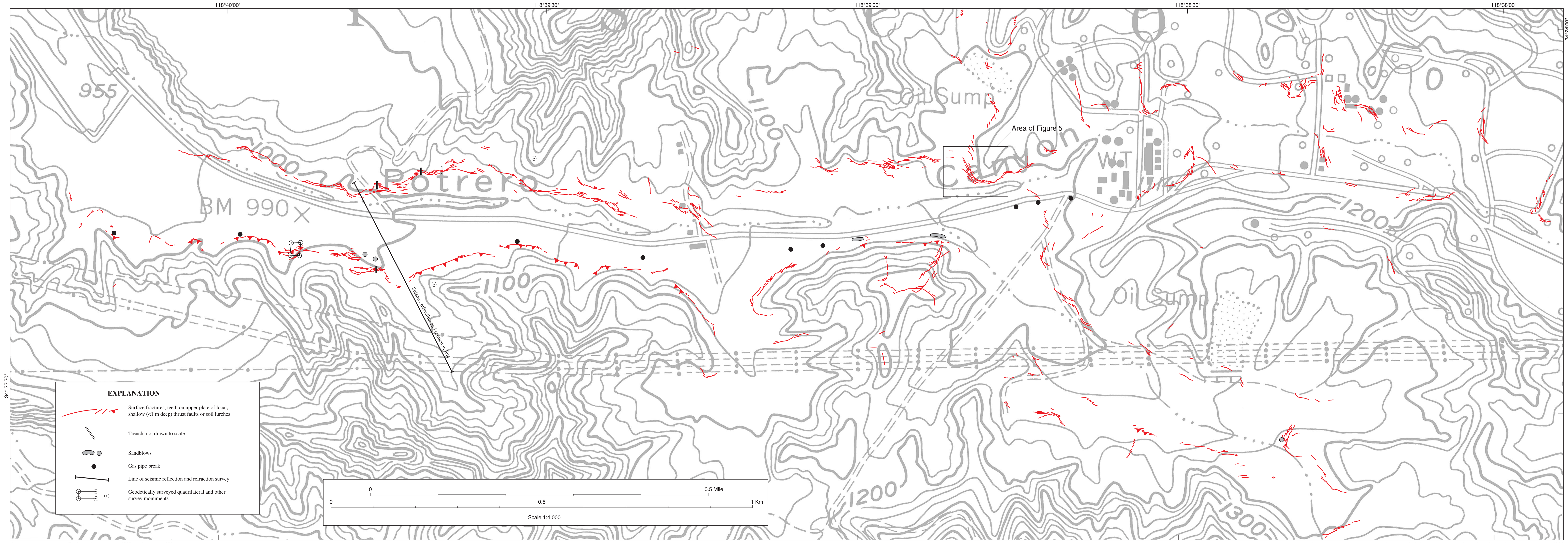


Base from Val Verde, Calif. 7 1/2-minute quadrangle,1952, photorevised 1988

Map 1. Surface fractures and other earthquake-induced features formed in Potrero Canyon in association with the 1994 Northridge earthquake (see Fig. 1).

Features mapped by M.J. Rymer, T.J. Powers, F.R. Cinti, T.E. Fumal, D.P. Schwartz, J.C. Hamilton, and J.A. Treiman, 1994
Manuscript approved for publication February 20, 2001

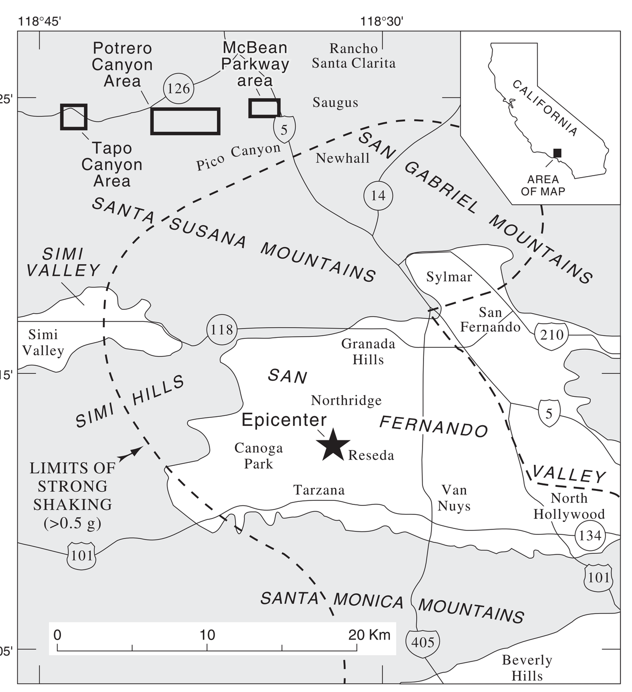


Figure 1. San Fernando Valley, California, area, showing location of the Potrero Canyon, Tapo Canyon, and McBean Parkway study areas relative to the 17 January 1994 Northridge earthquake (solid star). Dashed line, boundary of strong ground motion greater than 0.5 gravity (g).

