Soil Slips, Debris Flows, and Rainstorms in the Santa Monica Mountains and Vicinity, Southern California

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 851

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By RUSSELL H. CAMPBELL

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Southern California residents have suffered death, injury, and property damage from debris flows generated by soil slips that occur during heavy rains; the process is a recurring major natural geomorphic agent in the region. Defenses and warning are possible but require speical engineering and procedures

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SOIL SLIPS, DEBRIS FLOWS, AND RAINSTORMS IN THE SANTA MONICA MOUNTAINS AND VICINITY, SOUTHERN CALIFORNIA

By Russell H. Campbell

ABSTRACT

On the record of the past decade, debris flows generated by soil slips during rainstorms present a greater risk of death and injury to southern California residents than all other kinds of slope failure combined. During the years 1962–71, 23 people in the greater Los Angeles area died as a direct result of being buried or struck by debris flows that probably originated as soil slips. Soil slips are shallow failures of colluvial soil and ravine fill. They have in common several characteristics and associations with rain storms that set them apart from other classes of landslides, such as rotational slumps and block glides. The latter, for example, depend more upon deep percolation of ground water and may not respond to the effects of heavy rainfall until long after a storm. In contrast, the shallow soil slips occur during, and only during, heavy rainfall. Soil slips appear to occur only on steep slopes, whereas other classes of landslides may occur on low slopes as well. Moreover, unlike the more deeply rooted landslides that damage structures situated on them by differential movement of the foundations, damage is due chiefly to inundation by, or high-velocity impact of, debris flows generated by the shallow slides. Debris flows are generated when the initial movement of slabs of soil and wedges of ravine fill causes a reconstitution of the sliding masses into viscous, debris-laden mud, which then flows down available drainage courses (in some accelerating to avalanche speed) until reaching gradients gentle enough for deposition to begin.

Soil slips require a combination of three conditions: (1) A mantle of colluvial soil or a wedge of colluvial ravine fill, on (2) a steep slope, where (3) soil moisture is equal to or greater than the liquid limit of the remolded colluvial soil. The most common range of slopes for soil slips that give rise to destructive debris flows is from about 56° (150 percent) to about 27°(50 percent). Slopes steeper than 56° generally do not have a continuous mantle of colluvium; most commonly they are bare bedrock. Soil slips on slopes of less than 27° are less common; moreover, the debris flows that they generate do not tend to accelerate downslope, though flows originating on steeper slopes above may be transported across with little or no loss of destructive power. The lowest slope on which a soil slip has been reported in coastal California is 15°. Most of the debris flows begin to deposit their coarser material on slopes of 12° (about 20 percent) or less, as indicated by the many fanhead slopes of from 10° to 12°, though transport on much gentler slopes is common. The soil moisture is almost entirely a direct result of seasonal rainfall. Because of the long dry season, the soil moisture at the beginning of the rainy season is generally well below field capacity. Once field capacity has been reached, further increase in the moisture content of the slope mantle requires rates of rainfall high enough so that water is added at a faster rate than it can drain away through the underlying subsoil.

The exceptional storm period of January 18–26, 1969, presented an unusual opportunity to determine the times of occurrence of numerous debris flows, establish their origin from soil slips, and compare the times of those events with rainfall records from an extensive network of continuously recording rain gages, as well as with a sequential set of radar weather maps. An empirical association between soil slips and rainfall was noted for that storm period; the same association seems applicable to the less severe storms of February 1969, February 1962, November 1965, and December 1965, during which smaller numbers of soil slips occurred. In all cases where the times of soil slip failure could be documented or reliably inferred, the rainfall intensity at nearby recording gages exceeded 0.20 inch per hour, and nearly all exceeded 0.25 inch per hour. Moreover, there were few reports of debris flows, interpreted to have originated as soil slips, that occurred before the total seasonal antecedent rainfall has reached 10 inches. A 10-inch antecedent rainfall appears to represent the total required to bring most of the colluvial soil of the area to field capacity, and a 0.25 inch per hour intensity apparently represents the minimum rate at which surface infiltration exceeds subsoil drainage for most of the colluvial soils of the area. With radar weather maps showing the distribution of high-intensity rainfall and slope maps showing the distribution of slopes of the most susceptible steepness, the empirical association may provide a means of recognizing areas where the hazard is greatest at any given time during a storm, and warnings to residents could be more specific and reliable.

INTRODUCTION

The exceptionally heavy rainstorm of January 18 to 26, 1969, covered a large part of coastal southern California. The area affected includes the Santa Monica Mountains, the southernmost of the east-west-trending Transverse Ranges. The central Santa Monica Mountains has been the subject of a continuing program (since 1961) of general-purpose geologic mapping by the U.S. Geological Survey in cooperation with the Department of the County Engineer, Los Angeles County (fig. 1). A poststorm reconnaissance of the project area was made in early February 1969 to assess the effects of the storm on slope stability. Although many different

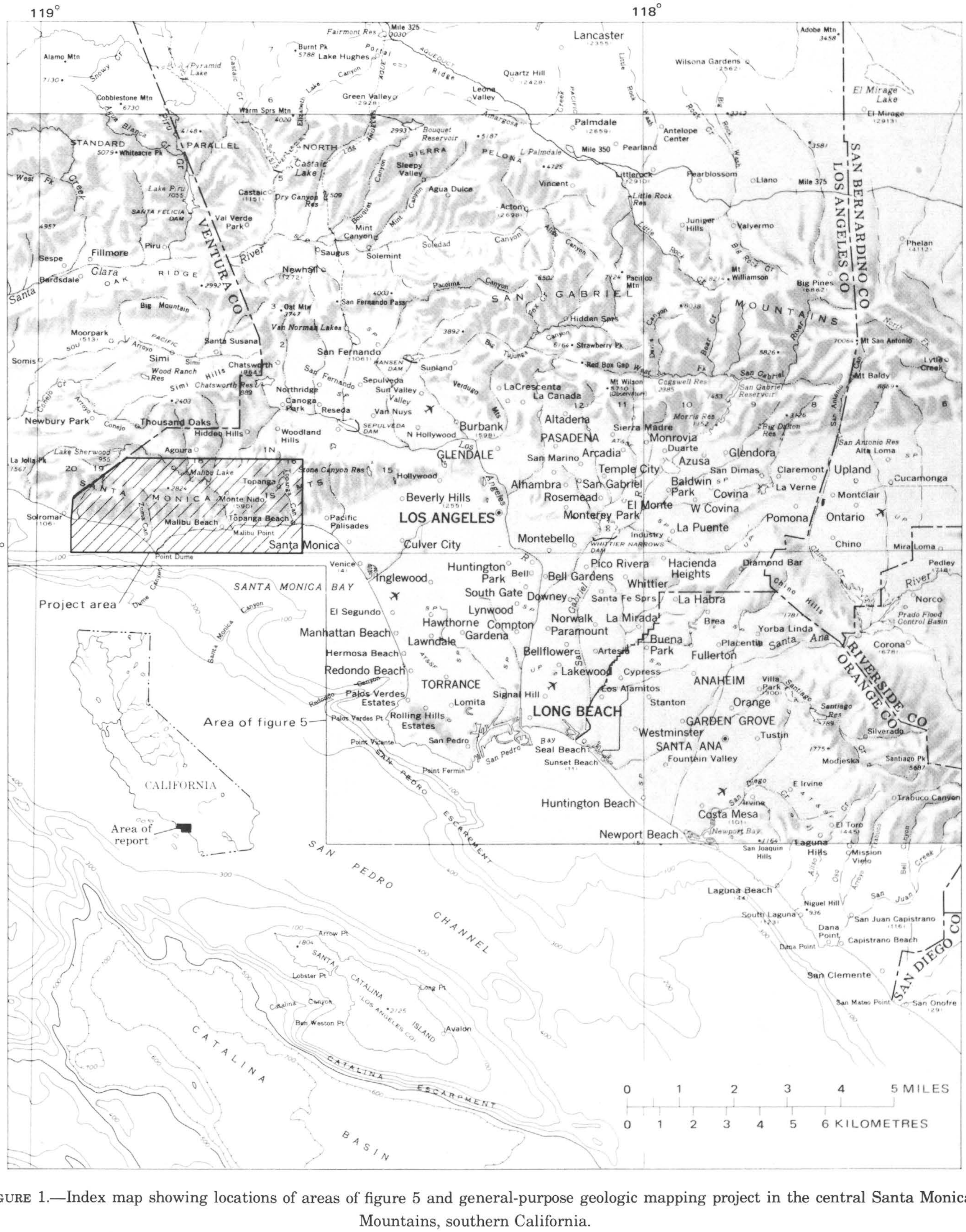


FIGURE 1.—Index map showing locations of areas of figure 5 and general-purpose geologic mapping project in the central Santa Monica Mountains, southern California.

kinds of landslide activity were in evidence, from rockfalls to deep rotational slumps, it was immediately obvious that hundreds of shallow scars had resulted from the mass failure of colluvial soil cover of steep hillsides and colluvial fill in steep ravines (Campbell, 1969). Most scars were on natural slopes (fig. 2), though some also occurred on manmade slopes.

Investigation of the downslope effects of these shallow failures indicates that, in many instances, the initial movement of slabs of soil and wedges of ravine fill caused reconstitution of the sliding wet masses into flowing, viscous, debris-laden mud, which then flowed down available drainage courses (accelerating to avalanche speed in some) until reaching a gradient gentle enough for deposition to occur. Structures in the paths of these flows were either inundated or subjected to high-velocity impact (fig. 3), and sometimes both. On Saturday morning, January 25, 1969, 8 debris flows ("mudslides" in the press vernacular) of this probable origin caused 12 fatalities among residents of the Santa Monica Mountains and nearby hilly areas. One month later, on the morning of February 25th, two more debris flows, probably of the same origin, resulted in eight more fatalities—five in the Santa Ana Mountains and three in the San Gabriel Mountains. Further study added three more fatalities to the list of the past decade—two during a storm in February 1962 and another during a storm in December 1965. On this record, these shallow, relatively small landslides present a greater risk of bodily injury to southern California residents than the more slowly moving deep rotational and block-glide landslides. Furthermore, this hazard is not unique to coastal southern California. Debris flows that have apparently resulted from storm-related soil slips have also caused extensive damage in Brazil (Vargas and Pichler, 1957), Japan (Oka and Katsurajima, 1971), coastal Alaska (Bishop and Stevens, 1964; Swanston, 1969), and other parts of the world.

The initial failures are slab or wedge shaped, with length per thickness ratios generally in excess of 10:1. In the scheme of Skempton and Hutchinson (1969), see especially p. 295), they are probably best characterized as "slab slides"; in coastal California they are more commonly called "soil slips" (Kesseli, 1943; Bailey and Rice, 1969). The masses that continue downslope as flows are probably best termed "debris flows"—a relatively broad class that may be interpreted to include subclasses such as "mudflows" and "silt flows" of more specific grain size. "Semiarid mudflow" and "debris-avalanche" are terms proposed by Sharpe (1938, p. 57–63) that would include the flowing masses; however, Sharpe's emphasis was clearly on events of larger volume and, although he inferred an origin by "slippage" (1938, p. 61) for debris-avalanches, mudflows and debris-avalanches can occur in semiarid regions in some circumstances that do not require concurrent heavy rainfall nor restrict the originating slippage to the surficial mantle. For the purposes of this report it seems preferable to use the compound term "soil slip–debris flow" to specify debris flows that are known or reliably inferred to have originated from soil slips. Many soil slip–debris flow events have been referred to as "mudslides" in press reports and other nontechnical accounts; however, "mudslide" has been applied to other events of such diverse character that its connotations are too broad to be appropriate here.

The January 1969 storm also revealed that soil slips and debris flows may have more widespread significance in the evolution of local landforms than previously suspected. The removal of soil cover in slab-shaped masses preserves the inclination of steep slopes and tends to preserve a sharp break at the crown. The downslope transport by flow ensures removal of the material to lower gradients where deposition takes place, preserving the slope break at the foot and accounting for the buildup of large "alluvial fans" at the mouths of short, steep drainage basins (fig. 4). That debris flows contribute to the formation of some fans has long been recognized (Blackwelder, 1928; Sharpe, 1938), and the significance of soil slips in the erosion of steep slopes in the San Gabriel Mountains has recently been noted (Bailey and Rice, 1969, p. 176; Rice and Foggin 1971). However, the widespread, perhaps dominant influence of this mechanism in the natural evolution of the landforms has gone largely unrecognized owing to the long recurrence intervals—75–150 years (Simpson, 1969, p. 14)—between storms of the magnitude of that of January 1969. Of course, soil slips occur in smaller numbers much more frequently than record-breaking storms and pose a recurring debris-flow hazard to many hillside residents.

The exceptional storm of January 18–26, 1969, provided a unique opportunity to examine the relations between rainfall and the debris-flow hazard in the Los Angeles area because: The wide areal distribution of heavy rainfall ensured that representatives of the full range of slope angles, soil types, bedrock type, and vegetation were subjected to rainfall intensities, durations, and totals that were closely monitored by a net of continuously recording rain gages; and the affected region included several populated areas where the severe damage and injuries drew attention to the times of failure causing many events to be reliably reported by the press or by other investigating agencies (fig. 5). The comparisons permit some approximations of limiting slope angles, and some rough qualitative observations of the effects of geologic soil type, soil thickness, parent material (bedrock or other), and vegetation. In addition,

A, Prestorm; photograph taken November 1968.

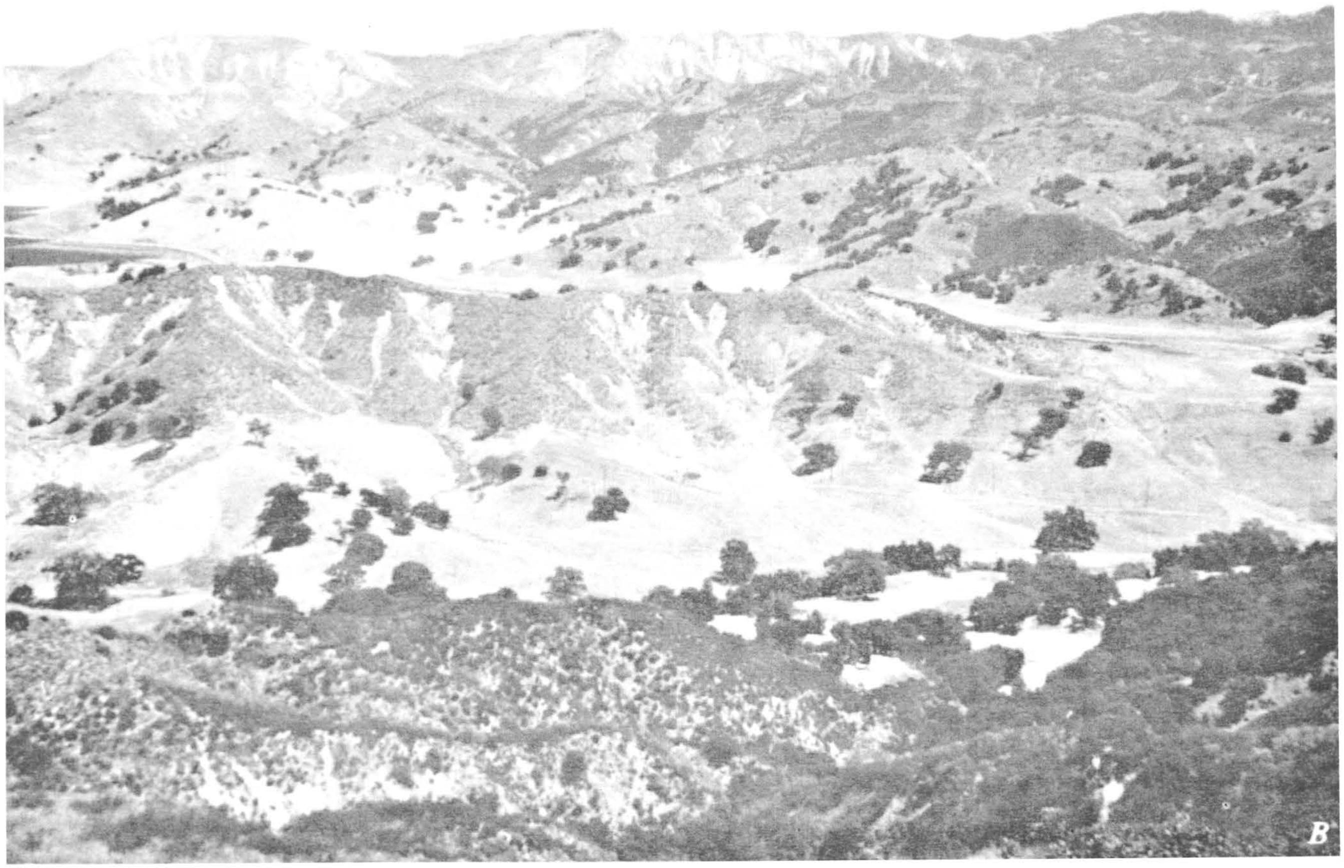
FIGURE 2.—Views northeast across

an empirical correlation between rainfall total and intensity and the times of observed slope failures leads to interpretations of the probable frequency of recurrence during lesser storms and to suggestions for minimizing the hazard to residents.

Summary accounts of the associations of events of debris-flow activity with rainstorms in the past 10 years in coastal southern California are included in a supplement at the end of the report. Events that are interpreted as of soil slip–debris flow origin are listed, with time, location, and the association of each event or group of events with rainstorm activity recorded at nearby continuously recording gages. Nearly all the pre-1969 reports of times, places, and nature of origin were taken from newspaper accounts—chiefly from the Los Angeles Times. The general sources of data for the 1969 storms are noted in "Acknowledgments." Low-altitude oblique aerial photographs supplied by the Los Angeles County Engineer and the Department of Building and Safety (City of Los Angeles) were particularly useful in recognizing scars of soil slips and freshly scoured ravines.

ACKNOWLEDGMENTS

My thanks to A. G. Keene, Head Engineering Geologist, and to S. H. Miller, Regional Engineer, of the Department of the County Engineer, Los Angeles County, for information on location and extent of damage by landslides in areas under their jurisdiction. Thanks, too, to C. A. Yelverton, Engineering Geologist, Department of Building and Safety, City of Los Angeles, for information on the location, character, time, and extent of damage at the sites of fatal landslides in the City of Los Angeles, and particularly, for an excellent photographic record of those failures. The personnel of the Los Angeles County Sheriff's Department, the Los Angeles County Fire Department, and the Los Angeles County Road Department also helped me to acquire information about the extent of damage and



B, Poststorm; scars formed during storm of January 18–26, 1969; photograph taken July 1969.

Liberty and Las Virgenes Canyons.

injury. The Los Angeles County Flood Control District kindly furnished rainfall records that supplemented those published by the ESSA (Environmental Science Services Administration) Weather Bureau; and the ESSA Weather Bureau Office (Radar) at Palmdale, Calif., generously loaned their set of radar maps of the distribution of precipitation that they made almost hourly during the 1969 storm periods. Much valuable advice and counsel was received from colleagues in the U.S. Geological Survey.

SOIL SLIPS AND OTHER LANDSLIDES

Shallow failures of colluvial soil and ravine fill have a number of characteristics and storm associations in common that set them apart from other classes of landslides, such as rotational slumps and block glides. The latter, for example, depend upon deep percolation of ground water and may not begin to move until many days or weeks after a storm. In contrast, soil slips occur only during heavy rainfall, and new ones do not appear after the rain ceases. (At higher altitudes, such as the higher parts of the San Gabriel Mountains, the water input into the soil may be provided by rapidly melting snow, instead of rain.) Because soil slips are generally limited to steep slopes, the kinds of landslides more commonly seen on gentle slopes are rotational slump, block glide, failure by lateral spreading, or liquefaction of sand and sensitive clay. The damage that may result is also different; differential movement of foundations is the major cause of structural damage by the more deeply rooted landslides, whereas inundation and lateral impact by flowing debris are the chief causes of damage that result from soil slips.

SOIL SLIPS: ANTECEDENT SLOPE CONDITIONS

The association of soil slips with rainstorms is clear evidence that slope-mantle materials that are stable under "normal" conditions become unstable during rainfall of sufficient duration and intensity. The antecedent conditions on the slopes that fail are probably

FIGURE 3.—Scar of soil slip and debris-flow channel above house in Old Topanga Canyon. Note train of deposits downslope from house. Slide of January 25, 1969; photograph taken within a few days by the Department of the County Engineer, Los Angeles County.

best seen by examining the slopes adjacent to soil-slip scars. Although the parts that fail and slide off must be less stable than those remaining, movement generally alters the soil structure so thoroughly that its nearest representative is the material that remains behind.

SLOPE ANGLES AND CHANNEL GRADIENTS

Although the total relief of the Santa Monica Mountains is not much more than 2,900 feet, many slopes exceed 30°, and slopes of 40° and more are common. Precipitous cliffs are present but are generally limited to the risers of flat-lying ledges of thick individual beds of resistant sandstone or volcanic rocks or to steeply dipping surfaces of resistant sandstone beds or volcanic rocks. Generally, slopes steeper than about 56° (ranging from about 45° to about 60°, depending on the character of the bedrock and the type of vegetation) are bare

FIGURE 4.—Soil-slip scars and debris-flow fans, Las Virgenes Canyon area. Photographs taken February 4, 1969.

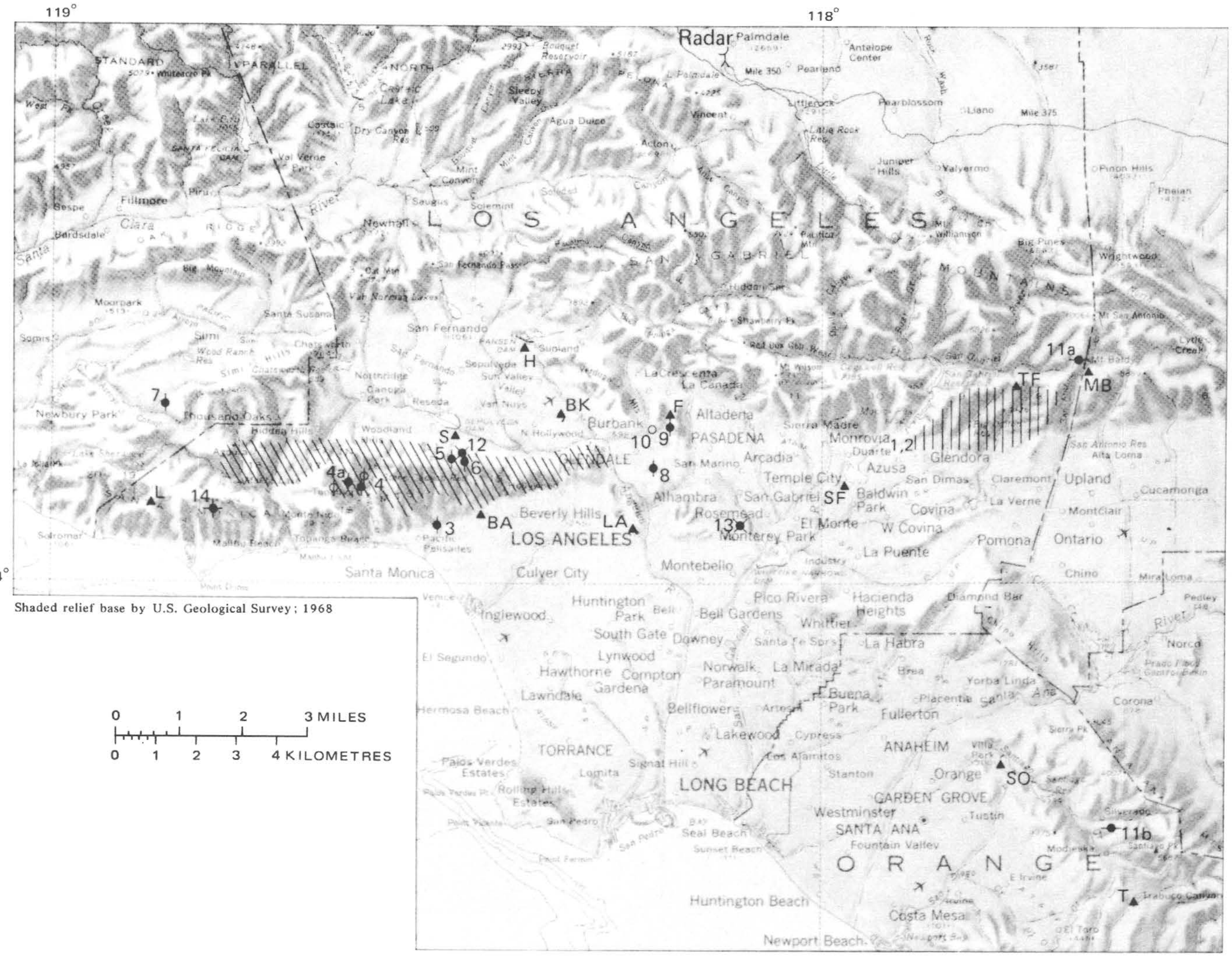
bedrock, too steep to retain a continuous mantle of colluvium. Generally, though by no means invariably, profiles of slopes of less than about 27° (50 percent) tend to be rounded, and profiles of steeper slopes tend to have relatively long straight segments. Depositional slopes of about 11° (20 percent) are common in the heads of many fans; consequently, the upper edges of depositional slopes are commonly marked by sharp breaks with steeper erosional slopes above. The more distal parts of fans have more gentle slopes. Alluviated valleys are more common on the north and south flanks of the mountains than in the mountain core where most of the canyons are V-shaped, and deposits in the bottoms are periodically flushed out by floods.

PARENT MATERIAL, COLLUVIAL SOIL, AND RAVINE FILL

The storm of January 18–26, 1969, was accompanied by soil slips in terrain underlain by every bedrock unit in the Santa Monica Mountains. Scars of similar shape and size were formed in the colluvial soils overlying granitic and slaty basement rocks, as well as the sandstone, shale, and volcanic rocks of the entire superjacent sequence. (For summary descriptions of the "basement" and "superjacent" rocks see Yerkes and others, 1965, p. 20–46.) The only evident controls by parent materials are indirect: (a) Generally, but not invariably, units containing more resistant rocks support steeper and longer slopes, and (b) colluvial soils developed over the volcanic rocks tend to be thinner and less continuous, perhaps because they do not generally support so dense a vegetal cover as the other bedrock types.

Almost all the soils on slopes steeper than about 11° are colluvial. They are derived from the parent material that underlies the slope (whether bedrock or surficial deposit, including artificial fill) by weathering and gravitational creep. Root wedging by vegetation, burrowing and walking by animals, and alternate swelling and shrinking of clays with changes in moisture contribute much to the breakup of the parent material and the downslope creep of the detritus. Rilling and other evidence of sheetwash by surface runoff are not common on the well-vegetated slopes, and raindrop impact is generally cushioned by the canopy of grass or chaparral. It seems probable that in years when rainfall intensities are low to moderate, soil creep on vegetated slopes during the dry season exceeds movement during the wet season, as reported by Anderson, Coleman, and Zinke (1959) and Krammes (1965) for slopes in the San Gabriel Mountains.

