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GEOLOGICAL SURVEY CIRCULAR 691–A, B

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Prepared on behalf of the Federal Disaster Assistance Administration

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ABSTRACT

The upper and lower Van Norman dams, in northwesternmost San Fernando Valley about 20 mi (32 km) northwest of downtown Los Angeles, were severely damaged during the 1971 San Fernando earthquake. An investigation of the geologic-seismologic setting of the Van Norman area indicates that an earthquake of at least M 7.7 may be expected in the Van Norman area. The expectable transitory effects in the Van Norman area of such an earthquake are as follows: peak horizontal acceleration of at least 1.15 *g*, peak velocity of displacement of 4.43 ft/sec (135 cm/sec), peak displacement of 2.3 ft (70 cm), and duration of shaking at accelerations greater than 0.05 *g*, 40 sec. A great earthquake (M 8+) on the San Andreas fault, 25 mi distant, also is expectable. Transitory effects in the Van Norman area from such an earthquake are estimated as follows: peak horizontal acceleration of 0.5 *g*, peak velocity of 1.97 ft/sec (60 cm/sec), displacement of 1.31 ft (40 cm), and duration of shaking at accelerations greater than 0.05 *g*, 80 sec.

The permanent effects of the expectable local earthquake could include simultaneous fault movement at the lower damsite, the upper damsite, and the site proposed for a replacement dam halfway between the upper and lower dams. The maximum differential displacements due to such movements are estimated at 16.4 ft (5 m) at the lower damsite and about 9.6 ft (2.93 m) at the upper and proposed damsites.

The 1971 San Fernando earthquake (M 6½) was accompanied by the most intense ground motions ever recorded instrumentally for a natural earthquake. At the lower Van Norman dam, horizontal accelerations exceeded 0.6 *g*, and shaking greater than 0.25 *g* lasted for about 13 sec; at Pacoima dam, 6 mi (10 km) northeast of the lower dam, high-frequency peak horizontal accelerations of 1.25 *g* were recorded in two directions, and shaking greater than 0.25 *g* lasted for about 7 sec. Permanent effects of the earthquake include slope failures in the embankments of the upper and lower Van Norman dams, rupturing of the ground surface by faulting along parts of the zone of old faults that extends easterly through the reservoir area and across the northern part of the valley, folding or arching of the ground surface, and differential horizontal displacement of the terrane north and south of the fault zone.

Although a zone of old faults extends through the reservoir area, the 1971 surface ruptures apparently did not; however, arching and horizontal displacements caused small relative displacements of the abutment areas of each of the three damsites. The 1971 arching coincided with preexisting topographic highs, and the surface ruptures coincided with eroded fault scarps and a buried ground-water impediment formed by pre-1971 faulting in young valley fill. This coincidence with evidence of past deformation indicates that the 1971 deformations were the result of a continuing geologic process that is expected to produce similar deformations during future events.

The 1971 San Fernando earthquake probably was not the largest that has occurred in this area during the last approximately 200 years, as indicated by a buried fault like scarp about 200 years old that is higher than, and alined with, 1971 fault scarps. In addition, the San Fernando zone of 1971 ruptures is part of a regional tectonic system that includes the San Andreas and associated faults; one of these, the White Wolf fault north of the San Andreas, is symmetrical in structural attitude with the San Fernando zone and ruptured the ground surface during the 1952 Kern County earthquake (M 7.7). Other large earthquakes associated with surface rupturing on faults of this system include the 1857 Fort Tejon earthquake (M 8+) and possibly the 1852 Big Pine earthquake. Several other historic earthquakes in this general area are not known to be associated with surface ruptures, but were large enough to cause damage in the northern San Fernando Valley.

The Van Norman reservoirs are in an area of high seismicity that was permanently deformed during the 1971 earthquake; this area could be subjected to even larger earthquakes. Such earthquakes could be accompanied by transitory and permanent effects that would impose severe deformations on an earth dam. Because the Van Norman area overlooks the densely populated central San Fernando Valley, the presence of the high seismic and fault risk justifies great conservatism in the selection of critical geologic and seismologic parameters to be used in the planning, design, review, and construction of dams in that area.

INTRODUCTION

The Van Norman reservoir complex is at the west margin of the northern San Fernando Valley about 20 mi (32 km) northwest of downtown Los Angeles. The complex consists of an upper dam and reservoir and a lower dam; the dams were built between 1912 and 1921 of hydraulic fill placed on young valley alluvium as thick as 50 ft

(15 m) at the upper dam and 20 ft (6 m) at the lower dam. A small bypass reservoir and dam, built of compacted fill and completed in 1970, is also part of the complex. Both the upper and lower Van Norman dams were severely damaged by slope failures in the embankments during the 1971 San Fernando earthquakes. The lower reservoir was immediately drained and the lower dam taken out of service, whereas the upper dam still impounds a reservoir operated at reduced capacity. A proposed new dam would be built of compacted earthfill placed on bedrock at a site midway between the upper and lower dams; the proposed dam would impound about 10,000 acre-feet (12,300,000 m^3) of water, about half the maximum capacity of the former lower reservoir.

PURPOSE AND SCOPE

This report contains the results of an investigation, made on behalf of the Federal Disaster Assistance Administration, of the geologic environment of the Van Norman area with respect to repair or replacement of the dams. The investigation included several phases, the first of which was a brief review of the regional geologic setting, structural framework, and seismic history. A second phase consisted of mapping (scale 1:12,000) the permanent deformation of the ground surface in the northern San Fernando Valley associated with the 1971 San Fernando earthquake, in part because a complete, detailed record of the effects of the 1971 earthquake will serve as an example of the effects to be expected from similar future events. The third phase was to map in detail (1:4,800 and 1:1,200) the distribution and attitude of faults in the reservoir area and to determine their history and degree of activity, with emphasis on their relation to the 1971 deformation and the regional structure. It was then necessary to determine whether these relations would persist and, finally, to estimate the effects that future earthquakes might have in the reservoir area.

PREVIOUS INVESTIGATIONS AND SOURCES

The present work is a continuation and extension of investigations of the February 9, 1971, San Fernando earthquake sequence. Early results of that multiagency investigation were reported in U.S. Geological Survey Professional Paper 733, published about 10 weeks after the earthquake, which includes numerous basic sources in geology, seismology, and effects of the earthquakes. A very useful product of similar investigations by the California Division of Mines and Geology is their map of surface effects of the San Fernando earthquake (Barrows and others, 1974, pl. III). The standard geologic reference for the area and for the western San Gabriel Mountains in general is Oakeshott's (1958) comprehensive report on the San Fernando quadrangle, which contains a geologic map of the western San Gabriel Mountains at a scale of 1:62,500 and a very useful review of the nomenclature of the geologic units. Other published sources valuable to the present study include a report by the California State Water Rights Board (1962) on the ground-water geology and regime of the San Fernando Valley and the Los Angeles Sheet of the Geologic Map of California by Jennings and Strand (1969).

We especially appreciate the cooperation of the Los Angeles Department of Water and Power in dressing and cleaning the cut slopes in the embankment area of the proposed damsite and surveying geologic control points, and in supplying numerous reports, maps, and data, all of which contributed significantly to the investigation. Most of the fieldwork for this report was done during the period April to August 1972; office work and report preparation extended into 1973.

GEOLOGIC SETTING

The San Fernando Valley is in the central part of the Transverse Ranges structural province of southern California (across center of fig. 1), athwart the northwesterly regional trend of the Coast Ranges and Peninsular Ranges provinces and faults of the San Andreas system such as San Jacinto, Whittier-Elsinore, and Newport-Inglewood. The Transverse Ranges province consists of numerous east-trending mountain ranges and valleys, characterized by late Cenozoic compressive structural features such as tight folds and reverse-slip and thrust faults of similar trend. One of the most impressive products of this late Cenozoic tectonism is the east-trending Ventura basin, northwest of San Fernando Valley, which is a syncline of Cenozoic sediments that include about 5,000 ft (1,500 m) of marine Pleistocene sediments. Both limbs of the syncline are overturned inward and overridden by thrust faults. A more spectacular feature of the province is the bold southern front of the San Gabriel Mountains, north and east of the San Fernando Valley, which

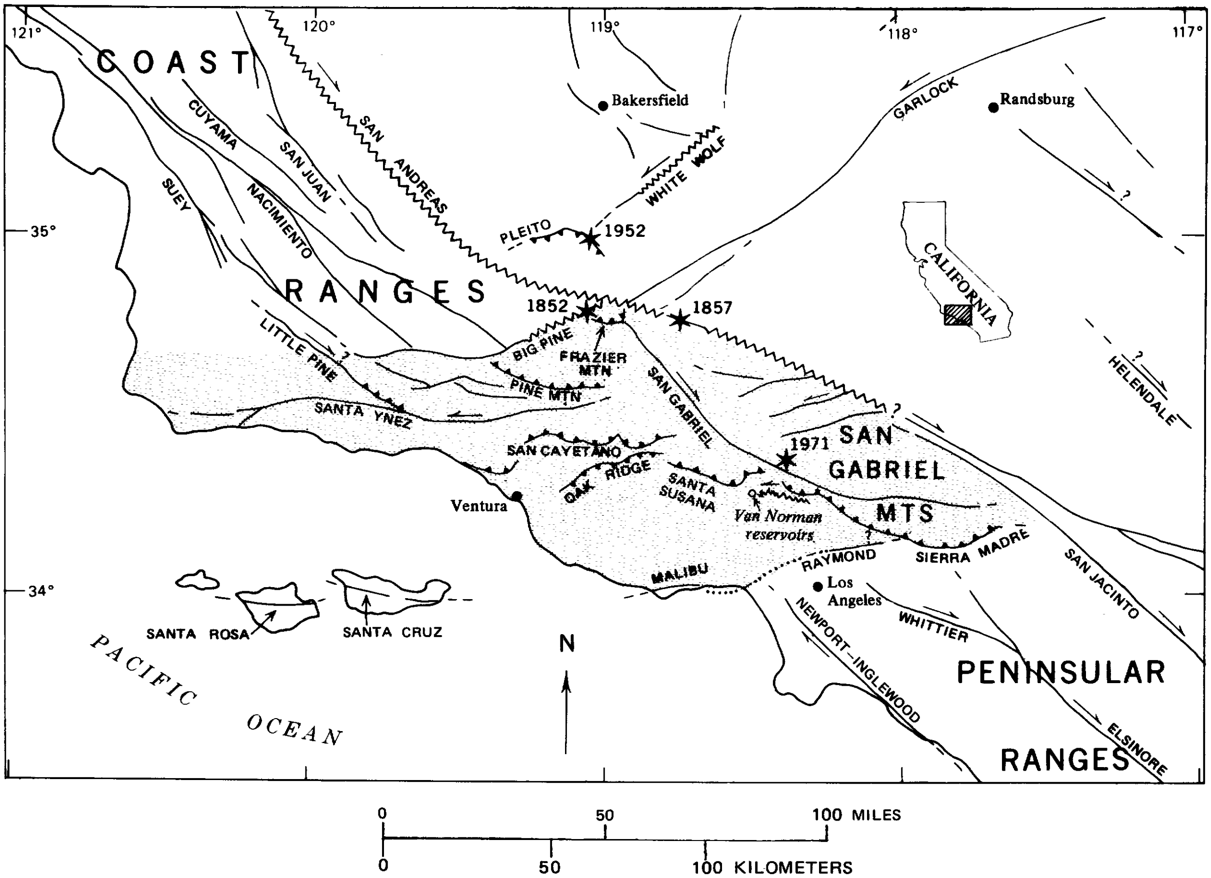

FIGURE 1.—Part of southern California showing western Transverse Ranges (shaded area between Coast Ranges and Peninsular Ranges), major faults, known or inferred epicenters of larger historic earthquakes (stars and dates), and associated tectonic ruptures (sawtooth lines) related to the San Andreas stress system. Arrows indicate relative horizontal movement on strike-slip faults; barbed lines indicate reverse faults, barbs on upper plate. Modified from Hill (1954, fig. 1).

has been elevated thousands of feet above the San Fernando Valley and the Los Angeles basin on the south along reverse or thrust faults such as the San Fernando and Sierra Madre.

Unlike most of the major features in California, which trend northwest-southeast, the mountains and valleys of the Transverse Ranges all trend east-west. The earthquakes, faulting, and mountain-building activity in the western Transverse Ranges reflect the influence of the San Andreas fault and the "great bend" that it forms as it passes through the province. North of the Transverse Ranges the San Andreas fault has a long, straight, south-southeasterly trend, but as it enters the Transverse Ranges, it swings more eastward to the "great bend." As the fault leaves the Transverse Ranges east of Riverside, it again assumes a more south-southeasterly path.

The parts of California northeast of the San Andreas fault, along with the rest of North America, are moving southeast relative to the part of California southwest of the fault and the adjacent Pacific Ocean floor. The direction of movement is parallel to the northern and southern segments of the fault. Because of the "great bend," however, the two major blocks are in part moving toward each other in that section, causing strong north-south compression over a fairly large area. The compression is relieved in part by other faults that move in a reverse and (or) left-lateral fashion. These faults generally have an east-west orientation and are responsible for much of the uplift of the mountainous terrain in the Transverse Ranges. The San Fernando fault is one of these reverse/left-lateral faults, as are the Santa Susana and Sierra Madre faults south of the San

Andreas and the Pleito and White Wolf faults north of the San Andreas.

The 1857 Fort Tejon earthquake (M 8±) ruptured a 220-mi (350-km) segment of the San Andreas fault between Cholame Valley and San Bernardino, essentially spanning the Transverse Ranges. Since then, this section of the San Andreas system has been relatively quiet, although stress has continued to accumulate across the area for the last 115 years. Some of the stress can be released on the left-lateral/reverse faults, as apparently happened during the 1952 Kern County earthquake (M 7.7), which occurred on the White Wolf fault, and during the 1971 San Fernando earthquake (M 6½). Because these stresses continue to accumulate throughout the region, additional fault movements are expected.

Movements on left-lateral/reverse faults of the Transverse Ranges, such as the San Fernando fault, are thus attributable to effects of stresses related to the San Andreas system of faults. Geologic evidence at all scales indicates that the faults have been active for several million years; there is no reason to expect significant changes in the system.

FAULTS IN THE SAN FERNANDO VALLEY

The San Fernando Valley is an asymmetric basin filled chiefly by Miocene and younger (less than 20 million years old) sedimentary rocks. The rocks have been deformed by late Cenozoic folding and, especially at the north margin of the valley, by thrusting along the Santa Susana fault and its eastward equivalents (fig. 2). It is chiefly this sequence of late Cenozoic sedimentary rocks that forms the foothills around the northern part of the valley.

The structure of the San Fernando Valley area is dominated by two intersecting regional fault systems: the northwest-trending San Andreas system of right-lateral strike-slip faults, including the San Gabriel fault, and the east-trending system of north-dipping reverse and thrust faults, including the Santa Susana–San Fernando–Sierra Madre zone, along which the mountain ranges have been elevated. Although the geologic history of the area formerly was dominated by the San Gabriel fault zone, the present structure of the north margin of the valley has been greatly modified by overthrusting along the mountain-front faults.

The Van Norman reservoirs occupy a southeast-draining stream course where it crosses elements of the Santa Susana–San Fernando fault zone. The Santa Susana is a zone of east-trending gently north-dipping thrust faults characterized by a sinuous trace. The zone extends from the Santa Clara River valley about 18 mi (29 km) west of the reservoirs to the foothills north of the reservoirs. Horizontal shortening across the zone exceeds 1.5 mi (2.4 km) (Hazzard, 1944). In the Santa Susana Mountains (west part of fig. 2), the fault includes two strands about 0.3 mi (0.5 km) apart. The northern or upper strand is entirely within Tertiary rocks, whereas the lower strand involves sedimentary deposits of inferred Quaternary age. Northeast of the reservoirs the two traces merge to form a series of east-trending reverse faults on which rocks of the basement complex have been thrust over sedimentary units as young as Pleistocene. Rupturing and reverse faulting occurred at the ground surface along or near the lower strand during the 1971 earthquake both northwest and northeast of the northern San Fernando Valley; the zone is therefore active.[1]

The Granada Hills fault extends westward from the southwest corner of the lower reservoir; in this area the trace is based on its expression in aerial photographs taken in 1952. The westward continuation and age relations of this fault are poorly known; eastward the trend merges with elements of the San Fernando fault zone.

The San Fernando fault zone, a zone of tectonic ruptures associated with the 1971 San Fernando earthquake (Wentworth and Yerkes, 1971, p. 13), extends eastward across the northern San Fernando Valley from the east shore of the lower reservoir. It coincides with young fault-induced topographic features, which attest to its continuing activity, and also coincides with the previously mapped trace of a buried ground-water impediment, which results in a 50-ft (15-m) fall in ground-water level from north to south (California State Water Rights Board, 1962). The ground-water impediment is attributed to prehistoric, but geologically young, faulting along the trend of the San Fernando zone, which has elevated bedrock on the north against alluvial gravels on the south

[1]As used here an active fault is one which, on the basis of its geologic history, is considered to have potential for causing vibratory ground motion and (or) differential displacement of the ground surface. Such faults commonly exhibit one or more of the following: (1) movement at or near the ground surface at least once in the past 35,000 years or more than once in the past 500,000 years, (2) instrumentally well-determined macroseismicity, (3) a relationship to a fault with characteristics (1) or (2) such that movement on one could be accompanied by movement on the other. These criteria are essentially those used by the U.S. Atomic Energy Commission for siting nuclear power plants (Atomic Energy Commission, 1971, p. 22602).