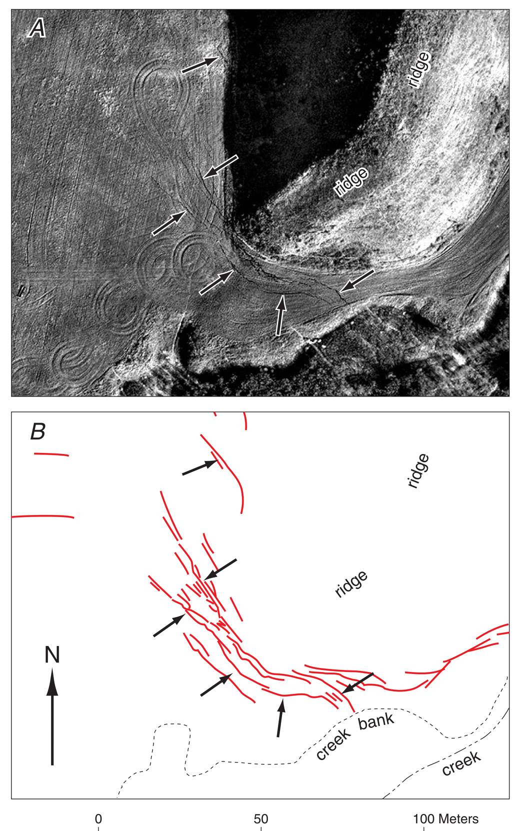
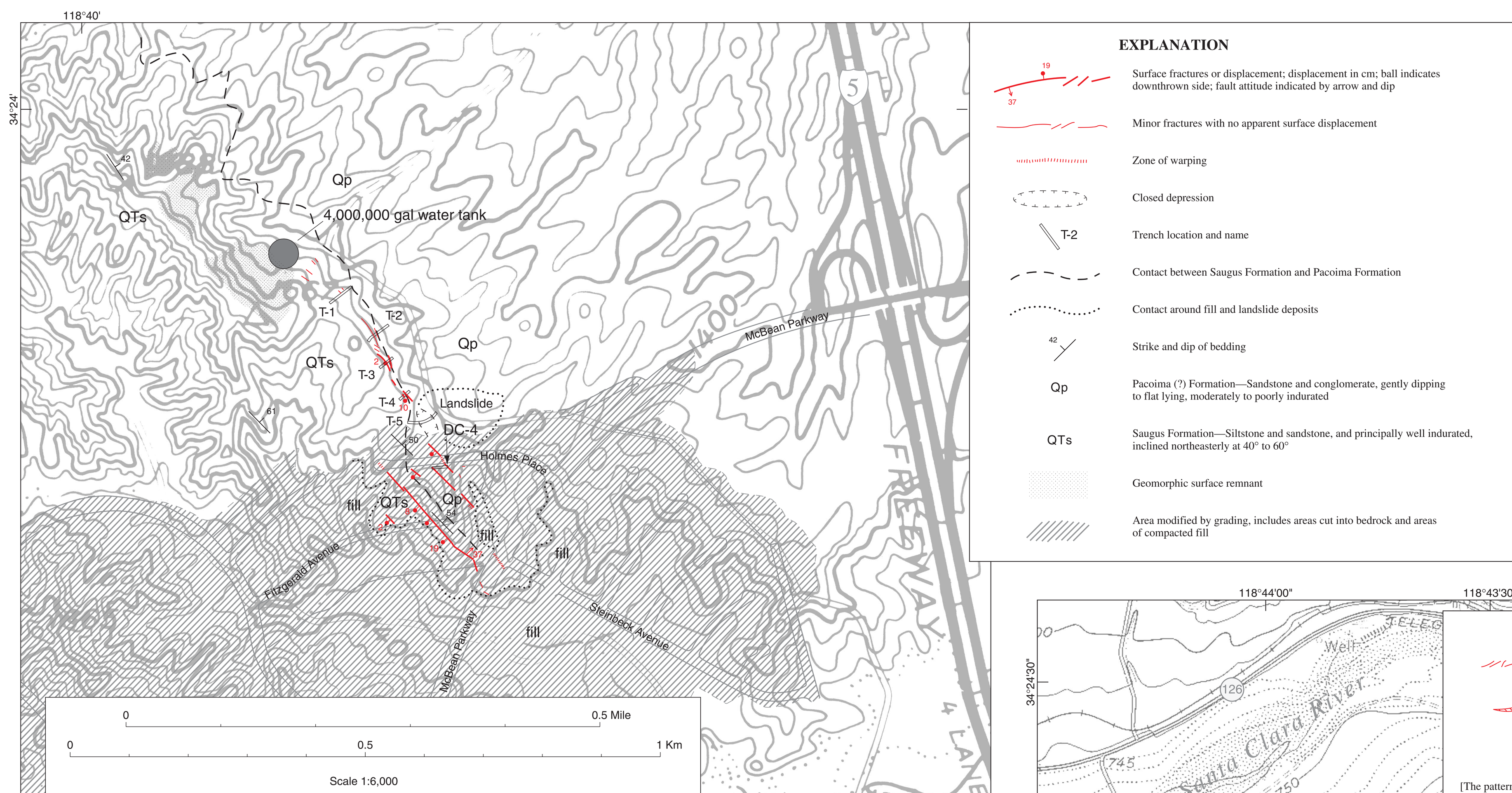