FIGURE 4.—Continued.



EXPLANATION

DEBRIS FLOWS

Numbers refer to descriptions in text and to times on rainfall curves

Feb. 10-11, 1962 — Dec. 29, 1965 — Jan. 25, 1969 — Feb. 25, 1969

Flows that caused fatalities
Represents a total of 23 fatalities

Jan. 22, 1969 — Jan. 25, 1969

Flows that caused damage but not injury

Area of most numerous scars in Santa Monica Mountains and vicinity, formed during storm of Jan. 18-26, 1969

Glendora-Azusa area of extensive damage (Jan. 22, 1969) and later heavy rainfall

L

Recording rain gage, showing initials of gage name

L, *Lechuza Pt FC;* S, *Sepulveda dam;* BA; *Bel Air FC;* BK, *Burbank;* Los Angeles Civic Center; F, *Flintridge FC;* TF, *San Dimas Tanbark flat;* MB, *Mount Baldy;* SF, *Santa Fe dam;* SO, *Santiago dam;* T, *Trabuco;* H, *Hansen*

FIGURE 5.—Locations of debris flows discussed in this report and of recording rain gages used to relate rainfall and soil slips.

The thickness to which colluvium accumulates on the slopes generally ranges from 1 to 4 feet, and the full range is from a few inches to an unknown upper limit that may be as much as several tens of feet. The ravines at the foot of the slopes serve as repositories for detritus from both adjacent slopes, and 2–10 feet is the most common range of thickness of the ravine fill. The retention of a colluvial soil mantle on slopes steeper than 34° (the common angle of repose for loose, dry colluvial materials) is probably best attributed to the cohesive effects of vegetation roots and soil moisture.

VEGETATION, FIRE, AND SOIL MOISTURE

Although vegetation has long been regarded as effectively retarding hillside erosion, grass and chaparral seem much less effective in preventing slabs of soil from sliding than in retarding grain-by-grain erosion. The vegetal canopy and litter reduce susceptibility to grain-by-grain erosion by raindrop impact and sheetwash, but the ratio of infiltration to runoff is thereby increased, leading to a more rapid and thorough saturation of the soil mantle. The consequence may be an increased susceptibility to soil-slip erosion, depending on specific site conditions. Vegetal cover has not prevented large numbers of soil-slip events on steep slopes covered by all kinds of grass and chaparral; however, the rooting character of the plants probably has a significant effect on susceptibility to failure by soil slip. Spreading, inlocking roots tend to bind relatively shallow parts of the soil together, and roots that penetrate deeply into the subsoil (including cracks in bed-rock) tend to bind the soil and subsoil zones together and wedge bedrock blocks apart. Detailed studies in the San Dimas Experimental Forest near Glendora (Corbett and Rice, 1966; Rice and others, 1969; and Rice and Foggin, 1971) have demonstrated that the frequencies and areas of soil slips are three to five times greater for grass-covered slopes than for brush-covered ones. A significant correlation between vegetation and the minimum angles at which soil slips occurred was also noted by Corbett and Rice (1966, p. 4–6) and Rice and Foggin (1971, p. 1488 Table 1, p. 1493, 1496), who found that the minimum angles for failure were less for grassy cover than for most chaparral vegetation. No comparable quantitative data are available for the Santa Monica Mountains area, where similar correlations would be in accord with general impressions but might be biased by the greater visibility of scars on grassy slopes. The rooting characteristics of the various kinds of vegetation also probably affect the degree to which the soil structure in different zones is remolded by movement.

Studies in the nearby San Gabriel and San Bernardino Mountains indicate that woody shrubs, such as chamise and scrub oak, have the deepest penetrating root systems (about 25 feet) of the chaparral vegetation, and that subshrubs such as California buckwheat, white and black sage, and chaparral yucca have maximum penetrations of about 5 feet (Hellmers and others, 1955). Many of the same species occur in the Santa Monica Mountains, where the storm of January 18–26, 1969, left the scars of soil slips on slopes dominated by both kinds of chaparral cover as well as by grass and mustard. Where the plants were the spreading, shallow-rooted type, the deposits below some scars included clumps of sod (fig. 6), suggesting that the near-surface zone of interlocking roots tended to hold together better than the deeper zones that were more completely remolded to fluid mud. Where more deeply rooted plant varieties predominated, some of the soil slips left the tattered remnants of bushes dangling from the scars by a few root strands or holding small island-like clumps of soil in place. Generally, however, the deeper rooted chaparral shrubs did not have sufficient binding effect to prevent large numbers of soil slips. Locally even large trees moved downslope together with the slabs of soil containing their shallow spreading roots (fig. 7).

The density and variety of vegetation may also affect the width and shape of slab failures. Where the slopes were covered with grass, mustard, and sage, the scars from the January 1969 storm were as much as several tens of feet wide, but where the stronger chaparral plants prevailed, the scars were generally only a few tens of feet wide and relatively longer, tending to resemble the failure of ravine fill. Where the chaparral plants were widely spaced and not mixed with grass, as in many areas underlain by the volcanic rocks, soil slips were less abundant. So many interrelated factors are involved, however, that these associations are not satisfactorily documented. The distribution of the grassy vegetation, for example, is controlled partly by slope (many low slopes have been cleared and pasture grasses encouraged), by the recency of destruction of the larger bushes by fire, and by the chemistry of the soils developed over the various parent materials. Grassy vegetation is particularly common over shaly bedrock units, and the steep slopes developed over shaly bedrock tend to be shorter than those developed over sandstone strata where chaparral predominates. The relatively long, narrow aspect of the slides in chaparral, therefore, may be as much (or more) dependent on slope length as on the variety of vegetation.

The effects of the states of growth of various types of

FIGURE 6.—Clumps of sod on soil-slip deposit. Note trace of drainage of excess water from deposit toward the left, across the cultivated field, and the similar trace in the foreground that comes from another soil slip out of sight to the right.

vegetation are not thoroughly known. However, the January 1969 storms struck when many of the annual grass seeds had germinated and green shoots, from a few millimeters to several centimeters long, had appeared on many slopes. These, of course, could have helped rainwater penetrate the surface of the soil.

From the historical record, it seems clear that during heavy rainstorms, watersheds that have been recently burned over yield greater amounts of debris than those that have not been burned (for example, see Simpson, 1969, p. 21). Fire destroys the vegetal canopy and some of the shallower roots, thereby exposing the surface to greater erosion by rain impact and sheetwash. Dry-season sliding is intensified (Krammes, 1965), probably resulting in much faster accumulation of channel-bed material (ravine fill). These conditions should not be expected to increase the probability of slab failures on the slopes but could increase the likelihood of ravine-fill failure and mobilization of bed material in lower channel reaches. Soil slips do occur on burned-over slopes, for Scott (1971) found that the 1969 debris flows generated in the burned watersheds above Glendora resulted from mobilization of channel-bed material, triggered, at least in part, by surficial slope failures. There were no large burned-over areas in the Santa Monica Mountains at the time of the January 1969 storms, so no comparative studies could be made there.

Loss of soil moisture during fire and, perhaps, drought conditions also may promote dry sliding because air-water surface tension in the soil interstices contributes to the cohesiveness of the colluvial soil. (At the other end of the scale, air-water surface tension is also reduced when excess water displaces the air in the interstices.)

As Krammes and DeBano (1965) report, many soils in chaparral watersheds have hydrophobic properties that appear to be associated with an organic coating on soil particles. The "nonwettability" may be intensified by the effects of brush fires. Hydrophobic properties are locally restricted to depth zones within the soil mantle where they can cause variations in moisture content and rate of infiltration in layers that are unrecognized without specific testing.

SOIL SLIPS: FAILURE CONDITIONS AND MECHANISM

It has long been accepted that debris flows are associated with the same kinds of rainstorms that gener-

FIGURE 7.—Large tree emplaced (nearly upright) in kitchen of residence in Old Topanga Canyon by soil slip–debris flow. Note doorframe on left strained from rectangle to parallelogram.

ate flood flows in the major streams of semiarid regions (Blackwelder, 1928); however, opportunities to document the association between rainfall and debris flows generated by soil slips, such as offered by the January 18–26 storm, are rare. The storm also enabled correlations between rainfall and soil slips that corroborate the applicability of the general mechanism suggested by Kesseli (1943).

SLOPE

Various observations on the relations of slope (or ravine gradient) to the characteristics of soil slips and their consequent debris flows are summarized in figure 8. Because both the slab-shaped slides of colluvial slope mantle and the elongated wedges of ravine fill are virtually identical in longitudinal section, the mechanism of failure is believed to be the same. The limiting angles appear to be the same for both, though significant differences may not yet have been detected. Of course, slope is only one of many parameters that affects the accumulation of colluvial soil mantle, its susceptibility to failure, and the behavior of consequent debris flows; therefore, the limits suggested on the diagram must be recognized as approximations and subject to large variations.

One requirement for slab failure of soil mantle is, of course, a soil cover of sufficient surface area, relative to its thickness, to be treated as a slab geometrically. This requirement is not met by most slopes steeper than about 55°, where bare bedrock predominates and soil accumulates only in small pockets and crevices. (Rockfalls are the most common failures from these precipitous slopes during rainstorms.) From about 34°—the common angle of repose for loose, dry colluvial soil—up to the steepest soil-mantled slopes, the area of soil cover decreases as the stability of surficial material is decreased. For most of the Santa Monica Mountains, the angle at which the lack of continuous soil mantle decreases the likelihood of soil slip is estimated to be about 45°.

Soil slips were common in the Santa Monica Mountains on slopes from about 25° to about 45° during the storm of January 18–26, 1969, and the lowest slope that failed was about 22°. For comparison, after the storm of November 21–25, 1965, Corbett and Rice (1966, p. 6) found that in the San Dimas Experimental Forest, in

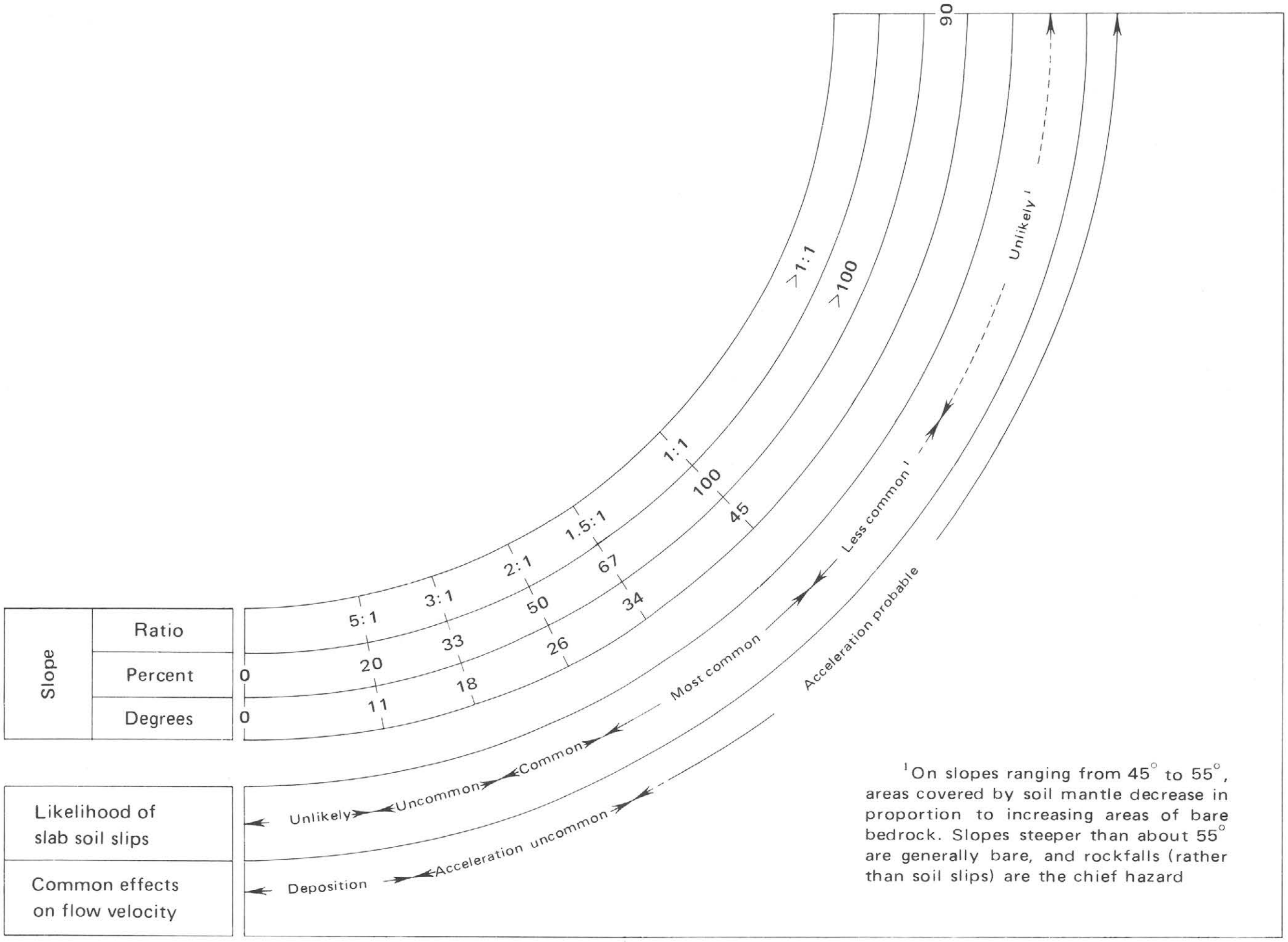


FIGURE 8.—Approximate relations of natural slopes to soil-slip failures.

the San Gabriel Mountains, no soil slips occurred on slope areas classed as less than 40 percent (about 22°), and most were in areas of slope-class 70 percent (about 35°) or greater. They add, however, that the slips reported in slope classes gentler than 70 percent are usually on small areas of steeper terrain within the slope-class boundary, and that most occurred on slopes of 80 percent (about 39°) or steeper. In contrast, Rice and Foggin (1971, p. 1489) found that the storm of January 18–26, 1969, caused soil slips on slopes as low as 60 percent (31°) in the same area.

In the Coast Ranges of central California, Kesseli (1943) reported numerous soil slips on slopes of from 18°–25° and one that originated on a slope as gentle as 15°. He referred to these as "disintegrating soil slips" because the slabs generally disintegrated into clods and blocks of sod that were scattered in discontinuous trains over the slopes below the failures. Although some were associated with lobate tongues of mud, indicating that parts of some slabs had liquefied and flowed, neither channel scour nor distant transport of material was noted, suggesting that any flows that formed underwent little or no acceleration as they progressed downslope. Gentler slopes, for which slab failures attributed to the same general mechanism have been reported (Skempton and DeLory, 1957, p. 379–381), have inclinations of about 10°; however, these are in London Clay, and movement was relatively slow and constant. Hutchinson and Bhandari (1971, p. 353) attribute a "mudslide" on a slope as low as 3.9° to a special circumstance involving pore water pressures above hydrostatic at the slip surface, caused by the rapid loading of the headward parts of the slide; here, too, the material involved in the failure was stiff fissured clay (Hamstead Beds).

FAILURE AND RAINFALL

Even though most of the soil slips occurred in uninhabited areas where they were not observed, the post-storm reconnaissance established that a vast multitude

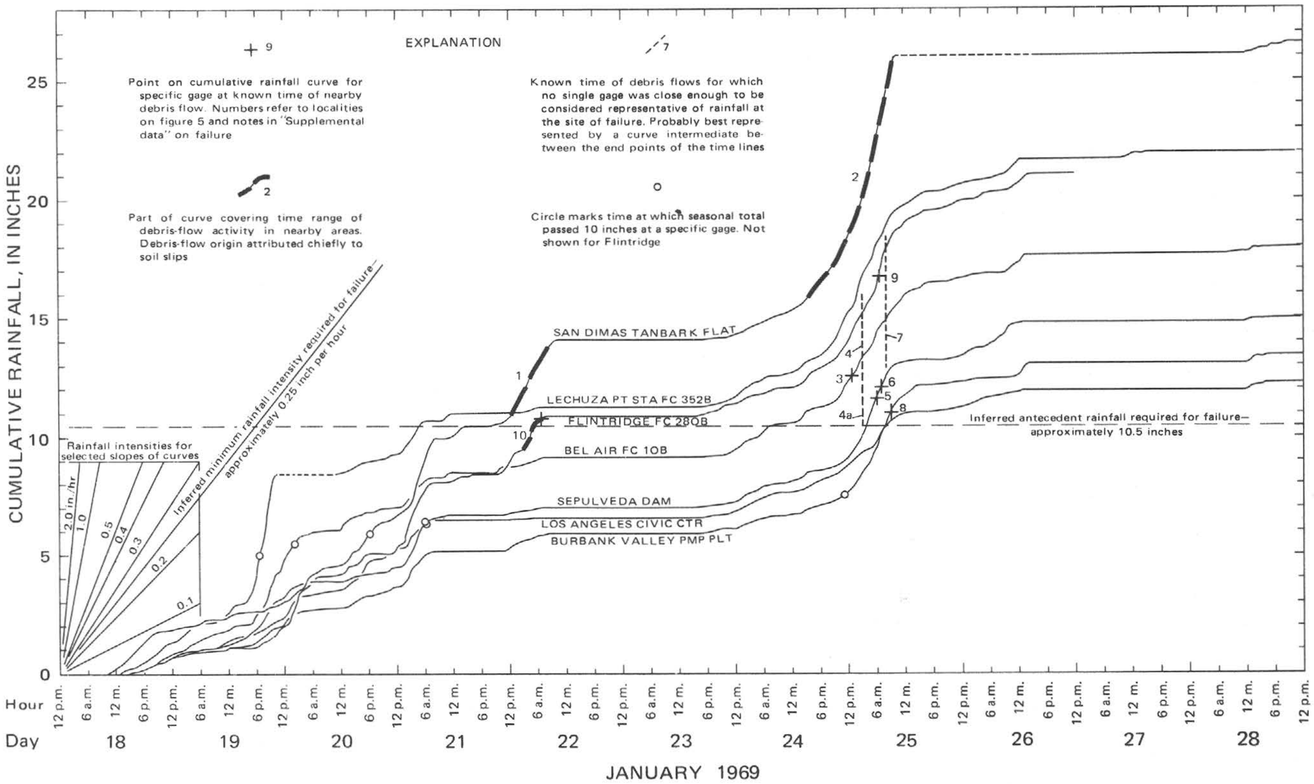


FIGURE 9.—Cumulative rainfall at selected continuously recording gages in and near the Santa Monica and San Gabriel Mountains, showing times of nearby slope failures, January 18–28, 1969.

of scars had appeared during the general 8-day period of storm activity. Of the many slides that occurred in inhabited areas, the best documented as to time are those that resulted in injuries and property damage. (See fig. 5.) These times are markedly clustered into two periods, a 9-hour period between midnight and 9:00 a.m., January 22, and an 8½-hour period between 12:30 a.m. and 9:00 a.m., January 25, and undoubtedly represent two climaxes of soil-slip activity in the area shown (fig. 9). The relationships suggest that few, if any, soil slips occurred at other times during the 8-day storm. Consequently, for the purpose of comparison with the time and distribution of rainfall of varying intensity, the times of the documented debris flows have been taken as representative of the time span of the great majority of the soil slips. Indeed, there seems little room for doubt that these failures occurred while rain was falling, and that failure was caused by dynamic conditions— conditions that were created by the storm, continued to build toward failure during periods of rainfall, and ceased when rainfall ceased.

The correlation in time between failure and heavy rainfall is strongly supported by comparisons of the documented slides with the hourly rainfall distribution maps made by the ESSA Weather Bureau Office (Radar), Palmdale, Calif., using FAA (Federal Aviation Administration) Air Traffic Control Radar. Figure 10A shows areas of rainfall at 11:30 p.m., January 24, 1969, 12:30 a.m, January 25, 1969, and 1:30 a.m., January 25, 1969; the dot shows the location of a debris flow in Brentwood at 12:30 a.m., January 25, 1969. (Figure 11 shows the residence and the slide scar.) Figure 10B shows rainfall at 2:26 a.m. and 4:26 a.m., January 25, 1969. The dot shows the location of a debris flow in the Topanga Canyon area (see pages 46–48 for description) at about 3:00 a.m., and the pattern shows the general area of many other slides that reportedly occurred in that vicinity at about the same time. Figure 10C shows rainfall at 5:29 a.m. and 6:26 a.m., January 25, 1969. The first of two fatal debris flows in Sherman Oaks occurred at 6:00 a.m. (Figures 12A and 12B show the residence and slide scar where one fatality occurred.) Figure 10D shows rainfall at 6:26 a.m. and 8:38 a.m., January 25, 1969. Fatal debris flows occurred in Glendale at 6:30 a.m., in Sherman Oaks at 6:50 a.m., and in Thousand Oaks at 7:45 a.m. (Figure 13 shows slide scars above the residence in Thousand Oaks.) Figure 10E shows rainfall at 8:38 a.m. and 10:15 a.m.,

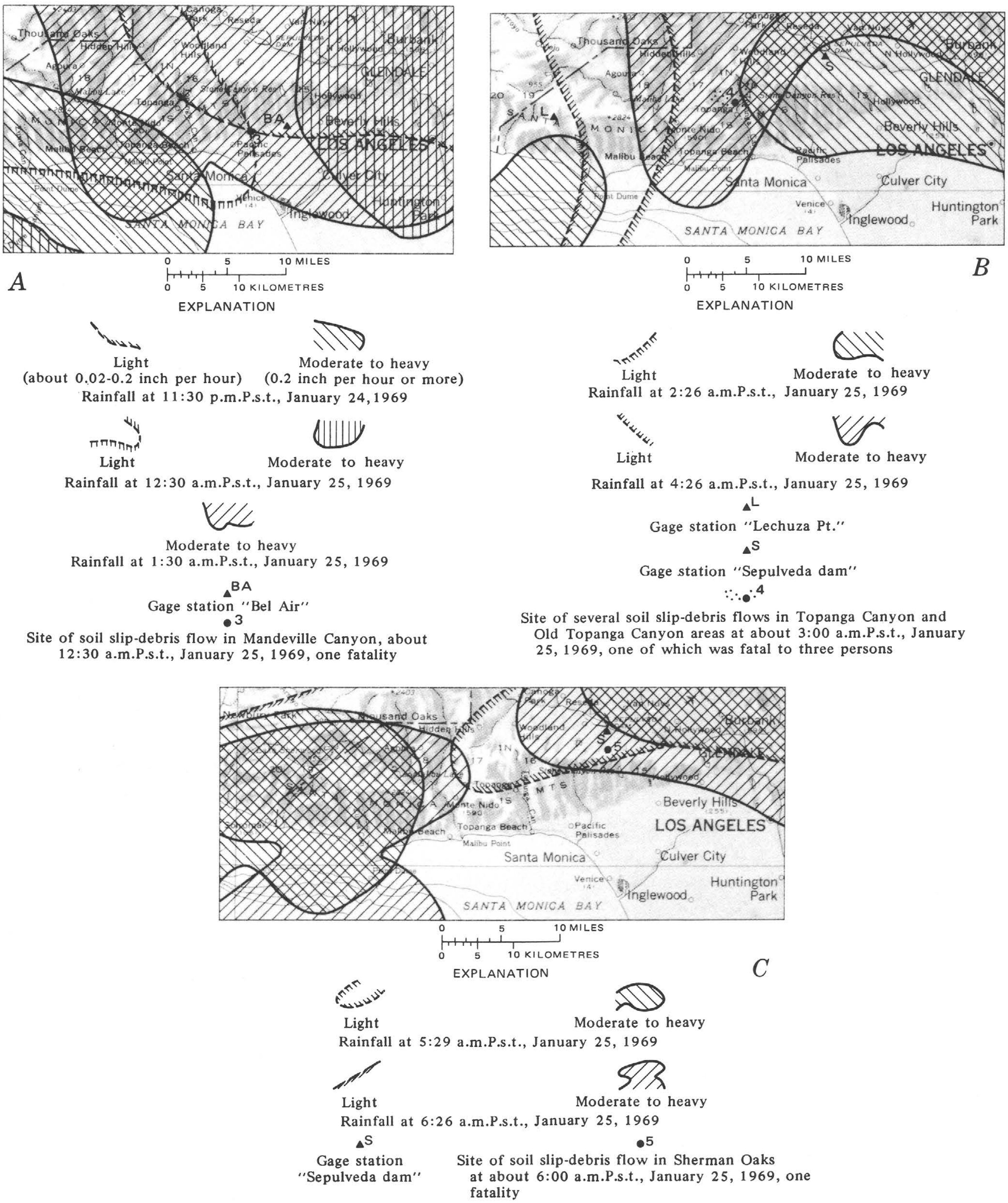
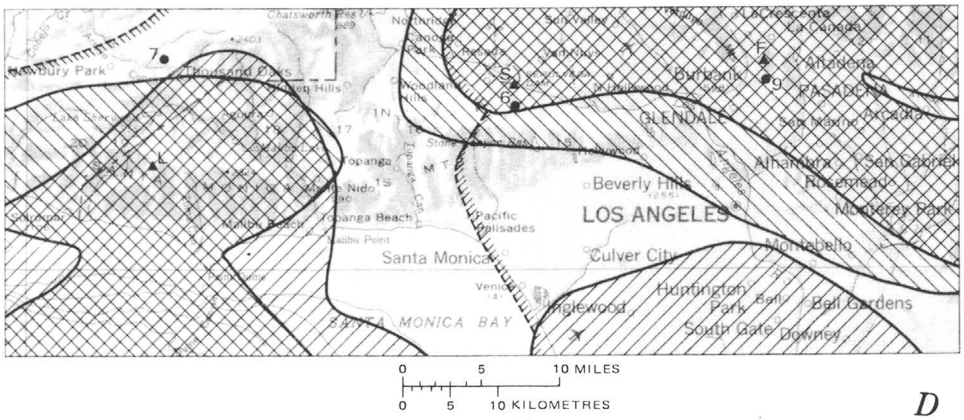


FIGURE 10.—Distribution of rainfall (radar) at times associated with soil slips. (Rainfall compiled from U.S. Weather Bureau maps made by FAA/ESSA Radar Unit, Palmdale, Calif.)



