

NOTES ON STREAM CHANNELS OFFSET BY THE SAN ANDREAS FAULT,
SOUTHERN COAST RANGES, CALIFORNIA*

By

Robert E. Wallace

U.S. Geological Survey, Menlo Park, California

ABSTRACT

Between Cholame and Camp Dix on Highway 33, more than 130 stream channels have been displaced by right-lateral slip on the San Andreas fault. Of these, 40 are offset between 20 and 50 feet. Many offsets of about 30 feet are possibly related to the great earthquake of 1857. A few left-lateral offsets are unexplained.

The configuration of an offset stream channel is a result of the interaction of two sets of processes, one erosion and sedimentation, the other tectonic movement. As a result, each offset channel has a unique complex history.

Recurrent slip along a narrow fault strand in the San Andreas fault zone is clearly indicated by the presence of more than one downstream channel segment related to a single upstream channel and by offsets of different amounts on nearby streams. Such evidence suggests that the most recently active strand is very likely to have recurrent movement and is likely to be active in the future.

Amount of displacement varies along a single fault strand, and many strands are only a few miles long. The individual strands are arranged in an echelon and other interrupted or interlacing patterns.

Accurate displacement rates have not yet been determined.

INTRODUCTION

The channels of many intermittent streams bend sharply to the right where they cross the San Andreas fault (fig. 1). This geometric pattern has long been considered to be one of the strongest pieces of evidence for right-lateral strike slip on the fault during late Pleistocene and Recent time. Along the 70-mile-long segment of the San Andreas fault between Cholame and Camp Dix (fig. 2), more stream channels are conspicuously offset, and the offsets are better preserved, than on any other comparable segment of the fault. The Carrizo Plain, a classic area from which many textbook illustrations of offset streams have been obtained, is within the area studied.

R. E. Wallace

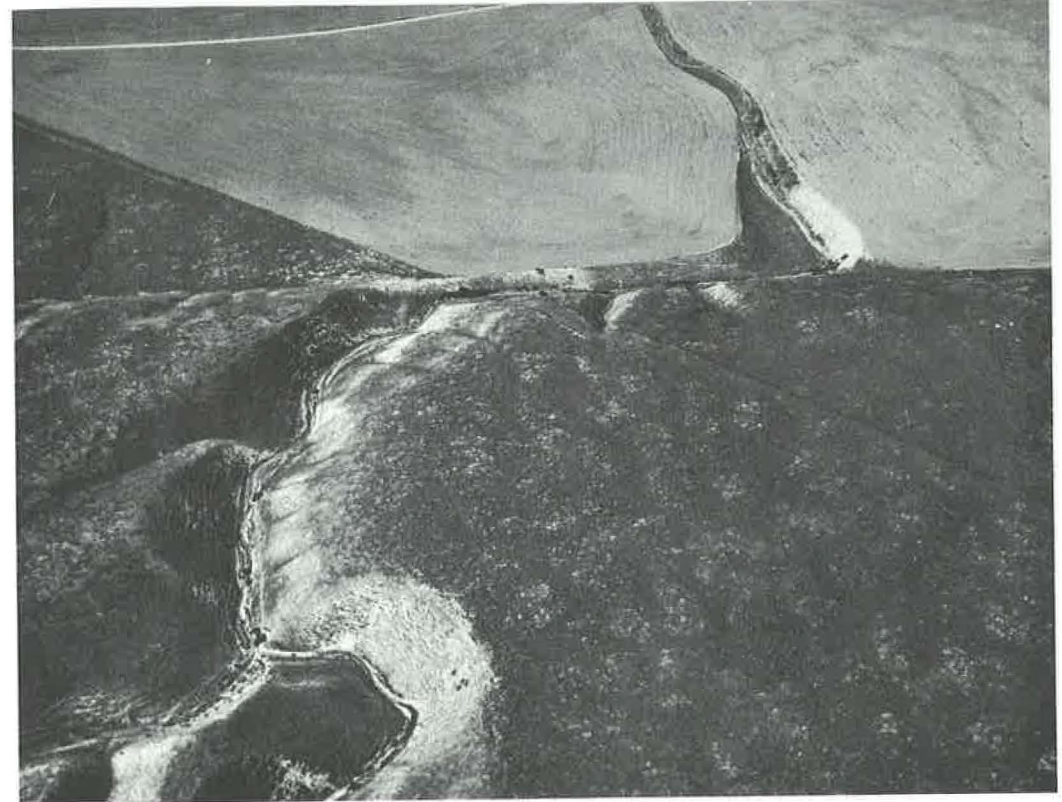


Figure 1.--Oblique view looking southwest across the San Andreas fault zone showing typical right-lateral offset of stream channel where it crosses fault. Offset is about 450 feet.

