ASPECTS OF THE LATE HOLOCENE BEHAVIOR OF THE SAN ANDREAS FAULT SYSTEM

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ABSTRACT

This contract supported continuing investigations of the late Holocene behavior of the faults of the San Andreas fault system. The purpose of these studies has been to determine the long-term fault slip rates and the frequencies and spatial relationships of large earthquakes along the faults. Such information may lead to forecasts of the location, time, and size of future large earthquakes along the fault.

During 1980, work progressed as outlined below:

1) A new series of radiocarbon dates from Pallett Creek (locality 2, Fig. 1) is enabling a more accurate determination of the dates of the 9 to 13 prehistoric earthquakes recorded in the late Holocene sediments there. The average recurrence interval is somewhere between 125 and 225 years. Variations among actual intervals are difficult to assess, in part because of imprecisions of the ^{14}C dates.

2) A program of three-dimensional excavations begun last summer at Pallett Creek (see 1979 Final Technical Report) has resulted in documentation of right-lateral offsets that increase with with age. Also, a complex pattern of evolution of faulting and other deformation is emerging.

3) New analyses of radiocarbon dates from Wallace Creek (locality 3, Fig. 1) suggest that 64 mm/yr is an upper limit on the Holocene slip rate for the San Andreas fault there. Analysis of this and older data reported at the end of 1979 indicate that the slip rate is between 34 and 64 mm/yr. These rates lead to the conclusion that great earthquakes occur on the average every 140 to 270 years at Wallace Creek. One implication of this fast slip rate is that plate motions are accumulating more rapidly than they are being relieved along the creeping segment of the fault to the north. We may therefore expect the creeping segment to generate large earthquakes

as well as creep. This also raises the possibility of continuous seismic rupture of the northern, central and south-central segments of the fault (see Fig. 1).

4) Surficial and subsurficial geologic mapping along the San Andreas fault near Indio (locality 1 on Fig. 1) began to reveal the prehistoric behavior of the historically dormant segment of the fault. Apparently, no large slip events have occurred at the site for at least the past 480 and perhaps the past 680 years. About 1 m of strike-slip has occurred during this time period, however. It may be associated with one or more moderate earthquakes or aseismic creep.

5) Howard Shifflett's studies of offset cultural features along the creeping segment of the fault (locality 4, Fig. 1) aimed at discovering variation in slip rate(s) during the past 100 years are progressing, but we have no conclusive results to report yet.

6) Ray Weldon has continued his studies of the Lost Lake terraces along the fault near Cajon Pass (locality 6, Fig. 1). Last year's final report, which described Weldon's work there during 1979, outlined his tentative evidence for a Holocene slip rate of 2 to 2-1/2 cm/yr at this site. Subsurface work this year provided additional samples that will confirm or modify this range of values. He has also identified several late Holocene colluvial deposits, each of which may represent one seismic event. ^{14}C dates of samples related to these deposits are not yet determined.

7) Surficial and subsurficial studies of earthquake recurrence at my site along the San Jacinto fault zone in San Bernardino (locality 7, Fig. 1) were partially successful. Flooding of the site forced termination of the work in late January. Resumption of work may be permanently prevented

by construction of a housing development at the site. Data in hand indicates an average recurrence interval of $\lesssim$800 years.

8) My work with Kristian Meisling on the effect of the 1857 earthquake on trees was published in the Journal of Geophysical Research (June, 1980). Now that it is clear that tree rings do record a known, historical seismic event, Don Piepgras and I have collected many cores and slabs from very old trees near the fault in an attempt to discover the exact year of the youngest large prehistoric event.

In the main text, only items 1) through 4) are discussed in detail.

INTRODUCTION

The San Andreas fault can be divided into four segments, based upon its historical behavior (Fig. 1). The northern and south-central segments have ruptured during great earthquakes in 1906 and 1857, respectively. They have been dormant since their great rupture events. The central segment is characterized by relatively continuous slip at rates as high as 3 cm/yr. The southern segment has been dormant during the entire historical period; that is, it has not produced a major or great event for at least the past ~210 years.

How will the San Andreas fault behave during the next few hundred years? This is a question of great importance for evaluation of earthquake hazard and assessment of earthquake risk. During the past five years, studies supported by the U.S.G.S. under this and earlier contracts have elucidated much of the recent behavior of the southern half of the San Andreas fault. The purpose of these studies, now at the end of their fifth year, is to gain an understanding of fault slip rates, recurrence intervals and patterns of occurrence of large earthquakes. Such information will continue to enable more direct and meaningful assessment of earthquake hazard and determination of seismic risk.

During the first three years of investigation (Contract No. 14-08-0001-15225), I completed (1) the determination of the right-lateral fault slip associated with the great 1857 earthquake in central and southern California (Sieh and Jahns, 1976; Sieh, 1978c); (2) analysis of the felt effects of the 1857 earthquake based on an analysis of over 60 hitherto unknown comtemporary reports (Agnew and Sieh, 1978) and, from these same documents, (3) the recognition and location of foreshocks of the 1857 event, which enable location of the mainshock epicenter and raise the hope that the next such event will also be preceded by recognizable precursors (Sieh, 1978a); (4) the recognition of nine large earthquakes produced by slip of the San Andreas fault at Pallett Creek between ~500 A.D. and the present (Sieh, 1976; 1978b); (5) preliminary studies of the amount of fault slip associated with the latest few large prehistoric earthquakes in the Carrizo Plain (Sieh, 1977, Chapter 2) and determination of an average minimum fault-slip rate for the past 3900 years in the Carrizo Plain (Sieh, 1977, Chapter 2; Hall and Sieh, 1977).