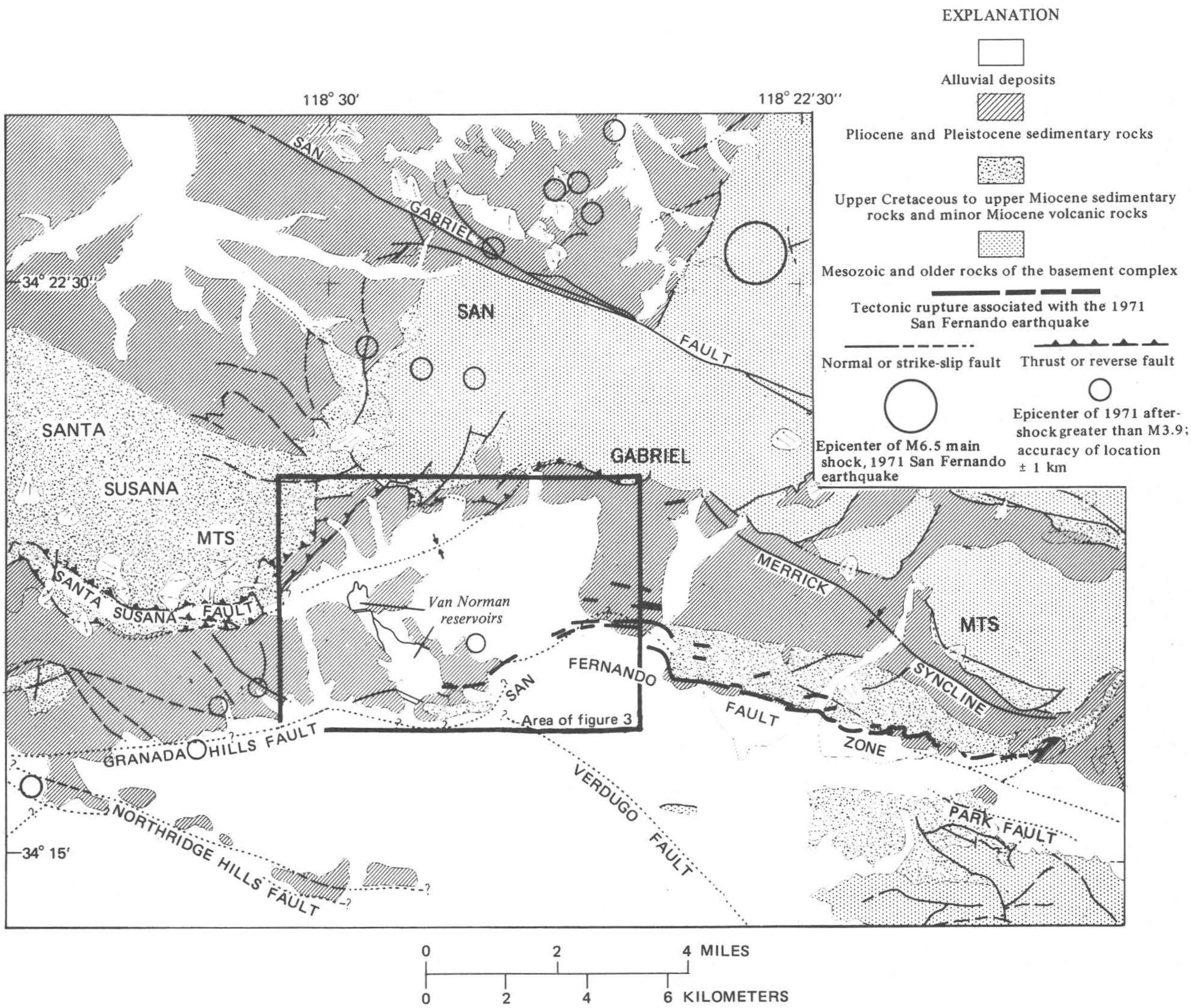

FIGURE 2.—Northern San Fernando Valley and western San Gabriel Mountains. Unpatterned areas with half arrows represent landslide deposits. Dotted line north of Van Norman reservoirs indicates buried axis of Mission Hills syncline. Modified from Wentworth and Yerkes (1971, fig. 2).

(Wentworth and Yerkes, 1971, p. 13). Near the east margin of the valley, the zone coincides with a topographic escarpment along the south margin of a low mesa of bedrock and stream terrace deposits. Between this mesa and the hills just east of the reservoirs, the ground-water impediment coincides with a very gentle south-facing topographic ramp on the valley floor, which may be due to faulting. Faults alined with the zone extend westward through the reservoir to merge with the Granada Hills fault.

During investigation of the 1971 ruptures in Lopez Canyon, 0.6 mi (1 km) east of the northern San Fernando Valley, ancient wood was discovered in rubble beneath a buried fault scarp, the top of which was eroded away and the lower part of which was more than 3.3 ft (1 m) high and alined with the 1971 ruptures (Bonilla, 1974). Displacement at the ground surface on the main fault and magnitude of the associated earthquake vary directly as based on correlation of these parameters for 50 historic events known from the world record (Bonilla and Buchanan, 1970). Thus, if the buried scarp at Lopez Canyon was formed during a single event, it is probable that a larger-than-1971 earthquake occurred along this zone some 100–300 years ago (the radiometric age of the wood; see Bonilla, 1974), since the vertical separation on the 1971 ruptures in Lopez Canyon is about 3.1 ft (0.95 m).

HISTORIC SEISMICITY AND FAULTING

Although the 1971 surface ruptures were the first to be recorded in historic time in the Transverse Ranges southwest of the San Andreas fault, the following historic record does include a number of large earthquakes capable of causing substantial damage in the valley area:

1700's (1769?). Magnitude and location unknown. Associated with buried faultlike scarp 3.3+ ft (1+ m) high in Lopez Canyon, dated by means of ancient wood at about 200 years before present (Bonilla, 1974).

1852, Big Pine. (See fig. 1.) Magnitude unknown. Probably associated with surface ruptures along east-trending left-oblique-slip fault opposite the great bend of the San Andreas.

1857, Fort Tejon. (See fig. 1.) About M 8. Associated with more than 220 mi (350 km) of surface rupture along the San Andreas in and north of the Transverse Ranges.

1893, "Pico Canyon". Location unknown. About M6 (Allen, 1971).

1916, Tejon Pass. About M 6 (Richter, 1958, p. 520).

1930, Location unknown. M 5.2. Intensity VIII (RF)[2] at Santa Monica, near VII at Olive View, 2 mi (3 km) northeast of the reservoirs. Shaking caused settlement (0.25 ft, 7.6 cm) and upstream displacement (0.06 ft, 1.8 cm) of the parapet of the lower dam; minor damage also was sustained by the Chatsworth dam, a hydraulic-fill dam about 9 mi (15 km) southwest of lower Van Norman dam.

1952, Kern County. M 7.7. (See fig. 1.) Three aftershocks greater than M 6. Associated with about 31 mi (50 km) of surface rupture along the White Wolf fault, an east-trending left-oblique reverse-slip fault opposite the great bend of the San Andreas.

1971, San Fernando. (See fig. 1.) M 6½. Associated with about 9.3 mi (15 km) of surface rupture along an east-trending left-oblique reverse-slip fault opposite the great bend of the San Andreas.

Local effects of historic earthquakes are also preserved as soft-sediment deformation of the deposits that accumulated in lower Van Norman reservoir after it formed in 1915. After the reservoir was drained following the 1971 San Fernando earthquake, evidence of soft-sediment deformation, attributed to effects of the 1971 earthquake, was found in the upper 1½–2 in. (4–5 cm) of the lake sediments (Sims, 1973). The deformation included low-amplitude folds, load-type structures, pseudonodules, and upward-penetrating heave structures. Two zones of similar deformation, buried at lower levels in the lake deposits, are truncated and overlain by underformed parallel-laminated or massive sediment. On the basis of the estimated rate of sediment accumulation, the deformed zones correlate in time with, and thus could have been produced by, the following earthquakes, otherwise known to have produced intensities of VI (MM)[3] or greater in the northern San Fernando Valley area:

February 9, 1971; San Fernando, Intensity VIII–XI

July 21, 1952; Kern County, Intensity VI–VII

August 30, 1930–March 10, 1933, "Los Angeles"–Long Beach. Intensity VI

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[2]Intensity scale of Rossi-Forel (1883). (See Richter, 1958, p. 650–651 for explanation.) Intensity VIII (RF) is equivalent to intensity VII–VIII on the Modified Mercalli scale. (See footnote 3.)

[3]Intensity refers to the degree of shaking at a given place; it is based on a qualitative judgment of the effects of shaking, chiefly on structures, assigned by an experienced observer. Excerpt from the 1956 version of the Modified Mercalli scale (Richter, 1958, p. 137) follows.

VI: Felt by all. Many frightened and run outdoors. Persons walk unsteadily. Windows, dishes, glassware broken. Books, etc., off shelves. Pictures off walls. Furniture moved or overturned. Weak plaster and poor-quality masonry cracked. Small bells ring. Trees, bushes shaken visibly or heard to rustle.

VII: Difficult to stand. Noticed by drivers of motorcars. Hanging objects quiver. Furniture broken. Damage to poor-quality masonry. Weak chimneys broken at roofline. Fall of plaster, loose bricks, stones, tiles, cornices, and unbraced parapets and architectural ornaments. Some cracks in unreinforced ordinary-quality masonry. Waves on ponds; water turbid with mud. Small slides and caving-in along sand or gravel banks. Large bells ring. Concrete irrigation ditches damaged.

VIII: Steering of motorcars affected. Damage to ordinary-quality masonry; partial collapse. Some damage to reinforced good-quality masonry, but none to well-designed masonry reinforced against lateral forces. Fall of stucco and some masonry walls. Twisting, fall of chimneys, factory stacks, monuments, towers, elevated tanks. Frame houses moved on foundations if not bolted down; loose panels thrown out. Decayed piling broken off. Branches broken from trees. Changes in flow or temperature of springs and wells. Cracks in wet ground and on steep slopes.

IX: General panic. Poor-quality masonry destroyed, ordinary-quality masonry heavily damaged, sometimes with complete collapse; good-quality masonry seriously damaged; general damage to foundations. Frame structures, if not bolted, shifted off foundations. Frames racked. Serious damage to reservoirs. Underground pipes broken. Conspicuous cracks in ground. In alluviated areas sand and mud ejected, earthquake fountains [ejection of fluids], sand craters.

X. Most masonry and frame structures destroyed with their foundations. Some well-built wooden structures and bridges destroyed. Serious damage to dams, dikes, embankments. Large landslides. Water thrown on banks of canals, rivers, lakes, etc. Sand and mud shifted horizontally on beaches and flat land. Rails bent slightly.

XI. Rails bent greatly. Underground pipelines completely out of service.

XII: Damage nearly total. Large rock masses displaced. Lines of sight and level [permanently] distorted [by deformation of the ground surface]. Objects thrown into the air.

The epicenter of the main shock of February 9, 1971 (M 6½) was at 34°24.7' N. and 118°24.0' W., about 7 mi (12 km) northeast of the Van Norman reservoirs in the westernmost San Gabriel Mountains (fig. 2). About 39 large aftershocks, 4 of which were greater than M 5 and 17 of which were greater than M 4.0 (Allen and others, 1974, table 2), occurred within 2 hours of the main shock. By the end of 1971, 55 aftershocks of M 4 and greater had occurred. The focal depth of the main shock was about 5 mi (8 km) (Allen and others, 1974). Tectonic ruptures associated with the earthquake formed discontinuously for about 9 mi (15 km) along a narrow zone trending N. 70–75° E. across the northern San Fernando Valley from immediately east of the lower reservoir. The U-shaped pattern formed by the epicenters of the aftershocks opens to the south and extends well north of the main shock epicenter; the south boundary of the epicenters essentially coincides with the zone of surface ruptures, although the aftershocks extended westward several miles beyond the rupture zone. (See fig. 2.) The focal depths of the aftershocks generally increase northward from near surface along the trend of the rupture zone to more than 6 mi (10 km) in the area north of the main-shock epicenter (Wesson and others, 1971, fig. 3).

Fault-plane solutions for the main shock indicate that the basic mechanism of the initial faulting was that of a thrust or reverse fault striking about N. 70° W., dipping about 50° NE, and including a significant component of left-lateral slip (Allen and others, 1974). These data, combined with the distribution and fault-plane solutions of the aftershocks, describe a thrust fault that strikes about N. 70° W. and is inclined about 36°in the direction N. 20° E. away from the rupture zone where it intersected the earth's surface as a left-oblique thrust fault, north block upthrown.

This general model is complicated by an alinement, trending about N. 20° E. along the west edge of the "U," of a series of aftershocks with focal mechanisms indicating chiefly left-lateral strike slip, in contrast to the common reverse-slip solution. These solutions may be explained by the hypothesis that the inclined fault surface is not planar, but rather that it is flexed or stepped down to the west along that trend, the trend being that of the basement rock–sedimentary rock contact north of the reservoirs and south of the San Gabriel fault (fig. 2; Allen and others, 1974).

The geologic and seismic evidence thus indicates that the main shock and tectonic surface ruptures were caused by displacement on a northeast-dipping thrust fault; the upper block of the thrust, north of the surface ruptures, was thrust southwestward up and over the main San Fernando Valley block south of the ruptures. The west-facing flexure or step postulated for the west margin of the fault surface is probably parallel to the trend of slip on the fault and may have controlled the west limit of the zone of surface ruptures.

TRANSITORY EFFECTS

The transitory effects of the main shock were unique in several ways. Most significantly, they included the most intense ground motions ever recorded instrumentally for a natural earthquake: peak accelerations of 1.25 *g* for both horizontal components and vertical acceleration of 0.7 *g*, velocity of displacement 3.75 ft (114 cm) per second, and magnitude of displacement about 1.25 ft (38 cm), measured at Pacoima dam, about 5½ mi (9 km) northeast of the reservoirs; duration of shaking at accelerations greater than 0.25 *g* was about 7 sec at Pacoima dam.

Records from seismoscopes (an inverted pendulum whose movement is recorded on a smoked glass) were obtained from the Van Norman reservoirs area. Prof. R. F. Scott of the California Institute of Technology (Scott, 1973) developed a time history of the ground movement from a seismoscope located on bedrock of the east abutment of lower Van Norman dam. His analysis indicates that maximum horizontal acceleration there was at least 0.6 *g* and that the duration of shaking at accelerations greater than 0.25 *g* was about 13 sec.

PERMANENT EFFECTS

As a basis for comparing the permanent effects of the earthquake in the Van Norman reservoir area, the maximum dimensions of differential ground surface deformation in the northern San Fernando Valley are summarized. These include the first record of tectonic surface rupture in the Los Angeles area in historic time, as well as prominent differential elevation of the block north of the rupture zone and minor depression of the south block, and horizontal displacements of the two blocks relative to each other.

TECTONIC RUPTURES

The main zone of surface ruptures extended discontinuously eastward for about 9 mi (15 km) from the east margin of the lower reservoir across the valley through San Fernando, thence eastward along the base of the foothills to Big Tujunga Canyon (fig. 2). The ruptures dip generally northward, from about 30° on the Tujunga segment east of San Fernando to about 70° on the Sylmar segment in the San Fernando area, 74° on the Mission Wells segment near the west margin of the northern valley, and 57° on the Freeway segment just east of the lower reservoir. (See fig. 3.) Relative displacement on all segments commonly included components of both reverse dip slip (upper or north block relatively up) and left-lateral strike slip (north block moved relatively westward). The average ratio of these components was about 1:1, but varied considerably from segment to segment. In the San Fernando area, where the maximum known displacements were measured across the Sylmar segment, left-lateral strike slip was 6.2 ft (1.9 m), reverse dip slip was 4.9 ft (1.5 m), vertical separation was 4.6 ft (1.39 m), and horizontal shortening normal to the trend of the zone was 1.8 ft (0.55 m), for a net left-oblique-reverse slip of 7.9 ft (2.4 m). (Data from U.S. Geological Survey, 1971, p. 62.) Equivalent data for the Mission Wells segment, about 1 mi east of the lower reservoir, are as follows: left-lateral strike slip 1.5 ft (0.46 m) and reverse dip slip 0.52 ft (0.16 m), for an inferred net left-oblique-reverse slip of about 1.59 ft (0.49 m). Data for the Freeway segment just east of the lower reservoir are as follows: left-lateral strike slip 0.53 ft (0.16 m) and reverse dip slip about 1.25 ft (0.38 m), for net left-oblique-reverse slip of about 1.36 ft (0.42 m). Thus, net slip along the San Fernando zone decreased progressively westward by about 83 percent over a distance of about 2.4 mi (3.9 km), from 7.9 ft (2.39 m) near the east margin of the valley to about 1.3 ft (0.40 m) just east of the reservoir.

