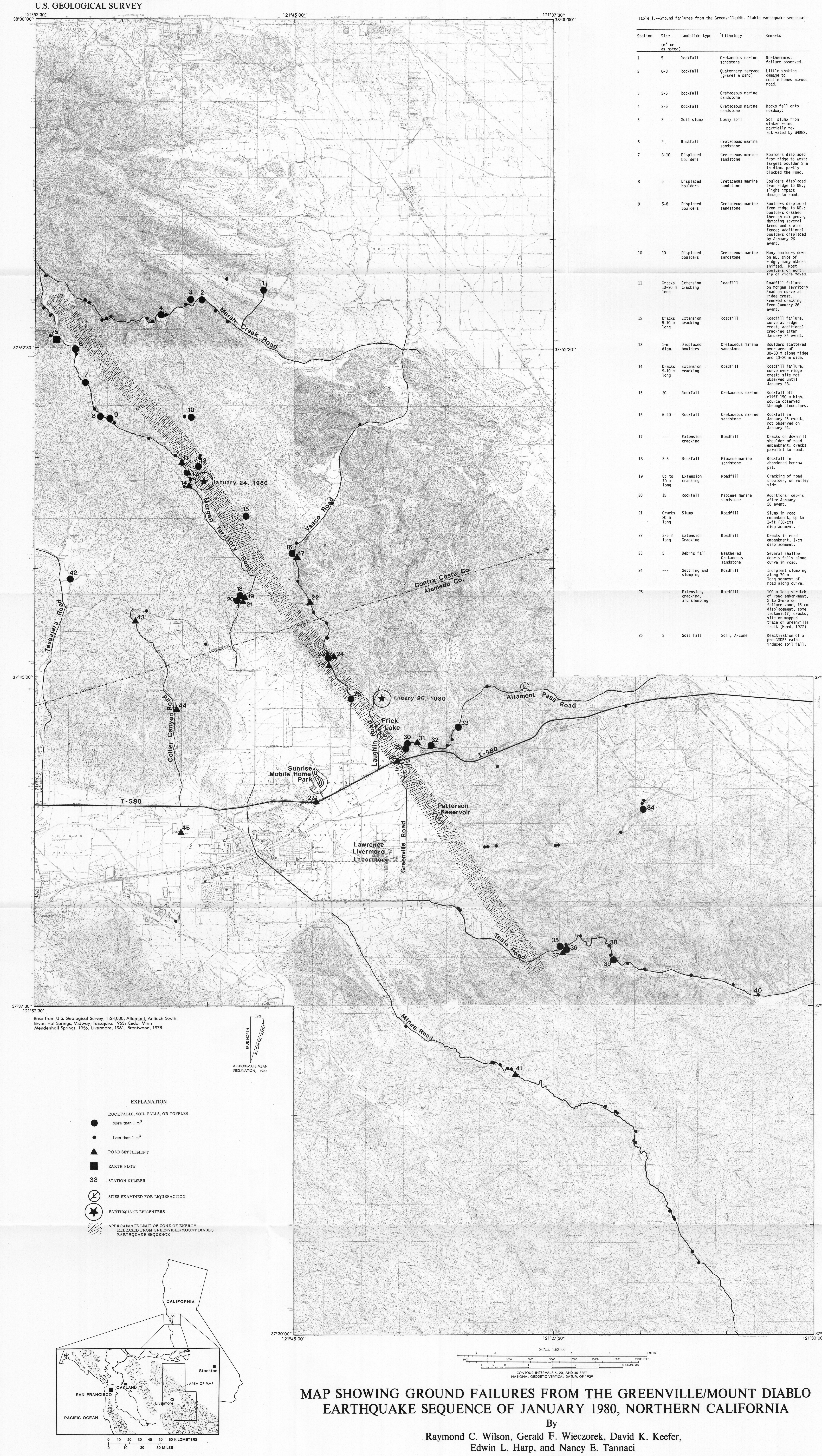
DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

MISCELLANEOUS FIELD STUDIES
MAP MF-1711



Base from U.S. Geological Survey, 1:24,000, Altamont, Antioch South, Bryon Hot Springs, Midway, Tassajara, 1953; Cedar Mtn.; Mendenhall Springs, 1956; Livermore, 1961; Brentwood, 1978

EXPLANATION

ROCKFALLS, SOIL FALLS, OR TOPPLES

- ● More than 1 m³
- • Less than 1 m³
- ▲ ROAD SETTLEMENT
- ■ EARTH FLOW
- 33 STATION NUMBER
- Ⓛ SITES EXAMINED FOR LIQUEFACTION
- ★ EARTHQUAKE EPICENTERS
- ▨ APPROXIMATE LIMIT OF ZONE OF ENERGY RELEASED FROM GREENVILLE/MOUNT DIABLO EARTHQUAKE SEQUENCE

SCALE 1:62500

CONTOUR INTERVALS 5, 20, AND 40 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

MAP SHOWING GROUND FAILURES FROM THE GREENVILLE/MOUNT DIABLO EARTHQUAKE SEQUENCE OF JANUARY 1980, NORTHERN CALIFORNIA

By

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Table 1.--Ground failures from the Greenville/Mt. Diablo earthquake sequence—

