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Displacements on tectonic ruptures in the San Fernando earthquake of February 9, 1971: discussion and some implications

by

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INTRODUCTION

This report discusses data on displacement of the ground surface along tectonic ruptures of the February 9, 1971 earthquake in San Fernando, California. The data were published in a paper by the author in Bulletin 196 of the California Division of Mines and Geology, pages 187-194. In this report, I examine some simple methods to quantify from that data the average slip of 1971 and the probability of future displacement to exceed a given amount, and discuss problems intrinsic to predicting the amount of average or maximum movement in a future earthquake event.

GENERAL DESCRIPTION OF THE SURFACE DISPLACEMENTS

Five separate strands of surface offset within the San Fernando fault zone were activated during the 1971 San Fernando earthquake. These surface ruptures are described by USGS Staff (1971), by Kamb and others (1971), and in the greatest detail by Barrows (1975), Kahle (1975), and Weber (1975). The names and locations of fault strands used in this report are those shown in Plate 3 of Bulletin 196 by Barrows and others (1975).

All or nearly all of the displacement was coseismic. This conclusion is based on searches for postearthquake movement by Lahr, Wyss, and Hileman (1971), by Nason (1971), and by Sylvester and Pollard (1975).

Mission Wells segment

The surface rupture in this segment was confined to a narrow zone that can be considered a single rupture. The maximum observed slip on this segment was about 0.5 m in left oblique reverse sense. The gaps in the surface rupturing between the Reservoir segment to the west and the Sylmar segment to the east are real; careful examination of the ground surface in these gaps revealed no evidence of surface rupture, although leveling surveys showed some distortion of the ground surface between the Mission Wells and Sylmar segments after the earthquake (Savage, Burford, and Kinoshita, 1975, p. 184; Lahr, Wyss, and Hileman, 1971, p. 87).

Sylmar segment

This zone of fault displacement was generally wider than other segments, with a zone of left-lateral shearing and compression concentrated within a belt up to 85 m wide along the southern edge of a much broader zone of deformation (Figures 2 and 3, USGS Staff, 1971). Approximately 80 percent of the surface faulting took place within a zone 5 m or less in width along the southern edge of the belt of left-lateral shearing and compression. The proportion is not exact because it was not specifically measured in the field. Its approximate accuracy can be judged, however, from the planimetric distortion of roads visible on large-scale aerial photographs and many photographs taken on the ground after the earthquake (see, for example, Figure 9, USGS Staff, 1971).

Within the Sylmar segment, I reported five measures of net slip ranging from 2.0 to 2.5 m (Table 1, in Sharp, 1975). Using the 80 percent figure discussed above, the net slip within a 5-m wide zone at the south edge of surface rupturing probably ranged from 1.6 to 2.0 m. Errors in measuring the apparent horizontal components of offset linear features used to determine net slip were not greater than 0.1 m. Vertical components were obtained from postearthquake surveys made by others (see Table 1, in Sharp, 1975). This implies that the maximum error of the net slip determinations would be less than 0.2 m.

The calculated net slips, from 2.0 to 2.5 m, are representative of at least 1.4 km of the 2.9 km length of the Sylmar segment.

Tujunga segment

In general, the zone of fault displacement was narrow in this segment, about 1 to 5 m wide where slip was measured. Only one determination of slip (vector H in Table 1, Sharp, 1975) was made across a zone wider than 5 m (about 30 m wide), but at this location too, horizontal deformation appeared to be strongly concentrated at the southern edge of the rupture zone.

Vector I, at the trailer park west of Lopez Canyon where 2.1 m of net slip was calculated, is one of the most reliable determinations of slip in Table 1 (Sharp, 1975) because it is based on a measured dip of the fault surface observed in a trench cut after the earthquake. The substantial difference in the net slips calculated for nearby locations, such as vectors I (2.1 m) and J (1.4 m) express the great variation of the surface displacements in short distances along the Tujunga segment.

Most of the Tujunga segment lies at or near the southern base of a mountain slope. Although large-scale landsliding (movement of blocks several thousand meters in size) could have contributed to the net slips measured along the mountain front, no evidence for this hypothetical landsliding was discovered. In view of the lack of direct observational evidence for landsliding, with one exception (vector M), the net slip calculations in Table 1 (Sharp, 1975) are probably representative of the amount and variation of tectonic displacement on this fault segment. Vector M is considered to be landslide-influenced because of its unusual azimuthal orientation compared to nearby points and because geodetic data showed anomalously large movement of the hill adjacent on the east in about the same direction (station PL1, Figure 7, Savage, Burford, and Kinoshita, 1975).