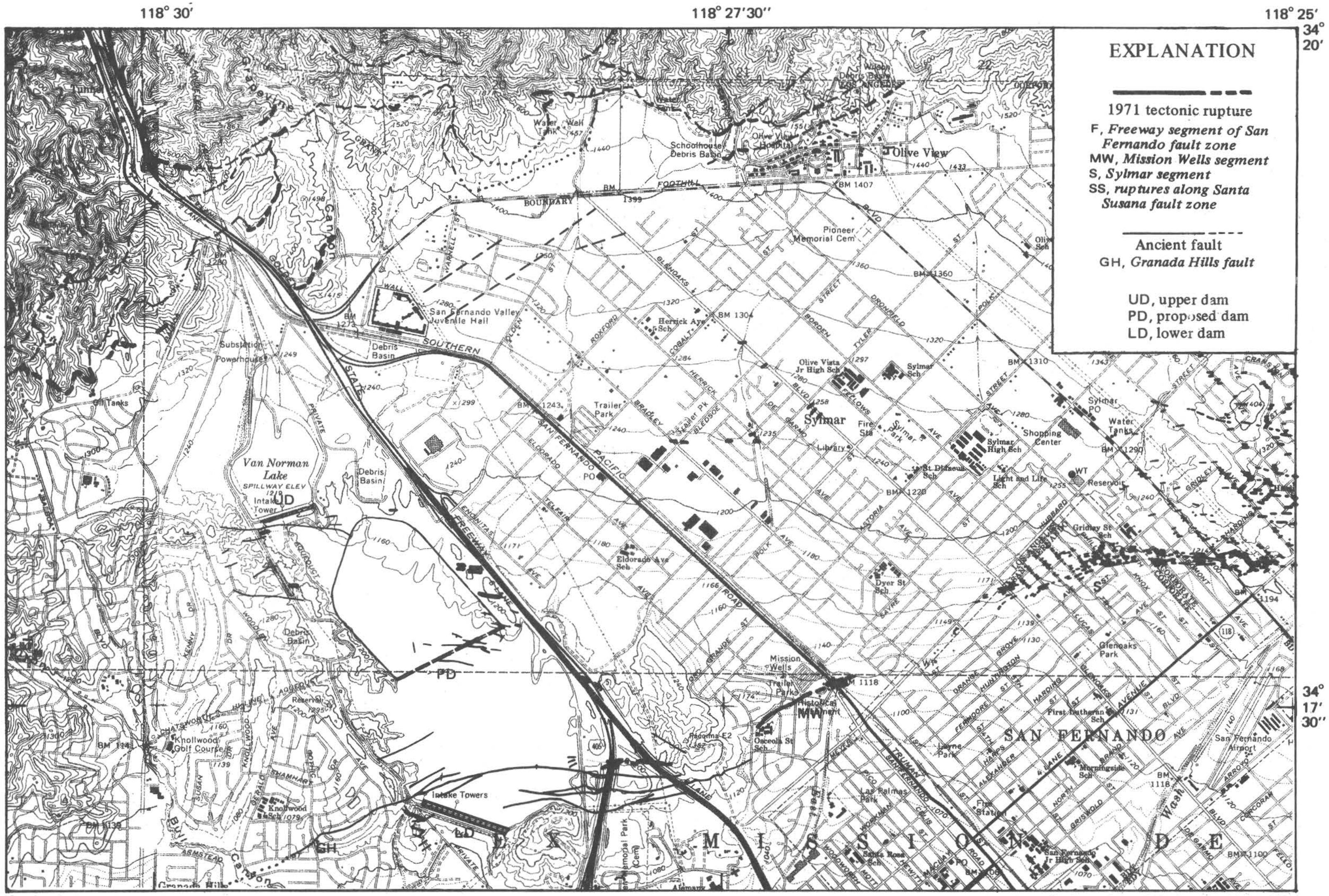
The displacements on the Sylmar segment during the 1971 event occurred across a zone about 350 ft (107 m) wide, but nearly all the lateral displacement and about half the vertical displacement occurred in a narrow zone about 100 ft (30 m) wide (U.S. Geological Survey, 1971, p. 57, figs. 2, 4). Within the broader zone individual ruptures were spaced as closely as about 50 ft (15 m); this zone in general contained about five subparallel ruptures, on which vertical displacements as much as 1.6 ft (0.5 m) occurred. Alternatively, displacements of 3.4 ft (1.05 m) of reverse dip slip and 2.6 ft (0.8 m) of left-lateral slip occurred on a single rupture that affected an area about 3 ft (1 m) wide in the natural ground of Lopez Canyon, where steeply dipping bedrock is at or near the surface (U.S. Geological Survey, 1971, p. 68–69).

A 1-mi (1.6-km) segment, subparallel to the lower trace of the Santa Susana fault about 1.5 mi (2.4 km) northwest of the upper reservoir, ruptured discontinuously during the 1971 earthquake sequence. Relative displacement of about 1 ft (0.3 m) left-lateral strike slip occurred near the south end of the rupture, under circumstances perhaps attributable to slope failure. The thick soil on ridgetops above all the ruptures was intensely churned, and the ruptures locally traverse ridgetops as well as slopes. The lower Santa Susana fault is intersected at depth by several active oil wells about 0.3 mi (0.5 km) northwest of the fault trace. None of the wells appear to have been damaged by movement of the fault. An extension of this zone of ruptures just northeast of the freeway showed left-lateral reverse displacement of about 0.25 ft (0.08 m).

VERTICAL DISPLACEMENTS

Comparison of leveling surveys before (1968–70) and after the earthquake (fig. 4) shows that changes in elevation formed an arch that affected much of the northern San Fernando Valley. The surveys have been referred to a common datum at Los Angeles Harbor; the elevation changes are accurate to about ±0.05 ft (0.015 m). The axis of the arch trends generally east-west and plunges westward; thus, the greatest changes were in the foothills east of the valley, where maximum uplift exceeds 6.3 ft (1.9 m). (See Burford and others, 1971; Savage and others, 1974.) The arch extends westward into the northern San Fernando Valley, where maximum uplift decreases progressively westward from more than 5 ft (1.5 m) just north of the Sylmar segment in the San Fernando area to more than 2.5 ft (0.8 m) just east of the lower reservoir and 1 ft (0.3 m) or less along the west margin of the reservoir. Maximums in the pattern of uplift coincide in general with topographic highs, indicating that the 1971 event continued a long-established pattern of uplift.

Profiles of elevation change (profiles B–B′, C–C′, D–D′, fig. 5) show abrupt changes in gradient

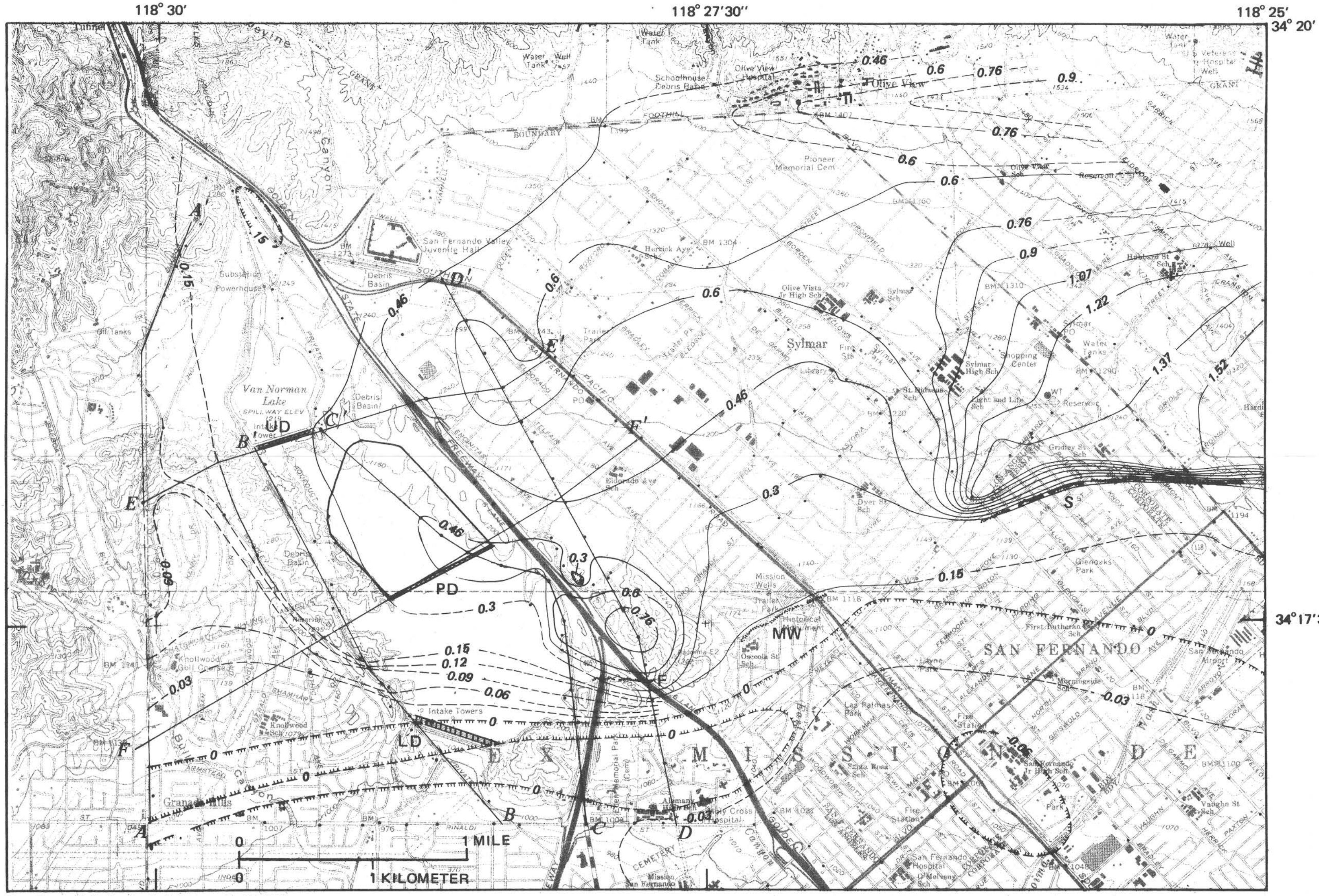


Base from U.S. Geological Survey, 1:24,000
Oat Mountain, 1952; San Fernando, 1966

0 — 1 MILE
0 — 1 KILOMETER

Geology from U.S. Geol. Survey, 1971
and supplementary mapping by
R. F. Yerkes and M. G. Bonilla, 1972

FIGURE 3.—Northern San Fernando Valley showing 1971 ruptures and ancient faults.



Base from U.S. Geological Survey, 1:24,000
Oat Mountain, 1952; San Fernando, 1966

Data collected and reduced by J. N. Alt and T. L. Youd;
interpretation by J. N. Alt and R. F. Yerkes

FIGURE 4.—Northern San Fernando Valley showing 1971 elevation changes determined from preearthquake and postearthquake surveys.

EXPLANATION

1971 tectonic rupture

F, Freeway segment; MW, Mission Wells segment; S, Sylmar segment

—— *0.3* —— Contour of equal elevation change, in meters, between 1968 and postearthquake surveys

Dashed where location poorly controlled. Heavy dots indicate control points. Hachures on side of depressed ground

A ——— *A′* Line of profile

Showing elevation changes between 1968 and postearthquake surveys (see figure 5)

U, upper dam; PD, proposed dam; LD, lower dam

where they cross the trend of the rupture zone just north of the lower dam, indicating that vertical deformation was concentrated along that trend in the lower reservoir, even though surface ruptures were not detected there. However, the degree of gradient change along the trend of the rupture zone clearly decreases westward (from profiles D–D′ to B–B′), and no equivalent change in gradient was detected along Balboa Boulevard west of the lower reservoir (profile A–A′).

The profiles also show that differential changes in elevation affected the damsites. Although only minor changes occurred between the abutments of the lower dam (less than 0.05 ft or 0.015 m), the east abutment of the upper dam was elevated about 0.34 ft (0.1 m) relative to the west abutment (profile E–E′), and the east abutment area of the proposed damsite was elevated about 0.76 ft (0.23 m) relative to the west abutment (profile F–F′).

HORIZONTAL DISPLACEMENTS

Deformation of the ground surface involved permanent horizontal displacements as well as vertical changes. The horizontal displacements of about 90 control points in the northern San Fernando Valley were mapped by means of vectors (fig. 6) that show the differences in station coordinates between 1940 to 1970 and postearthquake surveys. Free adjustments of the preearthquake and postearthquake coordinates of two survey points (PAC E2–ECC and Reservoir) were computed by B. K. Meade, U.S. National Geodetic Survey (written commun., Aug. 17, 1972). Preearthquake and postearthquake coordinates for the remaining stations were provided by the California Division of Highways, City of Los Angeles Bureau of Engineering and Department of Water and Power, Los Angeles County Engineer, Metropolitan Water District of Southern California, and the U.S. Geological Survey. The coordinates of these stations were then transformed to a common system, using the two freely adjusted National Geodetic Survey points for reference. Stations held fixed for the NGS free adjustments are in the eastern Santa Monica Mountains about 13.7 mi (22 km) S. 38° E. of the reservoirs and in the Verdugo Mountains about 18.6 mi (30 km) S. 62° E. of the reservoirs. The line between the fixed stations is about 8.1 mi (13 km) long and trends N. 76° E. The displacements indicated by the vectors are accurate to about ±0.2 ft (±0.06 m).

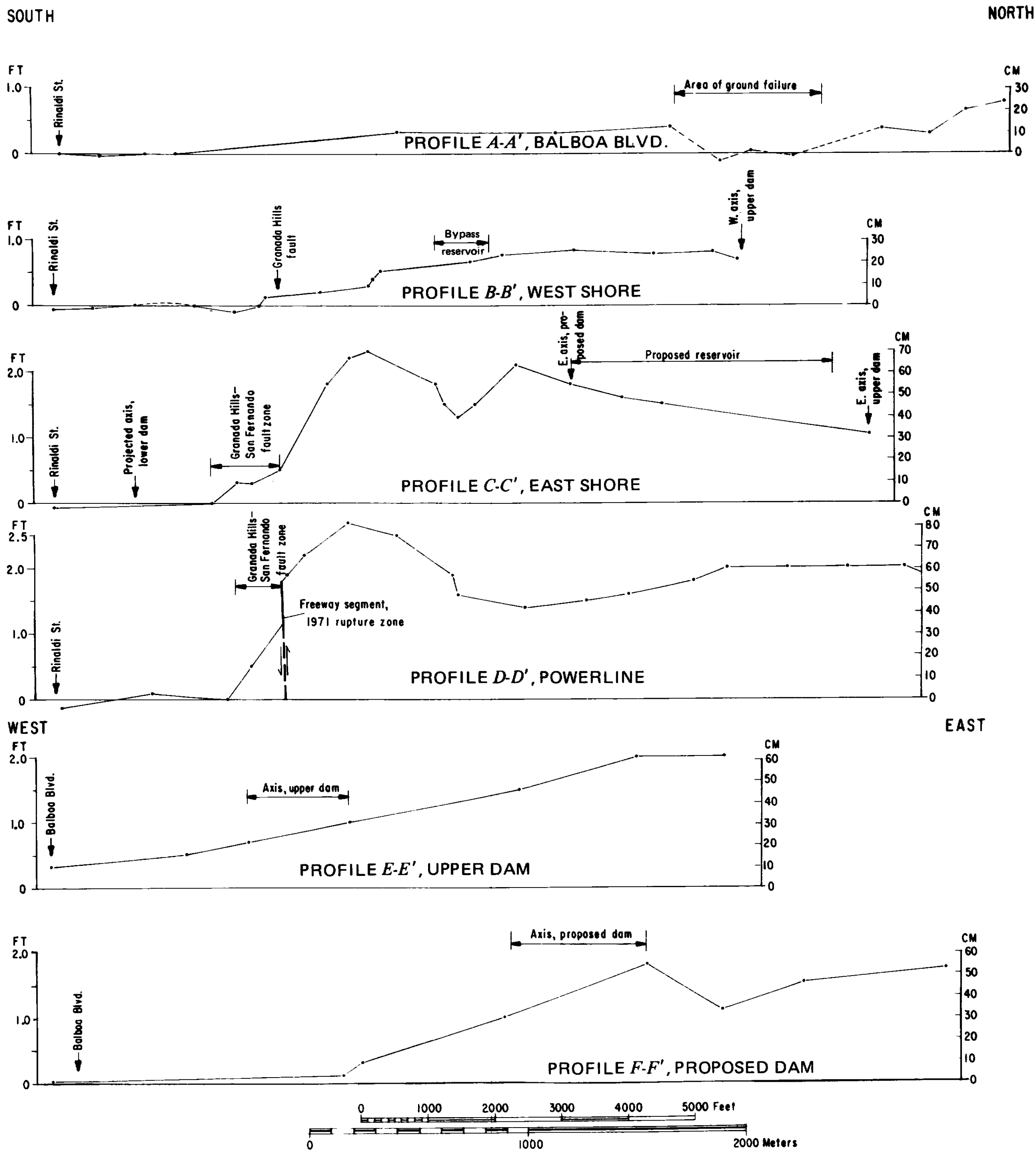


FIGURE 5.—Profiles of 1971 elevation changes determined from preearthquake and postearthquake surveys.

An abrupt discontinuity in the pattern and amount of horizontal displacements coincides with the rupture zone and its westward extension. North of the rupture zone displacement was generally westward; south of the zone it was northward. Distances between stations on opposite sides of the zone were shortened, consistent with thrust faulting. Northwest-trending lines that cross the zone at low angles were lengthened, whereas northeast-trending lines across the zone were shortened, consistent with left-lateral strike slip. North-south shortening and left-lateral displacement decreased progressively westward along the zone.

The discontinuity passes through the lower reservoir just north of stations CROFTS, WP 10, and ZEL L–3B. Although poorly defined because of widely spaced stations, the discontinuity appears to be subparallel to, but about 0.25 mi (0.4 km) north of, the Granada Hills fault and may coincide with an unnamed fault (fig. 6). Although this latter fault displaces surficial deposits, there is no evidence that it moved during the 1971 earthquake.

Plots of displacement versus distance along the Sylmar, Mission Wells, and Freeway segments of the rupture zone form fairly systematic curves (fig. 7), which indicate that displacement across the rupture zone decreases westward at rates of about 1 in 3,000. Alternatively, the rate across the westward extension of the zone in the area of the lower reservoir is less than one-third as much, approximately 1 part in 10,000.

The horizontal and vertical displacements of the east abutment area of each damsite relative to the west abutment, attributed to the 1971 deformation, are as follows:

Upper dam, (stations 1,550 ft or 472 m apart). Horizontal, 0.30 ft (0.09 m) S. 18° W; vertical, 0.34 ft (0.10 m) up.

Proposed dam, (stations 2,260 ft or 689 m apart). Horizontal, no significant relative displacement; vertical, 0.76 ft (0.23 m) up.

Lower dam, (stations 2,651 ft or 808 m apart). Horizontal, 0.476 ft (0.145 m) N. 44° E.; vertical, no significant relative displacement.

