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Surface faulting near Livermore, California associated with the January 1980 earthquakes

by

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Menlo Park, California

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ABSTRACT

The earthquakes of 24 January (M_S 5.8) 1980 north of Livermore, California, and 26 January (M_S 5.2), were accompanied by surface faulting in the Greenville fault zone and apparently in the Las Positas fault zone also. The surface faulting was discontinuous and of small displacement.

The main rupture within the Greenville fault zone trended about N.38°W. It was at least 4.2 km long and may have extended southward to Interstate Highway 580, giving a possible length of 6.2 km; both of these lengths included more gaps than observed surface rupture. Maximum displacements measured by us were about 25 mm of right slip (including afterslip through 28 January); vertical components of as much as 50 mm were seen locally, but these included gravity effects of unknown amount. The main break within the Greenville fault zones is very close to a fault strand mapped by Herd (1977, and unpublished data).

A subsidiary break within the Greenville fault zone was about 0.5 km. long, had a general trend of N.46°W., and lay 0.12 to 0.25 km east of the main break. It was characterized by extension of as much as 40 mm and right slip of as much as 20 mm. This break was no more than 25 m from a fault mapped by Herd (unpublished data).

Another break within the Greenville fault zone lay about 0.3 km southwest of the projection of the main break and trended about N33°W. It was at least 0.3 km long and showed mostly extension, but at several places a right-lateral component (up to 5 mm) was seen. This break was 80 to 100 m from a strand of the Greenville fault mapped by Herd (1977).

Extensional fractures within the Greenville fault zone on the frontage roads north and south of Interstate Highway 580 may be related to regional extension or other processes, but do not seem to have resulted from faulting of the usual kind. One exception in this group is a fracture at the east side

of Livermore valley which showed progressive increase in right-lateral displacement in February and March, 1980, and is directly on the projection of a fault in the Greenville fault zone mapped by Herd (1977).

A group of more than 20 extensional fractures in Laughlin Road 1 km north of Interstate 580 probably are related to small tectonic displacements on faults in the Greenville fault zone. They are adjacent and parallel to two faults mapped by Herd (1977), are diagonal to the road, and most of them developed between 25 and 29 January, a period that included the M_S 5.2 shock of 26 January.

Observations at two locations indicate tectonic displacement on the Las Positas fault zone as mapped by Herd (1977). At Vasco Road a prominent break on a strand of the fault showed about 0.5 mm of left-lateral strike slip on 7 February. An alinement array across this and other fractures at the locality indicates about 6 mm of left-lateral displacement occurred between 21 February and 26 March. On Tesla Road several right-stepping fractures, one of which showed 1.5 mm of left-lateral strike slip, lie on or close to previously mapped strands of the Las Positas fault zone. The evidence at these two localities indicates that tectonic surface displacement occurred along at least 1.1 km of the Las Positas fault zone.

INTRODUCTION

About 11:00 a.m. Pacific Standard Time on 24 January 1980 an earthquake of surface-wave magnitude M_S 5.8* occurred about 17 km north of Livermore, California, and on 26 January about 6:30 p.m. local time an earthquake M_S 5.2** occurred about 4 km north-northeast of Frick Lake and about 12 km southeast of the 24 January shock. When the location of the first shock was approximately known, reconnaissance teams of the U.S. Geological Survey began looking for surface faulting and landsliding related to the earthquake. During the afternoon of 24 January an aerial reconnaissance by small fixed-

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* $M_S = 5.76 \pm 0.09$ (Std. Dev. of Mean) was determined from 9 vertical-component amplitudes with magnitude observations computed as described in USGS Earthquake Data Reports (BRG 6.2, KRA 6.1, SJG 5.8, NNA 5.8, COL 5.7, MAT 5.6, NUR 5.6, CAR 5.6, PMR 5.4.); data supplied by John Minsch National Earthquake Information Service. USGS Preliminary Determination of Epicenters (PDE) lists a body-wave magnitude M_b 5.3 and Berkeley, a local magnitude M_L 5.5. Reconstruction of two USGS short period vertical maxima give local magnitudes of 5.8 and 6.1 (J. P. Eaton, oral communication.)

** $M_S = 5.17 \pm 0.20$ (Std. Dev. of Mean) from 3 observations (BRG 5.5, HFS 5.2, COL 4.8; PMR 4.4, not averaged.) More complete magnitude data will be available in Earthquake Data Reports. PDE M_b is 5.0. Three observations of local magnitude from USGS short period vertical maxima are 5.4, 5.4 and 5.2 (J. P. Eaton, oral communication.) U.C. Berkeley Seismographic Station reported a local magnitude of 5.8 using the record of their strong-motion "Wood-Anderson"-type instrument.

wing plane was completed by R. E. Wallace and M. G. Bonilla while ground reconnaissance was carried out by E. E. Brabb, E. H. Pampeyan, J. C. Tinsley, R. V. Sharp, J. J. Lienkaemper, P. W. Harsh, R. C. Wilson, D. K. Keefer, N. E. Tannaci, and G. F. Wieczorek. On 25 and 28 January additional reconnaissance was carried out and systematic mapping of surface faulting began.

The ground reconnaissance on 24, 25, and 28 January included examination of paved roads in the vicinity of the principal shocks of 24 and 26 January; unpaved roads crossing the Marsh Creek and Morgan Territory faults of Brabb and others (1961) in sections 11, 14, 15, and 16 of T.1 S., R.1 E. (this through the courtesy of Mr. W. G. Morgan who provided both guidance and a four-wheel-drive vehicle); and the Concord fault at points where tectonic creep has been occurring. Our reconnaissance along with information from other investigators indicated the areas where more detailed work was required.

Systematic mapping was done intermittently from 25 January through 15 February, primarily by Bonilla, Lienkaemper, and Tinsley, but ably assisted at various times by R. V. Sharp, S. E. Carson, E. B. Newman, J. C. Yount, D. G. Herd, Rex Upp, M. J. Rymer, E. J. King, and B. F. Atwater. Some field checking was also done 29 February and 1 April 1980.

SURFACE FAULTING

The surface faulting associated with the earthquakes of 24 and 26 January was characterized by small displacements, discontinuous traces, and difficulty in distinguishing some of it from landslide effects; nevertheless a main break and at least two subsidiary breaks were identified in the Greenville fault zone, and fracturing with progressively increasing left-lateral displacements indicates faulting in the Las Positas fault zone also. The following general description of the faulting and fracturing makes use of the numbered locations marked on plate 1. Details of field observations are given in table 1 for all locations except those numbered 33 to 36, which are fully described in the text.

Main break within the Greenville fault zone

One of the January 1980, breaks within the Greenville fault zone of Herd (1977) can be designated the main break on the basis of its close proximity to a major strand of the Greenville fault zone (pl.1), its linearity, its length, and its right-lateral displacement (about 25 mm) which was greater than on any other break. The main break extended discontinously between the consecutively-numbered locations 1 through 19, and probably to location 23 (pl. 1).