Lakeview segment

Where fault slip was measured, the zone of surface displacement was narrow, usually less than 5 m wide. At other locations that I observed but where I did not determine slip, the rupture zone was typically 1-2 m wide.

The three slip vectors calculated (A, B, and C in Table I, Sharp, 1975) vary by a factor of 3 in a short distance. Variations of this magnitude may occur in other parts of this segment where accurate displacements could not be measured. As pointed out earlier (Sharp, 1975, p. 190), a net slip of at least 4.4 m in a very narrow zone at Oliver Canyon can be calculated from data provided by Proctor and others (1972), but I question the reliability of the measured vertical component of slip at that locality, which is critical in establishing the minimum estimate of net slip there.

AVERAGE DISPLACEMENT FOR THE 1971 SAN FERNANDO EARTHQUAKE

Average slip for the activated strands of the San Fernando fault zone was not computed in my earlier paper (Sharp, 1975). The most appropriate method that can be used to determine average slip is to integrate the area under a slip-versus-distance curve and divide by the total length of the surface faulting. This method has the virtue of partly cancelling the effect of nonuniform spacing of measurements, which can lead to a biased average if the slips are treated as unweighted samples in obtaining an arithmetic mean. Although the best possible distribution of slip measurements would include uniform spacing and numerous observations per unit length along the fault traces, in general it is impossible to obtain this ideal data set in an actual investigation of earthquake fault rupture.

The calculation

To make an estimate of average slip from the 1971 data set that I obtained (Table 1 in Sharp, 1975), I assume a linear distribution of slip between the actual measured values together with the additional unreported slips that equal zero at the end points of ruptures. Although such an assumption cannot accurately model reality, in my opinion a better slip distribution can only be obtained by using those additional slip components from other published data that add to the area under the slip-versus-length curve, as discussed below. I have taken my data for the San Fernando event and have made calculations of average slip in two ways: (1) by using the data set directly as published in Table 1 of Sharp (1975); and (2) by using an adjusted data set where those slip measurements made across a zone wider than 5 meters have been reduced to 80 percent of the published values. The calculated average of (2) would represent slip on a fault zone no wider than 5 meters at any point. The slip distribution obtained by method 1 is shown in Figure 1, and that by method 2 in Figure 2.

The results

The average slip by method 1 is 0.78 m for a fault length of 14.64 km. This length was scaled from Plate 3 of CDMG Bulletin 196, omitting the Reservoir segment and overlaps of separate fault segments but including the gap between the Mission Wells and Sylmar segments. Note that in the regions of overlap of the Sylmar and Tujunga segments and the Tujunga and Lakeview segments, displacements on the pairs of breaks were not summed for this calculation. If the overlapping lengths are added to the rupture length, giving a total length of 19.25 km, additional area under the slip curve must be added also. The average slip decreases to 0.62 m if these adjustments are made, using method 1.

The average slip calculated from the modified data set (method 2) is 0.74 m for a fault length of 14.64 km. Again, slips in the overlap areas of the fault segments were not summed. If the overlap lengths and corresponding areas under the slip curve are added, the average slip decreases to 0.59 m, using method 2.

Other data could be added to the slip profiles of figures 1 and 2. Although slip vectors by Kamb and others (1971) could be used without modification, the slip components reported by Barrows and others on Plate 3 of Bulletin 196 also can be employed in a special way. Because slip must be equal to or greater than its components, single components or pairs of components (combined by taking the square root of the sum of squared single components) can be used to increase the area under the curve because they represent minima. However, they cannot be used to reduce the area because the unknown slips will in general exceed the measured components.

If the length of rupture represented by the Reservoir segment is included in the total length of surface breaks, the total length increases by 1.03 km to 19.25 km. I do not attribute slip to this segment because net slip was not determined by anyone there. By increasing the length, the average slip by method 1 decreases to 0.59 m. By method 2, it decreases to 0.57 m. Actually, since some unknown amount of slip did occur in the Reservoir segment, the figures given here for the two methods are minimal.

