An offset Holocene stream channel and the rate of slip along the northern reach of the San Jacinto fault zone, San Bernardino Valley, California

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ABSTRACT

The three-dimensional geometry of a buried channel-fill deposit that crosses, and is offset by, a strand of the San Jacinto fault zone in San Bernardino, California, is reconstructed from an extensive suite of trench logs. The reconstruction shows that the original course of the channel was deflected for a short distance along strike of the fault before it was offset. As a result, apparent offset of the channel deposit across the fault zone is about 12 m in a right-lateral sense, but only 3.5 to 6 m of the apparent offset is due to fault slip. The age of the deposit is \( \leq 1931 \pm 109 \) yr B.P. based on radiometric dating of detrital charcoal collected from the unit. Our excavations do not encompass all active strands of the fault at this site. Hence, our study points to a minimum slip rate of 1.7 to 3.3 mm/yr along the northern San Jacinto fault zone. Historical records show that it has been at least 64 to 90 yr since the last large earthquake occurred along the northern San Jacinto fault. It can thus be inferred from our estimate of fault slip rate that at least 10 to 30 cm of slip is currently stored along the northern segment of the San Jacinto fault. Because prior studies along the same fault zone to the southeast indicate much higher slip rates (on the order of 10 mm/yr), and coseismic offsets for the largest historical earthquakes along the San Jacinto fault zone have been on the order of 30 cm, it is inferred that the northern reach of the San Jacinto fault is now in the later stages of the strain accumulation cycle prior to a moderate to large M 6-7 earthquake. Additionally, the complex geometry of the reconstructed channel serves to illustrate the caution that must be exercised when determining the true offset of buried channel deposits.

INTRODUCTION

The San Jacinto fault zone, a principal member of the San Andreas fault system, splays from the San Andreas fault at a point east of Los Angeles. The San Jacinto fault zone is a major, dextral striking slip fault located along the eastern margin of the San Gorgonio Pass fault zone (S.G.P.F.Z.), which is the major dextral wrench fault that bounds the San Jacinto fault zone on the south and east.

Figure 1. Location of the San Jacinto and other major active fault zones within southern California. Epicenters and extent of surface ruptures during the largest historical earthquakes along the San Jacinto fault zone are shown by stars and shading, respectively. Site of this study is along the northern San Jacinto fault in the densely populated and rapidly growing San Bernardino Valley. The San Gorgonio Pass fault zone (S.G.P.F.Z.) strikes northwest between the San Andreas and San Jacinto fault zones.

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SAN JACINTO FAULT SLIP RATE STUDIES

Figure 2. Results of prior geological fault slip-rate studies along the San Jacinto fault zone. Sites of the studies are marked by arrows. The ages of the offset features used to estimate the slip rates are given in parentheses. References to the studies are (1) Morton and others (1986), (2) Prentice and others (1986), (3) Sharp (1981), (4) Rockwell and others (1986), and (5) Merrifield and others (1987).

Angeles, California, and strikes southeastward to the Mexican border (Fig. 1). Marked by a series of en echelon fault segments, the San Jacinto, although not responsible for the largest historical earthquakes in California, has produced more moderate to large earthquakes than any other fault zone during the recorded history of California (Fig. 1). Historically, at least seven and perhaps as many as eleven M 6–7 earthquakes have been reported on or very near the trace of the fault zone (Thatcher and others, 1975; Sanders and Kanamori, 1984). Most notable among these are the surface-rupturing events that occurred along segments of the southern reach of the fault zone in 1968 and 1987. As a result of the high degree of activity, and questions concerning the relationship of the San Jacinto fault zone to the San Andreas fault, several geological studies of fault slip rate have been undertaken and reported. The results of those studies are summarized in Figure 2. Three of the studies are of the Holocene slip rate. These studies have been centered on parts of the fault that lie well south of San Bernardino, near Anza. To determine the fault slip rate along the northern San Jacinto fault zone during Holocene time and, in turn, to gain insight to the current level of seismic hazard in the San Bernardino Valley, the most populated region astride the fault zone, we excavated and logged an extensive suite of trenches along and across a trace of the fault zone in San Bernardino (Fig. 2).