At its north end it consisted of two subparallel zones about 30 m apart extending about 0.1 km southeast from locations 1 and 2 respectively. Between locations 4 and 5 no fault ruptures were seen. Northeast of a line joining locations 4 and 5 are some short fractures that are probably related to slope movements, although one break showed 6 mm of right-lateral separation combined with 27 mm of extension. At location 5 two isolated en echelon left-stepping fractures in a dirt road indicate right-lateral displacement, but we were unable to measure the amount.

Between locations 5 and 6 and on both sides of a line joining the two locations is an area in which extensive shallow downslope movement, apparently at the time of the 24 January earthquake, has obscured any faulting that may be present. At location 6 is a prominent fracture trending N.36°W that shows evidence of right-lateral strike-slip displacement and probably is faulting. An alinement array installed by P. W. Harsh crosses this fracture. Farther south at location 7 are two subparallel northwest-trending fractures some 2 to 8 m apart. The western one shows mostly downhill extension with possibly a right-lateral component, but the eastern one exhibits compression, the downhill side being thrust over the uphill side, and has a suggestion of a left-lateral component. The origin of these two fractures is not clear, but the western one joins a landslide to the south.

From location 8 a series of fractures can be traced intermittently to location 12 on Vasco Road. Evidence of right-lateral displacement, ranging up to about 25 mm, was found at several places along this portion of the fault zone. Possibly the fracture zone between locations 8 and 12 extends much farther to the northwest across the area of landslides to connect with the fractures near location 1.

No surface faulting was found for 1.4 km southeast of location 12 along the line of the main break, but a series of hairline fractures trending northeast are visible in the pavement at location 13. Most of these fractures are about on the projection of the main break and a fault strand mapped by Herd (1977), and have the proper orientation to be fault breaks; however, the fractures are also perpendicular to the road, and to the east, where the road runs east-west, the fractures trend north-south. This group of fractures and a hairline crack in a paved farm road are the only suggestions of faulting that we saw between locations 12 and 14.

Evidence of faulting was found at location 14, where 10 mm of

right-lateral strike-slip was measured, and at location 15, where north-south fractures in soil indicated some right-lateral displacement. At locations 16 through 19 right-lateral displacements of as much as 15 mm (resolved parallel to zone) were measured on 29 February. Between locations 9 and 16 the trend of the fault zone is about N.40°W., but between locations 17 and 19 the trend is about N.18°W. Whether this indicates a change in the trend of the main fault or the presence of a branch fault diverging from the general trend is not clear. No faulting was seen near Frick Lake on the projection of the N.40°W. trend, but an alinement array has shown right-lateral afterslip just east of, but not at, location 19 (P. W. Harsh, personal communication). This evidence suggests that the ruptures at locations 18 and 19 are on a branching break and that the main break continued on a more southeasterly trend, along the fault strand mapped by Herd (1977), probably to location 23 where the right slip on a fracture increased from about 1 mm on 29 January to about 2 mm 29 February and 3 mm on 1 April. No paved roads exist between Frick Lake and location 23, and faulting of such small displacement would be extremely difficult to find between those places.

Subsidiary breaks within the Greenville fault zone

A zone of faulting, here referred to as the northeast break, extended discontinuously from near location 26 southeastward across Vasco Road to location 31, close to a strand of the Greenville fault zone mapped by Herd (see pl. 1). The part extending northwest from Vasco Road showed extension perpendicular to its trend and generally some vertical displacement, with the southwest side relatively down-dropped by 20 to 30 mm. The strike-slip component of displacement at the time of our examination (24 January and 5 February) was both right- and left-lateral. This peculiar circumstance is probably the result of right-lateral faulting of small amounts (20 mm or less) accompanied or followed by local downslope movement of the wet soil as the

result of shaking. In support of this explanation are the facts that a) the fractures usually are left stepping even where left-lateral components are present; b) on flat ground (such as location 29 and the northern part of location 27) the strike-slip component is right-lateral; and c) the continuation of the zone southeast of Vasco Road shows right-lateral components of displacement. At the white line on the southeast side of Vasco Road (location 29), Wilson and Keefer measured 20 mm of right slip, 40 mm of extension, and 30 mm of vertical displacement (down on the southwest) about 3:30 p.m. 24 January. The part of the northeast break that lies southeast of the Vasco Road crossing left-steps about 20 m to the east of the part northwest of the road, but has the same general trend. The fractures in the part southeast of Vasco Road generally show extension and little or no vertical component, and in many places have evidence of a right-lateral slip component and a left-stepping pattern. The greatest extension and right-lateral strike-slip displacement measured on this part of the northeast break were about 25 mm and 13 mm respectively.

The fracture zone in the west half of section 23 (location 32, pl. 1) is here referred to as the southwest break. It extends at least 0.3 km (access problems prevented complete mapping) over a hill, across a valley and up another hillside. This fracture, like many of the others, shows mostly extension, but a right-lateral component (maximum 5 mm) was observed at several places.

Other fractures within or near the Greenville fault zone

New or newly-widened fractures were seen at various places within or near the Greenville fault zone; some of these are probably directly related to faulting and others are probably related to ground vibration. On Laughlin Road at location 20 a group of more than 20 hairline fractures trend about N.40-60°W., diagonal to the road. Although only extension was seen on these

fractures they probably resulted from faulting because they cross the road diagonally instead of perpendicularly, they are parallel and adjacent to two faults mapped by Herd (1977), and they have grown with time (only two fractures were detected on 25 January but more than 20 could be seen on 29 January). Locations 19 and 20 possibly are on one splay parallel to the west side of Frick Lake.

Many fractures cross the north frontage road of Interstate Highway 580 and Greenville Road between locations 21 and 23. These fractures are perpendicular to the roads, changing trend as the pavement changes direction. Many of these fractures are obviously old, having been patched or having weeds growing in them before the earthquakes, but some seem to be new. Near location 22 are several conspicuous open fractures. One fracture on the north-south part of Greenville Road showed extension of 6 mm, stepped to the right, but showed no lateral or vertical component and did not break the concrete divider. At location 23 a probably old fracture trending N.40°W. (also perpendicular to road) showed new movement, including right-lateral displacement that was about 1 mm on 29 January, but was about 2 mm on 29 February and 3 mm on 1 April. This fracture, which is directly on the projection of a strand of the Greenville fault zone shown by Herd (1977) is the only one between locations 21 and 23 that showed definite lateral displacement, and the displacement may be directly related to faulting. The fault on the projection of which it lies is shown by Herd (see pl. 1) as extending northwestward close to locations 14 through 17, where faulting occurred this year.

The south frontage road (location 24) and the adjacent parts of Greenville Road show numerous fractures. These almost all trend perpendicular to the roads, trending about north-south on the frontage road and about east-west on Greenville Road. One fracture about 160 m west of Greenville Road had weak indications (small differences in width along length) of less than 1 mm of

right-lateral displacement but none of the others had evidence suggestive of tectonic lateral displacement.

