San Fernando Earthquake of 9 February 1971: Pattern of Faulting

Abstract. *Mapping of the surface breaks that resulted from the San Fernando earthquake of 9 February 1971 reveals that the pattern of faulting was highly complex; it consisted of a number of segments that produced ground displacements and acceleration throughout the entire northern end of the San Fernando Valley. Instead of occurring on the frontal fault zone, as might have been expected, the faulting occurred on the valley side of the frontal fault system, which separates the crystalline rocks of the San Gabriel Mountains from the Tertiary sediments of the San Fernando Valley. However, the new fault system does, in many cases, follow breaks in slope and subtle escarpments that suggest faulting along these zones in the recent geologic past.*

The San Fernando earthquake of 9 February 1971 (Los Angeles County, California) resulted in the death of more than 60 persons and in property damage of the order of $1 billion. The earthquake was moderate in size (approximately 6.6 on the Richter scale) and occurred near the highly populated San Fernando Valley. The extent of the damage in this area resulted in part from a complex pattern of tectonic faulting, which caused significant ground displacement and acceleration on a regional scale.

The northern San Fernando Valley, where the earthquake effects were greatest, lies to the southwest of the western portion of the San Gabriel Mountains (Fig. 1). The San Gabriel Mountains consist of a core of Precambrian metamorphic and Mesozoic plutonic rocks flanked by thick sections of Cenozoic marine and nonmarine sedimentary rocks (*1*). Both the sedimentary and crystalline rocks show widespread evidence of deformation on a continuing basis throughout Tertiary and Quaternary time. The crystalline core complex of the San Gabriel Mountains is regionally sheared and deformed; exposures of fresh rock are almost nonexistent. The Pleistocene Saugus and Pacoima formations are sharply folded locally, and numerous faults with large offsets crosscut as well as border the range. It is interesting to note, however, that there is essentially no evidence for recent offset along these faults with the exception of the San Andreas fault, which borders the range on the northeast (*1*).

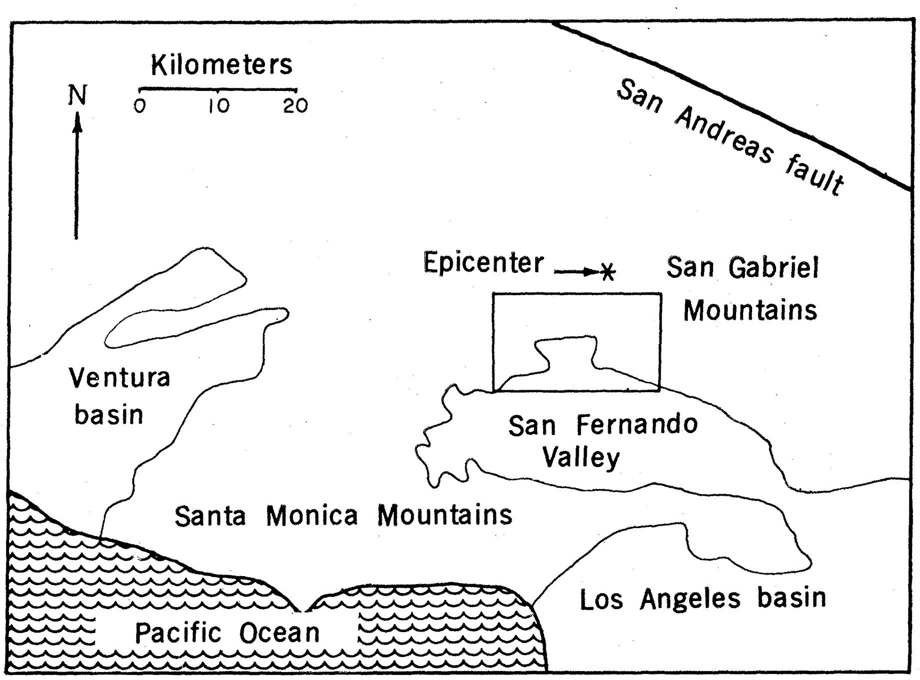

Fig. 1. Location map of epicenter and faulted area in the San Fernando Valley, Los Angeles County, California. The rectangular box outlines the area shown in Fig. 2.

