MASS WASTING in coastal Alaska

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INTRODUCTION

An understanding of erosion processes involving the downslope movement of earth materials is essential to the forest-land manager in Alaska. This has become increasingly clear in recent years with the apparent acceleration of slope erosion following large-scale clear-cutting of steep, timbered slopes in southeast Alaska. Erosion occurs primarily as soil mass movements associated with oversteepened slopes and high soil-water levels.

In 1961, a marked increase in slide activity associated with a period of high rainfall was observed in a number of recently logged areas. These observations brought about a survey of potential sliding in these areas. As a result of this survey, the principal sliding phenomena were identified and classified, and major factors contributing to their occurrence and distribution were evaluated (Bishop and Stevens 1964). Later work has concentrated on detailed investigations of landslide distribution, processes of movement, and factors affecting occurrence.

This paper summarizes and interprets the accumulated data and knowledge about slope erosion in southeast Alaska, particularly in relation to recently logged areas, with general suggestions and quidelines for prediction and control.

MASS WASTING, A DOMINANT EROSION PROCESS IN COASTAL ALASKA

Southeast Alaska is in an early stage of development both structurally and geomorphologically. Slopes are steep due to recent uplift and glacial activity. Many of them are above the angle of stability of natural soil materials.[1] Soils on these oversteepened slopes are youthful, postdating the last major continental glaciation approximately 10,000 years ago. As a result, the soils are shallow, generally less than 3 feet thick, and coarse textured. Permeabilities are relatively high, and surface runoff on the slopes is minimal despite high rainfall (Patric and Swanston 1968; Swanston 1967b; Gass et al. 1967). Principal drainage is subsurface directly into main stream channels and major tributaries. The dominant natural slope erosion process under these conditions is "mass wasting"--the slow to rapid downslope movement of large masses of earth material of varying water content, primarily under the force of gravity.

CLASSIFICATION

Soil mass movements in timbered areas of southeast Alaska have developed under varying conditions of slope gradient, soil composition, and soil-water content. Some are the direct result of logging and logging road construction. The majority, however, are natural manifestations of mass wastage and slope reduction.

Dyrness (1967) described common classes of soil mass movements in the Coast Ranges and Cascades of western Oregon, based on mode of disturbance in a forested area. Many of these classes can be applied directly in southeast Alaska. Morphogenetically, mass movements in southeast Alaska range from rockfalls to mud flows, but the majority are classified as debris avalanches or debris flows involving the rapid downslope movement of a mixture of soil, rock, and forest debris with varying water content.[2]

Mass movements caused by road fill failures, road backslope failures, and concentration of road drainage water are common; however, they are limited for the most part to small-scale soil slips and slumps. Large-scale mass movements in both recently logged and undisturbed areas are the most frequent and damaging. These involve debris avalanches and debris flows on steep valley sideslopes and narrow V-notch tributary drainages. These movements begin either as sudden rotations or translations of more or less intact masses of soil above an impermeable boundary and quickly revert to debris avalanches as stresses within the soil masses cause breakdown of soil structure.

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[1] The angle of stability referred to in this paper is that slope angle which equals the angle of internal friction. This is the angle at which the ratio between the driving forces due to gravity in a soil mass and the resisting forces due to friction equals unity. Simply, it is an indication of the shear strength of the soil mass due to interlocking of individual soil grains.

[2] Slide classification used contained in National Research Council Highway Research Board Special Report 29, No. 21, "Landslides and engineering practice," edited by E. B. Eckel, 232 pp. 1958.

Downslope, a debris avalanche frequently becomes a debris flow because of substantial increases in water content.

OCCURRENCE AND DISTRIBUTION

Inspection of aerial photos of the Tongass National Forest, covering approximately 99 percent of the southeast Alaska land area, reveals evidence of widespread active mass wasting in timbered areas.[3] More than 3,800 large-scale debris avalanches and flows have been counted, most having occurred within the last 150 years. Evidence of older sliding, predating the present old-growth forest, is masked from air photo identification but has been observed in the field in the form of buried soils and overturned profiles.