The horizontal deformations (strains) in the Van Norman reservoir area were analyzed through the use of finite element methods. The area west of San Fernando Road was divided into 250 triangular elements with corners at horizontal control points whose preearthquake and postearthquake positions are known. For each element the following surficial strains were determined:

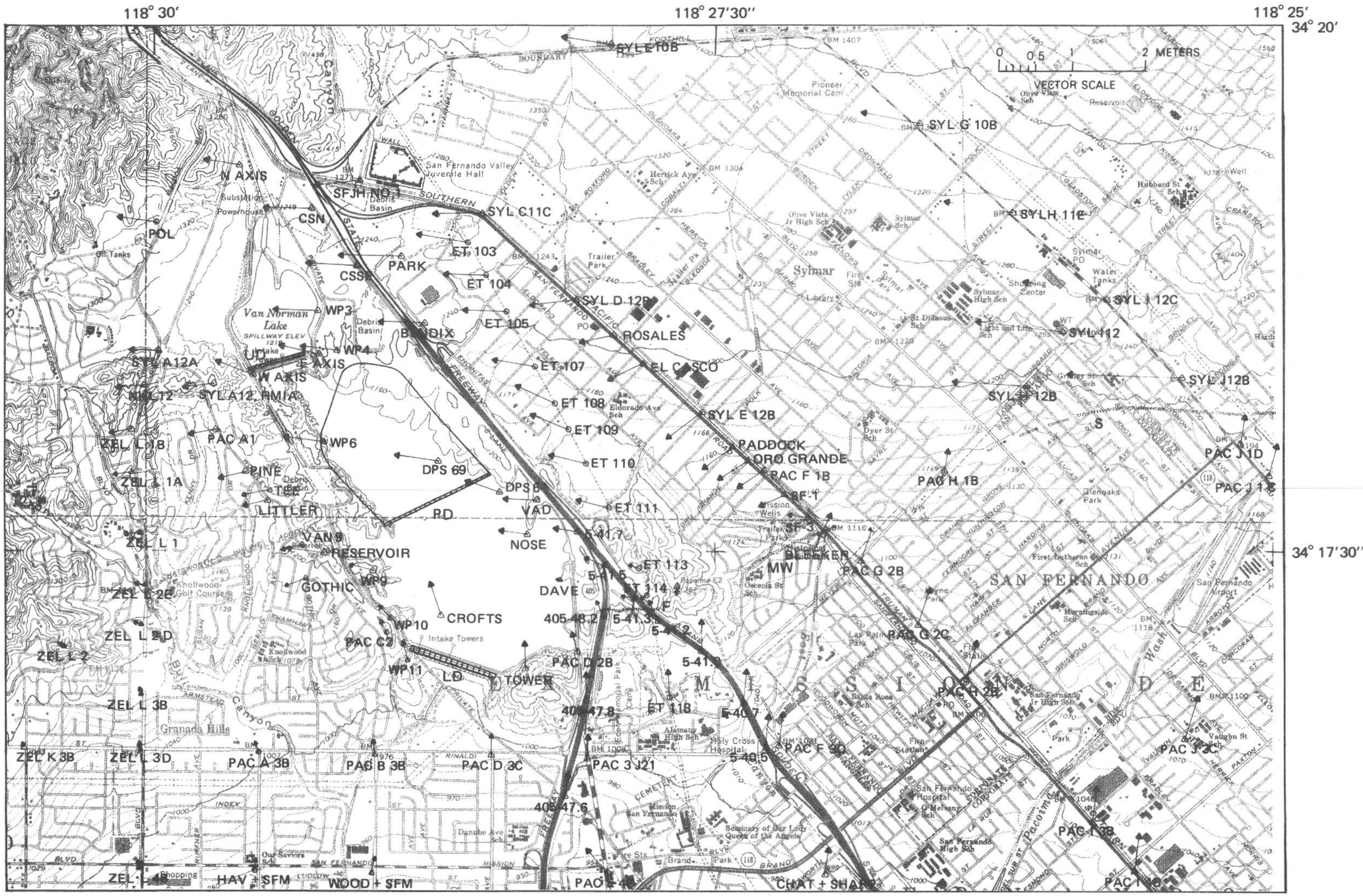
1. The dilatational strain (a measure of the amount and sense of change in area);
2. The maximum shear strain (a measure of the change in shape);
3. The principal strains and their orientation.

The accuracy of the strain values depends on the accuracy of the horizontal surveys (estimated at ±0.01 ft or 0.003 m) and the size of the particular triangular element. Using an average-size element this accuracy is estimated at ±0.01 percent strain, the value used as contour interval. In addition, it was assumed that the strains within each element were homogeneous. Because of these uncertainties and assumptions, the mapped strains are approximate; however, the general orientation and relative intensities shown are generally valid.

The dilatational strain (percent change in element area) is contoured and shown as positive (expansion) or negative (contraction) in figure 8. The most conspicuous feature on the map is the narrow band of contraction that coincides with the rupture zone, the greatest values (as large as −0.33 percent) being concentrated around the west end of the rupture zone just east of the lower reservoir. Westward across the reservoir along the trend, the values of contraction decrease by a factor of 5−10, although the general trend continues as far west as Balboa Boulevard. A broad area of weak expansion (values less than 0.02 percent) extends generally east-west across the map south of the rupture zone, coincident with areas of slight depression. Areas of greatest expansion (values as great as 0.15 percent) coincide with areas of greatest positive elevation change. The most conspicuous of these coincides with the low hills about 0.6 mi (1 km) northeast of the lower dam; this area of deformation extends northwestward toward the east abutment of the proposed dam. An east-trending band of milder expansion is present in the west abutment area of the upper dam, and a third is roughly coincident with the area of differential elevation 0.5 mi (0.8 km) east of the upper dam.

Angular distortion of the elements is mapped as (1) maximum shear strain (the maximum angular change of previously orthogonal lines within each element, in percent; fig. 9) and (2) axes of principal strain showing the magnitude and orientation of the most extensional and most contractional normal strains in each element (fig. 10). The map of maximum shear strain is similar in some aspects to the dilatation map. A narrow band of relatively high shear strain (values greater than 0.03 percent) coincides with the west end of the rupture zone. The band broadens and decreases in intensity westward across the lower reservoir. High shear strain and relatively large expansion also characterize the areas along the east margin of the lower reservoir that were elevated, most notably the area just southeast of the proposed dam.

The pattern of principal strains (fig. 10) also clearly delineates a discontinuity coincident with



Base from U.S. Geological Survey, 1:24,000
Oat Mountain, 1952; San Fernando, 1966

0 — 1 MILE
0 — 1 KILOMETER

Data collected and reduced by T. L. Youd and Sammy Shaler; interpretation by T. L. Youd and R. F. Yerkes

FIGURE 6.—Northern San Fernando Valley showing 1971 horizontal displacements determined from comparison of preearthquake and postearthquake surveys.

EXPLANATION

1971 tectonic rupture

F, Freeway segment; MW, Mission Wells segment; S, Sylmar segment

SYL G 10B

Survey station and vector

Showing direction and magnitude of horizontal displacement of points surveyed between 1940 and 70 and resurveyed after the 1971 earthquake

U, upper dam; PD, proposed dam; LD, lower dam

the rupture zone and its westward extension; strains north of the rupture zone and its westward extension are, in general, considerably larger than those to the south. The major principal strains in the vicinities of the upper and proposed dams are generally parallel to the axes of the dams; they range in magnitude from about 0.01 percent to 0.02 percent in extension. The minor principal strain is oriented generally normal to the axes of the dams, with values of about 0.03 percent contraction.

SUMMARY

In general, the intensity of surface deformation associated with the 1971 earthquake decreased westward across the northern San Fernando Valley and northward away from the rupture zone and its westward extension across the lower reservoir; the Van Norman area is well within the deformed area. Deformation was concentrated along the rupture zone and its westward extension; but another prominent area of deformation is the ridge of low hills east of the lower reservoir, where relatively large vertical uplift, areal expansion, and shear strain were combined. The map of principal strains emphasizes the general north to northwest trend of the most contractive strain, the correlation of discontinuities in the principal strain field with areas of relatively large shear strain and mapped faults, and the slight extensional strains (<0.02 percent) parallel to the axes of the upper and proposed dams.

The deformations of the ground surface that accompanied the 1971 earthquakes are integral parts of an established regional pattern of tectonic deformation that includes left-oblique-reverse displacements along the San Fernando fault zone and differential arching and horizontal displacements that extend across the northern San Fernando Valley into the reservoir area just north of the rupture zone.

GEOLOGY OF THE VAN NORMAN RESERVOIRS AREA

The reservoirs occupy a southeast-draining stream course at the west margin of the northern San Fernando Valley; the bedrock flanks of the reservoirs area are formed by irregular ranges of low hills that rise about 200 ft (60 m) above the adjoining lowlands. The hills were formed in late geologic time by arching and faulting of the sort that occurred in 1971 and subsequently were

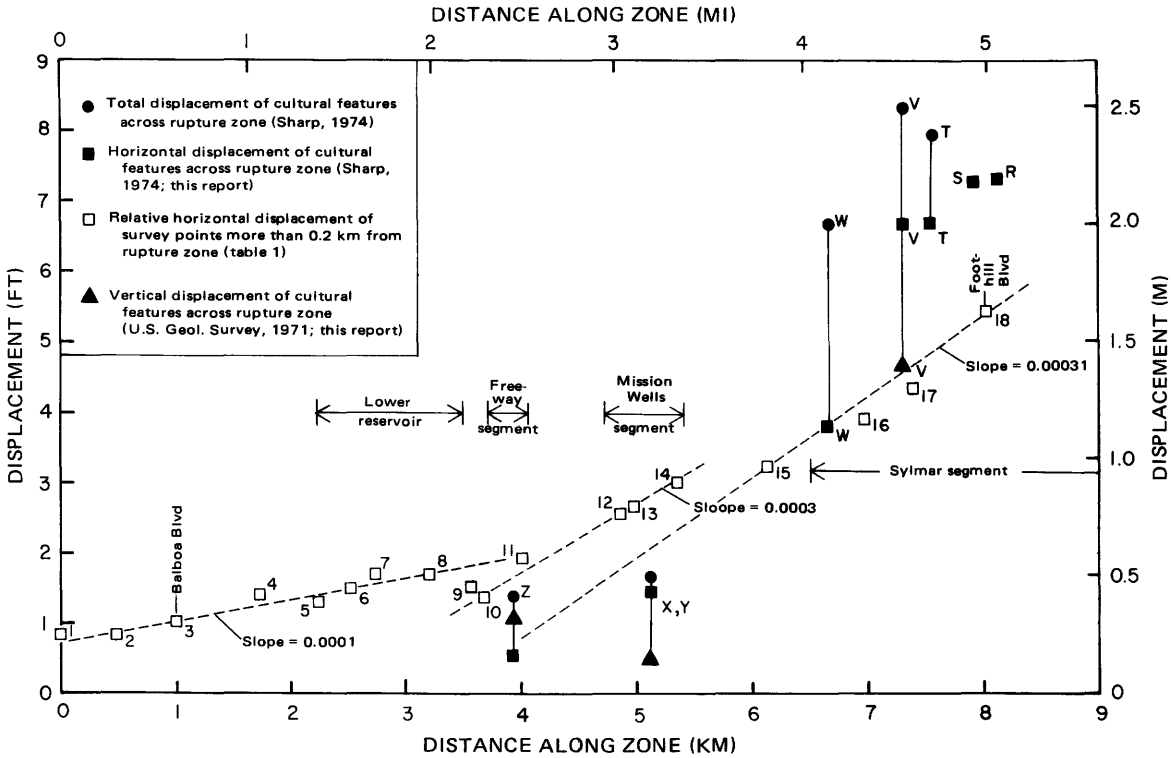


FIGURE 7.—Horizontal displacements, 1971, including total displacements and vertical components where known, across the several segments of the San Fernando zone between Foothill Boulevard on the east and Balboa Boulevard on the west. Displacements based on offset of cultural features (from Sharp, 1974; U.S. Geol. Survey, 1971; this report); relative horizontal displacements across the zone and its westward extension determined from displacement of survey points more than 0.2 km from the zone (from table 1, this report).

TABLE 1.—*Data on displacements along the San Fernando zone and its westward extension*

A. Total displacements and horizontal components across segments of rupture zone, based on offset of cultural features (from Sharp, 1974; U.S. Geological Survey, 1971; this report)

RVS No.	Total (m)	Horizontal (m)	Vertical (m)
R	----	2.2	----
S	2.1	2.1	----
T	2.4	2.0	----
V	2.5	2.0	1.4
W	2.0	1.1	----
X,Y	.5	.4	.15
Z	.41	.16	.32

B. Relative horizontal displacements across rupture zone and its westward extension based on displacement of survey points more than 0.2 km from zone (this report)

Vector pair	Vector difference (ft)	Orientation of difference[1]
ZEL L-1/ZEL K-3B	0.8	S. 66°W.
ZEL L-1/ZEL L-3D	.8	S. 60°W.
Avg of ZEL L-1+LITTLER/ PAC A 3-B	1.0	S. 50°W.
GOTHIC/PAC B-3B	1.4	S. 42°W.
WP 9/WP 11	1.3	S. 72°W.
LF 9/avg of WP 11+TOWER	1.5	S. 44°W.
LF9/TOWER	1.7	S. 61°W.
NOSE/TOWER	1.7	S. 52°W.
5-41.7/405-47.8	1.5	S. 45°W.
5-41.5/405-47.8	1.4	S. 48°W.
Proportioned avg of 5-41.5+SF-1/ET 118	1.8	S. 50°W.
Proportioned avg of 5-41.5+SF-1/avg of 5-41.0+PAC G-2B	2.6	S. 45°W.

TABLE 1.—*Data on displacements along the San Fernando zone and its westward extension—Continued*

B. Relative horizontal displacements across rupture zone, etc.—Continued

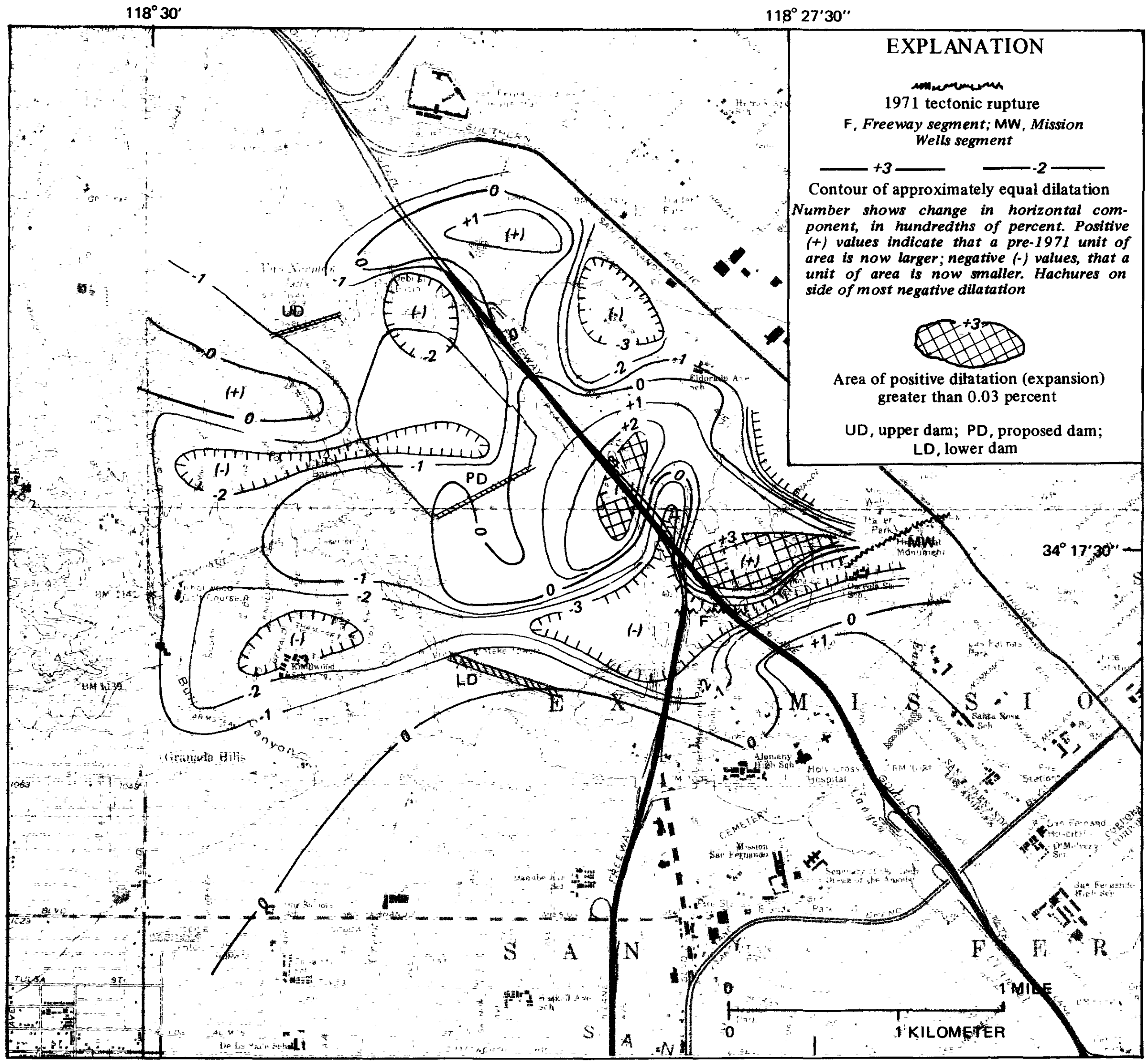
Vector pair	Vector difference (ft)	Orientation of difference[1]
SF-1/avg of 5-41.0+PAC G-2B	2.7	S. 32°W.
PAC F1-B/PAC G-2B	3.0	S. 38°W.
Avg of PAC F-1B+SYL H-12B/ avg of PAC G-2B+avg of PAC G-2C+PAC J-1D	3.2	S. 57°W.
SYL H 12-B/avg of PAC G-2C+PAC J-1D	3.9	S. 70°W.
SYL I-12/proportioned avg of PAC G-2C+PAC J-1D	4.3	S. 75°W.
SYL J-12B/PAC J-1D	5.4	S. 76°W.

[1]Assuming the south block fixed, this represents the direction of transport of the block north of the zone.

modified by erosion. As a consequence of the structural deformation, the bedrock strata throughout the reservoirs area are steeply tilted and faulted, and flat-lying stream terrace deposits that cap the bedrock hills, as well as younger valley fill deposits, are locally faulted.