PROBABILITY OF SLIP EXCEEDING A GIVEN AMOUNT IN A FUTURE EVENT

An alternative way of looking at the slip data for the 1971 San Fernando earthquake would be to consider the probability of slip at one point on the fault trace to exceed a specified amount, say 1 meter. At least two ways of estimating this probability are relatively simple. One way is to assert that this probability is equal to the ratio of the 1971 rupture length where slip did exceed 1 meter to the total rupture length. Using the data in Figures 1 and 2, the probability of slip in excess of 1 meter for a given point is about 33 percent (from Figure 1) and about 31 percent (from Figure 2). These values are obtained by dividing the lengths of lines ab (4.87 km) in Fig. 1 and ab + cd (4.55 km) in Fig. 2 by a rupture length of 14.64 km. If allowance is made for the additional fault length represented by the Reservoir segment and the overlaps between fault segments, the probabilities decrease to about 25 percent (from Figure 1) and 24 percent (from Figure 2).

A second way to estimate this probability would be to take the ratio of observations where slip exceeded 1 meter in 1971, to the total number of observations. Such a calculation made from the slip vectors used in Figure 1 and 2 yields a probability of about 39 percent. This method, however, is unacceptable because the distance between measured slip values is not uniform along the length of the fault. The higher probability yielded by this method merely reflects the greater relative abundance of slip measurements where the displacement exceeded 1 meter.

PREDICTION OF FUTURE FAULT DISPLACEMENTS

Although the values of average slip reported here are interesting in their own right I would question their usefulness or applicability to the problem of predicting what amount of movement may happen at a given point on the San Fernando fault zone during a future slip event, or on another fault of similar character. The problem is quickly brought into focus by considering strike-slip displacements that occurred on the Imperial fault in southern California during earthquakes in 1940 and 1979. This pair of slip events is probably unique among historic earthquakes in that both were documented well enough to allow meaningful comparisons of the average and maximum displacements. Although the rupture length, displacement, and magnitude (M7.0)[1] of the 1940 earthquake were larger than those of the M6.5[1] event of 1979, the ground surface broke along nearly identical traces in the fault segment common to both events. If we had attempted to predict the 1979 earthquake magnitude, rupture length, and maximum and average displacement

[1]Magnitude determined from seismic moment.

from the 1940 event, we would have overestimated each. If the order of the events were reversed, however, the less than 0.4 m average displacement and the 0.8 m maximum movement of the 1979 earthquake would have seriously underestimated the more than 1.7 m[1] average and 6 m maximum slip of the 1940 shock. Underestimation would have been minimal if the maximum 1979 displacement were used to predict the average 1940 displacement.

No similar detailed comparison of well documented historic surface ruptures for successive thrust faulting events is possible. If we allow that such large variations for successive movements are likely in other kinds of faulting, including thrust and normal faults and those with coseismic slip not followed by significant afterslip, we should recognize by the Imperial Valley examples that slip for one event is not necessarily a reliable predictor of slip for the next event, nor does it always provide a margin of safety.

From these examples the one measure that stands apart from the others as a credible predictor of slip during a future earthquake is the maximum slip observed for one event. Although one might question the comparison of strike slip events on the Imperial fault to oblique thrusting on the San Fernando fault zone, the lack of data for consecutive events on the latter kind of faulting forces the use of the strike-slip examples. To predict the average slip for the 1940 Imperial fault displacement from the 1979 slip data, one must allow that the most likely (the average) displacement can be larger by a factor of 2 than the maximum observed slip from another earthquake. It would be inappropriate, however, to extend the use of this factor to other faults, particularly faults that are not strike-slip in character, until further comparative studies are made after future fault displacements.

[1]Average slip determined by integration of unpublished data on displacement.