On Vasco Road about 2 km north of the county line (location 25) several fractures in the pavement were found by D. K. Keefer and R. C. Wilson on 24 January. These fractures trend about N.70°E., are right-stepping, and on 6 February had as much as 2 mm of left-lateral and 3 mm of vertical displacement on them. The fractures are visible only in the pavement and for a short distance onto one shoulder of the road. The roadbed is probably on bedrock but a thin fill could underlie at least part of the pavement. The origin of these fractures is not clear. They are not readily explained by downslope movements. If they are the result of faulting, it must be very local.

Two cracks across Morgan Territory Road (near S. line of sec. 5, T. 2 S., R. 2 E., 3.4 km northwest of location 1 and beyond the limits of pl.1) were observed by Brabb on 25 January. The cracks trended N.35°W. and had about 2 mm of right-lateral displacement. They are on the extension of the Greenville fault as shown by Brabb and others (1971) and could represent tectonic displacement, but they could also be related to settlement of the road. At least 15 other cracks were visible in the pavement of Morgan Territory Road on 1 April within 0.7 km north of the cracks noted by Brabb. One crack was 0.2 km north of the Marsh Creek fault as shown by Brabb and others (1971). It had a trend of N.81°W. (nearly perpendicular to the road) and showed 2 or 3 mm of right-lateral displacement. At least half of the road is on fill at that point. This crack, like the others in this area, is probably not the result of faulting.

Breaks within the Las Positas fault zone

The Las Positas fault zone, recognized and mapped by D. G. Herd (1975, 1977), strikes northeast along the southeastern margin of Livermore Valley. Fractures were observed at locations 33, 34, 35, and 36 along Mines Road, Tesla Road, Las Positas (Vasco Road) and Greenville Road where mapped traces

of the Las Positas fault intersect paved roads. Plate 1 and figure 1 show these 4 localities in relation to the mapped fault traces. On 7 February these localities were inspected and the fractures were described and mapped (figures 2, 3, 4, and 5). On 29 February the localities were revisited and inspected for new fractures or modifications to earlier fractures.

At Mines Road (location 33) eight sets of fractures designated 33A-33H were observed on 7 February as sketched in figure 2. The fractures are located 210 to 250 m south of the centerline of Tesla Road. Azimuths of segments of the fractures range from 76° to 109° but trend approximately perpendicular to Mines Road; the fractures are largely confined to the northbound lane. Only 33A was noted to extend across the centerline on 7 February. Prior to 7 February, other investigators used orange spray paint to mark fractures 33A, 33B and 33C; fractures 33D-33H had not been painted. On 7 February, no measurable vertical or lateral displacements were associated with the fractures 33A-33H. No apparent post-paint propagation or extension of fractures 33A-C was observed.

On 29 February location 33 was reinspected. Blue paint had been applied to fractures 33D-33H. Fracture 33G now crossed the centerline of Mines Road, but had not grown since application of the blue paint. No displacements or apparent propagation of fractures other than 33G was observed.

The fractures at Mines Road (location 33) exhibited dusty, weathered surfaces and did not expose freshly broken, black asphalt as did other fractures caused by tectonic displacement or by non-tectonic ground failure. Although fractures 33A-33C apparently coincide most closely with the trace of the Las Positas fault (Herd, 1977; figures 1, 2, this report), the absence of measurable displacement and the rather aged appearance of the fractures and their geometry (perpendicular to Mines Road) suggests a non-tectonic origin. The extension of fracture 33G across the centerline of Mines Road observed on 29 February followed a period of heavy rain. The extension of this feature,

if tectonic in origin, is the apparent southwestern limit of effects related to probable surface rupture on the Las Positas fault.

At location 34 along Tesla Road (inspected 7 February) nine fractures comprise three right-stepping en echelon sets of fractures (sketched in figure 3). Fractures 34A, 34B, and 34F-34I coincide with mapped traces or lie on the projections of mapped traces of the Las Positas fault zone (figures 1 and 3). Fracture 34C displays about 1.5 mm left-lateral strike slip displacement. Post-earthquake propagation of fractures C, E, and F apparently occurred; the cracks extended through and beyond spots of blue spray paint which reportedly marked the ends of the cracks at the time the paint was applied. Surfaces of all fractures at location 34 exposed fresh, black asphalt. Commonly, pebbles had been "popped" from their position adjacent to the fracture edge.

The observed left-lateral strike-slip displacements, the right-stepping en echelon distribution of fractures associated with mapped traces of the Las Positas fault, the unquestioned recency of the fractures and their growth or extension following the earthquakes of 24 and 26 January indicate that the fractures on Tesla Road are probably tectonic in origin.

At location 35, examined 7 and 29 February, five fresh fractures were mapped (figure 4) near the Las Positas fault intersection at Vasco Road (called "Las Positas Ave" on pl. 1 and fig. 1). Positions of fractures were measured, using a tape, north from the centerline of Tesla Road. Fracture 35E, a prominent break near the crest of the scarp of the Las Positas fault, exhibited left-lateral strike slip displacement of about 0.5 mm. Fractures 35 A-D did not exhibit displacements. Fractures 35A-35C occurred only in the southbound lane; only 35D extended across the center line of Vasco Road. Fractures 35A-35D trend generally perpendicular to Vasco Road, and have merely opened with slip vectors oriented downslope and perpendicular to fracture trend; these features are interpreted as non-tectonic ground failure.

The small amount of left-lateral strike-slip measured at 35E coincident with the trace of the Las Positas fault indicates that surface rupture on the Las Positas fault extended at least 1.1 km from Tesla Road to Vasco Road. This interpretation is strongly supported by data from an alinement array which showed about 6 mm of left-lateral displacement across the fractures at location 35 between 21 February and 26 March (P. W. Harsh, personal communication), even though fracture 35E showed no obvious change between 7 February and 1 April 1980.

At location 36, near where the Las Positas fault zone intersects Greenville Road (figure 1), four fresh fractures without measurable lateral displacement were noted. Three fractures trend perpendicular to Greenville Road and one is diagonal to it. As mapped on 7 February these features are shown relative to the northeast abutment of the Greenville Road bridge where it crosses the South Bay aqueduct (figure 5). No extension or growth of fractures was observed on 29 February. The orientation perpendicular to Greenville Road and the absence of growth or a history of propagation indicate a probably non-tectonic origin for these fractures.

The explanation that best accounts for all observations, including the left-lateral displacements, the right-stepping en echelon fracture patterns at Tesla Road, the continued propagation of fractures after the earthquake, the alinement array data, and the spatial association of all observations with the mapped traces or scarps of the Las Positas fault zone, is that left-lateral tectonic displacement occurred on the Las Positas fault zone during and after the earthquakes of January, 1980.