The most recent debris avalanches and debris flows are clearly identified by bare linear strips on valley sideslopes and in deep V-notch channels where soil and vegetation have been removed (fig. 1). Increasingly older avalanche and flow scars are identified successively by strips of pioneering species such as willow (*Salix* spp.) and alder (*Alnus* spp.) and finally by even-age stands of Sitka spruce (*Picea sitchensis* (Bong.) Carr.) which are younger than the surrounding timber (figs. 2 and 3). Such

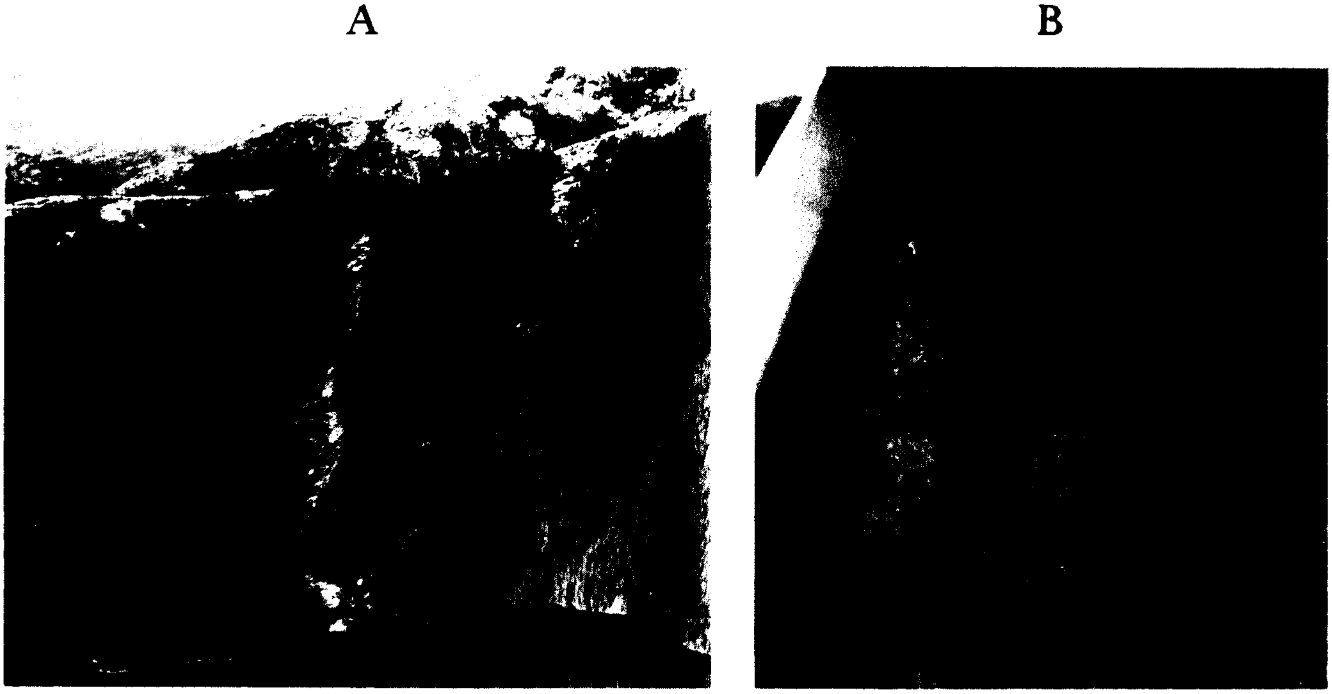

Figure 1.—Aerial views of recent debris avalanche-debris flow combinations on oversteepened slopes of southeast Alaska. A, Slide near Walker Cove, Behm Canal. A debris avalanche was apparently initiated by a rockfall from bluff directly above head of slide trace. Resultant debris flow lower on the slope carried debris directly to the sea. B, Two recent slides near Mirror Lake, Thorne Arm. In this case, much of the debris from the resultant flow has accumulated near the lower end of the slide trace.

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[3] Landslide occurrence in coastal Alaska. Study No. 1604-12; data on file, Pacific Northwest Forest and Range Experiment Station, Institute of Northern Forestry, Juneau.