Station	Size (m³ or as noted)	Landslide type	¹Lithology	Remarks
1	5	Rockfall	Cretaceous marine sandstone	Northernmost failure observed.
2	6-8	Rockfall	Quaternary terrace (gravel & sand)	Little shaking damage to mobile homes across road.
3	2-5	Rockfall	Cretaceous marine sandstone	
4	2-5	Rockfall	Cretaceous marine sandstone	Rocks fell onto roadway.
5	3	Soil slump	Loamy soil	Soil slump from winter rains partially re-activated by GMDES.
6	2	Rockfall	Cretaceous marine sandstone	
7	8-10	Displaced boulders	Cretaceous marine sandstone	Boulders displaced from ridge to west; largest boulder 2 m in diam. partly blocked the road.
8	5	Displaced boulders	Cretaceous marine sandstone	Boulders displaced from ridge to NE.; slight impact damage to road.
9	5-8	Displaced boulders	Cretaceous marine sandstone	Boulders displaced from ridge to NE.; boulders crashed through oak grove, damaging several trees and a wire fence; additional boulders displaced by January 26 event.
10	10	Displaced boulders	Cretaceous marine sandstone	Many boulders down on NE. side of ridge, many others shifted. Most boulders on north tip of ridge moved.
11	Cracks 10-20 m long	Extension cracking	Roadfill	Roadfill failure on Morgan Territory Road on curve at ridge crest. Renewed cracking from January 26 event.
12	Cracks 5-10 m long	Extension cracking	Roadfill	Roadfill failure, curve at ridge crest, additional cracking after January 26 event.
13	1-m diam.	Displaced boulders	Cretaceous marine sandstone	Boulders scattered over area of 30-50 m along ridge and 10-20 m wide.
14	Cracks 5-10 m long	Extension cracking	Roadfill	Roadfill failure, curve over ridge crest; site not observed until January 28.
15	20	Rockfall	Cretaceous marine	Rockfall off cliff 150 m high, source observed through binoculars.
16	5-10	Rockfall	Cretaceous marine sandstone	Rockfall in January 26 event, not observed on January 24.
17	---	Extension cracking	Roadfill	Cracks on downhill shoulder of road embankment; cracks parallel to road.
18	2-5	Rockfall	Miocene marine sandstone	Rockfall in abandoned borrow pit.
19	Up to 70 m long	Extension cracking	Roadfill	Cracking of road shoulder, on valley side.
20	15	Rockfall	Miocene marine sandstone	Additional debris after January 26 event.
21	Cracks 20 m long	Slump	Roadfill	Slump in road embankment, up to 1-ft (30-cm) displacement.
22	3-5 m long	Extension Cracking	Roadfill	Cracks in road embankment, 1-cm displacement.
23	5	Debris fall	Weathered Cretaceous sandstone	Several shallow debris falls along curve in road.
24	---	Settling and slumping	Roadfill	Incipient slumping along 70-m long segment of road along curve.
25	---	Extension, cracking, and slumping	Roadfill	100-m long stretch of road embankment, 2 to 3-m-wide failure zone, 15 cm displacement, some tectonic(?) cracks, site on mapped trace of Greenville fault (Herd, 1977)
26	2	Soil fall	Soil, A-zone	Reactivation of a pre-GMDES rain-induced soil fall.

Table 1.--Ground failures from the Greenville/Mt. Diablo earthquake sequence—Continued

Station	Size (m³ or as noted)	Landslide type	¹Lithology	Remarks
27	2 to 5 cm settle-ment	Settling and cracking	Roadfill	Cracking and settling of fill under NE. abutment of I-580/Livermore Blvd. overpass.
28	20-cm settle-ment	settling and cracking	Roadfill	Greenville overpass on I-580; eastbound lanes of I-580 closed for 6 hours.
29	5	Rockfall	Cretaceous marine sandstone	Railroad cut, sandstone weakly cemented.
30	10-15	Rockfall	Cretaceous marine sandstone	Rockfall in scarp of large old landslide; sandstone weakly cemented; rocks on railroad tracks.
31	12-cm displace-ment	Slump	Embankment fill (sandy)	Railroad embankment.
32	2	Rockfall	Cretaceous marine sandstone	Railroad cut, dropped rocks onto tracks.
33	3-5	Rockfall	Cretaceous marine sandstone	At roadcut, old U.S. 50; no damage or blockage of road.
34	2	Rock/soil fall and (or) topple	Miocene marine sandstone	Failure from vertical canyon face, 6-7 m high.
35	10	Rockfall	Tesla(?) Fm., (weakly cemented sandstone)	Roadcut failure, ½-1-m boulders; partly blocked Tesla Rd.
36	5	Rock topple	Quaternary terrace (sand and gravel) (weakly cemented)	Topple in stream bank, collapse of erosional remnant ridge; left boulders up to 2 m in diameter.
37	---	Settlment	Roadfill	Cracking of road shoulder.
38	1-2	Rock/soil fall	Miocene marine sandstone	Several (5?) soil and rock falls of tensile, popping type from above midpoint on slope.
39	5	Rock/soil fall	Miocene marine sandstone	Several coalescing rock and soil falls, tensile popping failures.
40	2	Rockfall	Miocene marine(?) sandstone	Conchoidal, tensile popping failures midslope on a 6-m-high roadcut.
41	---	Extension cracking	Roadfill	Minor cracking of roadway; no significant damage.
42	2-5	Soil fall	Unconsolidated alluvium	Tensile(?) failure of vertical river bank.
43	Minor	Extension cracking	Roadfill	Minor damage to Collier Canyon Road
44	Minor	Extension cracking	Roadfill	Minor damage to Collier Canyon Road
45	Minor	Extension cracking	Embankment fill	Minor settlement (1 cm) of embankment of sewage treatment pond; hairline cracks in tunnel.

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¹Stratigraphy from California Department of Water Resources (1974).

TABLE 2.--Point load tests of samples from sites of slope failure in GMDES

Station	Point-load index, I_{s50} (psi)	Mean grain size, D_{50} (μ)	Water content (%)	Remarks
35	6.72	150	1.1	Combination tensile, shear failure in white tuffaceous sandstone.
36	12.52	84	0.9	Rock topple.
38	30.19	140	2.0	Rock and soil tensile failure--rock appears to have extensive jointing.
39	17.30	64	1.2	Several popping failures near midheight in soil and rock
40	8.59	154	0.9	10 tensile popping failures at midheight.
30	11.04	190	1.3	Rockfalls in massive calcite cemented sandstone.
10	157.23	100	0.7	Rock slides and topples along bedding and joint planes.

INTRODUCTION

The Greenville/Mt. Diablo earthquake sequence of January 24-26, 1980, was composed of small and moderate earthquakes; the two largest shocks, on January 24 and 26, were of magnitudes (M) 5.5 and 5.6, respectively (Bolt and others, 1981). A 5.5 event is at the lower end of the range of earthquake magnitudes which cause observable ground failure (Youd and Perkins, 1978; Keefer, 1984). While none of the slope failures produced by the Greenville/Mt. Diablo earthquake sequence (GMDES) was larger than a few tens of cubic meters, they were both widespread in area (see map) and rich in variety, and thus have much to teach us about seismically induced slope failures in the San Francisco Bay area.

