PATTERN OF FAULTING AND NATURE OF FAULT MOVEMENT IN THE SAN FERNANDO EARTHQUAKE

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PURPOSE AND SCOPE

In an effort to understand the mechanism of the February 9, 1971, San Fernando earthquake in relation to seismic observations and regional geology, we have gathered information on the occurrence and amount of ground displacement by surface faulting. Most of the field data were obtained within the first 4 days after the earthquake, because we wished to describe the fault features as much as possible in their pristine state. Systematic observations were made only in the area generally east of Sylmar and Olive View Hospital, that is, in the eastern part of the area strongly affected by the earthquake, where manifestations of surface faulting were particularly well developed. While our description of faulting is therefore limited to this area and while there doubtless are fault features that we have missed in the area studied, our results are presented here as a contribution to the general body of knowledge about the earthquake.

AREA STUDIED

Figure 1 shows the area of detailed study, and, in summary form, the results obtained. The geology of the area has been described by Oakeshott (1958). The San Gabriel Mountains, forming a steep escarpment at the northern edge of the area, are underlain by crystalline rocks thrust southward toward the San Fernando Valley along the north-dipping Hospital Fault, whose roughly east-west trace lies near the foot of the escarpment, about 0.7 km north of Veterans Hospital. The alluviated San Fernando Valley to the south is underlain by Tertiary sediments. These are exposed only at isolated places near the mountain front, being elsewhere deeply buried by Quaternary alluvium. East of Pacoima Wash, however, an area of foothills intervenes between the mountain front (here marked by the Lopez Fault, the apparent eastward continuation of the Hospital Fault) and the alluviated valley into which empties Big Tujunga Wash. These foothills, with relief of 90–180 m, are underlain by Tertiary sediments which, in the southern part of the hills, dip uniformly northward at about 65°.

In reconnaissance fashion we have searched for surface faulting in the San Gabriel Mountains northward from the area of figure 1 to Soledad Canyon, in the vicinity of the epicenter of the main shock.

FAULT PATTERN

Fault displacements of the ground surface that occurred in the earthquake are shown in figure 1, in as much detail as is possible at the map scale. Faulting extends almost continuously over a distance of 10 km from south of Sylmar eastward to the mouth of Little Tujunga Canyon, with small discontinuous manifestations continuing at least another 2 km farther east. This zone of faulting is here called the San Fernando fault zone. Its overall trend in the area studied is N. 72° W.

Some 2 km east of the easternmost fault feature shown in figure 1, there occurs a 1.0 m left-lateral offset of Oro Vista Avenue where it crosses Big Tujunga Wash. That this is not an isolated tectonic feature is shown by a number of indications of surface faulting in the intervening area (Perry Ehlig, personal commun.), which we have not studied. The San Fernando fault zone thus continues about 2 km beyond the eastern edge of figure 1. The total length of the zone of fault movement so defined is at least 12 km, and is comparable to the distance from the surface ruptures to the epicenter of the main shock, which lies about 13 km north of the mouth of Lopez Canyon (C. R. Allen, personal commun.). Although the fault breaks that we studied die out westward as indicated in figure 1, other isolated manifestations of tectonic faulting, including the re-
The fault breaks in the area studied can be conveniently placed in five groups: 1. A zone of breakage extending approximately westward from Pacoima Wash toward Sylmar, and here called the Sylmar fault segment. (See fig. 1.) 2. A fault line along the southern edge of the foothills, from Pacoima Wash eastward almost continuously to Little Tujunga Canyon and discontinuously farther eastward into the Big Tujunga; this is called the Tujunga fault segment. 3. A group of short faults within the foothills some 0.3–0.9 km north of the Tujunga segment, and trending subparallel to it. 4. A complex group of short breaks in the area between the west end of the Tujunga segment and the east end of the Sylmar segment. 5. A short fault just west of the mouth of Pacoima Canyon, which we will here call the Veterans fault, since it lies about 1 km east of Veterans Hospital (fig. 1). In the terminology used here and by the U.S. Geological Survey (this report), the Sylmar and Tujunga segments are a part of the San Fernando fault zone, which includes also the Mission Wells segment farther west. Fault groups 3 and 4 are also part of this zone, but the fault in group 5 is a separate feature.

The different groups of faults (with exception of group 5) have in common a generally east-west strike, northward dip, and combined thrust and left-lateral displacement. They differ in their relationships to the underlying bedrock, in the types of surface rupture produced, and in detailed features of attitude and displacement. The displacements along the Sylmar fault segment are generally larger than those in the other groups. The Sylmar segment reaches the surface in alluvium, and displacements along it tend to be distributed somewhat diffusely over a zone about 50 m wide, with few scarps,
The Sylmar fault segment, there is relatively little faulting, even though in some examples, particular separate scarps is so good that movement along a single continuous fault surface at depth is clearly considered the result of ground displacement by fault-fissures caused by compaction of artificial or alluvial fill or by the motion of landslide blocks. In the Sylmar fault segment, there is relatively little possibility of landslide motion because of the low relief; but in the foothill areas to the east, as well as in the San Gabriel Mountains to the north, very widespread landsliding took place during the earthquake. Numerous headwall fissures of landslide blocks, up to hundreds of meters in extent, are recognizable from their pattern and location on the affected slopes. A few of the scarps plotted in the foothill area of figure 1 have some attributes of such fissures but are retained in figure 1 because landslide blocks bounded by them are not recognizable as such and would have to be unexpectedly large. An example is the prominent scarp, about 1 m high located near lat 34°16.8', long 118°20.9'. (fig. 1). If this scarp, which is accompanied by an extension crack about 1.2 m wide, were the head of a large landslide block, there should be a prominent toe somewhere lower on the slope, but none is found. It is possible that such scarps are in part tectonic in origin and have been accentuated and modified by down-slope movement, so that they take on some attributes of landslide fissures.