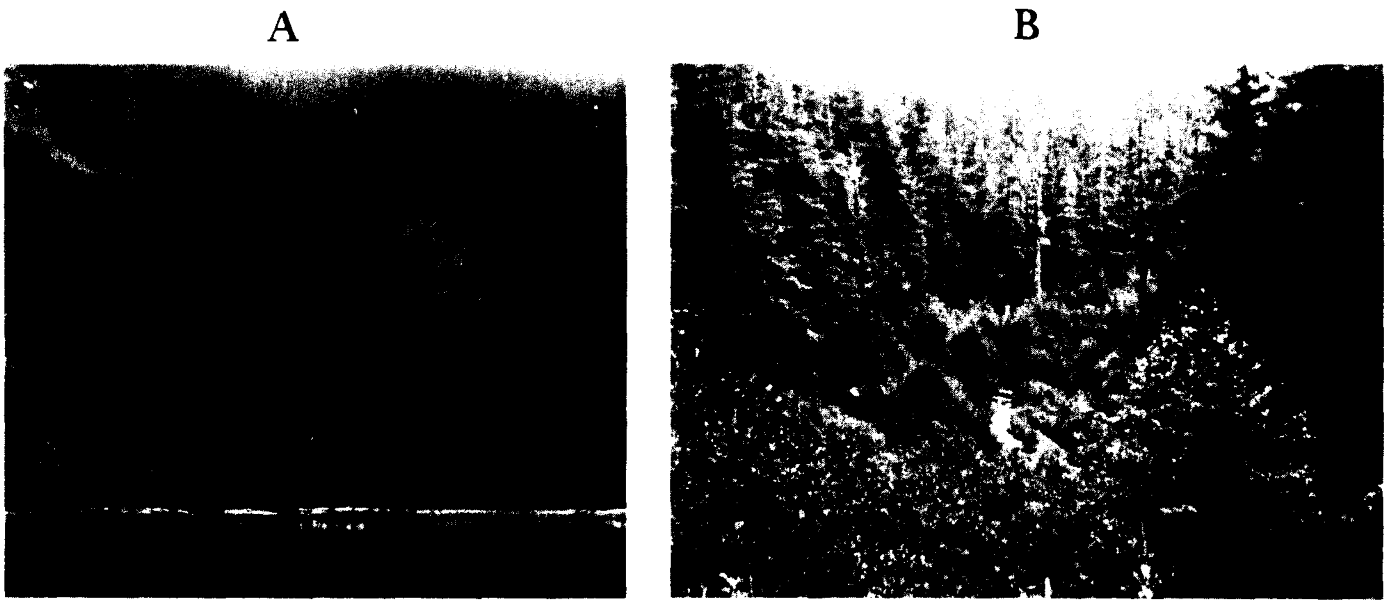

Figure 2.—Older debris avalanche-debris flow traces showing successional regrowth of willow, alder, and Sitka spruce. A, Aerial view of two slide traces revegetated by alder near the head of Walter Island Arm, Port Houghton. B, View of lower slide trace on the south side of Blake Channel Narrows. Note successional regrowth starting with willow and alder in the foreground with spruce moving in behind.

successional regrowth on the older slide traces is easily recognized on aerial photos and provides a convenient means of estimating present stability and past sliding history of a slope. Snow avalanches which produce similar linear tracks on timbered slopes can be differentiated and eliminated from these estimates by observation of the following characteristics. If the track origin lies below the upper timbered boundary, it is probably a debris avalanche track. If the track extends above the timber boundary, it probably originated as a snow avalanche. Also, a snow avalanche produces little soil deposition at the slope base, and there is little or no soil removal in the slide track.

A study of the distribution pattern of these debris avalanches and debris flows reveals two areas of concentration. The largest area occurs south of the 57th parallel,

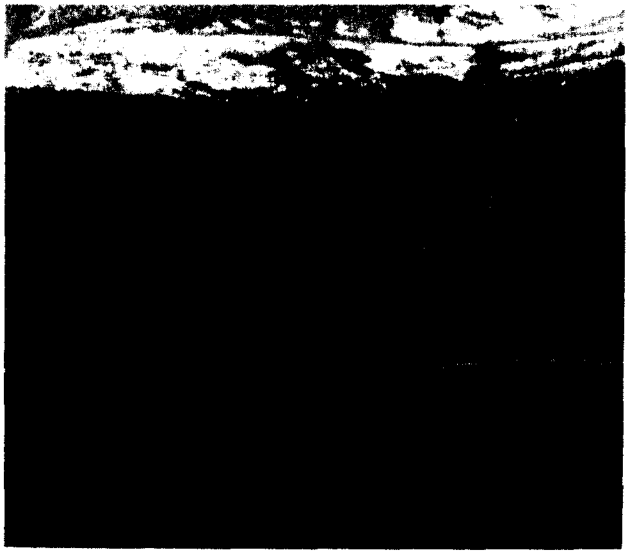

Figure 3.—Old debris avalanche-debris flow traces along Bradfield Canal. Old slide areas (1) and (2), marked by even-age stands of Sitka spruce, are almost indiscernible, but can be picked up on aerial photos by noting the finer texture of the forest cover in the old slide trace. Note recent debris avalanche at right center of photograph.

with principal concentrations on Revillagigedo and Prince of Wales Islands (fig. 4, area A). A second area occurs south of the 58th parallel, centered around Peril Strait on Baranof and Chichagof Islands (fig. 4, area B). Both areas coincide approximately with zones of maximum precipitation in southeast Alaska (Miller 1963).