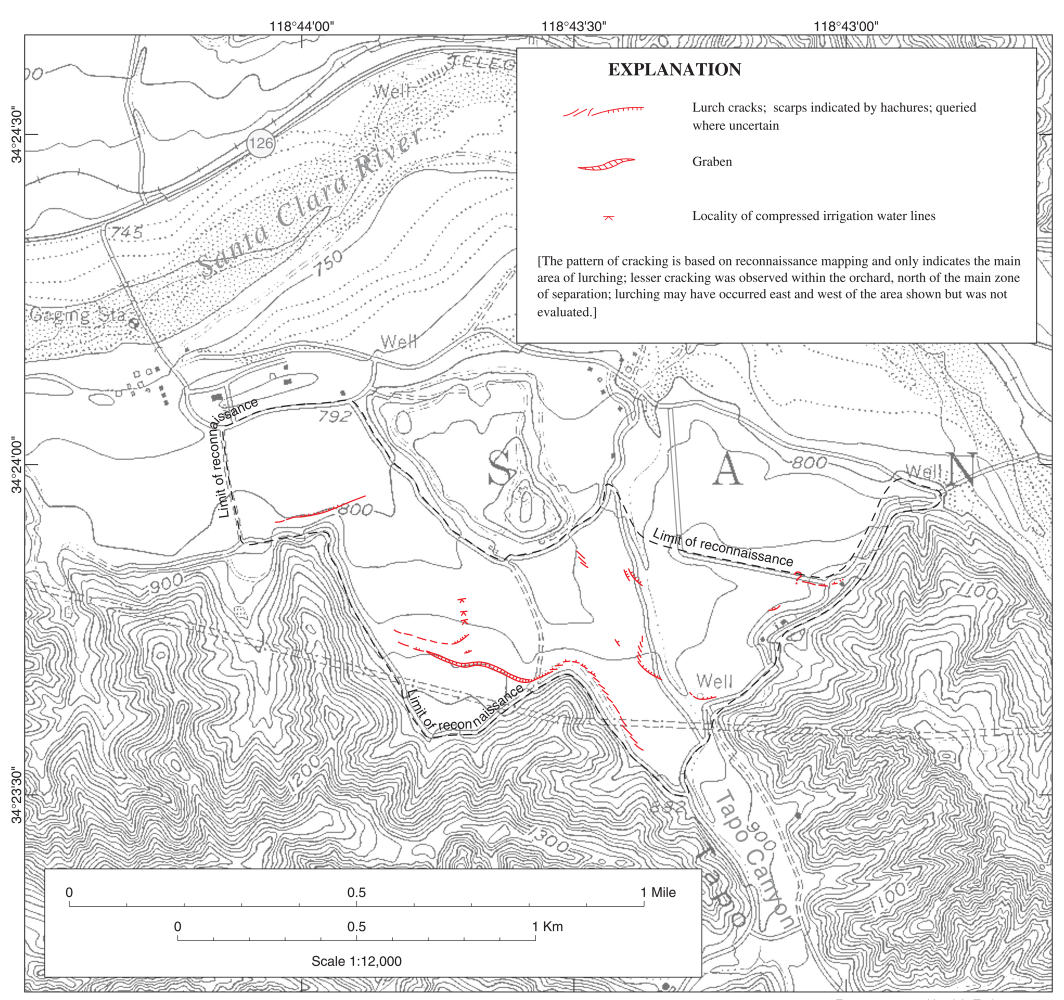
Figure 5. Surface fractures on north side of Potrero Canyon showing better developed cracks on west side of ridge spur that protrudes into canyon. A, aerial photograph of surface fractures, prominent fractures marked by arrows. Features seen on cultivated ground include plow marks, tractor turn marks (not crop circles), and cattle trails. B, Line drawing of same area shown in A. Heavy red lines, surface fractures.



Base from Val Verde, Calif. 7 1/2-minute quadrangle,1952, photorevised 1988

Features mapped by J.A. Treiman, 1994

Map 2. Bedding-plane faulting and related fractures north of McBean Parkway, northwest of Newhall, resulting from the 1994 Northridge earthquake (see Fig. 1).



Base from Val Verde, Calif. 7 1/2-minute quadrangle,1952, photorevised 1988

Features mapped by J.A. Treiman, 1994

Map 3. Ground deformation resulting from the 1994 Northridge earthquake in the Las Brisas orchard, vicinity of Tapo Canyon at the Santa Clara River (see Fig. 1).