Scarp of the Tujunga segment have an attitude and sense of displacement appropriate to landslide toes and are consistently located near the base of the foothill front, where the toes of landslides on the steep south-facing slope of the foothills could be expected. However, the uniform northward dip of bedding in this area tends to inhibit landslide motion on these slopes. Recognizable landslides are relatively rare on the south-facing slopes, whereas they are abundant on eastward- and especially westward-facing slopes in the canyons that cut southward through the foothills. If the scarps along the southern foot of the hills were primarily toes of landslide blocks, one could expect that headwall fissures would be most prominent on the hill slopes above places where the scarps at the foot were largest. In fact, an inverse relationship is observed. The most prominent potential headwall fissure (at long 118°20.9', fig. 1) is at a place where there is no scarp at the foot of the hills, and few indications of ground disruption there.

The scarp of the Tujunga fault segment is shown definitely to be tectonic in origin where it crosses the 0.5-km-wide mouth of Little Tujunga Canyon. In this locality there is no high ground to the north within 0.5 km of the scarp, and hence no source area for a landslide block of reasonable dimensions.

It is possible that in other places the scarps of the Tujunga fault segment contain some contribution from landsliding or general downslope motion along the front of the hills, but for the reasons given we believe that the displacements seen in these scarps are primarily tectonic in origin.
FAULT DISPLACEMENT

Figure 1 shows the slip, in inches, that occurred across the observed fault lines. In measurements repeated at given localities on different days, we found no change in displacement, and we therefore believe that essentially all the displacement occurred during the main earthquake.

In figure 1 the slip is given in terms of its vertical, lateral, and transverse components. Where the fault break has the more common form of a ramp several meters wide and where the ground surface is rough and irregular, the accuracy is as poor as ±5 inches or worse. The lateral slip component (horizontal component parallel to the fault strike) is measurable where preexisting straight features such as fences or curbs cross the fault line. In favorable situations the measurement is accurate to a fraction of an inch, but it is uncertain by 5 inches or more when the offset is distributed over many meters. Large errors arise if pre-existing jogs in streets or fence lines are not taken into account. The transverse slip component (horizontal component perpendicular to the fault strike) manifests itself either as extension or compression across the fault zone. Longitudinal shortening of street or sidewalk pavement is a very common feature of the San Fernando earthquake. Its usual form is a brittle failure of the pavement along a fracture perpendicular to the street or sidewalk and an overriding of the pavement from one side (the upthrown side, if any) over that on the other. In this situation the compression can be measured to an accuracy of about 1 inch. Compressional overthrusting along fault scarps in unpaved ground is also very common, and the amount of shortening can sometimes be determined to an accuracy of about 5 inches, particularly where turf overrides turf. Overall, the accuracy of the slip values given in figure 1 is ±5 inches, although many values are more reliable than this.

The largest slip component in the San Fernando earthquake is left lateral and occurs near the middle of the Sylmar segment, where it reaches about 1.6 m (64 in). Left-lateral slip of up to 0.8 m (32 in) occurs in fault groups 2 and 3 but is not as consistently present as in the Sylmar segment. Vertical displacement, north side up, is shown by almost all faults. The maximum uplifts are comparable in fault groups 1 to 3 and amount to 0.8–0.9 m (30–34 in.). North-south compression across the generally east-trending faults is also a consistent feature. Transverse compressions of up to 0.8 m (30 in) are typical of fault groups 1 and 2, with a maximum of 1.1 m (42 in) recorded in Little Tujunga Canyon. Displacements are generally smaller in groups 4 and 5 than in 1 to 3.

The data in figure 1 indicate that the overall fault-displacement in the San Fernando earthquake involved nearly equal amounts of north-south compression, vertical uplift (north side up), and left-lateral slip and hence may be described as a thrusting of a northern block to the southwest over a southern block, along a fault surface dipping about 45° north.

A more detailed assessment of the fault motion is provided in table 1, which gives the displacement vector for faults of groups 1 to 3 at 13 locations where the slip components are relatively well determined. The vectors in table 1 are obtained from the slip components in figure 1 and are expressed in terms of the motion of the southern block relative to the northern. The directions of these vectors are plotted stereographically in figure 2. The grouping of the points in figure 2 reveals that in the central part of the San Fernando fault zone, from long 118°23' to 25.8', the displacement vectors tend to

![Figure 2.—Stereographic plot of fault displacement vectors at the localities listed in table 1. Vectors represent motion of south side of fault with respect to north side, and are plotted on the lower hemisphere. Solid circles refer to localities in the central part of the San Fernando fault zone, between longitude 118° 23' and 118° 25.8', open circles to localities outside this interval. The triangle is the plunge of slickensides at locality 13 in table 1. The great circle represents a fault plane striking N. 72° W. and dipping 45° north.](image)
cluster about a plunge of 55° toward N. 60° E., whereas toward the ends of the zone the plunge azimuth swings northward. This behavior suggests that mechanical constraints require the lateral slip component to die out more rapidly toward the ends of the fault zone than the transverse component does. Relative to the overall S. 72° E. trend of the zone, the N. 60° E. plunge azimuth makes an angle of about 45°, implying equal components of lateral slip and transverse compression.