Progress made under last year's contract (14-08-0001-16774) is reported in the 1979 Final Technical Report and summarized below:

1) I continued work on fault and deformational history at Wallace Creek and Van Matre Ranch (Sieh and Jahns, 1980).

2) Liz Thomas began geomorphic and subsurface studies in the Elkhorn Hills and the Elkhorn fault, east of the San Andreas fault in the southern Carrizo Plain.

3) Kristian Meisling and I completed our manuscript on the effect of the 1857 earthquake on trees (Meisling and Sieh, 1979 and 1980).

4) Ray Weldon's work on offset river terraces near Cajon Pass allowed him to make the tentative conclusion that the long-term slip rate of the San Andreas fault is only 2 to 2-1/2 cm/yr there (Weldon and Sieh, 1980).

Some of the work carried out in 1980 is discussed in detail below.

TECHNICAL DISCUSSION

Pallett Creek

Several years ago, a detailed record of late Holocene large earthquakes was uncovered at Pallett Creek (Locality 2, Fig. 1) [Sieh, 1976,1978b]. The record indicated that 9 large earthquakes which occurred between 500 and 1857 A.D. had an average recurrence interval of about 160 years. Additional radiocarbon dates and studies of the affected sediments are allowing a more refined analysis of the seismic history at this site. Fig. 2 summarizes the refinements made this year and last. Firstly, several earthquakes that occurred prior to 500 A.D. have been recognized. Secondly, the dates of the earthquakes have been changed slightly from those reported in Sieh [1978b]. Thirdly, closely-spaced serial excavations and mapping of parallel trenches have revealed many laterally offset reference features at various horizons within the section. These have enabled determination of the lateral offsets associated with several of the younger earthquakes. Combined with maps of vertical deformations associated individual earthquakes, these data are enabling me to conclude that at least some of the events (in left-central column) have slip values about as large as the slip values for 1857.* Analysis of offset reference features related to other events (right-

*T. Davis (unpublished Ph.D. manuscript, U.C. Santa Barbara) has convincingly identified events V, X, and Z (1857) in an excavation across the fault about 125 km to the northwest, confirming my conclusion that at least these latest three were very large and perhaps even great events.

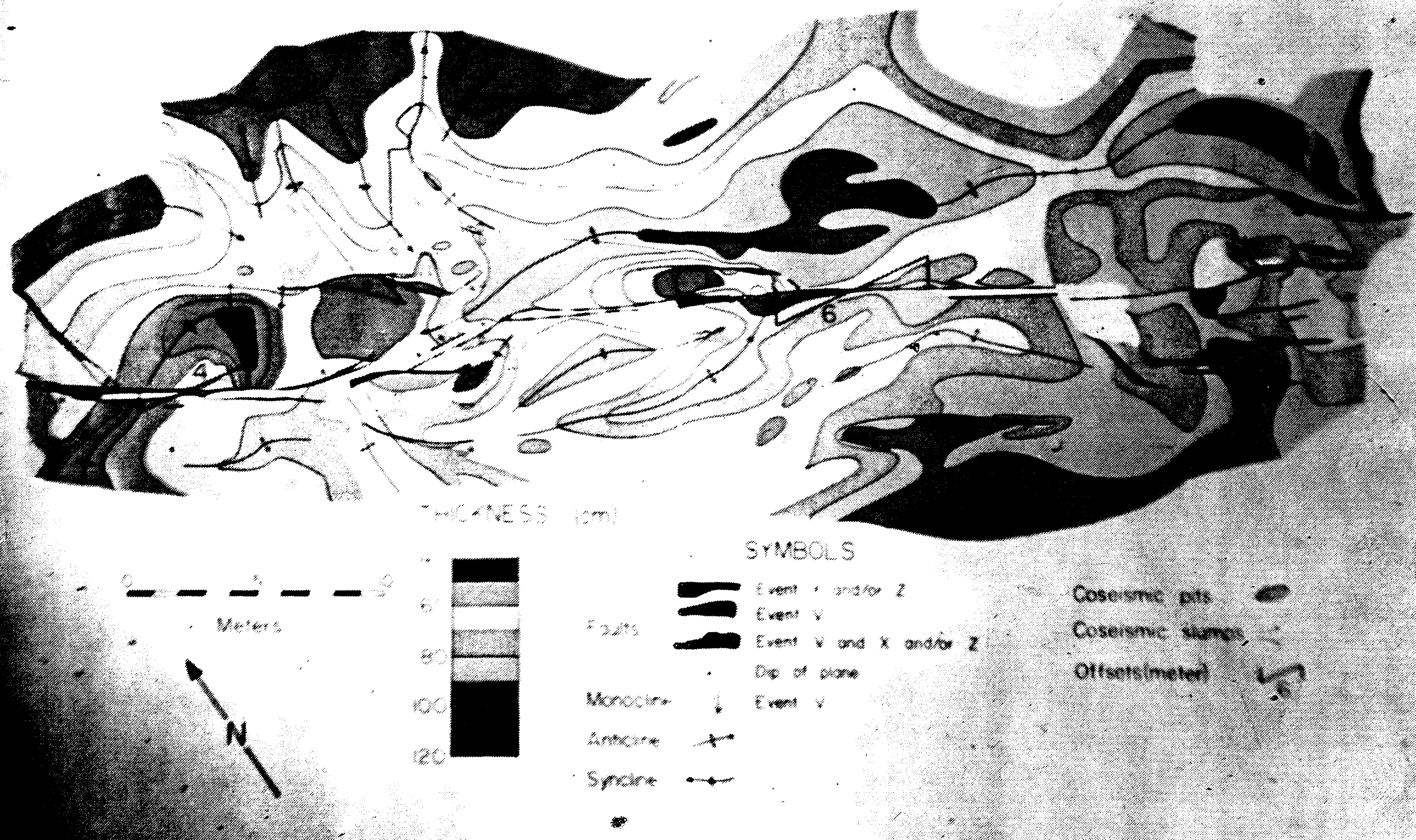
center column) is not yet completed, so I do not know whether they had slippage of the magnitude determined for 1857 or not. The left-hand column displays individual recurrence intervals for great events that are calculated on the assumption that only events F, R, T, V, X, and Z are great. The right-hand column displays the intervals determined if one assumes that all the events are great. One extreme would indicate an average of about 225 yrs. These extremes bracket the actual average interval. The implications of each extreme and a more moderate estimate are summarized in Fig. 3.