Relation of the January 1980 faulting and fracturing to previously mapped faults

As shown on plate 1 the main break between locations 1 and 17 lies very close to a fault strand in the Greenville fault zone mapped by Herd (1977, and

unpublished data). As discussed previously, a possible extension of the main trace southeastward from location 17 to location 23 would closely follow the fault strand shown by Herd (1977).

The northwest break was within about 25 m of a fault strand mapped by Herd (unpublished data); see plate 1. The southwest break was 80 to 100 m from a strand mapped by Herd (1977).

The diagonal northwest-trending fractures on Laughlin Road at location 20 are parallel to and within about 100 m of two faults shown by Herd (1977).

The fractures at localities 33 through 36 are nearly coincident with strands of the Las Positas fault zone as shown by Herd (1977). Evidence at locations 34 and 35 indicates left-lateral tectonic displacement in the fault zone in 1980. Herd (1975, 1977) had previously inferred left-lateral oblique slip on the Las Positas fault zone.

Relation of faulting and fracturing to the earthquakes

The northernmost surface faulting is about 9 km southeast of the epicenter of the 24 January earthquake, but an eyewitness account (San Francisco Chronicle, 25 January 1980, p. 3) at the time of the earthquake and field observations by Harsh, Wilson, and Keefer the afternoon of 24 January show that the breaks across Vasco Road (locations 12 and 29, pl. 1) were associated with the 24 January event. Faulting associated with this event or its aftershocks evidently extended at least to Laughlin Road 0.4 km northwest of Frick Lake (location 16), where a few left-stepping en echelon fractures having a N-S orientation were observed by Brabb on 25 January. Other fractures were observed by Brabb on the same date along Laughlin Road (location 18), 0.4 km south of Frick Lake (location 20), and along the frontage road of Interstate Highway 580 near locations 22 and 23. Following the 26 January earthquake the number of fractures northwest of Frick Lake was found to have increased, as was the number of fractures on Laughlin

Road at location 20. At the latter place Brabb found only two fractures on 25 January, but by 29 January more than 20 fractures were visible. The amount of right slip at location 23 increased in February and March.

The timing of the fracturing in the Las Positas fault zone is not well known. We first saw the fractures on Tesla Road and Vasco Road on 1 February. As described above, some growth of the fractures occurred at locations 33 and 34 between 7 and 29 February, and the alinement array data indicates left-lateral displacement was continuing between late February and late March at location 35.

Other individuals and organizations have more data on the changes in number, length, and displacement on the various fractures (some data of this kind is given by Bedrossian and others, 1980) and the reader is referred to their future reports.

SUMMARY

The surface faulting associated with the earthquakes on 24 and 26 January 1980 was confined to the area more than 9 km southeast of the 24 January epicenter. The surface faulting was discontinuous, had small displacements, and in places was difficult to separate from downslope gravity movements that accompanied the earthquakes. The main break within the Greenville fault zone had a trend of about N.38°W., could be recognized at several locations over a distance of 4.2 km and may have extended as far as the vicinity of Interstate Highway 580, giving a possible length of 6.2 km; both of these lengths include more gaps than observed surface ruptures. Along 0.5 km of its length near the northwest end the main break may have consisted of two subparallel traces about 30 m apart, but extensive slope failures in that area did not permit a definite interpretation regarding that point. Maximum displacements measured by us were about 25 mm of right slip on 28 January;

vertical components of as much as 50 mm were seen locally, but these were difficult to separate from gravity effects. The main 1980 break was very close to a fault within the Greenville fault zone mapped by Herd (1977, and unpublished data).

The northeast break (locations 26-31) within the Greenville fault zone could be followed for about 0.5 km, and lay 0.12 km to about 0.25 km east of the main break. The part northwest of its intersection with Vasco Road has a general trend of about N.46°W., and the part southeast of the road crossing, which left-steps about 20 m to the east, has a general trend of about N.44°W. Both parts were characterized by extension (as much as 40 mm) and, in many places, a right-lateral strike slip component (as much as 20 mm). The northwestern part generally had a vertical component, relatively down on the southwest side; part of the vertical component may result from downslope gravity movement which is believed to account for local areas of left-lateral displacement found on this part of the break. The northeast break was very close to a fault strand mapped by Herd (unpublished data).

The southwest break (location 32) is at least 0.3 km long. It lay 0.25-0.3 km southwest of the projection of the main break and trended about N.33°W. This fracture showed mostly extension, but a right-lateral component (as much as 5 mm) was seen at several places. This break was within 100 m of a strand of the Greenville fault zone mapped by Herd (1977).

Extensional fractures on the frontage roads north and south of Interstate 580 and on adjacent parts of Greenville Road do not seem to be related to faulting of the usual kind, but may be related to regional extension or other processes. An exception to this generalization is the fracture at location 23 which showed progressive increase in right-lateral displacement over time and is directly on the projection of a fault in the Greenville fault zone mapped by Herd (1977).

A group of more than twenty fractures, most less than 1 mm wide, are visible in the pavement of Laughlin Road at location 20. They are diagonal to the road, are parallel and adjacent to two previously mapped faults, and most of them developed between 25 and 29 January. Their orientation, location, and growth suggest that they are related to small tectonic displacements on mapped and unmapped faults in the Greenville fault zone.

The small left-lateral displacements observed at locations 34 and 35 and the right-stepping fracture sets and propagating fractures observed at location 34 indicate that small tectonic surface displacements, as well as non-tectonic ground failure, occurred along the Las Positas fault zone during and probably after the earthquakes of January 24-27, 1980. Data from an alinement array at location 35 indicates about 6 mm of left-lateral displacement between late February and late March 1980. Concurrent surface displacement on two faults having a conjugate relation to one another, such as between the Greenville and Las Positas faults, has occurred before. Examples are the faulting associated with the Tango, Japan, earthquake of 1927 (Yamasaki and Tada, 1928) and the North Izu, Japan, earthquake of 1930 (Matsuda, 1972).

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Table 1. Field Observations

Location	Observations
1	Zone 100 m long, trend N.47°W.; individual open fractures in soil trend N.25° - 35°W., have left-stepping in echelon relation to the zone. At one point, right lateral displacement of 11 mm parallel to zone and extension of 20 mm perpendicular to zone (1 Feb.). Local minor left-lateral component, probably from downslope gravity movement.
2	Zone trends N.30°W., consists of at least 7 fractures in soil, on most of which right lateral separation could be seen. Site of survey quadrilateral installed by P. W. Harsh. Zone may extend 40 m farther NW. where a pair of left-stepping fractures could be followed for 15 m; extends at least 20 m to SE. Includes small graben with maximum depth of 70 mm.
3	Zone trend N. 30°W. consists of discontinuous fractures that trend N.30°-35°W. A taut root and match of pebble with its mold provided a calculated right lateral displacements of 18 mm parallel to zone and extension of 47 mm perpendicular to zone.
4	Zone trend N.38°W. individual cracks generally show relative uplift (max. 50 mm) of northeast side and as much as 30 mm extension; a "bridge" of sod attached to both walls indicated a right lateral component.
5	Two isolated en echelon left-stepping fractures in dirt road indicate right-lateral displacement but unable to measure amount. Northeast of a line joining locations 4 and 5 are some short fractures that are probably related to downslope gravity movements, although one showed 6 mm of right-lateral separation

combined with 27 mm of extension. Between locations 5 and 6 and on both sides of a line joining them is an area of extensive landsliding.