EXPLANATION

Light	Moderate to heavy	Light	Moderate to heavy
Rainfall at 6:26 a.m.P.s.t., January 25, 1969		Rainfall at 8:38 a.m.P.s.t., January 25, 1969	

▲F Gage station "Flintridge"

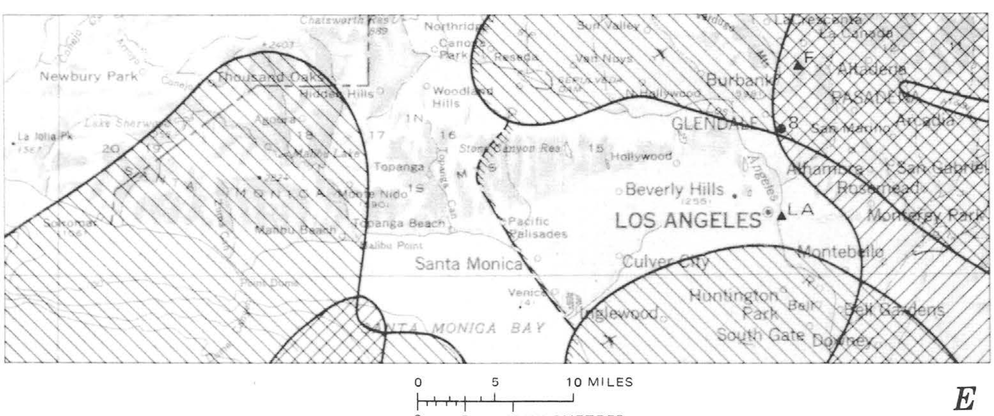
▲L Gage station "Lechuza Pt"

▲S Gage station "Sepulveda dam"

●6 Site of soil slip-debris flow in Sherman Oaks at about 6:50 a.m.P.s.t., January 25, 1969, one fatality

●7 Site of soil slip-debris flow in Thousand Oaks at about 7:45 a.m. P.s.t., January 25, 1969, one fatality

●9 Site of debris flow of probable soil slip origin in Glendale at about 6:30 a.m.P.s.t., January 25, 1969, two fatalities



EXPLANATION

Light	Moderate to heavy	Moderate to heavy
Rainfall at 8:38 a.m.P.s.t., January 25,1969		Rainfall at 10:15 a.m.P.s.t., January 25,1969

▲F Gage station "Flintridge"

▲LA Gage station "Los Angeles"

●8 Site of soil slip-debris flow in Highland Park at about 9:00 a.m. P.s.t., January 25, 1969, two fatalities

FIGURE 10.—Continued.

January 25, 1969, bracketing the 9:00 a.m. time of a slide in Highland Park. The time of a debris flow in the Old Topanga Canyon area (see pages 48–50) could be determined only as between 1:00 a.m. and 9:00 a.m., January 25, 1969; however, neighbors reported that many debris flows occurred, beginning about 1:00 a.m., and were particularly frequent for the next 4 or 5 hours. Figure 14 shows the damage to the residence.

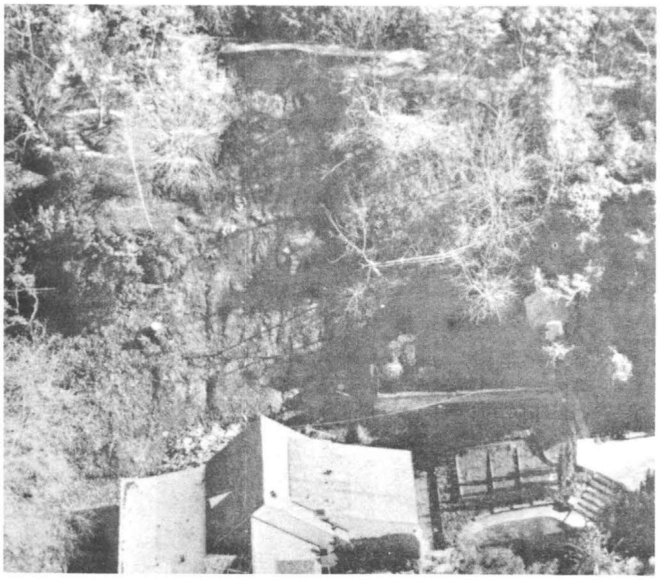


FIGURE 11.—Soil-slip scar behind house in Mandeville Canyon damaged by debris flow; one fatality. Photograph taken February 13, 1969, by the Department of Building and Safety, City of Los Angeles.

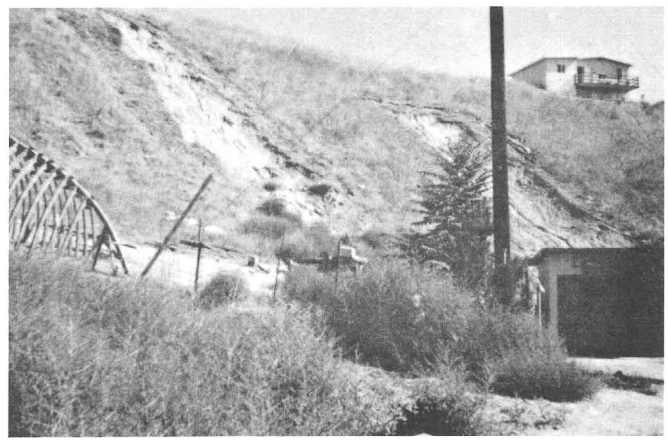
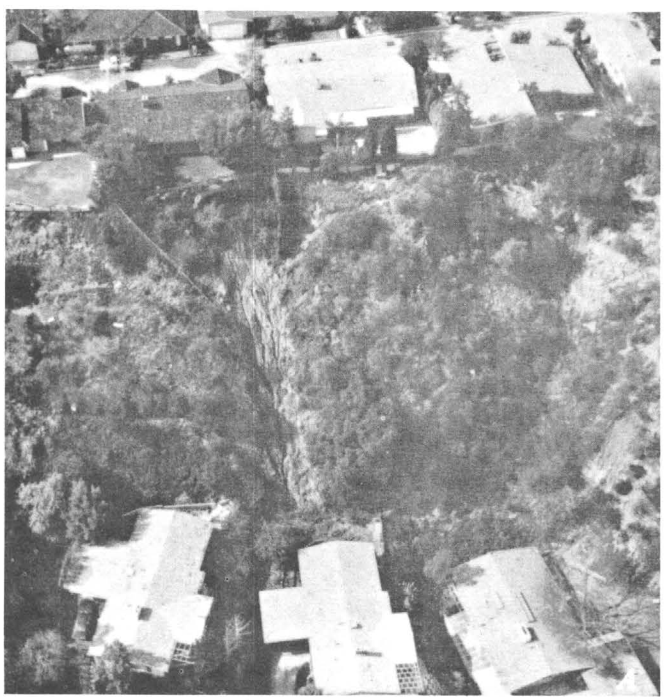
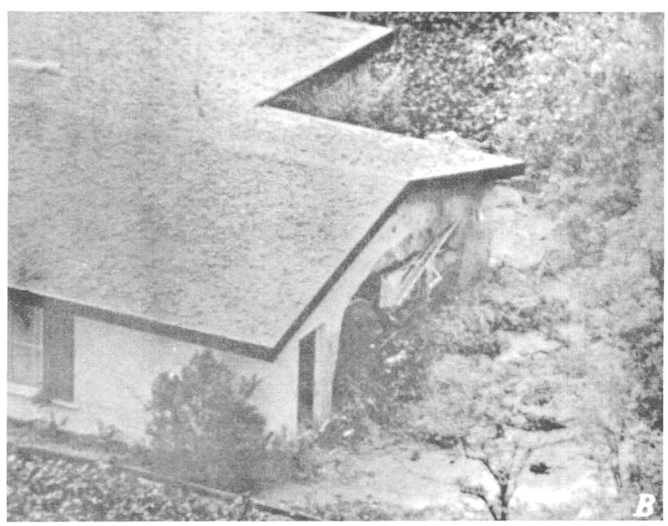


FIGURE 13.—Scars of soil slips above residence in Thousand Oaks. About 7:45 a.m., on January 25, 1969, a debris flow generated by the slip on the left broke into the rear of the house, killing a sleeping guest in the back bedroom.

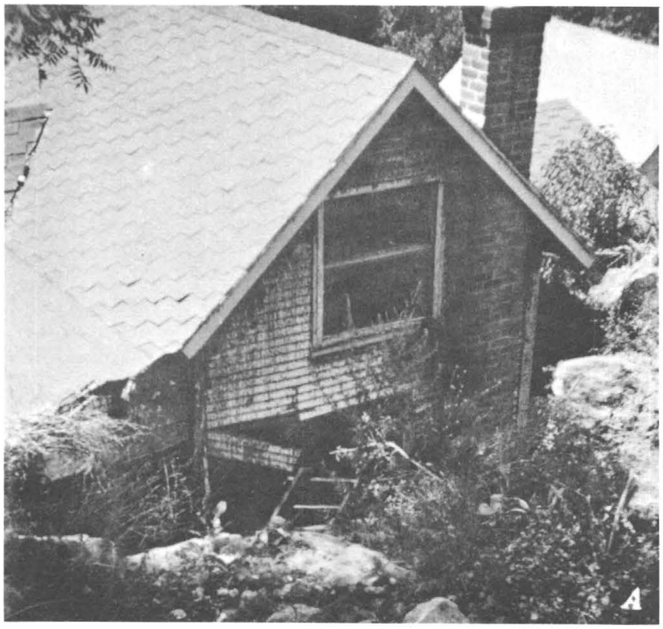


A, Scar on hillside behind house. Note rills eroded by rainwash on bare scar area. Photograph taken February 13, 1969, by Department of Building and Safety, City of Los Angeles.



B, Damage to upslope side of house, showing broken wall of room where sleeping resident was killed. (Photograph by Hollywood Citizen News, courtesy of Department of Building and Safety, City of Los Angeles.)

FIGURE 12.—Residence in Sherman Oaks damaged by soil slip–debris flow about 6:00 a.m., January 25, 1969; one fatality.



A, Flow broke through rear wall of lower story of a two-story house after "ski jumping" from top of vertical cut about 8 feet high. Upper story splattered (note broken window) but not entered by main flow.

B, View through house from the front. Refrigerator and other heavy appliances, carried from kitchen in rear and through partition into living room in front, trapped and killed one occupant. All coarse debris remained inside, only muddy water flowed out the front.

FIGURE 14.—Residence in Old Topanga Canyon damaged by soil slip-debris flow between 1:00 a.m. and 9:00 a.m., January 25, 1969; one fatality.

The maps (fig. 10) document that rain was falling at the sites of failure when failure occurred, and they indicate that the rainfall at the sites of failure was "moderate to heavy" (about 0.2 in/hr or greater) at the times of failure. The lack of "moderate to heavy" rain covering the Mandeville Canyon site at 12:30 a.m., January 25, 1969 (see fig. 10A) may be partly attributable to radar characteristics[1] rather than to an actual absence of rain over the area at 12:30 a.m.

FIGURE 15.—Scar above site of residence destroyed by debris flow indicates origin by soil slip; Highland Park, two fatalities at about 9:00 a.m. January 25, 1969. Photograph by City of Los Angeles, Department of Building and Safety.

Some uncertainty in the correlation of the radar maps with ground effects arises from the transfer of the radar data from compilation sheets at about 1:2,000,000 scale to the more detailed bases needed for plotting soil-slip locations (about 1:500,000 scale, at a minimum). Although the radar-scope image is sufficiently precise to warrant such enlargement (John W. Fassler, Chief Radar Meteorologist, ESSA/FAA Radar Unit, Palmdale, California, oral commun., September 9, 1970), the enlarged base for the radar maps was difficult to register to the more detailed maps on which soil-slip locations were plotted.

All the foregoing time-documented debris flows are believed to have originated from soil slips. I examined all but two of the sites (Glendale and Highland Park) and found distinctive scars in the source areas of each. Photographs of the Highland Park site by the City of Los Angeles, Department of Building and Safety, clearly show a slide scar in the source area (fig. 15). Only newspaper accounts of the debris flow at the Glendale site have been examined, and although they do not explicitly indicate the presence of slide scars in the

[1]Radar at the Los Angeles International Airport, the one nearest the site of failure, was temporarily operating with circuits that are designed to increase sensitivity to aircraft by removing effects of precipitation but that prevent detection of weather activity within 30 miles of the radar site (Benner and Smith, 1968, p. 18).

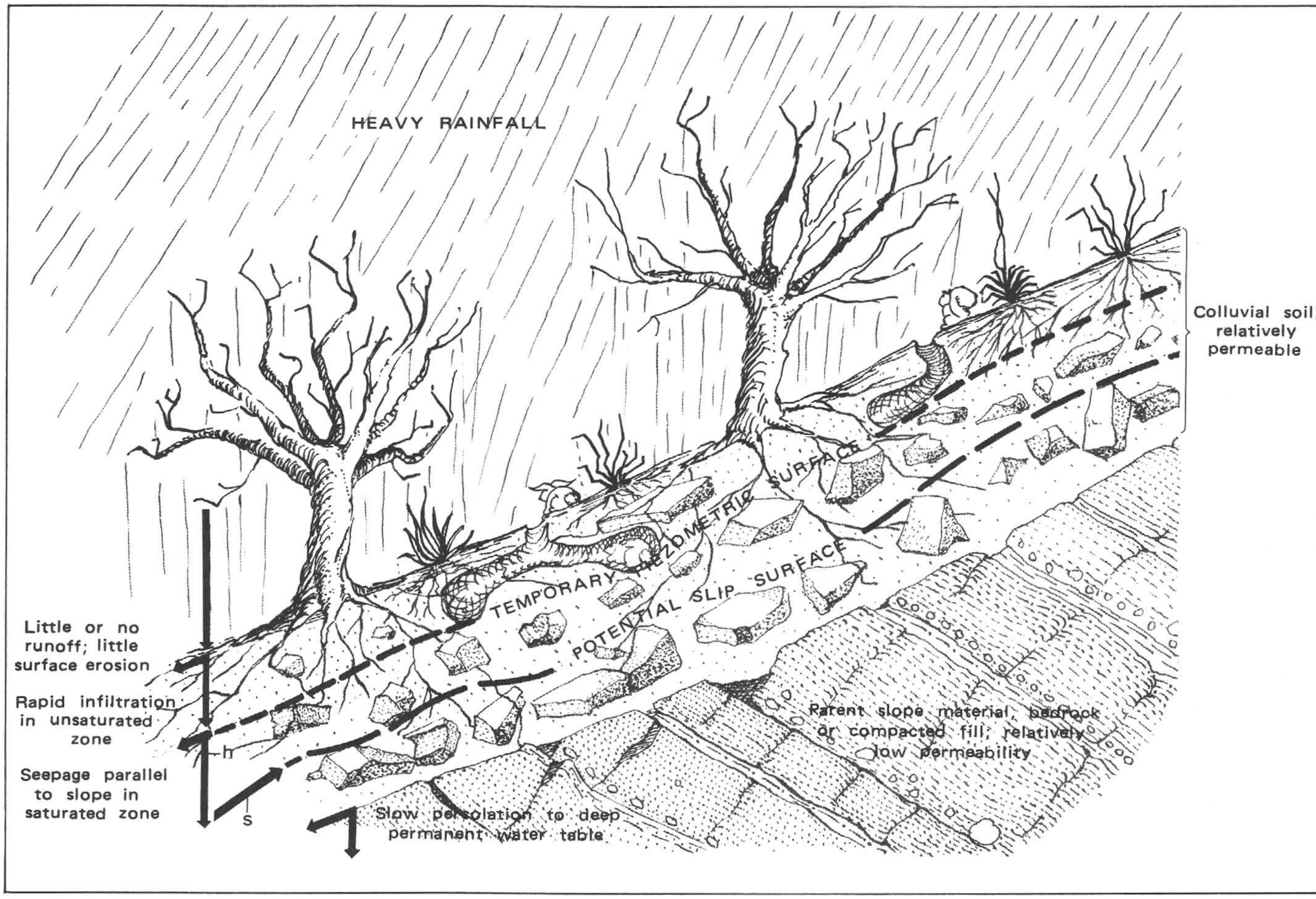


FIGURE 16.—Diagram showing buildup of perched water table in colluvial soil during heavy rainfall. Bedrock subsoil is shown here; however, soil slips also occurred over compacted fill slopes where the transition from parent material to colluvial soil is more obviously gradational. The significance of the piezometric head (h) in reducing the shearing resistance (S) is discussed in the text, with regard to the formula $S = c + (p - hw) \tan \phi$ (Terzaghi, 1950).

source area, a soil-slip origin may be inferred from the reports of many "mudslides" that occurred in this neighborhood at about the same time as the fatal one.

MECHANISM

The strong correlations between debris-flow activity and rainfall of moderate to high intensity (fig. 9) support the hypothesis of Kesseli (1943, p. 347) attributing the disintegrating soil slips of the California Coast Ranges to the buildup of water in the regolith when infiltration at the surface takes place at a greater rate than deep percolation—a dynamic imbalance that can occur only when rainfall intensity exceeds the rate of deep percolation.

The mechanism is illustrated by figure 16, which shows shallow-rooted vegetation with a thin mulch of dead leaves and grass growing in a regolith of colluvial soil, the upper part of which contains abundant living and dead roots as well as animal burrows. When the rate of infiltration into and through the upper layers is equal to or less than the capacity of the bedrock to remove it by deep percolation, the water moves toward the permanent water table far below, and the stability of the surficial material on the slope is not affected. When infiltration through the regolith exceeds the transmissive capacity of the rocks below, a temporary perched water table is formed. Its head will continue to increase as long as infiltration continues at the high rate until the whole surficial zone is saturated, at which time all the rainfall in excess of the transmissive capacity of the bedrock is distributed as surface runoff and downslope seepage within the saturated surficial zone. In this manner, the slope approaches the special condition described by Haefeli (1948, p. 59–60) of seepage flow parallel to the slope surface.

Even long after the warning of Hacker (1940), many lists of causes of landslides include "overloading," without qualification as to the geometry of the load distribution, and state or imply that failure can be caused by an added downslope driving force derived from the increase in weight of the soil mantle through the infiltration of water (for example, Bishop and Stevens, 1964, p. 6; Corbett and Rice, 1966, p. 1; Nilsen, 1971; and Putnam, 1971, p. 194). Mechanically, this concept is inappropriate, for if the weight is added uniformly, as might be expected in the case of vertical rainwater infiltration, it should increase the normal force of the soil mantle on the underlying slope (the frictional force that resists sliding) as well as the tangential force (downslope shearing force of the slab) in such a way that the ratio of the two remains constant. The criterion for failure of a slab is that the ratio of the tangential and normal forces must exceed a critical number—a number that is different for different materials and determined by experiment. That ratio is independent of the weight of the material in the slab. Specifically, the only part of the "added weight" of the water that contributes to failure is the weight of the column of interstitial water above the potential slip surface, and this weight serves to increase the pore fluid pressure.

The effect of the addition of water in changing a slab of slope mantle from stable to unstable may be illustrated by reference to the familiar Terzahgi (1950, p. 92) formula for resistance to shear:

$$S = c + (p - hw) \tan \phi,$$

where, at a point on a potential surface of sliding, s is the shearing resistance per unit of area, ϕ is the angle of sliding friction for the surface of potential sliding, hw is the pore pressure from the unit weight of water (w) and the piezometric head (h), p is the pressure due to the weight of the solids and water, and c is the cohesion per unit area. Note what happens to the equation when a water-saturated zone forms above the slip surface: (1) The component of cohesion (c) that is derived from intergranular air-water surface tension is reduced as water replaces air in the interstices; and (2) $(p - hw)$ is decreased as the piezometric head increases—both lead to a reduction in shearing resistance (S).

T. L. Youd, U.S. Geological Survey, suggested (written commun., 1969) that the formula developed by Skempton and DeLory (1957, p. 379) for the condition that ground-water flow is parallel to the slope at shallow depth might serve to cast the Terzaghi equation into terms of more readily measured soil parameters. It may be written in the form:

$$F = \frac{c' + (\gamma - m\gamma_w) z \cos^2 B \tan\phi'}{\gamma z \sin B \cos B}$$

where F is the factor of safety, c' is the cohesion intercept, z is the vertical depth of the slip surface, B is the slope angle, γ is the unit weight (density) of the soil, γ_w is the unit weight of the water, m is the fraction of z such that mz is the vertical height of the ground-water table above the slip surface, and ϕ' is the angle of shearing resistance. (See fig. 17.) As m approaches 1, F decreases to a minimum value dependent upon γ, z, and $\tan \phi'$ for any given slope angle.[2]

If cohesion (c') may be neglected, the formula for the safety factor may be written:

$$F = \left(1 - \frac{m\gamma_w}{\gamma}\right) \frac{\tan\phi'}{\tan B}.$$

And, where $F = 1$ (failure criterion):

$$\tan B = \left(1 - \frac{m\gamma_w}{\gamma}\right) \tan\phi'.$$

A graph can then be drawn showing a family of curves of $F = 1$, with varying combinations of measured soil parameters γ (unit weight) and $\tan \phi'$ (fig. 17). Thus, from the graph (fig. 17) a slope overlain by a colluvial soil mantle having an angle of shearing resistance (ϕ') of 46° and a unit weight of 90 lb per cu ft will be stable in the field to the left of curve number 3, and unstable (at $F = 1$) to the right of it. Thus, on a slope of 30°, failure can be expected when the piezometric surface rises to a proportion (m) of 0.63 of the thickness of the soil above the potential slip surface. For soils with higher unit weights, the value of m required to achieve $F = 1$ is higher. Thus, for $\gamma = 132$ lb per cu ft (curve 4), the piezometric surface must rise to 95 percent of the thickness of the zone above the potential slip surface. The intercepts of the curves with the ordinate $m = 1.0$ imply that failure *by this mechanism* should not occur on slopes gentler than the intercept values even if the soil is fully saturated to the ground surface.

A set of similar curves, prepared for the soil and slope

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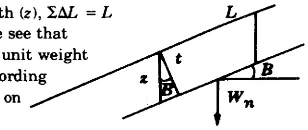
[2]Swanston (1970), working on the mechanics of similar soil slips in the shallow till soils of southeast Alaska, used the "method of slices," in which the formula takes the form:

$$F = \frac{\sum[C\Delta L + (\Delta W_n + Q_n - u\Delta L) \cos\alpha \tan\bar{\phi}]}{\sum(\Delta W_n + Q_n) \sin\alpha}$$

where $\bar{C}$ is the intercept cohesion (assumed to be 0 for shallow granular soils) and Q_n is the "surface loading" and is assumed to be negligible, ΔW_n is the weight of the soil in each slice, ΔL is the slope width of each slice, u is pore water pressure, $\bar{\phi}$ (same as ϕ') is effective angle of internal friction, and α (same as B) is the slope angle. Now, for a slab having a length (L) that is large with respect to a relatively uniform depth (z), $\Sigma\Delta L = L$ and $\Sigma\Delta W_n = W_n$. Further, from the diagram we see that $W_n = Lt\gamma = \gamma Lz \cos B$, where γ is the saturated unit weight of the soil. Moreover, because γ is measured according to unit *horizontal* cross section, the weight of γz on the larger inclined surface is reduced to $\gamma z \cos B$ and $W_n = L\gamma z \cos^2 B$. Similarly, following Skempton and Hutchinson (1969, p. 319) for the case of piezometric surface parallel to the slope, $u = \gamma_w mz \cos^2 B$.



Integrating equation 1 for the slab geometry and substituting yields:

$$F = \frac{\bar{C}L + (W_n - uL) \cos\alpha \tan\bar{\phi}}{W_n \sin\alpha}$$

$$= \frac{C'L + (L\gamma z \cos^2 B + L\gamma_w mz \cos^2 B) \cos B \tan\phi'}{L\gamma z \cos^2 B \sin B}$$

$$= \frac{C' + (\gamma - m\gamma_w) z \cos^2 B \tan\phi'}{\gamma z \sin B \cos B}$$

Thus, for cases where L/z is large (that is, slab slides), formula (1) transforms to the formula of Skempton and DeLory (1957).

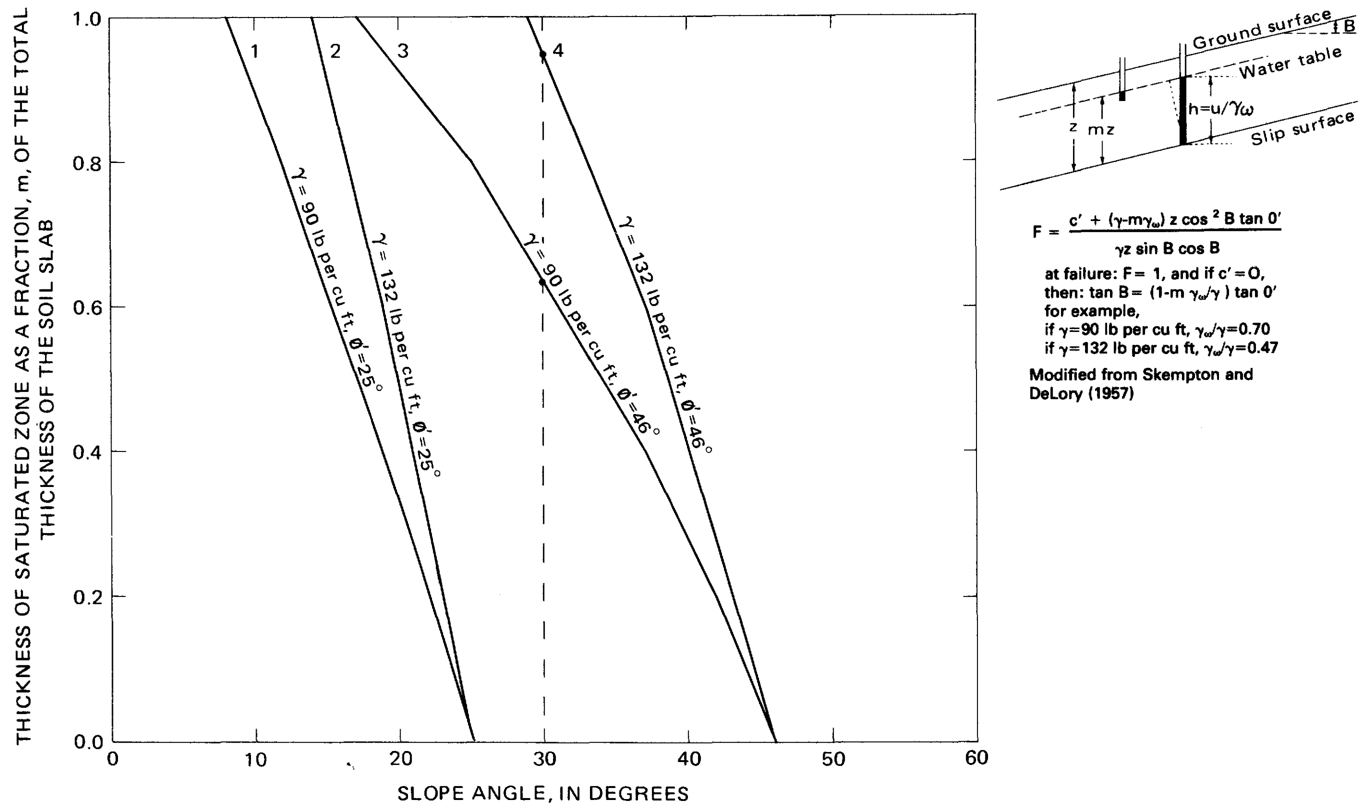


FIGURE 17.—Relation of failure in some typical soils to ground-water content and slope angle. Computed curves for $F = 1$ (failure criterion) at selected values of γ (unit weight) and ϕ' (angle of shearing resistance). The curves for most natural nonclayey soils lie between curves 1 and 4. Fields to the left and right of each curve are stable and unstable, respectively.

parameters of a given site, should permit a preliminary evaluation of recurrence interval for failures due to rainstorms. If the thickness and infiltration rate are known for the regolith on a slope of known angle, the recurrence interval for values of m at $F = 1$ can be approximated by using the recurrence intervals of rainfall of sufficient intensity and duration. If infiltration rates are very low, duration of rainfall should be the dominant factor; if they are high, rainfall intensity should be more important. Either way, the buildup of a temporary perched water table requires that the infiltration rate for the soil mantle be greater than the infiltration rate for the underlying parent material.