Fig. 4 illustrates four plausible sets of large earthquakes that fit the Pallett Creek data relatively well. The first column shows that a uniform recurrence interval of 173 yrs gives dates for all the earthquakes that fall within the $\pm 2\sigma$ limits of those events. It requires that two of the recognized events (I and N) not be large earthquakes. The second column indicates that a uniform interval of 130 yrs would give earthquake dates within the determined $\pm 2\sigma$ limits for all but 3 of the earthquakes. This model would require that all recognized earthquakes be large. Two more realistic schemes are shown in columns three and four. These earthquake dates are selected from the actual record of large earthquakes for parts of the Chilean and Japanese subduction zones and probably give a more realistic irregularity to recurrence intervals. In each case, only the 1857 event does not fit the mold.

The point of the exercise is to show that ambiguities in the Pallett Creek data allow a large number of actual recurrence histories. These range from uniform recurrence intervals as short as 130 yrs or as long as 173 yrs to non-uniform recurrence intervals that scatter by as much as 45% from the average interval. A substantial increase in the precision of the dates of the Pallett Creek events will be necessary before we can know just

Fig. 6

ISOPACH MAP OF UNIT WHICH BURIED EVENT-V SURFACE IS A "MOLD" OF EVENT-V GROUND DEFORMATION



how regular the recurrence intervals actually are.

I mentioned above that I have made much progress in understanding the lateral offsets and vertical deformation associated with the pre-historic earthquakes. Figs. 5 and 6 illustrate the type of information I have acquired. Fig. 5 is a plan view of a channel that was cut into the Pallett Creek section and filled between 900 and 1100 A.D., prior to events T, V, X, and Z. The map was constructed from many trenches cut from left to right across the map with spacing of about 1 m or less. The channel is offset a total of 6 m across two fault traces. Detailed inspection of the trench exposures revealed that post-channel slip along the northern trace occurred only during events T and V, whereas slip on the southern trace occurred only during events X and Z. Thus it appears that a total of 4 m of slip can be apportioned among events X and Z, and 2 m of slip must be shared by T and V. The cross-section of the channel shows that vertical slip is much larger along the older, northern fault than along the younger, southern fault.

Fig. 6 affords a better overview of the excavation. (The top margin of Fig. 5 is the same boundary as the left edge of Fig. 6). This complicated diagram is a isopach map of the unit that was deposited after event V and before event X. The isopach unit represents a "mold" of the topography produced by event V, because the top of the unit was deposited nearly flat-lying. The warm colors represent thinner strata, deposited upon higher points of land. The colder colors indicate thicker strata, which fill topographic depressions. These indicators of paleotopography allow identification of the anticlines and synclines shown with black lines and symbols.

The red structures shown on the map are faults that moved during event V. The black faults moved only later, during events X and/or Z. The dashed red and black faults are those that have broken during all three events. The pattern of faulting during event V is markedly different than that produced during the later two events. Event-V surface faulting, for example, was not continuous near the left edge of the figure. One fault terminates northwestward into a monocline (indicated by red arrows and close spacing of isopach lines). Associated with the discontinuity of the fault trace are a pronounced anticline and syncline. Several hundred years after event V, during events X and Z, the syncline was offset 4 m along the new fault shown in black. This is identical to the value determined from the offset 900-1100 A.D. channel of Fig. 5, which nearly underlies the syncline. The interpretation of these and similar sets of data is incomplete, but even at this state it is clear that the magnitude of the lateral offsets and vertical deformations of several events and the evolution of fault geometries will be invaluable in assessing the sizes of the events relative to the great 1857 event.

In addition, the fault-slip rate and variations in the rate during the past millenia will be determined from these data. Currently it appears that the average rate for the past several hundred years is astonishingly low -- only 10 to 20 mm/yr. This is even lower than the 20 to 25 mm/yr rate we have reported for our site 30 km to the southeast (Locality 6, Fig. 1) [Weldon and Sieh, 1980] and is much lower than the rate at Wallace Creek, about 200 km to the northwest (Locality 3, Fig. 1).