The structure of the western San Gabriel range is dominated by the San Gabriel fault (Fig. 2), a right-lateral, strike-slip fault subparallel to the San Andreas fault. Crowell (*2*) has suggested 15 to 25 miles (25 to 40 km) of displacement along this fault since upper Miocene.

North of the San Gabriel fault, the smaller faults are generally steeply dipping, northeast-southwest trending, with apparent left-lateral displacements. These faults are subparallel to the Garlock fault and presumably represent conjugate faults to the right-lateral San Andreas system.

South of the San Gabriel fault and of prime importance with respect to the new fault complex is the Sierra Madre fault zone (*3*) along the southwestern flank of the San Gabriel Mountains (Fig. 2). This fault zone includes the eastern extent of the Santa Susana thrust, Grapevine, Hospital, Buck Canyon–Watt, Lopez, and Sunland faults, a series of arcuate reverse faults that separate the pre-Tertiary crystalline rocks to the north from the Cenozoic sediments to the south. The faults are discontinuous and dip northward at angles ranging between 15° and vertical (*1*). Displacements of these faults rapidly die out as the strike of these faults changes from the general east-west trend to a more northerly trend. We suggest that the inferred Mission Hills thrust (Fig. 2) can also be considered a member of this frontal fault system.

The epicenter of the San Fernando earthquake occurred on the north flank of the San Gabriel Mountains, but the ground breakage due to faulting occurred at the northern end of the San Fernando Valley, approximately 11 km south of the epicenter. Those regions north of the fault breaks were overthrust and were elevated with respect to regions to the south; locally measured and inferred dips on the actual fault planes ranged between 30° and 75°. These observations are thus consistent with a northward dipping reverse fault.

The major fault surface breaks that resulted from the San Fernando earthquake are mapped in Fig. 2. Definiton of major surface breaks depended upon the following observational criteria, which were most prevalent a few meters to 10 or 20 m from the fault trace, and only in a few cases were they found at distances of 50 m or more from the mapped break:

1) Uplift of one block with respect to the other.

2) Large-scale overthrusting in pavement, curbing, sidewalks, hillsides, and lawns (of the order of 30 cm or more).

3) Small-scale compressional features, such as the buckling of roadways, sidewalks, fences, and pipes, as well as the pressure-chipping of rigid structures such as curbs.

4) Continuation of the above three features along narrow linear trends for several city blocks or more.

Mapped traces for surface breaks fall into three categories: (i) fault scarps characterized by all four of the above criteria; (ii) lines or narrow zones of overthrusting and compression characterized by criteria 2, 3, and 4; (iii) lines or narrow zones of overthrusting and compression characterized primarily by criteria 3 and 4. The first of these categories includes definite tectonic breaks directly coupled with slip planes within the underlying bedrock. Such faults consisted of scarps with up to 1 m of vertical displacement and an equivalent amount of horizontal displacement. Often well-developed scarps were reduced to a few centimeters in each direction along strike, with the relative uplift either dying out or being distributed over an area of broad warping. Scarps created by slumping were easily distinguished from faults, since criteria 2 and 3 were lacking. Breaks included in the second and third categories have a less definite tectonic significance. In some places in the San Fernando Valley, overthrusting and compression resulted from lateral ground shaking. Where this was the case, features of compression and overthrusting (i) were associated with extensional breaks of equal magnitude, (ii) occurred in limited zones, and (iii) did not necessarily strike parallel to the major faults. In Fig. 2, we present only the compressional features that we believe to be closely linked to tectonic breaks. Our decision to include these compressional features is based on the following:

1) Along fault scarps where displacements were large, uplift, overthrusting, and compression could be easily recognized, and mapping was straightforward. Typically, however, apparent vertical displacements decreased rapidly along strike. When this occurred, overthrusting and other compressional features often persisted along strike, which suggests the continuation at depth of the same tectonic feature, although it did not produce a surface expression of uplift along a

