracket event Y, 
and both have nearly identical dates. Statistical combination 
of the dates according to (1) and (2) gives the date of event Y 
as 1470 ± 40 A.D.

Event T. This event is bracketed by deposition of units 61 
and 68 (1225 ± 45 and 1470 ± 50 A.D., respectively). The 
Intervening unit 65 consists in part of postseismic gravel and 
sands but also contains coesioseismic sandbox deposits. The unit 
displays abundant evidence of animal burrowing and/or rooting 
which does not affect overlying units. This suggests that 
Event T preceded the deposition of unit 68 by several decades or 
longer. Event T probably occurred as the last of unit 61 was 
deposited. Assuming that the midpoint in unit 61 deposition 
was 1225 ± 45 A.D., the final accumulation of that 50-mm-
thick unit using (6) was 18 ± 6 years later. Thus event T is 
assigned a date of 1245 ± 45 A.D.

Event R. The layers deposited after event R and prior to 
event T are the unit 61 peat (T_0 = 50 mm), a silt at the very top 
of unit 50 (for which T_0 averages 40 mm in thickness), and a 
gravel or sand (which averages 200 mm in thickness). The date 
of event T is 1245 ± 45. To calculate the date of event R, (1) 
subtract the accumulation time t_0 of the peat of unit 61, 
calculated according to (6), and (2) subtract the accumulation 
time t_0 of the silt of upper unit 50, calculated according to (7):

\[ t_0 = T_0/R_0 \]  

In this case, t_0 = 36 ± 6 years, and t_0 = 21 ± 7 years. Thus the 
time of event R is estimated to be (t_0 + t_0) years prior to event 
T: 1190 ± 45 A.D. The uncertainty of this date is the square 
root of the sum of the squares of the uncertainty in t_0, t_0, and 
event T.

Event D. This event occurred before deposition of unit 35 
and after deposition of lower unit 34. The bracketing dates are 
565 ± 55 (unit 33) and 510 ± 75 (unit 36). The dates are 
reversed chronologically, but the reversal is statistically in-
significant. The statistical average of these two dates is 545 ± 
45 A.D. This is probably the best estimate of the date of event 
D.

Event F. Event F occurred after deposition of the basal silt 
of unit 39 and before deposition of unit 41. Radiocarbon dates 
that bracket the event are those for unit 38 (600 ± 80 A.D.) 
and unit 41 (820 ± 70 A.D.). In view of the difficulties of 
assessing the time between unit 41 deposition and event F, the 
unit 38 date is probably the better one to use in calculating the 
date of event F.

Unit 38 is a 30-mm-thick laminated clayey peat; 600 ± 80 
A.D. is the average date of all laminae in the unit. The date of 
deposition of the top of the unit determined using (6) is 611 ± 
80 A.D. A silt layer averaging 100 mm in thickness then was 
deposited above unit 38 before event F occurred. Using R_0 = 
1.9 mm/yr ± 32% in (7), the time of accumulation of this unit 
is estimated to be 53 ± 17 years. Adding this to the event 38 
date (using (6)) yields a date of 665 ± 80 A.D. for event F.

Event I. Three 14C dates bracket event I. The radiocarbon 
date of the 10-mm-thick peat of uppermost unit 45 directly 
below the event I horizon is 845 ± 75 A.D. The 10-mm-thick 
peat of unit 47 directly overlying the event I horizon has a date 
of 850 ± 55 A.D. Sedimentation times must be added or subtracted from these dates to give 
event I dates. The unit 45 date becomes 849 ± 75 A.D. upon 
adding 5 mm of peat. The unit 47 date becomes 951 ± 60 A.D. 
upon subtracting 5 mm of peat. The unit 49 date becomes 788 
± 57 A.D. upon subtracting an average of 20 mm of peat and 
90 mm of silt. The average of these dates (using (1) and (2)) 
gives the best estimate for the date of event I: 860 ± 35 A.D.

Event N. Like the 1857 event, this event occurred just prior 
to the beginning of deposition of a thick gravel and sand 
sequence. The 14C date of a group of small wood and bark(? 
fragments found in the gravel of unit 53, directly on top of the 
event N horizon, is 830 ± 90 A.D. Because the material could 
represent a tree that was several hundred years old at the time 
of deposition, this age must be considered to be maximal for 
unit 53. The 14C date of a small lump of charcoal in unit 51, a 
sand below the event surface, is 1120 ± 100 A.D. Because this 
date is incongruous with dates higher and lower in the section 
and with estimated rates of sedimentation, it is assumed to be 
eroneous.