6 Prominent fracture in soil, at least 30 m long; trend N. 36°W.; strong suggestion of right-lateral component based on differences in crack width and probable match of points across break; relative vertical displacement mostly down on downhill side but not consistent. Survey alinement array installed by P. W. Harsh on 26 January crosses this fracture.

7 A pair of fractures, in soil, that intersect an E.-W. fence on the half-section line. West fracture trends N.27°-32°W. shows mostly downhill extension (maximum vertical 90 mm, 6 Feb) but may have a right lateral component. Extends south of fence where it becomes part of a landslide studies by R. V. Sharp. About 2.4 m to 9.8 m east is another fracture, somewhat concave upslope in plan, with a general trend of about N.28°W. This fracture is in compression with thrusting of downhill side over uphill side; maximum vertical component 70 mm. The one place where lateral component could be inferred (6 Feb) indicates left lateral, but very uncertain. The origin of these fractures is not clear.

8 Fracture zone in soil, trend N.27°W., consists of left-stepping fractures, extends SE. from N-S fence that is on the quarter-section line. Right-lateral displacement parallel to zone at two points (28 Jan) ranged from 10 mm to 25 mm. Farther to NW are other fractures with the same trend but they may not be of tectonic origin.

9 Fracture zone in soil, trend N.27°-30°W., traced 52 m. Unable to match edges of fracture to measure right-lateral

displacement but could be a few centimeters.

10. Single fracture in soil, trend N.30°W., right-lateral strike slip 8 mm, calculated parallel to average zone trend of N.44°W. Between locations 10 and 11 the fault trace was visible at several places; although evidence of right-lateral displacement was seen, we could not measure it.

11 Left-stepping fractures in soil; measured 22 mm of right-lateral strike slip 1 February which had increased about 1 mm when remeasured 6 February. Unable to find fault traces between localities 11 and 12.

12 At Vasco Road. Pressure ridges and fractures formed in the pavement which is built on artificial fill. At time of our detailed examination (28 January) the pressure ridges had been removed and many of the edges of the fractures had been modified by truck traffic, but right-lateral strike-slip displacement was estimated at about 2 cm parallel to the zone trend of N.30°W. Fault traces were not visible within 0.5 km SE. of Vasco Road.

13 Road to East Alameda County Dump. Seven hairline fractures extending perpendicularly across this paved road were visible 31 January; at least 4 cracks were present 25 January. Most of the cracks lie near the projection of the main break, have a NE trend, and may represent incipient faulting.

14 A short fracture zone, trend N.40°W., was found in soil at the base of a scarp-like rock outcrop. Individual fractures trend about N.18°W. Right-lateral strike slip was 8 mm parallel to zone and extension was 4 mm perpendicular to zone on 30 January.

15 Zone of fractures in soil; individual fractures trend N-S; probable right-lateral strike-slip.

16 Fracture zone trending about N.30°W. crosses Laughlin Road; first observed by us on 25 January. Individual fractures trend N-S, step to left. Difficult to confidently match points across the fractures but strike slip parallel to zone may be as much as 6 mm on a single break (29 February) including afterslip. Fractures could be traced NW. into cultivated field but we did not see them to the SE. of the pavement.

Between locations 16 and 17 several hairline cracks with no displacement cross the pavement approximately perpendicular to the road.

17 A fracture trending N.19°W. showing about 3 mm of right lateral displacement (measured parallel to crack; 28 Jan) in dirt NE. of pavement.

18 Group of northeast-trending fractures in pavement. The most conspicuous one trends N.7°E. Slip vectors measured at two places on this fracture 29 February were 13 mm in N.20°W. direction and 15 mm in N. 25°W. direction. Resolved parallel to trend of zone (between localities 18 and 19) the right lateral strike slip was 14 to 15 mm; right lateral displacement resolved parallel to the fracture ranged from 12 to 13 mm, of which as much as 6 mm occurred after a white line was painted across the fracture by Woodward-Clyde consultants on 25 January. On 29 February extension perpendicular to the fracture was as much as 8 mm, and vertical separation near center of road was as much as 2 mm (down to SE) but was not detectible at edges of road. Only one hairline fracture was observed at this locality on 25 January. The fracture had widened and moved 2 mm right-laterally by 13 February; many more fractures were present on 13 February

than on 25 January, indicating that they were related to the 26 January event or subsequent movement.

19 Fracture zone in shoulder of road crossed low cut at SW edge of right-of-way and extended into field. On 28 January right-lateral displacements were 7 mm resolved parallel to fracture zone and 6 mm resolved parallel to the direction between locations 18 and 19. Site of alinement array installed by P. W. Harsh 30 January.

20 More than 20 hairline fractures in the pavement of Laughlin Road. Spacing between fractures (29 January) ranged from 1 m to 20 m and trends ranged from about N.40°W to about N.60°W., diagonal to the road. The number of fractures increased thru time - only two fractures were visible on 25 January.

21 Fractures between locations 21 and 22 cross frontage road N. of Interstate 580 perpendicularly. Some, perhaps all, are old fractures in the pavement that apparently opened wider during the earthquakes.

22 Intersection of Greenville Road and frontage road. Several fractures, some old (possibly associated with previous seismic events) and some apparently new. Nearly all confined to asphalt pavement and not breaking concrete curbs; orientation about N-S. One conspicuous crack on N-S part of Greenville Road showed (29 January) extension of 6 mm, no lateral displacement, did not break the concrete divider and died out to south within 11 m.

23 Between locations 22 and 23 are at least 17 fractures, most if not all old, but with additional extension presumably at the time of the earthquakes. Spacing between fractures ranges from about 3 to 73 m with concentrations of fractures in certain areas. The

fractures show only extension except for one at location 23; there a fracture trending about N.40°W. showed about 1 mm of right-lateral displacement (29 January) and 2 mm of extension. The right lateral component had increased to about 2 mm on 29 February and to 3 mm on 1 April. The fracture was best developed in the north part of the road. It did not reach the south edge of the pavement on 29 January, but did by 1 April. It could not be seen in the dirt north or south of the pavement. This location is directly on the projecton of a fault shown by Herd (1977) within the Greenville fault zone.

24 South frontage road of I-580, west of Greenville Road. Examined in reconnaissance fashion 29 February. At least 21 fractures, perpendicular to the road, show only extension except for one about 160 m west of the centerline of Greenville Road which had a suggestion of less than 1 mm of right lateral displacement. Close to Greenville Road are several fractures most if not all of which are old; apparent right lateral displacement (1 mm or less) on two of them seems to be the result of vertical movement of the inclined face of the concrete curb. Fractures on Greenville Road are mostly perpendicular to that road and at right angles to the fractures on the frontage road.