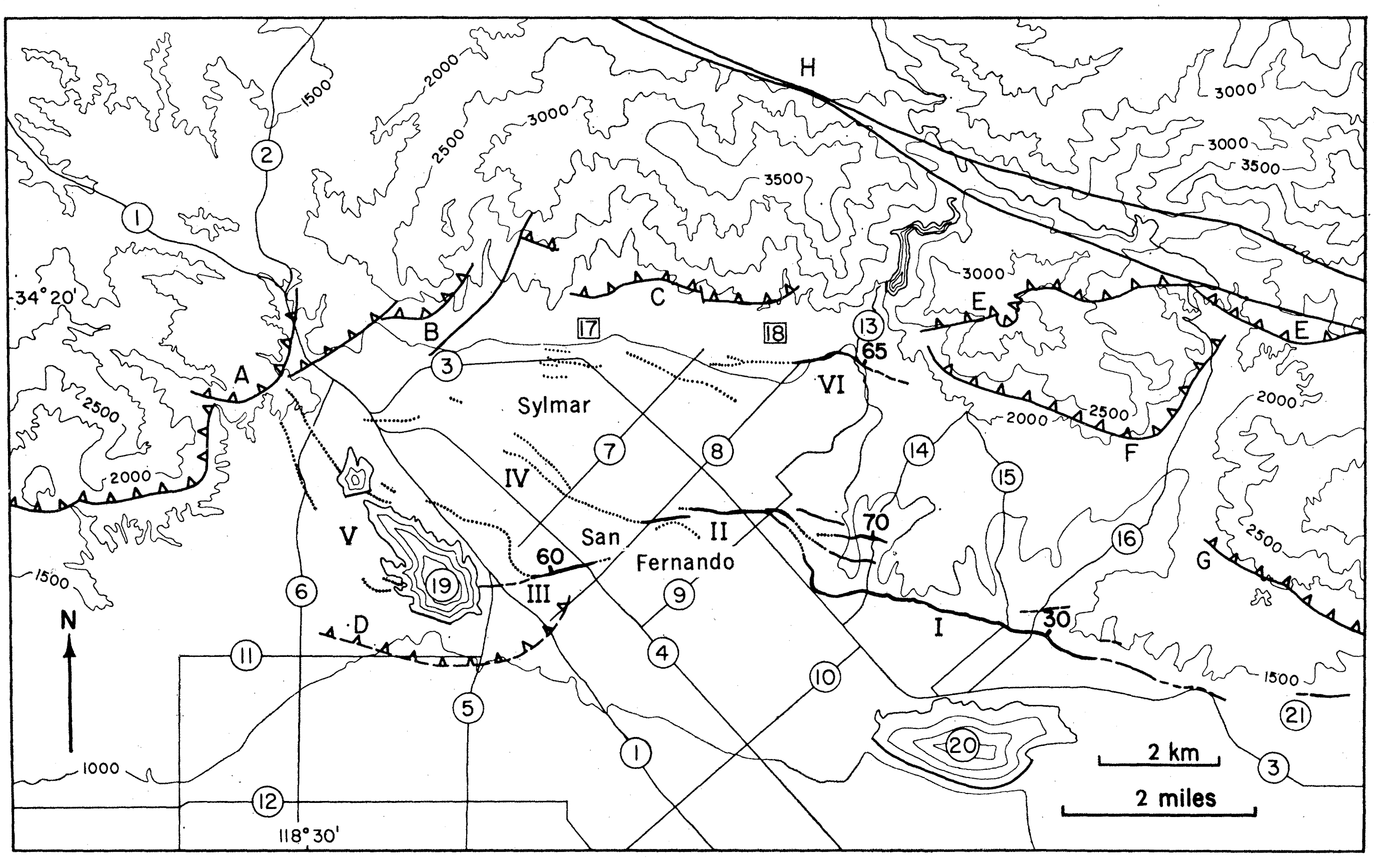

Fig. 2. Fault map of the northern portion of the San Fernando Valley, which shows previously mapped faults and new faults from the San Fernando earthquake of 9 February 1971. With the exception of the San Gabriel fault zone (*H*) and the northeast-trending fault near (*B*), all previously mapped faults are represented by hachures. New fault scarps are denoted by solid lines; dashed lines indicate approximated locations. Dotted lines represent faults located on the basis of compressional features. The following key can be used for reference to place and fault names referred to in the text. Place names: (1) Golden State Freeway; (2) Highway 14 to Palmdale; (3) Foothill Boulevard; (4) San Fernando Road; (5) San Diego Freeway; (6) Balboa Boulevard; (7) Polk Street; (8) Hubbard Street; (9) Maclay Avenue; (10) Van Nuys Boulevard; (11) Rinaldi Street; (12) Devonshire Street; (13) Pacoima Canyon Road and Dam; (14) Lopez Canyon; (15) Kagel Canyon; (16) Little Tujunga Canyon; (17) Olive View Hospital; (18) Veterans Hospital; (19) Van Norman Dam and reservoirs; (20) Hansen Dam and reservoir; (21) Big Tujunga Wash. Faults of the Sierra Madre fault zone: (A) Santa Susana thrust; (B) Grapevine fault; (C) Hospital fault; (D) Mission Hills thrust (inferred); (E) Buck Canyon–Watt fault; (F) Lopez fault; (G) Sunland fault; (H) San Gabriel fault zone. Segments of the San Fernando fault zone are represented by Roman numerals (see text).

narrow, easily recognizable zone. Small vertical displacements need not always produce a visible fault scarp.

2) The continuity of compression and overthrusting along narrow linear belts suggests coupling of these features with rather narrow zones of movement in the underlying bedrock. The features mapped as compression in Fig. 2 consist of linear zones of compression that were rarely 50 m and, more commonly, 10 to 20 m wide. Furthermore, these features cross a very heterogeneous terrain of fields, streets, and other man-made structures with little or no change in strike.

3) Extensional features equal in magnitude to the compression and overthrusting are not found on either side of the mapped zones. In parts of the San Fernando Valley, measurements of extensional and associated compressional features could be made, but along the mapped zones the lack of comparable extensional features strongly suggests real crustal shortening rather than simply shaking and lateral sliding.