STRATIGRAPHY

The oldest bedrock exposed in the reservoirs area is siltstone and shale of the upper Miocene



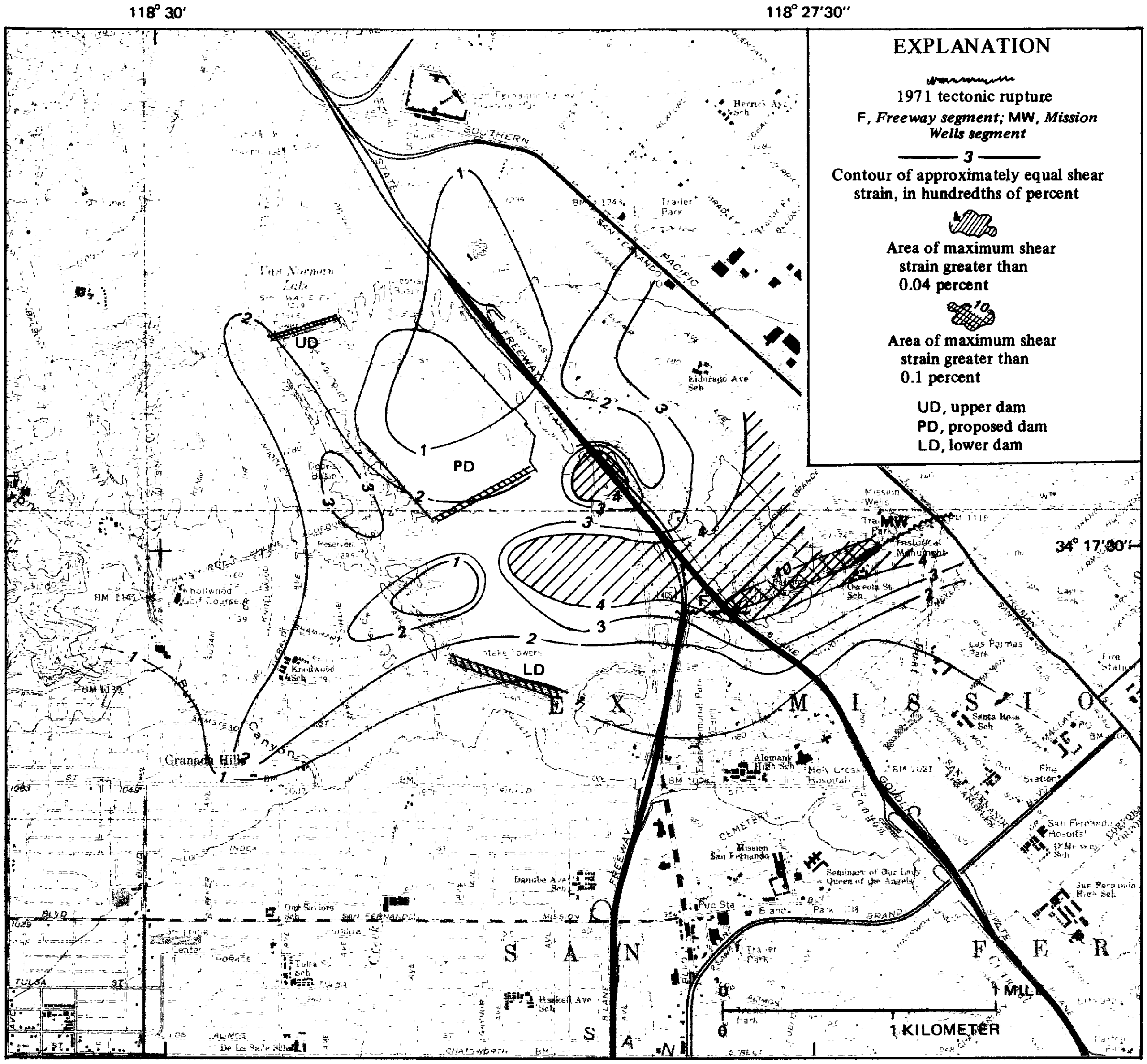
Base from U.S. Geological Survey, 1:24,000
Oat Mountain, 1952; San Fernando, 1966

Data preparation and programing by
T. L. Youd, A. T. F. Chen, and
D. Lichtenstein; interpretation
by T. L. Youd and R. F. Yerkes

FIGURE 8.—Northern San Fernando Valley showing orientation and magnitude of dilatational strains derived from horizontal displacements based on 1940–70 and postearthquake surveys (fig. 6; see text for explanation).

Modelo Formation. This unit forms the east abutment area of the lower dam and, together with younger rocks, is folded into a west-plunging anticline that places strata of the Pliocene Pico Formation under the west abutment. (See Yerkes and others, 1973, sheet 1.) An intervening 400 ft (120 m) of marine sandstone and thin sandy shale of the Towsley Formation, exposed north of the east abutment on the north flank of the anticline, is missing in the west abutment area because of faulting, gradational variations, or erosion prior to deposition of the Pico.

The Pico Formation is about 400 ft (120m) thick and consists of friable coarse-grained marine sandstone that contains lenses of calcareous sandstone, locally having abundant mollusks representative of the middle Pliocene of Pacific Coast usage. (See Oakeshott, 1958, p. 81.) The Pico is



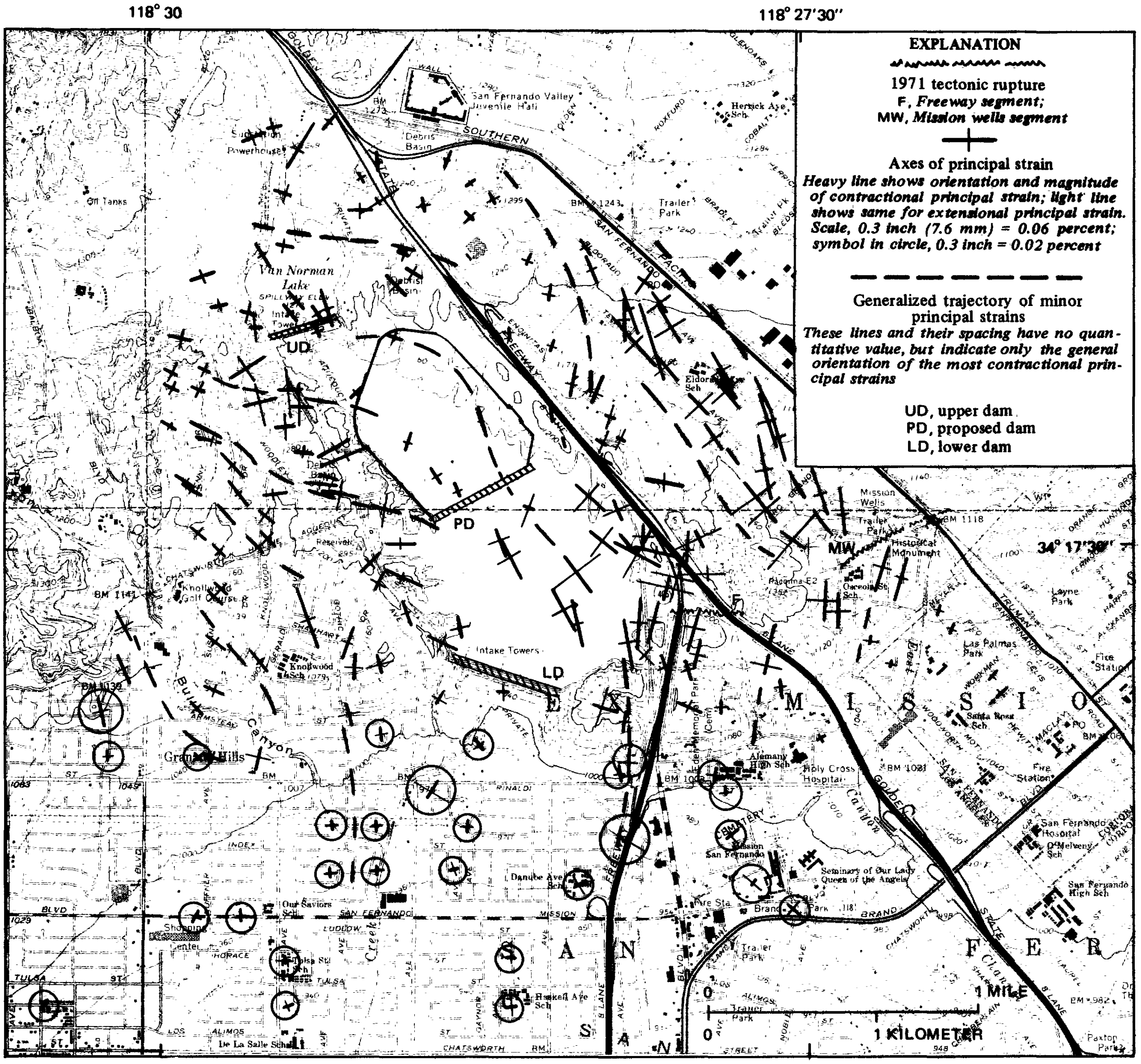
Base from U.S. Geological Survey, 1:24,000
Oat Mountain, 1952; San Fernando, 1966

Data preparation and programing by T. L. Youd, A. T. F. Chen, and D. Lichtenstein; interpretation by T. L. Youd and R. F. Yerkes

FIGURE 9.—Northern San Fernando Valley showing distribution and magnitudes of maximum shear strains derived from horizontal displacements based on 1940–70 and postearthquake surveys (fig. 6; see text for explanation).

overlain unconformably by nonmarine gravels, mudstone, pebbly sandstone, sandstone, and fresh-water limestone, the Sunshine Ranch Member of the Saugus Formation. This unit underlies much of the reservoirs area north of the lower dam. On the west margin of the reservoir, the Sunshine Ranch is about 3,000 ft (910 m) thick and on the east less than 2,000 ft (610 m) thick; the lower part of the sequence is missing on the east, perhaps because of faulting. The Sunshine Ranch Member was assigned a probable late Pliocene age on the basis of correlation with marine equivalents to the west and general stratigraphic position (Oakeshott, 1958, p. 82). Fossil horse teeth of middle or late Pliocene age, referred to *Pliohippus mexicanus* or *P. osborni,* were collected from the Sunshine Ranch Member in an exploratory trench along the axis of the proposed dam.

The Sunshine Ranch Member is unconformably overlain by the upper member of the Saugus



Base from U.S. Geological Survey, 1:24,000
Oat Mountain, 1952; San Fernando, 1966

Data preparation and programing by
T. L. Youd, A. T. F. Chen, and Sammy Shaler;
interpretation by T. L. Youd and R. F. Yerkes

FIGURE 10.—Northern San Fernando Valley showing axes of principal strains and trajectories of most contractional principal strains derived from horizontal displacements based on 1940–70 and postearthquake surveys (fig. 6; see text for explanation).

Formation—fluvial and alluvial deposits consisting of poorly sorted loosely consolidated sandy conglomerate and crossbedded pebbly sand. These deposits form the bedrock margins of the reservoirs area north of the proposed damsite, where they are about 3,000 ft (910 m) thick. Oakeshott (1958, p. 85) assigned them to the lower Pleistocene on the basis of a tooth of the primitive horse *Equus*, found in Saugus beds on the east margin of the reservoir. He noted, however, that some strata lower in the unit could be older.

In some parts of the reservoirs area, the bedrock is overlain by generally subhorizontal surficial deposits of varying ages. The older and more intensely faulted and weathered surficial deposits are preserved on the relatively high margins of the reservoirs. Oakeshott (1958, pl. 1, p. 86) mapped a small exposure of distinctly tilted and faulted reddish-brown fanglomerate that caps the hills immediately south of the west abutment of the lower dam and tentatively correlated it with his Pacoima Formation, of inferred middle Pleistocene age. This is probably the oldest surficial deposit in the reservoirs area.

Stream terrace and alluvial deposits of late Pleistocene and Holocene age form erosional remnants that overlie bedrock of the low hills northeast of the reservoirs, as well as that in the foundation area of the proposed dam. The basal contact of these flat-lying deposits forms a prominent reference horizon against which to measure the tectonic deformation of the area.

STRUCTURE

The Van Norman reservoirs area overlies the steep south limb of a broad syncline (Mission Hills syncline) that extends under the entire western part of the northern San Fernando Valley (fig. 2). The buried axis of the syncline, as inferred from its exposed limbs, trends about N. 60° E. north of the upper reservoir. The attitude of the south limb in the reservoirs area is such that the bedrock there dips northward between 50° and 80°, with steeper and locally overturned dips toward the south.

Immediately north of the lower dam, the south limb of the syncline intersects the east-trending zone of generally north-dipping faults that extends westward along the trend of the San Fernando zone. This zone includes an element of the Granada Hills fault (fig. 3) which extends westward from immediately west of the lower dam within the Sunshine Ranch Member. East of the lower dam, faults of the zone form boundaries of the stratigraphic units. The faults generally dip northward subparallel to stratification in the bedrock, and the compressive nature of the faulting has locally caused overturning of the bedrock and greatly decreased the exposed thickness of the bedrock units. The westernmost (Freeway) segment of the main zone of 1971 tectonic ruptures is about 1,200 feet (360 m) long and parallels the zone of older faults immediately east of the lower reservoir. The 1971 displacement on this segment and on the San Fernando zone in general was left-oblique-reverse, which is compatible with north-south compressive deformation. The similarity in attitude and compressive nature of deformation along the older faults suggests that movement on them was similar to that of 1971.

Faults and ruptures in the proposed damsite have been mapped at a scale of 1:1,200 (Yerkes and others, 1973, sheet 2) and those in the Van Norman reservoirs area have been mapped at a scale of 1:4,800 (Yerkes and others, 1973, sheet 1). Bedrock faults that displace the basal contact of the surficial deposits are differentiated and shown by special symbols on those maps. Many faults were recognized on the basis of bedrock exposures only; and some of these probably would displace surficial deposits if such deposits were present at the particular localities. The distribution and density of faults shown on the maps are chiefly functions of exposure; virtually all the faults were first detected in artificial cuts, and areas of bedrock shown as unfaulted generally have no artificial cuts. Thus, faults shown as discontinuous in the reservoirs area because they have not been continuously exposed in artificial cuts should be considered as segments of continuous, throughgoing zones. On this basis the Granada Hills fault would be an integral element of the zone that merges eastward with the San Fernando zone of 1971 tectonic ruptures.

A similar but narrower zone of generally north-dipping faults extends eastward through the bedrock abutments of the upper dam, generally on trend with the 1971 ruptures on the east margin of the reservoir area near the proposed damsite. A large number of short fault segments having the same general trend are present at the site of the proposed dam. These fault segments are inferred to be parts of a relatively broad zone that extends northeastward through the reservoirs area from the main San Fernando zone. Lateral displacement on these faults cannot be determined from present evidence. Maximum measured vertical separation at the proposed damsite is about 0.33 ft (0.1 m) on faults that clearly displace the bedrock–surficial deposits contact; steplike discontinuities of the contact as much as several feet high are alined with bedrock faults in a number of places where evidence for fault displacement of the contact is ambiguous (Yerkes and others, 1973, sheet 2). The latest movement is as young as late Pleistocene for at least some of the faults in each of the damsites. On the basis of the distribution and age of faulting, each of the damsites is intersected by elements of fault zones that are active or capable of movement.

LOWER DAMSITE

The abutment areas of the lower dam have been extensively exposed by exploratory trenches cut after the 1971 earthquake: 2,550 ft (777 m) of trench north of the east abutment, several trenches totalling 1,850 ft (564 m) north of the west abutment, and 1,850 ft (564 m) of trench extending south of the west abutment. (See Yerkes and others, 1973, sheet 1, for locations.) The bedrock geology exposed in the trenches has been logged graphically at a scale of 1 in. equals 10 ft (1 cm=1.2 m) by the Los Angeles Department of Water and Power; we have reviewed copies of the logs in the field.

Trench 1 extends northward across the main elements of the zone of faults north of the east abutment. Bedrock there dips steeply north or is overturned to the south. A number of east-trending folds are exposed near the trend of the 1971 rupture zone. The limbs of some of the folds have been thrust over adjoining strata along gently dipping faults. The bedrock is also cut by numerous closely spaced steeply dipping faults that transect bedding at low angles; these faults are common in the Pico Formation north of both abutments and may be related to the position of the Pico as a sliver between two of the more continuous faults of the zone.

The most likely spatial correlative of the Freeway segment of the 1971 ruptures is an east-trending older fault that dips 68° N. near the south margin of the small valley that is alined with the rupture. Reverse separation of about 3 ft (1 m) is indicated by bedrock relations on either side of this older fault, which thus correlates with the 1971 fault in alinement, attitude, and apparent displacement. However, no surficial deposits cap these exposures, nor is there any evidence of 1971 movement on the fault. Where surficial deposits are preserved, as in the central part of this small valley, they apparently are not disturbed by the bedrock faults.

Bedrock north of the west abutment of the dam, as exposed in trenches 2, 3, 4, and 5 (numbered from east to west), dips steeply north; although the stratification is only locally tightly folded or overturned in this area, numerous closely spaced faults transect bedding in the upper part of the Pico Formation.

Trench 2, north of west abutment, exposed a narrow zone of east-trending faults that traverses the former island just south of survey station CROFTS (Yerkes and others, 1973, sheet 1). The northernmost of the faults dips 70–80° S. and the southern fault dips 73° N.; the two faults intersect or merge near the floor of the trench. Both faults are subparallel to adjoining bedrock strata, which are overturned in the area just north of the zone. The base of the surficial deposits apparently is stepped down to the south about 2 ft (0.6 m) over the south-dipping fault, whereas the bedrock surface over the north-dipping fault extends down about 5 ft (1.5 m) into the clayey gouge of the fault but apparently is not offset appreciably. The faults were not well exposed in the overlying surficial deposits, which are so very poorly sorted and poorly bedded that no strata could be traced with confidence across the fault trace. The ground surface and the modern lake deposits that formed on the reservoir floor apparently were undisturbed over the upward extension of the fault traces.

