Map showing areas susceptible to different hazards from shallow landsliding, Marin County and adjacent parts of Sonoma County, California

by

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Introduction

This map shows the distribution of various forms of hillside topography in most of Marin County and a neighboring small part of Sonoma County, an area characterized by dry summers and rainy winters. These topographic forms, herein called "terrain types," have been defined so that each is characterized by particular kinds of shallow landslides. The shallow landslides occur in the surficial mantle (i.e., the unconsolidated materials that overlie bedrock). They are generally less than several meters deep. These landslides are too small and too numerous to be distinguished individually at map scale, and so we have used the terrain types to indicate kinds of landslide movement and likely landslide habitats. The terrain types and the shallow landslide processes that characterize them are described in the map explanation and are discussed below.

Approach

We have developed this map by means of a procedure that permits the regional description of landslide hazards without the mapping of each landslide. We have employed this approach only in those parts of the county that are underlain by the Franciscan assemblage, a highly diverse and disrupted rock mass consisting largely of clayey sheared rock, graywacke-type sandstone, and greenstone. Rather than mapping landslides on the detailed, large-scale aerial photographs used in conventional landslide inventories, we mapped terrain types on small-scale (1:80,000) aerial photographs. Within ground-control study areas shown on the map, the earth materials and landslide processes that occupy different terrain types were investigated in detail. Those investigations revealed consistent relations between the terrain type, the bedrock, the surficial mantle materials, and the shallow landslide processes at work on the hillslopes (Ellen and others, 1979; Peterson, 1979; Reid, 1978). Our approach relies on these relations; by means of terrain types we have extended the local field observations to that (largest) part of the map area, which was studied on the ground only in reconnaissance.

Acknowledgments and responsibility

Ellen mapped the terrain types and characterized each by style, abundance, and habitat of shallow landsliding, using data from ground-control studies by Peterson, Reid, and to lesser extent by M. E. Savina, C. H. Trautmann, and J. M. Coyle. Our understanding and description of the timing, rates of movement, and other aspects of landslide movement relies on work by R. H. Campbell, D. K. Keefer, A. M. Johnson, and J. D. Rodine. C. M. Wentworth conceived the approach. We are indebted to the Marin Municipal Water District and to numerous landowners for access to ground-control study areas.

Use of the report

The map shows the distribution of hillslopes that in their natural state are susceptible to different kinds of shallow landsliding. The tabular explanation and the text describe the movement and timing of these kinds of landslides, the hazards presented by each, and the measures appropriate to mitigate those hazards.

The body of the map indicates the general areas in which given kinds of shallow landslides can be expected on natural hillslopes. Official decisionmakers can use this information to anticipate the general areas where various kinds of shallow landslides may occur, as well as the times (with respect to rainfall) when the occurrence of such landslides is most likely. Residents in a given locality can use the information to predict the kind of shallow landslide likely to occur there, and thus they can know when to be alert for signs of movement. Such uses of the map will be most effective in the hard terrains, where landslide style is uniform. Intermediate terrains -- and, to a lesser extent, soft terrain -- include kinds of landsliding so various that the information here may not be useful in distinguishing the kind of movement to be expected.

The map does not directly show the likelihoood of hazard at specific points. To predict the likelihood of hazard at a given site, the user must first determine the topographic setting of that site (fig. 3) and then evaluate that setting in terms of the landslide habitats of the appropriate map unit as they are described in the tabular map explanation. This use of the information, too, will be most successful in the hard terrains, where landslide habitats are defined most specifically. Note that the information is by no means sufficient to replace the site investigations usually required for development. The proper functions of this information are to guide such site investigations, to provide preliminary information for land-use decisions, and to alert residents and local officials to shallow landslide hazards.