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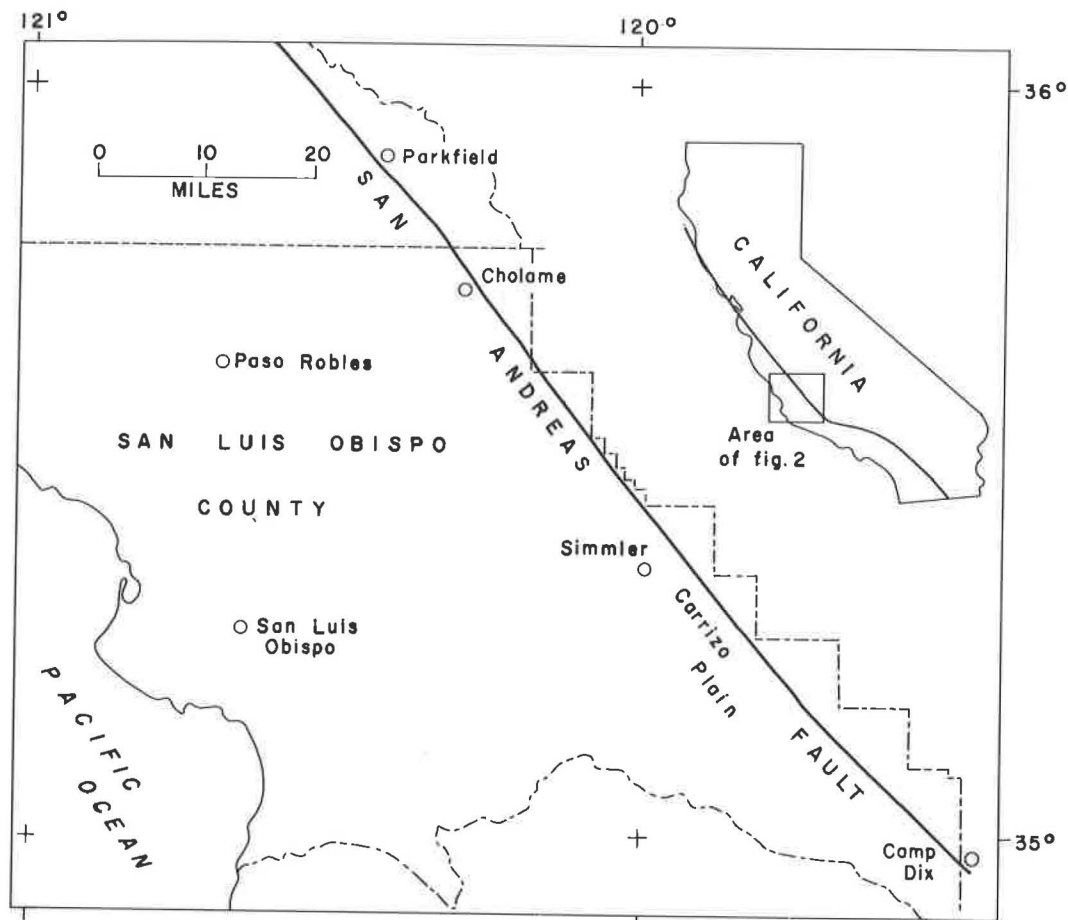


Figure 2.--Index Map.

The aim of the present study is to determine the rate and nature of movement--for example, whether relatively continuous or spasmodic--on the San Andreas fault in late Quaternary time, and to examine carefully the validity of relating misaligned streams to such fault movement. These studies are incomplete, but observations and interpretations thus far obtained are reported here.

Vertical aerial photographs of the entire area at scales of 1:24,000 and 1:6,000 are available, and many of the more conspicuous features were photographed at low altitude by the author. Infrared and side-looking radar images of the area are also available. The study is being carried out by field examination and mapping and by interpretation of aerial photographs.

GEOMORPHIC PROCESSES AND EFFECTS RELATED TO CHANNEL OFFSET

The offset of a stream channel by strike slip on the San Andreas fault, and the preservation of the offset, involves the interaction of two sets of processes--one, erosion and sedimentation, the other, tectonic movements including both fault displacement and warping or tilting. Both processes are in part spasmodic or catastrophic and in part relatively continuous. The rates of the two sets of processes are, in general, of the same order of magnitude; for example, fault slips are measured in feet in the same period of time that channel erosion or sedimentation is measured in feet; however, relative size of streams and activity of a given fault segment are naturally important variables. In the area studied, the rainfall is less than 10 inches per year, and flash floods play an important part in the erosion-sedimentation process. The spasmodic nature of each set of processes permits one or the other to dominate for periods of time measured in years or perhaps even hundreds of years, and during such periods control and adjustment of the channel pattern can be affected primarily by either set of processes. As a result of the interaction of the processes, each channel tends to have a unique history, and the history generally is complex.