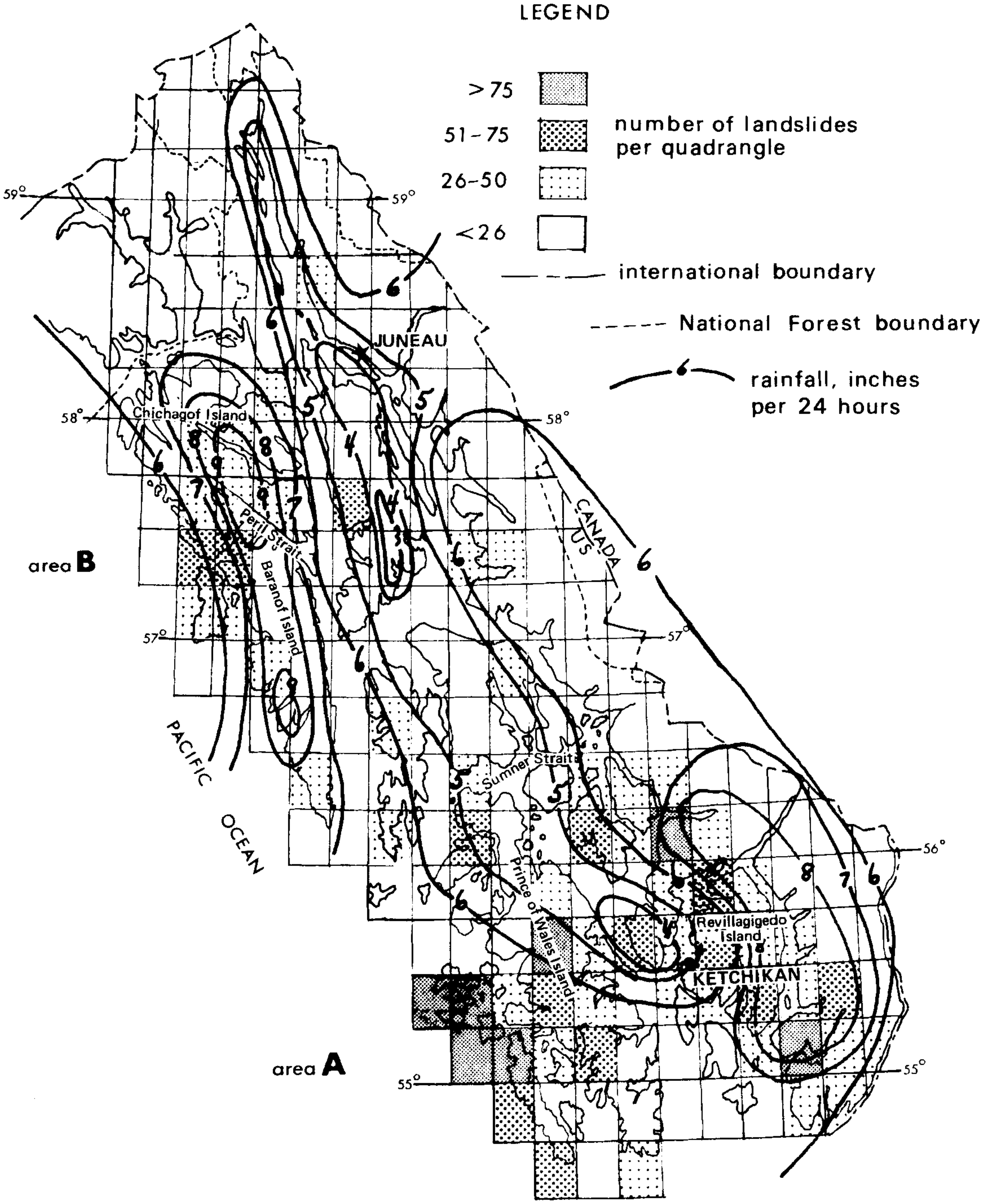

Figure 4.—Relation of landslide distribution to 5-year, 24-hour rainfall occurrence in southeast Alaska. Landslide occurrence expressed as number per 15-minute map quadrangle. Rainfall data adopted from Miller (1963).