Although we recognize that mapped compressional features are not true fault scarps, the continuity of the features, the parallelism between these and fault scarps, and the lack of extension suggest coupling of these surface breaks with tectonic movement in underlying bedrock.

The eastern extent of the San Fernando fault system (segment I, Fig. 2) is first observed in and along the northern bank of Big Tujunga Wash. The maximum displacement in Big Tujunga Wash is about 60 cm on a scarp dipping about 75° to the north. To the west, the main scarp follows the break in slope between the Tertiary sediments on the north and the alluvium on the south. In addition, a series of apparently discontinuous breaks occurs to the north of the frontal scarp. These scarps may be more continuous than shown; they are most clearly seen in canyon bottoms but are difficult to trace over the ridges. At Little Tujunga Canyon the frontal scarp has 50 cm of uplift and 1.5 m of overthrusting, with a small component of left-lateral offset. A second scarp 400 m to the north has about 25 cm of uplift with about the same amount of apparent right-lateral offset, the only right-lateral offset observed along the entire fault. West of Kagel Canyon, the main scarp occurs as three discrete breaks over a zone that is 10 to 50 m wide. At Lopez Canyon, the zone becomes more complex; a series of breaks trend roughly east-west, up to 1 km north of the main break and then converge near Maclay Avenue and Foothill Boulevard. A north-south profile through the mouth of Lopez Canyon shows vertical displacements of about 50, 15, and 75 cm, respectively, for the three breaks crossed. Total left-lateral motion is of the order of 1 m. These displacements were the maximum observed in the field, but they may be en echelon and would therefore not represent the total displacement field at this point. A second major break occurs about 3 km to the north near the mouth of Pacoima Canyon (segment VI, Fig. 2). The maximum displacement on this fault is 20 cm of dip-slip motion immediately to the west of the mouth of Pacoima Canyon, with apparent displacements decreasing westward and eastward from this point. Left-lateral displacement is negligible along this fault.