RAINFALL INTENSITY AND DURATION

From the foregoing mechanism, the minimum conditions for failure would seem to be: an initial period of enough rainfall to bring the full thickness of the soil mantle to field capacity (the moisture content at which, under gravity, water will flow out as fast as it flows in), followed by rainfall intense enough to exceed the infiltration rate of the parent material underlying the soil mantle, and lasting long enough to establish a perched ground-water table of sufficient proportional thickness (m, fig. 17) to cause failure. (Note that rainfall intensity need not exceed, nor even equal, the maximum infiltration rate for the soil; therefore, surface runoff may not be in evidence on a slope about to fail.) Evaluation of the data from the storm of January 18–26, 1969, suggests that, in the greater Los Angeles area, these minimum conditions were reached when the sites of failure had received a total of about 10 inches of rain, after which they were subjected to rainfall intensities of about 0.25 inch per hour or more. (See fig. 9.) The numerical values are, of course, preliminary and subject to revision as more data are examined.

Certainly, the threshold total rainfall should be expected to be less for thin soils than for thick soils, and the 10-inch antecedent total suggested here must reflect conditions for colluvial soil mantles of average thickness. Any loss of soil moisture by evaporation or transpiration during dry interstorm intervals should tend to increase the minimum threshold for a following storm; however, comparisons of the records for the storm seasons of 1961–62, 1965–66, and 1968–69 suggest that the threshold may be more closely associated with antecedent rainfall for the season than the immediately preceding hours of storm.

Damage accounts from the winter seasons of 1961–62 and 1965–66 appear to support the suggested minimum for intensity of 0.25 inch per hour (figs. 18, 19), although at a few sites, failure may have occurred at intensities as low as 0.20 inch per hour. They do not, however, give unequivocal support to the inferred minimum antecedent total. Debris flows did occur well before that total was reached. Although most of these early flows may be attributed to causes other than soil slips, such as surface runoff in association with soilfalls, rockfalls, and rockslides, the possibility that some originated in soil slips has not been eliminated. Such a "premature" failure by soil slips can be reconciled with the proposed mechanism only if the soil slabs that failed were significantly thinner than the "average" thickness of colluvial soil, or if the soil zone was already wetted from an agency other than rainfall. A full evaluation of the significance and numerical value of a "minimum antecedent season total" would require additional details and documentation, particularly with regard to time of occurrence, classification (whether clearly a debris flow or muddy floodflow or slide), and whether there was clear evidence of soil-slip origin (such as a scar) or origin by some other means.

The curves for the storm of January 18–26, 1969 (fig. 9) show varying areal, orographic, and episodic characteristics of the storm. The high totals for the gages at San Dimas Tanbark Flat and Lechuza Pt. Station represent the orographic effects of their relatively high altitudes in the San Gabriel and Santa Monica Mountains, respectively. Most of the episodes of moderate- to high-intensity rainfall during the storm period were recorded by all the gages. However, during the high-intensity rainfall along the front of the San Gabriel Mountains on January 22 (as represented by the San Dimas and Flintridge gages), only light rain was falling in the Santa Monica Mountains and vicinity. As the curves indicate, there were early episodes of high-intensity rainfall during which soil slips did not occur. Rainfall of similar, in part greater, intensity than that associated with the failures of January 22 and 25 occurred during earlier episodes on January 19 and 21 when no significant number of debris flows were observed. This lack of sliding during the earlier storm episodes seems to indicate that at those times the total antecedent rainfall had not been sufficient to bring the regolith up to field capacity.

The 10.5-inch "threshold total" indicated in figure 9 is probably an empirical representation of the range of minimum field capacities for the slope mantle materials of the general Los Angeles area. The numerical value of the "threshold total" may be different for different storms, depending upon the soil moisture content at the beginning of the storm. Soil moisture at the time the storm of January 18–26, 1969, began was probably relatively low for that time of year because the total rainfall through January 17 was only a little over half of the seasonal normal to that date (Simpson, 1969, p. 12). This condition contrasts markedly with the antecedent conditions at the beginning of the storm series of February, 1962, which began after seasonal totals of 6–11 inches, approximately the "normal to date" (fig. 18), had already been attained.

In February 1962, the storm precipitation totaled less than 2 inches when the first debris flows were reported. The seasonal totals, however, generally exceeded 10 inches (with possible exceptions as low as 9.8 inches in the Hollywood area, and as low as 9.2 inches in the Monterey Park area, providing the Bel Air and Los Angeles recording gages, respectively, are representative). The storm series of February 1962 also records debris-flow activity associated with heavy rainfall of relatively short duration. On February 12, 15, and 19, heavy rainfall lasting as little as 2 hours apparently caused numerous debris flows.

The significance of antecedent totals for events associated with the storms of November and December 1965 is difficult to evaluate. (fig. 19). From newspaper accounts, (see section on "Storms of November 14 to December 30, 1965") it appears likely that debris flows occurred in several areas after antecedent totals of as little as 3 inches; however, their origins are not clearly established. Some were reportedly associated with active construction projects. Others may have originated as soilfalls or rockfalls from road and highway cuts. Only a few were clearly associated with circumstances where soil slips may have been the most likely origin. Even there, the possibility that the antecedent soil moisture was partly a result of irrigation cannot be discounted. Seasonal totals reached 10 inches at most gages on November 22, during widespread heavy rainfall that was associated with debris flows in several places. The best documented soil slip–debris flow event occurred on December 29, during an episode of heavy rainfall at the beginning of which all gages showed seasonal antecedent totals of over 10 inches (fig. 5, no. 14).

Damaging debris flows that occurred in the greater Los Angeles area during February 1969 began well after season totals had exceeded 10 inches. As indicated in figure 20, high-intensity rainfall in the San Gabriel Mountains was accompanied by renewed debris-flow activity in the Glendora area on February 6, after only 2–4 inches of antecedent storm rainfall, and again on February 23–25, after relatively little antecedent storm rainfall. According to Scott (1971, p. C244), damage from these later storms was minor compared with that of the January 18–26 storm period. Simpson (1969, p. 187) ascribes the smaller debris production of the February storms to lesser rainfall intensities.

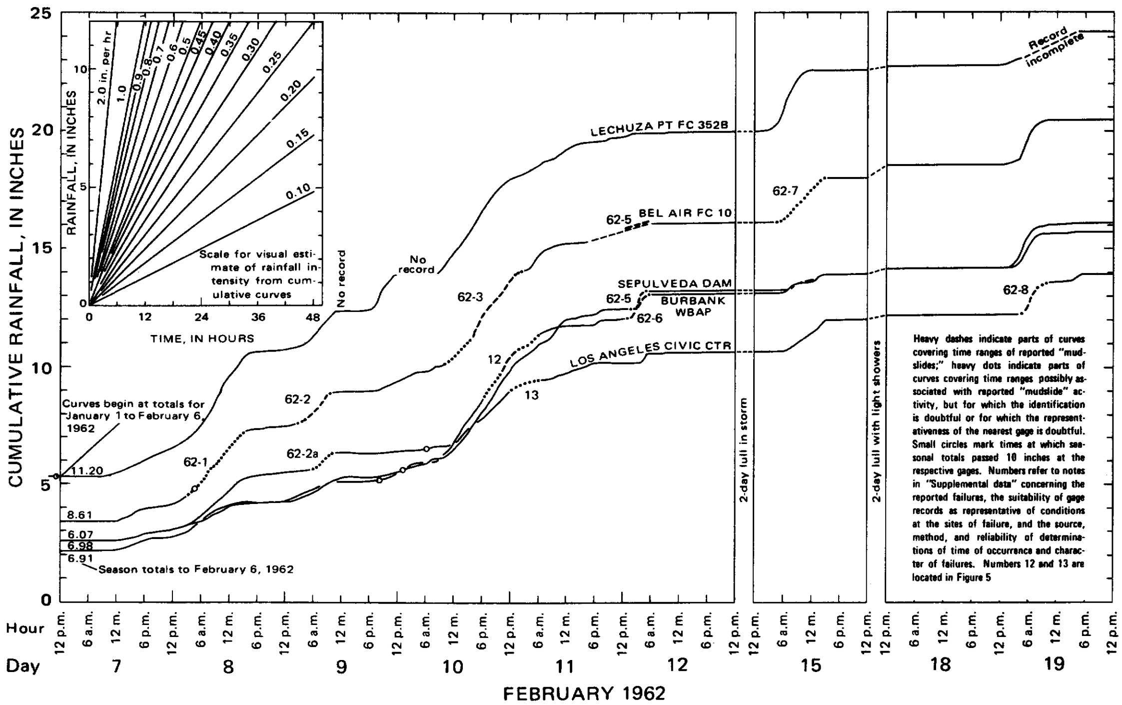


FIGURE 18.—Cumulative rainfall at several continuously recording gages in the vicinity of the Santa Monica Mountains, February 7–19, 1962, showing times of associated debris-flow activity.

The intensity of rainfall at the times of nearby soil slips, as shown by figure 9, was nowhere significantly less than 0.25 inch per hour. Long periods of lighter rainfall (see, for example, curves for January 24, 1969) apparently were not accompanied by any debris flows. Again, during the storm of February 23–25, 1969, the gage records (fig. 20) in the Santa Ana Mountains and San Gabriel Mountains indicate that the minimum intensity at the times of soil-slip failures was about 0.25 inch per hour. A minimum intensity at failure as low as 0.20 per hour is suggested by a few parts of the curves for the storm series of February 1962 (fig. 18), but items 62–2a, 13, and 62–7 (fig. 18) are subject to further interpretation as to the representativeness of the curves on which they are plotted. Items 2a and 13 refer to events in Monterey Park; the nearest continuously recording rain gage is that at the Los Angeles Civic Center. A comparison with the nonrecording gage at San Gabriel Fire Station, closer to the sites of failure in Monterey Park, indicates that the Monterey Park area may have received as much as 0.43 inch more total rainfall on February 9, 1962. If, as seems most likely, most of it fell during the same 3- to 4-hour period as the heavy rainfall at the Los Angeles gage, the intensity would have been in excess of 0.30 inch per hour. On February 11, 1962, (fig. 18, item 13,) the Los Angeles station received a total of 1.24 inches, while the San Gabriel Fire Station received 2.43 inches, nearly twice as much, indicating that some significant storm activity in the Monterey Park area was not represented on the Los Angeles gage. Item 7 (fig. 18) may be reasonably well represented by the Bel Air gage.

RECURRENCE INTERVALS

The recurrence interval for storms of the magnitude of that of January 18–26, 1969, has been reported at 75 to 150 years by Simpson (1969, p. 14). Some residents have interpreted news reports that this was an 80-year storm to mean that they need not expect another such storm and its associated hazards for the next 80 years—a dangerously misleading belief. Perhaps only an "80-year storm" could cause such widespread and numerous soil slips, but it may be more important to note that during the storm period of January 18–26, 1969, a great many of the soil slips occurred well before the end of the storm, before the rainfall had reached its record and near-record totals. Debris flows probably caused by soil slips have resulted in fatal injuries during at least four storms in the decade 1960–70 —February 1962, December 1965, January 1969, and February 1969—and have occurred, with less disastrous results, during some of the other storms of the 1960's.

The recurrence interval for rainfall intensities of over 0.25 inch per hour in the greater Los Angeles area may be inferred to be less than 1 year. The "Rainfall frequency atlas of the United States" (Hershfield, 1961) indicated (p. 23) that 1-hour periods of rainfall ranging

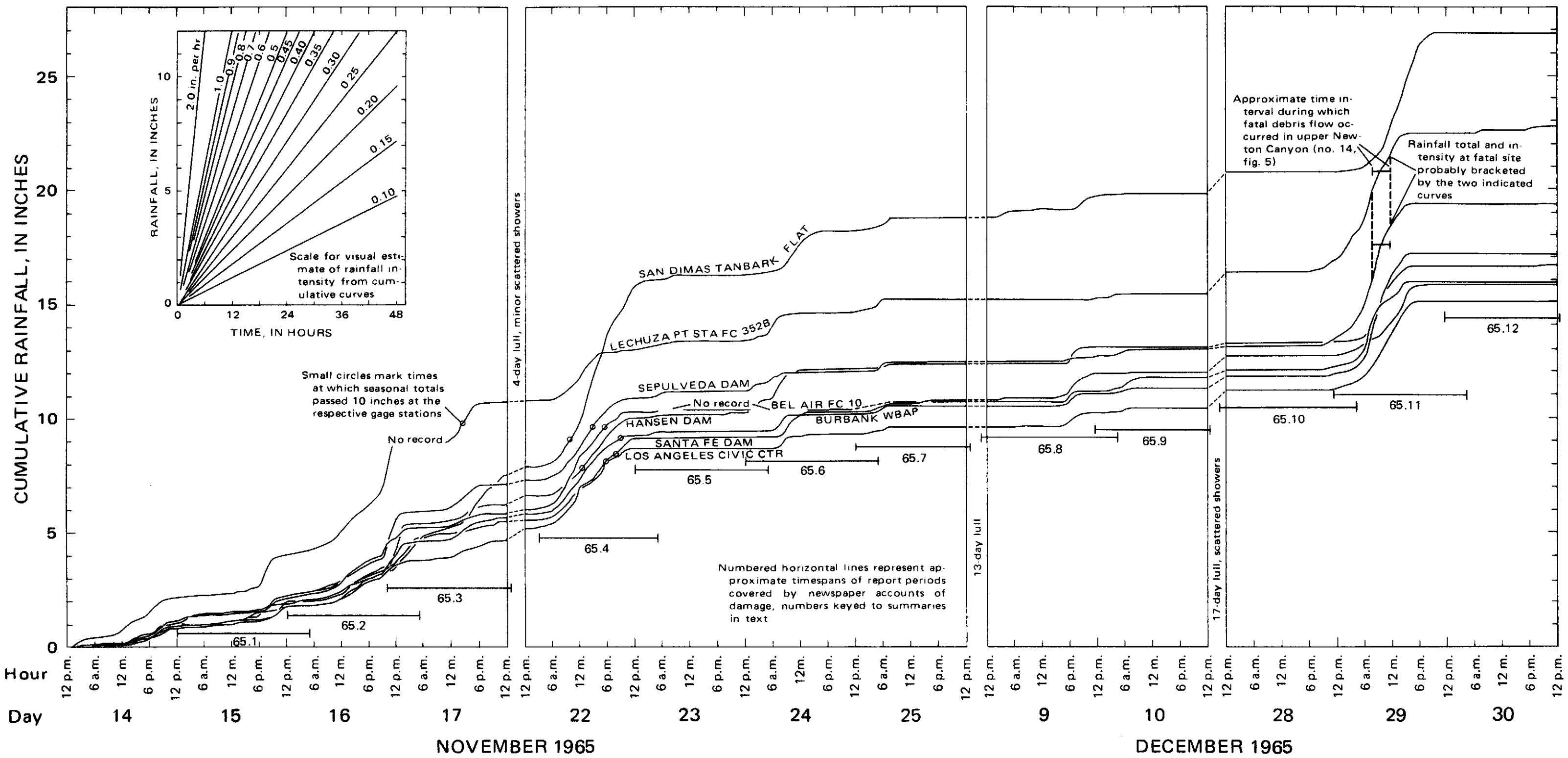


FIGURE 19.—Cumulative rainfall at selected continuously recording gages in and near the Santa Monica and San Gabriel Mountains, November 14 through December 30, 1965, showing times of associated debris-flow activity.

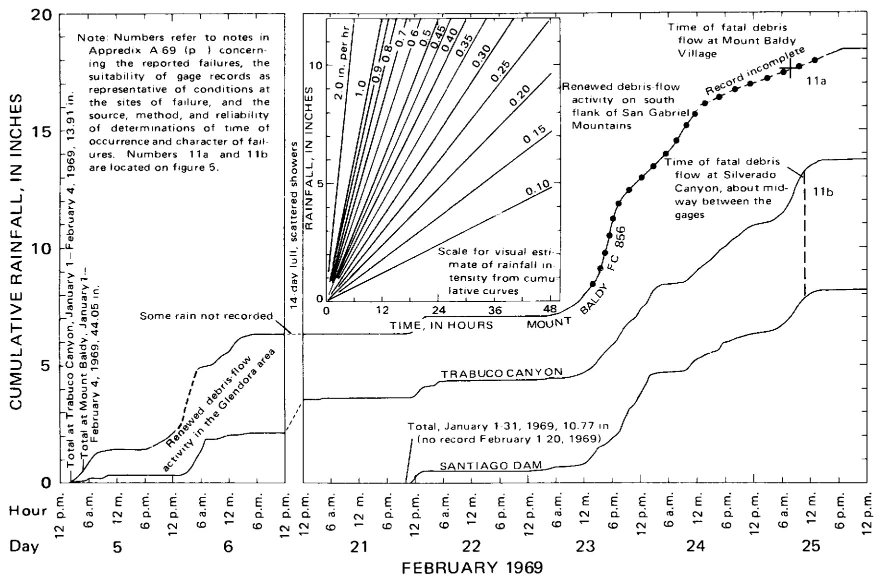


FIGURE 20.—Cumulative rainfall at continuously recording gages at Mount Baldy, Trabuco Canyon, and Santiago Dam, February 5–25, 1969, showing times of associated debris-flow activity.

from 0.40–0.80 inch normally recur each year. Therefore, the inferred minimum intensity to trigger soil slips (0.25 inch per hour) may be expected at least once each year, and some years twice. The observed recurrence is less frequent, perhaps because the soil moisture content derived from antecedent rainfall must exceed the field capacity when high-intensity rainfall occurs.

The normal annual rainfall at the Los Angeles Civic Center is 12.63 inches (U.S. Environmental Science Services Administration, 1969B, p. 44), nearly all of which falls during the October through March rainy season. Most nearby hillside areas probably have higher "normals" than the Los Angeles station because of the pronounced orographic effect so common in storms in the area, therefore, in most "normal" years most hillsides will have received the inferred threshold "seasonal to date" total of about 10.0 inches by the latter part of the season. Combinations of minimum antecedent rainfall and rainfall intensity that may cause a few scattered soil slips, particularly at higher altitudes, probably recur nearly every year.

Some inferences may also be made about the recurrence intervals of more severe storms. The data for the storm of January 18–26, 1969 (see fig. 9) show that a significantly large number of soil slips had taken place by the time the storm total had reached about 13 inches. Miller (1964, p. 20–21) indicates that the return interval for a 7-day period of rainfall totaling 10 inches is 10 years, and that for a return interval of 25 years as much as 15 inches may be expected during a similar period (7 days). It would seem, therefore, that storms capable of causing numerous soil slips in the Santa Monica Mountains and vicinity may be expected to recur at intervals of between 10 and 25 years.

CHANGE OF STATE

When a relatively rigid slab changes to a viscous fluid (a characteristic also observed by Bishop and Stevens, 1964, p.11), the conditions of resistance to downslope movement change from sliding friction to viscous flow. This change helps to explain how, on a given slope, a mass that has just become unstable (under conditions of sliding friction) can accelerate to avalanche speed rather than move at a steady slow velocity. Although the exact manner in which the change of state begins has not been observed or reported, some reasonable speculations may be made on the basis of the postulated mechanism for the slab failures (p. 18–20) together with the phenomenon of "spontaneous liquefaction" (Terzaghi and Peck, 1967, p. 108). For instance, the change should begin in the saturated zone adjacent to the slip surface of the slab failure and quickly encompass all the saturated zone. If an upper zone of the soil remains unsaturated (but at field capacity), it, too, may become fluid if field capacity provides enough moisture to surpass the liquid limit and if the soil structure is reworked thoroughly enough to effect remolding. That many such zones did not become completely fluid is shown by clumps and blocks of sod found well downstream from their scars of origin (fig. 6).

DEBRIS FLOWS

Once a slab of soil becomes detached at an underlying slip surface and at the margins and begins moving, part or all of the mass is effectively remolded by its own motion, and it changes from a rigid slab to a viscous fluid. As it moves downslope, the material flows together into a relatively narrow stream, moving down established drainages—ravines, gullies, swales, and so on—as a discrete slug. The speed of the flow depends on its fluidity and on the length and gradient of the channel.

A comprehensive discussion of the mechanics of downslope flow of debris slurries is beyond the scope of this report. In general, the tendency of the flows to accelerate on steep slopes seems to indicate that the dominant conditions are those of viscous flow. Because visible effects of viscous or plastic creep of the soil mantle are not commonly associated with the storm-related slab failures in the Santa Monica Mountains, it seems necessary to consider elements of plastic or quasiplastic deformation (Leopold and others, 1964, p. 31) only on gentle slopes where flows decelerated to slow speeds just before depositing. Bagnold (1968, 48–51) and Johnson (1970, p. 461–534) have recently discussed the mechanics of viscous slurry flow (mudflows).

The same processes may operate on the bedload of flooding drainage channels. Discrete debris flows resulting from individual slope failures can cause significant but temporary increases in volume upon joining streams of flowing floodwater and can cause discrete surges in their flow. During the January 1969 storm, Scott (1971, p. C245) noted surges in flow from several drainage basins in the San Gabriel Mountains that were apparently generated by small slope failures. In some drainage channels he observed (Scott, 1971, fig. 3) high-water marks above debris-flow levees in the lower reaches of drainage channels but no evidence of water flowing above the debris flows in the upper reaches. The proportions of slurry flow (bedload?) to floodwater flow ranged from 100 percent (where no overflowing floodwater was evident) to 70 percent.

DOWNSLOPE TRANSPORT

Many flows clearly moved at avalanche speeds; damage caused by high-velocity impact attests to this. Other flows reportedly oozed slowly down relatively gentle slopes, building up against the upslope walls of structures until a window or some other weak point gave way under the lateral pressure, permitting fluid mud to inundate the interior. Judging from the appearance of the deposits, the character of the damage, and newspaper accounts of witnesses, most of the slower flows probably moved at not much less than 1 ft/s (foot per second), and the extremely rapid flows probably moved at not much more than 40 ft/s. Slower and faster flows are, of course, not excluded by the mechanism, and the estimated range of rates cannot be expected to apply where other conditions of slope angle, slope length, soil character, and climate prevail. It is interesting, however, to compare the estimated rates with those measured and computed for mudflows (debris flows) elsewhere. For example: Johnson and Hampton (1969, p. 6.4–6.5) computed velocities for mudflows in channels that cross a small alluvial fan in the Panamint Range and found them to range from about 12 to 40 ft/s. D. M. Morton (written commun., 1971) measured velocities of channeled mudflows ranging from 2 to 12 ft/s at Wrightwood (1969 mudflow activity), where they moved through the channel in the alluviated canyon just above the apex of the fan. In the same part of the Wrightwood area, Gleason and Amidon (unpub. data)[3] measured velocities (for 1941 mudflow activity) ranging from 4 to 14.5 ft/s. (These computed and measured velocities are for flows in confined channels with gradients of about 17° or less.)

The flows were generally laminar in appearance; however, considerable turbulence must have occurred in at least two general circumstances: (1) Where relatively wide slabs were funneled into relatively narrow ravines downstream; and (2) where the roughness of a channel bottom imposed a cascading, plunge-and-pond character to the flows.

No direct measurements of viscosity were made during the debris-flow activity of January and February 1969. Debris-flow consistencies, however, have often been likened to wet concrete (for example, Rantz, 1970, p. B10). (The subject of visual estimates of viscosity has been discussed by Van Wazer and others, 1963, p. 38–39, who comment that it is difficult for the eye to distinguish differences in viscosity in the range of 0.001 to 0.1 poise. In contrast, relatively small differences in viscosity are clearly recognized in the range from 1 to 100 poises. The eye again has trouble distinguishing between viscosities greater than 1,000 poises because Newtonian fluids of such high viscosity do not pour and appear "solid.") Surprisingly, very few viscosity measurements on wet concrete have been reported. According to Reiner (1960, p. 345, 352), V. P. Lobonov measured Bingham[4] viscosities of 24 poises and 34 poises, respectively, for fresh cement paste and for fresh cement mortar. Table 1 lists viscosities for a number of Newtonian and non-Newtonian fluids to aid in comparative judgments.

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[3]Gleason, C. H., and Amidon, R. E., 1941, Landslide and mudflow, Wrightwood, California: California Forest and Range Experiment Station, RI-CAL, July 21, 1941, 7 p.

[4]Viscosities for single-phase liquids are commonly calculated using formulae derived from a "Newtonian" mathematical model, whereas most slurry flows are thought to be better represented by the "Bingham" model. Although both ways of calculating viscosity yield values expressed in poises, the numbers are generally significantly different.

TABLE 1.—*Viscosities of common Newtonian and non-Newtonian (Bingham) fluids*

Newtonian fluid	Viscosity (poises)	Source
Water, 20°C	0.01	Hodgeman and Holmes, 1942, p. 1638–1641.
Machine oil, light, 15.6°C	1.14	Do.
Machine oil, heavy, 15.6°C	6.61	Do.
Glycerine, 14.3°C	13.87	Do.
Glycerine, 2.8°C	42.20	Do.
Asphalt, 47°C	10.4×10^3	Shaw, Wright, Peck, and Okamura, 1968, p. 239.
Pitch, 15°C	13.0×10^9	Hodgeman and Holmes, 1942, p. 1644.