### Table 1.—Magnitude and direction of fault displacements

<table>
<thead>
<tr>
<th>No.</th>
<th>Fault group</th>
<th>Location</th>
<th>Dip of fault plane</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>Glenoaks-Lucas</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>Phillip-Cometa</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>Gridley</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>Fernmont-Harding</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>Adelphia-Harding</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>Freeway210-Phillippi</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>Chippewa-Newton</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>2</td>
<td>Foothill (hospital)</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>2</td>
<td>Lopez Canyon</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>2</td>
<td>Little Tujunga (lower)</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>2</td>
<td>0.25 km east of No. 10</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>3</td>
<td>Little Tujunga (upper)</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>3</td>
<td>Lopez Canyon-Bailey</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The total fault displacements indicated in table 1 range from 0.8 to 1.9 m (31–74 in). The largest displacements are near the middle of the Sylmar fault segment. If we sum the displacements across faults of groups 2 and 3 in Lopez Canyon or in Little Tujunga Canyon, we see that the aggregate displacement across the Sylmar-Tujunga fault segments is as large or somewhat larger in the foothill area than it is farther west, amounting to about 2 m. The maximum aggregate uplift across the zone, calculated along a traverse in Lopez Canyon, is about 1.9 m (74 in), north side up.

The relative magnitudes of the vertical and transverse slip components provide a measure of the dip of the fault planes. Dips inferred on this basis are given in table 1 and are compared with dips measured directly on the fault planes at two locations where this was possible. The agreement is not close but suggests that individual inferred dip values are reliable to ±20°. A similarly low reliability is implied by the scatter of the inferred dip values in table 1, if the actual fault planes of the zone have a nearly constant dip. At the level of accuracy of the inferred dip values in table 1, there is no clear distinction between overall fault-plane dips for groups 1 and 2, but there is a suggestion that faults of group 3 dip somewhat more steeply than those of group 2, in agreement with the available surface observations of fault attitude.

The average of the dip values in table 1 (omitting Nos. 1 and 2) is 42° north and may provide a measure of the overall dip of the master fault plane at depth. This dip is consistent with the observed hypocentral depth of 13 km for the main shock, in relation to the epicenter location about 13 km north of the zone of surface faulting (C. R. Allen, personal commun.).

### Detailed Features of the Sylmar Fault Segment

The representation of the Sylmar fault segment in figure 1 is based on the detailed observations of surface deformation shown in figure 3. The zone of fault movement is outlined by fractures in the paving of streets, sidewalks, and driveways. As indicated by the heavy solid lines in figure 3, with very few exceptions these fractures run either transverse to the streets or parallel to them along their margins. Because of this control of fracture orientation by the street pattern, the individual fractures do not generally give direct expression of the fault displacement in the Sylmar segment. Owing to the distributed character of the deformation, its effects in unpaved ground are generally too diffuse to be traced continuously. However, major structural damage to buildings is confined to the immediate zone of surface deformation outlined by the distribution of street fractures, even in places where deformation of unpaved ground adjacent to buildings is so diffuse as to be not clearly recognizable as the result of fault displacement. The zones of deformation indicated by the lighter lines in figure 3 were
FIGURE 3.—Surface faults and street offsets in the Sylmar fault segment and in the area between the Sylmar and Tujunga segments. The Tujunga fault scarp terminates in the southeast corner of the map. Base map derived from aerial photography.

To obtain displacements across the Sylmar fault segment from the street offset data in figure 3, some interpretation is necessary. In principle, the three perpendicular components of offset (vertical, longitudinal, transverse) across a single street completely determine the slip vector, which is obtainable by vectorial addition of these components. If the fault displacement is faithfully registered across each street crossed by the zone and if the south side moved as a rigid block with respect to the north side, then it follows that in a network of perpendicular streets the lateral offset across one street should in principle be equal to the longitudinal offset along nearly perpendicular streets nearby, the longitudinal offset being compressional or extensional as required by the sense of lateral offset and the trend of the fault with respect to the streets.

When this rule is tested against the street offset data of figure 3, it is found to be poorly satisfied. Examples of violation of the rule are found near intersections of the following streets: Chippewa and Gladstone, Harding and Adelphia, Cometa and Fernmont, Knox and Gridley, Gridley and Phillippi. The last of these is striking: the 21-inch left-lateral offset on Gridley between Knox and Phillippi requires 21 inches of longitudinal extension on Phillippi where the fault zone crosses it, but instead of...
this, 33 inches of longitudinal compression is observed.

On some streets the lack of any recorded lateral offset, to correspond with longitudinal compression on perpendicular streets, may be simply a detection difficulty, if the original street alignment was not linear enough to allow observation of a distributed lateral offset. Inconsistent observations of longitudinal displacement may be due to the occasional operation of some mechanism of pavement sliding that distributes the longitudinal offset so widely as to be undetectable or that transfers it to seemingly inappropriate locations. Thus the 72-inch longitudinal compression on Gridley is more appropriate to a location near Knox than to its observed position between Phillippi and Chivers. The lack of longitudinal offsets on either Fernmont or Cometa near their intersection, in spite of the definite lateral offsets on these streets, argues clearly for some mechanism whereby the expected longitudinal displacements are redistributed elsewhere or masked.

To arrive at displacements across the Sylmar fault segment in the face of the problems discussed above, we adopt a somewhat arbitrary procedure. For each location listed in table 1, we select from figure 3 the street-offset observations considered representative, restricting the choice to streets in the immediate vicinity and ignoring any offsets that conflict in the sense discussed above. Where observations are compatible on adjacent streets, they are averaged. The selections are listed in table 2 in a format that shows also which offset observations are ignored at each location. Consistent with the previous discussion, the selections are made from the point of view that observed offsets are more significant than a lack of confirmatory offset observations on adjacent streets. Hence, the selections in table 2 give larger fault displacements than would be obtained if the offset observations on all streets crossed by the fault zone were simply averaged.