Figure 2. Broad zone of surface fractures, located between vertical and diagonal arrows, on north side of Potrero Canyon. Fractures below vertical white arrows in midground show stair-step pattern indicative of valley fill, located to right, that moved away from bedrock. View to the northeast.

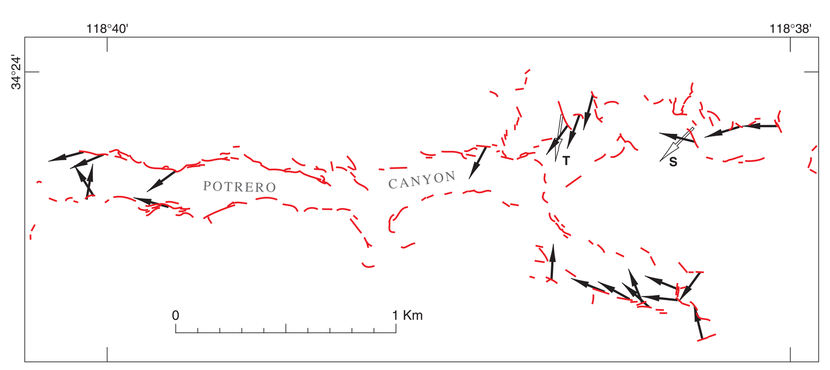


Figure 6. Map of horizontal slip directions across matching soil-block irregularities plotted relative to surface fractures in Potrero Canyon. Two hollow arrows in the northeast indicate horizontal dislocation directions of man-made features on the ground surface; these are marked with S = tank of soda ash and T = transformer.

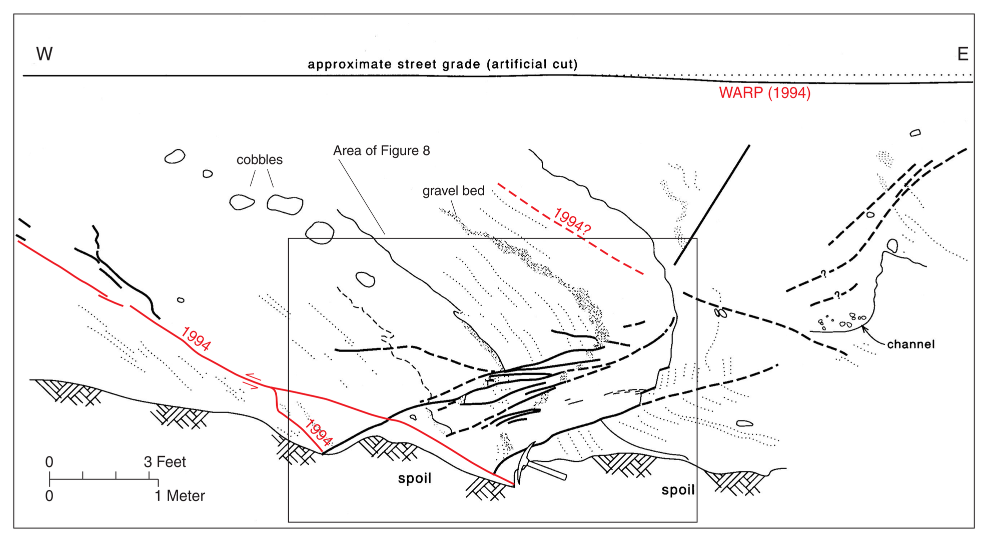


Figure 7. Sketch log of trench exposure (DC-4) south of Holmes Place (drawn from a 35-mm slide). North wall of trench is shown. Trench depth is approximately 3.5 m below street level. Bedrock, represented by east-dipping bedding features, is Pacoima (?) Formation. Multiple low-angle thrust faults (thick black lines) document a history of previous displacements that have folded the coarse sediments of the Pacoima (?) Formation. 1994 rupture surface (red lines), in the left portion of this sketch, offsets the older southwest-dipping thrust surfaces. Rupture follows bedding planes up to the left, from 2.5 m depth to the surface (left of this view). Surface warping in 1994 mirrored the older folding and was probably accompanied by incremental growth of this structure.

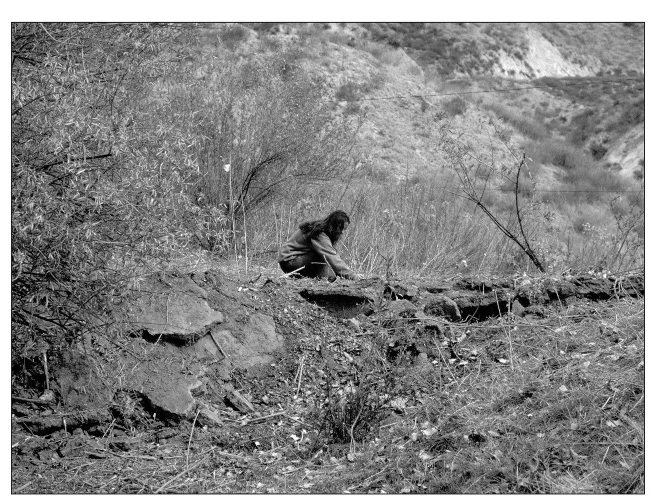


Figure 3. Surface fracture with large vertical component of slip on north side of Potrero Canyon. Fracture developed at base of hillslope, near contact between bedrock and alluvium. View to the northeast.