25 On Vasco Road about 2 km north of the County line. Several right-stepping fractures in the pavement. One zone trends about N.70°E., crosses entire pavement and showed 1 to 2 mm of left lateral and up to 3 mm vertical displacement (side up not consistent) on 6 February; a subparallel zone a few meters away shows only extension (maximum 5 mm), doesn't reach northeast side

of pavement but visible in dirt on southwest side of pavement. Unable to find fractures beyond shoulder of road. Roadbed probably on bedrock (sandstone and shale dipping 30° S.50°W.) but thin fill could be under pavement.

26 Fracture zone in soil, trend N.38°W., could be traced about 30 m by very careful search, including pulling of grass. Zone at least 5 m wide, consists of three or more fractures up to 5 mm wide, about parallel to zone. Except for a left-stepping pattern in places, no evidence of lateral movement was found. Other fractures to the east, on a northeast-facing slope probably result from downslope movement of the soil.

27 Fracture zone in soil, trend N.55°N., was traced 43 m. It consists of prominent discontinuous left-stepping fractures. Near south end, differences in widths of fracture indicate a left-lateral component, but 15 m to the northwest had 15 mm of right-lateral strike slip measured parallel to trend of zone; southwest side generally downdropped, the vertical component being as much as 20 mm locally.

28 Fracture zone in soil, trend N.48°W., traced about 45 m. Near middle of zone, left-lateral strike slip 10 $\pm$ 5 mm, extension about 30 mm, and vertical component (down to SW) about 30 mm. About half way between locations 22 and 28 is a fracture zone locally trending N.58°W. At one point on it both the extension and the vertical component (down on SW) about 20 mm and the right-lateral strike-slip component was 11 mm and 7 mm resolved parallel to the local zone trend and general zone trend respectively.

29 At Vasco Road breaks in the pavement had been repaired at time of our visit except near centerline of road, where there were three principal cracks formed a zone about 1 m wide, and a vertical component (down on SW.) was visible. About 3:30 p.m. on 24 January, just before the repairs were made, R. C. Wilson and D. K. Keefer measured and photographed the break at the southeast side of the road where it was a single fracture. At the white line there they measured 20 mm of right lateral displacement, 40 mm of extension, and 30 mm of vertical displacement, down on southwest. Because the white line is perpendicular to the fault, its lateral displacement represents right slip. Later visits showed that additional displacements have cracked the asphalt that was placed 24 January. This fracture zone could be followed continuously (25 January) as open cracks in the soil for at least 100 m northwest of Vasco Road and about 30 m southeast.. About 40 m northwest from the road on 5 February the fracture showed 20 $\pm$ 10 mm of left lateral displacement measured parallel to the fracture (locally N.26°W.) and some vertical displacement (down on SW, the downhill side).

30 Fracture zone in soil, general trend about N.45°W., was traced for 45 m. At one point right-lateral strike slip parallel to zone was 13 mm and the extension was 24 mm, with no vertical component. This site is on top of a flat spur with a slight inclination to the southeast. Southeastward from this fracture zone others were found in the next 50 m; these were open, generally had no vertical component and in places showed a left-stepping pattern.

31 Fracture zone in soil, general trend N.45°W., could be followed

for 27 m. At one point extension was about 25 mm, vertical component 27 mm (down to SW), and right-lateral strike slip was 8 mm; downslope movement alone would have given a left-lateral component. No other fractures were found to the southeast along the trend of this fault zone.

32 West of Vasco Road in W. 1/2 sec. 23, T. 25, R. 2 E. Fracture trending N.30°W. extends discontinuously for at least 0.3 km, extending over a hilltop, across a valley and up another hillside where access problems prevented a further search. Fracture shows mostly extension but at several places a right-lateral component was found. The maximum measured right-lateral strike slip was 5 mm combined with 6 mm of extension, both resolved with respect to the map trend of N.33°W.

33 to 36 Described in text, pages 10 to 13.

37 Five cracks trending N.35°E. in dirt road and embankments, observed by Brabb on 25 January. Northeast of this location at least 20 cracks trending about N.40°E. were visible in the pavement of Vasco Road. Some cracks step to the right and others step to the left; no lateral or vertical displacement was visible on them on 1 April.

38 Two cracks in Vasco Road, observed by Brabb on 25 January. One crack trends N.76°E., and crosses the pavement; the other trends N.81°E. and extends across the west lane only. No lateral or vertical displacement visible on 1 April.