Simple Model of Offset Stream

Discussion of a relatively simple model will provide a background for considering and assessing more complex situations. The setting for a simple model which operates with minimum complications is one in which (1) the stream channel crosses the fault at nearly right angles, (2) the stream channel has a relatively steep and uniform gradient across the fault zone so that the stream overrides minor vertical tectonic changes due to faulting and tilting, (3) the stream is large enough to produce a clearly defined channel both upstream and downstream from the fault, and (4) movement on the fault is principally strike slip.

In figure 3 a straight channel which formerly crossed the fault at right angles is shown after having been offset by right-lateral strike slip. No vertical component of displacement is considered in this example. This simple strike slip partially or temporarily dams the stream causing upstream alluviation at C. A fresh fault scarp is produced in

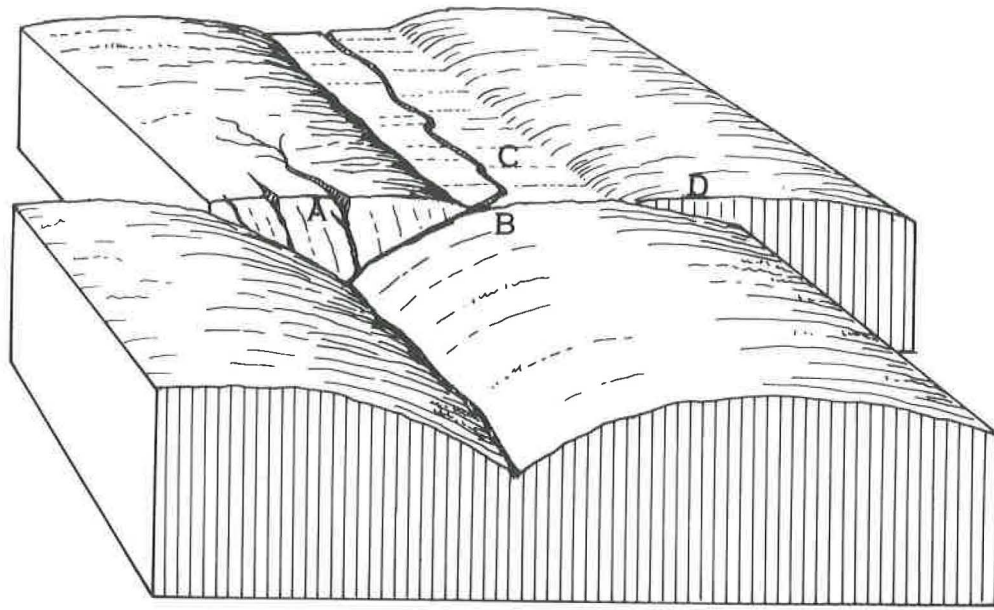


Figure 3.--Block diagram illustrating general features produced when a stream channel is offset by strike slip on a fault.

the vicinity of A. As time passes the dam at B is eroded and the alluvium deposited earlier at C is dissected. The scarp at A becomes gullied. Successive offsets expose new scarp areas to the left of A, and they, in turn, also become gullied. As offset progresses further, the channel segment along the fault trace, between B and A, is continually being elongated, thus lowering the channel gradient more and more. Because of this decreasing gradient, alluvium is deposited upstream from A to and beyond C; and eventually the stream, having difficulty maintaining a channel along that course, spills across the fault trace and creates a new channel more nearly in alignment with the segment upstream from the fault.

After fault movement has progressed sufficiently, the downstream segments of other channels are brought into, or nearly into, alignment with the original channel. For example, in the vicinity of D in figure 3, drainage flowing to the right in an adjacent channel would tend to erode headward toward C, and capture of the original stream would take place. The gradient of this capturing segment, in which flow is to the right, is progressively increased because right-lateral slip shortens the channel, thus accelerating erosion; at the same time the channel flowing to the left is being elongated, gradient is being decreased, and erosion is decelerating.

For offsets of the order of a few tens of feet, streams of small to intermediate size--for example, ranging from 500 to 1,500 feet long from fault to headwaters--which have well-developed channels, record the displacement most clearly. For offsets of hundreds or thousands of feet,

the streams that are moderately large--for example, ranging in length from a mile to several miles from fault to headwaters--seem to record the displacement most clearly. To state the size relation another way, a channel of a width about equal to, or one order less than, a given amount of strike slip best preserves the record of that slip. Stream channels that are too small will be obliterated in the time required for hundreds of feet of displacement, but streams that are too large will soon obliterate the effects of small offsets.

Variations from Simple Model of Offset

Although the rather simple model of offset described in the previous section is approximately duplicated in numerous places, models including some major variation or special conditions are more the rule than the exception. Inasmuch as this paper is in the nature of a progress report, only brief reference to, or examples of, the many variables will be given.