This map depicts the location, type, and relative size of the ground failures observed during our reconnaissance, which began at 2:30 pm PST on January 24 and continued on January 25, 26, and 28 and February 6. Our observations were generally limited to that part of the Livermore region that is accessible by state and county roads.

Information about the individual ground failures may be obtained from the map and the brief descriptions in table 1. The following text is a general discussion of the distribution and the mechanisms of the ground failures, followed by a discussion of the effects of wet winter conditions and of topographic amplification on the distribution and mechanisms of slope failure, and it concludes with a description of our (unsuccessful) efforts to locate any ground failures due to liquefaction. The discussion is intended not only to describe the GMDES slope failures but also to place them into the larger general context of seismically induced slope failures.

DISTRIBUTION OF SLOPE FAILURES

The two most abundant types of slope failure were rockfalls on roadcuts and roadfill failures. The zone of surface rupture as mapped by Bonilla and others (1980) lies near the center of the area defined by the outline of the most distant slope failures; a similar relationship of slope failure to surface rupture was noted in the M=5.5 1979 Coyote Lake, California, earthquake (Keefer and others, 1980). This pattern indicates a symmetry to the energy distribution around the epicenter of the January 26 event (see map). This symmetry, however, is misleading, for all slope failures southeast of the January 26 epicenter were in fact triggered by the January 24 event. Moreover, most of the new (or renewed) failures caused by the January 26 event occurred to the northwest of the January 26 epicenter. Renewed failures caused by the January 26 event also occurred in the vicinity of the January 24 epicenter (stations 7, 11, 12, and 14), and station 35, to the southeast of the January 26 epicenter, underwent renewed failure. Thus, both the January 24 and the January 26 shocks were "directed", in that their shaking intensity was asymmetrically distributed; that asymmetry probably indicates a unilateral propagation of the fault rupture in the direction of higher intensity. In short, the energy of the January 24 event was directed to the southeast, whereas the energy of the January 26 event was directed to the northwest. On the basis of their study of the relation of the peak acceleration ratios to the azimuths from source to station for the two events, Boore and Porcella (1980) came to a similar conclusion for these events.

SEISMIC INTENSITY

The intensity of ground motion is one of the principal parameters controlling the occurrence and the distribution of earthquake-induced landslides. Strong-motion seismograms record the ground motion as plots of acceleration versus time. The peak acceleration is the measurement most commonly used to indicate seismic intensity, although it is generally recognized that the duration of shaking is also a factor affecting structural damage and ground failure (Dobry and others, 1978). In the absence of strong-motion records, the intensity of ground motion may be estimated from careful study of shaking damage (both structural and nonstructural), other shaking phenomena, and perceptual impressions of witnesses, and then expressed according to the Modified Mercalli Intensity (MMI) scale (Wood and Neumann, 1931; Richter, 1958).

The closest strong-motion record for the January 24 event of the GMDES was written at San Ramon, 16 km northwest of the epicenter, where a peak acceleration (A) of 15 percent g (ground level) was registered (Bedrossian, 1980). However, two portable strong-motion instruments which were deployed after the January 24 event recorded the January 26 event in the near-field: Fagundes Ranch, 6 km northwest, where A=25 percent g was recorded and Morgan Territory Park, 9 km northwest, where A=27 percent g was recorded (Bedrossian, 1980).

The damage at the Lawrence Livermore Laboratory and in nearby downtown Livermore from seismic shaking during the January 24 event (see map) was confined to the breaking of window glass, jarring objects from shelves, overturning bookshelves, and failure of nonstructural building elements such as light fixtures and accoustical ceilings (Bedrossian, 1980). These types and this degree of damage are consistent with an intensity of MMI 7 (Richter, 1958). A house just south of Frick Lake (<1 km from the surface trace of the Greenville fault) suffered a broken chimney (Bedrossian, 1980); such damage is also consistent with MMI 7 (Richter, 1958).

Witnesses at a roadside store on Vasco Road, 2 km southwest of the Greenville fault, described the January 26 event as being approximately as intense as the January 24 event (objects knocked off shelves, but no structural damage--MMI 7), but of shorter duration. Witnesses to the northwest of the January 24 epicenter described the January 26 event as the stronger of the two, while those to the southwest described the January 24 event as the stronger.

At the Sunrise Mobile Home Park, just north of I-580 and Livermore Boulevard (sec. 34, T. 2 S., R. 2 E.), several tens of mobile homes were thrown off their jacks during the January 24 event, and they suffered significant damage as a result (Bedrossian, 1980). We visited this site on the early afternoon of January 26 and found that not only were many mobile homes knocked off their jacks, but most of them had been knocked over in the same direction, N. 60° E. This was true not only for mobile homes along a street on which they were oriented so that they fell off in their short direction, but also for those on the cross street, where the homes fell off in their long direction, and even for those mobile homes around a cul-de-sac, where they fell off obliquely --all to the northeast. This remarkable uniformity in the direction of displacement suggests that these mobile homes all were dislodged by the same pulse of ground motion.

The direction of displacement of the mobile homes, N. 60° E., is approximately normal to the trace of the Greenville fault in this vicinity (see map). The mobile home park is approximately 3.2 km from Frick Lake, which is the closest point to it that is located on the surface trace of the Greenville fault (Bonilla and others, 1980). The single seismic pulse which threw these mobile homes off their jacks may have been either a dilatational wave traveling normal to the fault or a transverse wave traveling along the fault (the other half of a double-couple source).

We measured the jacks under one of the dislodged mobile homes: their rectangular pyramid base width was 22 cm, their height, 40 cm. There were five or six jacks on each side of the mobile home, and they rested on wooden blocks, approximately 40 cm on a side, which in turn were laid on bare earth. Cursory inspections of a number of the other dislodged mobile homes showed similar sizes and arrangements of jacks. On the basis of the dimensions of the jacks, we made a rough estimate of the amplitude of the seismic wave that had dislocated the mobile homes. A ground acceleration of at least (A=½ g (base/height) =) 0.28 g would have been required to begin to rock the jacks. This estimate of 28 percent g for the January 24 peak acceleration agrees well with the acceleration measured at Morgan Territory Park (27 percent g), at a similar magnitude and distance, for the January 26 event. A peak ground displacement of at least 11 cm (½ (base)) would have been required for complete toppling of the jacks (assuming the mass of the mobile homes to be much greater than the mass of the jacks). These estimated values for peak ground acceleration and ground displacement during the seismic wave which traversed the Sunrise Mobile Home Park--28 percent g and 11 cm--are roughly equivalent to the values expectable given a seismic shaking intensity of MMI 7+ to 8- (R. C. Wilson, unpub. data).