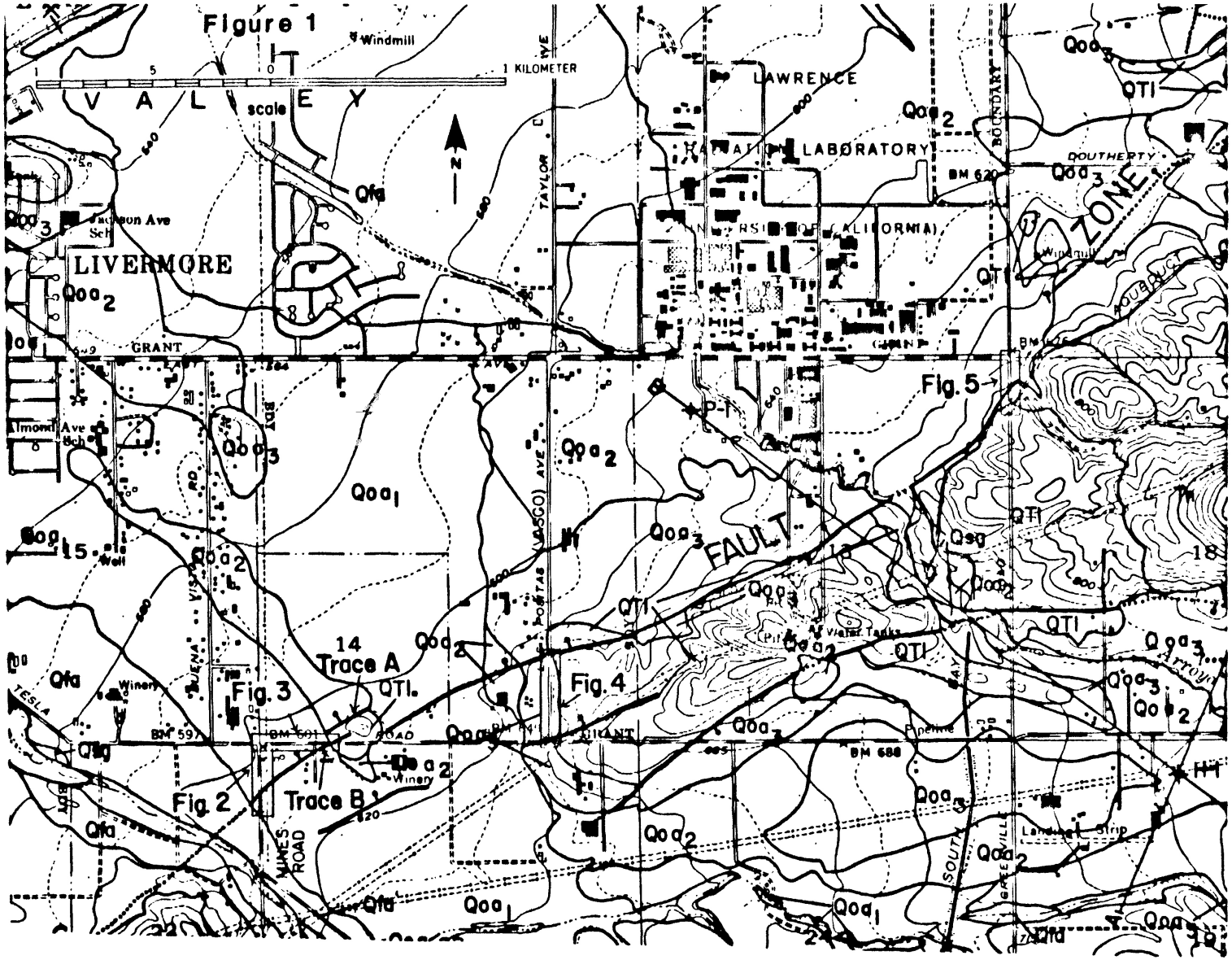

Figure 1. Index map excerpted from Herd (1977) showing locations of figures 2 through 5 in relation to mapped traces of the Las Positas fault zone.

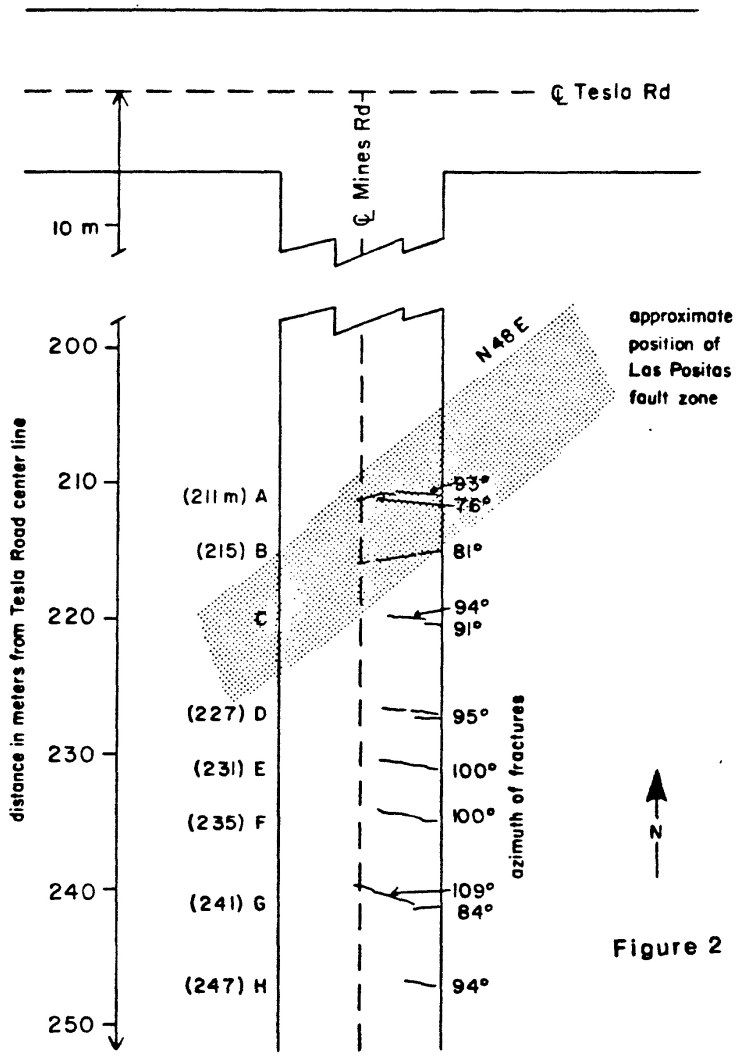

Figure 2

Figure 2. Sketch map showing fractures in the pavement of Mines Road in relation to the centerline of Tesla Road and the approximate position of the Las Positas fault zone.

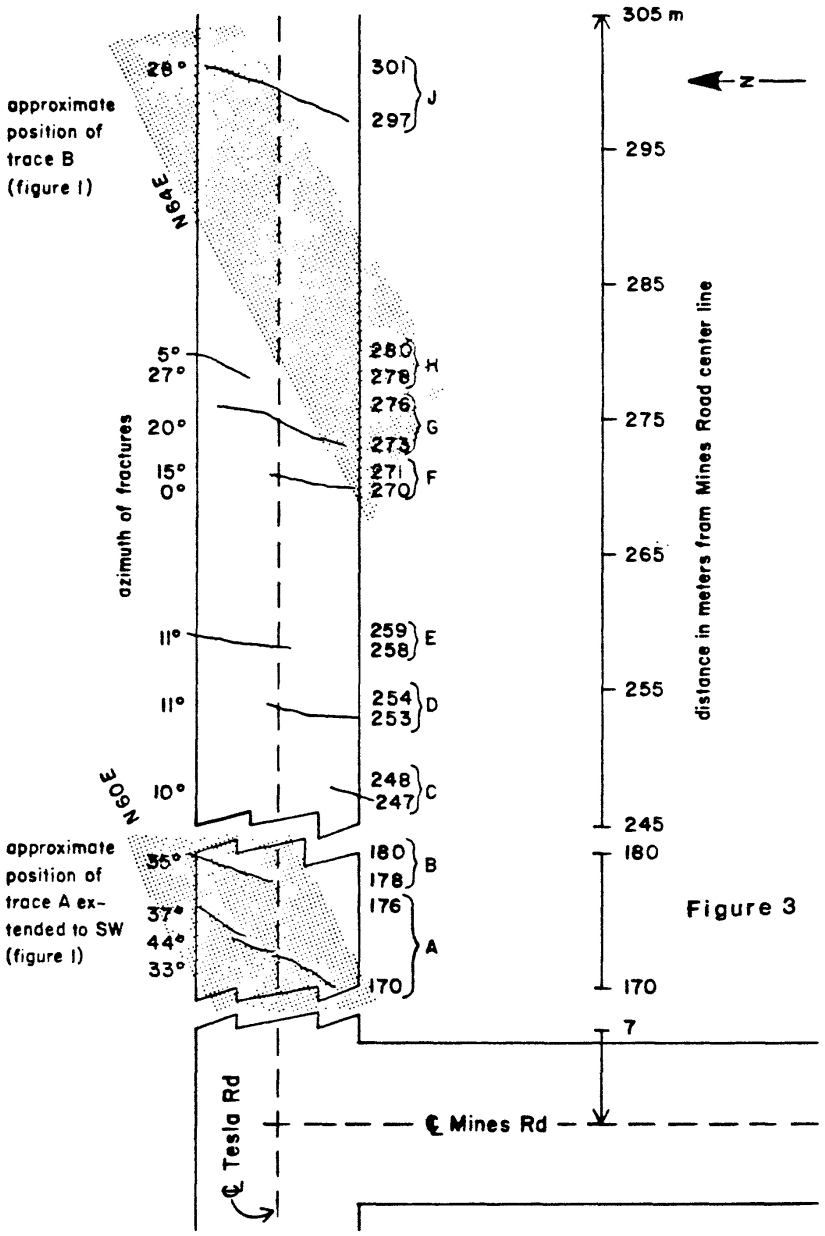

Figure 3

Figure 3. Sketch map showing fractures in the pavement of Tesla Road in relation to the centerline of Mines Road and the approximate positions of traces of the Las Positas fault zone, designated Trace A and Trace B in Figure 1.