The fault vectors obtained in this way for the Sylmar fault segment are listed in table 1. The horizontal slip components shown along the Sylmar segment in figure 1 are obtained by projecting the vectors of table 1 onto the strike and the dip lines of the fault.

The street-offset data along the Sylmar fault segment in figure 3 show certain regularities that bear on the fault displacements derived in table 1. Lateral offsets are consistently left lateral, and on northwest-trending streets they are consistently larger than on northeast-trending streets. By itself this implies that across the generally east-trending fault zone there is some north-south compression in addition to left-lateral slip, but the lateral slip exceeds the transverse compression. This agrees with the displacement vectors found at locations 3 to 5 and at 7. If it were generally true, then longitudinal extension would be expected on northwest-trending streets crossing the fault, but, instead, these streets show only longitudinal compression. There are, however, indications of northwest extension in two areas of tension cracks, one between Foothill Boulevard and the 210 Freeway and the other between Glenoaks Boulevard and Lucas Street (figure 3). Both of these areas lie slightly northeast of the zone of fault deformation as indicated by breaks in street pavement. Indications of compression along northwest-trending streets are generally weak along the fault line east of Gridley Street, and in this portion we may conclude that, on balancing the indications from lateral and longitudinal street offsets, the overall fault displacement must have carried the south side approximately northeast relative to the north side and the lateral and transverse slip components on the west-trending fault must be approximately equal.

Near Gridley Street (long. 118°25.8'), the trend of the Sylmar fault segment swings rather abruptly from west to southwest. West of the bend, prominent longitudinal compressions on northwest-trending streets are found, which cause the indicated displacements to swing toward the north (locations 1 and 2, table 1). The approximate equality of longi-
tudinal and transverse displacements across the
fault is thus preserved west of the bend, but this re-
quires that the rock masses north and south of the
fault moved in a manner quite different from rigid
blocks.

TUJUNGA FAULT SEGMENT

Because this fault is generally marked by a scarp
or as a sharply localized zone of surface displacement,
the components of slip across it can be measured di-
rectly, without the complications discussed above
for the Sylmar segment. However, since the scarp traver-
ses an unpaved and irregular ground surface
over most of its length, the individual slip measure-
ments cannot generally be made with the accuracy
attainable along the Sylmar segment.

The fault scarp is most prominent at its western
end and near Little Tujunga Canyon. Its detailed
continuity is interrupted in several places between
Lopez and Little Tujunga Canyons. The largest
such interruption is at long 118° 22.8'. Traced from
the west, the scarp here decreases in height and
separates into several small parallel scarps or fis-
sures, which gradually become more diffuse and are
replaced by parallel "mole tracks" in a zone about
15 m wide; finally this zone disappears in plowed
fields.

Five-tenths km east of Little Tujunga Wash, the
scarp enters an area of residential subdivision and
becomes obscure. However, the line of faulting
clearly extends 1 km farther east, as indicated by
aligned breaks in street pavement and in water
mains. The displacement here is generally small
(about 0.2 m of north-south compression, with little
detectable vertical and no lateral movement), and
there is relatively little major structural damage to
houses along the fault line. Farther east the surface
effects of faulting die out entirely, except for two
broken water mains and some small north-south
compressions in driveway pavement near long
118° 20.4'.

Although the displacement on the Tujunga fault
segment dies out toward the east edge of figure 1,
substantial displacement reappears farther east, as
mentioned earlier, along the segment of the fault in
Big Tujunga Wash, where left-lateral slip of as
much as 1.0 m is observed. This segment of the
fault has a due-east trend and appears to turn to-
ward the northeast near its eastern end, where it
crosses Oro Vista Avenue.

Left-lateral displacement across the Tujunga
fault segment is definite at Lopez Canyon, and a
similar displacement vector is indicated at location
No. 8 (table 1), where the fault reaches Foothill
Boulevard and turns northwest (long 118° 24.6').
The general lack of left-lateral offsets recorded else-
where may be due in part to the scarcity of linear
features crossing the fault line. However, at the
Little Tujunga road there is definitely no lateral
offset, and in an orange grove 250 m to the east
there is a definite right-lateral offset of 25 cm.

FAULTS OF GROUP 3

The sharp, 0.8-m-high scarp in Lopez Canyon at
lat 34° 17.8', 0.9 km north of the Tujunga fault seg-
ment, is one of the more striking fault features pro-
duced in the earthquake. It will be called here the
Oak Hill fault scarp because it passes near Oak Hill
School. Where the scarp cuts bedrock (Tertiary sed-
iments) in the canyon bottom, it exposes the slick-
ensided fault surface, dipping 64° N., in agreement
with the dip indicated by the trace of the scarp on
the west wall of the canyon. The plunges of slicken-
sides, projected onto a vertical plane parallel to the
fault strike, are in the range 40° to 55° E, indicat-
ing on the average about equal amounts of vertical
and left-lateral offset across the fault. The average
slickenside plunge vector is plotted as a triangle in
figure 2.

The amount of clay gouge exposed in the fault
scarp indicates that previous movements have oc-
curred on the Oak Hill fault, but does not reveal
their age.