Superimposed on this rough correlation of rainfall and slide occurrence is the effect of regional bedrock and glacial geology which modifies the effect of rainfall on landslide initiation through changing slope and soil characteristics. On the mainland and interior islands of the Alexander Archipelago (Revillagigedo, Etolin, Mitkof, Kupreanof, and Admiralty), the majority of debris avalanches and debris flows are developed in shallow, bedrock-derived soils[4] with bedrock serving as the sliding surface. In this area, slopes are extremely steep, frequently more than the internal friction angle of the soil, due to vigorous erosion during the last continental glaciation. Glacial till deposits are thin or absent, due partly to the resistance of local bedrock (granite, diorite) to glacial erosion and partly to the distance of the area from major Pleistocene ice centers east of the Alaska-Canada Boundary Range. Conversely, many of the large-scale debris avalanches and debris flows, developed on the outer islands of the Alexander Archipelago, occur in soils derived from glacial till with compact, unweathered till serving as a sliding surface.[5] In this area, more easily erodible bedrock (graywacke, black argillite) predominates, and local glaciations have deposited a thicker veneer of till, frequently extending to elevations of 1,200 to 1,300 feet. Slopes are less steep, although still at or near the internal friction angle on the upper slope, due to deposition of the till veneer over the steeper bedrock walls. Above the till limit and in areas of nondeposition of till, slides again occur predominantly in bedrock soils.

RELATIONSHIP OF DEBRIS AVALANCHES AND DEBRIS FLOWS TO SITE CHARACTERISTICS

Bedrock-Colluvial Soil Slides

Debris avalanches and debris flows developed in shallow bedrock-derived or colluvially derived soils are the most frequently occurring natural soil mass movements in southeast Alaska. Observations in active slide areas with soils of this type (Bishop and Stevens 1964, Swanston 1967a, Swanston[6]) indicate that the slopes on which these slides commonly develop are extremely steep,

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[4] These soils belong to the Tolstoi series. They are shallow, well-drained soils of a very stony, silt-loam texture (particles below 2 mm. fall into the sandy silt range, according to the Unified Classification) developed from colluvium or fractured parent rock. Gravel content approaches 80 percent by weight. Depth to bedrock averages 12 inches.

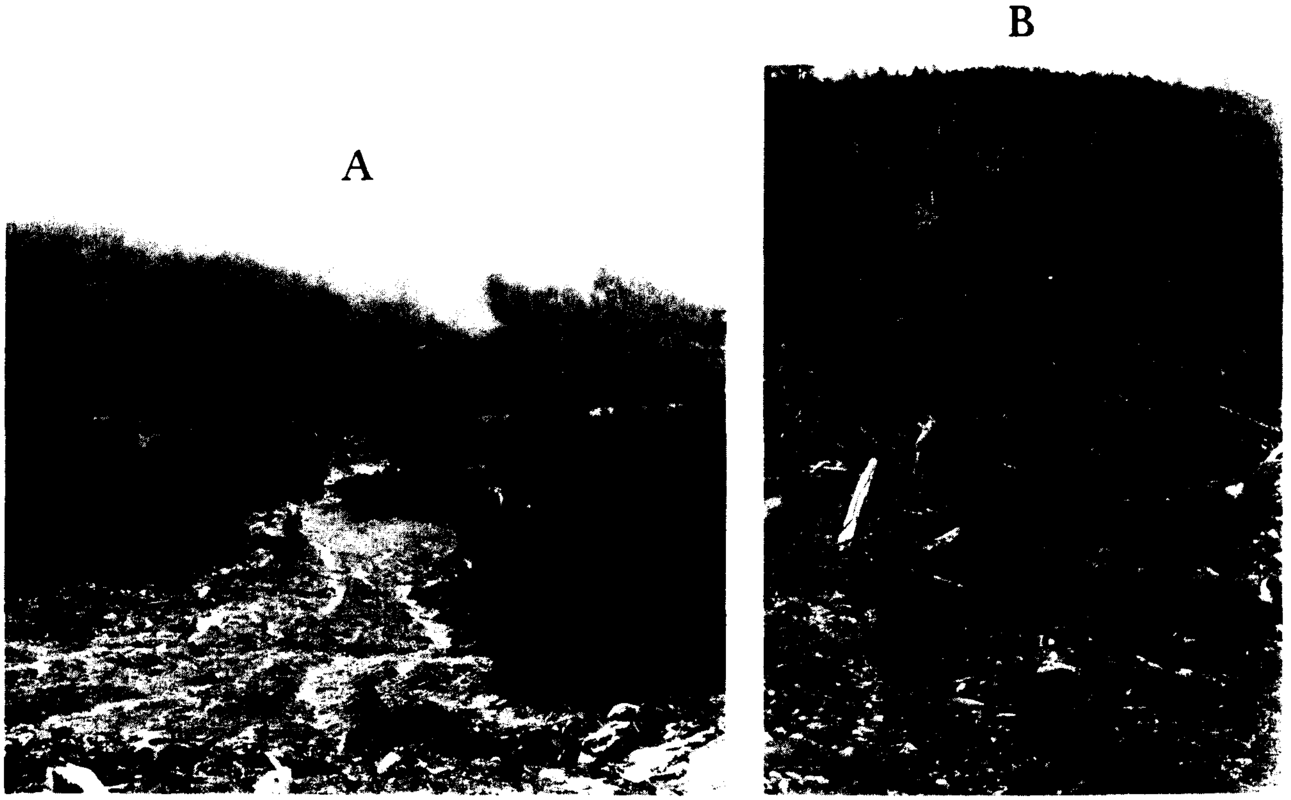
[5] These soils are podzols belonging to the Karta series. They are moderately well-drained, very gravelly loam soils (size fraction below 2 mm. falls into the silty sand category, according to the Unified Classification), derived from glacial till and overlying compact glacial till. Gravel content approaches 50 percent by weight. Depth to compact till varies from 15 to 60 inches but averages around 36 inches in the zone of slide initiation.