A date for event N is estimated from sedimentation rates 
and the dates of unit 49 (850 ± 55 A.D.) and unit 61 (1225 ± 
45 A.D.). First, a date is estimated from the unit 61 date. A 
date for event R (1190 ± 45 A.D.) has already been calculated 
using unit 61, by subtracting the estimated sedimentation 
times between event R and unit 61. To derive an event N date, 
the following must be subtracted from the event R date: (1) 
300 mm of silt and clayey silt at 1.9 mm/yr ± 32% = 158 ± 51 
years and (2) 50 mm of clayey peat silt at 1.9 mm/yr ± 32% = 
26 ± 8 years. This gives a date of 1004 ± 69 A.D.

In calculating the event date from unit 49, the following 
must be added to 850 ± 55 A.D.: (1) an average 120-mm 
thickness of silt at 1.9 mm/yr ± 32% = 63 ± 20 years and (2) 
an average 13-mm thickness of peat and peaty silt at 1.4 mm/ 
yr ± 18% = 9 ± 2 years. The event N date thus calculated from 
the unit 49 date is 922 ± 72 A.D.

A final date for event N is derived by statistically combining 
the dates calculated from unit 61 (1004 ± 69 A.D.) and unit 49 
(922 ± 72 A.D.) according to (1) and (2). This gives an event 
N date of 965 ± 50 A.D.
Recurrence Intervals at Pallett Creek

Figure 27 summarizes the estimated dates of occurrence of events D-Z. The vertical bars show the 68% (1 standard deviation) confidence limits for each event date. More 14C date determinations would refine and probably modify some of these dates and uncertainties. Study of additional exposures could conceivably yield evidence for one or two additional large events. Recurrence intervals (RI) are calculated for any two successive events in the manner suggested by Beers [1962, p. 33]:

$$RI = \frac{|A - B| \pm (\sigma_A^2 + \sigma_B^2)^{1/2}}{2}$$ (8)

where $A$ and $B$ are the dates of the events. Lower limits on the recurrence interval shown in parentheses in Figure 27 are the times required to deposit the silts and peats in the section between events, according to (4), (6), and (7).

Nonuniform recurrence of large earthquakes at Pallett Creek is an almost inescapable conclusion. Although the average recurrence interval is about 160 years, intervals as short as 57 ± 9 years and as long as 275 ± 68 years do exist in this 1400-year period. The intervals appear to have a bimodal distribution, with clusterings of intervals around about 100 and 230 years. The short intervals in most cases alternate with the long ones. Thus there appears to have been a fairly stable pattern in the Pallett Creek seismic history. The following are the shorter intervals: X-Z is 112 ± 55 years (but not less than 88 years), R-T is 57 ± 9 years, I-N is 105 ± 61 years (but not less than 72 ± 20 years), and D-F is 120 ± 92 years (but not less than 95 ± 19 years). Lower limits for each recurrence interval (in parentheses) derived from sedimentation rates suggest that the true intervals are more likely to be among the higher values in these ranges. The following are the longer intervals: V-X is 275 ± 68 years, T-V is 225 ± 60 years, N-R is 225 ± 67 years, and F-I is 195 ± 87 years. This apparent alternation of long and short intervals is, of course, less convincing if the dates of the events are shown with an uncertainty of 2 standard deviations rather than just 1.

4. Summary

The evidence for large earthquakes at Pallett Creek is of three types: (1) sedimentary deposits and faulted relationships along the main fault (e.g., Figures 17, 19, 21, and 22), (2) secondary faults that are overlain by sediments that accumulated after the faults moved (e.g., Figures 14, 15, and 16), and (3) liquefaction phenomena, especially sandblow deposits (e.g., Figures 10, 11, and 12). Evidence of all three types that is visible in the mapped exposures (in pocket) is summarized in the Appendix.

A brief summary of the evidence for each event follows.

1. The 1857 earthquake is associated with a large (300 mm) scarp, 3-4 m of right lateral slip, and a broad warp of the ground surface. I have found no secondary faults or sandblows that were produced during this great event, but evidence that liquefaction of the surficial units occurred is locally very pronounced.

2. Event X (1745 ± 24 A.D.) resulted in scarps and ground deformations similar in magnitude and style to those of the great 1857 event. Therefore several meters of right lateral slip probably occurred. One sandblow and one large secondary fault developed at this time.