Wallace Creek

Previously [Sieh, final report for contract no. 14-08-0001-16774, 1979, and Sieh and Jahns, 1980] described studies enabled determination of a minimum average slip rate of 33 mm/yr for the past $\lesssim$3900 yrs at Wallace Creek, 200 km northwest of Pallett Creek (Locality 3, Fig. 1).

This was based on the relationship of the 3900-yr-old stratum in Fig. 7 to a 130-m offset channel. The stratum antedates the channel immediately to its left in Fig. 7. That channel is offset 130 m. New analyses now provide a <u>maximum</u> slip rate for the past $\gtrsim$5,900 yrs of 64 mm/yr. This is based on the interpretation that the high-channel gravels of Fig. 7 were deposited within a channel that is now offset 380 m. The channel must have been cut well before 5900 yrs B.P., but the 5900 yrs date provides a minimum amount of time (and therefore a maximum rate) during which the 380 m of slip accrued. Extrapolated ages for the top and bottom of the high-channel gravels are 2800 and 7800 yrs, respectively. These, if valid, would indicate that the 130-m and 380-m offsets accumulated at an average rate somewhere between about 46 and 49 mm/yr.

The fault slip rates determined at Wallace Creek almost certainly are greater than those determined near Cajon Pass and at Pallett Creek. They are probably about twice as large. This suggests that my "uniform earthquake" model [Sieh, 1978b, p. 3935] applies to the south-central reach of the San Andreas fault. That is, the 1857 earthquake, with its 9 m offsets near Wallace Creek and 3 to 4-1/2 m offsets near Pallett Creek may be the characteristic earthquake along this 360±-km-long segment of the fault -- the southeastern half of the segment, with a characteristically smaller offset per event, may <u>not</u> experience earthquakes twice or thrice as frequently as the northwestern half of the segment.

Another possible implication of this high rate of slip at Wallace Creek is that the central segment of the fault (Fig. 1), much of which creeps at about 30 mm/yr, is not relieving all the plate motion by creep. If the relative velocity between the Pacific and North American Plates is between about 46 and 49 mm/yr, $\gtrsim$15 mm/yr of elastic strain is being stored adjacent to the creeping reach of the fault. This requires either bursts of very rapid creep or large earthquakes with ruptures propagating into the creeping segment. Thus the northern and south-central segments of the fault, which broke independently in 1906 and 1857, respectively, may not be separated by a central segment characterized completely by creep. Perhaps an 1857-type event could propagate northwest through the creep zone and involve the northern segment in a "maximum credible" 900-km rupture event.

The southern 200 km of the San Andreas fault (Fig. 1) has not produced a great earthquake during at least the past 210 years of historical record. This is a disconcertingly long period of dormancy, since the average recurrence intervals to the northwest, at Pallett Creek and Wallace Creek, are between 125 and 225 yrs and 140 and 270 yrs, respectively. Thus, the current period of dormancy of the southern segment of the San Andreas fault is at least as long as the longer plausible values for average recurrence intervals for the south-central segment. If the average recurrence interval along the southern segment is about equal to those measured to the northwest, we have reason for great anxiety. Thus, I began this year to search for evidence of prehistoric event on the southern segment near Indio (Locality 1, Fig. 1). Field studies conducted during the winter and spring of 1980 are described in detail in the 1980 semi-annual technical report and are not repeated here. Basically, sediments associated with the latest three high-stands of ancient Lake Cahuilla were found to be broken by two major fault traces. The rupture planes through the deposits of the youngest two lakes are less than a centimeter wide and probably have a combined lateral offset of about 1 m in the deposits of the penultimate lake. The offset is substantially smaller in the younger lake sediments. I suspect these two units have been faulted by either aseismic creep or by slip associated with one or more moderate earthquakes. The fault traces through a subaerial, fluvial deposit underlying the deposits of the penultimate lake also is very narrow. The fluvial unit, however, rests upon a disconformity which truncates a much broader and more complex fault zone. This zone breaks an older lake deposit and older subaerial units. I suspect that the latest large or great earthquake occurred before creation of this disconformity. Radiocarbon analyses of several carbon samples have provided ages for the various deposits. The disconformity dates from somewhere between about 1300 and 1500 A.D. The penultimate lake filled sometime between 1390 and 1650 A.D. The latest lake filled sometime between 1540 and 1590 A.D. or 1625 and 1665 A.D.* Although further work is needed and planned, my tentative conclusion is that no great earthquake has ruptured this segment of the fault since before 1300 to 1500 A.D. (i.e. $\gtrsim$480 to 680 yrs). At least three or four large earthquakes have involved the south-central segment of the fault at Pallett Creek within this period of possible dormancy of the southern segment. Whether this indicates that the southern segment should be considered less hazardous than its northern neighbor for the next 100 yrs is unclear. Dating still older events at the Indio site hopefully will yield a more complete understanding of the southern segment.

*These dates have been dendrochronologically corrected, but the isotopic fractionation corrections have not yet been made. The ranges given are $\pm 2\sigma$ ranges.