The trench logs are used to document the geometry of a buried Holocene channel deposit that crosses, and is offset by, the fault. Our observations show that the channel was originally deflected for a short distance along fault strike. The apparent offset of the channel across the fault zone is thus significantly greater than the offset due to fault slip since deposition of the channel fill. This paper documents the geometry of the channel deposit, reports a minimum slip rate on the northern San Jacinto fault, discusses the current level of seismic hazard in San Bernardino in light of this and prior studies along the fault zone, and illustrates why excavations across fault zones should be closely spaced if confidence is to be placed in estimates of fault slip determined from buried channel deposits.

THE FIELD STUDY

The site of our study is near the I-10 and I-215 freeway interchange in San Bernardino (Fig. 3A). Locations of the active strands of the San Jacinto fault zone as they traverse San Bernardino Valley have been documented previously in greater detail than shown in Figure 3A on a set of annotated aerial photographs by Sieh and others (1973). Sieh and others (1973) also reported that the Holocene stratigraphy along strike of the fault and a few hundred meters to the southeast of our trenches (Fig. 3B) is characterized by alluvial silt and sand interbedded with marsh or pond clay and peat. They also presented geological evidence of at least two paleoearthquakes but provided no information about the dates of the paleoevents. On the basis of these observations and knowledge that few undeveloped areas remain along the fault within the San Bernardino Valley, we decided to re-examine the site. The site is now graded for development, and an artificial drainage channel excavated by developers both satisfies provisions of the California Alquist-Priolo Act (Fig. 3B; Hart, 1980) and effectively erases the potential for exposing late Holocene stratigraphy along much of the fault where Sieh and others (1973) originally worked. Fortunately, a major strand of the fault zone was left undisturbed near the northern boundary of the subdivision in Lot 1, buried and preserved by 1–2 m of artificial fill. Unfortunately, earlier construction of a concrete wasteway prevented study of a second, parallel strand immediately to the west of the preserved strand (Fig. 3B). Additionally, several active northwest-trending fault traces have been reported west of Hunts Lane to the southwest of Lot 5 near the mouth of Reche Canyon (Fig. 3). The fault traces near the mouth of Reche Canyon are discontinuous, have a uniform sense of dip slip to the northeast, have no conclusive evidence of lateral offset, and hence do not appear to be accommodating a major part of the strike-slip displacement along the San Jacinto fault zone (Leighton, 1988). It is the study of the preserved strand noted in Figure 3B that is the basis of this paper.

Trenches along and across the preserved trace were excavated to produce nearly vertical exposures. The face of each trench wall was subdivided into a grid of 1-m-square panels. Each panel was logged at a scale of 3 to 5 in. per meter, depending on the complexity of the fault.

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Figure 3. Locality of study is (A) along the San Jacinto fault zone in San Bernardino, California, and (B) within the artificially graded parcel of land labeled “Lot 1.” The site of the trenches is within the fault-zone setback for residential developments required by the California Alquist-Priolo act (solid dotted lines; Hart, 1980). A previously documented strand of the main fault zone in Lot 1 was excluded from study by recent installation of a concrete wasteway. Our study centered on the remaining, preserved western trace in Lot 1. Subsidiary fault breaks have also been identified to the southwest of the main trace of the fault zone (see Fig. 3a and text for discussion). Trenches were surveyed with respect to a baseline between nail survey markers B1 and B2. Elevation of B1 is 999.45 ft above mean sea level. Contours are in feet. Regions of high topography are outlined by small triangles.
Figure 4. Index map with the trace of each trench wall as a thick hachured line. Trench walls are given a numeral or letter designation depending on whether they cross or parallel the trace of the fault zone (stippled), respectively. Hachures along the trench walls are generally located at 1-m intervals and correspond to vertical bars above each trench log presented in this paper. For example, the ten hachures here along strike of Trench 1 correspond in location to the dark vertical bars placed above the log of Face 1 shown in Figure 5. The two short dashed lines adjacent to face C represent slots excavated in face 1 to provide control on the trend of a buried channel deposit.