3. Event V (1470 ± 40 A.D.) is indicated by a large (400 mm) scarp on the main fault and ground deformation similar in magnitude and style to that of the 1857 event. Hence several meters of right lateral slip probably occurred during event V. A fissure also developed during this event, but I have not identified any sandblow features.

4. During event T (1245 ± 45 A.D.), liquefaction of a subsurface unit(s) occurred, and several small faults and other deformations and small sandblows resulted. Cracks and a scarp developed along the main fault trace, and ground deformation seems to have occurred. Right lateral slip of several meters is probable.

5. Event R (1190 ± 45 A.D.) may not be associated with a scarp on the main fault or ground deformation similar in style or magnitude to that of the 1857 event. Horizontal slip of at least several hundred millimeters did occur, however, on each of three secondary faults exposed in the excavation. This indicates an event with displacements at least as large as those of the 1968 Borrego Mountain earthquake ($M_L = 6.4$).

6. Event N (965 ± 50 A.D.) resulted in ground deformations at least as large as those produced by the 1857 event. In one exposure an 800-mm-deep flexure occurred adjacent to the main fault. These deformations indicate right lateral slip of several meters. In addition, small secondary faults and flexures developed during event N.

7. Event I (860 ± 35 A.D.) produced a large number of medium to small size sandblows and abundant evidence of
surficial soft sediment deformation. Secondary faults moved during the event also. There is evidence supporting offset along the main fault during this event, but it is not conclusive. Ground deformation that occurred adjacent to the fault may indicate that substantial horizontal slip accompanied the event.

8. Event F (665 ± 80 A.D.) is characterized by many large sandblow deposits. Slip on several secondary faults accompanied the event, in some cases preceding the sandblow activity. Ground deformations associated with the event are similar in magnitude and style to those of event N and the 1857 event. Thus event F must have involved several meters of horizontal slip.

9. Event D (545 ± 45 A.D.) produced sandblow deposits as large as or larger than those produced by event F. Whether or not the many secondary faults that formed during this event are tectonic or related to liquefaction is unclear. Exposures of the strata containing evidence for event D are inadequate for observing scarp on the main fault or ground deformations. Hence I cannot determine with certainty that this event was associated with large horizontal slip on the fault. The sandblow features, however, indicate an event of \( M \geq 6 \), and their similarity to those of large event F suggests that event D was a large event.

Figure 27 summarizes the estimated dates of occurrence of events D-Z. Dormant periods between these events range from about 1 century to perhaps 3 centuries. Long periods of inactivity (~230 years) appear to alternate with short periods (~100 years).

5. DISCUSSION

The Pallet Creek earthquake record is only one set of data necessary for assessing the late Holocene and future behavior of the San Andreas fault. From this solitary record it is apparent that at least at one locality along the fault the average period between large seismic events has been about 160 years. Also it seems that dormancy between large events has alternated between short (~100 year) and long (~230 year) intervals in a fairly regular fashion. At least seven and perhaps all nine of the large events since the sixth century A.D. are associated with displacements at Pallet Creek as large as the 1857 displacements (i.e., several meters). Ultimately, data from elsewhere along the fault are needed to estimate the extent of rupture and amount of displacement associated with each of these Pallet Creek events and their relation to other large events not affecting the Pallet Creek sediments. Nevertheless, some inferences and educated guesses can now be made regarding the late Holocene and future behavior of the San Andreas fault in central and southern California.

A 'Uniform Earthquake' Model

The rupture length and displacement values for the 1857 event are relatively well known (Figure 2). It is possible that large 1857-like events dominate at least the Holocene history of that reach of the fault. Although this was first suggested on the basis of the post-1857 seismic dormancy and the bedrock geology [Allen, 1968], preliminary analyses of late Holocene geomorphic features along the fault also lend credence to this hypothesis [Sieh, 1977, chapter 2]. These analyses and studies in progress suggest that the past several displacement events in the Carrizo Plain and near Pallet Creek are characterized at each locality by very similar displacements. Thus the 1857 displacements and rupture length may be fairly representative of past (and future) events along that reach. If so, the Pallet Creek seismic history would be applicable to the entire 300-km-long south central reach of the fault. This would imply, however, that the long-term slip rate is about 60 mm/yr (a 9.5-m displacement every 160 years) in the Carrizo Plain but only about 30 mm/yr (a 4.5-m displacement every 160 years) near Pallet Creek. Studies of a large offset channel in the Carrizo Plain [Sieh, 1977, chapter 2] indicate that the average late Holocene slip rate there has been no less than about 37 mm/yr. Continuing study of this channel may place an upper bound upon the slip rate, thus enabling acceptance or rejection of the hypothesis that 1857 events alone characterize slip along the fault.