We conclude, therefore, that most of the slope failures which occurred during the GMDES took place under a seismic shaking of intensity MMI 7. Those failures located within 1 km of the fault, or in sites subject to topographic amplification (see discussion below), may have experienced somewhat higher intensities (MMI 8), whereas failures located more than 10 km from the zone of surface rupture (see map) may have been undergone shaking at the MMI 6 level.

ROCKFALLS

As in previous moderate (M=5-6) California earthquakes--Oroville 1975, Santa Barbara 1978, and Coyote Lake 1979--the predominant types of slope failure were rockfalls and soil/debris falls (as defined by Varnes, 1978). As in the 1978 Santa Barbara earthquake (Harp and others, 1980), most of the rockfalls from the GMDES occurred along artificial roadcuts rather than on natural slopes. These rockfalls usually occurred in steep roadcuts in Cretaceous marine sandstone, and they were generally very small (< 5 m³), although somewhat larger rockfalls occurred at sta. 15 (~ 20 m³), sta. 16 (~ 10 m³), sta. 30 (~ 15 m³), and sta. 35 (10 m³). Figure 1 shows a typical rockfall at sta. 35.

A number of these rockfalls shed debris onto roadways during the GMDES, but there were no road closures and there was very little other damage from rockfalls. Note, however, that in a larger earthquake in this area rockfalls could cause much damage in the form of road blockage and damage to vehicles and structures.

Several of the rockfalls caused by this earthquake (stas. 35, 38, 39, 40, and 42) showed signs of popping or spalling, which indicated that the rock had failed in tension. These failures occurred on very steep slopes ($>70°$) of roadcuts and of arroyo walls. They occurred in massive, unjointed, weakly cemented, fine-to-medium-grained Miocene marine sandstones. Several rockfalls left concoidal-shape scars near the midpoint of the slope (fig. 2) and did not develop typical shear surfaces. During the 1976 Guatemala earthquake, similar slope failures were observed in Quaternary volcanic ash (Harp and others, 1981).

In rock with high tensile strength (>150 psi), discontinuities (such as joints and bedding planes) commonly control the geometry of rockfalls during earthquakes (Keefer and others, 1978). However, materials with low tensile strength (< 50 psi), such as some of the weakly cemented soils and rocks of the Livermore area, do not develop prominent joints. Failure occurs when the tensile or shear strength of the intact rock is exceeded.

Dynamic modeling by Sitar and Clough (1983) of slope failures in weakly cemented soils and rock has shown that on slopes greater than 70°, regions of tension develop as does shear at different stress levels during earthquakes (fig. 3). According to this model, the first part of the slope to fail (at low seismic stress levels) lies near the midpoint of the slope, where a concentration of tensile stresses develops. This region fails once the tensile strength of the intact rock or of any discontinuities is exceeded. The geometry of the failures at stas. 35, 38, 39, 40, and 42 indicates that this model accurately predicts some of the observed failures in weakly cemented materials.

At higher stress levels, particularly on vertical slopes, tension cracks develop behind the slope; these tension cracks may interconnect with a potential zone of shear failure near the toe and lower part of the slope, to cause a topple. Topples of vertical slopes in Quaternary alluvium were observed at stas. 34 and 36. At sta. 36 during the January 24 shock, a section of a narrow ridge, approximately 0.5 m high, 7 m long, and 1-2 m thick (fig. 4), which had been left as an erosional remnant between two steep-walled gullies, was broken off at the base and it fell. The relative paucity of vertical slopes in the Livermore area limited the observation of this type of failure mechanism.

The fact that the most distant slope failures (at sta. 40; also several small rockfalls in Del Puerto Canyon 25 km southeast of map area) occurred as tensile failures near the midpoint of the slope is consistent with the model cited just above, which predicts that a tensile failure near the midpoint of a steep slope will occur at the lowest stress levels (presumably those farthest from the fault rupture).

By means of the procedure for testing irregular-shape samples described by Brock and Franklin (1972), we determined the point load index, I_{s50}, which is a measure of tensile strength, for a variety of samples of intact material taken from several of the slope failure sites. Table 2 shows mean values of point load index. For comparison, we also measured the point load indexes of some materials collected from sta. 10 which did not fail in tension. These results suggest that below a lower bound (between 17 and 30 psi) the tensile strength of intact rock governs its failure.

ROLLING BOULDERS

An unusual type of slope failure during the GMDES was the dislodging and rapid rolling of large boulders on steep hillsides. Some of the Cretaceous marine sandstones that crop out in the area have a characteristic spheroidal weathering pattern which produces rounded boulders up to several meters in diameter. These sandstones are resistant to erosion and so they form ridges in this area. The seismic shaking during the GMDES dislodged a number of boulders, particularly from the ridge just east of Morgan Territory Road (see map). Once dislodged, those boulders rolled down steep hillsides, picking up speed, until they crashed into trees on the hillsides or came to rest in the valley below. The dislodged boulders were up to several meters in diameter and weighed several tons, and the slopes are as steep as 70 percent and several hundred feet in relief; therefore, the boulders had considerable momentum and thus a high destruction potential.

At sta. 9, some 10 to 20 boulders from 0.5 to 3 m in diameter crashed through a grove of oak trees, stripping off bark and chunks of wood (fig. 5), and finally came to rest in the soft earth of the valley floor. (Some formed impact craters.) Several boulders reached Morgan Territory Road, and those left impact imprints on the pavement.

At sta. 7, a boulder 2 m in diameter hit Morgan Territory Road, punching completely through the asphalt pavement (fig. 6). Several other boulder impact imprints were found there. When we searched for the tracks of these boulders, we found that several, including the largest, seemed to have left no tracks. This mystery was resolved when we looked overhead and saw that large holes had been knocked through the canopy of leaves and branches. Fresh stubs of broken-off oak branches confirmed that, for at least the last part of their journey, these large boulders had dropped in an extremely steep arc through the air onto the road.