We show terrain types and corresponding types of shallow landslides only for that portion of the erosional terrain of Marin County that is underlain by bedrock of the Franciscan assemblage. Excluded from the study are areas underlain by the Great Valley sequence, an unnamed sedimentary unit near Burdell Mountain, the Sonoma Volcanics, the Merced(?) Formation, and Quaternary alluvial and marine deposits, as well as areas where the natural form of hillsides has been obscured. Large, deep-seated landslides recognized on the 1:80,000-scale aerial photographs are shown on the map, and for most of these we have inferred the style of past movement. Future hazard from these large landslides, or from shallow landslides within them, is not assessed.

The map area includes numerous landslides that are intermediate in scale between the shallow landslides discussed in this report and the large, deep-seated landslides excluded from the terrain units. These intermediate-scale landslides are not shown on this map, although most of them probably occur within the intermediate and soft terrains; they are shown on landslide-inventory maps, such as those by Wentworth and Frizzell (1975), and on detailed geologic maps of local areas within Marin County, such as those by Rice and others (1976).

Shallow landslides on natural hillslopes

Many types of shallow landslides occur on natural hillslopes of the area. A contrast in style of movement divides most of these types into two principal groups, herein called rapid flows and slow slides.

Rapid flows

Rapid flows involve sudden failure of steep slopes, followed by rapid downslope movement of noncohesive, granular materials (such as silty sand), generally during sustained heavy rainfall. Failure occurs within granular material, but overlying clayey material may also be transported. The landslide mass commonly moves far downslope, leaving an empty scar on the hillside above (fig. 1A). Deposits from rapid flows are rarely reactivated.

Rapid flows include debris flows, debris avalanches, and disintegrating soil slips (fig. 1A; Varnes, 1978; Kesseli, 1943). Because of their fundamental similarity, these types of movement are difficult to distinguish in many cases, even where deposits are fresh. Most debris avalanches have disintegrated at least in part, or have flowed to some extent. Similarly, disintegrating soil slips commonly leave evidence of flowage as well as disintegration (Kesseli, 1943).

Conditions of failure and rates of movement

Debris flows in southern California studied by Campbell (1975) occurred only during heavy rainfall (generally at least 0.64 cm/hr (0.25 in./hr)), and only after approximately 25 cm (10 in.) of rain had fallen in the several days before failure. Similar conditions are suggested for disintegrating soil slips observed in the vicinity of Marin County by Kesseli (1943, p. 346), who found that fresh scars "are particularly conspicuous shortly after heavy rains lasting a number of days." In rare cases, rapid flows may occur as much as a day after the intense rainfall.

The rates of movement of rapid flows range from walking speed to avalanche speed. Varnes (1978) describes debris-flow movement as very rapid (faster than 0.3 m/min) to extremely rapid (faster than 3 m/s), and debris-avalanche movement as extremely rapid. Debris flows studied by Campbell (1975) moved at 0.3-12 m/s. In many cases movement is rapid enough to produce noise (Rodine, 1974; Peterson, 1979).

Hazards

The suddenness and high velocity of rapid flows threaten life as well as property, as documented for southern California by Campbell (1975). These landslides offer little warning. They often move too fast for people to escape. Damage may occur by failure of materials supporting a structure; more commonly, damage or casualties result from impact of the moving material on structures or on people located on gentle slopes lying well below the site of the initial failure. Thus, although most of the terrain occupied by rapid flows is too steep for dense development, much of the limited gently sloping ground in such terrain is subject to impact, particularly by debris flows.

Mitigative and preventive measures

Measures to mitigate the effects of rapid flows must center on knowledge of the locations and timing of such landslides. In new developments, hazardous parts of the terrain can be avoided. Where hazardous parts of the terrain are already occupied, buildings can, in many cases, be protected by check dams or diversion embankments placed in critical positions. Where protective structures are not feasible, residents can leave endangered buildings during the infrequent periods of sustained heavy rainfall when rapid flows are most likely.