A 'Uniform-Slip' Model

Elsewhere in the Carrizo Plain, three small alluvial fans, offset in 1857 about 6.5 m from their source gullies, provide a geomorphic hint that the predecessor to the 1857 event may have occurred about 300-400 years prior to 1857 [Sieh, 1978]. Hence I cannot determine with certainty that this event was associated with several meters of strike-slip offset in 1857 about 6.5 m from their source gullies, provide a geomorphic hint that the predecessor to the 1857 event may have occurred about 300-400 years prior to 1857 [Sieh, 1978].

Figure 28 illustrates how this uniform-slip model might be extended into the more distant past. Events Z (1857), V, T, N, and F are assumed to be 1857 type events, and events X, R, I, and D are assumed to be event X type events. Two rupture
lengths are postulated for the event X class (Figure 29). In both cases their northwestern terminus is coincident with the northwestern limit of 3- to 4-\(\text{m}\) 1857 displacements. To the southeast it is plausible that those ruptures might extend only as far as San Bernardino and be associated with a \(M_s \geq 7\) earthquake (Figure 29a). Alternatively, they may be much more extensive ruptures (Figure 29b) associated with a truly great (\(M_s \geq 8\)) earthquake. In other words, the postulated non-1857-type events recorded at Pallett Creek may be either smaller ‘fillers’ at the historically slip-deficient southeastern end of the 1857 type ruptures or great earthquakes with ruptures overlapping in the vicinity of Pallett Creek. Two observations may indicate that the latter is the more reasonable expectation:

1. Although at Pallet Creek the average recurrence interval for large events is about 160 years and in the Carrizo Plain is \(\leq 255\) years [Sieh, 1977, chapter 2], the San Bernardino–Salton Sea segment of the fault has not experienced a large event in over 200 years.

2. The southern California uplift of 1959–1974 [Castle et al., 1977], which may indicate slip on faults below several tens of kilometers [Thatcher, 1976], extends from northwest of Pallett Creek to the Salton Sea.

What does this speculative model suggest about future activity? If 1857 type events do occur as the second member of a closely timed pair, then the next event will not be of the 1857 type. Instead it will be an event like X, R, I, or D, perhaps a truly great event with large fault offsets from the Salton Sea to Palmdale or perhaps a major event with large offsets from about San Bernardino to about Palmdale. Its occurrence should follow the 1857 event by the amount of time that event I followed event F (195 ± 67 years), event R followed event N (225 ± 67 years), event V followed event T (225 ± 60 years), or event X followed event V (275 ± 68 years). A best estimate for its time of occurrence might be the average of these past recurrence times: 233 ± 34 years after the 1857 event (i.e., 113 ± 34 years from now).

Such extrapolations of the Pallett Creek data must be confirmed or repudiated by data from other localities along the fault before any detailed model of long-term fault behavior can be considered to be useful or reliable.

**APPENDIX: SUMMARY OF EVIDENCE FOR EACH EVENT**

**Event Z, 1857 A.D.; Stratigraphic Location, Unit 88/Unit 93 Boundary**

Major fault slip. The geomorphic and historical record shows 3–4\(\text{m}\) of right lateral slip (Figures 1 and 2). There is also slip on the main fault (Z-10-2), where very loose pebbly sand of unit 78 is faulted against unit 88. The fault does not break unit 93, implying that the faulting occurred between deposition of units 88 and 93. In faults Z-11-1, Z-11-2, and Z-11b-1, shearing of unit 88 does not affect unit 93.

Ground deformation. The deviation from horizontal of the upper surface of unit 88 in exposure 11 reflects deformation due to the 1857 event. See the text and Figure 22 for details.

Soft sediment deformation. Diapirs of unit 81 and lower unit 88 pierce unit 88 (Z-10-1, Z-10-3, Z-10-4, Z-11-3, Z-11-4, Z-11-5, and Z-11-6). Distortions of unit 88 are not reflected in overlying unit 93, implying that the distortions occurred between deposition of units 88 and 93.