Non-Newtonian (Bingham) fluid	Viscosity (poises)	Source
Experimental kaolin slurry	0.30	Johnson, 1970, p. 509.
Oil well drilling muds, from	0.0x	Sutter, in LeRoy,
to	>3.0	1950, p. 715.
Ketchup	0.83	Weltmann, 1960, p. 241.
Mustard	2.94	Do.
Mayonnaise	6.33	Do.
Wet cement paste	24	Reiner, 1960, p. 345, 352.
Wet cement mortar	34	Do.
Natural mudflows at Wrightwood:		D. M. Morton, 1972, written commun.
Muddy water between mudflow surges	1.0	
Mudflows, range of 45 measurements	400–1,000	
Natural mudflow at Wrightwood	760	Johnson, 1970, p. 513.
Basaltic lava (25 percent crystal slurry)	6,500	Shaw, Wright, Peck, and Okamura, 1968, p. 248.

The ability of the debris flows in the Santa Monica Mountains to deepen their own channels by erosion appears related to the steepness of the gradient and the thickness and moisture content of old channel-fill deposits. Most of the flows began to deposit debris upon reaching fanhead gradients of 10°–12°, and many passed with little or no scour through reaches with gradients as steep as 27°. This is inferred to reflect a relation of gradient to acceleration (as indicated in fig. 8) such that, generally, flows accelerated down channel gradients steeper than 27° and flowed at relatively constant speed through transitional reaches with gradients between 27° and 11°. At gradients of about 11° and less, the flows began to decelerate, and debris deposition began.

These inferred limits must be regarded cautiously, and only used as tentative guides because soil character, soil moisture, storm duration and intensity, and debris-flow velocity and viscosity can cause deviations of many degrees. (For example, the erodability of unconsolidated channel-fill debris depends on its degree of saturation—the more nearly saturated the easier it is mobilized by a passing debris flow and incorporated into the flowing mass.) Moreover, the numbers are generalized, for the most part, from observations of relatively small single-pulse events (virtually one slope failure generating one debris flow at a particular time), generally depositing at the foot of a first- or second-order drainage. Where debris flows move down higher order drainages, fed by other tributaries with additional debris flows or with surface runoff water, both velocity and duration of flow will probably be increased with increasing size. In the larger drainage areas, there may also be runoff water available for addition to the unconsolidated deposits below the flow, and scour in relatively gentle gradients might be expected. Scott (1971) found evidence that debris flows generated in small drainage basins along the south flank of the San Gabriel Mountains during the storms of January and February 1969 had scoured into channel-bed material of higher order (third- to fourth-order) drainages in reaches with gradients as low as 4°.

The debris flows appear capable of transporting the largest boulders available. Except for some very large blocks, obviously derived by rockfall from adjacent canyon walls, most of the coarse-cobble- to boulder-size clasts in the ravines and canyons were probably emplaced by debris flows (including the mobilized bedloads of flooding streams in only a few of the larger canyons) rather than by running water (floodflow). Generally, the coarsest material is found in flows derived from failure (or mobilization) of ravine fill, apparently because the fill includes coarse rockfall debris that did not come to repose upslope. The soil mantle of the slopes does not generally contain material coarser than cobble size, though there are important local exceptions.

Figure 21 shows size range of boulders deposited in the bottom of a fifth-order channel from a debris flow that issued from a third-order tributary in December 1965. The flow destroyed a residence (killing the occupant) at the confluence of the two drainages and had sufficient carrying power to completely remove a separate garage structure, together with the car inside it, and deposit the wreckage about 100 yards downstream from the original site.

The size of the clasts available for transport by the debris flows depends greatly on the character of the bedrock units that have contributed debris. Thus, thick beds of resistant sandstone or volcanic rock commonly contribute large blocks and boulders, whereas thin, friable sandstone and mudstone may contribute clasts no larger than pebble size.

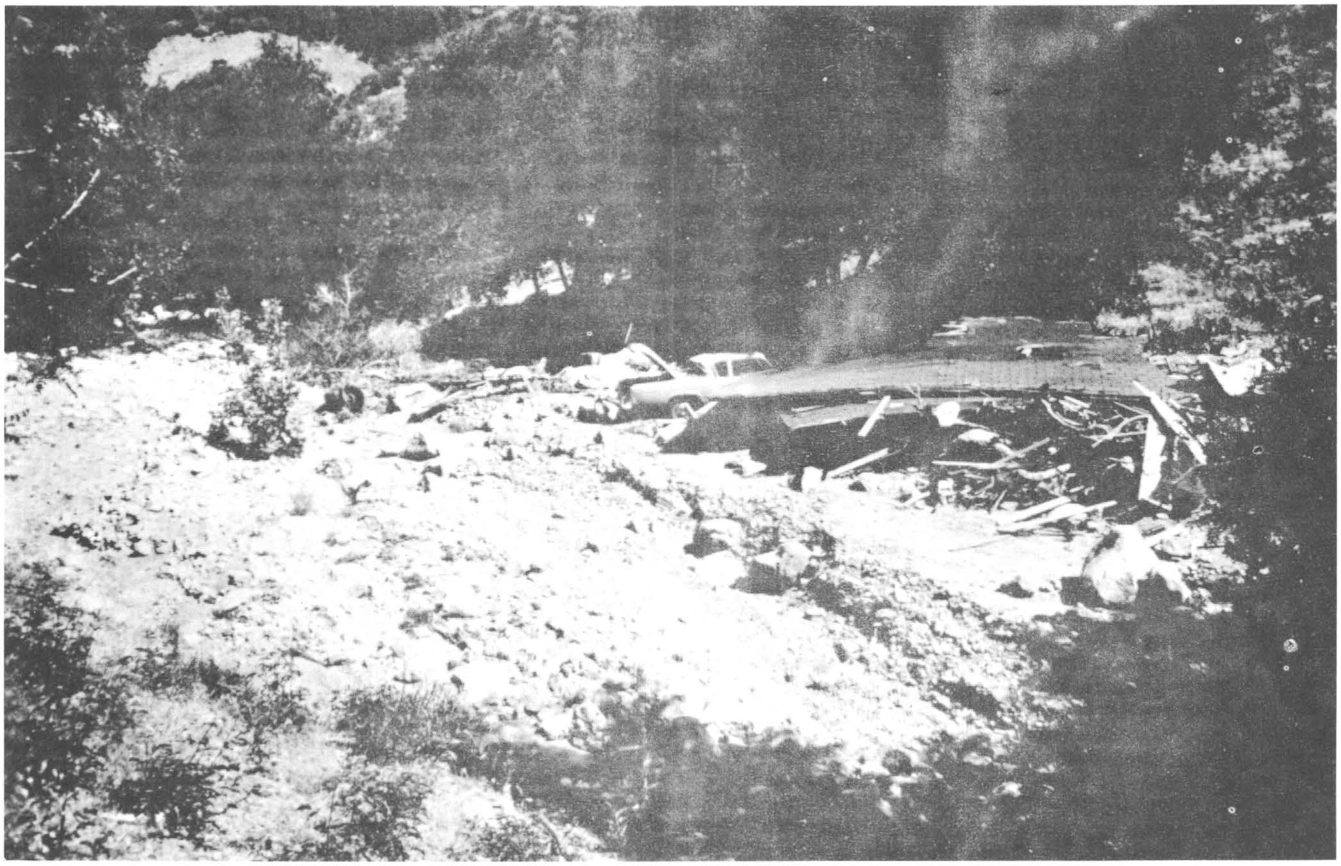


FIGURE 21.—Boulders, garage, and car transported by debris flow; Newton Canyon, December 29, 1965.

DEPOSITS

Except where influenced by manmade impediments, debris-flow deposits are found in two principal forms: debris fans (including many "alluvial fans") and debris trains.

Fans, coalesced into aprons in many places, are most common in the broader valleys and on the flanks of the mountains where steep, low-order drainages on the hillsides descend abruptly to slopes of relatively gentle gradient (figs. 2 and 4). Extensive fans have been built at the mouths of some remarkably small drainages, including first- and second-order drainages so small that they show no bare, stream-washed channels even after very severe rainstorms. This condition suggests that surface runoff in many of the small drainage basins is not sufficiently powerful, even during the severest rainstorms, to have eroded and transported all the debris now deposited in the fans. Fans of this kind, therefore, indicate a history of recurring debris flows. Moreover, their abundance indicates that, at least within the recent geologic past, erosion by slab failure of colluvial soil, transport of the debris by slurry flow, and deposition from slurry flow are major elements in the geomorphic processes that formed the present landscape.

Debris trains are found in the bottoms of mountain canyons in drainages of intermediate and higher order (generally fifth or higher) at and immediately downstream from the mouths of tributaries of lower order (commonly first to third). The trains are elongate, extending down the trunk canyons for distances of from a few tens of feet to as much as 2,000 feet from the upstream ends, which commonly mark the junction of the trunk canyon with the tributary that served as a channel for the flowing debris (see fig. 21). Postdepositional settlement, winnowing, sheetwash, and trunk-stream erosion have, in some places, resulted in localized distinctive drainage and morphologic features. The most commonly recognized feature is an irregular, rough, bouldery surface, including large generally angular boulders of resistant rock types that crop out in the drainage of the source tributary. In several places, debris trains have blocked the original junctions of

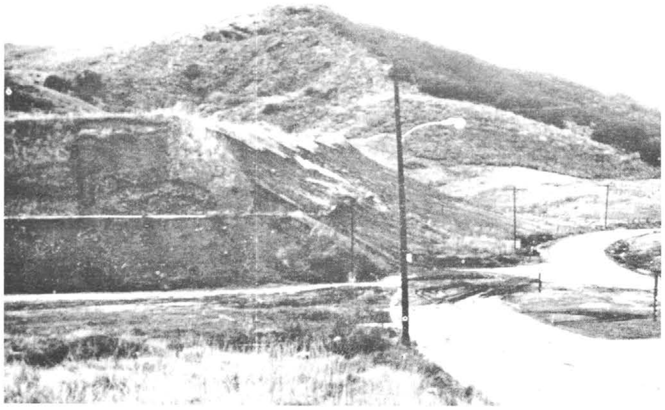
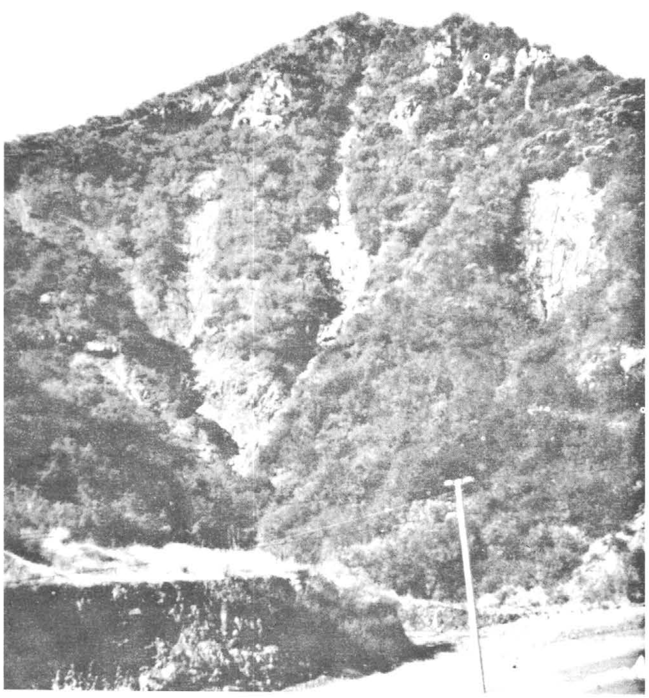


FIGURE 22.—Compacted-fill slope with surface-drainage interceptors rendered ineffective as a result of small soil slips. Liberty Canyon area, storm of January 18–26, 1969.

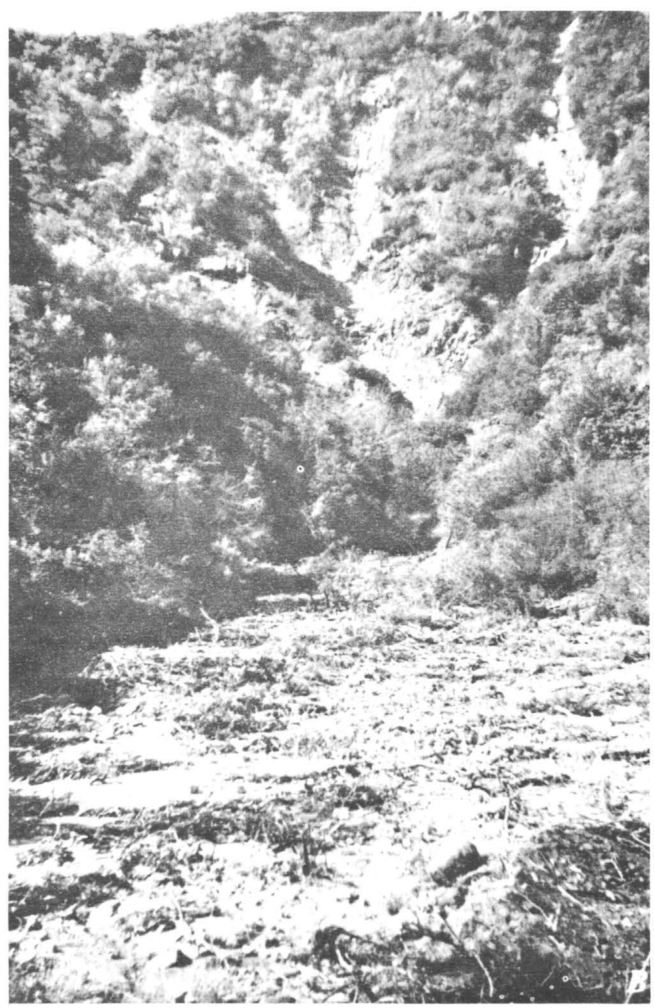
tributaries and trunk drainages, forcing them to migrate downstream and leaving boulder-covered medial ridges in the canyon bottoms.

Where the debris flows strike manmade structures, a wide variety of effects result , depending on the kind of structure and the size and velocity of the flow. For example, in January 1969, many paved drainage interceptors on engineered slopes were dammed by the deposition of relatively small amounts of debris, causing undesirable diversion of surface runoff across slopes below, which resulted in erosion by sheetwash (fig. 22). Debris flows may quickly fill the basins behind small check dams, rendering them ineffective in controlling subsequent surface runoff. Similarly, road and highway fill may impound large amounts of debris in basins formed when culverts become blocked (fig. 23). Drainages so small and gentle that no culverts were installed where roads cross them may disgorge tons of muddy debris onto roadways (fig. 24).

The effects on relatively small residential dwellings (commonly 1- or 2-story frame construction) range from quiet inundation to complete destruction by high-velocity impact. Debris flows of sufficient volume and momentum have smashed such structures into pieces and moved the remains off their foundations (figs. 25, 26). Debris flows of relatively small volume but high



A, Soil-slip scars in headwall drainage of ravine crossed by road fill.



B, Impounded debris, part of the scoured bedrock debris-flow chute, and lower parts of some of the soil-slip scars.

FIGURE 23.—Soil-slip scars and debris-flow deposits impounded behind road fill; Lobo Canyon area, storm of January 18–26, 1969.

FIGURE 24.—Debris flow through drainage that does not yield enough surface runoff of water to require a culvert; Mulholland Highway, storm of January 18–26, 1969. Road has been cleared after inundation.

momentum have punched holes into and even completely through structures (figs. 14A, 27). Some structures show little evidence of damage other than a hole in the wall (fig. 14A), but many have been distorted from their normal erect positions (fig. 7). Some buildings have had even layers of muddy debris deposited inside them, commonly accompanied by little structural damage. Apparently, the debris flows were moving at relatively low velocities; the flows entered dwellings through open doors or pushed laterally through windows and doorways and quietly flooded the interiors.

REMEDIAL MEASURES AND WARNING SYSTEMS

The hillside sites where soil slips may generate future debris flows are so small, numerous, and widely scattered that the safety of all downslope residents cannot be ensured merely by the construction of defensive works such as check dams, debris basins, and levees. Preventive measures, particularly the careful control of all surface and subsoil drainage, are generally practicable only where an entire slope area is carefully engineered. Many hazardous sites, however, lie downslope from natural, undeveloped areas, where access is difficult; moreover, the slopes on which the debris flows originate may be divided among several owners. Both of these factors may complicate the installation, operation, and maintenance of preventive and protective works. In some locations, where the anticipated flows would be of sufficiently low volume and velocity, and where the probable paths of debris flows can be predicted, relatively simple protective structures might be erected. However, these would have to be carefully located after hillsides above vulnerable dwellings had been thoroughly studied. The extensive literature on snow-avalanche defenses may suggest some kinds of structures of possible practical value (for example, U.S. Dept. Agriculture, 1961; Bucher, 1956; Flaig, 1955; Fuchs, 1955; and Roch, 1956). Of particular interest might be the design, bracing, and reinforcement of upslope walls of dwellings so as to deflect or resist lateral pressures and impacts from material moving downslope. In general, however, it does not seem economically feasible to prevent debris flows from forming, nor to protect all dwellings within the immediate

FIGURE 25—Wood-frame house, right side caught by edge of debris flow from the right, crushed and spun off foundation by impact. One fatality at this site. Newton Canyon area, debris flow of December 29, 1965.

future. On the other hand, the injuries caused when those dwellings are damaged or destroyed by debris flows must be classed as preventable because with warning people can avoid the relatively small flowing masses.

THE VALUE OF WARNING

During the early morning hours of January 25, 1969, there were 12 fatalities from 8 debris flows in the Santa Monica Mountains and adjacent areas. All the victims were inside residential structures that were damaged by impact or inundation by flowing debris. Eight—six adults and two children—were in their own bedrooms when crushed beneath collapsing walls or buried by muddy debris. The mother of the two children had reportedly awakened and was on her way to their bedroom when the house was crushed and part of it was pushed into the flooding stream below, resulting in the death of all three (fig. 26). Two of the victims who were awake were also small children, playing in one room of their home while their mother worked in another. Only one fatally injured adult was awake and fully clad. He had evacuated his family and had just returned to his house when it was struck by a high-velocity debris flow, which trapped and killed him (fig. 14).

The stories of many who escaped injury when their homes were damaged or destroyed are also enlightening. If an adult of the household was alert to problems outside the house (chief concerns were storm-runoff drainage, including small mudflows), almost invariably the approaching hazard was recognized in time to evacuate the remaining occupants—though very hastily in several instances (for example, the residents of the dwellings shown in figs. 7, 27).

The value of advance warning, therefore, seems clear. Residents who are notified that storm conditions have reached a point where debris flows may be generated by soil slips if high-intensity rainfall continues should be alert, should be prepared to recognize approaching danger, and should move quickly out of harm's way. Small children, invalids, and elderly people might be evacuated at such a time, but general evacuation of whole neighborhoods should not be necessary. The records show that even without advance planning, many people were able to react in ways that saved them from

FIGURE 26.—Debris flow from above left crushed wood-frame dwelling and pushed most of it downhill into the floodwaters of Topanga Creek. Photograph taken after partial excavation for rescue operations. Three fatalities at this site. West side of Topanga Canyon, debris flow of January 25, 1969.

injury. Obviously, advance planning would provide for quicker and better protective response.

CONTINGENCY PLANS

Because each hillside dwelling is in a unique position and orientation with respect to the slopes above, each household needs an individualized set of contingency plans. When residents are warned that critical rainfall conditions have been reached in their area and are likely to be exceeded, some may elect to leave immediately, others to evacuate only small children and invalids; still others to remain at home, trusting in their ability to keep a sharp lookout, recognize approaching danger, and evacuate only when and if the hazard becomes an immediate threat. Those who remain after being alerted should be prepared for a round-the-clock vigil until the end of the storm. Their preparations should provide for a nighttime illumination of the slopes above them.

The preparations for each adult and older child should also include a careful look at the slopes above and below their homes during clear weather. They should take careful note of slope angles and of the locations of small gullies (and even gentle swales) which may become the channels for flowing mud. Note should also be taken of prestorm soil moisture conditions that might advance the time of the threat to their property from upslope locations. Such conditions might be recognized in irrigated gardens or in natural springs and seeps. Downslope areas should also be examined for similar conditions, and care should be taken in design of landscaping and drainage so as not to increase the hazards to residents below. Evacuation routes and destinations should be planned, and alternatives studied. Evacuation centers should be carefully selected to avoid the sort of tragedy that occurred in Silverado Canyon on February 25, 1969, where a fire station being used to shelter about 60 storm refugees was struck by a debris flow, killing 5 persons and injuring 20 (fig. 28).

Satisfactory contingency planning by individuals clearly requires effective and timely public education. Given a timely warning and a well-planned response, alert adults can expect to avoid injury, even though they may not be able to prevent damage to their homes.

A WARNING SYSTEM

The many variables that influence the origin of each individual debris flow make the prediction of small soil slips in specific places extremely difficult. Prediction might be possible if the geologic properties of entire slope areas were studied in detail and a network of instruments capable of continuously monitoring soil moisture were installed. Such extensive studies and instrumentation may be feasible during construction of a large subdivision but are not generally economic for one or two small residences at the foot of a steep slope area covering several acres.

A means by which the general time of greatest debris-flow hazard may be recognized is suggested by the empirical association of soil slips with a threshold total of about 10 inches of rainfall and a minimum intensity of 0.25 inch per hour. Although these specific empirical numbers should be tested further and may need considerable revision, the basic association appears established. Moreover, it should be possible to use slope maps or topographic maps, in conjunction with hourly radar weather maps showing areas of moderate- to high-intensity rainfall, to determine areas subject to the greatest hazard at particular times during a storm. A warning system, therefore, could be constructed of three major elements, each of which is partly or wholly operative at the present time: (1) A system of rain

FIGURE 27.—Hole punched through house of 975 Old Topanga Canyon Road, debris flow of January 25, 1969. Occupants reportedly escaped without injury. Soil-slip scar above house is shown in figure 3. Photograph by Department of the County Engineer, Los Angeles County.

gages, recording total rainfall on an hourly basis; (2) a weather-mapping system capable of recognizing centers of high-intensity rainfall in the storm area and, at frequent intervals, plotting the locations of these centers with respect to locations of gages with adequate registry for accurate transfer to slope maps or topographic maps; and (3) an administrative and communications network to collate the data, recognize when critical factors have been exceeded in a particular area, and inform the residents there. Such a system is probably well within the capability of existing technology.

SUPPLEMENTAL DATA ON ASSOCIATIONS OF DEBRIS FLOWS WITH HEAVY RAINFALL OF RECENT YEARS

The following summary reports are intended to supplement text discussions of the association of debris flows with rainstorms in coastal southern California over the past several years. The times and places of events that are interpreted as of soil-slip–debris-flow origin, and the association of each event or group of events with rainfall recorded at nearby continuously recording gages, need to be further examined in order to test any general hypothesis of rainfall–soil-slip relations. Nearly all of the pre-1969 reports of times, places, and nature of origin were taken from newspaper accounts—chiefly from the Los Angeles Times. (Sources of information are listed with each description.) The general sources of data for the 1969 storms are noted in the "Introduction" and "Acknowledgments" sections of this report; low-altitude oblique aerial photographs supplied by the Los Angeles County Engineer and the Department of Building and Safety (City of Los Angeles) were particularly useful in recognizing scars of soil slips and freshly scoured ravines.

The chief drawback to the use of news accounts is the lack of rigorously defined descriptive terminology. For example, the most widely used term is "mudslide"; there is however no widely accepted, scientifically characterized definition for the term. Although "mudslide" has been recognized and used in a few technical and semitechnical papers (for example, Hutchinson and Bhandari, 1971; Rantz, 1970), the term has been applied to events of such diverse character as rapidly flowing debris and slowly creeping coherent soil mantle. Southern California newspapers have been generally consistent in using "mudslide" to describe soil slips and debris flows generated by soil slips. However, the same term is also frequently used to refer to other events such as very muddy floodflows of streams, rockfalls and slumps from steep highway cuts and bluffs (especially when they occur during heavy rains), and even to some deep-rooted rotational or block-glide types of landslides that may be in motion at varying (but generally slow) rates. Many news stories contain enough background information on which to base a reliable inference concerning origin, but many others do not.

The reader is referred to figures 9, 18, 19, and 20 for cumulative curves of recording rain gages that illustrate the times and distributions of episodes of heavy rainfall during four storms in 1962, 1965, and 1969. Numbers on various parts of the curves refer to individual events or to groups of events described. The locations of selected events are shown in figures 5 and 10. Notes include an evaluation of the probability that nearby gages represent the rainfall at the sites examined, as well as a discussion of factors that bear on the interpretation that the events began as soil slips.

STORMS OF FEBRUARY 7–19, 1962

The storms of February 7–19, 1962, deposited their rainfall on ground that had already received seasonal totals of from 6.9 to 11.2 inches. The next previous rainfall had occurred in January, and had ended on the 22d or 23d, about 2 weeks earlier. The early February soil moisture had accumulated from brief storms in late November and early December, and in mid-January, from which no severe damage by "mudslides" had been reported.

A comparison of the various gage records (fig. 18) reveals some interesting patterns of distribution of individual episodes of the February storms. Episodes of heavy rainfall along the north side of the Los Angeles basin were not matched in intensity in the San Fernando Valley (Sepulveda dam and Burbank gages) on February 8 and 9. In contrast, the intensities in the valley and in the Santa Monica Mountains were nearly equal on February 10 and February 11, while the Civic Center gage indicated lower intensities in the central Los Angeles basin. The latter, however, may be anomalous with respect to nearby areas, as discussed on page 22.

Damage estimates published by the Los Angeles Times of February 17, 1962, totaled about 4 million dollars, about evenly divided between public and private property. (This amount is total storm damage, including flood damage and traffic accidents as well as "mudslide" damage.)

The following summary account is derived chiefly from newspaper reports published in the Los Angeles Times. The numbers refer to episodes of storm activity as indicated in figure 18.

62–1: The report of several tons of mud and rock on the Pacific Coast Highway near Corral Beach (Los Angeles Times, February 9, 1962, p. 25) is probably better attributed to rockfall than to debris flow. The cliff above the highway cut just west of Corral Beach has been the site of many such failures. Activity reported as "numerous rock and mud slides" above Sunset Strip on Sunset Plaza Drive, on Hollywood Boulevard west of Laurel Canyon Boulevard, on Creston Drive in Laurel Canyon, on Mulholland Drive, and along the Angeles Crest Highway (op. cit., 27) probably included some debris flows of unknown origin. The Bel Air gage record is probably the most representative of the rainfall at the Sunset Plaza Drive, Hollywood Boulevard, Laurel Canyon, and Mulholland sites. It is, however, probably a minimum, as many of the sites are at higher altitudes than the gage and the storms commonly show a strong orographic effect.

62–2: Reports of damage from mud in motion in the Laurel Canyon area—2611 Laurel Pass Avenue; 2227 Nichols Canyon Road (north of Hollywood; Los Angeles Times, February 10, 1962)—and in the Topanga Canyon area (19963 Observation Drive); both are parts of the Santa Monica Mountains. Rainfall at those sites is best represented by Bel Air gage record, though that is probably a minimum because of the expected orographic effect of the storm at the generally higher altitudes of the sites of damage. The times of the events were not precisely determined. The descriptions permit (but do not require) soil-slip origin.