A more risky tactic for residents of hazardous sites is to prepare to leave quickly when rainfall intensities reach the critical levels, and once so prepared (with, for example, the houses's occupants assigned places to sleep close to the downslope door), to remain vigilant, alert for signs or sounds of incipient movement. Typical signs are the development of cracks on a hillslope, the occurrence of small failures in a part of a hillslope, increased muddiness of water in drainages or gutters, tilting of brush or trees, trembling or shaking of vegetation, or abnormal uneasiness of animals. Sounds that signal incipient movement range from low rumbles that can be felt as well as heard, to crackling sounds suggestive of falling trees, to "swish" or "whoosh" sounds somewhat like those of flowing water or of jet airplanes. Such signs and sounds may precede rapid flows by as little as several seconds; their occurrence should prompt immediate evacuation in a direction away from the threatening hillslope.

Stabilization of landslide source areas is generally not a feasible measure because many sites are threatened by failure from several potential source areas. In cases that involve a single potential source area, however, it may be feasible to stabilize that source area by means of surface and subsurface drainage facilities. Mitigation measures and warning systems are discussed by Campbell (1975).

Slow slides

Slow slides involve the slow downslope movement of cohesive clayey materials. Failure occurs in clayey material, but overlying granular material may also be transported. This style of landslide includes earthflows and slump-earthflows, both of which in many places occur as complexes that cover broad areas (fig. 1C; Varnes, 1978). Movement of these landslides commonly recurs during subsequent rainy seasons.

Conditions of failure and rates of movement

Earthflows studied by Keefer (1977) in the San Francisco Bay region began their seasonal movement after at least 31 cm (12 in.) of rain had fallen during the initial months of the rainy season. Movement apparently continued through both the rainy and the dry portions of a given rainy period, but it slowed markedly after the end of each rainy period. Slight movement continued on some earthflows after the end of seasonal rainfall, but, for the most part, movement coincided with the last several months of rainfall.

The rates of earthflow movement measured by Keefer were typically several centimeters per day, but they were as much as 39 cm/day. Earthflows measured in Marin County in the course of the present study moved as much as 10 cm/yr during two successive years of abnormally low rainfall (Peterson, 1979; Reid, 1978). Average velocities of earthflow reported in the literature range from 2 mm/day to 4.5 m/day, but rare surges of up to 8 m/min have been recorded (Keefer, 1977; Keefer and Johnson, 1978).

Hazards

Because they move so slowly, slow slides rarely threaten life directly. Damage takes the form of slow, progressive distortion of foundations, embankments, or pavement, although buried utilities may break suddenly because of accumulated strain. Careful inspection at appropriate times in the rainy season can reveal such distortion before structures are damaged enough to threaten life. Slow slides can be deceptive, in that they occur on relatively gentle slopes (commonly as low as 12°) that appear inviting for development.

Mitigative and preventive measures

If areas of active or potential slow slides can be identified in advance of construction, they can be avoided or they can be stabilized by means of careful design and placement of cuts, fills, retaining structures, and drainage facilities. In critical areas, the shallow materials susceptible to slow slides can be removed and replaced by engineered fill including an appropriate drainage system. Once structures are built, removal of underlying sliding materials is less practical, but successful remedial drainage and retaining structures may nevertheless be feasible because the moving material is shallow.

Other kinds of landslides

Slumps and block slides in surficial mantle represent a style of landslide intermediate between rapid flows and slow slides. Failure occurs in clayey material, but most of the slide mass may be granular material that rides on the clay slip surface. Landslides of this style commonly slip into incised drainages (fig. 1B). They probably move at rates between those reported for rapid flows and those reported for slow slides. Hazards and mitigation measures are generally similar to those for slow slides, but in some cases movement may be rapid enough to threaten life directly.

Yet another kind of landslide, rockfalls, occur from steep-sided, protruding masses of rock that lie scattered within soft and intermediate terrains. As with rapid flows, falling or tumbling blocks move rapidly, and this can be hazardous. In contrast with rapid flows, a rockfall may not coincide with rainfall, and a rockfall commonly does not travel as far as do rapid flows. Avoidance of sites at the base of steep slopes is the best precaution against rockfalls, but where avoidance is not feasible, retaining structures can be created.