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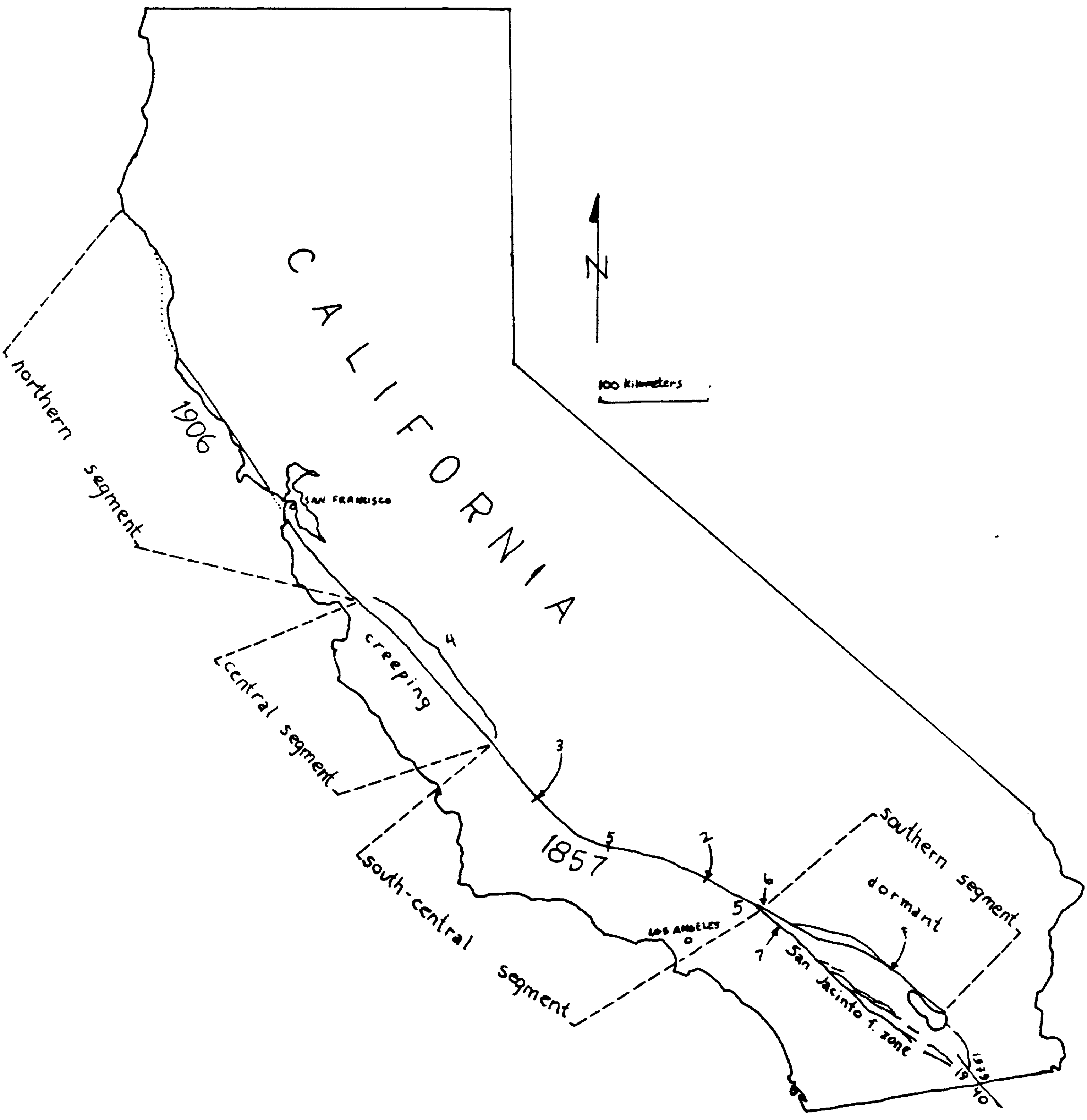