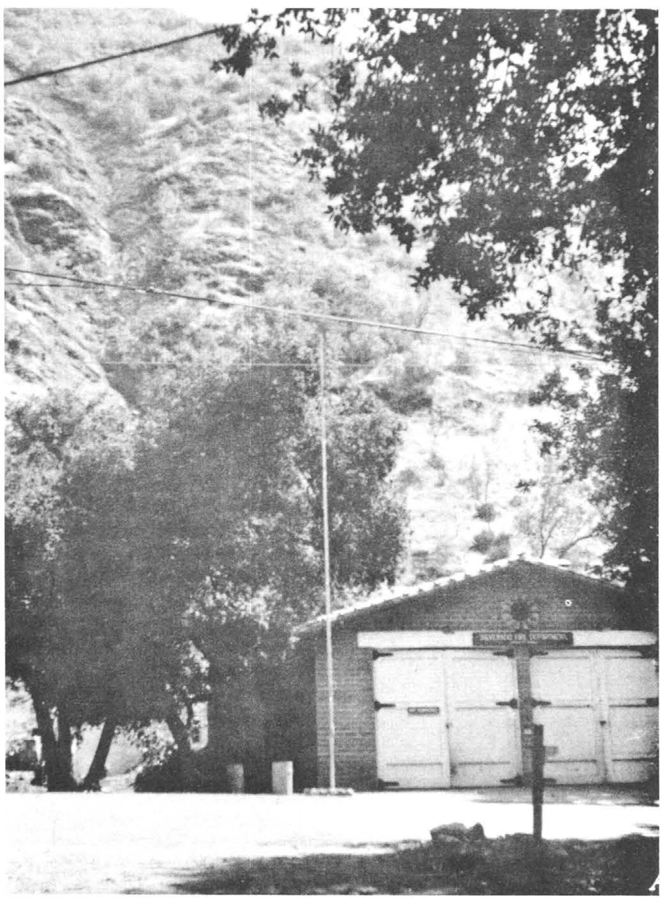
62–2a: Damage from mud was reported (Los Angeles Times, February 10, 1962) at three places in Monterey Park (916 East Monney Drive; 923 County Road; 985 County Road). The nearest recording gage is at Los Angeles. A comparison with the nonrecording gage at San Gabriel Fire Station, which is located much closer to the sites of failure in Monterey Park, indicates that the Monterey Park area may have received as much as

0.43 inch more total rainfall on February 9 than the Los Angeles gage. If, as seems most likely, most of the excess fell during the same 3- to 4-hour period as the heavy rainfall at the Los Angeles gage, the intensity would have been more than 0.30 inch per hour. The times of occurrence were not precisely determined; they were probably, but not demonstrably, debris flows of soil-slip origin.

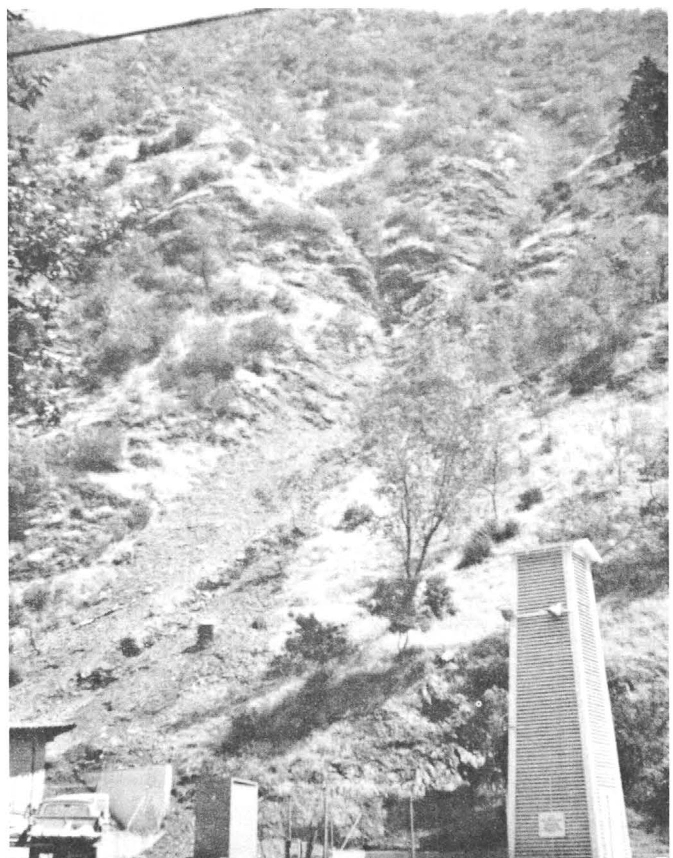
62–3: "Mudslides" were reported in the Bel Air, Mandeville Canyon, and Brentwood areas (Los Angeles Times, February 11, 1962). The nearest recording gage is at Bel Air and is probably representative of the minimum total and intensities at sites of failure. The descriptions permit (but do not require) soil-slip origin.

12 : Fatal debris flow occurred "early Sunday morning" February 11, 1962, killing one child "in bed" while damaging a residence in Sherman Oaks (Los Angeles Times, February 12, 1962, p. 1, photographs p. 3). The nearby recording gage record at Sepulveda dam is probably representative of the minimum total and intensity at the place and time of failure. Descriptions and photographs permit and suggest (but do not require) origin by soil slip. (Address: 3519 Camino de la Cumbre, Sherman Oaks.) (See figs. 5, 18).

13 : A debris flow crushed the rear of a house in Monterey Park about 1:00 a.m. Sunday February 11, 1962, killing one child in bed (Los Angeles Times, February 12, 1962, p. 1, 2, and photographs p. 3.) The nearest recording gage is at Los Angeles Civic Center, and that record is probably not fully representative of storm conditions at the time and place of the failure. A comparison with the nonrecording gage at San Gabriel Fire Station, which is located closer to the sites of failure in Monterey Park, shows that on February 11 the Los Angeles station received a total of 1.24 inches while the San Gabriel Fire Station received 2.43 inches, nearly twice as much. It is evident that some significant storm activity in the Monterey Park area was not represented



A, Fire station, located on the flood plain of a major stream at the foot of a long steep slope drained by low-order tributary gullies.



B, Slope above rear of fire station. Note head of scar in gully at upper right and mouth of gully directly upslope from the rear wall of the station.

FIGURE 28.—Three views of Silverado Canyon Fire Station. Debris flow of February 25, 1969, broke through back wall an swept the taken August 2,

at downtown Los Angeles. The debris flow was very probably of soil-slip origin. (Address: 2011 Emerald Way, Monterey Park.) (See figs. 5, 18.)

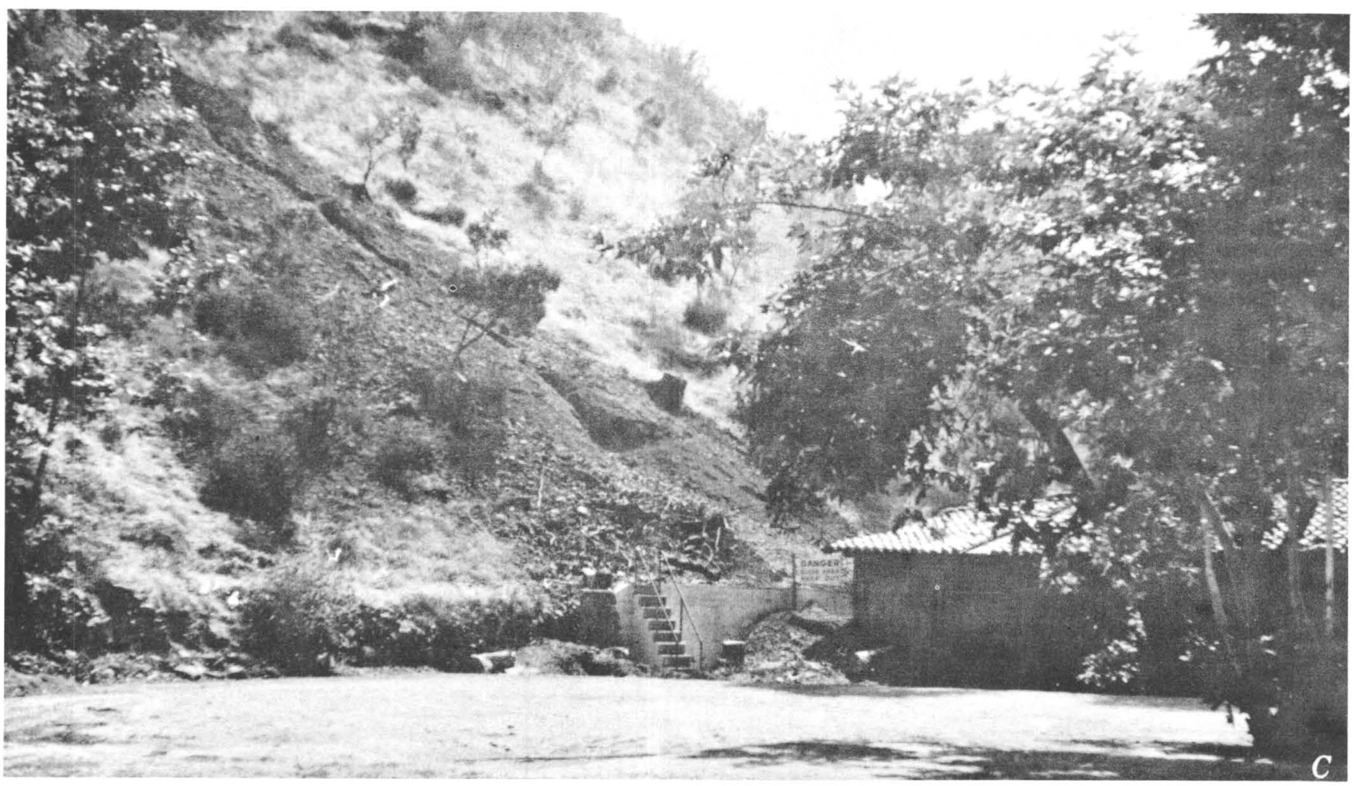
62–5: Many "mudslides" reported (Los Angeles Times, February 13, 1962, p. 1, photographs p. 3). Hollywood hills "hard hit"; area ordinarily best represented by recording gage at Bel Air, which was not operating at the time. Other gages, such as Sepulveda Dam, Burbank, and Los Angeles, give fair indication of conditions at times and places of failures. (Note on fig. 18 that the area of storm activity at that time apparently did not extend as far west as the Lechuza gage.) Descriptions and photographs show damage from debris flows; they were probably, but not necessarily, of soil-slip origin.

Damage described as:

1. 2934 Beechwood—shoved off foundation
2. General area of Beechwood ran mud and debris; Cahuenga Boulevard partly closed.
3. Photograph (op. cit., p. 3) shows cars mired in mud in vicinity of Beechwood.

62–6: The other area "hard hit" on the morning of the 12th was the Burbank–Sierra Madre area (Los Angeles Times, February 13, 1962, p. 1, photographs p. 3), probably best represented by the gage record at Burbank. In Sierra Madre, a "mudslide" buried to its eaves a residence at 660 Canyon Crest Drive. The photograph (op. cit., p. 3) shows no muddy marks or water marks on the exterior of the house above the level of the firm mud deposit, a strong indication that the mud was emplaced as a debris flow. It was probably (but not necessarily) of soil-slip origin. The time was not precisely reported, but the event was reportedly associated with the "final fury of the storm" which occurred at about 4:00 a.m. Monday (February 12). Also in Sierra Madre, at about the same time, a house at 1440 Carriage House Road was flooded with mud nearly to the ceiling, and a swimming pool was filled with mud.

In Burbank, at the same time, floodwaters, mud, and tons of rocks reportedly crashed down a narrow canyon road and into nearly every home along a mile-long stretch of Country Club Drive, swamped swimming pools and yards, and mired 30 cars and 3 boats on trailers. A photograph (Los Angeles Times, February 13, 1962, p. 3) shows the interior of one house with the mud deposited inside. The lack of mud or water marks above the top of the deposit strongly indicates emplacement by debris flow. The flow was probably at least partly of soil-slip origin.



C, Natural levee deposits on steep, small debris-flow fan, the toe of which has been undercut to increase the flat area where the station was built.

length of the refugee-filled building, killing five. Note relative lack of severe structural damage to side walls and doors. Photographs 1969, after cleanup.

No new debris flows or slope failures were reported for the 2-day lull of February 13–14. The Los Angeles Times (February 15, 1962), however, did report continued movement of landslides in the Alginet Drive area of Encino that, from the descriptions (including cracks beginning to open a month earlier), were clearly not soil slips nor did they develop debris flows.

62–7: The Los Angeles Times for Friday, February 16 (p. 1, 30), reports that the storm of Thursday, February 15, was of short duration and heavy rainfall—heaviest in Montibello and Santa Monica. A garage wall in West Los Angeles (9780 Peavine Drive) was punched through when "boulders tumbled from hillside at rear." (This description could fit either a rockfall or soil-slip–debris-flow event.) The Bel Air gage is probably near enough to be representative of the rainfall at the site of the failure.

Other reports covering this storm period deal chiefly with larger, more slowly moving landslides and their continued movement. John Lambie, County Engineer, Los Angeles County, announced that although street and road flooding were widespread, the landslide problems in hill and canyon areas were not so severe as those that had resulted from the earlier storm.

No new debris flows or other slope failures were reported for the 2-day lull of February 16–17. The Los Angeles Times (February 18, 1962, section K, local classified, San Gabriel Valley, p. 2) printed a photograph of the debris flow at 2011 Emerald Way, Monterey Park; (see number 13, fig. 18). It was fatal to a 9-year-old child whose parents were watching the slope through a window from another room when the slide suddenly crashed down into the boy's bedroom. The suddenness of the event indicates origin by soil slip.

62–8: In East Los Angeles a residence (3908 Eagle Street) was abandoned when a slide washed mud and water through the kitchen (Los Angeles Times, February 20, 1962) during severe storm on the morning of February 19. The recording gage at Los Angeles probably yields a fair representation of the intensity and duration of rainfall at the site of failure. The slide was possibly (but not necessarily) of soil-slip origin.

(The "big" weather news for February 19 was the occurrence of damage from tornados in Northridge and Santa Ana.)

The Los Angeles Times, February 21 and 22, reports minor damage from two more short, localized flurries that are not plotted in figure 18. The first occurred on the evening of February 20, and apparently it caused some minor debris flows that partly blocked roads in the Benedict Canyon area of the Santa Monica Mountains. The second, on late Wednesday, February 21, was heaviest in the San Gabriel Valley–Whittier area where minor landslides were quickly removed by street maintenance crews. The Bel Air gage would provide a representative record of rainfall at the Benedict Canyon site, but it was apparently not operating on February 20. The Los Angeles gage is the nearest of those plotted (fig. 18) to the San Gabriel Valley–Whittier area, but judging from the higher totals registered at nonrecording gages in the most affected area, the storm intensities there may have been as much as two or three times as great as in downtown Los Angeles. Some damaging debris flows occurred, but they were probably not all of soil-slip origin.

STORMS OF NOVEMBER 14 TO DECEMBER 30, 1965

The rains of the 1965–1966 winter season began unseasonably early—in September 1965. A few scattered light showers fell on September 5 and 6. More scattered showers fell on September 16 and 17, but on the 18th the showers turned into extremely heavy (as much as 1 inch per hour) rains of relatively short duration and irregular distribution. (For example, Los Angeles Civic Center reported 1.39 inches for the same day that Bel Air reported no precipitation. The rain tapered back to scattered, light showers on the 19th. Although Elford (1966, p. 314) reported damage from "mud flows" as well as flooding, an examination of newspaper accounts of the storm damage indicates that debris flows of soil-slip origin probably did not occur. During the remainder of September, throughout October and through the first two weeks of November, only traces of precipitation were reported in the area. The series of storms of November 14 through December 30 is illustrated by figure 19. The numbered horizontal lines (fig. 19) indicate the approximate timespans covered by newspaper reports that are summarized and keyed to those numbers in the following text.

September 1965: No storm damage was reported in the Los Angeles Times until September 19, when a story by Eric Malnic (p. B) listed reports of street blockage by flowing mud, debris, and water (presumably a mixture, rather than discrete spurts of each) in Highland Park. Also in Highland Park, Malnic (Los Angeles Times September 19, 1965, p. B) related reports of mud oozing into a backyard of a residence at 442 West Avenue 37 from a road construction project above. The reports do not mention "mudslides" or "landslides," and probably do not refer to debris flows of soil-slip origin. The first incident is probably best interpreted as surface-runoff flooding. While the second incident probably depicts a slow debris flow, its origin in an area of active construction complicates any interpretation of mechanism of origin. Although the intensity of rainfall was high (the Malnic story reports over 1 inch per hour locally), soil-slip–debris-flow activity was, at most, extremely sparse and slight, and it may have been nonexistent. The Times of September 20 recapped the unusually early storm with emphasis on the early snow in the mountains, extraordinarily high total rainfall for September, and traffic deaths on rain-slickened streets, without mention of landslides, mudslides, mud or debris.

September 19 through November 13, 1965: From September 19 through November 13, only trace amounts of precipitation were recorded in the area. The Los Angeles Times for the morning of November 15 provides the first indication of storm damage, referring to rains that fell on the 14th and, perhaps, including rain of the early hours of the morning of the 15th (fig. 19). Most reports were clearly of flood damage. The only account even vaguely resembling a debris flow was that of a "river of mud" in the 3800–3900 block of Bluff Street, Palos Verdes Hills, whose origin was attributed to "runoff waters in a uncompleted subdivision."

65.1: On the morning of November 16, the Los Angeles Times, reporting events chiefly of November 15, noted: (a) A mudslide from a hillside construction project in Torrance invaded the yards of homes at 3429 and 4255 Newton Street. Its origin was attributed to water runoff (Los Angeles Times, November 16, p. 1). (b) In the Santa Monica Mountains, expensive homes in the 1800 block of Laurel Canyon Boulevard were "threatened" (op. cit., p. 1), and small slides were noted along Beverly Canyon Drive by the Bureau of Street Maintenance (op. cit., p. 3). From these accounts, the events in Torrance and in Laurel Canyon probably included debris flows, and those on Beverly Canyon Drive possibly included debris flows. It seems unlikely that the origin of the Torrance events involved soil slips. Soil slips may have contributed to the Laurel Canyon and Beverly Canyon events but are not required by the data in the reports. Specific times for the events were not reported; however, there was at least one significant flurry of high-intensity rainfall at nearly all the recording gages between 6:00 p.m. and 11:00 p.m. on November 15 during the report period.

65.2: On the morning of November 17, the Los Angeles Times noted that continuing rainfall had caused additional problems from mud and debris: (a) In the Palos Verdes Hills section of Torrance at Newton and Bluff Streets (p. 1, cc) there was possibly but not necessarily a debris flow. (b) In the hills of Glendale, Chevy Chase Boulevard between Glenoaks and Linda Vista was blocked by mud and debris (p. 1); the blockage was probably, but not necessarily from a debris flow. (c) In the Santa Monica Mountains, Topanga Canyon Boulevard was listed as impassable (p. 1), and there were problems with mud and debris above Hollywood at 1825 Prospect Drive (p. 1, cc). The material probably, but not necessarily, includes some debris flows. (d) To the north, U.S. Highway 99 and Interstate 5 were partly blocked by "mudslides" in the Welden Canyon area, and the Santa Susana Pass Road was closed by a "slide" (p. 1). These blockages probably, but not necessarily, include some debris flows. Many flooded areas were noted also. Soil slips may have contributed to some of the probable debris flows, but none are required by the data in the reports. Specific times for events were not reported; however, all gages examined (fig. 19) recorded steady rainfall beginning before noon on November 16, climaxed by a general high-intensity rainfall between about 10:00 p.m., November 16, and about 3:00 a.m., November 17, during the probable report period.

65.3: On the morning of November 18, the Los Angeles Times reported widespread damage from high water and flood erosion. In the vicinity of the Santa Monica Mountains: (a) "Mudslides" were reported clogging Beachwood Drive in Hollywood and Sunset Boulevard in Pacific Palisades (Los Angeles Times, November 18, 1965, p. 1), and thick deposits of silt and mud were reported (op. cit., p. 36) in the Hollywood hills at 1836 Laurel Canyon Boulevard and in Mandeville Canyon. These deposits probably include some debris flows. Mud deposited on properties on Prospect Drive and Laurel Canyon Boulevard was attributed to runoff water that cut a deep channel in an unpaved road in the area (op. cit., p. 1). (b) In the Elysian Park hills, Glendale Boulevard between Riverside Drive and Waverly Drive was barricaded because of "slides" (p. 1); the account does not distinguish whether loss of roadway was due to moving slide mass or blockage by slide debris. (c) Along the east side of the San Fernando Valley, "landslides" were reported in the vicinity of Little Tujunga and Pacoima Canyons (op. cit., p. 36), and the mud and debris that reportedly "rolled out of Stetson Canyon" above Sylmar (op. cit., p. 1) probably included some debris flows. (d) On the north side of San Gabriel Valley, "landslides" reportedly closed Fish Canyon Road above Duarte, and in Temple City, pavement was eroded by floodwaters (op. cit., p. 36). (e) Floods were reported in the Simi Valley, and the Thousand Oaks area was troubled with high water (op. cit., p. 1). (f) In Santa Susana Pass the road was blocked by rocks and mud, and in nearby Chatsworth, some retaining walls collapsed in Box Canyon (op. cit., p. 1). (g) "Mudslides" were reported as occurring in the San Diego area.

Some of the foregoing are probably best assigned to "debris flows," but for many others the assignment is questionable. Although soil slips may have contributed to some of them, none is required by the data in the reports. Specific times for the above events were not reported; however, the curves (fig. 19) show that the steady rainfall that had begun on November 15 had continued until nearly midnight on November 17. The report period covers two parts of the storm in which high-intensity rainfall occurred. Many events associated with the general high-intensity flurry of the early morning hours of November 17 were probably not reported until the morning of the 18th. The high-intensity phases of the evening of November 17 were somewhat lower and less pervasively distributed than the previous one, and it shows a stronger orographic effect with higher intensities at the higher stations.

November 18 through 21 was relatively clear with a few sparsely scattered showers. The only new site of storm damage reported was the closing of Sepulveda Boulevard east of Torrance, between Normandie and Western, because of mud, debris, and floodwaters (Los Angeles Times, November 19, 1965, p. 3). The closing was probably caused by a flood runoff problem rather than debris flow, judging from the low relief of the area. By the morning of November 22, showers had begun, and heavier rains were predicted to follow (Los Angeles Times, November 22, 1965). Storm totals through Thursday, November 18, in adjacent areas were 13 inches at Lake Arrowhead in the San Bernardino Mountains (Los Angeles Times, November 19, 1965, p. 3) and 15 inches in the Simi Valley area of Ventura County (Los Angeles Times, November 22, 1965)

65.4: On the morning of November 23, the Los Angeles Times reported: (a) There was extensive damage as eight homes along Laurel Canyon Boulevard were invaded by mud and water, attributed to drainage from a subdivision under construction uphill from the damage (Los Angeles Times, November 23, 1965, p. 26). A photograph (op. cit., p. 3) shows mud flowing around the garage at 1836 Laurel Canyon Boulevard; because there is no free water, it is very probably a debris flow, possibly, but doubtfully, of soil-slip origin. (b) In Woodland Hills, Topanga Canyon Boulevard was closed by a "mudslide" between Ventura Boulevard and Mulholland Drive (op. cit., p. 26); it was very probably caused by a debris flow, and was possibly but not necessarily of soil-slip origin. (c) In Thousand Oaks, Meadows School was closed for fear that an access road would be blocked by a "mudslide." (d) In Pacific Palisades a "slide" closed the Pacific Coast Highway (op. cit., p. 3). J. T. McGill (written commun., 1972) assigns it to soilfall–debris avalanche class. (e) Minor "mudslides" were reported along Rosecrans Avenue in Fullerton, Orange County (Los Angeles Times, November 23, 1965, p. 8).

Some of the foregoing are clearly debris flows. Soil slips may have contributed to some, but no unequivocal assignment to that origin can be made. Specific times for the events were not reported; however, the curves (fig. 19) show that rainfall of high intensity was continuous throughout much of the probable reporting period, beginning about 4:00 a.m. and continuing to about 10:00 p.m. on November 22.

65.5: On the morning of November 24, the Los Angeles Times reported no further storm damage in the Los Angeles area but reported (p. 3) flash floods and "mudslides" farther south including three fatalities in Tijuana, Mexico where two children were killed when their family residence (a "flimsy shack") was crushed by debris and an elderly woman was killed at her home in a "mudslide."

65.6: On the morning of November 25, the Times' stories featured discussion of mopping-up, fears of more damage if new rains should come, disaster assessments, and financial aid programs. Although there was a relatively short flurry of moderate to heavy rainfall on the morning of November 24, between about 3:00 a.m. and 12:00 noon it received no specific mention, and there was no report of new damage.

65.7: On the morning of Friday, November 26, the Los Angeles Times' weather news emphasized high winds and a tornado in Pomona and noted that weather was clearing. Although there had been a short general flurry between about 6:00 a.m. and 8:00 a.m., November 25, no new damage was reported aside from that caused by the tornado.

During the 13-day lull that followed, there were no reports of new damage that could be interpreted as debris flow. The lull was broken by a couple of short, locally heavy rain flurries beginning about 7:00 p.m. on December 9, 1965.

65.8: On Friday morning, December 10, the Los Angeles Times (p. 1, 30) reported mostly light to moderate rain, locally heavy rains with thunder and lightning, but no major flooding or slides in the Los Angeles area. In San Diego, however, there were heavy rains and floods with damage and evacuations, and at Needles, heavy rains.

65.9: On Saturday morning, December 11, the Los Angeles Times (p. 1) reported that the storm was fading, but that some clouds remained. There were no reports of floods or slope failure.

The 17-day lull that followed was broken by only a few scattered showers. One "slide" that occurred in Pacific Palisades on December 25, about 2:00 a.m., blocked the Pacific Coast Highway between Chautauqua and Sunset Boulevards (Los Angeles Times, December 28, 1965, p. 3). It was very probably a soilfall from the coastal bluff. There were no other reports of new events that could be interpreted as being caused by debris flows.

65.10: On Wednesday morning, December 29, the Los

Angeles Times reported showers falling and predictions of rain, heavy at times for the Los Angeles area, from a north Pacific storm already pounding northern California. There were no reports of new events that could be interpreted as being caused by debris flows.