Where the Oak Hill fault passes into alluvium in
the canyon bottom, its scarp becomes diffuse. Al-
though it reappears in the bedrock of the canyon
walls, the scarp rapidly decreases in height as
traced both east and west, and it disappears within
250 m of the canyon bottom on both sides. This be-
havior is peculiar, in view of the initial prominence
of the fault scarp and the general absence of al-
luvial fill that might obscure its lateral continua-
tion. Other scarps of group 3 are similarly re-
stricted in their lateral extent. We believe that this
is a real effect, although landsliding could in places
obscure the faults and although our search was not
thorough enough to rule out additional fault seg-
ments in some of the more remote parts of the
foothill area.

The location, alinement, and displacement (table
1, location No. 13) of the Oak Hill fault might sug-
gest that it represents an eastward continuation of
the Sylmar segment, but there is definitely no
connection between these two segments in terms of
scarps or other recognizable features of surface
faulting that formed in the San Fernando earth-
quake.
Lateral motion on group 3 scarps shows an inconstancy similar to that of group 2. Although the Oak Hill scarp 100 m west of Lopez Canyon Road shows an 0.8-m left-lateral displacement, the road itself is displaced right-laterally by 0.1 m along the same line. Small left-lateral displacements appear at several isolated places in the group 3 zone, including the northern scarp cutting the highway in Little Tujunga Canyon, but there are also examples of fault breaks with no lateral offset, such as the one in Lopez Canyon 300 m south of the Oak Hill scarp.

The northern fault break in Little Tujunga Canyon cannot be traced continuously eastward, and the only evidence of eastward continuation is an alinement of small scarps with reversed sense of vertical displacement (south side up), at long 118°21.8'. The prominent scarp at long 118°20.9' lies on a continuation of the suggested S. 70° E. trend, but we found no evidence of fault continuity over the intervening distance of 1 km.

On the west side of Little Tujunga Wash, there is evidence, discovered by J. L. Smith (personal commun.), that the base of old terrace gravels is offset vertically 2.5 m, north side up, along the northern fault break. Since the displacement during the San Fernando earthquake was only about 0.6 m, this shows that previous displacements have occurred on this fault in Quaternary time.

Traced westward, the northern break in Little Tujunga canyon follows a number of discontinuous small scarps as far as long 118°22.7'. Its trend over this interval is due west and suggests that it might join the Tujunga fault segment farther west. Similar behavior is suggested for the rupture at long 118°22.9', lat 34°17.4'.

If the dip observed for faults of group 3 (about 65° N) continues beneath the surface, these faults will meet the more shallowly-dipping Tujunga fault segment at depth. Since the 65° dip at the surface is controlled by bedding, it seems likely that at depth the faults will swing around into a tectonically-controlled orientation with an approximately 45° dip, as inferred for the fault zone as a whole. Thus, the faults of group 3 will tend to merge with the Tujunga fault segment at depth.

From their limited lateral extent and their relationship to the Tujunga fault segment, it appears that the faults of group 3 are secondary effects produced by fractures that splayed off from the main thrust fault and up into the overriding block. The tendency for secondary fracturing to affect the upper block is reflected also in the relatively shallow focal depths of the aftershocks, by comparison with the main shock (C. R. Allen, personal commun.). However, there is no evidence that any of the scarps of group 3 were formed during one of the aftershocks. Although the above interpretation identifies the Tujunga fault segment as the surface trace of the master thrust, it should be noted that the displacement across the zone of group 3 faults is comparable to that across the Tujunga fault segment itself. West of Pacoima Wash, the role of the master break is assumed by the Sylmar fault segment, but here there is no secondary faulting in the upper block, unless the Veterans fault is of this type.

**Faults of Group 4**

These faults, shown in detail in figure 3, occupy the area between the eastern end of the Sylmar fault segment (northeast corner of fig. 3) and the western end of the Tujunga segment (southeast corner of fig. 3). They represent the mechanical connection between these two major fault segments during the earthquake. Viewed in general terms, the line of surface displacement along the Tujunga fault segment turns northward around the southwest corner of the foothill area and follows the western edge of the foothills north to the trace of the Sylmar fault segment, which then carries the displacement westward. In detail, however, this northward connection is complex. Instead of a single clear break, there is a maze of small ruptures.

As shown in figure 3, the scarp of the Tujunga fault segment disappears shortly after turning northward at Foothill Boulevard. On its projected trend to the north is an area of three city blocks southeast of Arroyo Street in which numerous small pavement ruptures indicate ground deformation. The fractures here are almost exclusively perpendicular or parallel to the streets, showing again, as in the Sylmar zone, that the pavement largely controls the individual fractures.

The style of deformation in this area is remarkable: there is little lateral or vertical displacement, but fractures of both northeast and northwest orientation show consistent shortening, which indicates a net loss of surface area. The aggregate compression (given in fig. 1) is, however, greater in the northeast direction than in the northwest, which is consistent with the relative motion indicated elsewhere for the blocks between which the deformed area lies.

In the northeast part of this area is a small scarp (maximum height 0.4 m, or 15 in.) that extends irregularly northeast, ignoring the street pattern, for
about 200 m. Landsliding from the nearby west-facing hill slope might be responsible for this scarp, but its configuration is not clearly that of a landslide toe, and the abundant other evidences of tectonic deformation in the immediate area make the appearance of a fault scarp plausible.

Although there are some small indications of surface deformation farther north, the main line of displacement appears to proceed westward across Arroyo Street to the roughly westward-trending fault scarp of maximum height 0.6 m (24 in.) that lies southwest of Gladstone Street. We shall refer to this feature as the Power Line scarp because it crosses a Southern California Edison Co. transmission line right of way at this point. It displaces a northwest-trending freeway fence line by 0.9 m (36 in.) left-laterally. From the Power Line scarp, the line of displacement goes northward to the Pacoima flood-control channel, following a north-trending break that shows definite right-lateral displacement where it crosses the freeway fence line. How the further connection northward to the Sylmar fault segment is made remains undetermined.