Fig. 1 - Map of current studies along the San Andreas fault system

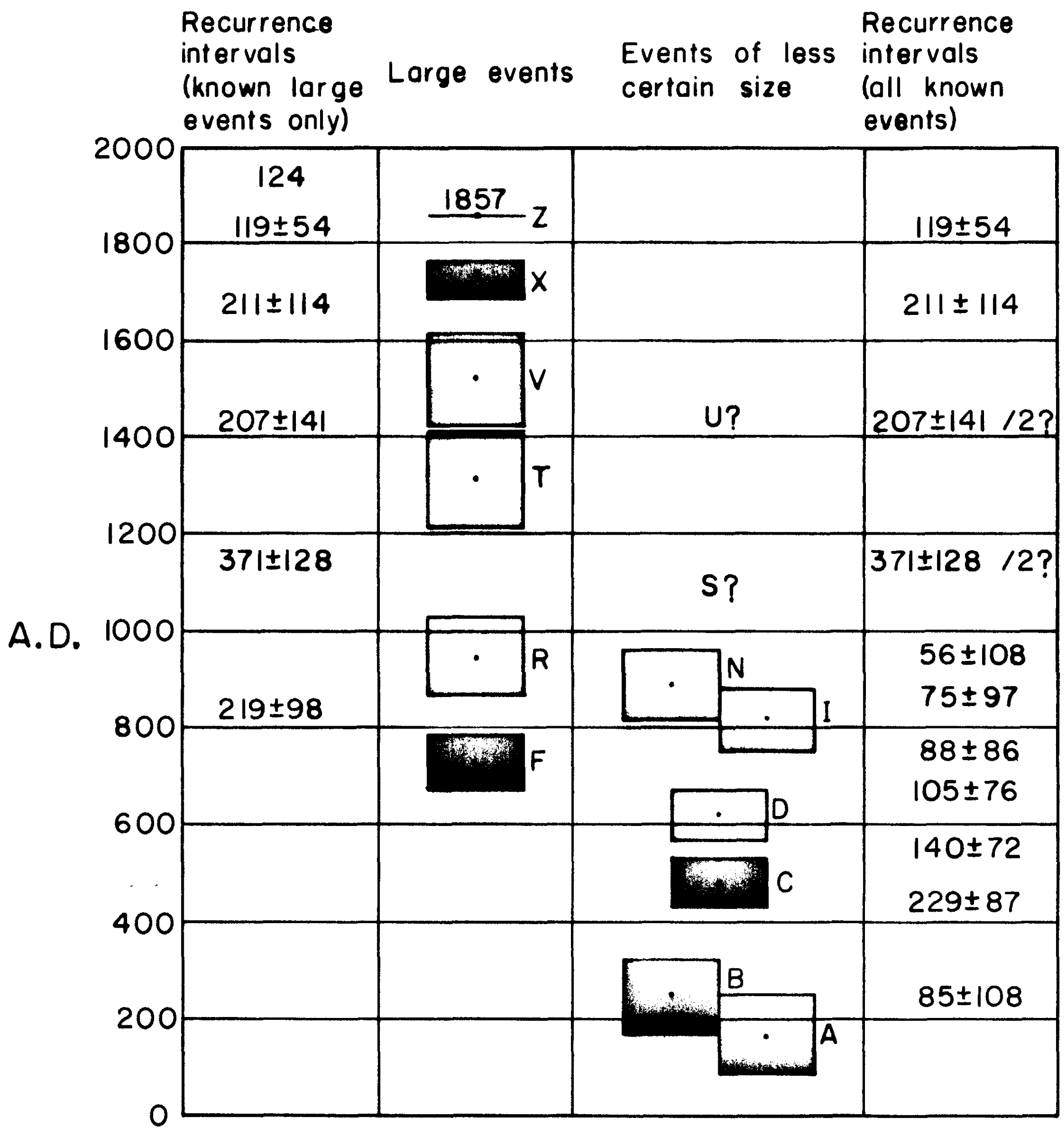


Figure 2

Preliminary dates and recurrence intervals for earthquakes at Pallett Creek

Based on least-squares fit of 28 ^{14}C analyses

Vertical width of color band indicates uncertainly ($\pm 2\sigma$) in date of earthquake.

Average recurrence interval could be anywhere between 123 and 225 yrs.

150± 30 years may be the best estimate

	Scheme	Average Recurrence Interval	Implication
①	Only use known large events (Z,X,V,T,R,F)	225±11 yrs	R.I. is non-uniform; Next event may well be more than 50 yrs from now
②	Use all known events since ~600 A.D.	154±6 yrs	R.I. is non-uniform; Current dormant period is greater than most past R.I.s
③	Use all known events and two unrecognized events (U and S) since ~600 A.D.	123±5 yrs	R.I. may be nearly uniform; Current dormant period may be greater than all but 1 of past 9 R.I.s