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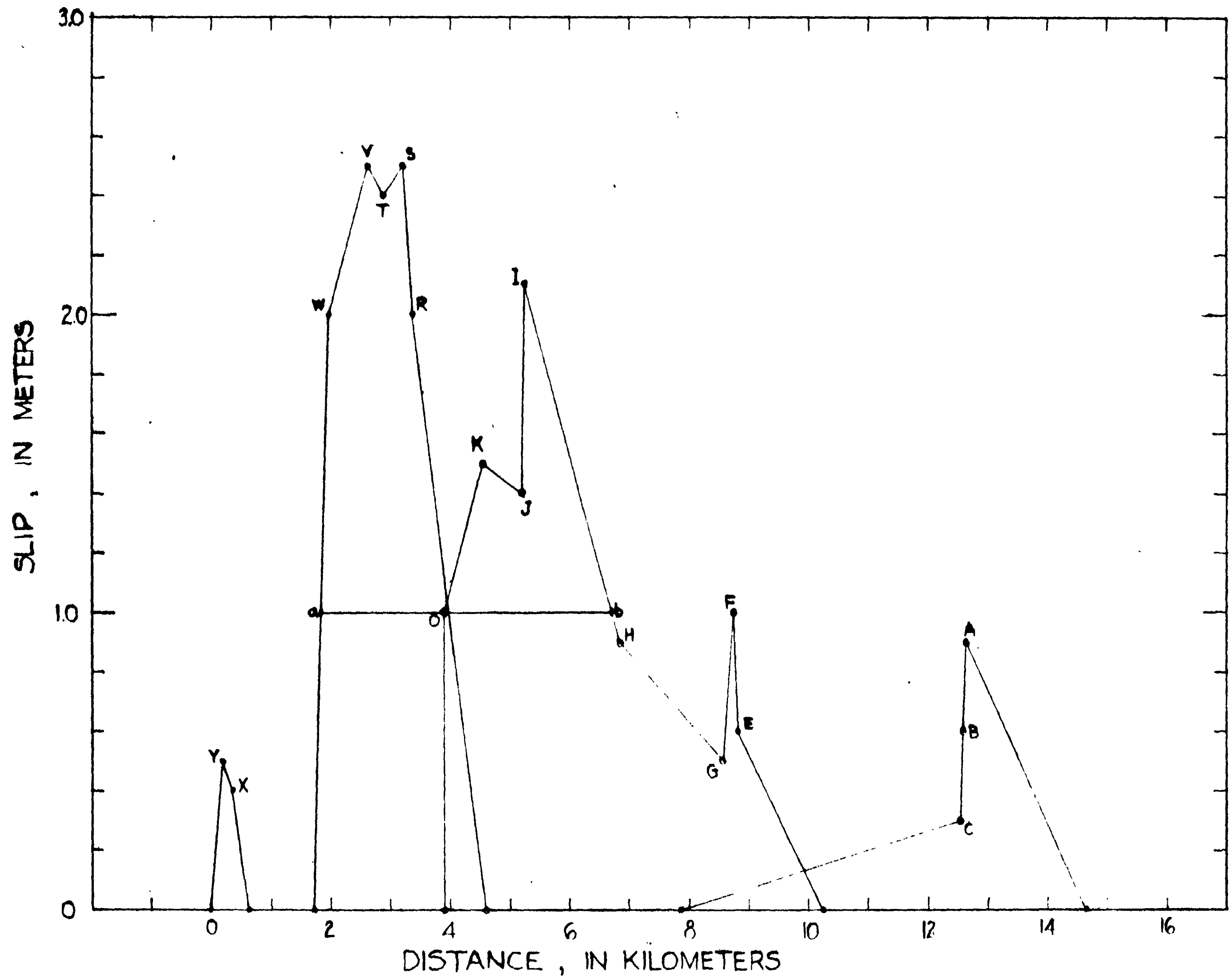
Figure captions

Figure 1. 1971 displacement versus distance along the San Fernando fault zone. Capital letters refer to slip vectors in Table 1 of Sharp (1975). Vectors A to C, Lakeview segment; E to O, Tujunga segment; R to W, Sylmar segment; X[1] and Y, Mission Wells segment. Line ab, length of surface rupture where displacement equalled or exceeded 1 m.

Figure 2. Adjusted 1971 displacement versus distance along the San Fernando fault zone. Slip measured at points H, R, S, T, V, and W are reduced to 80 percent of amount reported in Table 1 of Sharp (1975). Capital letters are the same as in Figure 1. Line ab and cd, lengths of surface rupture where displacement equalled or exceeded 1 m.