Tectonic conditions that affect the patterns of streams include such variables as surface warping or tilting, a dip-slip as well as a strike-slip component on the fault, multiple strands of the fault, and oblique cross strands between or connecting more continuous throughgoing fault segments. Of these tectonic conditions, perhaps the one that most drastically affects the simple model of offset is relative upthrow of the block on the downstream side of the fault. Even a few inches of vertical throw can produce a dam across a small stream that will divert its course, and whether the stream turns to the left or right along the scarp may depend on pre-existing microrelief rather than strike slip on the fault. A few apparent left-lateral offsets may be caused in this way. On a larger scale, where the downstream block has risen tens or hundreds of feet by faulting or local warping, as along the Elkhorn Scarp in the Wells Ranch and Panorama Hills quadrangles, the effect can be to maintain the deflection of the stream that was already started by simple strike slip, or to cause deflection of major streams that might otherwise have maintained an undeflected course across the fault. For example, the large stream deflections, such as one of 3,200 feet (NW 1/4 sec. 19, T. 22 E., R. 32 S.) and one of more than a mile and a half (in sec. 29, T. 32 S., R. 22 E.) along the Elkhorn Scarp, seem likely to be related in part to diversion of stream flow by vertical uplift rather than by simple strike slip.

John Proffett (1966), in analyzing displacements of streams in the segment of the San Andreas fault near the Gabilan Range, suggested the following general relation of fault displacement to erosion and sedimentation: (1) when the ratio of dip slip to strike slip on the fault produces a channel segment along the fault trace steeper than the original stream gradient, erosion is initiated on that segment, but (2) when the ratio of dip slip to strike slip produces a channel segment along the fault trace of lower gradient than the original stream, aggradation is initiated on the segment.

Factors of erosion and sedimentation may also override the simple model of strike-slip offset of a stream channel. Figure 4 illustrates a situation in which ease of erosion of the fault zone may have influenced the pattern of the stream channels as much or more than strike slip; note that the streams bend both to the right and left. But more streams are deflected to the right, and by greater amounts, than to the left--a relationship very likely attributable to strike slip. In this example, and in many others, deflection due to strike slip cannot be distinguished from that controlled by headward erosion along the fault. Note also in figure 4 at least four subparallel lineaments, which represent parallel faults. Strike slip as represented by stream offset is exhibited only on the main trace of the fault, second from the bottom.



Figure 4.--Oblique view looking southwest across the San Andreas fault zone, Carrizo Plain area. Note multiple fault traces and deflection of streams at most active strand (second from bottom). The largest deflection, from A to B, is about 700 feet.

Some apparent left-lateral offsets can be explained by stream capture. Figure 5 illustrates a situation (SE1/4 sec. 3, T. 32 S., R. 21 E.) in which stream capture and continued right-lateral strike

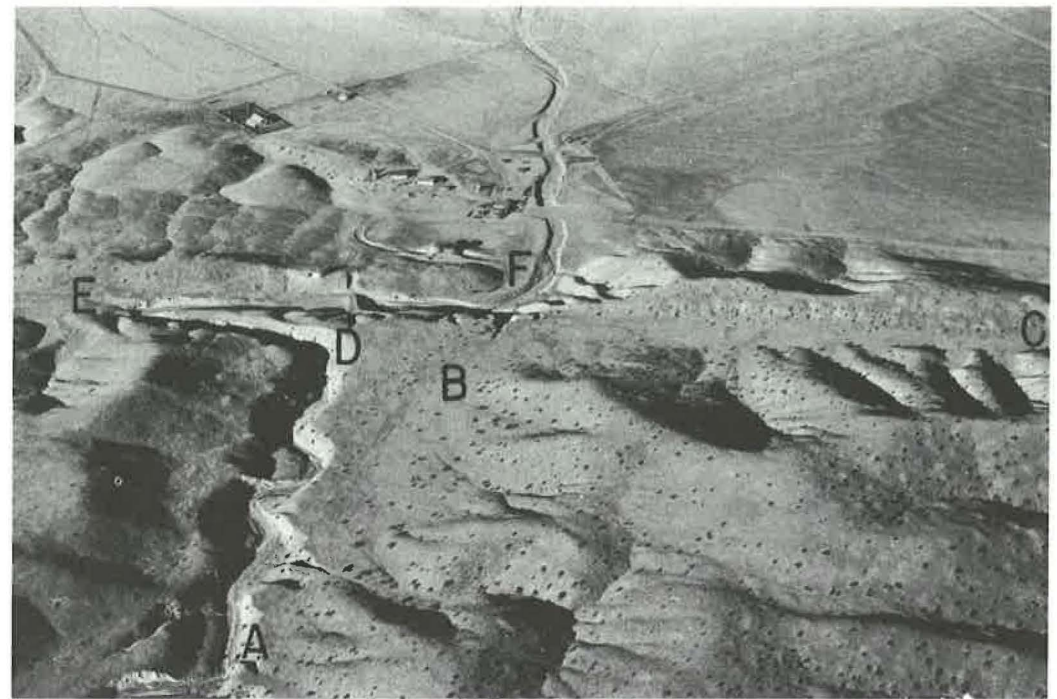


Figure 5.--Oblique view looking southwest across the San Andreas fault zone, Carrizo Plain area, showing sigmoid pattern of stream channel offset by slip on the fault. Fault passes through points E and C. The distance between E and D is about 400 feet.