Figure 3

ONE MODERATE AND TWO EXTREME SCHEMES AND THEIR IMPLICATIONS

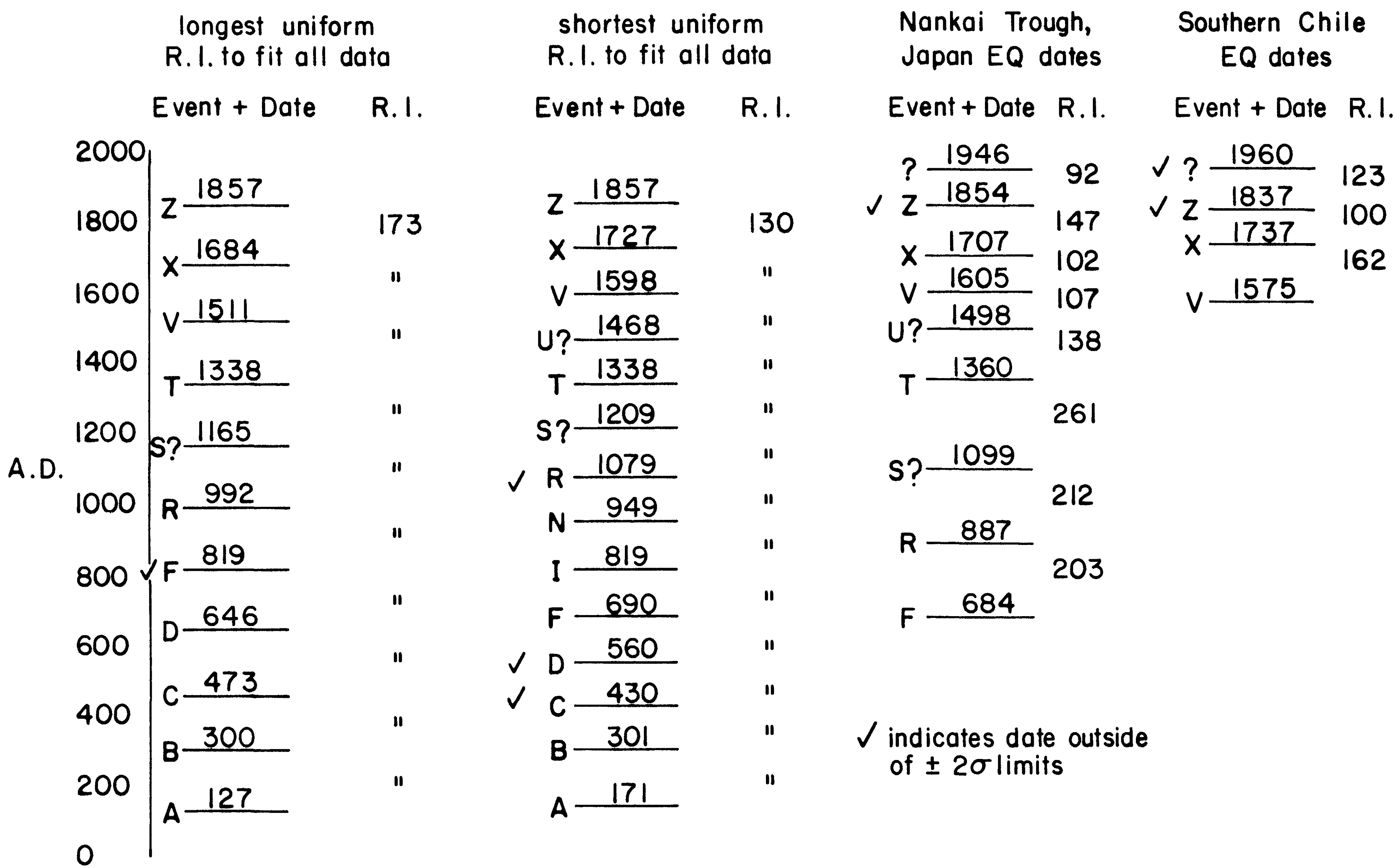
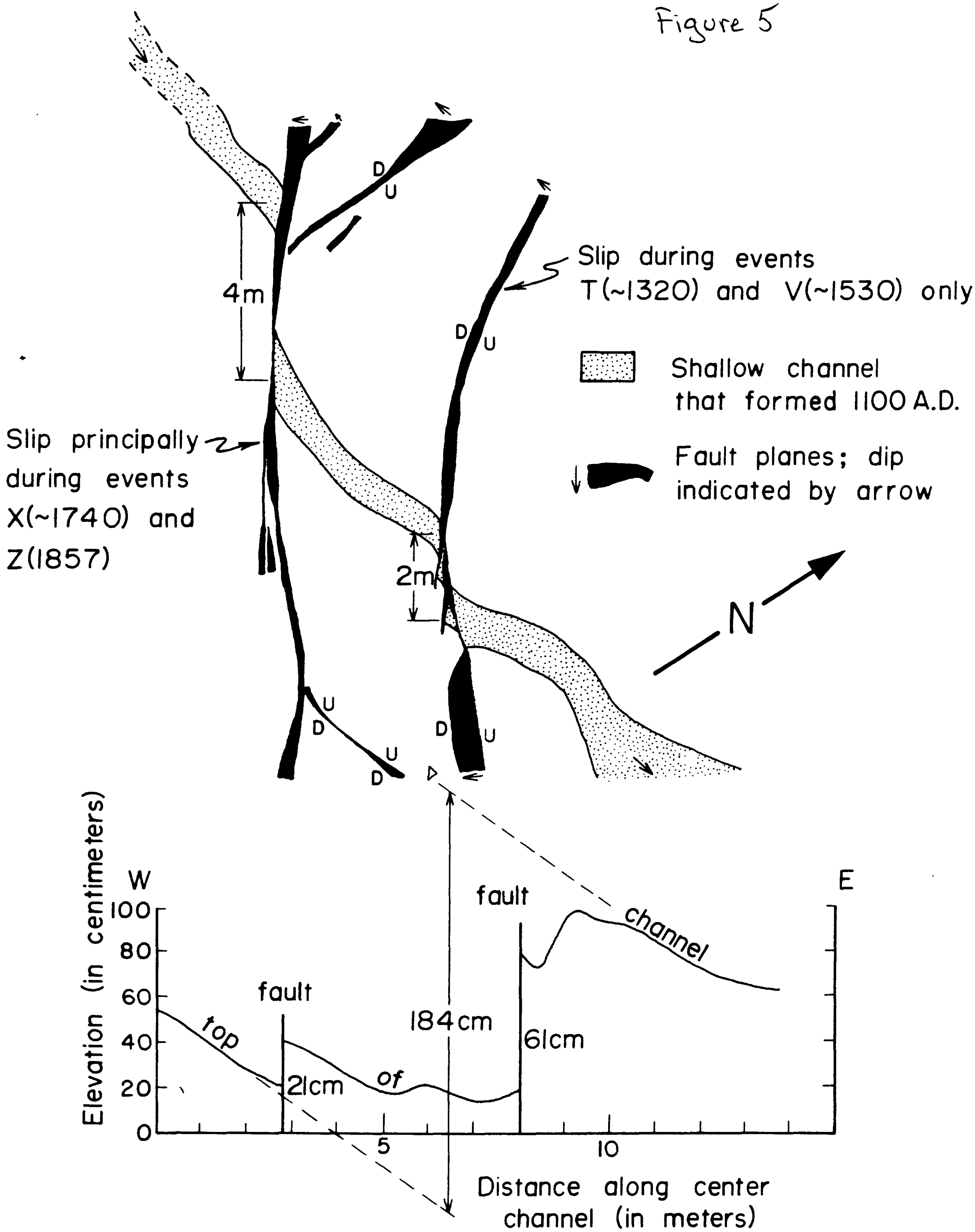