65.11: On Thursday morning, December 30, the Los Angeles Times reported extensive damage from heavy rains. Flooding was reported in the San Fernando Valley (p. 1), in the Encino area (p. 3), and in Ventura County in the Simi Valley, and at Oak View (p. 3) as the storm swept southeast through Los Angeles. Several road washouts were noted (op. cit., p. 1). "Mudslides" and flooding were reported north of Newhall (op. cit., p. 3); "mudslides" were reported in the Jackson Lake area, near Big Pines (op. cit., p. 3); and many highways in the mountains and canyons were closed by landslides, including I–15 at Cajon Pass (op. cit., p. 3). In the Santa Monica Mountains, a woman was reported missing (op. cit., p. 3) when her residence at 1400 Latigo Canyon Road was destroyed.

This last event has been documented as a debris flow of soil-slip origin (see p. 42–46) and is shown in figures 5 and 19 as item 14. Of the other reported events that might have been of soil-slip–debris-flow character, the one near Big Pines was sufficiently close to one of the plotted recording gages—the San Dimas Tanbark Flat gage—to provide an acceptable basis for the evaluation of storm conditions. Specific times for the events were not reported, but the contexts contain no implications that any of them occurred before or after the general period of high-intensity rainfall between about 3:00 a.m. and about 2:00 p.m. on December 29.

65.12: On Friday morning, December 31, the Los Angeles Times (p. 1, 3) reported that a search of debris for the missing woman continued. The recovery of her body was reported in the Los Angeles Times the following morning (January 1, 1966, p. 2). Mud (of unreported origin) was photographed on Chevy Chase Drive in Glendale, where it blocked the street (Los Angeles Times, December 31, 1965, pt. 2, p. 1). The Los Angeles Times of Saturday morning, January 1, 1966, also reported a home above the Sunset Strip as wrecked by a landslide (p. 2). This landslide was probably not a debris flow.

The end of the high-intensity rainfall on the afternoon of December 29 apparently marked the end of the severe storm activity that had begun on November 14.

STORM PERIOD OF JANUARY 18–25, 1969

The following paragraphs summarize episodes of mudflow activity in specific areas and specific debris-flow events as reported by the general sources listed in the sections "Introduction" and "Acknowledgments" of this report. The numbers following the prefix 69 refer to locations plotted on the map (fig. 5) and times plotted on the cumulative rainfall curves (fig. 9).

69.1. Glendora-Azusa area, "morning," January 22, 1969: First spate of debris flows inundated some residential areas. Total rainfall and intensities in tributary watersheds are probably well represented by the gage record for "San Dimas Tanbark Flat." Kevin Scott (1971, p. C242–C247) attributes origin, in large part, to superficial slope failures in the short steep drainage basins on the south flank of the San Gabriel Mountains; he cites scars as evidence.

69.2 Glendora-Azusa area, "morning," January 25, 1969: Debris flows again inundate some residential areas, many of the same ones damaged by the flows of January 22. Scott again attributes origin largely to superficial slope failures. Rainfall total and intensity probably well represented by gage "San Dimas Tanbark Flat."

69.10. Glendale, Chevy Chase Canyon area, 7:00 a.m., January 22, 1969: Glendale News-Press reports that a residence at 3086 Chevy Chase Drive damaged by "mudslide" at 7:00 a.m.; occupants escaped without injury. The approaching slug was heard, and described as a "crash" or a "roar." A soil-slip origin is inferred from its description as a single-pulse episode; no photograph or description of scar. Reports also mention other storm-related activity that includes problems clearly of surface-runoff origin, such as washouts and gullying of roads.

69.9. Glendale, Chevy Chase Canyon area, 6:30 a.m., January 25, 1969: Two persons were killed at 3048 Buckingham Road when walls of bedroom were crushed by a "mudslide." A soil-slip origin is inferred from the apparent single-pulse episode as described in Glendale News-Press report dated January 25. (See Sunday Mercury-News, San Jose, California, for photograph of rescue operations at site, credited as Associated Press Wirephoto). No photographs or description of scar. Gage "Flintridge FC" is probably best representative of rainfall character at site of "mudslide." Much other "mudslide" activity was reported (Glendale News-Press) in the same general neighborhood at the same time. Some descriptions indicate soil-slip–debris-flow character rather clearly; however, damage from other types of landslides and from muddy floodwaters has also been included.

69.8. Highland Park, 9:00 a.m., January 25, 1969: Two children were killed when their home at 1279 El Paso Drive was crushed by a debris flow at about 9:00 a.m., January 25, 1969 (time and address from report in Los

Angeles Times for January 26, 1969). A soil-slip origin is documented by photographs (Photograph by Associated Press Wirephoto on p. 16, San Jose Mercury-News for January 26; photograph by Los Angeles City Department of Building and Safety, see fig. 15). Rainfall characteristics at site of failure probably best represented by gage "Los Angeles Civic Center."

69.5. Sherman Oaks, 6:00 a.m., January 25, 1969: One person was killed by a debris flow that crashed into the back bedroom of a residence at 15421 Deerhorn at 6:00 a.m., January 25 (C. A. Yelverton, oral commun., July 27, 1969). A soil-slip origin is indicated by the scar. Rainfall at the failure site is probably well represented by the characteristics of the curve for gage "Sepulveda Dam." (See fig. 12.)

69.6 Sherman Oaks, 6:50 a.m., January 25, 1969: One person was killed by a debris flow that broke through bedroom wall of a residence at 3830 Sherview at 6:50 a.m., January 25 (C. A. Yelverton, oral commun., July 20, 1969). A soil-slip origin is indicated by the scar. The rainfall at the failure site is probably well represented by the characteristics of curve for gage "Sepulveda Dam."

69.3 Brentwood, Mandeville Canyon area, 12:30 a.m., January 25, 1969: A debris flow ("mudslide") crashed into back of a house killing one man in bed at 2077 Mandeville Canyon Road. About 45 minutes later, six firemen attempting to rescue him were temporarily trapped in the house by a second slide. A photograph (fig. 11), courtesy of C. A. Yelverton, Los Angeles (City) Department of Building and Safety, shows the soil-slip scars from which the flows were derived. (C. A. Yelverton, oral commun. and photograph, July 29, 1969.)

69.4 Topanga area, about 3:00 a.m., January 25, 1969: Three people were killed and one seriously injured when a debris flow crushed the rear of a house about 0.15 mile north of the Greenleaf Canyon bridge. Part of the house was pushed into the floodwaters of Topanga Creek, normally about 15 feet below, and carried downstream. Scars establish the soil-slip origin. The time of the event is tentatively established by neighbors who were awakened by less damaging slides on their own property; they heard a noise that they believe to have marked the destructive slide nearby at about 3:00 a.m. (See case description, p. 46–48.)
None of the continuously recording gages is sufficiently close to be satisfactorily representative of the site of failure; however, the site is about midway between the gage locations at "Sepulveda Dam" and "Lechuza Point," so that the two gages probably bracket the rainfall at the failure site (fig. 9).

69.4a. Old Topanga Canyon area, between 1:00 a.m. and 9:00 a.m., January 25, 1969: One man was killed by debris flow at 874 Old Topanga Canyon Road. The impact of the debris broke a hole in the back wall of the house through which the flow entered at high velocity. The soil-slip origin was indicated by slide scars (ravine fill). The time was established from accounts of neighbors. The neighbors also described many other debris flows, some causing serious damage, beginning between midnight and 12:30 a.m., January 25, and reaching a climactic frequency about 3:00 a.m. (See case description, p. 48–50.)

69.7. Thousand Oaks, 7:45 a.m., January 25, 1969: One person was killed by debris flow which crashed into the back bedroom of the residence at 818 Combes Road. The soil-slip origin is documented by scars (see fig. 13) and by an eye-witness account published in the Thousand Oaks News-Chronicle of Sunday, January 26, 1969. Rainfall characteristics are not well represented because there is no nearby continuously recording gage; however, reasonable maximum and minimum totals and intensities may be inferred to be somewhere between the curves for gages "Lechuza Point" and "Sepulveda Dam." ("Lechuza Point" is at about the same meridian, but much higher; "Sepulveda Dam" is about the same altitude, but far to the east.)

STORM PERIOD OF FEBRUARY 5–25, 1969

The following summary of episodes of storm and debris-flow activity is taken largely from accounts in the Los Angeles Times covering the stated period. The numbers following the prefix 69 that head the paragraphs on the events of February 25 refer to locations plotted on the map (fig. 5) and times plotted on the cumulative rainfall curves (fig. 20).

On Wednesday morning, February 5, the Times reported (p. 1) that scattered showers fell in advance of the storm, more showers were expected during Wednesday, and storm rains by Thursday.

On Thursday morning, February 6, the Times reported (p. 1, 32) thunderstorms, but no floods or landslides were noted.

On Friday morning, February 7, the Times (p. 1) reported "giant mudslides" in the Glendora area and other storm damage, all apparently occurring on Thursday. Reports included a page-1 photograph of debris deposited in a suburban neighborhood in Glendora. Flooding and high winds—including tornadoes—were reported at several locations. These events are at localities not well represented by the gages plotted in figure 20, but the general period of high-intensity rainfall indicated on the morning of Thursday, February 6, is the most probable association. Although the Mount Baldy gage is at a much higher altitude, where the orographic effect usually produces heavier rainfall, a visual comparison of the hourly records of that gage with those of the gage at San Dimas Tanbark Flat in the mountains directly above Glendora (U.S. Environmental Science Services Administration, 1969A) establishes that the general periods of high-intensity rainfall for the two gages were virtually identical.

On the morning of Saturday, February 8, the Times noted only a slow-moving landslide at Princess Park Estates, in the Newhall area. The weather was clear and remained so until Tuesday, February 11. Photographs of some flood damage in Big Tujunga wash, from the storm of February 6, were published in the Times for Sunday, February 9 (section L, p. 1).

On the morning of Wednesday, February 12, the Times reported that a storm front had reached Los Angeles Tuesday night and that heavy rains might be expected.

On Thursday morning, February 13, the Times reported that the expected storm had brought only a few showers. Reports and photographs of damage from landslides on the Pomona Freeway (p. 1), at Mount Washington, and in Laurel Canyon (p. 3) show very clearly that they are probably of the slump-earthflow class, involving deep rotational slip surfaces and large volumes of material.

On Friday morning, February 14, the Times reported no new damage, no new rainfall; however, a photograph (p. 1) shows a good view of the slide on the Pomona Freeway. Judging from the crown scar and deposit head, the failure was a deep rotational slump in weak late Tertiary sedimentary rocks. The toe has the steep-fronted lobate appearance of a very viscous debris flow, and discrete blocks are few, but accounts of one witness who "rode it out" in his car indicates that the movement was very rapid.

On Saturday morning, February 15, the Times reported that scattered light showers fell Friday night; clouds and rain were forecast.

On Sunday morning, February 16, the Times reported a short period of heavy rain, leaving about ⅓ inch at the Civic Center between 6:00 p.m. and 7:00 p.m. on Saturday; snow was reported at Mount Baldy and a chance of showers was forecast. No new slides were reported. Mention was made of continued movement of the slide in the Mount Washington area which overturned a house.

No rain or storm damage was reported on Monday, February 17, or Tuesday, February 18.

The light rainfall that began on Tuesday, February 18, continued through to the evening hours of Wednesday, February 19, but generally did not exceed 0.10 inch per hour except at the highest altitudes, and even there, it rained only for an hour or two on the evening of February 19. The maximum hourly intensities recorded in the Los Angeles area during that period were 0.22 inch for the hour ending at 7:00 p.m., February 19, at the Mount Wilson gage and 0.18 inch for the hour ending 10:00 p.m., February 19, at the San Dimas Tanbark Flat gage.

On Wednesday morning, February 19, the Times reported (p. 1) that several homes in the Encino area were evacuated when mud threatened to slide into two of them. (The relatively slow rates of movement implied suggest that the slide may have been a slump of some sort, although the soil-slip–debris-flow class cannot be excluded.) In the Castellammare area of Pacific Palisades, a slow-moving slide was reported (Los Angeles Times, February 19, 1969, p. 22) in an area long plagued with slumps on complex surfaces of weakness in highly deformed bedrock. No unequivocal debris flows were reported even though scattered rains of light to moderate intensity fell during the probable report period (Tuesday, February 18, and the first few hours of Wednesday, February 19).

On Thursday morning, February 20, the Times reported (p. 1) slides in Laurel Canyon, Encino, and Highland Park occurring on Wednesday. A photograph (op. cit., p. 3) of the slide in Encino shows deep cracking that affects a house on the slide mass. The slide seems to be a large slump. The description (op. cit., p. 3) of the Laurel Canyon slide suggests a massive slump rather than a soil slip. At Highland Park, the slide description (op. cit., p. 3) mentions a "twisting fissure" beginning to "buckle" two houses. This seems most likely to be associated with slump failure rather than soil slip. Two descriptions on page 3 possibly, but not necessarily, represent debris flows: one mentions the "caving in" of the rear part of an abandoned house, and at another locality a garage was reported "buckled." However, no unequivocal debris flows were recorded.

No rain fell on Thursday, February 20, over most of the area, and no new damage was reported in the Times on the morning of Friday, February 21.

On Saturday morning, February 22, the Times reported that rain had begun Friday night and was expected to continue until Monday, with possible heavy rains forecast for Sunday. The brief, heavy rainfall of 2:00 a.m., February 22, (fig. 20) resulted in no reports of debris-flow activity.

On Sunday morning, February 23, the Times reported scattered showers falling Saturday night. A "mudslide" was reported blocking Mount Baldy Road about 9 miles above Claremont and "mudslides" were reported blocking Valencia Road and Ortega Highway in Orange County.

On Monday morning, February 24, the Times reported heavy rain (see also fig. 20) and snow in the mountains. A "mudslide" was reported (op. cit., p. 1) on Glen Oaks Boulevard in Pasadena in the San Rafael Hills. On page 3 it was noted that although there were no new areas with earthslides in the Los Angeles area, areas affected in the previous weeks were still unstable; and at Newhall there was a renewed threat of landslides.

The storm episode that began the afternoon of Saturday, February 23; extended through the morning hours of Tuesday, February 25, with little respite. On the morning of Tuesday, February 25, the Times reported widespread flooding, earthslides, and mudslides. In the Santa Ana Mountains, two damaging "mudslides" were reported in Silverado Canyon and another in Mojeska Canyon (op. cit., p. 2). "Mudslides" contributed to the closing of numerous roads in the State (op. cit., p. 2). The large slump at Mount Washington continued to move causing more damage (op. cit., p. 1, 20), but conditions in other areas of active slumping, including Highland Park and Laurel Canyon, remained unchanged (op. cit., p. 2).

On Wednesday morning, February 26, the Times reported the continuation of widespread flood and "mudslide" damage through the morning of Tuesday, February 25. Two "mudslides," one in the Santa Ana Mountains (see 69.11b, below) and one in the San Gabriel Mountains (see 69.11a, below) resulted in a total of eight fatalities. In addition, there was a damaging "mudslide" in Eagle Rock, at 1114 Oak Grove Drive, on Tuesday morning (op. cit., p. 13), and another in Sherman Oaks (op. cit., p. 13), at 3733 Loadstone Drive. Many major roads and highways throughout southern California were closed, and "mudslides" were prominently mentioned as causes (op. cit., p. 3, 13) along with floods and heavy snow in the mountains.

At the Eagle Rock site, residents evacuated on Tuesday morning, early enough so that they were still in their nightclothes. Although the time is not precisely reported, and nearby gages have not been plotted, there appears to be a general correlation with a local peak in the rainfall intensity. Visual inspection of the Hourly Precipitation Data (U.S. Environmental Science Services Administration, 1969) shows that, within a longer period of light to moderate rainfall, a flurry of intensity greater than 0.20 inch per hour lasted from 4:00 a.m. to 6:00 a.m. at the Los Angeles Civic Center and from 4:00 a.m. to 7:00 a.m. at Santa Fe Dam. An average of those two gages is probably a fair representation of the rainfall intensity at the time and place of failure.

At the Sherman Oaks site the time is not even approximately reported. Inspection of the Hourly Precipitation Date (U.S. Environmental Sciences Services Administration, 1969), however, shows that, within the longer period of light to moderate rainfall, a flurry of intensity greater than 0.20 inch per hour lasted from about midnight to 4:00 a.m. hours at the nearby gage at Sepulveda Dam. Time correlation is permitted but is not required by the circumstances.

69.11a Mount Baldy Village, 8:00 a.m., February 25, 1969: (Number following the prefix 69 refers to location in fig. 5 and time plotted in fig. 20.) A slide killed three members of one family in a residence at Mount Baldy Village, San Gabriel Mountains, at about 8:00 a.m., February 25 (Los Angeles Times, February 26, p. 13). The nearby gage at Mount Baldy (fig. 20) was, unfortunately, not operating at the time of failure; however, the gage at San Dimas Tanbark Flat, less than 10 miles away and at a slightly lower altitude, recorded 0.73 inch of rain for the hour ending 8:00 a.m. and 0.69 inch for the hour ending 9:00 a.m., February 25. Therefore, the failure was almost certainly associated with a rainfall of high intensity. The event was very probably a soil slip–debris flow, however, the phrasing of the report would also permit interpretations of origin as a rockfall or rockslide.

69.11b. Silverado Canyon, 11:00 a.m., February 25, 1969: (Number following the prefix 69 refers to location in fig. 5 and time plotted in fig. 20.) A "mudslide" swept into the back and through the length of a fire station in Silverado Canyon, Santa Ana Mountains. Fire engines, crew, and many of the 60 flood refugees who had sought shelter there were carried out through the doors into the road in front of the station (Los Angeles Times, February 26, p. 1, 13). Five of the people were killed and about 20 others were injured. The incident occurred suddenly at about 11:00 a.m., February 25. The newspaper description of the debris flow and personal examination of the scar establish its character as a debris flow of soil-slip (ravine fill) origin. Figure 28 shows three views of the station after cleanup and placing the structure back into service. Note the scar of the soil slip and course of the debris flow. Nearby gages at Santiago Dam and in Trabuco Canyon approximately bracket the failure site, and the storm conditions there at the time of failure are probably represented by a curve somewhere between those. (See fig. 20.)

CASE DESCRIPTIONS AT THREE SELECTED SITES OF SOIL-SLIP–DEBRIS-FLOW EVENTS

The sites of the five fatal injuries from soil-slip–debris-flow events that have occurred within the past 10 years (1962–71) in the area of the Los Angeles County Cooperative project were examined in more detail.

Case description, soil slip–debris flow of December 29, 1965, in Newton Canyon, Santa Monica Mountains, California

1. *Reference number:* Figure 5, No. 14.

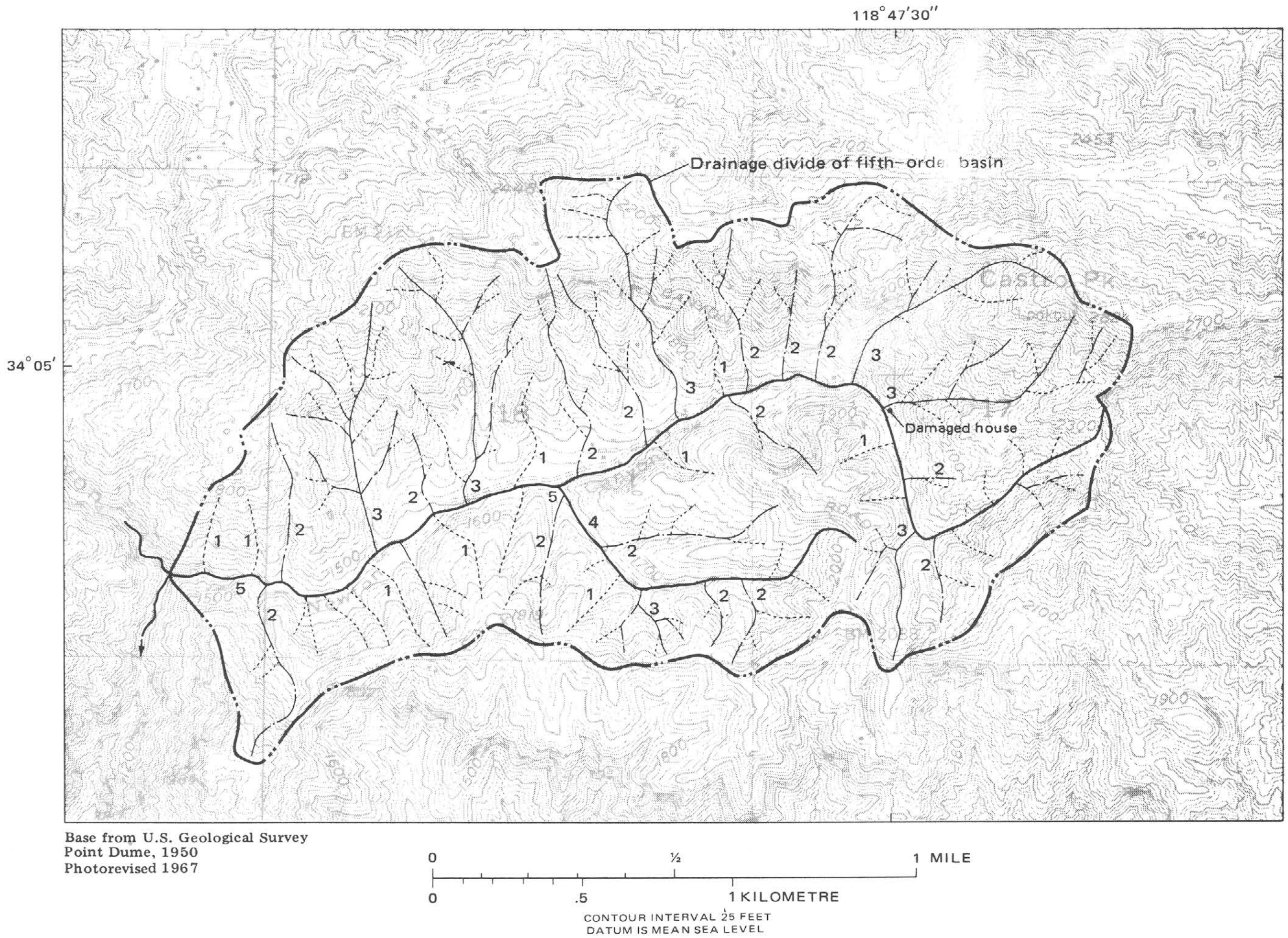
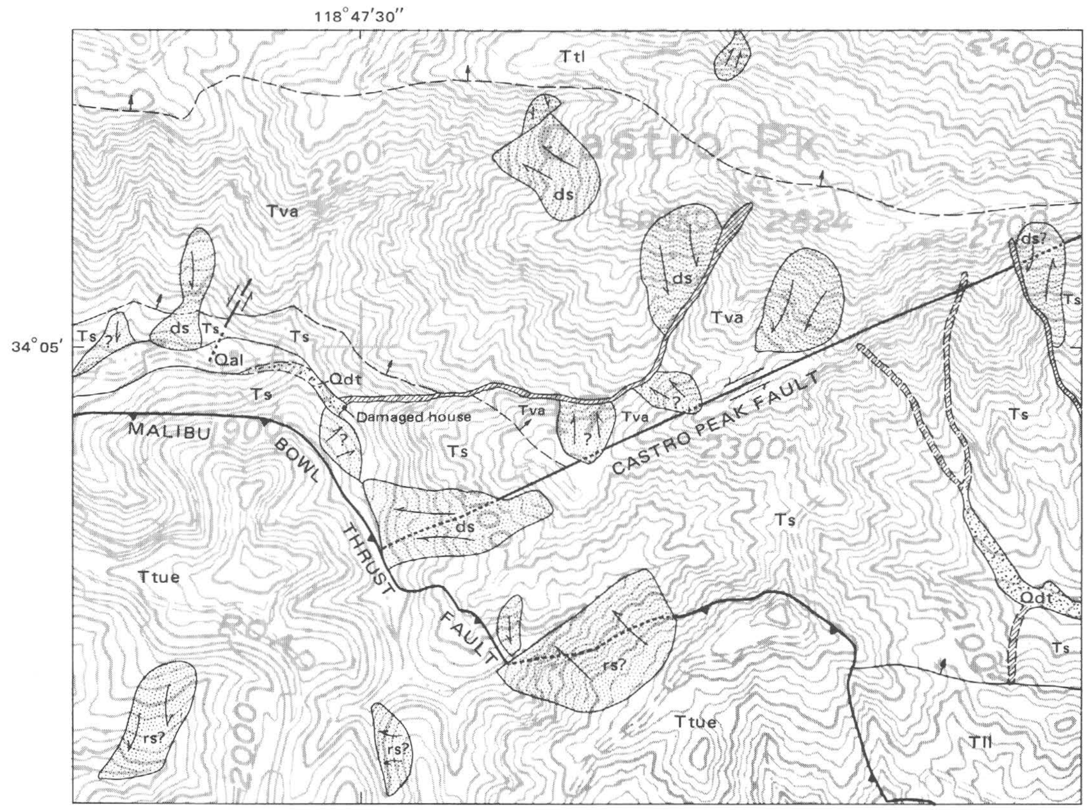


FIGURE 29.—Drainage basin of Newton Canyon, showing location of house destroyed by debris flow of December 29, 1965, at junction of third-order tributary with fifth-order trunk stream. Rank of tributary shown by number.

2. *Location:* Point Dume 7.5′ quadrangle, sec. 17, T. 1 S., R. 18 W., 1400 Latigo Canyon Road, Malibu, Calif. (fig. 29).
3. *Landslide type:* Soil slip (ravine fill)–debris flow.
4. *Date and time of occurrence:* December 29, 1965, after about 11:00 a.m. (probably shortly after, certainly well before 6:00 p.m. when the destruction of the house was reported on a news broadcast).
   a. *How established:* Neighbor spoke to victim on telephone in late midmorning.
5. *Landslide dimensions:* (fig. 30).
   a. *Slope length:* Scar, 3,100 feet (fig. 31). Debris train, 600 feet.
   b. *Width:* Scar, about 60 feet wide at widest part of the head, generally no more than 20–25 feet wide through most of its length. Debris train, variable, 60–80 feet wide at upper end, diminishing downstream rapidly below crossing of Latigo Canyon Road.
   c. *Thickness:* Scar.—Judging from thickness of material remaining adjacent to scar, colluvium was 1–3 feet thick in headwall and on flanks of channel. May have been as much as 15 feet thick in the bottom of a few parts of the gentler reaches of the ravine, but was probably generally less than 5 feet thick; Deposit.—Highly irregular piles of boulders and brush from a few inches to as much as 6 feet (mostly brushy), but mostly less than 4 feet high. Much of deposit reworked by bulldozer during search for the missing resident. Much of silt and fine sand probably continued downstream as muddy floodflow.
   d. *Volume:* Estimate approximately 6,000–8,000 cubic yards maximum removed; probably only 3,000–4,000 cubic yards retained in deposit.