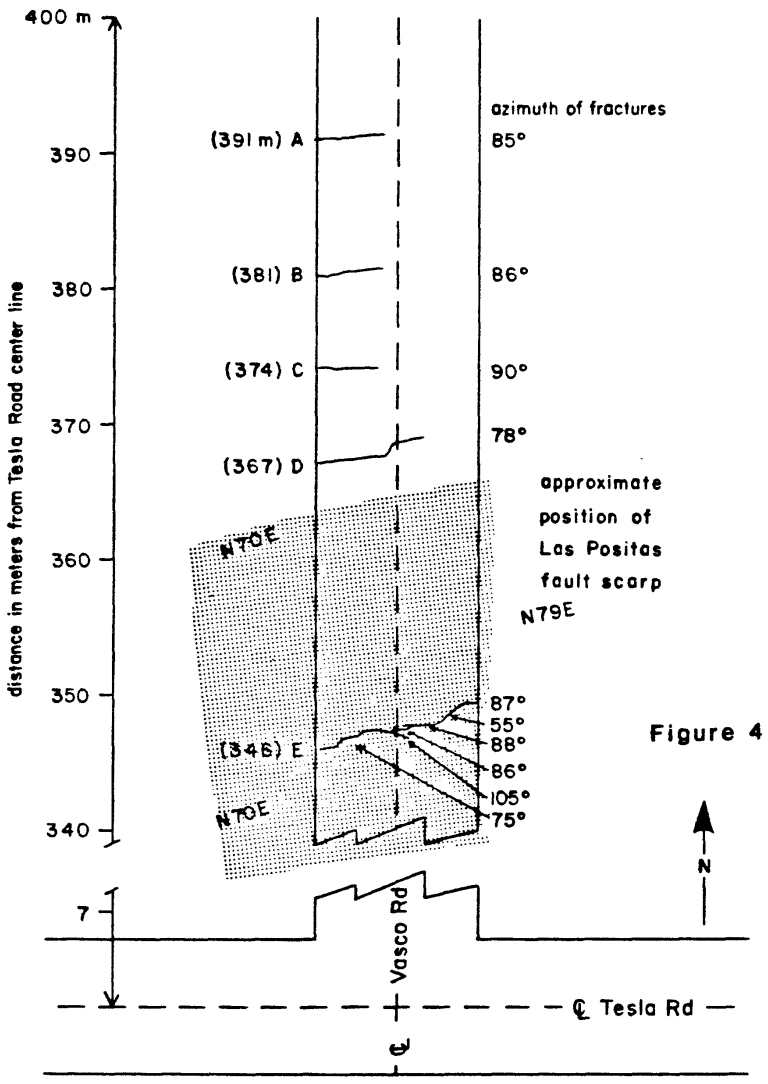

Figure 4. Sketch map showing fractures in pavement of Vasco Road in relation to the centerline of Tesla Road and the approximate position of the north-facing scarp of the Las Positas fault.

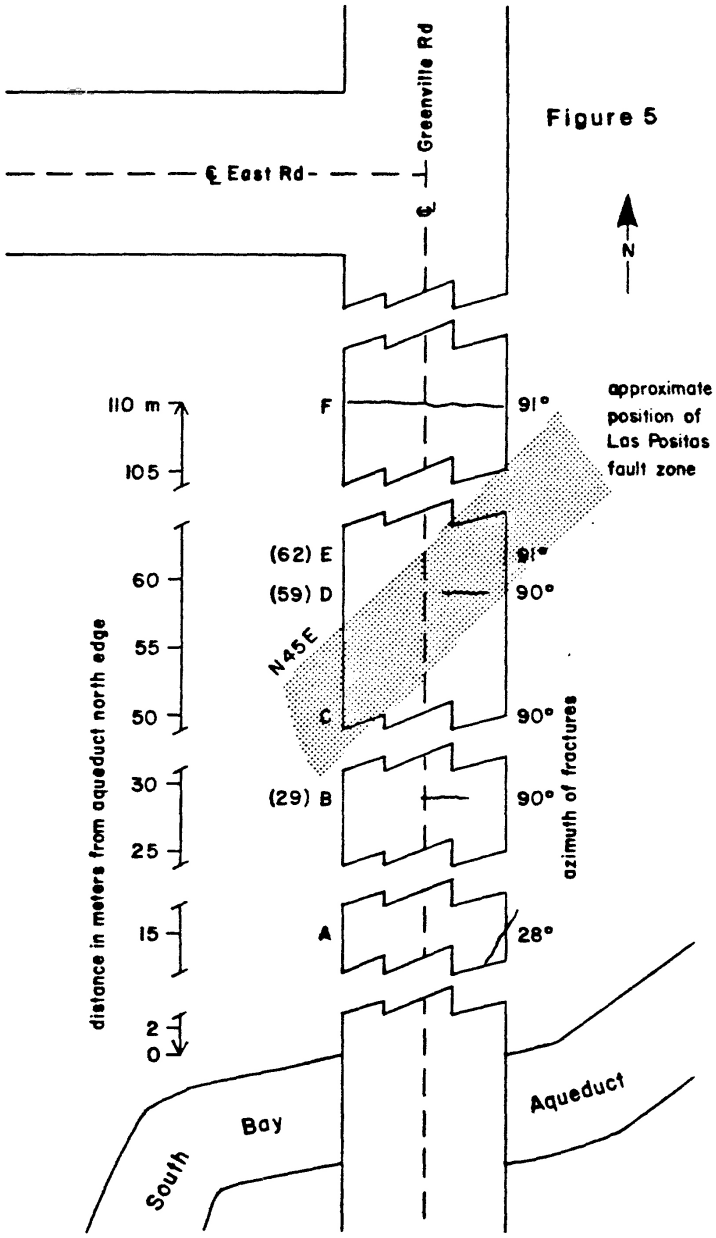

Figure 5. Sketch map showing fractures in Greenville Road in relation to the South Bay aqueduct and the approximate position of the Las Positas fault zone.