Abundance of landslides

In the map explanation, we report the approximate areal and (or) temporal abundance of the various types of landslides for each terrain type. Because slow slides are commonly seasonally active and cover substantial ground area, we describe their abundance as the average percentage of areal coverage. Because rapid flows occupy small areas, are active only briefly, and do not reactivate seasonally, we describe their abundance as the frequency of occurrence averaged over both area and time. The abundances reported are approximate, particularly for rapid flows. Actual abundances may vary even more widely than the broad ranges reported here.

Estimates of abundance are based on data from the ground-control study areas. Activity of slow slides was determined in the field by the freshness of landslide features and, in places, by precisely monitored rates of yearly movement. The approximate time when past rapid flows occurred was determined by several means, including eyewitness accounts, radiocarbon dating (at one site), and the inspection of sequential aerial photographs dating as far back as 1953 (Peterson, 1979; Reid, 1978). Scars from rapid flows that occurred before 1953 are assumed to have occurred within the last hundred years.

The temporal abundances reported for rapid flows would be misleading if they were misinterpreted as short-term frequencies of occurrence. For example, the statement that a debris avalanche will occur once in 1-10 years in each square kilometer does not mean that this type of landslide can be expected more or less regularly every 1-10 years. Rather, such landslides commonly occur in numbers during widely separated periods of extreme conditions, such as times of earthquake or of sustained, intense rainfall (Williams and Guy, 1973). The abundances reported in the explanation are the averages, over time, of the number of rapid flows mapped in an area; they describe the long-term temporal abundance of this type of landslide rather than its short-term frequency of occurrence, which can be highly variable.

Abundance of debris flows expresses the average number of years between events in a typical canyon. The term "canyon" is loosely defined here to mean a drainage basin of 0.1 to 0.5 km^2, one that is larger than most flutes (fig. 3) but smaller than an alluviated (flat-bottomed) canyon.

These estimates of abundance are crude, but they convey a sense of the levels of hazard presented by the different types of landslide. Debris flows can be expected frequently enough to significantly threaten lives and structures both at the canyon mouths and in the canyon bottoms of hard terrains. Active slow slides occupy a significant proportion of both soft terrain and smooth intermediate terrain.

Shallow landsliding on disturbed hillslopes

The kind of shallow landslide movement is more difficult to predict where natural conditions on hillslopes have been altered by the activities that accompany residential or other development. Grading imposes new configurations on the hillslopes. Shallow materials are redistributed. Drainage is changed, and so access of water to the ground is altered. Such modifications upset the long-term equilibrium between slope conditions and slope processes and thus break the tie between material character and landslide style. On disturbed hillslopes, clayey materials can slide rapidly and in some cases even form debris flows (Rodine, 1974); granular materials probably move by rapid flow, as described above for natural slopes.

Slope disturbance affects the abundance of shallow landslides as well as their style. In terrains that are subject to rapid flows, careless modification of hillslopes may increase the abundance of failures, largely by way of changes in drainage that concentrate water in unaccustomed parts of the terrain. Carefully planned drainage can mitigate the hazard and may even reduce landslide abundance below natural levels. In terrains subject to slow slides, the effects of slope modification can be predicted somewhat more precisely. At the time of our ground-control studies, from 25 percent to at least 70 percent of the soft terrain was underlain by recognizable deposits of either dormant or currently (seasonally) active slow slides; roughly 6-10 percent of the soft terrain showed evidence of current activity. Under natural conditions all these deposits, whether active or dormant, are marginally stable at best and hence are sensitive to artificial slope modification. If developers and residents in such terrains are to avoid man-induced landslide movement, they must deal carefully with much if not most of the ground.

Terrain mapping

The erosional terrain of the map area is particularly well displayed on small-scale aerial photographs viewed stereoscopically (fig. 2). Note that the small scale of the photographs reveals strong contrasts in terrain form but leaves most individual shallow landslides imperceptible. The variety of terrain displayed in the photographs has been subdivided on the basis of criteria that have been found useful for distinguishing different surficial mantle materials and the different styles of shallow landsliding associated with those materials. The criteria used are the development of fluting (incision of sidehill drainages), the regularity of terrain form, and the sharpness or rounding of crests. These criteria are illustrated by example in figure 2, and they are described briefly for each unit in the map explanation, using the nomenclature defined in figure 3. Photomapping of terrain types according to these criteria has been supplemented by a slope map (U.S. Geological Survey, 1972, unpublished version at 1:62,500) in order to distinguish those steep areas in unfluted terrain that are particularly subject to rapid flows. Unit si is mapped, rather than unit s, where more than half of the ground is shown as steeper than 26° (50 percent) on the slope map.