[1] The slip shown for vector X in this figure and figure 2 differs slightly from the value reported in Table 1 of Sharp (1975). The change is due to a correction that was overlooked in the original calculation of slip.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2.0
1.0
0
SLIP , IN METERS
0
2
4
6
8
10
12
14
16
DISTANCE , IN KILOMETERS
V
S
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b
H
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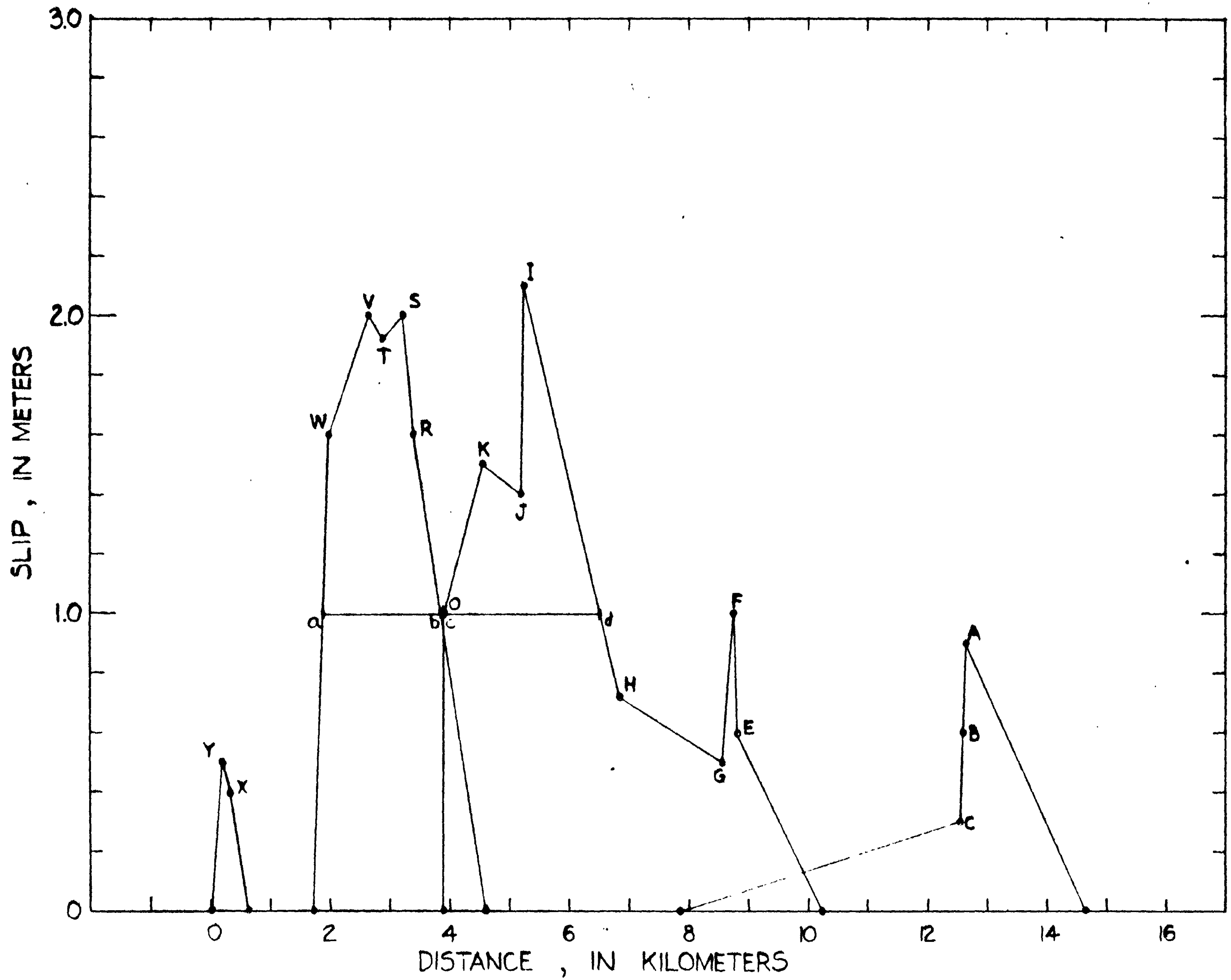
C
Y
X

FIGURE 1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SLIP , IN METERS
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12
14
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DISTANCE , IN KILOMETERS
Y
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FIGURE 2

APPENDIX

The slip vectors reported in Table 1 of Sharp (1975) are based on data listed in Table A-1. Coordinate systems used in the field measurements and for reporting of slip components in Table A-1 are shown in Figure A-1 and Figure A-2, respectively.