[6] Swanston, Douglas N. Geology and slope failure in the Maybeso valley, Prince of Wales Island, Alaska. 1967. (Unpublished Ph. D. dissertation on file at Mich. State Univ., East Lansing.)

lying between 40° and 60° (88- to 133-percent grade) and support mature forests of Sitka spruce and western hemlock. The soils are coarse and very permeable with a high proportion of angular rock fragments and some organic material. The soils are mechanically cohesionless, although Stephens (1967) reports the presence of unusually large amounts of organic material which may provide substantial "secondary" cohesion.

These debris avalanches and debris flows begin characteristically on open slopes, frequently related to local drainage concentrations, and generally clear the slide trace of soil and vegetation to bedrock for the entire length of the slope (fig. 5). The movement is translational, beginning with failure of a small mass of soil along an impermeable bedrock surface and spreading outward and downward in a wedge-shaped path (type B, fig. 6). In all active slide areas which were investigated, the underlying bedrock surfaces either dipped into the valleys or were smoothed by glacial erosion, providing little natural obstruction to downslope movement of soil under the force of gravity.

Figure 5.—Combination debris avalanche-debris flows developed in bedrock-derived soil (Tolstoi). A, Martin Creek valley, Bradfield Canal. View toward valley floor from center of slide trace, showing extensive debris flow deposit at base of slope which has broken through the trees at several points to deposit broken timber and other debris in small muskegs beyond. Note shallowness of soil typical of this type of landslide. Glacially rounded dioritic bedrock is exposed by complete removal of the soil layer in the slide trace. B, Maybeso Creek valley. Slide initiated by rockfall from bluff above slide head.