Some unique evidence as to ground displacements in the vicinity of the Power Line scarp is provided by an array of 173 large cable spools, each weighing about 6 tons, which stood in neat rows in the transmission-line right of way as outlined by the dotted rectangles in figure 3. The spools stood on their rims, like wheels, with the spool axes oriented northeast. The rims had pressed down as much as 10 cm into the sandy soil. Although the spools were oriented so as to roll northwest-southeast, during the earthquake very few of them rolled. Instead, most of them shifted 10-20 cm sideways, gouging out a track in the soil. The sideways (NE-SW) motions are plotted in figure 4, in a format which shows schematically both the displacement of each spool and also the position of the spool in the entire array. Figure 4 shows that some of the spools did not move and that some oscillated back and forth, but many moved in a consistent pattern to one side or the other. As a whole, the spools outlined in group A moved consistently toward the southwest, and those in group C moved toward the northeast, while those in group B showed no preferred direction of motion and represent a transition group between A and C. The actual positions of these groups on the ground are shown in figure 3.

The ground surface had little or no lateral slope in the area of the reels, and there was no consistent difference in lateral slope between groups A and C; hence, we believe that the reversal in response from group A to group C reflects a reversal in the sense of ground motion in the earthquake. Such a reversal is consistent with the geologic evidence that an important line of fault offset passed through the spool array. The Power Line scarp cut obliquely through the array, following a northwest trend along one of

![Figure 4](image-url)
THE SAN FERNANDO, CALIFORNIA, EARTHQUAKE OF FEBRUARY 9, 1971

the rows of reels for about 75 m before turning westward and out of the array, as shown schematically in figure 4. Although the reels that stood on or very near the scarp (which was here only 10 to 20 cm high) showed no preferred displacement, suggesting that the fault was a nodal line in the displacement field, the complete pattern of displacements in figure 4 indicates that the line of reversal in ground motion passed through the array along a roughly north-south line and did not follow the scarp.

The mechanics of the response of a 6-ton spool to the ground motion of an earthquake is a matter of some complexity that we must leave for future investigation. The simplest possible assumption is that the spools tended to remain stationary in space during the initial large ground displacement that occurred as nearby faults slipped. In this case the displacement pattern in figure 4 indicates that the west side of the nodal line, containing reel group A, moved northeast, and the east side southwest. The indicated type of displacement and fault orientation are the same as seen in the north-trending, right-lateral fault that lies northwest of the Power Line fault, as mentioned previously. We cannot explain the discrepancy between the fault pattern inferred from the reels and the pattern of fault displacement actually found on the ground surface in this area. Nevertheless, the fact that most of the reels moved sideways toward the northeast or southwest, whereas mechanically they could much more easily have rolled northwest or southeast, is strong evidence for a northeast-southwest polarization of the ground motion and a corresponding direction of fault displacement.

Although the faults of group 4 show, in aggregate, displacements comparable to those of the Tujunga fault segment at its western end, the detailed surface path by which the rupture on the Tujunga fault segment connected with the Sylmar zone was complex and remains obscure, as the preceding discussion shows.

VETERANS FAULT

Because of its position 1 km east of Veterans Hospital (fig. 1), which was severely damaged in the earthquake, this fault has special importance. It lies at the east end of a zone along the base of the San Gabriel Mountain escarpment, where the greatest structural damage to buildings occurred. Within this zone, the Veterans fault is the only feature of ground disruption that has a direct tectonic origin, as far as we have been able to find. It is also the only tectonic feature produced during the San Fernando earthquake outside of the San Fernando fault zone, within the area studied by us.

The Veterans fault forms a low scarp, with maximum vertical offset of about 20 cm, extending for 350 m along a generally east-west trend. Some extension to the east beyond the visible scarp is indicated by a broken sewer pipe, but the scarp definitely does not cross Pacoima Wash or cut the paved road east of the wash. A southwestward extension of about 250 m beyond the recognizable scarp is defined by a zone of major structural damage to houses, but this zone cannot be traced to, or toward, the wing of the Veterans Hospital that collapsed in the earthquake.

The fault is clearly exposed cutting bedrock at several places. The fault plane dips consistently northward at about 61°. It is parallel to bedding in sediments of the Saugus formation (Plio-Pleistocene), which lie immediately north of the fault. Along the fault these sediments are brought into thrust contact with old (uplifted) Quaternary fan gravels. The total thrust displacement of Saugus over fan gravel amounts to at least 5 m, much larger than the displacement in the earthquake. This indicates a prior history of displacement on the fault in Quaternary (and possibly Holocene) time.

There was no detectable lateral component of displacement on the fault as a result of the earthquake.

The comparatively steep dip of the Veterans fault, and its relation to the underlying Tertiary sediments, is similar to the situation in faults of group 3 and by analogy suggests a relationship with the Sylmar fault segment. However, because of the proximity of the Veterans fault to the San Gabriel Mountain front and its accompanying thrusts, a mechanical connection with these important faults seems more likely.

RECONNAISSANCE SURVEY OF THE EPICENTRAL AREA

Previously mapped faults in crystalline rocks of the epicentral area between the north edge of figure 1 and Soledad Canyon, at the northern foot of the San Gabriel Mountains, were examined for indications of displacement in the earthquake. Where possible, the actual fault planes were examined. In most cases the faults could be located to within 10 m or better, so that even a small amount of displacement could have been recognized if present. The traverses for this purpose, which were made during the first 7 days following the earthquake,
also permitted a reconnaissance search for movements on previously unmapped faults.