Similar instances of dislodged boulders have been reported in previous earthquakes. For example, in the 1906 San Francisco earthquake, a boulder crashed through a home near Hollister and killed a man (Youd and Hoose, 1978, p. 86). Since the GMDES, a number of boulder falls have been observed in the May 1980 Mammoth Lakes, California, earthquake. This mechanism of ground failure has not received much attention from technical observers. Yet, where they do occur, boulder falls represent a considerable hazard. Motorists on Morgan Territory Road during either the January 24 or the January 26 events could have been killed or seriously injured either by having a boulder strike a car, or by collision of a car with boulders lying in the roadway. Furthermore, any structures within the path of the rolling boulders would have been in danger. Fortunately, no reported injuries or loss of life resulted from falling boulders in the GMDES, and the only immediate cost appears to have been the expense of clearing and repairing Morgan Territory Road. However, any structures erected in this valley would be subject to this hazard in future earthquakes.

ROADFILL FAILURES

After rockfalls, the next most common type of ground failure from the GMDES was the settling and cracking of embankments under roadways (fig. 1). Similar effects were noted from the 1978 Santa Barbara earthquake (Harp and others, 1980) and the 1979 Coyote Lake earthquake (Keefer and others, 1980). These roadfill failures appear to be due to simple vibratory compaction of the roadfill materials caused by seismic ground shaking, although slumping may also occur if the embankment is especially steep (>70 percent grade) and has a relief of several meters or more, as at Vasco Road and Morgan Territory Road.

While the roadfill failures from the GMDES necessitated repairs of roadways in a number of locations (see map), only one--the settling of the Greenville Road overpass on I-580 eastbound (sta. 28)--caused closure of a roadway; I-580 eastbound was closed to traffic for approximately 6 hours, during which time traffic was rerouted over the older Altamont Pass Road. The settling of the roadfill at sta. 25 caused one lane of traffic to be closed on Vasco Road, but that damage was repaired within 5 hours. Figure 7 shows a typical roadfill failure (sta. 11).

One pertinent question was, why would roadfill which has undergone considerable vibration from heavy vehicle traffic over long periods of time evidence significant additional vibratory compaction after a brief period of seismic ground shaking? Perhaps the seismic shaking had a higher amplitude than the traffic-caused shaking. Another possibility is that the vibration from traffic is generally polarized in the vertical plane, while seismic vibration has significant horizontal components. Also, seismic shaking induces pervasive body forces which act on the entire embankment, whereas the traffic vibration involves the shifting of point loads on the surface. Further, the slopeward edge of the fill may not be as well compacted as the center portion, which bears the traffic and absorbs most traffic-caused vibration. In any case, it is clear that some roadfills are highly susceptible to seismically induced settlements and may fail even under a moderate earthquake such as the GMDES.

Another notable set of roadfill failures took place along Morgan Territory Road (see map, stas. 11, 12, and 14). These three failures each occurred along an outside lane of a curve in the road where it crosses the ridge-tops. The failures at stas. 11 and 12 were first noted on the evening of January 24; they were reexamined on January 25 and 26. By the afternoon of January 26, these sites had also been visited by a number of other reconnaissance teams, and a number of the fractures had been spray painted in order to detect subsequent displacements. On January 28, after the shock of January 26, we found new fractures and new extensions of previous January 24 fractures at these sites. Whereas the fractures from January 24 were most pronounced on the eastern and northeastern quadrants of the curves in the road, the January 26 fractures occurred preferentially on the southeastern and southern quadrants. The January 26 fractures were not as extensive or as abundant as the January 24 fractures, but they were significant--for example, a new January 26 fracture at sta. 12 extended some 5 m past the previous January 24 zone of cracking.

GROUND FISSURES NEAR THE FAULT TRACE

Several sets of ground fissures were observed on or near the trace of the Greenville fault just northwest of Vasco Road (see map, sta. 23). These fissures, also noted by Bonilla and others (1980) and by Bedrossian (1980), occurred in a zone approximately 100 m wide that extends approximately 500 m northwest from Vasco Road (between stas. 25 and 23, see map). Within much of this zone, the Greenville fault trace runs obliquely across steep hillsides (grade > 20 percent). The fissures exhibited both shear displacements (1-2 cm right lateral) and extensional displacements (up to 15 cm), most of them in a downslope direction. The interpretation of these fissures is somewhat problematical: they may reflect surface-fault rupture, slope failure of the surficial soils due to shaking, or a combination of the two. For a more detailed description and a map of these fissures, see Bonilla and others (1980, p. 5-8).

EFFECTS OF WET WINTER CONDITIONS

When we began the GMDES reconnaissance, one of our principal interests was in the effect of wet winter conditions on the mechanisms and distributions of seismically induced slope failures. Although the weather was fair and clear on January 24 and no measurable rainfall had been recorded since January 17, heavy winter rains (6.5 in. in the preceding month) for several weeks preceding the GMDES had saturated the surficial soils on the hillsides around the Livermore Valley. In some areas, the soil was still noticeably damp on January 24. Therefore, this appeared to be an excellent opportunity to observe the ground-failure effects of a significant earthquake under wet, winter conditions.

Our reconnaissance discovered a number of rainfall-induced preearthquake slope failures, most of them small (< 100 m³) earthflows that had been initiated by soil slumps. Many of these flows and slumps appeared to be very fresh; many contained buried patches of turf which were still green. Indeed, one of our concerns as we began the reconnaissance was that we might confuse these very recent rainfall-induced failures with failures caused by the earthquake. Fortunately, a close examination of our first few stations showed that this distinction was not difficult to make. Most of the rainfall-induced failures showed signs of postfailure erosion by subsequent rainfall (probably as the storm subsided). Small-scale channeling and some very small (< 1 m³) debris flows from the lobes of earthflows also provided clues of value to the identification of preearthquake failures induced by rainfall. In addition, the earthquake-induced soil failures presented a drier and more granular appearance than did the smoother and more flowing textures of the rainfall-induced failures.

Contrary to our expectations, we found the fact that the GMDES occurred during the winter rainy season apparently had minimal effect on the types of slope failure and the distribution of those failures. Despite careful search, only one very small (3 m³) earthflow was found (at sta. 5) that appeared to have been caused by the GMDES. A number of other earthflows were investigated, but they were all demonstrably pre-GMDES. A number of rotational slumps on hillsides in the northwestern quadrant of the map were also investigated; they too were all found to be pre-GMDES.