Figure 4. Extensional surface fractures on south side of side canyon located south of Potrero Canyon. Fracture set occurs as narrow zone in right-stepping echelon pattern. View to the east.

Figure 8. Photograph of trench exposure DC-4, south of Holmes Place (see Map 2 for location and Fig. 7 for log).

SURFACE FRACTURES FORMED IN THE POTRERO CANYON, TAPO CANYON, AND MCBEAN PARKWAY AREAS IN ASSOCIATION WITH THE 1994 NORTHRIDGE, CALIFORNIA, EARTHQUAKE

By
MICHAEL J. RYMER[1], JEROME A. TREIMAN[2], THOMAS J. POWERS[1], THOMAS E. FUMAL[1],
DAVID P. SCHWARTZ[1], JOHN C. HAMILTON[1], and FRANCESCA R. CINTI[3]

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INTRODUCTION

The magnitude 6.7 (M6.7) Northridge earthquake of 17 January 1994 strongly shook the Los Angeles urban region, resulting in 33 direct deaths, more than 20,000 people forced out of their homes, and an estimated $20 billion in damage (Hall, 1994). The earthquake was caused by slip on a previously unrecognized south-dipping fault buried beneath the San Fernando Valley. Slip on the fault propagated from a depth of about 19 km to about 8 km below the ground surface (USGS and SCEC, 1994). Although there was no surface faulting associated with the causative fault, surface fractures did develop along at least one fault (Mission Wells fault) and also in areas without recognized faults (Hart and others, 1995; Hecker and others, 1995a, 1995b; Rymer and others, 1995; Treiman, 1995). The term "surface fractures" is used herein to describe ground breakage that is not associated with primary faulting or with triggered, secondary, surface faulting on a deep seismogenic fault.

This report describes fault- and nonfault-related surface fractures that occurred at three sites, Potrero Canyon, Tapo Canyon, and the McBean Parkway area, 22 to 28 km north-northwest of the main shock (Fig. 1). Investigation of these sites documents far reaching effects of even moderately large earthquakes. Study of such effects has become increasingly important with further urbanization and development. Hecker and others (1995a, 1995b) documented the distribution of surface deformation associated with the Northridge earthquake in the Granada Hills area.

The search for surface faulting and surface fracturing was initiated within hours of the earthquake. Both ground and airborne searches were made of the region. After fresh surface fractures were found in Potrero Canyon, aerial photographs were taken of the area (including the McBean Parkway site) by I.K. Curtis, on 21 January 1994, at scales of about 1:2,000 and 1:6,000. These aerial photographs were studied under high magnification to supplement ground-based observations of surface fractures.

FRACTURES IN POTRERO CANYON

Potrero Canyon, a 5-km-long, 200-m-wide, east-west-trending valley incised into the Pliocene Pico Formation (Winterer and Durham, 1962), is situated on the up-dip projection of the seismogenic rupture plane of the main shock. Local secondary or side canyons, notably two such features on the south side, extend from Potrero Canyon. Valley fill within Potrero Canyon consists of Holocene and late Pleistocene alluvium (silt, sand, and conglomerate) with a thickness of at least 15 to 20 m (Holzer and others, 1999; Catchings and others, 1998).

Extensive sets of surface fractures formed in alluvium around the margins of Potrero Canyon in association with the earthquake. Map 1 is a plot of the fractures, which extend east-west and north-south about 3.6 km and 1.3 km, respectively. Most fractures plot near the surface projection of the bedrock and alluvium contact at depth, near the base of hill slopes (Figs. 2, 3). In areas where bulldozers cut back the base of the hill slope, surface cracks were associated with this bedrock-alluvium contact in spite of the artificial change in topography.

Characteristics of surface fractures varied somewhat along the north and south sides of the canyon. On the north side of Potrero Canyon, discontinuous crack sets developed with extensional displacements, commonly in zones as wide as 30 m (Map 1). Fractures found along the south side were most commonly restricted to discontinuous narrow zones (Fig. 4), no wider than 15 m, and had both extensional and compressional surface displacements. Compressional fractures occurred only on the south side of the canyon, including the south edge of a side canyon that extends to the southeast from Potrero Canyon (Map 1).

Characteristically, surface fractures on both sides of Potrero Canyon and the side canyons were more common or more pronounced on the west sides of spurs or ridges that protrude into the canyons (Map 1, Fig. 5). Fractures on the north side of the canyons have left-stepping crack sets and those on the south side have right-stepping sets, indicating a net down-canyon motion. Measurements of horizontal of slip directions across individual fractures and some of the narrower crack sets similarly indicate a general westward motion of the alluvial fill (see horizontal slip arrows in Fig. 6). In addition, fractures on both sides of the canyon dip steeply toward the center of the canyon.