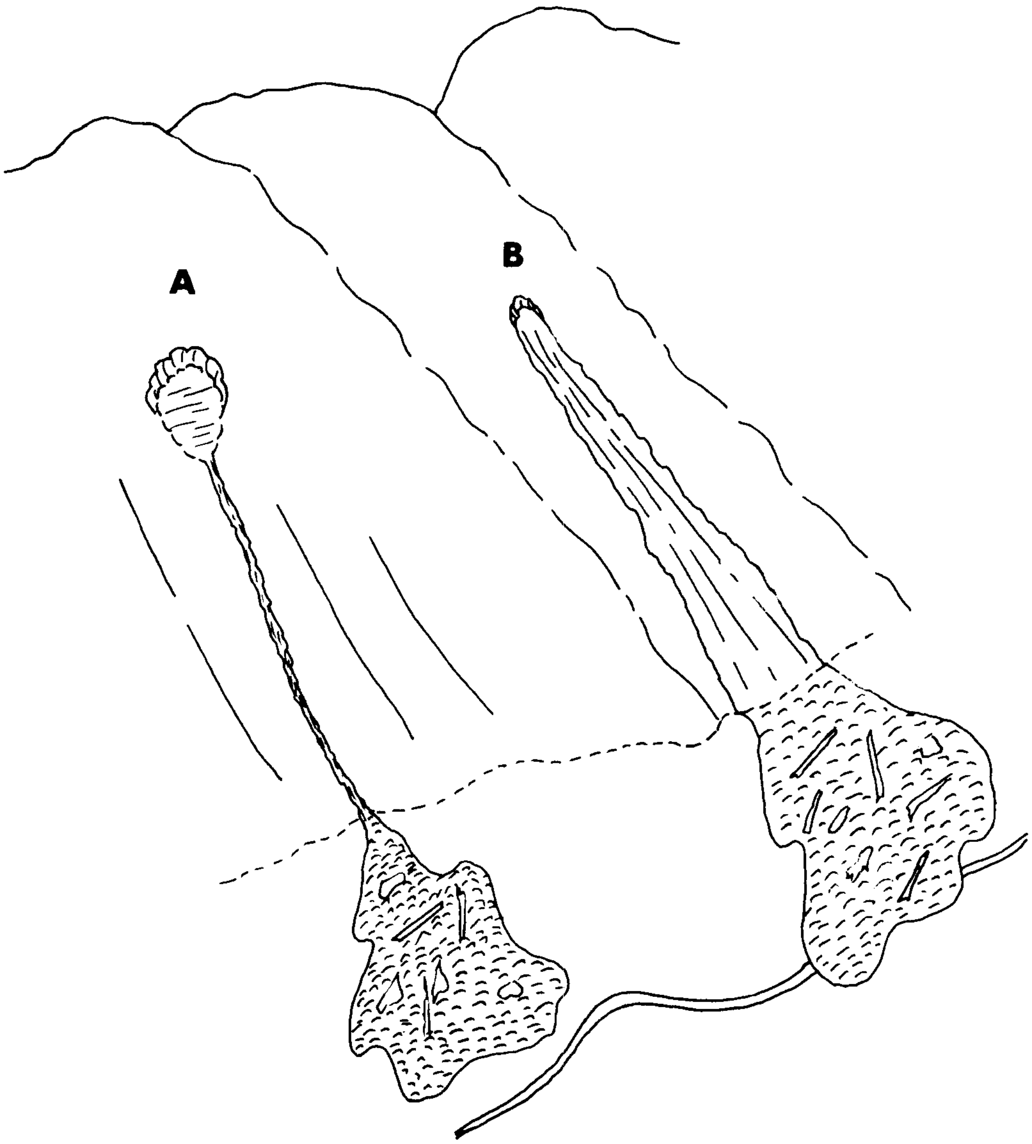


Figure 6.—Representative diagram of debris avalanches and debris flows on a glacially oversteepened slope.

A. Debris avalanche-debris flow combination developed on a till-covered slope. Note typical spoon-shaped configuration in zone of initial failure with sliding material more or less confined within a narrow zone until it reaches the valley floor.

B. Debris avalanche-debris flow combination developed in bedrock-derived or colluvial soil. Note the characteristic wedge-shaped trace expanding toward the slope base.

Slope angles in the slide initiation zone characteristically exceed the probable angle of internal friction of coarse-grained soils of the Tolstoi type. The internal friction angle varies from 27° to 35° for well-graded silty sands and from 34° to 46° for loose sands, the actual value depending on soil density and weight of overlying material (Terzaghi and Peck 1962). Although laboratory analyses have not been made, the actual internal friction angle of the Tolstoi soil probably lies at the upper end of the silty sand range, based on its relative content of coarser particles and apparent lack of preconsolidation. The effect of the overlying forest weight is largely negated since most of the weight is carried by roots passing through the soil and lying on the bedrock surface.

The balance between slope stability and failure is critical on these slopes. The anchoring effect of root growth through the thin soil and into joints and fractures in the bedrock probably increases the stability of these soils somewhat, as does the cohesion provided by organic colloids. The effectiveness of these stabilizing factors, however, may be reduced during periods of high rainfall by development of seepage and pore-water pressures associated with rising soil-water levels. With the bedrock-derived soils in their least stable condition, only a small triggering force is required to cause total failure and rapid downslope movement of the soil mass. Such a force can be produced by sharp increases in soil-water content, rapid increase in soil mass, and direct destruction of stabilizing root mass. Field observations indicate that the latter two, resulting from tree blowdown, dynamic loading of the soil mass by wind forces acting on the tree cover, and rapid addition of rock masses by direct fall, are the principal causes of sliding on unlogged slopes (Swanston 1967a).

Till Soil Slides

Debris avalanches and debris flows in glacial till soils on valley sideslopes frequently begin within linear seepage depressions that dissect the till deposits (fig. 7). These depressions were originally formed as consequent drainage channels[7] by surface runoff after retreat of glacier ice from the valleys. Since glacier retreat, a shallow podzol soil has developed in the channels and on the surrounding till slopes. At present, the soil in the depressions serves as a center of concentration for soil-water seepage. Surface runoff occurs in the depressions only during periods of extremely high rainfall when the till soil becomes saturated. The occurrence of buried soils, overturned profiles, and buried organic lenses in the lower end of these depressions indicates a past history of active sliding and suggests that, at present, the depressions enlarge themselves chiefly in this manner.

The soil in which the slides develop is well-drained podzol, 1 to 3 feet thick, above compact, unweathered till. The movement is rotational with the impermeable, unweathered till surface serving as the lower limit of sliding. The slide trace characteristically exhibits a spoon-shaped

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[7] Consequent drainage channels are those formed as a direct consequence of the original slope of the surface on which they developed. A new runoff channel formed as a consequence of till deposition on the slope.