A 1971 surface rupture, generally alined with the faults in trench 2, extends across the top of the former island (Barrows and others, 1974, pl. III). The surface rupture had an apparent vertical separation of 0.8 in. (2 cm) down on the north in bedrock on the upper part of the east slope of the island, in opposition to the separation as exposed in the trench wall. The surface rupture occupied the steeply north-dipping bedding surface between relatively hard pebbly sandstone and soft mudstone. On the west slope of the island, the rupture appeared as a somewhat discontinuous, but linear, narrow fissure in the loose sand and gravel that covers the surface there.

Although the surface rupture may be attributable to local effects of shaking rather than to tectonic faulting, the fact that it coincides with a fault directly alined with the San Fernando zone east of the lower reservoir indicates that it should be considered a significant element of that zone. A fault exposed 400 ft (120 m) to the west in the wall and floor of trench 3 is alined with the island faults; in plan view the trench 3 fault is offset about 9 ft (2.7 m) by a north-trending cross-fault.

Trenches 3, 4, and 5 expose north-dipping sandstone and pebbly sandstone of the Sunshine Ranch Member, which is cut by numerous faults and shear zones, generally subparallel to stratification in bedrock. None of the faults exposed in these trenches disturb the contact at the base of surficial deposits.

Trench 6 extends southward along the east edge of the hills south of the west abutment; it exposes northwest-dipping strata of the Pico Formation and Sunshine Ranch Member of the Saugus Formation. A number of bedrock faults in the Sunshine Ranch exposed in this trench trend west to northwest, generally at a considerable angle to the trend of the Granada Hills–San Fernando zone.

Most of these faults dip southward, thus transecting bedrock, and show relative movement down on the south with dip separation of locally more than 25 ft (7.6 m) measurable at the bedrock–surficial deposits contact. Many of these faults extend well up into the stream terrace deposits that cap the hills; although some are truncated by beds within the surficial deposits, others extend up into or near the soil zone near the ground surface.

In summary, some of the faults in the area of the lower dam have moved since deposition of the middle Pleistocene(?) terrace gravels that cap the hills southwest of the dam. Unambiguous evidence that the modern reservoir sediments were displaced by 1971 faulting was not found, but such evidence could have been obliterated by drawdown of the reservoir. Even though such evidence is lacking, the west abutment area of the lower dam is cut by a number of bedrock faults that show late Pleistocene movement and that are elements of the active San Fernando zone.

UPPER DAMSITE

The bedrock abutments of the upper dam are also cut by faults. The bedrock consists of steeply dipping strata of the upper member of the Saugus Formation, the youngest bedrock unit in the area. The west abutment was exposed in 1968 by a trench about 250 ft (76 m) long that trended S. 30° E. from a point about 90 ft (27 m) west of the west end of the dam parapet; bedrock was exposed to a depth of about 40 ft (12 m) below the ground surface. A map and graphic log of the trench were furnished by the Los Angeles Department of Water and Power (DWP drawings D–3936–G–5, L 955–G–1). The bedrock consists of interbedded silty to pebbly sandstone, siltstone, and shale, dipping 70°–80° N.; the sandstone is firm and well consolidated but not cemented. The shale is very stiff and contains slickensides parallel to bedding surfaces. The trench exposed a fault zone that forms the boundary between two sequences of shale that have discordant attitudes; the zone trends N. 80° E. and dips 67° N. (Yerkes and others, 1973 sheet 1) and extends westward more than 1,000 ft (300 m) into the bedrock ridge west of the reservoir. There is no evidence for sense of slip or age of last movement on the fault.

An east-trending rupture associated with the 1971 earthquake, on the southwest slope of the west abutment (DWP drawing D–4222–G–5), is approximately alined with a north-dipping fault mapped during the present investigation. This alinement extends eastward toward a pressure ridge on the valley bottom at the toe of the dam embankment. The pressure ridge probably was formed by a slide in the dam embankment during the 1971 earthquake; the slide moved downstream and involved the south slope, crest, and upstream face of the embankment. The pressure ridge extends almost continuously across the toe of the embankment (Yerkes and others, 1973, sheet 1) and is as much as 1.7 ft (0.52 m) high (DWP drawing D–4222–G–5). The pressure ridge was exposed at three localities along its length by exploratory trenches. In each trench the ridge overlies small north-dipping thrust faults in the fill material; the trenches were not deep enough to determine whether the thrust faults are related only to the slope failure within the embankment or, possibly, to deformation of the underlying alluvium. Seed, Lee, Idriss, and Makdiṣi (1973, p. 141) found no evidence of slide movements in the foundation alluvium. The alinement of the pressure ridge coincides with a vertical fault in the bedrock of the east abutment.

The east abutment of the upper dam was exposed by a pipeline trench opened after the 1971 earthquake. The trench trends N. 13° W. along the crest of the ridge south of the east abutment and was cut deep enough to expose bedrock only discontinuously along the southernmost 185 ft (56 m) of the ridge. The trench was not examined by us; a graphic log of the west wall of the trench, at a scale of 1 in. equals 10 ft (1 cm=1.2 m) (DWP drawing N–762–G–1), forms the basis of this description. Bedrock exposed in the trench consists of steeply north-dipping silty to pebbly sandstone of the upper member of the Saugus Formation. Near the south end of the bedrock ridge, there is a zone 25 ft (7.6 m) wide of east-trending north-dipping reverse faults and gouge. About 65 ft (20 m) north of this fault zone, there is a south-facing step in the bedrock surface at least 13 ft (4 m) high. The upper 4 ft (1.2 m) of this step is erosional; the bottom part is not exposed but the step dips northward so that the upper part overhangs, and thus it could coincide with a north-dipping bedrock fault.

Exploratory drilling in the area southeast of the east abutment of the upper dam indicates that the south-facing step in the bedrock surface extends at least 400 ft (120 m) S. 65° E. from the trench; in that area it also coincides with a south-facing topographic scarp. Additional drilling another 150 ft

(45 m) southeast indicates that the bedrock step is not present there on the same trend, although its absence does not preclude a fault.

About 28 ft (8.5 m) north of the upper lip of the bedrock step in the trench, a vertical east-trending fault cuts the bedrock and apparently displaces the base of the surficial deposits about 1 ft (0.3 m) down on the north. North of this fault the bedrock surface slopes about 10° N.; thus, the vertical fault marks a pronounced change in slope of the bedrock surface, from 10° N. to 12° S. About 122 ft (37 m) north of the vertical fault an east-trending north-dipping reverse fault displaces surficial deposits with a vertical separation (up on the north) of more than 1 ft (0.3 m).

The several east-trending faults in the abutments of the upper dam, including their probable correlatives in the bedrock ridge west of the dam, constitute a zone about 300 ft (90 m) wide and at least 2,600 ft (790 m) long. The trend of these faults extends eastward across the northern part of the proposed reservoir toward the 1971 ruptures on the bedrock ridge to the east. It is reasonable to consider that all these faults and ruptures are segments of a zone, the total length of which is at least 6,000 ft (1,830 m) from the ridge west of the upper dam to the ridge east of the proposed reservoir. Such a zone may be part of a yet broader and longer zone, other elements of which, subparallel in general attitude, are exposed in the bedrock of the proposed damsite. This distribution of subparallel bedrock faults is considered to be part of a broad throughgoing zone that extends northwestward, perhaps from the San Fernando zone east of the lower reservoir, through the site of the proposed dam and the abutments of the upper dam, through the ridge west of the upper dam, and on toward the Santa Susana fault. This zone contains 1971 ruptures as well as older faults that displace surficial deposits and is thus considered active.

Displacement may have occurred in 1971 on an inferred, buried fault approximately coincident with an extensive zone of ground failure that trends northeastward across the valley floor north of the upper reservoir. The trend of this zone of damage overlies the inferred axis of the Mission Hills syncline; it also coincides with a prominent 1971 rupture near the Santa Susana fault about 1.25 mi (2 km) west of the upper dam and with the older faults that extend northeastward across the lowland area northeast of the San Fernando Valley Juvenile Hall (fig. 3). Postearthquake resurveys of horizontal control stations on bedrock well north and south of the zone of ground failure indicate that there was about 0.4 ft (12 cm) of right-lateral displacement across the zone during the earthquake. (See Youd, 1974, for details.) In addition, the lower part of Grapevine Canyon bends in a right-lateral sense near the north margin of the zone of failure just west of San Fernando Valley Juvenile Hall. The bend of the stream course suggests that similar movements may have occurred in the geologic past; consequently, such ground failures as occurred along this zone in 1971 should be expected to accompany future large earthquakes.

PROPOSED DAMSITE

Bedrock at the site of the proposed dam consists of steeply north-dipping sandstone, pebbly sandstone, and siltstone of the Sunshine Ranch Member of the Saugus Formation. These rocks have been exposed throughout most of the embankment area by excavation and removal of the subhorizontal surficial deposits, which are as thick as 70 ft (21 m). The basal contact of the surficial deposits is a sharp angular unconformity, representing the time interval during which the bedrock was consolidated, steeply tilted and faulted, and eroded. The age control for dating these events, and for dating the faults that displace or are truncated by the unconformity, varies considerably, depending on the ages of the materials above and below the unconformity. The upper limit or minimum age is determined by the age of the surficial deposits, which were examined and mapped in detail in order to determine their absolute and relative ages.

SURFICIAL DEPOSITS

The surficial deposits exposed on the north wall of the perimeter cut of the embankment area were differentiated and mapped on Polaroid photographs at various scales (between approximately 1 in.=25 ft or 1 cm=3 m and 1 in.=70 ft or 1 cm=8.4 m). The lithologies of the mapped units were described in the field with emphasis on the contact relations between lithologic subdivisions and buried soil profiles. A vertical section of the surficial sediments (fig. 11) was constructed from coordinates and altitudes of surveyed markers (U–222, U–214, and so on) placed on the contact between the bedrock and surficial deposits and

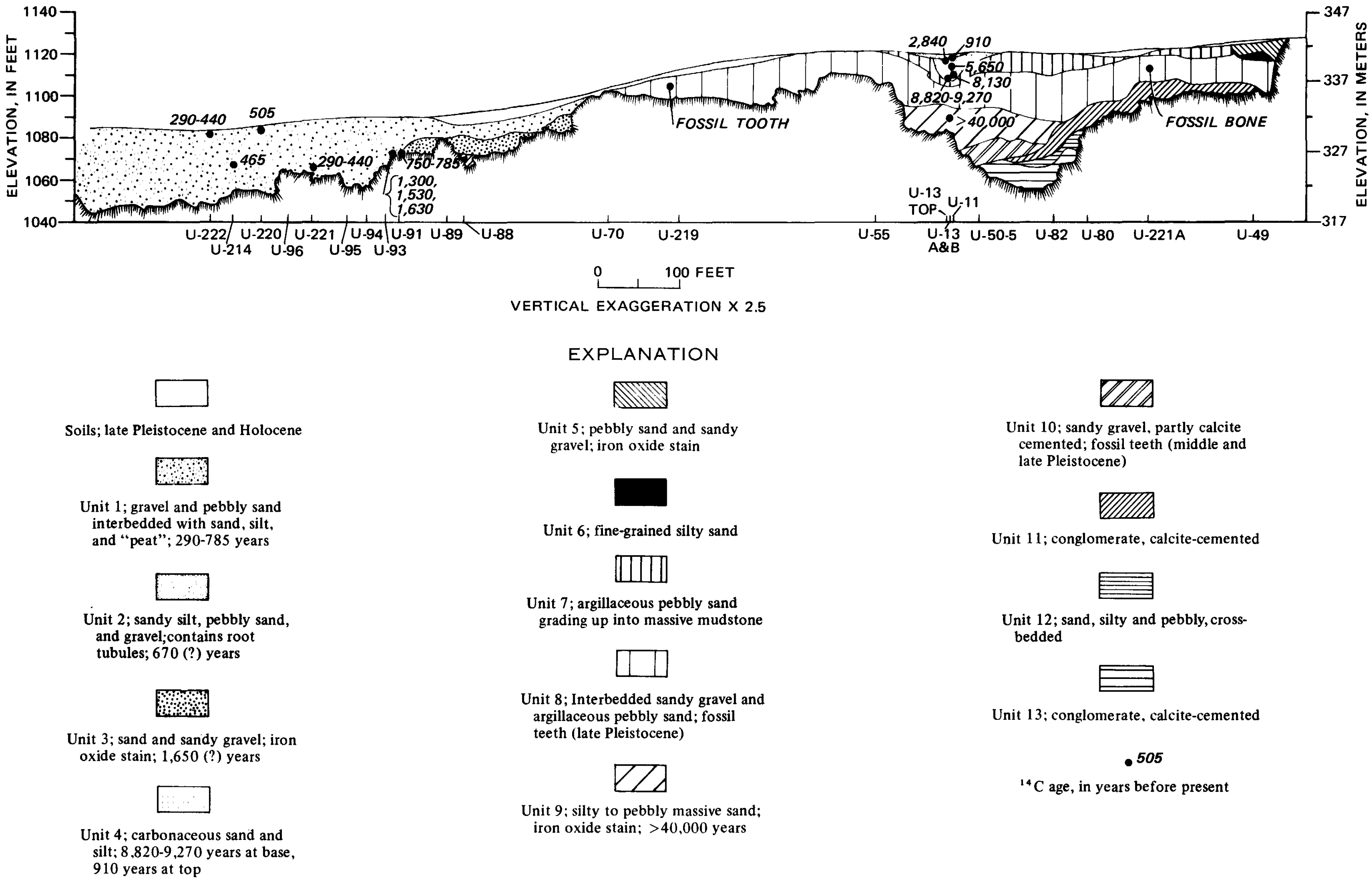


FIGURE 11.—Generalized vertical section, north wall of proposed damsite, showing inferred ages of units. Modified from Yerkes, Bonilla, Sims, Wallace, and Frizzell (1973, sheet 2).

within the surficial deposits. The mapped association of the markers and surficial deposits was then projected onto the vertical section.

The surficial deposits consist of a complex gradationally interfingering association of noncemented gravel, sand and silt, and subordinate amounts of calcite-cemented gravel and peaty sand and silt. They rest unconformably on an irregular surface that was eroded on the steeply dipping bedrock. The thickness of the surficial deposits ranges from 3 to 70 ft (1–21 m).

The deposits have been grouped into 13 units on the basis of lithology, buried soils, erosional-depositional features at contacts, and radiocarbon (^{14}C) age determinations of wood and carbonaceous sediments. The units are discussed in chronologic order from youngest to oldest. The ^{14}C age dates are corrected for temporal variations of ^{14}C flux (table 2).

TABLE 2.—*Radiocarbon dates from surficial deposits, proposed damsite*

Location No.	Material	Conventional radiocarbon date (radiocarbon years B.P.)	Corrected radiocarbon date (in calendar years B.P.)[1]
U–222	Carbonaceous sediments.	[2,3]285±85	[4]290–440
U–221	do	[3]285±85	[4]290–440
U–214	do	[3]355±90	[4]465
U–220	do	[3]430±85	[4]505
U–16A	do	[3]660±95	[4]670
U–91–EQ–5VN	Peat #3	[3]1615±85	[4]1630
U–91	Carbonaceous sediments.	[3]830±90	[4]750–785
U–91–43VN	Peat #1	[3]1,350±90	[4]1,300
U–91–39VN	Peat #2 wood	[3]1,595±95	[4]1,530
U–210	Carbonized wood.	[3]1,700±90	[4]1,650
U–13–37VN	Carbonaceous sediments.	[3]945±90	[4]910
U–13 Top	do.[5]	[3]2,715±90	[4]2,840
U–13–40VN	do.[5]	[3]4,890±255	[4]5,650
U–13A	do	[6]9,580±300	[7]8,820
U–13–41VN	do	[3]8,665±120	[7]8,130
U–13B	do	[6]10,000±300	[7]9,270
U–11	do	[6]>40,000	--------

[1]Corrected for variation in ^{14}C flux with time.
[2]±figures are a measure of the precision of the counting statistics for the specific sample.
[3]Age determination by James Buckley, Teledyne, Isotopes.
[4]Corrected to bristlecone pine chronology of Seuss (1970). Range in age is due to secular ^{14}C fluctuations in the atmosphere with time. Such fluctuations yield nonunique solutions to bristlecone pine corrections of conventional ^{14}C age determinations.
[5]Total organic carbon used because humic material and plant debris were inseparable.
[6]Age determination by Meyer Rubin, U.S. Geological Survey.
[7]Corrected to varve chronology of Lake-of-the-Clouds (Stuiver, 1970).

Unit 1. Gravel with subordinate amounts of interbedded sand and peaty sand and silt in three beds, and silt and sand interbedded with gravel and pebbly silt in the upper one-third to one-half. Massive sandy gravel rests on the bedrock surface. The peaty sand and silt units occupy abandoned stream channels cut into underlying gravel units. Five ^{14}C age dates were determined on wood and peaty sand and silt from this unit (U–222, U–221, U–214, U–220, U–91) ranging from 1,630 to 290–440 years B.P. (before present) (table 2). ^{14}C ages for U–214, U–221, and U–220 represent the time of growth of the wood that constitutes the samples and indicate the maximum ages of the adjacent sediments. The deposits between U–91 and U–93 represent swampy conditions following a period of channel cutting and filling that ended about 1,630 years B.P. A similar deposit of carbonaceous silt and sand between U–94 and U–96 has a channellike cross section and is between 290 and 440 years old. Sample U–91 probably represents a contaminated sample.

Unit 2. Silt and pebbly sand containing root tubules. Unit is correlated on the basis of lithology and stratigraphic position with the carbonaceous sandy silt of U–16A (southeast wall). ^{14}C age determination on rootlets at U–16A yielded a date of 670 years B.P. This unit is channellike in cross section and is underlain by carbonaceous silty sand.