Five potential sets of offset piercing points (a–a’ through e–e’) are noted in Figure 8a. Three of these (c–c’, d–d’, and e–e’) are analogous to features observed in our excavations and are labeled on the structure contour map in Figure 7. Two of the pairs (a–a’ and b–b’) were too poorly defined in our excavation to provide a measurement of offset.

The offset of the channel thalweg c–c’ is about 4.5 m. The measurement takes into account the oblique trend of the thalweg across the

zone in the panel. The corners of each panel were surveyed with an electronic distance-measuring device. An index map showing the location of each panel with respect to the location of the fault strand studied is shown in Figure 4. The logs of each exposure are collected in Figure 5 and the Appendix.

The trenches exposed a sequence of faulted alluvial deposits (Fig. 5 and Table 1) of the Santa Ana River drainage system (Fig. 3a), buried beneath about 1.5 to 2 m of artificial fill (unit G). No individual paleoseismic events are recognizable in this sequence; however, a clearly defined channel deposit (unit Ch) is truncated and displaced by the fault (Fig. 5). Rusted pieces of barbed wire in unit F indicate that the upper portion of the unit formed the ground surface during historical time. The base of unit F is broken by the fault, but, due to the massive and thoroughly bioturbated nature of the unit, it is not possible to determine whether the upper part of the unit is faulted. The uppermost unit clearly broken in its entirety by the fault is unit E. Unit Ch (subsequently referred to as the channel) is characterized by very sharp contacts with adjacent units (Fig. 6) and is clearly offset by the fault (Fig. 5).

The rest of this section describes the age and original configuration of the channel, and the distance the channel is offset by fault slip. The apparent right-lateral offset of the southern channel margin is about 12 m (Fig. 7); however, a small piece of the channel deposit is located on the western side of the fault zone, within the 12-m apparent offset. This geometry and the trend of the thalweg (dark-stippling) indicate that the course of the channel originally followed the fault for a short distance along strike. Hence, much of the 12-m apparent offset is not due to fault displacement but reflects the original configuration of the channel deposit (Fig. 8).

Figure 5. Logs of faces 1 and 2. Locations and unit descriptions of logs are given in Figure 4 and Table 1, respectively. Each face is presented as viewed from the south. Unit Ch (stippled), a channel deposit, is between units B and D on the east side of the fault. In face 1, the western channel margin is well defined and located just to the east of the fault zone. Face 2, in contrast, shows the channel truncated by the fault. The channel is not present between units B and D to the west of the fault zone, indicating that the channel deposit has been offset by the fault. Depth is given in meters below benchmark B1 (Fig. 3b). The age of disseminated carbon (sample 86BRT13A in Table 2) taken from the part of unit Ch noted, dendrochronologically corrected to years before A.D. 1950, was found to be 1931 ± 109 yr.
fault zone. The thalweg is not a well-defined piercing point on the western side of the fault zone, because of the westward thinning of the channel deposit by erosion during deposition of overlying unit D (Fig. 5) and the broadening of the channel on the west side of the fault zone (Fig. 7). Furthermore, trench spacing provides little control on the location of the thalweg on the western side of the fault. The data hence do not place concise limits on the estimated 4.5-m offset. Points d–d' and e–e' correspond to the edges of a small piece of the channel that crossed the fault zone for a short distance (Fig. 8b). The offset of d–d' (4.2 ± 0.7 m) corresponds to the separation of the 4.2- to 4.4-m contour intervals. Because the features analogous to points e–e' form a relatively steep channel wall that strikes at a high angle into the fault zone, as evidenced by the closely spaced contours shown in Figure 7, this offset pair provides our best estimate of fault slip. The offset of e–e' is 5.4 ± 0.6 m and corresponds to the horizontal separation of the 4.0- to 4.4-m contour intervals. In summary, the three measures of horizontal separation are internally consistent. Our preferred estimate of offset is 5.4 ± 0.6 m, although uncertainties in the three measurements allow for offsets of 3.5 to 6.0 m. Evidence regarding the number of seismic events responsible for the offset was not recognized in the trench exposures. Because no systematic trend of vertical offsets is observed in the trench logs (Appendix), our measurements of horizontal separation are interpreted to reflect true fault slip.