Base from U.S. Geological Survey
Point Dume 1:24,000, 1950;
Photorevised 1967

0 1000 2000 3000 FEET

0 200 400 600 800 METRES

CONTOUR INTERVAL 25 FEET
DATUM IS MEAN SEA LEVEL

Geology modified from
Campbell and others, 1970

EXPLANATION

Unconsolidated deposits

QUATERNARY

Scar of soil slip-debris flow

Dashed where approximately located. All scars shown may have formed during the same storm period (December 29, 1965), but only the Newton Canyon event provides a record of date and approximate time

Qdt

Debris trains

Gravel, debris, and sand deposited from debris flows. The debris train in Newton Canyon is mainly that from the December 29,1965, event. The debris trains in the other drainage, further east, include deposits overgrown with brush as well as fresh deposits, showing the recurring character of the events

ds?

Landslide deposits

Boundaries approximately located, queried where doubtfully recognized ds, *debris slide;* rs, *rotational slump; queried where classification uncertain. Chiefly Holocene, possibly older in part; none have historic movement. Arrows indicate apparent direction of movement*

Qal

Alluvium

Stream-deposited silt, sand, and gravel

Bedrock

TERTIARY

Ttue

Upper Topanga Formation of Durrell (1954)

Thin-bedded shale, sandy shale, and volcaniclastic beds. Middle Miocene. Synvolcanic and postvolcanic in age

Ttl

Lower Topanga Formation of Durrell (1954)

Thick-bedded sandstone and mudstone, minor shale. Middle Miocene. Prevolcanic in age

Tva

Vaqueros Formation

Thick-bedded sandstone and mudstone, separated from overlying Lower Topanga by distinctive molluscan faunas. Early Miocene

Ts

Sespe Formation

Very thick bedded continental sandstone and conglomerate, locally red. Age may range from late Eocene to early Miocene

Tll

Llajas (?) Formation of McMasters (1933)

Very thin bedded to medium-bedded turbidite sandstone and sandy shale. Middle Eocene

Contact, showing direction of dip

Dashed where approximately located, and where inferred from faunal control

High-angle fault

Dotted where concealed. Arrows show direction of apparent lateral displacement

Low-angle fault

Dotted where concealed. Sawteeth on upper plate also point downdip

FIGURE 30—Geologic map of upper Newton Canyon, showing path of debris flow of December 29, 1965, and similar scars in nearby uninhabited areas.

FIGURE 31.—Upper part of scar of ravine-fill failure on south face of Castro Peak.

6. *Distance moved:* Material from the head of the scar moved at least 3,100 feet.
7. *Original slope at failure:* Steepest gradient in headwall about 50 degrees. Gentlest reach 11° (fig. 32).
8. *Estimated rate of movement:* Very rapid to extremely rapid—probably greater than 10 ft/s. The impact damage at the head of the debris train indicates momentum from high velocity of debris.
9. *Precipitation conditions:* Prolonged heavy rains preceded and accompanied the failure.
10. *Subsurface water:* Prior to seasonal rains, there were no springs or other indications that a permanent water table in the bedrock intersected the ground surface in the drainage that failed, though small seeps might have gone unrecorded. Close association of failure and seasonal rains (heavy rainfall, at that) suggests rapid, near-surface circulation—probably entirely within the soil zone.
11. *Monetary damage:* House, garage, car, and landscaping destroyed. Road partly blocked, partly eroded, requiring repairs. Emergency crew and equipment for most of 2 days searching debris for remains of victim (figs. 21, 25).
12. *Injury:* Elderly widow, the sole resident, and her pet dog were killed.
13. *Slide material:* Colluvial soil and ravine fill, chiefly derived from the Vaqueros Formation, including numerous large boulders of sandstone that clearly originated from that formation. Deposited on alluvium of Newton Canyon composed chiefly of silt, sand, and gravel derived from the shale and sandy shale of the Upper Topanga Formation, overlying bedrock sandstone of the Sespe Formation (fig. 30).
14. *Cause:* Concluded to be increases in pore pressure in soil owing to dynamic imbalance of infiltration and deep percolation during heavy rainfall. Incremental loading from the rear of the sort described by Hutchinson and Bhandari (1971) may have contributed to the mobilization of material below the steepest part of the slope; however, the narrowness of the debris flow channel and the persistent low level of the "mudline" that marks the depth of flow precludes piecemeal, randomly distributed ponding and flow erosion of the ravine fill.
15. *Treatment:* Event not predicted and proceeded too rapidly to permit erection of defenses. Recognition of potential for event and evacuation during high-intensity rainfall would have saved resident

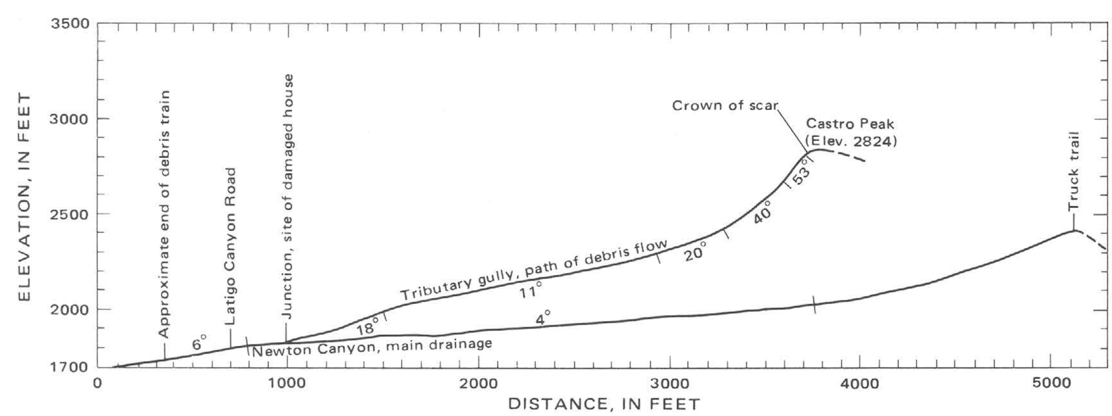
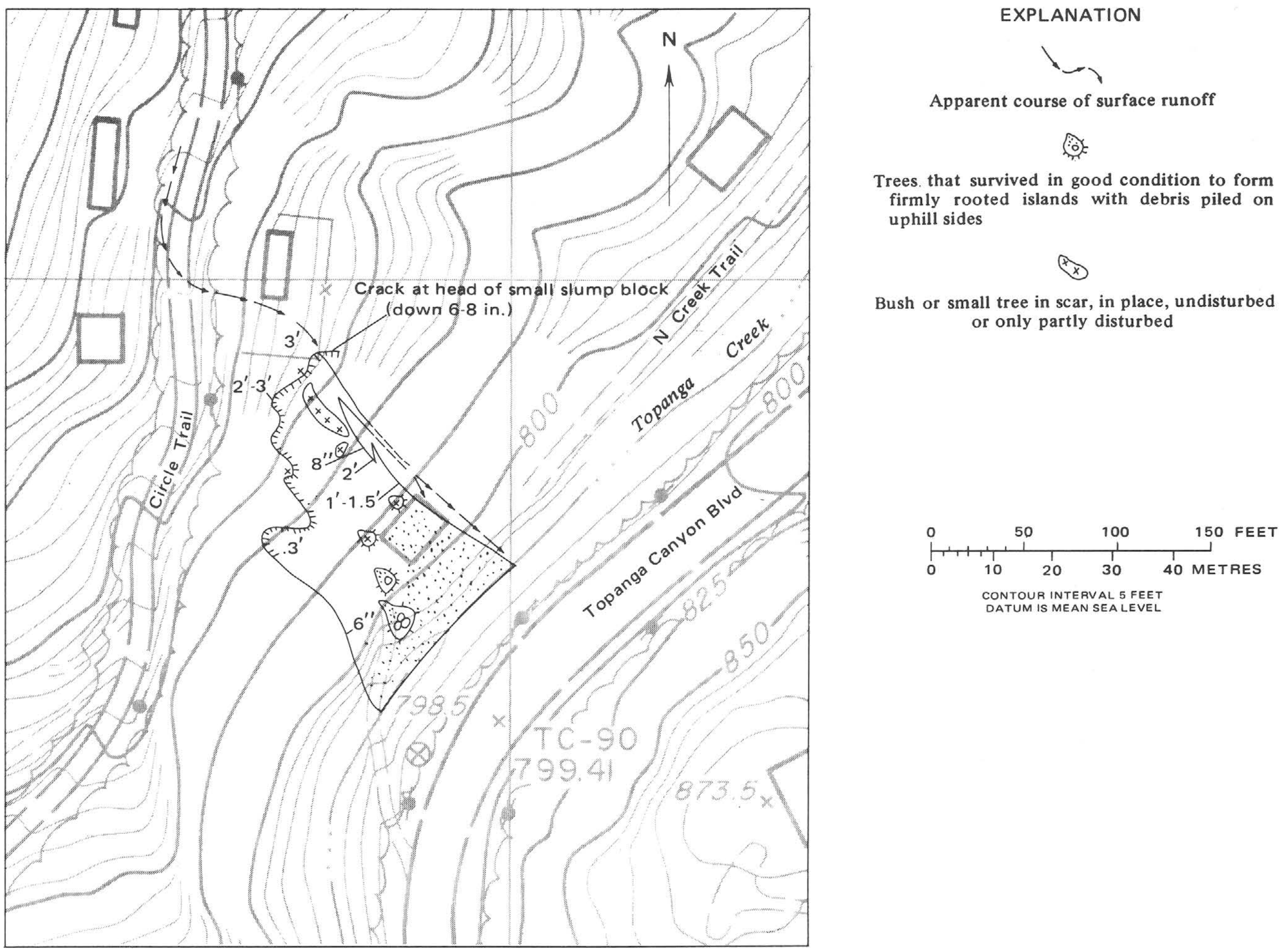


FIGURE 32.—Profile of Newton Canyon debris flow of December 29, 1965, comparing gradients of trunk canyon and tributary. Note that there is no vertical exaggeration.



Base from Survey Division, Department of the County Engineer, Los Angeles County, 1964

Geology by R. H. Campbell, 1969

FIGURE 33.—Soil slip–debris flow of January 25, 1969, at 3221 South Topanga Canyon Boulevard, Topanga, Calif.

from death or injury by the slide. Recognition of hazardous location and removal of residence from most probable path of debris flows by relocation of only a few tens of feet should have been possible. Defense by debris dam possible, but with maintenance costs included, would probably not have been economical. Defense by bracing the dwelling to resist lateral stresses might have added to protection but would also require ties of dwelling to foundation capable of resisting impact which, in this case, was sufficient to remove the building from its foundation.

Case description, soil slip–debris flow of January 25, 1969, in Topanga, Santa Monica Mountains, California

1. *Reference number:* Figure 5, No. 4.
2. *Location:* Topanga 7.5′ quadrangle, sec. 7, T. 1S., R. 16 W., 3221 South Topanga Canyon Boulevard (529 North Creek Trail), Topanga, Calif.
3. *Landslide type:* Soil slip–debris flow.
4. *Date and time of occurrence:* January 25, 1969, probably about 3:00 a.m. Survivor reported having been asleep in an upstairs bedroom and awakened by the mother of two children asleep downstairs, who reported hearing a loud rumbling noise. At this time the house collapsed, and the next he knew he was in the hospital. A neighbor reported being awakened by a loud noise at about 3:00 a.m.; he presumes that was the sound of the destructive debris flow; immediately afterward, a small mudflow entered his back window.
5. *Landslide dimensions:*
   a. *Slope length:* Scar, about 130 feet. Debris train, about 50 feet minimum, with toe having been removed and reworked by floodwaters of Topanga Creek.
   b. *Width:* Scar, as much as 75 feet wide in places. (See fig. 33.)
   c. *Thickness:* Material at edges of scar ranges

from about 6 inches to as much as 3 feet thick.

d. *Volume:* Probably no more than 600 cubic yards removed from scar. Probably no more than a few tens of cubic yards deposited, mostly on pad of destroyed residence and on road below; remainder apparently removed by stream erosion of flooding Topanga Creek. Bedrock is exposed in the scar only where the remaining coating of colluvium is cut through by rills that are probably best attributed to rainwash erosion of the post-failure scar. The nearly uniform coating of colluvium that remains in the scar area indicates that failure took place within the soil zone rather than exactly at the bedrock-colluvium interface. Scar area may represent more than one failure—small nondamaging failures may have occurred both before and after the larger damaging failure. Moreover, the scar was deepened and rilled by rainwash subsequent to the slab failure. These factors tend to reduce the estimate of the volume of the damaging slab failure.

6. *Distance moved:* Material from the head of the scar moved at least 130 feet.
7. *Original slope at failure:* Overall slope in scar area about 40°; some local variations as gentle as 35°.
8. *Estimated rate of movement:* Very rapid to extremely rapid, probably greater than 1 ft/s. Failure of awake adults to escape from house during collapse indicates that it happened very suddenly, suggesting high-velocity impact rather than the slower application of lateral pressure by inundation.
9. *Precipitation conditions:* Prolonged heavy rains preceded and accompanied the failure. Interpolation of records from gages at Sepulveda Dam and Lechuza Point Station indicates that rainfall intensity was between 0.40 and 0.50 inch per hour at the time of failure. (See fig. 9.)
10. *Subsurface water:* Prior to the seasonal rains, there were no reported springs or other indications that a permanent water table in the bedrock intersected the ground surface above the level of Topanga Creek. Close association of failure and seasonal rains suggests rapid, near-surface circulation—probably entirely within the soil zone.
11. *Monetary damage:* Complete destruction of house and contents (fig. 26). Emergency crew and equipment were employed for much of 2 days searching the debris for bodies of victims.
12. *Injuries:* Three residents were killed—a mother and two children. Another was seriously injured (hospitalized).
13. *Slide material:* The material that failed consisted almost entirely of colluvial soil derived from the sandstone and shale of the underlying "Upper Topanga Formation" (of Durrell, 1954). The interbedded sandstone and shale dip gently into the hillside; this resistant obsequent geometry may account for the general steepness of the slope.

    The bedrock is chiefly sandstone, very coarse to medium grained, moderately to poorly indurated; beds 1 inch–2 feet thick, thicker beds seem to predominate at this site; interbedded with thin partings to 3-inch beds of laminated silty shale. The attitude of the beds is nearly flat, with a slight dip into the hillside. There are some cross joints perpendicular to the bedding, and their steepness may contribute to maintaining the general steepness of the slope. Bedrock is exposed in the scar only where eroded by subsequent rill and sheetwash. The coating of colluvium that remains in the scar area indicates that failure took place within the soil zone rather than exactly at the bedrock-colluvium interface.

    The cover, as represented by exposures at the edges of scar, consists of colluvial soil, generally 2–4 feet thick. The top 1–3 inches commonly is gray in color from admixed organic material; it is commonly root filled and friable. Rodent burrows are abundant in the zone 3–6 inches below the surface. Below about 6 inches slabby, angular clasts of sandstone, from small pebbles to large boulders in size, are common. One clast in the debris deposit was as much as 3 feet across and 1 foot thick. The vegetation is predominantly tall grasses and mustard, with scattered thorny bushes (*Ceanothus?*) as much as 15 feet high. The bushy plants are more deeply rooted and appear to have prevented the failure of a couple of "islands" now surrounded by scar.
14. *Cause:* Concluded to be from increase in pore pressure in soil owing to dynamic imbalance of infiltration and deep percolation during heavy rainfall. Sudden failure of large mass is indicated by the sudden and complete destruction of the residence downslope.

    There is evidence that surface runoff entered one part of the scar area from uphill. Its contribution to the failure is unknown; however, its location indicates that it could not be solely responsible. The scar extends significantly higher on the

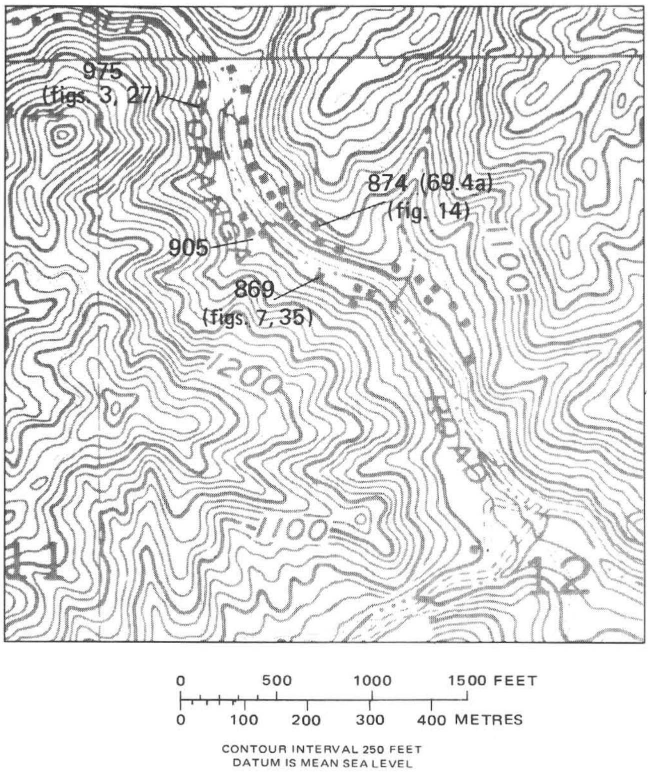


FIGURE 34.—Map of NW¼ sec. 12, T. 1 S., R. 16 W., Topanga 7.5′ quadrangle, showing location of several damaging debris flows in Old Topanga Canyon. Numbers refer to street addresses.

slope than the point at which the runoff channel entered (fig. 33). Moreover, it is possible that the runoff did not occur until after the slope failure.

15. *Treatment:* The event was not predicted and took place too rapidly to permit erection of defenses. Recognition of the potential for the event could have led to evacuation during high-intensity rainfall, removing residents from harm's way. Recognition that the particular site had greater potential for hazard than other sites on the same hillside would have been possible only with extremely detailed field and laboratory study of the entire hillside and does not appear to have been a practical economic possibility. Therefore, relocation of the house on the property would not have been an effective practical defense. It would appear that the best defenses for such structures in such sites would be: deeply anchored revetments upslope to divert the force of the moving mass, some sort of avalanche-shed structure to pass the moving mass over the top of the residence, or massive bracing of the upslope walls to resist lateral pressure and impact, combined with stronger anchoring of the structure to the bedrock.

Case description, soil slip–debris flow of January 25, 1969, in Old Topanga Canyon, Santa Monica Mountains, California

1. *Reference number:* Figure 5, No. 4a.
2. *Location:* Topanga 7.5′ quad., NW¼ sec. 12, T. 1 S., R. 17 W. 874 Old Topanga Canyon Road, Topanga, Calif. (fig. 34).
3. *Landslide type:* Soil slip (ravine fill)–debris flow.
4. *Date and time of occurrence:* January 25, 1969, probably after about 1:00 a.m., before 9:00 a.m.
   a. *How established:* According to interviews with residents, only a few small mudflows had occurred in the neighborhood prior to about 1:00 a.m. After that time, nearly all were awake and alert to their own danger, having been awakened by the storm. Event occurred prior to about 9:00 a.m., at which time the victim's body had been recovered and seen by one of the interviewed neighbors. The residents at 905 Old Topanga Road reported hearing the slide that damaged 869 Old Topanga Road (figs. 7, 35) at 3:00 a.m.
5. *Landslide dimensions:* See sketch plan and profile, fig. 36.
   a. *Slope length:* Scar about 250 feet (by visual estimate). Debris train, about 30 feet (inside dimension of house).

FIGURE 35.—Scar above house at 869 Old Topanga Canyon Road (roof of house at 874 Old Topanga Canyon Road, on near side of canyon in foreground). Brush-covered colluvial soil above lip of cliff (bedding surface of steeply dipping sandstone) failed and cascaded over bedrock cliff into back of frame dwelling below. (See fig. 7.)

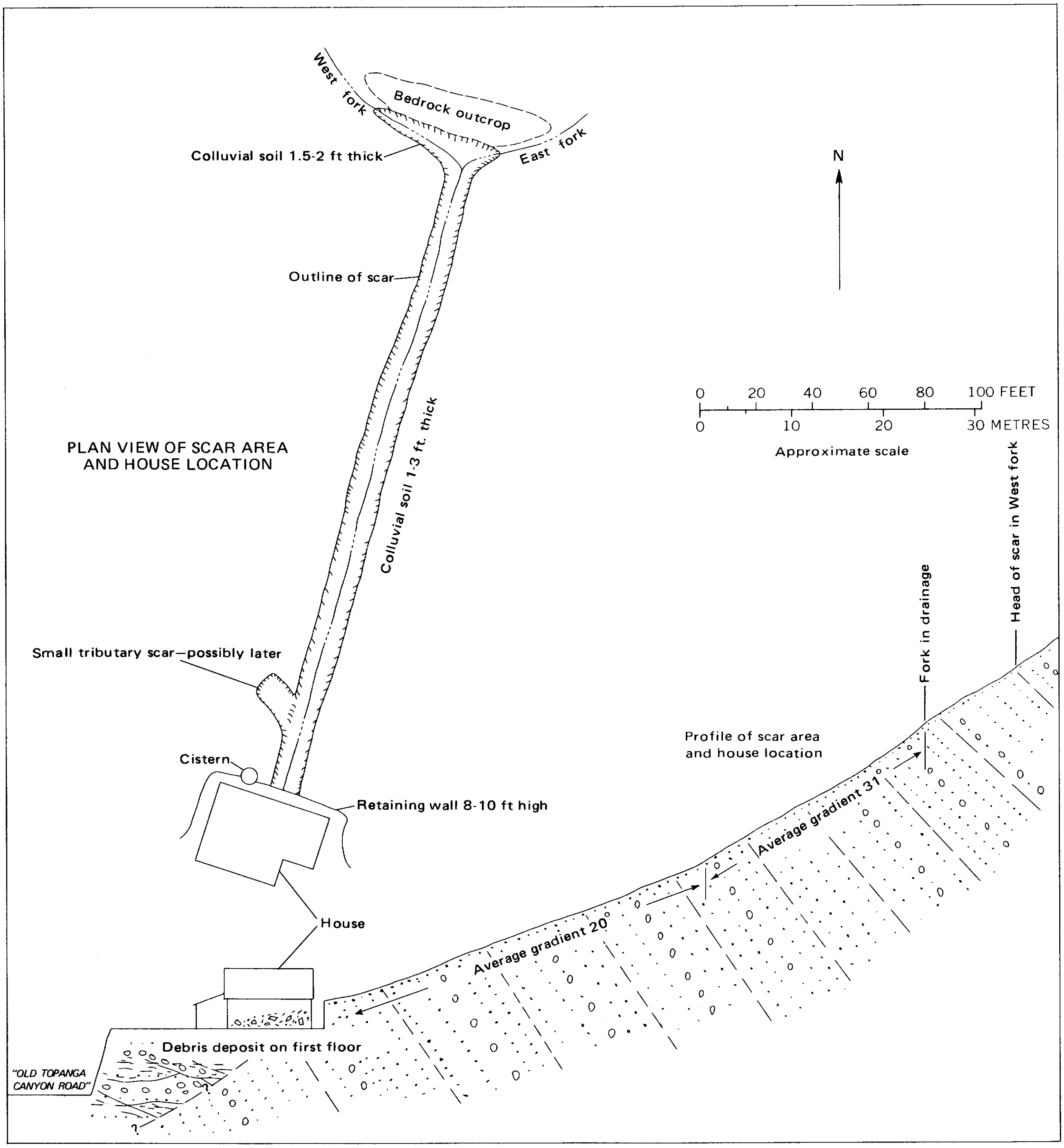


FIGURE 36.—Soil slip-debris flow at 874 Old Topanga Canyon Road.

b. *Width:* Scar, fairly constant width of 10–12 feet. Deposit, no more than about 30 feet (inside dimension of house).

c. *Thickness:* Judging from thickness of material remaining adjacent to scar, colluvium 18 inches–2 feet thick in headwall, ravine fill apparently no more than 3 feet thick; deposit in house estimated 6 inches–3 feet thick (fig. 14B).

d. *Volume:* Estimate about 200 cubic yards removed from scars; probably not more than 70 cubic yards deposited in discrete deposit inside house, remainder probably continued downstream as muddy floodflow, leaving no distinct deposit in vicinity.

6. *Distance moved:* Material from head of scar moved the full length of scar—about 250 ft.
7. *Original slope at failure:* Average gradient in upper part of ravine 31°, may steepen to 35° at the fork in ravine drainage where bedrock is exposed. Average gradient in lower part of ravine about 20°. (See profile, fig. 36.)
8. *Estimated rate of movement:* Very rapid to extremely rapid, probably greater than 10 ft/s. The impact damage to the house and contents indicates momentum from high velocity of debris.
9. *Precipitation conditions*: Prolonged heavy rains preceded and accompanied the failure. (See fig. 9.)
10. *Subsurface water:* There were no springs or seeps reported in the drainage prior to the seasonal rains, nor were there other indications that a permanent water table in the bedrock intersected the ground surface, though small seeps might have gone unrecorded. The use of a cistern (fig. 36) to store some surface runoff suggests that, on the contrary, the permanent water table was beyond easy reach by a dug well. The close association in time of failure and heavy seasonal rainfall suggests rapid near-surface circulation—probably mostly within the soil zone.
11. *Monetary damage:* Virtually total loss of 2- or 3-bedroom frame dwelling and contents. Questionable whether battered shell can be restored.
12. *Injury:* One adult man killed.
13. *Slide material:* Colluvial soil and ravine fill, derived chiefly from underlying sandstone and conglomerate sandstone assigned to the Sespe Formation. Deposited on the building site, which is underlain by stream terrace deposits of Old Topanga Creek.
14. *Causes:* The principal cause is concluded to be increases in pore pressure in the colluvial soil owing to the dynamic imbalance of rates of shallow circulation and deep percolation during heavy rainfall. The narrowness of the debris-flow channel and the relatively constant depth of erosion (and apparent depth of flow), seem to preclude piecemeal, randomly distributed ponding and flow erosion of the ravine fill. The character of the damage below is a strong indication of sudden and complete failure of all or nearly all of the relatively small mass of debris. It is unlikely that progressive, piecemeal failure could have produced a single surge with enough momentum to break through the wall of the house at chest height and move large appliances around violently inside.
15. *Treatment:* The general danger of the situation was apparently recognized by many residents of the neighborhood, including those at this house, where the family had been evacuated and only one man remained behind. It is difficult to determine whether or not the residents were aware of the specific hazard of high-velocity debris flows. Recognition of a hazardous location and removal of the house from the most probable path of debris flow should have been possible by relocation of only a few tens of feet. Defense by debris dam would be possible, but with consideration of maintenance costs, may not have been economical. Defense by bracing the dwelling to resist lateral stresses might have added to protection, but would probably not have been sufficient at that site. The site might have been protected by diverting the drainage above or around by an avalanche shed or a levee system.

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