Figure 4

SOME PLAUSIBLE SCHEMES FOR RECURRENCE OF QUAKES AT PALLETT CREEK

Figure 5



D
U
4m
Slip during events
T(~1320) and V(~1530) only
D
U
Shallow channel
that formed 1100 A.D.
Slip principally
during events
X(~1740) and
Z(1857)
Fault planes; dip
indicated by arrow
2m
N
U
D
D
U
U
D
W
E
fault
fault
channel
top
of
184cm
61cm
21cm
Elevation (in centimeters)
100
80
60
40
20
0
5
10
Distance along center
channel (in meters)

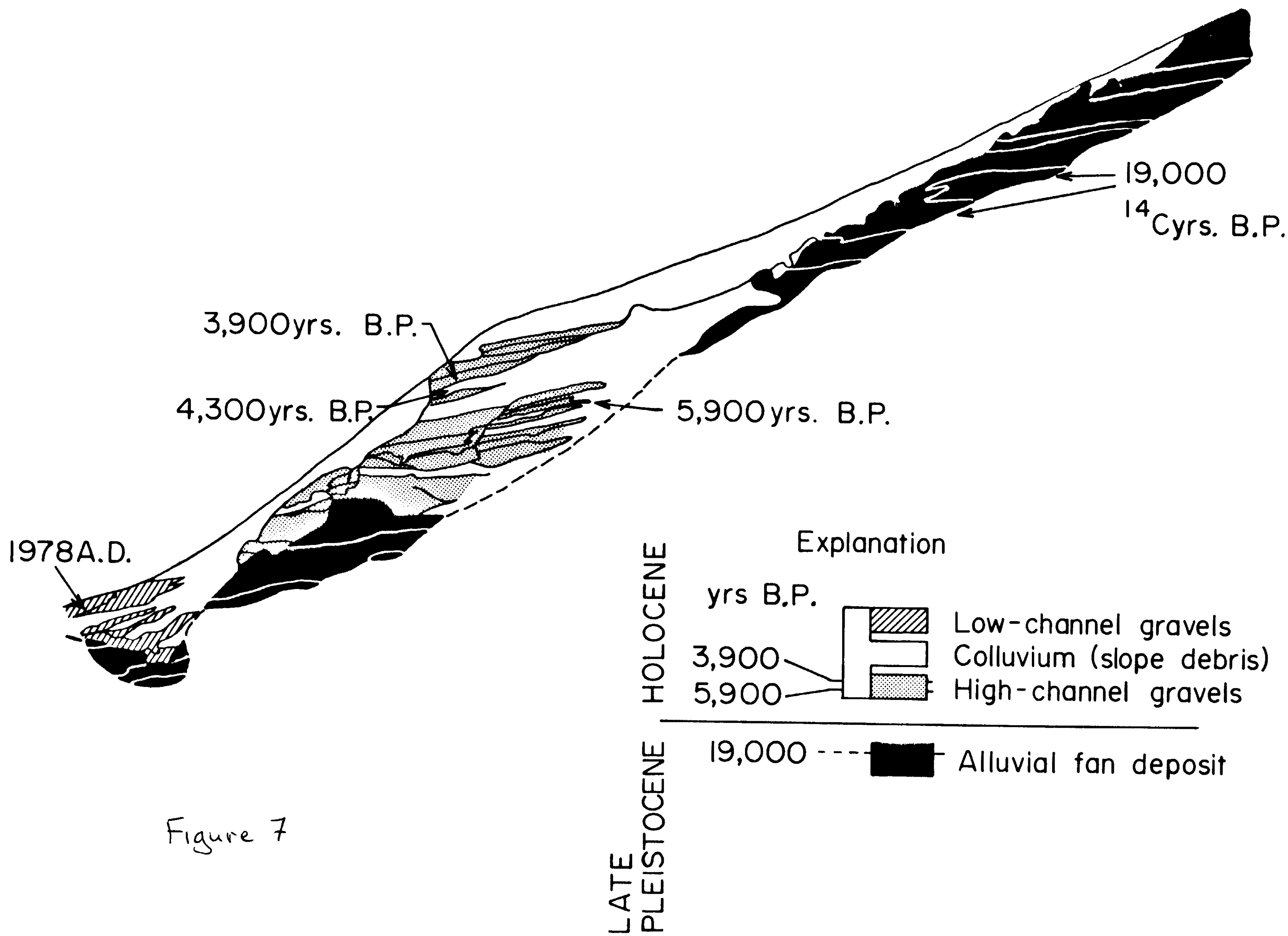

19,000
^{14}Cyrs. B.P.
3,900yrs. B.P.
4,300yrs. B.P.
5,900yrs. B.P.
1978A.D.
Explanation
HOLOCENE
yrs B.P.
3,900
5,900
Low-channel gravels
Colluvium (slope debris)
High-channel gravels
LATE PLEISTOCENE
19,000
Alluvial fan deposit

Figure 7