**Event X, 1745 A.D.; Stratigraphic Location, Top of Unit 81**

Major fault slip. This is evidenced by scarp on the main fault (X-10a-1 and X-11-1). Scarp on unit 78 is buried by unit 88, implying movement between deposition of units 81 and 88. See Figure 21 for explanation. Ground deformation is similar in style and magnitude to that of the 1857 event. This implies several meters of horizontal slip on the fault. See text and Figure 22 for details.

Secondary fault slip. A fault breaks unit 81 and older units (X-10-1 and X-10a-2) but is overlain by unit 88, implying that faulting occurred between deposition of units 81 and 88.

Liquefaction phenomena. The absence of most of unit 81 (X-11-2) suggests soft sediment deformation after deposition of the unit. Sandblow dike and cone (X-10-2) were deposited onto unit 81. Thin peat mantling part of sandblow deposit is a clear indication that the structure is extrusive, not intrusive.

**Event V, 1470 ± 40 A.D.; Stratigraphic Location, Unit 68/Unit 71 Boundary**

Major fault slip. This is evidenced by a scarp on the main fault (V-11-1 and V-11b-3). A major fault disrupts unit 68 and underlying units, but its surface trace on unit 68 is buried by unit 71. Later unit 70 deposits completely mask the scarp. Facies differences in unit 60 across the fault indicate substantial horizontal slip. The slip occurred before deposition of unit 71 but after deposition of unit 68. V-11b-3 has the same structure as V-11-1; it appears in association with a large monoclinal flexure. Unit 73 appears to have been deposited on the flexure, or scarp, as it thins to the northwest. Slumping of later units off this scarp occurred (V-11b-1). Disturbed

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**Fig. 29. Hypothetical extent of rupture of non-1857 type events recorded at Pallett Creek (PC). Those events which were not associated with 1857 type ruptures extending from southeast of Pallet Creek to the northwest corner of these maps (for extent of 1857 rupture, see Figure 3) may have been associated with rupture of those segments shown in Figures 29a and 29b by a heavy line.**
units 61-68 (V-11-2) or unit 68 (V-11b-2) overlain by undisturbed unit 71 indicate slip on the adjacent main fault.

**Ground deformation.** There is an arch in units 68-75 (V-11-4). Because units above and including unit 72 thin toward the arch, the arch probably developed before unit 72 was deposited. At V-1-1, units 68, 71, and 72 sag; units 71 and 72 may have been deposited in a hollow formed just after deposition of unit 68 and buried by a thick riverine silty sand (unit 73). Evidence discussed in the text and Figure 22 indicates that the style and magnitude of ground deformation are similar to those produced in 1857. This implies horizontal slip of several meters on the main fault.

**Fissure.** Unit 71 and later units clearly cover a fissure that formed after deposition of unit 68 (V-10-1). One meter northwest, silt of unit 71 fills the fissure (Figure 18).

**Soft sediment deformation.** Unit 68 shows distortion below undistorted unit 72 (V-1-2).

**Event T, 1245 ± 45 A.D.; Stratigraphic Location, Top of Unit 61**

**Major fault slip.** This is evidenced by a fissure along the main fault which opened between deposition of units 61 and 68 (T-2-1). Sand and silt that fill the crack may be sandblow materials. A crack filled with clay of unit 68(?) probably formed during event T (T-10-3 and T-10a-1). Ground deformation possibly as large as deformations in 1857 implies several meters of horizontal slip. See the text and Figure 22.

**Secondary fault slip.** See Figure 16 for interpretation of fault T-2-2. Movement which occurred on this fault after deposition of unit 61 was followed by slip until deposition of the middle parts of unit 68. This later faulting may represent slumping toward the main fault trace in response to the existence of a fissure or unstable scarp at the main fault.

**Liquefaction phenomena.** T-1-1 is a clastic dike continuous with materials deposited on the top of unit 61. This is probably a sandblow vent and deposit. Lenses of silt separating units 61 and 68 (T-1-3, T-1-4, and T-11-1) probably are small sandblows. Soft sediment deformation is in evidence: unit 61 is discontinuous at T-1-2. A minor fault (T-10-1) breaks units 55-61 but not the overlying or the underlying units. It is probably not tectonic in origin but rather is related to liquefaction of unit 50 during event T. The slab of unit 61 (T-10-2) and the general disruption of units 50 and 61 for 1 m to the southwest may indicate liquefaction of these units during event T (see Figure 15). Contortions of unit 61 (T-11-2) appear to antedate deposition of the overlying unit.