slip have combined to produce a sigmoidal channel pattern. The pattern is interpreted as follows: The stream seen in the foreground A (which flows away from the viewer) was offset by strike slip on the San Andreas fault (which passes through E and C) to a point to the right of C, and the channel was alluviated and grade established from A to B to C. As described in the simple model earlier in the paper, a stream channel adjacent on the left moved close enough to capture the original stream near point D, and flow then was established from A to D to E and beyond to the left. But the downstream section of the adjacent channel continued to move right laterally carrying the captured stream with it until it now is at point F. Thus this downstream channel segment has passed the upstream segment of its captured neighbor and has been entirely detached from its original headwaters far to the left of the picture.

OFFSETS AND THEIR SIGNIFICANCE

Along the 70-mile segment of the fault between Cholame and Camp Dix, more than 130 measurements of stream-channel misalignments are believed to represent essentially true offset by right-lateral strike slip on the fault; many other deflections and apparent offsets are believed to be a result of other processes, or combinations of strike slip and other processes, as described earlier.

As shown on figures 6 and 7, 40 of the 130 channels display offsets of from 20 to 45 feet, 32 feet being the average amount, and 10 show about 30 feet of offset. Seventeen have offsets of less than 20 feet, and 15 show no apparent offset. Ten are offset between 1,000 and 3,000 feet, but of these offsets the three that are greater than 1,500 are questionable.

Most commonly, offsets of approximately 30 feet are not found near offsets of lesser amounts, so that it seems likely that a single slip of approximately 30 feet is represented--an offset that was probably related to the great earthquake of 1857 (Wood, 1955). Displacement may have taken place either as a sudden slip or as a combination of sudden slip and tectonic creep similar to that recorded in the Parkfield-Cholame earthquakes of June-August 1966 (Wallace and Roth in Brown and others, 1967, p. 23-40). If some displacement was by tectonic creep, however, a quiet period has existed here for several decades, because fences, including several more than 40 years old, which cross the fault show no evidence of offset. If all the 30 feet or more of displacement was by sudden slip during the 1857 earthquake, it was the largest strike slip yet recorded during an historic earthquake.

In attempting to locate the smallest clearcut offset that is related to the 1857 earthquake, 15 streams with no offset were found. Some of these, no doubt, represent channels developed or straightened by flash floods since 1857, but some are of such large size that they must have existed before 1857, and yet there is no clear evidence of a shift to a new channel cut after 1857. One such large channel displaying no apparent offset is in NW1/4 sec. 29, T. 31 S., R. 21 E., in the Painted Rock quadrangle.

Because streams with no apparent offset lie along fault segments on which tens of feet of offset occur, one is led to the conclusion that the amount of offset varies along a given fault strand. An example is a particularly well-defined linear fault segment extending from about Highway 58 near Simmler south for about 9 miles. This fault segment displays over 30 feet of offset near its midsection but has at least one stream channel showing no displacement near its southern end, which bows slightly to join an en echelon segment that overlaps it on the southwest side. A comparable pattern was noted in the surface fractures developed during the earthquakes at Parkfield and Cholame in June-August 1966 (Brown and Vedder in Brown and others, 1967, p. 2-23). Here, en echelon segments of fracture zones, each several miles in length, had slips

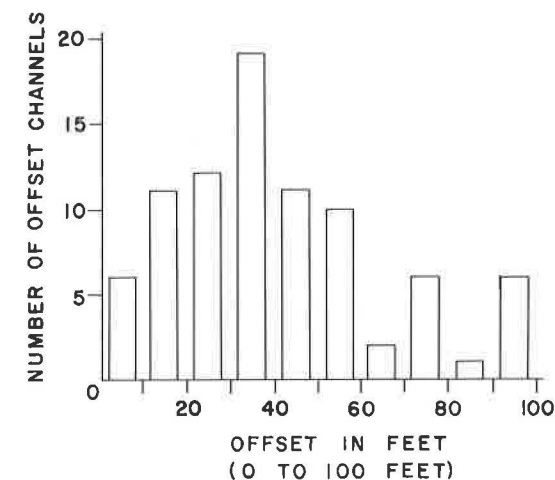


Figure 6.--Histogram showing number of channels displaying various amounts of offset up to 100 feet. All offsets are right-lateral.