Three samples of detrital charcoal were taken from the channel and submitted for radiocarbon analyses (Table 2). Sample 86BRT13A was taken from near the base of the channel in face 1 (Fig. 5) and analyzed by conventional counting techniques. The dendrochronologically corrected age of the sample is 1,931 (±2σ = 109) yr B.P. Two very small samples (88SPT28-3 and 88SPT26-2) were also collected from faces 7 and 9 (Fig. A1) and analyzed using accelerator mass spectrometry (AMS). The dendrochronologically corrected ages of those two samples are 2,438 (±2σ = 278) yr B.P. and 2,211 (±2σ = 148) yr B.P., respectively. The age range of the first sample (86BRT13A) differs at the 95% confidence level from the two AMS samples, implying that either the channel sediment was deposited over a long period of time or that carbon of different sources and ages was incorporated into the unit at about the same time. In either case, the age of the channel deposit is less than, or equal to, 1,931 ± 109 yr B.P.

Division of the offset (3.5 to 6.0 m) by the age of the deposit (≥1,931 ± 109 yr) yields an estimate of fault slip rate between 1.7 and 3.3 mm/yr during late Holocene time. Our best estimate of offset (5.4 ± 0.6 m) gives a slip rate of 2.3 to 3.3 mm/yr. The value of the estimate is limited by a lack of evidence regarding the number, timing, and size of events that produced the offset subsequent to channel formation. A most representative estimate of slip rate should take into account only the period of time between the seismic events that produced the offset. From the evidence we have gathered, it cannot be ruled out that the entire offset occurred during a single event and that the average recurrence of such events is much greater than the age of the channel deposit, in which case our measure of the slip rate for this strand of the fault zone could be significantly overestimated.

In contrast, if the offset is due to a sequence of earthquakes with an average repeat time less than the age of the channel deposit, then we are likely underestimating the true fault slip rate, because the age of the channel deposit used in the calculations includes both the periods of time before and after the first and last earthquakes in the sequence, respectively. Some support for this latter mode of behavior is the reported occurrence of a M 6.3 earthquake in the San Bernardino Valley in 1923, although lack of reports of surface offset with that event make correlation with the San Jacinto somewhat tenuous. The slip rate might also be underestimated because we have used a maximum age for the channel in the calculation. Our estimate of fault slip rate should thus not be considered as either a maximum or minimum for this strand of the fault zone but, rather, as a best estimate.

When viewing the entire San Jacinto fault zone in San Bernardino, the 1.7–3.3 mm/yr slip
rate likely represents a minimum because (1) prior work shows that our excavations do not encompass all active strands of the fault zone in the vicinity of this site (Fig. 3b; Sieh and others, 1973) and, as described further in the following summary and discussion, (2) analyses of fault slip-rate data, historical earthquakes, and fault-trace complexity of the entire fault zone are consistent with the interpretation that the largest earthquakes along the San Jacinto fault zone are generally characterized by average return times significantly less than the age of the channel deposit and coseismic displacements less than the offset of the channel deposit (Wesnousky, 1986).

SUMMARY AND DISCUSSION

We have used an extensive suite of excavations to determine the geometry of a buried, late Holocene channel deposit that is offset by the San Jacinto fault zone. Reconstruction of the original channel geometry allowed us to calculate a minimum slip rate (1.7 to 3.3 mm/yr) for the fault in San Bernardino Valley. Our observation that the original course of the channel was deflected along strike of the fault zone prior to being offset illustrates a potential problem in determining the true offset of this type of deposit. In this case, the apparent offset of the channel is about 12 m in a right-lateral sense, but only 3.5 to 6.0 m of the separation is due to fault slip (Figs. 7 and 8). With excavations spaced at insufficiently close intervals, it is probable that the 12-m separation would be interpreted as due to true fault slip. Indeed, based on far fewer excavations than reported here, we previously reported an incorrect estimate of the fault slip rate based on the 12-m separation (Wesnousky and others, 1987; Prentice and others, 1988). Our initial estimate was based on the assumption that the channel originally flowed straight across the fault zone. That further work showed this assumption was incorrect should be taken by other investigators as notice of the caution that must be used in measuring fault offset from similar deposits.