Unit 3. Crossbedded and wavy-laminated iron oxide-stained medium sand and locally crossbedded iron oxide-stained sandy gravel; gravel overlain by a thin (<20 in. or 50 cm) irregular ashy white friable sand overlain in turn by a thin (<8 in. or 20 cm) carbonaceous sand. These sediments in part overlie calcite-cemented coarse sandy gravel of unit 11 between localities U–88 and U–89. This unconsolidated sand and gravel is correlated with the deposits in the vicinity of U–210 (southwest wall) on the basis of lithology. ^{14}C age determination on carbonized wood at U–210 yielded a radiocarbon date of 1,650 years B.P. (The peat in the vicinity of U–91 from unit 1 can be traced into the soil zone mapped on top of unit 3 and thus yields a minimum age for the soil and underlying deposits of 1300–1630 years B.P. (samples U–91–43VN, U–91–39VN, and U–91–EQ–5VN).

Unit 4. Very carbonaceous sand and silt with a peaty bed at the base. This unit is channellike in cross section, as is the overlying unit 2. Bedding is indistinct, and the upper three-fourths is massive and contains rootlets in apparent growth position. This unit represents a swampy or nearly perennially wet condition that promoted abundant plant growth in an abandoned channel of the depositing stream system. Two samples (U–13A, U–13B) from near the base of this unit gave ^{14}C ages of 8,820 and 9,270 years B.P. One sample (U–13–37VN) gave a ^{14}C age of 910 years B.P. These dates indicate that the wet plant-promoting environment persisted for at least 8,000 years. Other samples at intermediate stratigraphic positions are of intermediate ages (table 2, samples U–13–40VN, U–13–41VN, U–13 Top).

Unit 5. Iron oxide-stained pebbly sand and sandy gravel; gravel concentrated near the base of the unit. This unit truncates units 6 – 8 and is thus younger than those units. No material datable by the ^{14}C method was found in unit 5, and so its absolute age relative to unit 4 is not known.

Unit 6. Buff-colored fine to very fine silty sand. Upper and lower contacts are erosional, and the unit partly fills channels cut into units 7 and 8 and is overlain unconformably by unit 5. Thus, unit 6 is older than unit 5 and younger than units 7 and 8. No material suitable for ^{14}C age dating was found.

Unit 7. Argillaceous pebbly sand with iron oxide stain grading up into massive sandy pebbly well-consolidated mudstone. Calcareous root tubules locally common. The bottom contact of the unit is indistinctly channellike between U–55 and U–50–5. Eastward of U–50–5 an indistinct soil zone forms the base of the unit, beyond which it is truncated by unit 6. No material for ^{14}C age determination was found; the unit underlies unit 4, and so it is more than 9,270 years old.

Unit 8. Complexly interfingering and intergrading lithologies, dominantly sandy iron oxide-stained gravel and massive argillaceous pebbly sand, locally iron oxide stained and crossbedded. The unit contains subordinate amounts of massive silty sand that is locally iron oxide stained or pebbly. Bone fragments were found at U–218, U–219, and U–221A. The bone material from U–221A was insufficient for ^{14}C age determination. A complete fossil first(?) molar of *Paramylodon* sp. was found with other bone fragments at U–218. The tooth, identified by C. A. Repenning, U.S. Geological Survey, is of Rancholabrean (late Pleistocene) age.

Unit 9. Massive sand, locally silty or pebbly and locally iron oxide-stained, crossbedding, and wavy lenticular lamination common. A lenticular unit of carbonaceous silty sand contained a carbonized tree stump in apparent growth position, from which a ^{14}C age determination of >40,000 years B.P. was obtained. Parts of the calcite-cemented coarse gravels at the contact between units 9 and 11 were eroded at the eastern end prior to deposition of unit 9. The contact with the underlying unit 10 is poorly exposed, undulatory, and may also be an erosional unconformity.

Unit 10. Sandy coarse gravel, locally indistinctly crossbedded in the lower two-thirds and slightly cemented by calcite in the upper one-third. This unit probably represents a point bar deposit. No material for ^{14}C age determination was found. This unit is correlated with nonindurated deposits in the vicinity of U–14 (center of south wall) where a large fragment of a fossil tooth was found. The tooth was identified by C. A. Repenning of the U.S. Geological Survey as questionably from *Equus (Hemionus)* sp. or *Equus (Amerhippus)* sp. of early to late and middle to late Pleistocene age, respectively. This tooth fragment may have been reworked from older materials because the fractured surfaces are abraded and slightly rounded.

Unit 11. Calcite-cemented conglomerate; coarse grained with a sand matrix. This unit rests on the eroded surface of the bedrock east of U–80 and is in erosional contact with unit 12 west of U–80. Unit 11 is truncated by units 8–10. A small eroded remnant of cemented gravel, which fills a depression eroded in bedrock at U–88, is correlated with unit 11 on the basis of lithology. This remnant is overlain by unit 3 at U–88. Thus, at station U–88 unit 11 is more than 1,650 years old and between stations U–50–5 and U–80 is more than 40,000 years. This latter age is probably also the age of the conglomerate at U–88, on the basis of its lithologic similarity and stratigraphic position.

Unit 12. Silty to pebbly poorly crossbedded sand; gravel concentrated near contact with unit 11. Upper contact of the eastern one-third of this unit is erosional and partly stained by iron oxide. The age of this unit, based on stratigraphic criteria and the ^{14}C date at U–11, is greater than 40,000 years.

Unit 13. Calcite-cemented conglomerate; coarse grained with sand matrix. This unit rests on the eroded surface of the bedrock between U–82 and U–50–5. The upper contact is undulatory and may be truncated by units 10 and 12. This gravel is not contiguous with unit 11, although the lithologies are similar, unit 11 having slightly more sand matrix. Because of the similarity of lithologies the eroded remnant at U–88 may be correlative with unit 13, but correlation with unit 11 is preferred.

Soils. Soils developed on the surficial deposits are divisible into A, B, and C zones, of variable but nearly equal thickness. The A zone is dark olive gray, sandy, and carbonaceous. The B zone is dark yellow brown, commonly calcareous, breaks into peds, and is hard owing to relative enrichment of clay derived from the A zone. The C zone is yellow gray, with a variable development of caliche.

The surficial deposits represent a continental fluvial environment. The sediment was deposited intermittently by streams of dominantly high-flow regime, as shown by the coarse gravels, and swampy or low-flow regimes at other times, as shown by the peaty units.

The surficial deposits are separable for purposes of discussion into two areas on either side of U–70, where the uppermost soil horizon is in contact with weathered bedrock. The depositional history east of U–70 was about as follows: Unit 13 was deposited in the bedrock depression between U–50–5 and U–80 and was at least partly cemented and partly eroded before units 12 to 10 were deposited. The contacts of units 10, 11, and 12 with unit 13 are irregular; each records a period of erosion prior to deposition of the next younger unit. The gravel of unit 11, however, was at least partly cemented and partly eroded prior to deposition of units 10 to 8. After unit 8 was deposited, the deposition of units 7, 4, and 2 records the almost uninterrupted fillings of an ancient stream channel. A smaller channel was eroded at the easternmost end of the embankment, where units 5 and 6 were deposited. Unit 4 evidently required about 8,000 years to accumulate. Unit 2 is correlated with deposits at U–16A (on the southeast wall) and is thus inferred to be about 670 years old, an age substantiated by the upper age limit of unit 4. There may be a hiatus of about 240 years between units 4 and 2.

The early history west of U–70 has been largely destroyed by erosion down into bedrock (fig. 11). After unit 3 was deposited and a soil formed on it, the modern stream deposits of unit 1 buried the soil and filled the channel to the present level (fig. 11). The modern deposits (less than 800 years old) filled a channel cut to an elevation of 1,042 ft (317 m), whereas the earlier erosion before deposition of unit 13 cut to 1,055 ft (321 m). The significance of the differing depths of erosion cannot be assessed on the basis of lithologic and sedimentologic properties of the sediments.

The unconformity at the base of the surficial deposits may be as old as 2–3 million years, the approximate age of the beginning of the Pleistocene epoch in southern California. The oldest surficial deposits that overlie the unconformity (unit 13 between U–80 and U–50–5, northeastern part of the embankment area) are probably about 60,000–100,000 years old. The unconformity throughout the site area probably once was overlain by surficial deposits of this general age, but these deposits in part have been eroded and replaced by units that become successively younger westward toward the axis of the modern stream. In the north-central part of the site, where the unconformity is overlain by unit 8, the upper age limit of the time interval represented by the unconformity is about 10,000 years. In the western part of the site, where the unconformity is overlain by unit 1, the upper limit, excepting the deposits between U–91 and U–95, is about 500 years. More significantly, the oldest surficial deposits in the southeastern part of the site, which locally are cut by faults (at U–1, U–6, U–7, U–72–C, U–72–M, Yerkes and others, 1973, sheet 2), are correlated with unit 8, estimated to be 10,000 to about 40,000 years old. The faulting is therefore younger than about 40,000 years.

BEDROCK FAULTS

Bedrock faults are widely distributed throughout the area of the proposed damsite; some displace the unconformity between the surficial deposits and bedrock and are inferred to have moved within the last 40,000 years. Throughout the general area of the proposed damsite, the unconformity is an erosional surface of locally steep relief with steps as high as 24 ft (7.3 m) and locally overhanging. Some steps were formed by erosion along old bedrock faults, others by faulting that displaced the erosional surface, and still others by a combination of these. Since this erosional surface is the basal contact of the surficial deposits, bedrock faults that displace it must be younger than the deposits that are displaced. For this reason the unconformable contact was carefully cleaned, examined for evidence of fault displacement, and mapped at a scale of 1 in. equals 100 ft (1 cm = 12 m) around most of the 6,200-ft (1890-m) perimeter of the embankment area (Yerkes and others, 1973, sheet 2); the contact also was examined for evidence of faults in about 2,225 ft (678 m) of exploratory trenches east of the embankment area.

All bedrock faults that are alined with steps in the bedrock surface around the perimeter of the embankment excavation (except in the southwest part) were identified by station number and differentiated on the basis of whether or not they displace surficial deposits; the amount of vertical separation in feet, based on displacement of the contact across the fault, is opposite the station number (Yerkes and others, 1973, sheet 2). The relative age of last movement on many of the faults cannot be established, especially on the floor of the embankment, where surficial deposits have been stripped off, and around the periphery of the embankment site, where the surficial deposits are so poorly sorted, poorly bedded, and poorly consolidated that evidence of faulting can be detected only where the fault has been mineralized. Wherever the relative age of last movement cannot be established, it is assumed that movement could have been relatively recent.

Bedrock faults are expressed as bands of sheared and slickensided, finely brecciated, or even minutely comminuted (gouged) siltstone and shale a few millimeters to a few centimeters thick. About half are north-dipping "bedding plane" faults subparallel to stratification of the bedrock; the rest dip south and cut across the bedrock strata. Bedding-plane faults displace the base of the surficial deposits a few tenths of a foot at many places. Cumulative displacement on them equals or exceeds that on the south-dipping faults.

The fine-grained material along the fault surfaces commonly is striated or slickensided in the dip direction, and so the sense of movement during the last event was parallel to the dip of the faults. The most prominent, and almost the sole, exception is the northeast-trending fault at the south end of trench 2 east of the embankment area, where slickensides on the fault plunge 48° NE. Geometric reconstruction of bedrock relations there shows that displacement in bedrock was at least 40 ft (12.2 m) on this fault, although there is no vertical separation at the base of the surficial deposits. The only prominent correlation between attitude and apparent separation on the faults is that south-dipping faults are predominantly "normal"—the south side is downfaulted relative to the north side. The south-dipping faults are commonly truncated by north-dipping faults. Of the many north-dipping faults mapped, about half are "reverse" (north side relatively upthrown) and half are "normal" (north side relatively downthrown). Furthermore, the total amounts of vertical separation recorded for the two types of north-dipping faults are practically equal. However, if the displacement of the north-dipping reverse faults is added to that of the south-dipping faults (on which the displacement is almost all relatively up on the north side), the overall effect is one of relative upthrow on the north.

Bedrock faults in the perimeter of the embankment area could not be traced upward through the surficial deposits to the ground surface, although in several places they could be traced upward for a few feet. In some of these places, the fault was clearly truncated by an undisturbed bed in the surficial deposits, but in most places a clear truncation could not be discerned. There is no evidence of 1971 movement on the bedrock faults within the embankment perimeter.

There are several 1971 surface ruptures on the ridge east of the damsite; the longest, just northeast of the proposed site, was explored by trenches cut through the base of the surficial deposits into bedrock. This rupture coincides with a buried step in the bedrock surface that is alined with a bedrock fault, but the 1971 surface rupture can be attributed to a slope failure that caused a pressure ridge in the freeway to the northeast. Other ruptures, such as the pair 700 ft (213 m) northwest on the same ridge, were downthrown on the upslope side and therefore probably are not due to slope failure; the rupture at the south end of the same ridge showed compressive effects, also probably not due to slope failure. All these ruptures are considered to be evidence of buried bedrock faults that are elements of the zone of active faults that traverses the reservoir area.

Although the immediate site of the proposed dam is not known to have been affected by tectonic ruptures during the 1971 earthquake, it was subjected to differential uplift and horizontal displacement, and the embankment area is traversed by numerous closely spaced east-trending faults. A number of these displace surficial deposits and, with similar faults to the northwest and southeast, may form a zone that extends entirely across the reservoirs area, probably to merge with the known-active San Fernando zone to the southeast. Therefore, the proposed damsite is considered to be within a zone of faults capable of movement.

EXPECTABLE EARTHQUAKES AND THEIR EFFECTS

We assume that failure of a dam in the Van Norman reservoirs area is intolerable because such a failure could cause inundation of the central San Fernando Valley downstream, an area inhabited (in 1970) by about 80,000 people (Seed, 1972, p. 18). To prevent failure, dams built in the Van Norman area must be designed to survive without serious damage the most severe effects of expectable large earthquakes.

Available evidence does not permit precise statements of the frequency, magnitude, or effects of the largest earthquakes to be expected in the Van Norman area. Hence, we derive estimates, based chiefly on the structural-seismologic setting of the area, the relation between the effects of the 1971 San Fernando earthquake and that setting, and extrapolation of the 1971 effects.

Lower Van Norman damsite is in a zone of north-dipping faults alined with, and correlative in general attitude and history with, the active San Fernando fault zone. These faults combine to form an important element of the throughgoing Santa Susana–San Fernando–Sierra Madre zone of frontal faults, along which the Santa Susana and San Gabriel Mountains have been uplifted. The upper Van Norman and proposed damsites are traversed by numerous east-trending steeply dipping faults, some of which displace surficial deposits, and all of which probably are elements of a broad zone related to the active San Fernando zone.

The 1971 ground-surface deformations are integral parts of an established regional pattern of deformation that includes reverse faulting along the San Fernando zone and arching that extends westward from the foothills east of San Fernando, across the valley, and into the reservoir area north of the rupture zone. These deformations were similar to, if not identical with, those that formed the geologic features that underlie these areas: (1) The 1971 arching uplifted the steeply dipping bedrock that forms the foothills east of the valley and the topographic highs north of the rupture zone in the valley and reservoirs area; (2) the Sylmar and Mission Wells segments of the 1971 rupture zone formed along the base of old south-facing topographic scarps; (3) those two segments also coincide with a continuous fault-formed ground-water impediment in the young valley alluvium; (4) evidence of geologically young, pre-1971 reverse faulting has been found by trenching and drilling at several localities along the Tujunga segment of the San Fernando zone (Barrows and others, 1971; Bonilla, 1974); and (5) the pre-1971 buried fault-like scarp in Lopez Canyon east of San Fernando is alined with the 1971 ruptures there and reflects the same relative movement as formed the 1971 ruptures.

The 1971 earthquake and fault movements apparently were smaller than those that apparently occurred on the same zone about 200 years ago. The 1971 San Fernando earthquake was significantly smaller than the 1952 Kern County earthquake, which is attributed to the same tectonic stress system; thus, the 1971 events were not the largest that can be produced by this system. This stress system has produced at least six strong earthquakes in the last approximately 200 years, at least one and probably two of which involved tectonic rupturing at the surface along the San Fernando zone; therefore, the reservoirs area is expected to experience significant earthquake effects in the foreseeable future. These considerations indicate that earthquake effects from two different earthquake sources should be expected in the Van Norman reservoirs area: an M 8+ earthquake on the San Andreas fault 25 mi (40 km) northeast of the reservoirs and a local earthquake of M 7.7 on the Santa Susana–San Fernando –Sierra Madre fault system. (See part B of this report for details.)

TRANSITORY EFFECTS

The transitory ground motions expected in the Van Norman reservoirs area from these earthquakes are as follows (see part B of this report for derivation):

	San Andreas *M 8+*	*Local* *M 7.7*[1]
Peak horizontal acceleration (g)	≥0.5	1.15
Peak velocity of displacements, ft/sec (cm/sec)	2 (60)	4.4 (135)
Peak dynamic displacement, ft (cm)	1.3 (40)	2.3 (70)
Duration of acceleration ≥0.05g (sec)	80	40

[1]The values are for a single horizontal component of motion within 2–3 mi (3–5 km) of the causative fault; they are for sites at which ground motion is not strongly altered by extreme contrasts in the elastic properties within the local geologic section or by the presence of structures; they contain no factor relating to the nature or importance of the structure being designed.

PERMANENT EFFECTS

Estimated fault or fault-related displacements believed to be credible effects of an M 7.7 local

TABLE 3.—*Summary of credible fault and fault-related displacements, M 7.7 local earthquake*

	Feet	*Meters*
Lower Van Norman damsite:		
1. Total displacement, reverse-oblique slip on main fault (upper-bound curve of fig. 12)	16.4	5.0
Vertical component (upper-bound curve)	12.6	3.84
Vertical component (1971 ratio on Sylmar segment)	9.5	2.9
Vertical component (1971 ratio on Freeway segment)	13.3	4.05
2. Resolved components, east abutment relative to west:		
Horizontal convergence parallel to axis (range)	3.2–7.7	0.98–2.35
Differential change in elevation (range)	9.5–13.3	2.9–4.05
Total component in vertical plane along axis (range)	12.2–13.7	3.72–4.18
Horizontal component normal to axis (range)	9.0–11.0	2.74–3.35
Total differential movement	16.4	5.0
Upper Van Norman and proposed damsites:		
1. Vertical displacement, dip slip on subsidiary fault (range)	3–9	1–2.74
2. Resolved components, east abutment relative to west:		
Horizontal separation parallel to axis	1.7	0.52
Differential change in elevation (range)	[1]3–9	[1]1.0 to 2.7
Horizontal component normal to axis	3.3	1.0
Total differential movement (range)	[2]3.3–9.6	[2]1.0–2.93

[1]These values could be increased as much as 75 percent by the effects of regional tilting.