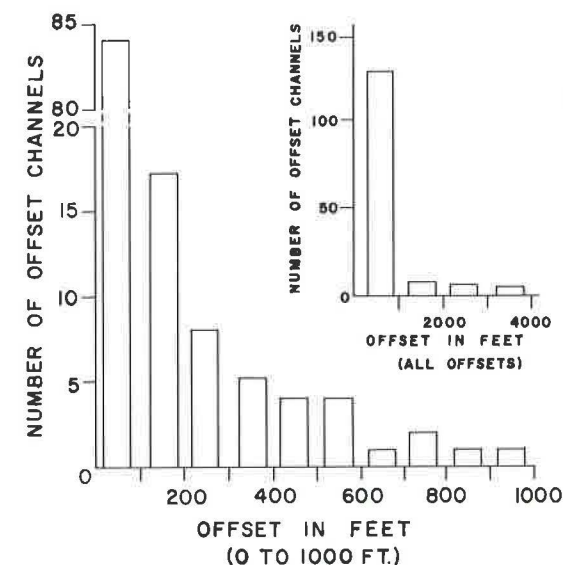


Figure 7.--Histogram showing number of channels displaying various amounts of offset.

that were larger near their midpoints and slips that decreased to zero at the ends. Thus even in great earthquakes, such as that of 1857, which accompany displacements of many feet, the pattern may consist of composite segments, each several miles long, along each of which displacement reaches a maximum near the midsection and dies out at the ends. A total fracture length of 180 miles or more, as in the 1857 and 1906 earthquakes, might be a composite of 20 or more such individual segments.

Four channels were found that have apparent left-lateral offset, but whether or not they actually represent left-lateral fault displacement is in doubt. Although the preponderance of evidence favors right-lateral slip on the fault, left-lateral offsets should not automatically be discounted. Locally it is entirely possible for left-lateral strike slip to develop within the overall field of right-lateral strain. Examples of left-lateral offset, admittedly on a small scale, were found during the study of the Parkfield-Cholame earthquakes of June-August 1966. Small thrust faults exhibiting left-lateral offset are shown by Brown and Vedder (in Brown and others, 1967, fig. 12, p. 19), and similar left-lateral offset was observed in the cracking of pavement on the Parkfield to Cholame road in April and May 1967, about 500 feet northwest of locality F-10 of Brown and Vedder (in Brown and others, 1967, fig. 2, p. 6-7). In these examples, local shortening produced small thrust slabs bounded by both right- and left-lateral tear faults.

Recurrence of right-lateral strike slip on a single, well-defined fault strand is clearly indicated. Good examples are shown in figures 8 and 9. The area of figure 8 lies on the east side of the Carrizo Plain near Simmler in secs. 33 and 34, T. 30 S., R. 20 E. The major stream channel has been deflected 450 feet right laterally from A to B, but a beheaded downstream segment has been offset 1,200 feet right laterally to C. Very likely, the segment of the present channel downstream from the fault at B came into existence at a time when flood waters overrode the banks of the original channel--a channel which had been repeatedly extended and its gradient lowered because of strike slip on the fault. The general altitude of the interfluvial alluvial plain downstream from the fault near the present channel is lower than near the abandoned channel. The spillover point was most likely (although not surely) at the place where the upstream segment first reached the fault. The small stream channel at D displays a series of offsets--represented by one deflection and three abandoned downstream segments--measuring 30, 70, 110, and 200 feet. Nearby channels show fairly clear offsets ranging from 25 to 40 feet.

The problem arises as to whether the 30-foot offset represents an accumulation of offsets of a few feet each during several events, or whether it was produced in one offset event during the 1857 earthquake. Two arguments favor the latter interpretation: (1) the general absence of smaller offsets on small channels nearby, and (2) the statistical preponderance of offsets of several tens of feet as compared to those under 20 feet (see figures 6 and 7). (I am not here attempting to