**Event R, 1190 ± 45 A.D.; Stratigraphic Location, Upper Unit 50**

**Fault slip.** Movement on the fault zone in exposure 7 occurred after deposition of unit 50 but before deposition of unit 61 (see exposure 7 in Figures 7 and 9). Movement on the fault in the bulldozer cut included at least several hundred millimeters of horizontal slip, as indicated by facies differences in unit 50 across the fault (see Figures 14, 7, and 9). Movement on fault (R-11-1) followed deposition of most of unit 50 but preceded deposition of unit 61. Difference in facies of unit 50 across the fault indicates at least several hundred millimeters of horizontal slip. Possible termination of a fault (R-11-2) in the main fault zone may have occurred in upper unit 50. A secondary fault (R-11-3) appears to terminate in upper unit 50.

**Fissure.** A fissure (R-10-1) reactivated during event V may have been active before deposition of upper unit 50 and unit 60.

**Event N, 965 ± 50 A.D.; Stratigraphic Location, Unit 52/Unit 53 Boundary**

**Major fault slip.** Fault scarp breccia occurs as a rubbly unit (N-1-6) which developed contemporaneously with deposition of gravel of unit 53. This unit may indicate the sudden production of a scarp along the fault just prior to deposition of unit 53. Fault and the rubble of the main fault zone (N-3-1) are overlain by unbroken unit 53. Ground deformation (N-1-5) occurs near the fault. Unit 45 through lower unit 50 tilt away from the fault, but younger units do not. This indicates development of a major flexure adjacent to the main fault sometime between deposition of unit 52 and unit 55. Also this deformation implies major fault slip at that time. Ground deformation associated with event N in exposure 11 is similar in style and magnitude to 1857 deformations in exposure 11. Thus I infer that several meters of horizontal slip accompanied event N. See the discussion in the text and Figure 22. Fault slip occurs in a major zone of faulting (N-1-1) that disrupts sediments below unit 53 but does not break unit 53.

**Soft sediment deformation.** Deformation of unit 52 (N-11-4 and N-11-5) does not continue upward into overlying unit 53 here or in the natural cut at the end of trench 11.

**Secondary fault slip.** Minor faults (N-1-2, N-2-1, N-1-3, N-3-2, N-3-3, N-11-1, N-11-2 and N-11-3) in lower unit 50 do not appear to offset unit 53. A minor fault (N-3-4) offsets layers below unit 53 more than it does younger layers. N-11-2 and N-11-3 juxtapose different facies and thicknesses of units 45-49, implying perhaps several tens of millimeters or more of horizontal slip.

**Event I, 1860 ± 35 A.D.; Stratigraphic Location, Unit 45/Unit 47 Boundary**

**Major fault slip.** Unit 47 rests on severely disturbed unit 45 near the main fault at I-2-1. This may imply slippage along the fault during event I. Inclination of unit 47 adjacent to the main fault at I-10a-2 appears to be the original depositional slope. This suggests that unit 47 was deposited upon a scarp. The text and Figure 13 consider the possibility that the scarp is not tectonic in origin. The text and Figure 22 consider evidence for ground deformation from exposure 11.

**Liquefaction phenomena.** Evidence for soft sediment deformation is abundant. At I-10-3, I-11-3, I-10-2, I-11-7, I-11-5, and I-11-9, unit 46 buries the undulatory and/or faulted upper surface of unit 45. At I-10a-3 and I-11-6, distortions of unit 45 do not continue into unit 47. At I-10-1, vertical ‘flames’ of laminations indicate a sandblow vent. The small fissure in unit 45 with vertically laminated silt filling is probably a vent. I-10a-1 is the same deposit 1 m to the northwest. Two small faults break the base of but not the top of the sandblow deposit. I-10-5 is a thin sand dike which probably served as a conduit for liquefied unit 39 sand to be deposited as unit 46 during event I. A lenticular sand body (I-11-1) is probably a sandblow deposit. The lack of a correspondingly thick lens on the opposite side of the bounding fault results from horizontal fault slip. This body thins to only a few centimeters about 200 mm into the trench wall. Across the trench on the opposite wall the body is a thick wedge on both sides of the fault. Small pods of sand are probably sandblow deposits (I-11-2, I-11-4, I-11-8, I-11-10 and I-11b-1). I-11b-1 disappears about 1 m to the northeast and does not appear in exposure 11 1 m to the southeast.