In many places, the contacts between terrain types follow ridgecrests or drainages that bound distinct hillslope segments. In other places, contrasts in terrain form clearly run across slopes. Map location of the contacts is generally within 30 m of the photomapped location, but locally it may vary up to 60 m from the photomapped location.

The map scale prevents depiction of every small element of contrasting terrain. Soft terrain, in particular, commonly includes small bodies of harder terrain, each with its accompanying materials and processes. Over most of the map area, contrasting terrains are distinguished only where they are larger than about 0.4 km in their maximum dimension. Map scale also hinders the depiction of areas of very active, steep slopes along rapidly eroding streams and seacoast. These steep slopes, which are being degraded rapidly by a variety of processes, are most common along the Pacific coast between the Golden Gate and Stinson Beach; some occur where streams such as Walker Creek and Lagunitas Creek undercut valley walls.

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NOTE: FIGURES 1, 2, AND 3 FOLLOW THE REFERENCES

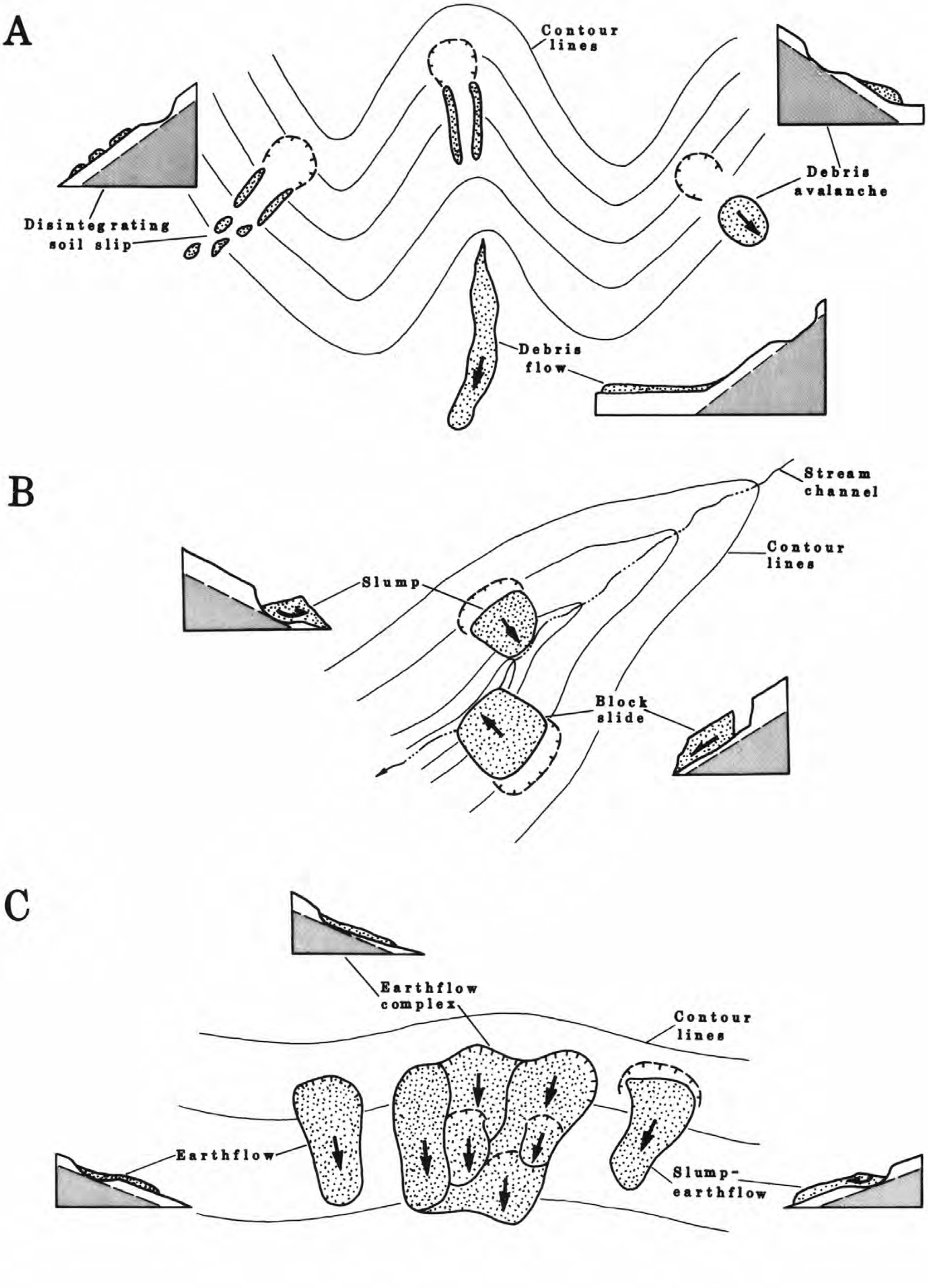

Figure 1. Schematic maps and downslope cross sections of some types of shallow landslides, grouped by style of movement. Landslide deposits are shown by stipple; landslide scarps are shown on the maps by hachured lines. In cross sections, bedrock is shaded, surficial mantle is unpatterned. A, Three types of rapid flow; all typically occur on slopes of 26° to 50°, but disintegrating soil slip can occur on slopes as gentle as 15°. B, Block slide and slump; typically occur along incised drainages. C, Three types of slow slide; typically occur on slopes of 12° to 25°.