The San Gabriel fault was examined near Bear Divide (long 118°23.8' W., lat 34°21.5'N.) and near Dillon Divide (long 118°21.1' W., lat 34°20.8'N.) and showed no evidence of displacement in either location.

In the area of the epicenter of the main shock near Soledad Canyon, three sets of faults can be distinguished, from oldest to youngest: (1) mostly east-west trending, probably right-lateral faults, with large vertical displacements (includes the Soledad fault); (2) left-lateral faults in a set trending about N. 35° E. and a slightly younger set trending about N. 55° E. with large displacements; (3) northwest-trending faults with small vertical and right-lateral displacements. All these are high-angle faults, with the exception of the Soledad fault, which dips at low angles to the north. None of these faults show evidence of Holocene activity, although all experienced movement in late Cenozoic time. The following faults of these sets were examined and showed no evidence of displacement: the Soledad fault at several places in Soledad Canyon in the vicinity of the originally located position of the epicenter near the mouth of Agua Dulce Canyon; north-northeast-trending fault which bounds part of the northwestern San Gabriel Mountains in upper Iron Canyon (long 118°23.8' W., lat 34°23.6' N.); the northeast-trending Magic Mountain fault in lower Sand Canyon (long 118°23.9' W., lat 34°22.8' N.) and Indian Canyon (long 118°16.3' W., lat 34°25.7' N.); and a northeast-trending fault in Bear Canyon (long 118°23.8' W., lat 34°22.2' N.), that is probably related to the Magic Mountain fault.

A small crack (2 cm wide and 15 m long) trends N. 55° E. along the trace of the Pole Canyon fault at long 118°23.0' W., lat 34°25.0' N. It cuts thin soil covering bedrock along the crest of a small ridge. It shows no horizontal offset, and might have been produced by differential settling of gravels on one side of the fault. The Pole Canyon fault showed no other evidence of movement at this location. In Soledad Canyon at long 118°21.4' W., lat 34°25.7' N., a zone of cracks in unconsolidated alluvium crosses the concealed trace of the Pole Canyon fault, which here trends N. 75° E. This zone is 2 to 3 m wide and about 300 m long, trends about N. 5° E. and consists of several tension cracks up to 4 inches wide. The cracks parallel the axis of the canyon and were probably caused by settling and compaction of the alluvium.

Several faults in Soledad Canyon near Ravenna (approx. long 118°14' W., lat 34°27' N.) were examined and show no evidence of breakage. However, there are cracks in road fill and asphalt in this area, which are noteworthy in that no comparable cracks occur along the Soledad Canyon highway for at least 10 miles to the west.

North of Pacoima reservoir, at lat 118°23.6' W., long 34°21.2' N., cracks were observed along several preexisting faults of unknown age and displacement. On the average, these faults strike N. 60° W. and dip 40° SW. Two examples showed dip-slip displacement of 1–2 cm, down to the southwest. This displacement could represent the movement of either tectonic or large landslide blocks downward toward the San Fernando basin. In view of the abundant other evidence of landsliding in the mountain area, the cracks in question cannot by themselves be taken as positive evidence of fault movement.

**RELATION OF SURFACE FAULTING TO BEDROCK GEOLOGY**

The overall fault motion that occurred during the San Fernando earthquake—combined left-lateral slip and thrusting across a north-dipping surface—is the type of motion expected in the Transverse Range structural province, on the basis of geological and seismological experience (Allen and others, 1965, p. 758). Faults along the southern edge of the San Gabriel Mountains have generally been interpreted as thrusts with predominantly dip-slip movement (Bailey and Jahns, 1954, p. 103), but faults elsewhere in the Transverse Range province, in particular the Malibu Coast fault and east-west faults of the Channel Islands, show definite left-lateral displacement (Lamar, 1961; Barbat, 1958; Kew, 1927; Rand, 1931).

The faults that actually moved during the earthquake, shown in figure 1, do not correspond closely with bedrock faults shown in recently published geologic maps (Oakeshoot, 1958; Jennings and Strang, 1969). However, an unnamed fault identical in surface trace with the Tujunga fault segment as defined here was indicated by Miller (1934) in a geologic map of the western San Gabriel Mountains. This fault was probably identified by Miller on the basis of the sharp topographic break at the south edge of the foothills. Miller represented the fault as turning abruptly northward at the southwestern corner of the foothill area, essentially at the point where the scarp of the Tujunga fault segment of the San Fernando earthquake turns northward toward the complex of group 4 faults described above. Although he did not individually discuss the partic-
ular fault in question, Miller (1934, p. 78) interpreted faults of this type as steeply northward-dipping reverse faults, which is in accord with our observations, except for the relatively shallow dip (about 25°) found here for the Tujunga fault segment.

The Tujunga fault segment as defined here is not the same as the Tujunga fault shown on the map of Hill (1930). Hill's fault, which was marked with a queried line, has a nearly east-west trend and lies 1.3 km south of the Tujunga fault segment as recognized here at the mouth of Little Tujunga Canyon. In defining the Tujunga in the way done here, we are proposing that the older definition introduced by Hill (1930) be dropped.

Near the south edge of the Little Tujunga foothills at long 118°20.9', a short thrust fault dipping 60° N., and carrying Modelo (Miocene) sediments over Quaternary terrace gravels is identified by Oakeshott (1958, pl. 1). The fault is shown as extending with a N. 85° E. trace for a distance of about 0.8 km. If plotted on figure 1, it would pass just south of the observed scarp at long 118°20.9', but with a distinctly different trend. No displacement was observed on this fault in the San Fernando earthquake. Its attitude and sense of movement are the same as observed for faults of group 3, and like these, it would joint the Tujunga fault segment if traced westward, according to the mapped trace shown by Oakeshott (1958). Its main significance is in establishing the prior occurrence of reverse faulting near the southern edge of the foothills.