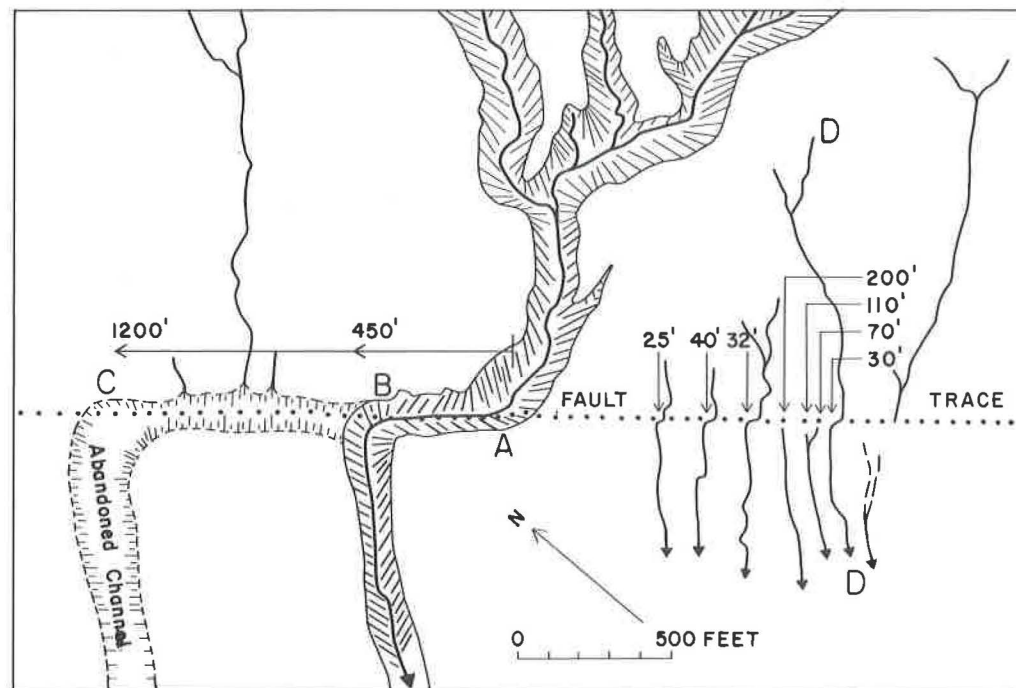


Figure 8.--Map sketched from aerial photograph showing streams offset by various amounts along the San Andreas fault.

distinguish between sudden slip and immediately succeeding tectonic creep; if both types of movement occurred within a period of a few years, they are considered part of a single event.) Whether or not 30 feet represents one event, the range in offsets from 25 feet to 1,200 feet on this segment of the fault is clear evidence that repeated offsets have occurred along a narrow well-defined strand. Even if each event produced as large an offset as 30 feet, 40 such events would be required to produce the cumulative offset of 1,200 feet.

Figure 9 shows a pair of channels offset 70, 450, and 750 feet by the San Andreas fault. The pair of channels upstream from the fault, toward the viewer from A, were offset about 70 feet to position B downstream from the fault. Older downstream segments at C and D were beheaded in the process of being offset about 450 and 750 feet, respectively. This example is about 1-1/2 miles southeast along the same fault segment as the area shown in figure 8. Here also, repeated displacement on the same narrow fault zone is indicated.

A conclusion of practical significance can be drawn from this evidence of repeated offset on the same narrow fault strand. In considering sites for engineering purposes within the broad San Andreas fault zone--a zone which may be a mile wide in places--one must assume that a fault strand having had historic or recent prehistoric movement is very likely to have had recurring movement, thus is likely to be active in the future. One must note, however, that the main fault strand most recently active

is not the only place a fracture may develop. In historic time displacement has developed on fault strands that branch from or are subparallel to but a mile or more from the main strand.

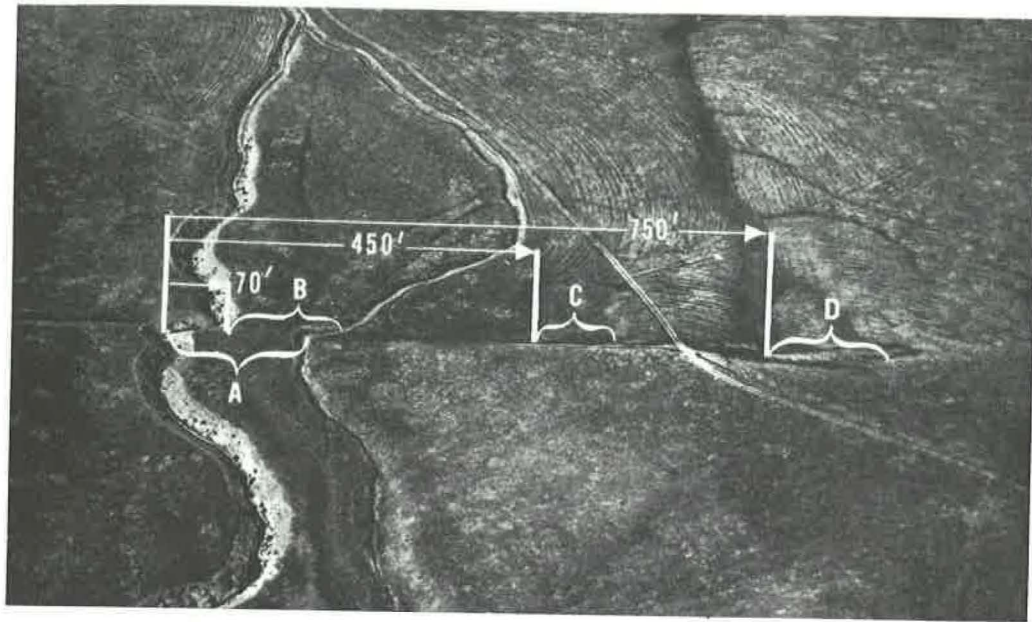


Figure 9.--Oblique aerial photograph looking southwest across San Andreas fault showing a stream that has been repeatedly offset and beheaded by right-lateral strike slip on fault.