Slip along fractures in Potrero Canyon was dominantly extensional, with small amounts of horizontal slip. Slip components were recorded only across single cracks and, because of the generally broad fracture zones (Map 1, Figs. 2, 5), measurements did not span most crack sets. Also, rigid manmade features that best record displacement are not present in Potrero Canyon. Thus, our measurements do not record the total slip associated with this earthquake. Because of the scarcity of data, we plot only the horizontal slip directions (Fig. 6). The closest approximation of total slip at a site is a measurement on the north side of the canyon about 400 m east of the western end of fractures. At this site, measurement of the vertical component across three of the larger cracks in a broad zone of fractures totaled more than 50 cm. Crude field estimates of maximum values of slip for the vertical, compressional, and extensional components of slip are about 1 m, 0.2 m, and 0.3 m, respectively.

Compressional fractures found along the south side of the canyon are believed to be shallow surficial features developed in or slightly below the soil layer. Trench exposures (described in detail in Rymer and others, 1995) revealed compressional fractures that were antithetic to the larger, more deeply extending extensional fractures. Compressional cracks exposed in the trenches represented slip only in the upper 50 cm of sediment, whereas extensional fractures were traced to depths of greater than 6 m without indication of slip-plane shallowing.

LANDSLIDES AND OTHER GROUND FAILURES

The 17 January earthquake triggered thousands of landslides throughout the greater Los Angeles region (Jibson and others, 1994; Harp and Jibson, 1995), including numerous slides that formed in the Potrero Canyon area. Although Harp and Jibson (1995) show some landslides in the Potrero Canyon area, their mapping of landslides was from small-scale aerial photographs that show only the larger slides. We mapped dozens of small landslides, which were readily apparent in the field and on the 1:2,000-scale aerial photographs, in the hills surrounding Potrero Canyon (landslides are not shown in Map 1). The most common landslide types in the Potrero Canyon area were, in decreasing order of abundance, soil falls, soil slides, rock falls, and soil slumps. The volume of individual earthquake-induced landslides in the Potrero Canyon area varied, but most commonly was small, less than 10 cubic meters. Landslides were most common in road cuts and along the edges of artificial fill. Landsliding on the north side of the canyon was quite extensive; local slides extended from the ridge crest to near the bedrock-alluvium contact along the canyon margin.

Cracks along ridge crests, shattered ridge effects not associated with landslides, also formed in the Potrero Canyon area in association with the Northridge earthquake. We saw these features on ridge crests south and west of Potrero Canyon, but because a systematic survey was not made of their distribution, a summary is not given.

Sandblows formed at several places in the valley floor of Potrero Canyon (Map 1). They were most prevalent near the south edge of the canyon, away from the principle stream channel and subsidiary drainages. The sandblows formed cones, about 1 to 3 m in diameter, which locally coalesced into zones tens of meters long. A discussion of sandblows and their source beds is presented by Holzer and others (1999).

PIPE BREAKS

Other earthquake-induced features in Potrero Canyon include pipe breaks in an east-west-trending natural gas line. Ten pipe breaks formed as tensile failures at pipe welds (T.D. O'Rourke, Cornell University, written commun., 1994). The breaks were not co-located with surface fractures (Map 1); pipe breaks were probably due to strong shaking, liquefaction, or differential down-canyon motion of alluvial fill rather than to movement across fractures.

GEODETIC AND GEOPHYSICAL MEASUREMENTS ACROSS SURFACE FRACTURES

A quadrilateral and other geodetic monuments were installed across breaks in Potrero Canyon to measure possible afterslip. The quadrilateral is located across surface crack sets that contained both extensional and compressional cracks (Map 1). Repeated distance measurements of the six possible line lengths were made on the quadrilateral. Measurements were made 7, 11, 16, and 57 days after the earthquake with a Wild T2002/DI2000 total station. Analysis of horizontal distances between quadrilateral monuments and the other geodetic monumnets shows only random motions, with uncertainty levels commonly in the 1 to 2 mm range, and occasionally up to 4 mm.

Two additional monuments were installed in bedrock highs on the north and south flanks of Potrero Canyon to measure possible net slip across the whole canyon. The line between these two monuments was measured 7, 11, and 16 days after the earthquake. Line length varied between the first and second surveys by 0.9 mm, and between the second and third surveys by 0.5 mm, measurements which are within the set-up error. There was no indication of postseismic movement beyond measurement uncertainty.

A high-resolution seismic reflection and refraction survey was run across Potrero Canyon in February 1994 to better understand the subsurface structure and its possible relation to fractures seen at the ground surface (Catchings and others, 1998). The location of the seismic profile near the west end of the canyon is shown in Map 1. Catchings and others (1998) found apparent south-dipping reverse faults buried beneath Potrero Canyon. Given the nature of surface fractures mapped in Potrero Canyon (Map 1) with net right-oblique slip on the north side of the canyon and left-oblique slip on fractures on the south side, we find it unlikely that the surface fractures represent coseismic slip on deep-seated faults. However, the apparent faults imaged in the seismic survey may have added further focused shaking to the Potrero Canyon area.