EVIDENCE FOR TOPOGRAPHIC AMPLIFICATION FROM THE GMDES

The preferential occurrence along ridge crests of the roadfill failures along Morgan Territory Road, north of the January 24 epicenter, (see map, stas. 11, 12, and 14), suggests that the interaction of topography with seismic waves may have had an important effect on the distribution of slope failures in this area during the GMDES. Seismic shaking can be amplified significantly on topographic promontories because of constructive interference or resonance effects (or both) (Wong and Jennings, 1975). Similar effects have been noted in previous earthquakes: San Fernando 1971 (Nason, 1971), Ferndale 1975 (E. L. Harp, unpub. data, 1975), Guatemala 1976 (Harp and others, 1981), as well as the post-GMDES (May 1980) Mammoth Lakes, California, earthquake (Harp and others, 1984).

With regard to topographic amplification effects, an intriguing observation is that the fracturing at stas. 11, 12, and 14 from the January 26 event occurred in a different quadrant of the road's curve than had the failures from the Jan. 24 shock. This difference in location probably reflects a difference in the direction of the strongest shaking, which in turn was due to the difference in location of the two shocks. Whatever the explanation, we know that the difference in the position of the roadfill fractures relative to the ridge crests is not due to local geologic control; if it had been so controlled, the new (January 26) fractures would have occurred in the same place as the old (January 24). These differences, therefore, must be due to the difference in the distance or the direction of the source relative to the ridge crests, or both; this strongly suggests the presence of a topographic amplification effect.

ABSENCE OF LIQUEFACTION EFFECTS

One common type of ground failure which was not observed in the GMDES was liquefaction-induced ground failure. A M=5.6 earthquake is large enough to present the opportunity for liquefaction at highly susceptible sites within 2-5 km of the fault surface (Youd and Perkins, 1978). We made a careful search of several sites potentially susceptible to liquefaction; we found no fissures, sand boils, nor subsidence. Frick Lake (see map), a shallow sag(?) pond on the Greenville fault, was carefully examined, but it yielded no evidence of liquefaction. The only fissures found in the vicinity were all on Laughlin Road, west of the lake, and they appeared to be either roadfill failures or surface ruptures along the Greenville fault (Bonilla and others, 1980). The seismic-shaking intensity at Frick Lake should have been fairly high, because of Frick Lake's proximity to the Greenville fault. Furthermore, we observed a nearby house to have a broken chimney, indicative of a shaking intensity of approximately MMI 7.

We also examined the embankment around Patterson Reservoir (see map), which is also very close to the mapped trace of the Greenville fault (Herd, 1977), and found there no significant fissuring nor other evidence of liquefaction.

During our reconnaissance of Altamont Pass Road (see map), we examined a small embankment failure in an earth dam constructed for a stock-pond just north of the road, but we found that failure to be a rainfall-induced slump that had occurred before the January 24 event and was not, therefore, related to the GMDES.

We therefore conclude that no liquefaction-induced ground failures occurred in this earthquake sequence.