It is common knowledge that the creation of fault scarps in Holocene alluvium often results in the deflection of stream channels along strike of active strike-slip faults. The question thus arises whether there exists some evidence within the local morphology or trench exposures to indicate why this particular stream deflected along the fault zone. Our and Sieh and others' (1973) examination of 1938 vintage aerial photographs indicates the presence of a small stream channel that is deflected about 50 m right-laterally along the fault in the vicinity of our site. Analysis of the photos, however, reveals no evidence of a fault scarp that may have produced the deflection, and hence the location of the deflection may be coincidental. Similarly, there exists no
Seismological and geodetic observations also provide information regarding the recent slip rate of the San Jacinto fault zone and are in general accord with geological studies. Thatcher and others (1975) determined and summed the seismic moments of earthquakes along the entire fault zone since 1890 to estimate a seismic slip rate of about 8 mm/yr along the San Jacinto fault zone. Geodetic and trilateration measurements spanning parts of the fault between San Bernardino and Anza for the periods 1969–1975 and 1973–1981 are consistent with 11–18 mm/yr of slip being stored elastically in a crust 10–15 km thick (Savage and Prescott, 1976; King and Savage, 1983).

Geological and geophysical observations prior to our study thus generally point to an average slip rate of, at minimum, 8–12 mm/yr across the San Jacinto fault zone during late Quaternary time; however, the only measures of Holocene fault activity have been well to the south of San Bernardino, near Anza. The complexity of the San Jacinto fault zone and the possible interaction of other nearby faults introduce an uncertainty into extrapolation of available Holocene slip-rate measurements northward to San Bernardino. The segmented character of the San Jacinto fault zone has been described by Sharp (1975) and is illustrated in Figure 2. Studies of the size and extent of historical earthquake ruptures show that no historical event of size sufficient to rupture the entire San Jacinto fault zone has occurred, but rather, earthquakes have been limited to specific segments of the fault zone. The 1968 Borrego Mountain and 1987 Superstition Hills earthquakes are examples of this type of activity (Fig. 1). The various segments of the fault zone may rupture somewhat independently, and it is not necessary that all share the same slip rate. For example, Matti and others (1985) proposed that a large part of the slip accommodated by the San Andreas may be shunted westward along the San Gorgonio Pass fault zone (Fig. 1) to the San Jacinto fault zone, based on the mapping of structural relations in the area southeast of San Bernardino. A necessary consequence of this observation, if correct, is that different segments of the fault zone can be characterized by different fault slip rates and, hence, different earthquake recurrence intervals.

Much of the motivation for our study was to understand whether or not the rate of slip has been constant along the entire length of the San Jacinto fault zone during Holocene time. Our estimate of slip rate for the San Bernardino site is much less than determined previously for sites to the south but must be recognized as a minimum estimate. In that regard, our study is consistent with but certainly does not prove the hypothesis to indicate an average of 17 mm/yr of slip during the past 0.7 m.y. Also within the San Timoteo Badlands, Prentice and others (1986) estimated a slip rate of 8–12 mm/yr on the San Jacinto based on observation of stream channels that are incised into a surface interpreted to be 50,000 to 100,000 yr old and displaced 0.6–0.7 km. South of Anza, along the segment of the fault that ruptured during the 1968 Borrego Mountain earthquake, Sharp (1981) interpreted geologic relations to conclude that slip has averaged 2.8–5.0 mm/yr for the past 400± yr and 1.4–2.0 mm/yr between 400± and 6,000± yr, respectively. Sharp (1981) interpreted these latter slip rates to suggest that the rate of slip may vary through time on the San Jacinto; however, the measurements of slip rate near Anza reported by Sharp (1981), Rockwell and others (1986), and Merifield and others (1987) imply a relatively steady slip rate at that site during the past 0.73 m.y. The Borrego Mountain segment is south of a tributary of the San Jacinto fault trace (Fig. 2) and may represent only a fraction of the total San Jacinto slip rate.

evidence within our trench exposures to indicate the presence of a scarp in Unit B that may have deflected the now buried channel.