Errors detected in Table 1 by recalculation of data:

1. Vector J, dip of fault surface be 44°, not 37°
2. Vector O, azimuth of slip vector should be S67°W, not S63°W
3. Vector Q, azimuth of slip vector should be S65°W, not S60°W
4. Vector X, because of error due to 80° intersection of roads, not 90°, the slip vector changes as follows: length, 0.44m; length of horizontal component, 0.36m; azimuth, S69°W; plunge, ≥35.5°NE; dip of fault surface, ≥76.5°SE.
5. Vector Z, plunge of slip vector should be 40°NE, not 39°NE.

Appendix figure captions

Figure A-1. Slip vector cell, coordinate system used in field. Conventions: (1) α is measured anticlockwise from fault trace east of location of slip vector. $180° > \alpha > 90°$ when first named feature in Table A-1 is so located; otherwise $\alpha \leq 90°$; (2) β is measured anticlockwise from first named feature; (3) a and b are measured perpendicular to the offset linear features.

Figure A-2. Equivalent slip vector cell, horizontal edges are computed slip components. Conventions: (1) Cell is orthogonal, with diagonal V the same as in Figure A-1; vertical component of slip is also the same; (2) Compressional component, K, is measured normal to vertical plane along the fault strike; (3) Lateral component, L, is measured parallel to fault strike.