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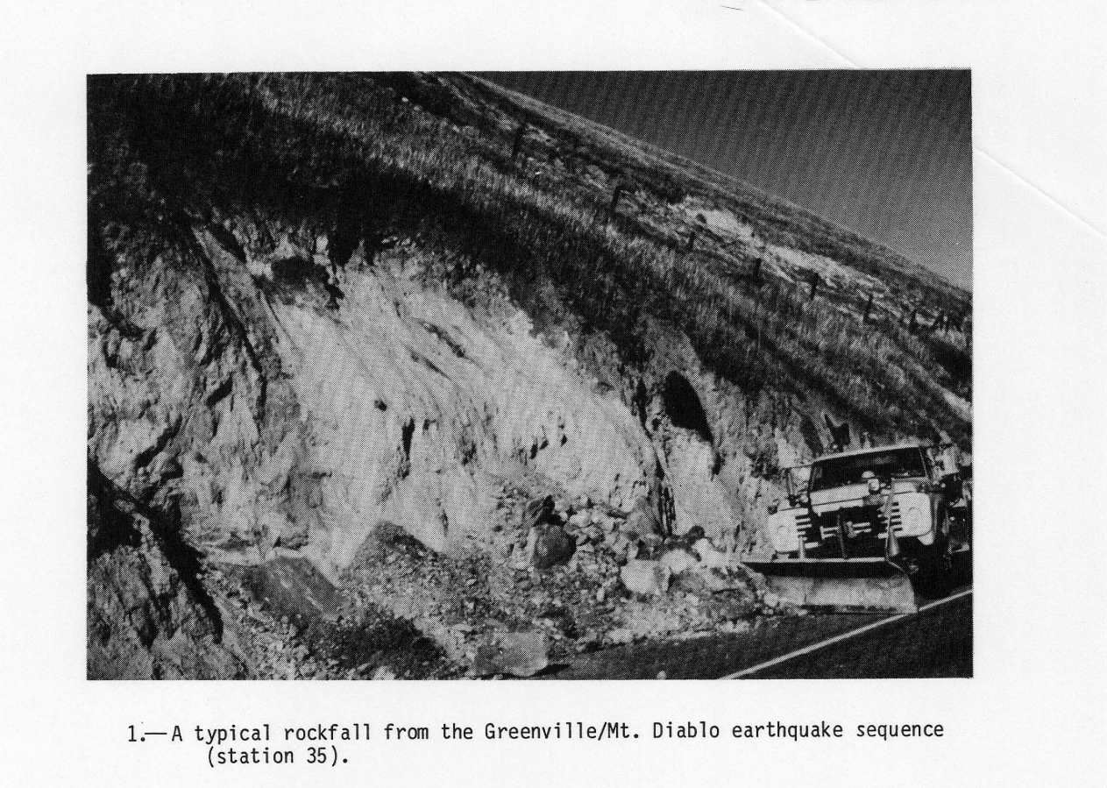
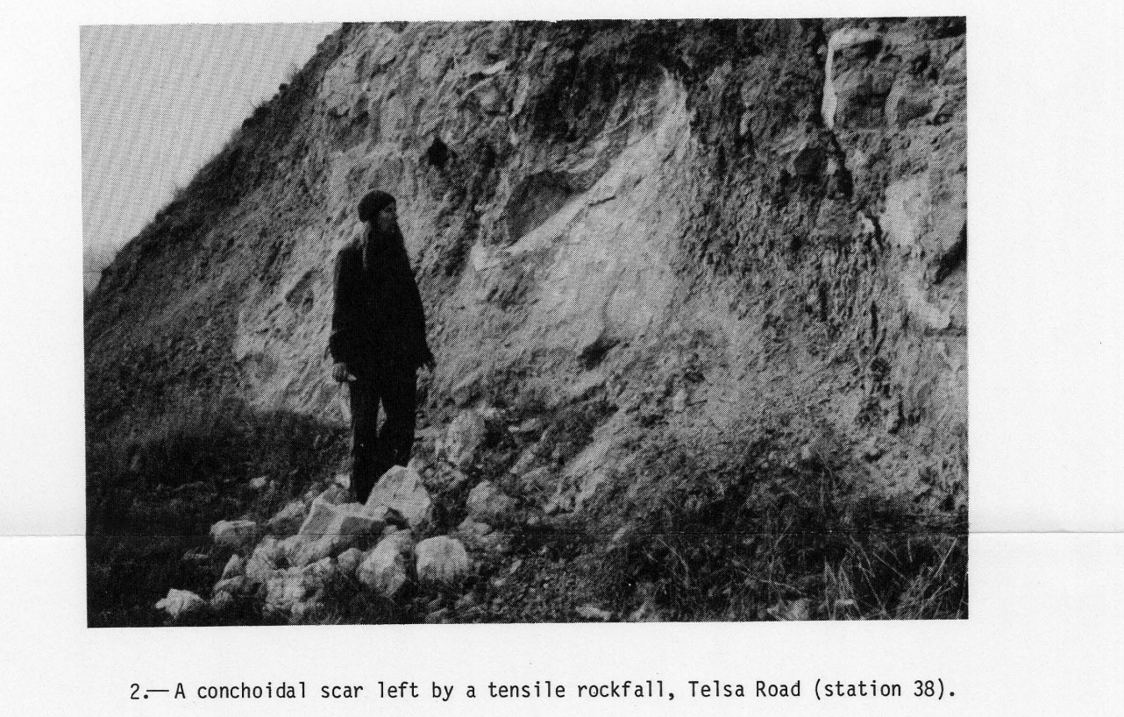
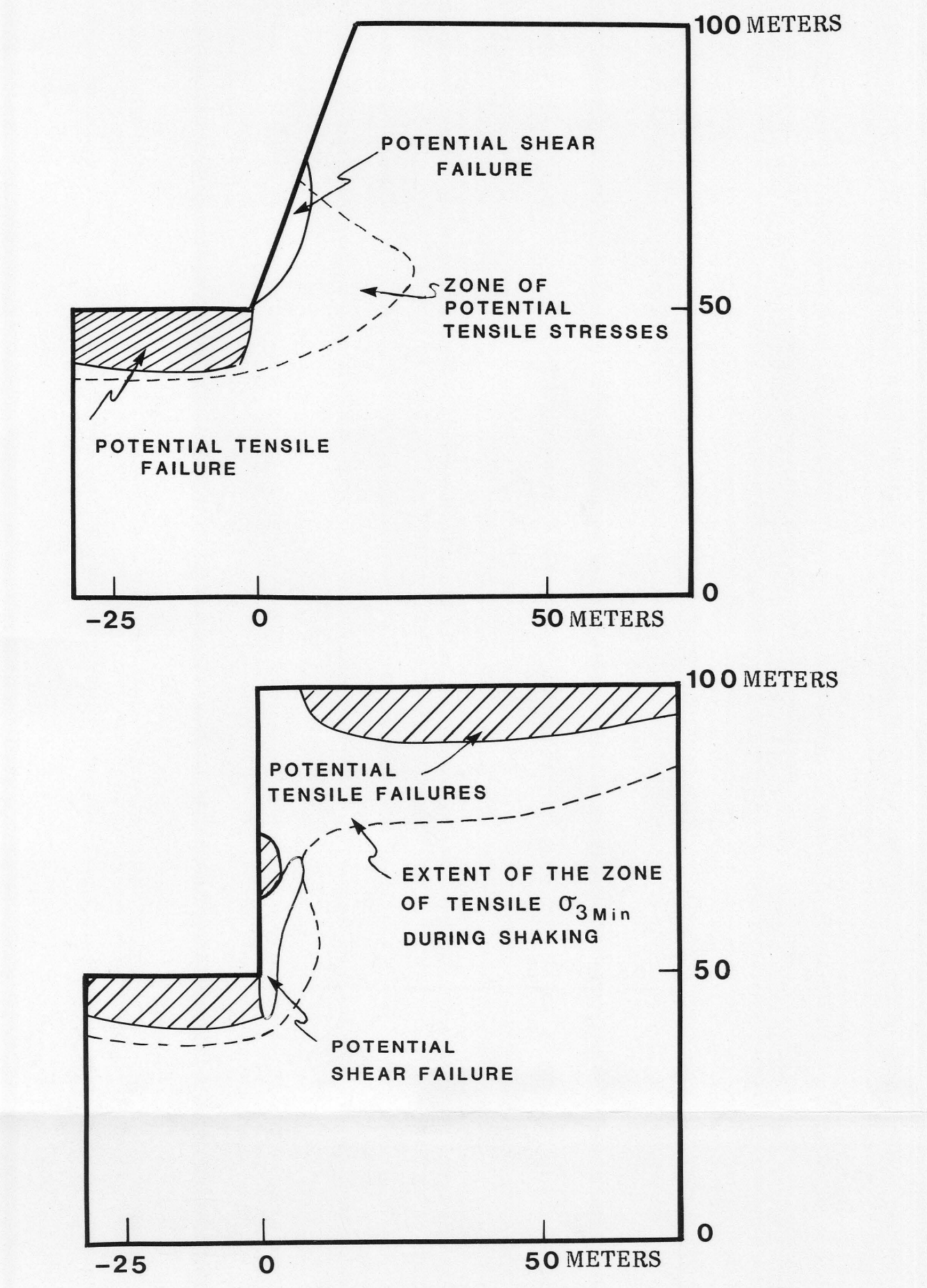