Although our estimate of slip rate for the northern reach of the San Jacinto fault is a minimum, 1.7 to 3.3 mm/yr is substantial and worthy of discussion within the context of prior studies of the San Jacinto and other nearby active faults. Geological estimates of the San Jacinto fault slip rate have been reported at a number of sites along the San Jacinto fault zone (Fig. 2). Sharp (1981) placed a minimum limit of 8–12 mm/yr of slip along the San Jacinto fault zone near Anza during the past 0.73 m.y. (Fig. 2). Work by Rockwell and others (1986), also near Anza, suggests a similar rate of 8–10 mm/yr during the past 9,500 yr. Merifield and others (1987) collectively interpreted Rockwell's (1986) measurements along with a suite of other observations near Anza to estimate the San Jacinto fault slip rate to be 12–17 mm/yr for the past 30,000 yr. North of Anza in the San Timoteo Badlands, Morton and others (1986) interpreted a displaced Pleistocene conglomerate...
that the Holocene slip rate has been similar along the entire length of the San Jacinto fault zone during Holocene time.

Ioseismal and instrumental evidence has led investigators (Thatcher and others, 1975; Sanders and Kanamori, 1984) to suggest that the July 22, 1899 (M 6.5) and July 23, 1923 (M 6.3) earthquakes occurred on the northern San Jacinto fault (Fig. 1); however, no evidence of surface rupture is known for either of these events, and the large uncertainties associated with locating such historical events based on sparse felt reports and limited or absent instrumental recordings permit the possibility that one or both of the events were the result of slip on other nearby faults. Historical records hence show that it has been at least 64 to 90 yr since the last large earthquake occurred along the northern San Jacinto fault.

Assuming that strain accumulation along the fault is constant through time, it can be inferred from our estimate of fault slip rate (1.7–3.3 mm/yr) that at least 10 to 30 cm of slip is currently stored along the northern segment of the San Jacinto fault. The upper bound of this range is comparable to the average value of co-seismic slip observed during the 1968 M 6.5 Borrego Mountain earthquake, which occurred 150 km to the south along this fault zone (Clark, 1972). Recalling that (1) our excavations do not encompass all active strands in the vicinity of the fault zone at this site, (2) larger slip rates are reported along strike to the south, and (3) it may be much longer than 90 yr since the last rupture of the fault zone, it is likely that sufficient slip has now accumulated along the northern reach of the San Jacinto fault to produce an earthquake of M 6.5 or greater in the San Bernardino Valley. Further noting that large earthquakes along the San Jacinto fault zone have historically ranged between M 6 and M 7, and assuming that this behavior is characteristic of the fault zone, it can be inferred further that the northern San Jacinto fault near San Bernardino is now in the later stages of the strain accumulation cycle prior to a moderate to large M 6–7 earthquake.

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APPENDIX

The results of this study are based on the trench logs indexed in Figure 4 and presented here. For convenience of interpretation, logs of all trenches that cross the fault zone are presented as viewed from the south, numbered sequentially from north to south (Fig. 4), and presented in Figure A1. Similarly, logs of all trenches that run parallel to the fault zone are presented as viewed from the east, labeled sequentially from A to G (Fig. 4), and presented in Figure A2.

Figure A1. Logs of fault-crossing excavations, faces 3 through 39. Conventions as in Figure 5. Ages indicated for unit Ch in faces 7 and 9 correspond to radiometric dating of carbon samples 88SPT28-3 and 88SPT26-2 in Table 2, respectively.
Figure A2. Logs of fault-parallel excavations, faces A through G. Conventions as in Figure 5.

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