RATE OF DISPLACEMENT

The hope throughout the study has been that material suitable for dating by C_{14} , paleontologic, or other techniques would be found and rates of displacement could thus be determined. Unfortunately, nothing as yet has provided an accurate time control.

In a general way, relative rates and a sequence of events can be determined from a study of relative aggradation and degradation along the fault. Thus, if absolute dates of only a few alluvial deposits could be determined, the rest could be arranged in order and ages approximated. Ground squirrel mounds, which are extremely abundant in the region, provide one key to relative ages of alluvial and colluvial surfaces. The newest alluvial deposits have no mounds developed, whereas older surfaces are characterized by well-developed mounds, and the oldest surfaces have mounds highly modified by solifluction, erosion, and wind action. Analysis of soil profiles also may provide a key to time, but this approach has not yet been adequately pursued.

In the absence of any age control other than late Pleistocene and Recent for the age of the offset stream channels, it is helpful in estimating possible rates of the processes involved to extrapolate backward

from rates of strain observed across the San Andreas fault in historic time. Rates of the order of 1/2- to 1-inch slip per year have been observed during historic time on some segments of the fault, but the segment studied here has been stationary during the past few decades (Tocher, 1960; Meade and Small, 1966; Wallace and Roth in Brown and others, 1967; Brown and Wallace, this publication). A comparable long-term rate since late Miocene time of about one-half inch per year (1.7 centimeters per year) has been estimated by Berry, Huffman, and Turner (1967, p. 15) and a minimum of about one-third inch per year by J. G. Vedder (oral commun., 1966) for this part of the San Andreas fault. Proffett (1966) has estimated rates ranging between 0.4 inch per year during the past 400,000 years and 2.7 inches per year during the past 20,000 years. If a long-term rate of 0.6 inch per year is assumed along the entire fault, offsets would be 5 feet per century, 100 feet per 2,000 years, and 1,000 feet per 20,000 years.

An inference, based on this assumed rate of slip and the suggestion made previously that 30 feet may be a reasonable amount of slip--although possibly near a maximum--for a single event, is that as much as 700 years may elapse between events on this segment of the San Andreas fault. This is much less than the 18,300-year recurrence interval suggested from magnitude-frequency curves by Allen, St. Amand, Richter, and Nordquist (1965, p. 785), although they state that such a high value is "grossly misleading." The 700-year recurrence interval, however, is more than 30 times that suggested by Brown and Wallace (this publication) from the historic record in the adjacent Parkfield-Cholame segment of the fault. Very possibly, recurrence intervals for earthquakes differ by as much as several orders of magnitude from segment to segment of the fault.

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DISCUSSION

L. S. Cluff (Woodward-Clyde-Sherard & Associates, Oakland):

You report hundreds and even thousands of feet of offset across a specific fault trace or strand within the mile-wide fault zone. How wide is the zone of ground rupture along these fault traces? Also, is there any evidence that would lead you to predict where future fault movements will occur and to predict how wide the zone of disturbed ground produced by these movements will be?

R. E. Wallace:

In the Carrizo Plain there has been recurrent movement on fault strands, and movement seems to have been confined to a zone 50 feet or less in width on many of these strands. Over most of the distance between Cholame and Camp Dix one or a few strands clearly have been the most recently active, as indicated by "fresh" geomorphic features, vegetation lines, etc. From the evidence for recurrence on some of the fault strands, one is led to the assumption that others may also have had recurrent movement.

A. D. Howard (Stanford University):

Did you find any direct relation between the size of streams crossing the fault and the magnitude of the offsets?

R. E. Wallace:

Yes, small offsets are recorded only by small streams, whereas large streams tend to obliterate small offsets. Conversely, small streams tend to be ephemeral in the length of time required for thousands of feet of offset. Only large, well-incised streams record large offsets.

R. Pestrong (San Francisco State College):

Is there any relationship between amount of stream offset and lithologic variation across the fault?

R. E. Wallace:

I found no such relationship, but the general lithologic similarity of the sedimentary formations involved might not be expected to provide an adequate test.

B. W. Troxel (California Division of Mines and Geology, Los Angeles):
Where there are multiple fault traces in the area you have investigated, have you been able to note any secular progression either east or west towards the most recent trace?

R. E. Wallace:

No, I have found no progression of displacement across the network of fault strands. In fact, displacement as recorded by stream offsets is confined almost entirely to one major fault strand.

Arrowsmith

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