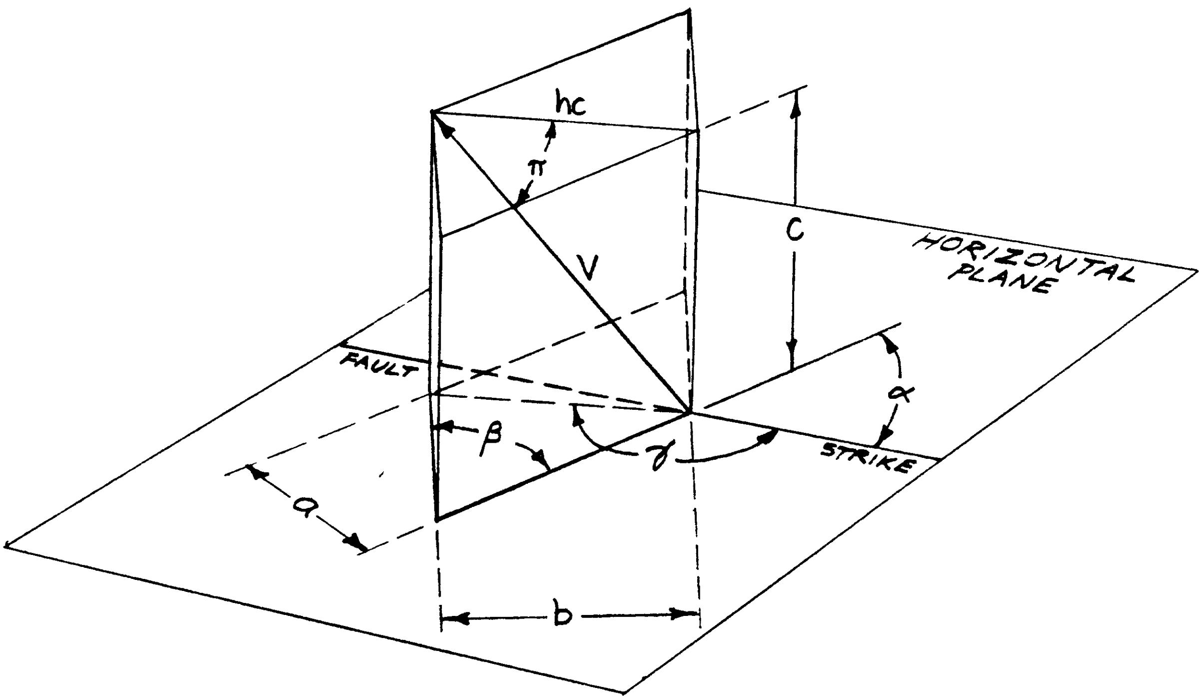

FIGURE A-1

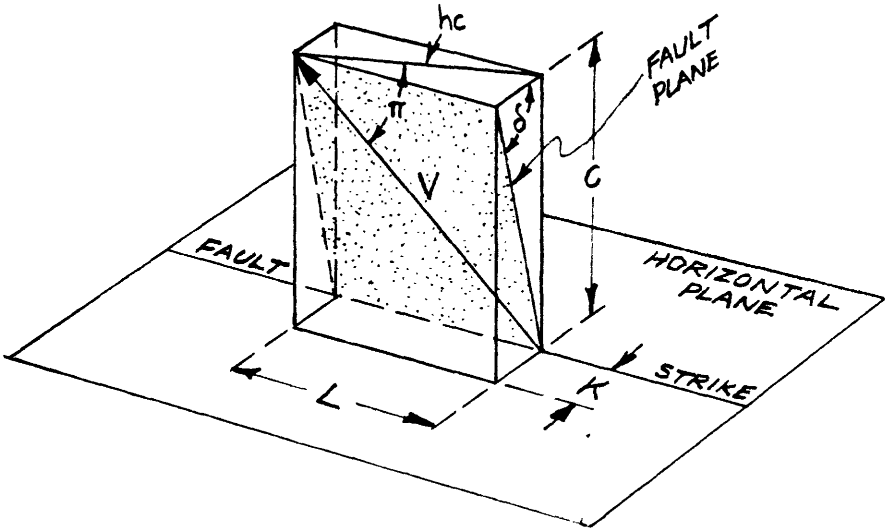

FIGURE A-2

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TABLE A-1. SLIP VECTOR DATA (See appendix figures A-1 and A-2)
(Quantities measured in field are underlined; quantities not underlined are derivative)

VECTOR	a(m)	b(m)	c(m)	α(deg)	β(deg)	L(m)	K(m)
A	0.80 (road)	0.50 (mound)	0.60	38	90	0.88	0.32
B	0.50 (bank)	0.40 (mound)	0.56	45	76.5	0.56	-0.15
C	0.00 (road)	0.30 (furrow)	0.30	150	95	0.26	-0.15
D	Data lost						
E*	0.30 (rank)	0.43 (file)	0.31	86	90	-0.26	0.45
F**	0.45 (rank)	0.80 (file)	0.55	60	90	0.01	0.92
	0.17 (rank)	0.90 (file)	0.50	77	90	0.04	0.91
	0.20 (rank)	0.75 (file)	0.50	68	90	0.10	0.76
G	-0.22 (rank)	0.22 (file)	0.40	57	90	-0.06	0.29
H			0.78			0.13	0.35
I	0.00 (road)		0.60	15		1.89	0.50
J	1.20 (wall)	0.19(road)	0.64	127	94	1.00	0.67
K	0.00 (drive)	1.07 (curb)	1.00	90	90	0.00	1.07
L***			0.95			0.80	0.32
M	0.20 (road)	1.07 (walk)	0.41	112	0	0.61	0.99
N	Data lost						
O	0.30 (channel)	0.90 (freeway)	0.26	150	90	-0.63	0.71
Q	≥0.70 (pipe)	0.20 (curb)		60	0	≥0.52	≥0.51
R	1.44 (road)	0.79 (road)	1.12	131	0	1.60	0.35
S	1.47 (Adelphia)	1.47 (Harding)	1.50	46	90	2.07	0.03
T	1.90 (8th)	0.64 (Fernmont)	1.30	40	90	1.87	0.72
V	1.90 (O.G.)	0.70 (O.G.)	1.39	123	0	1.94	0.46
W	0.20 (Glenoaks)	1.10 (Glenoaks)	1.27	110	0	1.12	0.03
X	0.325 (Havana)	0.20 (Bleeker)	≥0.25	65.5	80	0.35	-0.06
Y	0.24 (walk)	0.37 (wall)	0.24	44	73	0.39	0.04
Z	0.00 (Rajah)		0.10	68		0.05	0.11

Notes:
1. Vectors designated by letters and quantities a, b, c, α, and β as shown in Table 1 and Figure 3, p. 191 and 190, CDMG Bull 196.
2. Quantities L and K are left lateral and compressional components resolved parallel to, and perpendicular to the fault trace, respectively. Negative values for L (and a) indicate right lateral sense of movement.
3. Quantities a and b are apparent offsets measured normal to the linear features.
4. Blank spaces in this table are quantities not measured or indeterminate by computation.
5. Superscript marks: * - Original notes on field measurements have been lost. Reported values are from summary notes on slip vector, from which original quantities measured in the field have been recalculated. Error in these components about ± 0.01m. ** - Reported slip vector in Table 1 is average of four vectors measured in field. Data for one of the four is lost; the remaining three vectors are shown here in place of the one average of the four vectors. *** - Average of 3 vectors described in USGS Prof. Paper 733, p. 68.