No fault corresponding to the prominent Oak Hill scarp was recognized by Oakeshott (1958). The upper fault break in Little Tujunga Canyon would, if traced somewhat farther east than shown in figure 1, connect approximately with a fault of uncertain displacement and attitude shown by Oakeshott (1958). Further investigation is required to establish whether this bedrock fault does in fact connect with the fault that produced the scarp in Little Tujunga Canyon. As noted earlier, there is now evidence that both this fault and the Oak Hill scarp had a history of movement prior to the San Fernando earthquake.

Although published geologic maps do not show a fault along the trace of the Sylmar fault segment, it appears possible that this segment represents a northeastward continuation of the Mission Hills thrust, which was recognized by Oakeshott (1958) primarily from well data. If the southwest-trending western portion of the Sylmar fault segment is prolonged 1.6 km southwest, it connects approximately with the surface trace of the Mission Hills thrust as plotted by Oakeshott. Since the plotted trace of the thrust in this area was not based on specific geological control and was therefore marked with queries, the connection of the two fault segments is only hypothetical. Nevertheless, the Mission Hills thrust provides a reasonable example of the type of geologic and tectonic structure that probably underlies the trace of the San Fernando fault zone.

The Sierra Madre fault zone, a zone of major reverse faults and thrusts along which the crystalline basement rocks of the San Gabriel Mountains have been uplifted and thrust southward over Cenozoic sediments, is the most prominent tectonic element in the immediate vicinity of the region affected by the San Fernando earthquake. It extends east-west along the base of the mountain front near the north edge of figure 1. In that area, the main thrust contact between basement rocks and sediments is locally designated the Hospital Fault (Oakeshott, 1958). In view of the high intensity of ground shaking along the foot of the escarpment, as testified by the destruction at Olive View and Veterans Hospitals, and in view of the large thrust component of the overall fault motion that occurred, it would be reasonable to expect motion on the Hospital fault or other thrusts of the Sierra Madre zone. The only indication of such motion found by us is the small feature here called the Veterans fault. This fault lies 0.5 km south of the basement-sedimentary contact, which represents the major structural break and the probable trace of the Hospital fault, if it extends this far east (although it is not so shown by Oakeshott, 1958). The Veterans fault can be considered a part of the Sierra Madre fault zone, on the basis of its location near the basement contact, its attitude, and its sense of movement. Although the movement of the Veterans fault is thus a definite indication of activity on the Sierra Madre fault zone in the San Fernando earthquake, the fault feature involved was only a minor one and the extent and amount of displacement were small compared to what occurred to the south along the San Fernando fault zone. In a wider sense, however, the San Fernando fault zone can be considered an integral part of the same system of Transverse Range faults that includes the Sierra Madre fault zone, and in fact the two zones probably join when traced eastward to the vicinity of Sunland, about 5 km east of figure 1.

Geologic cross sections drawn from the San Fernando Valley northward across the San Gabriel
Mountains (Oakeshott, 1958) show faults of the Sierra Madre zone as dipping generally at angles of 60° and steeper northward. Although these relatively steep dips agree with the attitudes of faults of groups 3 and 5, they conflict with the previously discussed general indication that the active fault plane as a whole dips about 45° N.

CONCLUSIONS

The San Fernando earthquake was caused by movement on northward-dipping thrust faults that conform to a consistent pattern of such faulting in the Transverse Ranges. Almost all the fault movement in the area studied can be explained in terms of a single master fracture at depth, striking N. 72° W. and dipping about 45° toward the north. The individual fault segments that moved at the surface, forming collectively the San Fernando fault zone, strike more nearly east-west and bear an en echelon relation to the inferred master fracture. Although there are local divergences in displacements of individual faults, the overall fault motion was a thrusting of the north side approximately southwestward over the south side, with approximately equal amounts of vertical uplift, north-south compression, and left-lateral slip. This motion combines the types of displacement known to be characteristic of major faults of the Transverse Range province. The overall displacement was about 2 m.

Fault movement did not occur near the surface in the vicinity of the epicenter of the main shock. A reasonable model of the fault movement in the earthquake is initiation of fracture at a depth of about 13 km under the epicenter, followed by propagation of the fracture southward to the ground surface along a plane dipping about 45° N.

At the surface, only a small amount of localized fault movement took place along the Sierra Madre fault zone, the major tectonic feature in the immediate vicinity of the area most affected by the earthquake, and the most obvious candidate for movement of the type observed. Most of the fracturing reached the surface about 4 km farther south, along faults that are minor by comparison (the San Fernando zone). These faults nevertheless fit the general pattern of faulting set by the major faults, and they probably join the Sierra Madre fault zone a short distance to the east.

The tectonic model of the earthquake suggests that thrusts related to the Sierra Madre zone, which bound the San Gabriel range on the south, pass at depth entirely beneath the range to the north. Thus, they are not simply marginal reverse faults, as they are usually visualized. This model may apply to major Transverse Range thrusts generally.

None of the faults that moved in the San Fernando earthquake had been clearly identified in advance as active faults. There is now evidence that at least some of them had a prior history of movement. The Tujunga fault segment could have been suspected on the basis of its associated foothill topography. The Sylmar fault segment could have been recognized, if at all, only by subsurface investigations.

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