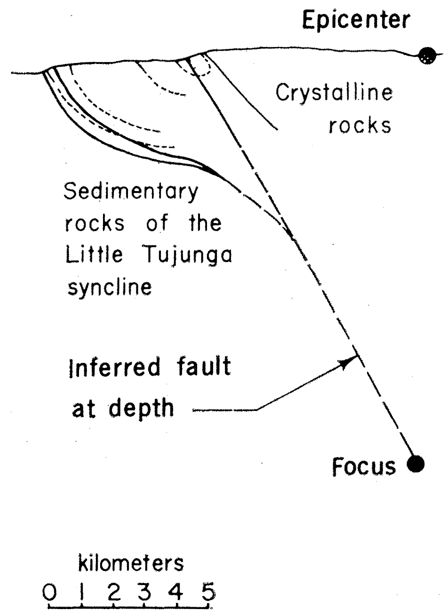

Fig. 3. Cross section from Lopez Canyon to the epicenter on the right. The inferred bifurcation of fault surface at depth is shown.

At Maclay Avenue north of Foothill Boulevard, the faults of Lopez Canyon converge into a single zone (segment II, Fig. 2). Here the ground breakage crosses the Pacoima wash and follows an abrupt change in slope through a residential district. The fault zone then crosses Foothill Boulevard northwest of Maclay Avenue and continues west through residential San Fernando. Discontinuous scarps along this zone exhibit 30 to 50 cm of uplift and up to 50 cm of horizontal compression or overthrusting. Much of the fault zone along segment II is characterized by a wide band of imbricate overthrusting and compression up to 100 m wide.

Northwest of Hubbard Street, segments II and VI bifurcate, and the complexion of faulting changes in the following ways:

1) Fault trends turn northwestward.

2) Imbricate faulting occurs over a width of about 5 km across the entire Sylmar district.

3) Vertical displacements appear to be secondary to horizontal movement or compression. Only one well-developed scarp is present.

Segment II splits into two branches, segments III and IV, one striking S75°W toward Van Norman Reservoir, and the other striking N70°W toward Sylmar. Segment IV is a narrow zone of compression with some overthrusting, which trends northwest toward the intersection of Foothill Boulevard and the Golden State Freeway. Segment III shows a well-developed scarp with the maximum displacement occurring about ½ km west of San Fernando Road. Here uplift was 30 cm, accompanied by 20 cm of overthrusting and an equivalent amount of left-lateral offset. To the west, this segment splits into two branches, one bifurcate trending westward toward the lower Van Norman Reservoir, and the other trending northwest and forming a line of discontinuous compression across the Golden State Freeway toward the upper Van Norman Dam and Balboa Boulevard (segment V). Displacements on this segment west of the Golden State Freeway are difficult to estimate but do not normally exceed 10 cm and appear to decrease to zero toward the northwest. Segment VI, northwest of Hubbard Street, is characterized only by compressional features, with total displacements probably not exceeding 10 cm.

The mapping of surface breaks reveals the following important aspects of faulting:

1) The break is not singular. It consists instead of a complex series of faults over the entire northern portion of the San Fernando Valley.

2) The breaks do not coincide with mapped faults, and no new displacements were observed at the contact between the crystalline and the sedimentary rocks north of San Fernando Valley.

3) Locally estimated dips on the near-surface fault plane range from 30° to 75° to the north.

4) The directions of motion have

in all cases raised the north block with respect to the south, with a varying component of left-lateral offset.

5) Where observable, the fault surfaces in the Tertiary sediments appear to be parallel or subparallel to bedding planes.

6) Individual breaks are discontinuous, with displacements often rapidly dying out along strike.

7) The major faults follow breaks in slope along the foothills and subtle escarpments in the alluviated valley. However, prior to the earthquake, proof that these escarpments represented fault traces was lacking.

The complexity of faulting can probably be related to (i) the poor competence of the Tertiary sediments and (ii) the general structure of the northern end of the San Fernando Valley. Where the fault traces cross hillsides or roadcuts, it is obvious that the fault is controlled by the bedding surfaces in the sedimentary rocks of the Little Tujunga syncline. The correspondence between the strike and dip of the bedding and the fault surface is so strong that we suggest that this control extends to those faults traced in the alluvium in the cities of Sylmar and San Fernando. Thus, the location of fault traces may be due to subsurface structures in the Tertiary sedimentary rocks underlying the northern San Fernando Valley (see Fig. 3). In addition, the poor competency of these sedimentary rocks would not preclude failure along isolated and random breaks.