[2]These values could be increased as much as 69 percent by the effects of regional tilting.

mated displacements are derived from the known effects of the 1971 San Fernando earthquake, scaled up on the basis of magnitude-displacement correlations from the worldwide record of historic displacements on similar faults. Although the estimated displacements are described separately for two areas (lower Van Norman damsite, upper Van Norman and proposed damsites), we emphasize that these and other deformations should be expected to occur simultaneously at all the sites. The estimated displacements are derived in the following two sections.

LOWER DAMSITE

Tectonic rupturing of the ground surface along faults in the area of lower Van Norman dam could accompany any strong local earthquake. The particular faults on which displacement could occur cannot be identified; therefore, we assume that displacement could occur any place near, beneath, or between the abutments of the present dam. As a means of quantifying the expected displacements, those associated with the 1971 earthquake on the Sylmar segment of the San Fernando zone (U.S. Geological Survey, 1971, p. 62) are scaled up on the basis of the worldwide record of historic displacements on reverse-slip or reverse-oblique slip faults associated with earthquakes of M 6½–8.4.

The maximum displacement on the Sylmar segment of the San Fernando zone during the 1971 earthquake was 7.9 ft (2.4 m), which, for an M 6½ event, is large compared with the least-squares curve of the magnitude-displacement plot for 50 cases, including all types of faults, from the worldwide record of historic events (Bonilla and Buchanan, 1970, table 1, fig. 2). Alternatively, the maximum displacement (3.9 ft or 1.2 m) associated with the 1952 Kern County, Calif., earthquake on the White Wolf fault is anomalously low for an event of its magnitude (7.7). The least-squares curve for the 50 cases passes midway between the points for the 1971 and 1952 events and indicates a displacement of 11.5 ft (3.51 m) for an M 7.7 earthquake.

Of the 50 cases used by Bonilla and Buchanan (1970) for the magnitude-displacement plot, however, only 12 pertain to shallow-focus events associated with reverse-slip and reverse-oblique slip faults such as the Santa Susana–San Fernando and White Wolf; the rest pertain to normal-slip and strike-slip faults. When considered separately the magnitude-displacement plots for these 12 (plus the 1971 San Fernando data) form a widely scattered pattern to which no significant curve can be fitted; however, an upper limit for displacement apparently is defined by four of these events:

	M	*Total displacement*	*Vertical component*
1964, Patton Bay, Alaska	8.4	26 ft (7.9 m)	23 ft (7 m)
1929, West Nelson, New Zealand	7.8	17 ft (5.2 m)	14.75 ft (4.5 m)
1968, Meckering, Australia	6.9	10 ft (3.05 m)	6.1 ft (1.86 m)
1971, San Fernando, California	6.5	7.9 ft (2.4 m)	4.6 ft (1.39 m)

The curves (fig. 12) indicate a possible maximum total displacement of 16.4 ft (5 m) and a possible maximum vertical component of about 12.6 ft (3.84 m) for an M 7.7 event on a reverse-slip or reverse-oblique slip fault. The physical basis of the apparent correlation between magnitude and displacement, and especially the apparent systematic variation in the ratio of vertical component to total displacement (fig. 12), is not understood. In the absence of that knowledge, and being unable to justify lower limits, we (1) must assume that the indicated maximum displacements could occur and (2) cannot guarantee on the basis of so small a sample that those maximums could not be exceeded.

The data for the upper-bound events on reverse-slip faults indicate that the ratio of maximum vertical component to total displacement varies directly with magnitude of the associated earthquake (fig. 12). However, the ratio on the Sylmar segment in 1971 (58 percent) was at the low end of the range shown by figure 12, whereas the ratio on the Freeway segment (81 percent) was

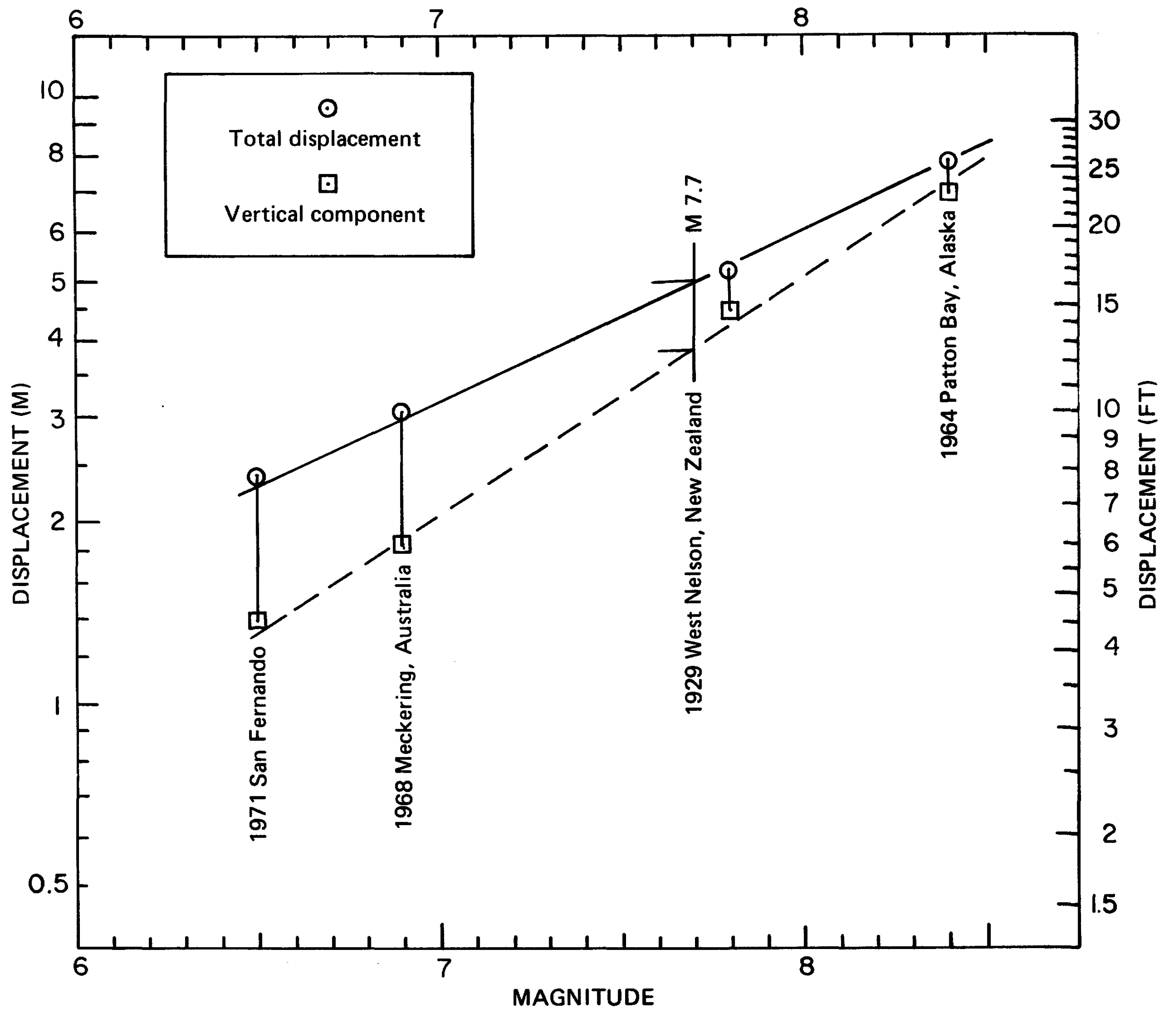


FIGURE 12.—Plot of total displacement and vertical component of displacement relative to magnitude of upper-bound events on reverse-slip and reverse-oblique-slip faults. Based on worldwide data of Bonilla and Buchanan (1970) and supplementary data.

nearly the same as that indicated by the curve for an M 7.7 earthquake (77 percent). Alternative estimates of the expectable vertical component for an M 7.7 event are derived as follows by applying ratios from the 1971 San Fernando displacements to the upper-bound total displacement of 16.4 ft:

	Displacement	
	Total	*Vertical*
1971 San Fernando (M6½):		
Sylmar segment		
(vertical=58 percent of total)	7.9 ft	4.6 ft
Freeway segment	(2.4 m)	(1.39 m)
(vertical=81 percent of total)	1.36 ft	1.1 ft
Estimates for M 7.7:	(0.42 m)	(0.34 m)
Vertical=58 percent of total	16.4 ft	9.5 ft
	(5.0 m)	(2.9 m)
Vertical=81 percent of total	16.4 ft	13.3 ft
	(5.0 m)	(4.05 m)

To determine the effects of the estimated displacements on a dam at the lower Van Norman site, the displacements are resolved into components of the east abutment area relative to the west (in effect holding the west abutment fixed). The dam axis trends N. 70°W. and the activated fault is assumed to trend N 70°E. and dip 70°N., essentially as in the 1971 case. First, the displacements are resolved on the basis of the 1971 Sylmar ratio (maximum vertical=0.58 of total); then the displacements based on the 1971 Freeway segment ratio (maximum vertical=0.81 of total) are resolved. The smaller ratio yields greater lateral separation of the abutments, whereas the larger ratio yields greater vertical separations, as follows:

	Feet	Meters
Components based on maximum vertical=0.58 of total:		
Horizontal convergence parallel to axis	7.7	2.35
Differential change in elevation	−9.5	−2.89
Total component in vertical plane along axis	12.2	3.72
Horizontal component normal to axis	11.0	3.35
Total differential movement (12.9 ft N. 56°E. and 9.5 ft down at about 36° to horizontal)	16.4	5.0
Components based on maximum vertical=0.81 of total:		
Horizontal convergence parallel to axis	3.2	0.98
Differential change in elevation	−13.3	−4.05
Total component in vertical plane along axis	13.7	4.18
Horizontal component normal to axis	9.0	2.74
Total differential movement (9.6 ft N. 40°E. and 13.3 ft down at about 54° to horizontal)	16.4	5.0

Thus, any dam at the lower Van Norman site should be able to withstand the strong earthquake motions cited, plus a differential movement of the abutments of an estimated 16.4 ft (5 m), about 0.8 percent of the 1971 axis length of 2,100 feet. Whether this movement would occur as a result of displacement on one fault, or on several faults, cannot be determined; either possibility should be assumed likely.

UPPER AND PROPOSED DAMSITES

In considering the effects of a local M 7.7 earthquake on the upper Van Norman and proposed damsites, we assume the most critical case—that the sites are less than 1 mi (1.6 km) north of the main zone of surface ruptures on the upper plate of the thrust fault and that they are traversed by active subsidiary faults related to the main zone. One or more of the faults in the sites should be expected to move during a strong local earthquake. The minimum expectable vertical component of displacement is the 3 ft (1 m) that occurred in 1971 on the subsidiary fault in Lopez Canyon. (See following discussion.)

One method for estimating the maximum credible displacements for a subsidiary fault is to compare displacements on such a fault with those on the main fault for the same event; however, this is difficult because of the scarcity of data. Bonilla (1970, fig. 3.7) summarized the known record for North America; at that time only one example of historic subsidiary faulting associated with a reverse fault event was available—the 1952 Kern County event, for which the maximum ratio was 0.25. Nevertheless, displacements occurred on a subsidiary fault in Lopez Canyon, 1 mi (1.6 km) east of the Sylmar segment of the main rupture zone, during the 1971 San Fernando earthquake. The displacements occurred in natural ground underlain by steeply north-dipping bedrock similar to that at the proposed damsite. The total displacement was 4.35 ft (1.32 m); the vertical component was 3.1 ft or 0.95 m (U.S. Geol. Survey, 1971, p. 68–69). The ratios of these displacements to those on the Sylmar segment of the main zone are 0.55 for total displacement and 0.68 for the vertical component.

Thus, taking the vertical displacement to be expected on the main zone from an M 7.7 earthquake (13.3 ft or 4.05 m), we would expect that a vertical displacement of $13.3 \times 0.68 = 9.04$ ft (2.76 m) could occur on a subsidiary fault associated with that event. Because the last movements (as indicated by striations and grooves) on the east-trending faults in the proposed site were essentially parallel to the dip of the faults, we expect the next movements to be dip slip in nature; in this case all displacement would be expressed as dip slip. As in the case of the lower Van Norman damsite, the fault or faults that would move cannot be determined, nor can the distribution of the displacement among one or more faults be determined.

The axis of the proposed dam trends N. 64° E. (Los Angeles Dept. Water and Power drawing D4244–G–1, Oct. 1973), and the faults in the area trend about N. 85° W.; therefore, the effects of such a displacement can be resolved into component displacements of the east abutment area relative to the west abutment. If vertical displacement of about 9 ft (2.7 m) were to occur on a normal fault dipping 70° N., horizontal separation of the abutments of about 1.7 ft (0.52 m) parallel to the axis, and horizontal offset normal to the axis of about 3.3 ft (1.0 m) would occur, for a total separation of about 9.6 ft (3.3 ft or 1 m N. 5° E. and 9.0 ft or 2.7 m down at 70° to the horizontal). If normal slip were to occur on a fault dipping less steeply, more horizontal extension would be expected. Conversely, if reverse slip were to occur, slight convergence of the abutments would be expected.

Although the zone of disturbance associated with reverse-slip ruptures may be relatively wide in soft rocks and alluvial cover, it may be very narrow where it is confined to bedrock. Examples of the former situation from the worldwide record include the 1968 Meckering, Australia, event (M 6.9), which had a vertical displacement of about 4.7 ft (1.44 m) over a zone about 5 ft (1.5 m) wide, and the subsidiary Hanning Bay faulting on Montague Island during the 1964 Alaska earthquake (M 8.4), where vertical displacement as great as 16.33 ft (5 m) occurred within a zone about 12.5 ft (4 m) wide.

A directly applicable example of a rupture confined to bedrock occurring during the San Fernando earthquake is presented by a scarp about 1 m high formed in Lopez Canyon. The circumstances there are comparable with those at the proposed damsite: The rupture was subparallel to bedding in steeply north-dipping sandstone and shale that was exposed at the surface. Even though a monoclinal warp formed where bedrock was covered by alluvium, a sharp overhanging scarp formed where bedrock was exposed (U.S. Geol. Survey, 1971, p. 67–71). Where the rupture was confined to bedrock, the principal displacement, as expressed both at the surface and exposed in a postearthquake trench, occurred within a zone a few centimeters wide (U.S. Geol. Survey, 1971, figs. 18–20; Bonilla, 1974). Thus, it is clear that a meter of vertical displacement can occur within a very narrow zone; we know of no reason why much larger displacements cannot occur within equally narrow zones, especially where confined to bedrock.

OTHER EFFECTS

In addition to discrete faulting, other expectable permanent surface deformations include differential uplift or tilting. Differential uplift in 1971, along a profile having the same trend as the proposed dam, was greatest just north of the Sylmar segment and immediately west of the San Fernando city boundary (along a line extending S. 64° W. from the intersection of Fellows Avenue and Hubbard Street). There the westward gradient of the 1971 arch averaged 0.15 percent over a 2250-ft (686 m) distance but was as much as 0.3 percent within a distance of 1,000 ft (300 m). If the steeper of these gradients were to occur in the proposed damsite, the differential change in elevation of the abutments (2260 ft or 689 m apart) could approach 6.8 ft (2.07 m); if the same sense of uplift were to occur, the east abutment would be elevated relative to the west.

Tilting or subsidence of the dam relative to the reservoir could lead to overtopping the dam and possible erosion of the crown and downstream face. This effect occurred at Hebgen Dam during the 1959 Hebgen Lake earthquake (M 7.1) in southwestern Montana. Regional deformation during the earthquake resulted in subsidence of the 20-mile-long Hebgen reservoir by an average of more than 10 ft (3.05 m), whereas the dam subsided less than 10 feet. Even so, warping of the lake basin produced damaging surges of water that overtopped the dam at least three times and eroded the downstream face (Myers and Hamilton, 1964, p. 70).

A dam built at the upper or proposed sites should be able to withstand the transitory ground motions of a strong local earthquake cited, as well as permanent displacement of the ground surface beneath the embankment. Vertical displacement due to fault movement could be as much as 9 ft (2.7 m) within a very narrow zone. The estimated effects of the inferred faulting might be compensated in part by the effects of differential tilting and horizontal displacement as based on their 1971 pattern in the northern San Fernando Valley. However, if the effects were additive, a differential change in elevation of the abutments of as much as 15.8 ft (4.8 m) and a small extension could be expected.

CONCLUSIONS

The Van Norman reservoirs are in an area of high seismicity that was permanently deformed by the M 6½ San Fernando earthquake—an area that could be subjected to an even larger earthquake. Such an earthquake would be accompanied by very severe shaking and could result in large permanent displacements due to faulting and tilting—effects that would impose severe strains on an earth dam. In addition, the Van Norman area overlooks the central San Fernando Valley, where a district inhabited (in 1970) by about 80,000 people could be inundated by a dam failure (Seed, 1972, p. 18). Thus, the Van Norman reservoirs area must be considered as one of high risk for earth dams. Because of the likelihood of seismicity and rupture by faulting and the severe consequences of a dam failure, we believe that great conservatism is justified in the selection of critical seismologic and geologic parameters used in the planning, design, review, and construction of dams in the Van Norman reservoirs area. Estimated values of the critical parameters, directly applicable to the Van Norman area, are given in this report (table 3) and in part B of this report.

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