DISCUSSION

Our surface investigations, along with trenching studies reported in Rymer and others (1995), indicate that primary faulting did not occur in Potrero Canyon. Rather, we conclude that the surface fractures likely formed in response to strong shaking that resulted in alluvial compaction. Stratigraphic and structural relations exposed in trenches on the south margin of the valley are consistent with surface displacements resulting from differential settlement and lurching (recorded as shallow thrusts) due to strong ground motion. Movement took place largely along the bedrock-alluvium contact but possibly also involved the soft uppermost part of the bedrock. The distribution and types of earthquake-induced features found in Potrero Canyon are also generally consistent with deformation due to strong ground motion rather than to surface faulting. The net down-canyon motion of the alluvial canyon fill (Fig. 6) supports this model, as does the presence of localized liquefaction, pipe breaks, and better developed crack sets on the western (down-gradient) sides of ridge spurs (Map 1, Fig. 5).

Unusually high strong ground motions recorded 10 to 25 km north of the epicenter are suggestive of up-dip directivity during rupture of the earthquake (Wald and others, 1996). A station at the east end of Potrero Canyon recorded a peak ground velocity of about 115 cm/sec; the width of the velocity pulse is nearly 2 sec. Such focusing of energy at the up-dip projection of the causative fault may have contributed to the observed ground deformation in Potrero Canyon. Southwest-directed horizontal movement of a 70-percent full, 3,780-liter tank of soda ash, which moved 35 cm, and a transformer, which moved 5 cm, (Fig. 6) are further indications of the north-northeast-directed strong ground motions sustained in Potrero Canyon.

BEDDING-PLANE FAULTING IN THE MCBEAN PARKWAY AREA

Ground rupture more closely related to tectonic deformation occurred a few kilometers east of Potrero Canyon (Treiman, 1995; Fig. 1), where bedding-plane slip was found in a limited area on the north flank of the Santa Susana Mountains, along the up-dip projection of the rupture plane. The most continuous zone of surface rupture was about 250 m long, with additional ground fractures for another 350 m to the north (Map 2).

The surficial geology of the area of faulting is simple (Treiman, 1986; Winterer and Durham, 1962). Sandstone and siltstone beds of the Pleistocene non-marine Saugus Formation are inclined to the northeast at 40° to 60°. This section of tilted strata lies roughly midway between the axes of the Pico anticline to the south and the broader Santa Clara syncline to the north. The Saugus Formation is unconformably overlain by the flat-lying to moderately northeast-dipping sands and gravelly sands of the late Pleistocene Pacoima (?) Formation, a local fluvial and colluvial basin-fill deposit laid down within the past 760,000 years. Local angular unconformities have developed within the Pacoima (?) Formation in response to continued late Quaternary deformation.

During the Northridge earthquake, reverse slip occurred along at least five bedding planes within the Saugus Formation that had been exposed in recently graded building pads and cut slopes of a residential development west of Interstate 5 (Map 2). No buildings had been constructed on the affected lots. Fault displacement was consistently northeast-side up, with measured slips of up to 19 cm; lateral separations varied from 4 cm right-lateral to 7 cm left-lateral, with left-lateral slip predominating. Individual ruptures were clearly compressional in nature and were expressed by low southwest-facing scarps. The most continuous rupture extended for about 250 m and had a general trend of N40°W. As exposed in a bedrock cut slope at its southeastern extremity, this fault surface dips 37°NE. Exposures in exploratory trenches confirmed that the faulting occurred along bedding planes, usually within a clayey unit (GeoSoils, 1995; Seward, 1995b). Smaller, parallel ruptures lay approximately 40-80 m to the northeast. One of these was traced part way up a cut slope at the northern margin of the development.

The ruptures to the northeast were associated with ground-surface warping. At Holmes Place, the road and curb were monoclinally warped down to the northeast about 15 cm across a zone about 6 m wide, even though individual surface breaks showed the reverse sense of displacement, southwest side down. Compression was also indicated by shortening of the sidewalk and curb. The surface faulting and warping are associated with strongly deformed Pacoima (?) Formation. Dips in one trench shallowed from 50° to horizontal within a distance of 10 m. These older alluvial deposits have been folded and faulted across a relatively narrow zone, generally less than 8 m. Bedding within the Pacoima (?) Formation is locally overturned (Figs. 7, 8). In addition to the northeast-dipping bedding-parallel shears, the rocks have been displaced in the past by multiple southwest-dipping thrust faults. Warping across Fitzgerald Avenue, south of Holms Place, was similar in magnitude but was broader, at least 20 cm vertical movement across a 25 m-wide zone. A post-earthquake leveling survey (GeoSoils, 1995) showed that the block defined by the width of the zone of deformation had been uplifted nearly 1 foot (30 cm), with relatively little internal deformation.