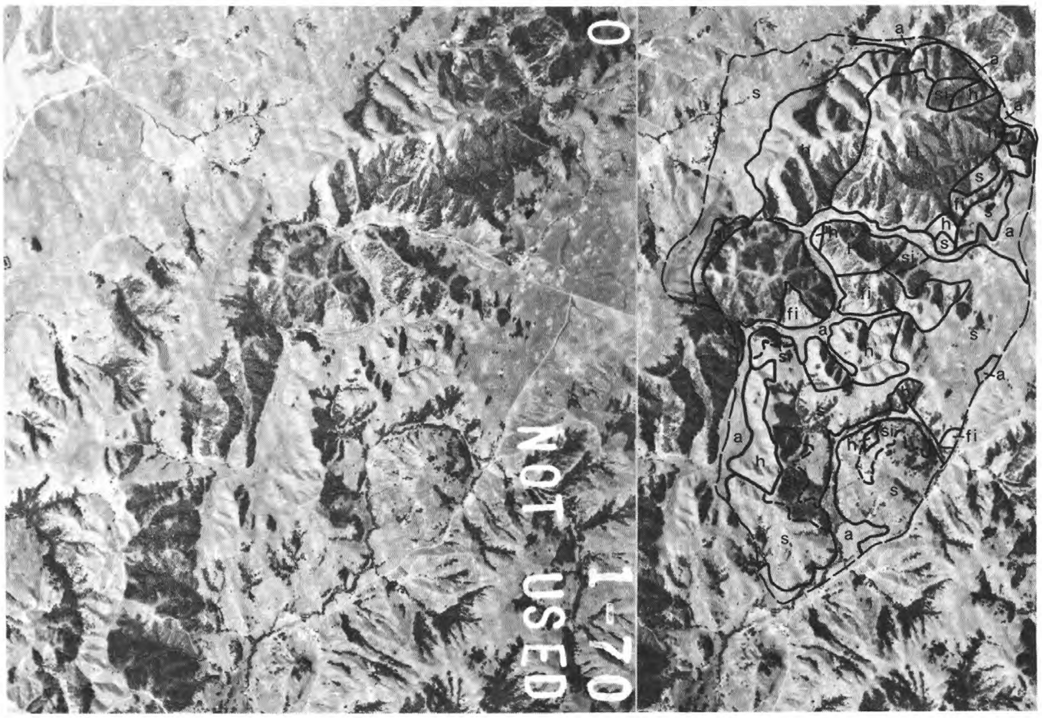

Figure 2.--Stereopair of aerial photographs (scale 1:80,000) showing variety in terrain near Hicks Mountain, in north-central part of the map area (outlined on the large map). Lines distinguish terrain types, symbols and criteria for which are described in the explanation for the large