The sense of motion on the major fault break appears to change from east to west on the basis of field evidence in the immediate vicinity of the fault break. Between the eastern extent of the fault and Little Tujunga Canyon, dip-slip motion appears to dominate, whereas west of Little Tujunga Canyon approximately equal portions of left-lateral and dip-slip offset occur. Along segment II, the exact amounts of vertical and horizontal offsets were difficult to discern visually, owing to the complete local disruption of most man-made structures, as well as the fact that the fault zone considerably widened in this area and no dominant scarps were created. Careful leveling and triangulation along old curblines on both sides away from the fault should yield the desired information. Along segment III, between San Fernando Road and Van Norman Reservoir, the amounts of left-lateral and dip-slip movement are subequal. To the north of Van Norman reservoirs, the complexity of faulting and the lack of appropriate structures preclude the determination of the amounts of dip-slip and lateral offset. The compressional features, however, certainly suggest a dipping fault plane with a major component of dip-slip motion. Thus, the gross sense of motion appears to change from a southerly to a more westerly direction as one proceeds from east to west along the fault.

The average strike of the San Fernando Valley fault system is subparallel to the San Gabriel fault and the nearest portions of the San Andreas fault, and yet the sense of motion along the present break differs from the normal right-lateral motions along the San Andreas by at least 90°. To explain this discrepancy, one must resort either (i) to an inhomogeneous strain field with local singularities, or (ii) to a uniform regional strain pattern that produces a special set of displacements. Case (ii) might be explained by a model in which a right-lateral regional strain field produces local clockwise rotations of major blocks with faulting occurring along zones of intrinsic weakness. This clockwise rotation is consistent with left-lateral offsets between the upthrust northern San Gabriel block and the southern block of the San Fernando Valley. The apparent increase in the amount of left-lateral displacement from the east to the west suggests a pole of rotation to the northwest of the fault system.

The directional trends and geometrical nature of the San Fernando fault complex fit well into the pattern of the Sierra Madre fault zone, as can be seen in Fig. 2. The San Fernando earthquake reveals continuing activity along the Sierra Madre fault zone, although careful examination of previously mapped faults revealed no displacements as a result of the earthquake of 9 February 1971. Noteworthy is the coincidence of new fault breaks with breaks in slope in the alluvium of the San Fernando Valley. We believe that these subtle breaks in slope surely represent old fault scarps and point to previous faulting along the present fault breaks.

This pattern of faulting extends to the southeast, along the southern base of the San Gabriel Mountains, and to the northwest, including the Santa Susana and Cuyama thrust zones. It is certainly clear from this event that this system of faults is highly complex and that potential faulting can occur within a rather wide zone in the neighborhood of the mapped fault traces. Fault scarps that appear old may be reactivated and, thus, their importance should not be overlooked.

In addition to the fact that faulting did not occur along previously mapped breaks, the pattern of faulting was unusually complex in terms of the great number and discontinuous nature of the breaks. Much of the damage in the San Fernando Valley was probably not the result of shaking produced by the passage of the seismic waves but was due instead to displacements and high accelerations near the numerous fault breaks. No cultural feature in the northern portion of the San Fernando Valley was very far from a given fault. For example, the major structures that were damaged, such as the Veterans and Olive View hospitals, Van Norman Dam, and the Foothill–Golden State Freeway interchange, were all within 1 km of a mapped tectonic break. Smaller, unmapped breaks may exist even closer to these structures, but field evidence is lacking because of the difficulties of recognizing such features under existing conditions. In addition, the fact that damage to the lower Van Norman Dam was apparently due to slumping and shaking does not preclude the possibility that further creep, settling, or aftershock activity along the same general fault zone might involve displacement through the Van Norman Reservoir properties. Furthermore, from the nature of the present system of faulting, earthquakes on other nearby segments of the Sierra Madre fault zone could trigger displacements on small fault segments in the vicinity of the reservoir.

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References and Notes

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4. We gratefully acknowledge the permission granted by many public and private groups for immediate access to most of the critical areas in the San Fernando Valley after the 9 February 1971 earthquake. In particular, we thank the Los Angeles Police Department, the Los Angeles County Hospital staff, the Los Angeles City Department of Water and Power, and the U.S. Forest Service for their cooperation. Supported in part by a University Research and Publication Fund grant from the University of Southern California. Contribution 233 of the Department of Geological Sciences.

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