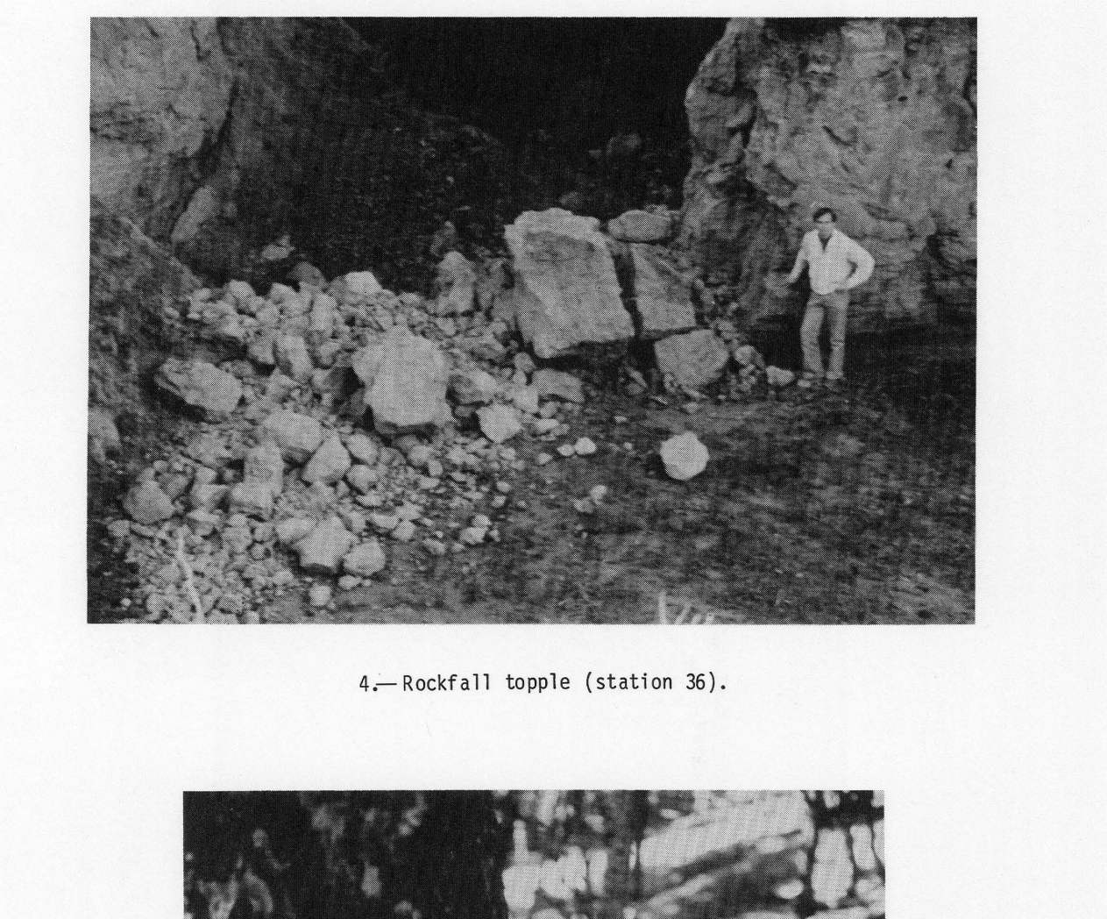
1.—A typical rockfall from the Greenville/Mt. Diablo earthquake sequence (station 35).



2.—A conchoidal scar left by a tensile rockfall, Tesla Road (station 38).

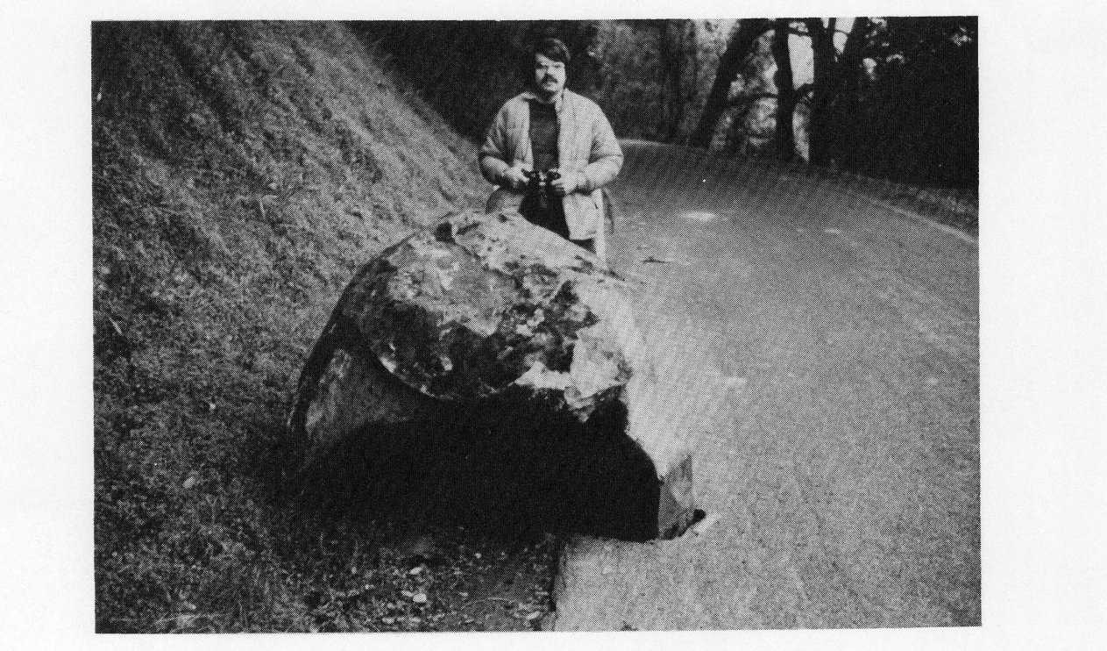


3.—Distribution of potential failure zones in very steep slopes. Adapted from Sitar and Clough (1983).



4.—Rockfall topple (station 36).

5.—Oak tree damaged by impact from a displaced boulder (station 9).



6.— Boulder that hit Morgan Territory Road (station 7).

7.—A typical roadfill failure from the Greenville/Mt. Diablo earthquake sequence (station 11).

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