The fault and fold zone may continue to the southeast across McBean Parkway. Cracking of the road and a subtle left-lateral displacement (6 to 8 cm) of the median along the Parkway may be related to slip along the fault zone. At the intersection of McBean Parkway and Steinbeck Avenue, the Los Angeles County Engineering Department performed street repairs to correct a monoclinal warp in the road. Deformation here amounted to 6 to 8 inches (15 to 20 cm) across a 20 m-wide zone with vertical uplift on the southwest (C. Nestle, L.A. County, oral communication, 1994). No surface fractures were noted at this locality. Farther to the southeast, the zone either dies out or is obscured by man-made fill. Possible fault displacements were not differentiated from the effects of fill settlement and cracking in this area.

To the northwest of the residential development, a naturally occurring northwest-oriented closed depression, about 70 m long and 40 m wide, is aligned with the zone of faulting (Map 2). Several traverses across this depression revealed only a few discontinuous fractures in the soil with no measurable displacement. A large bulldozer and backhoe excavation (T-5) by Seward (1995a) revealed gently to moderately northeast-dipping strata of the Pacoima (?) Formation with numerous fractures and shears. These included both northeast- and southwest-dipping reverse faults. Abrupt steepening of the bedding appeared in conjunction with southwest-dipping thrust faults, similar to the trench exposure near Holmes Place (DC-4). None of the bedrock shears could be shown to have moved in the recent earthquake.

A N35°W trend of soil fractures was found to extend about 350 m from the northwest end of the closed depression (Map 2). The fracture zone was best expressed where it crossed several northeast-trending ridge spurs, coming off a northwest-trending strike-ridge, but was also traceable through part of the intervening canyons. The southern 100 m of the fracture zone included one to two uphill-facing scarps, from 2 to 10 cm high. Minor, discontinuous cracks were observed across spur ridges for another 200 m to the northwest. The cracks dipped to the southwest near the ground surface (in the soil), normal to the sloping ground surface, and appeared to be extensional. They had no measurable vertical displacement at the surface.

Four trenches excavated by Seward (1995a) found most of the cracks north of the depression to be related to southwest-dipping fractures that cut across bedding planes. Several of the fractures were open or had filled with loose sand. Normal displacement of up to 2 cm was observed across these fractures within the trenches. These observations are consistent either with tensional fracturing along a fold or with ridgetop spreading. However, in one trench (T-2), bedding changed from an inclination of 37°NE to horizontal within a distance of about 13 m, demonstrating late-Quaternary monoclinal folding of the Pacoima Formation.

No cracks of a tectonic origin were noticed at or beyond the site of a 4-million-gallon water tank just to the northwest of the last fractures. A careful traverse for a distance of at least 500 m and a general reconnaissance along trend for another 2 km failed to detect any cracking, other than from shaking or landsliding. Subsequent subsurface investigation for additional development along this trend, 2 km to the northwest of McBean Parkway, has revealed similar faults and folds, although there is no evidence that this area to the north had deformation in 1994 (Treiman, personal observation).

The entire zone of deformation (faulting and folding) coincides roughly with a broad northwest-trending flexure, with steeper dips on the southwest limb and gentler dips on the northeast limb. This flexure is, in fact, the principal tectonic feature in this immediate area and the various surface ruptures are believed to be a response to this folding. The surficial faulting and folding are interpreted to be the result of bending-moment faulting within the axis of the northwest-trending flexure, an active fold, on the northern flank of the Santa Susana Mountains. The local normal displacements appear to be tensional fractures above the compressional fold axis, and may also be at least partly enhanced by ridgetop spreading and downslope movement associated with strong earthquake shaking.

FRACTURES NEAR THE MOUTH OF TAPO CANYON

Widespread ground failure occurred within the Las Brisas orchard, along the south side of the Santa Clara River, at Tapo Canyon (Fig. 1, Map 3). Observations reported herein were only reconnaissance in nature. The failure was principally lateral spreading or lurching within the elevated terraces of Tapo Creek. No sandblows were observed and liquefaction has not been verified as a mechanism in this locality, although the foreman of the ranch reported that the orchard had been heavily irrigated prior to the earthquake and that the ground was probably saturated. The most severe spreading occurred west of Tapo Canyon, where a shallow graben (with a depth as great as ~1 m) was wide enough (4 to 5 m estimated) to encompass a row of orange trees. Scarps bounding the graben were typically up to 0.5 m high. Except where smaller failures moved toward the creek, it was not clear how the ground movement was accommodated. Some compression, revealed by telescoped irrigation lines, was evident north, downslope, of the graben (Map 3), but a detailed survey was not made to account for all of the displacement.

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[1] U.S. Geological Survey, Menlo Park, CA 94025
[2] California Department of Conservation, Division of Mines and Geology, Los Angeles, CA 90012
[3] Istituto Nazionale di Geofisica, Roma, Italia

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