map. Photomapped terrain boundaries are shown by solid lines; boundaries obtained from slope map are shown by short dashes; boundary of area mapped in this figure is shown by long dashes.

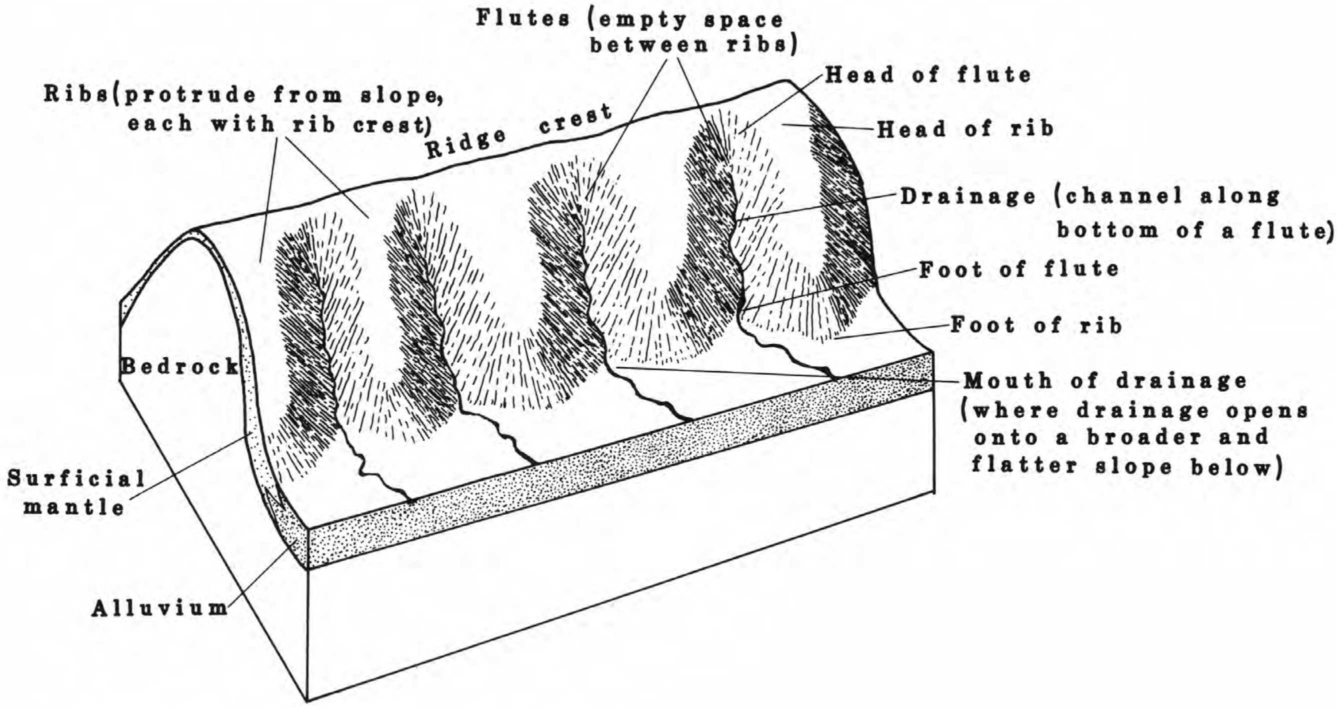

Figure 3.--Block diagram explaining the nomenclature used to describe terrain features and landslide habitats.