**Secondary fault slip.** Fault I-10-4 separates units 38, 41, and 45 by 160, 180, and 120 mm, respectively. Separation of
unit 47 is only 30 mm. This probably indicates fault slip between deposition of units 45 and 47.

**Event F, 665 ± 80 A.D.; Stratigraphic Location, Unit 39**

**Ground deformation.** At F-5-2, unit 38 displays large irregularities relative to overlying units 45 and 47. As units 45 and 47 are relatively flat lying in the plane of exposure 5, it appears that a faulting event tilted unit 38 before deposition of units 45 and 47. This tilting is attributed to event F and implies major fault slip at that time. Other evidence for deformations similar in magnitude to 1857 deformations is in the text and Figure 22.

**Liquefaction phenomena.** A sandblow vent and cone comprise unit 39 at F-7-1. Two large kettle-drum-shaped pits (F-10-1 and F-10-2) are filled with clays, silts, and sands of unit 39. Units 34–38 are ‘blown out’ of the section. A tabular plug deposited beneath the surface along a fault appears in exposures F-11-1 and F-11a-1, which are separated by about 1 m. Overlying the plug is a deposit of extruded sand. Notice the vent to the right of the letters ‘F-11a-1.’ A pit excavated into units 34–38 (F-11a-3 and F-11a-4) and filled with silt and clay is overlain by laminated sand. Soft sediment deformation occurs at F-10a-1, where units 39 and 41 cap deformed and faulted unit 38. Elsewhere, silty basal unit 39 is highly contorted. This indicates seismic shaking.

**Secondary fault slip.** At F-5-1, unit 38 and lower units are folded and faulted in a complex manner. Unit 39 and overlying units at this location are undisturbed. A sandblow deposit occurs along this fault immediately northwest of the plane of exposure 5. Along fault F-7-2, units 38 and 39 are offset about 80 mm. Unit 41 is offset only 20 mm. This suggests slip between deposition of units 39 and 41, perhaps related to the evacuation of the sand composing F-7-1. Fault F-10-3 appears to offset basal unit 38 but not unit 41. Unit 38 and older units are offset more than unit 41 along fault zone F-11-2 and F-11a-2.

**Event D, 545 ± 45 A.D.; Stratigraphic Location, Unit 34**

**Major fault slip.** Peaty and clayey unit 33 is downdropped about 300 mm on the southwest side of a wide fault zone (D-10-6). Later cratering of event F, laminated direct evidence that younger units are not faulted. It can be inferred that unit 38 is not offset across the event F sandblows. The difference in thickness of unit 34 across the fault zone also implies fault slip between deposition of units 33 and 34.

**Liquefaction phenomena.** Evidence of sandblow vents near exposure 7 connecting with unit 34 exists but is not documented in this paper. Linear, near-vertical streaks or laminae are more common along the san Andreas fault system. A thickened clay stratum (D-11-3) may suggest a dimple in the ground surface at the time of its deposition. The dimple may have been the remnant of an event D sandblow crater. A clay cone (D-11-4) that widens to the southeast is similar to cones associated with sandblow vents elsewhere at Pallet Creek.

**Secondary fault slip.** D-10-1 appears to fault all of unit 34 and ends at a buried scarp at the top of unit 34. D-10-2 faults basal unit 34 but not younger units. D-10-3 faults basal unit 34 and underlying units 150–250 mm but does not similarly affect upper unit 34 or units younger than unit 34. Faults terminating within unit 34 (D-11-1) probably moved before and during initial deposition of unit 34 but became inactive prior to later unit 34 deposition.

**Acknowledgements.** The advice, support, and insight of many friends and colleagues were critical to this effort. I am especially grateful to my Ph.D. advisor, Richard Jahns. Clarence Allen, Malcolm Clark, Tom Hanks, and Peter Molnar also suggested many improvements in the manuscript. In the field I was assisted principally by my brother, Rodger; my wife, Laurie; and my friend, David Drake. W. A. Crockett kindly allowed us to excavate on his property. U.S. Geological Survey contract 14-08-0015-1522 supported this work, which is contribution 2989 of the Division of Geologic and Planetary Sciences, California Institute of Technology.

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(Received November 9, 1977; revised April 13, 1978; accepted May 4, 1978.)