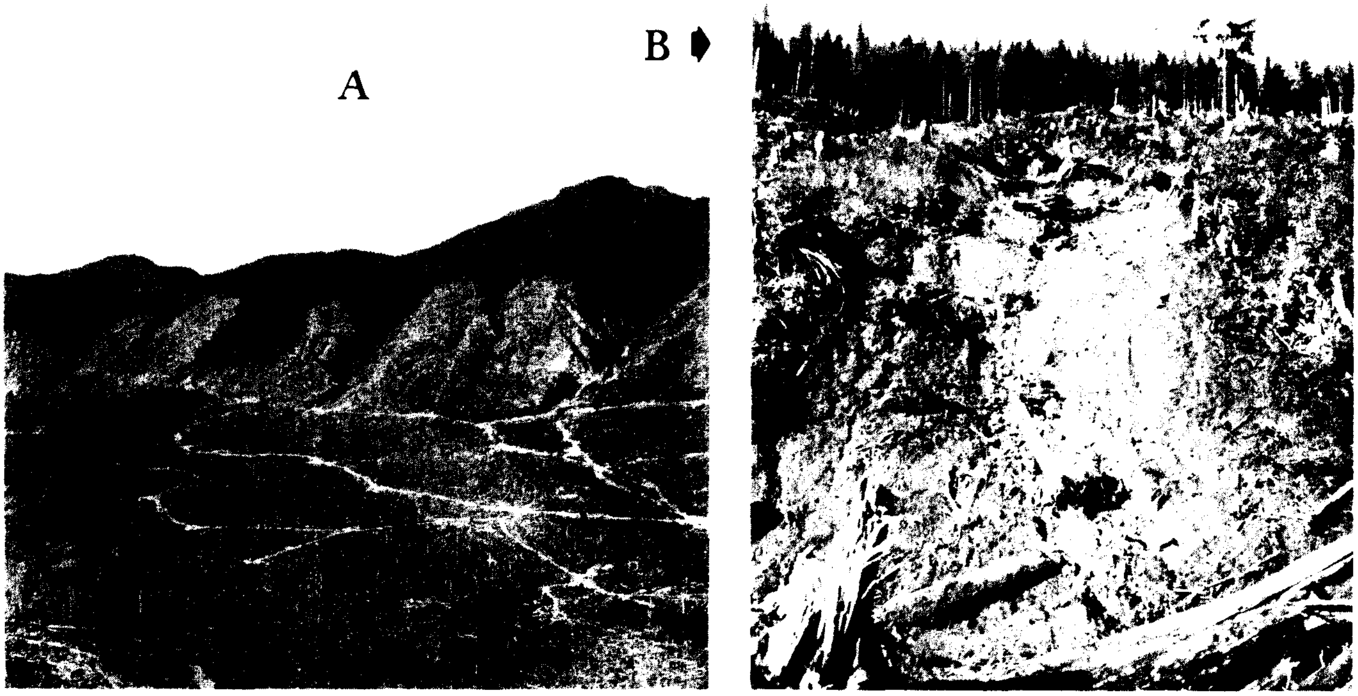

Figure 7.—Combination debris avalanche-debris flows in a glacial till soil (Karta), Maybeso Creek valley, Prince of Wales Island. A, Aerial view of dissected till-covered slope where active sliding is occurring. Recent sliding, directly correlated with a period of high rainfall and resultant concentration of soil water, has occurred to the right of the leave strip in the center of the photo (1). These are probably associated with clearcutting, but there is also much evidence of prelogging slide occurrence. B, Closeup view of slide at site 1. Note the shallowness of the slide trace. The unweathered till which served as the sliding surface is exposed in center foreground as a lighter soil zone next to the long-butted stump. The weathered till or Karta soil is the darker material above it.

configuration in the zone of initial rotational failure, with the slide material more or less confined within a narrow channel before reaching the valley floor (type A, fig. 6). The slides begin on 34°-40° slopes, with most common occurrence on slopes at or near 37°. This angle corresponds to the laboratory-determined angle of internal friction of the till soil obtained from samples taken in the Hollis area.[8]

Excess soil water is probably the principal factor in triggering these till slides. Soil permeability is good,[9] with subsurface flow concentrated above the unweathered till surface. During periods of extremely high rainfall following initial saturation of the soil, excess soil water produces a rising piezometric level. At saturation, maximum soil-water levels produce active pore-water pressures great enough to substantially reduce shear resistance of the soil. Studies relating rainfall to piezometric rise in the Maybeso Creek valley verify this. During the period of most recent sliding in 1961, the till soils with debris avalanches and flows were saturated. The resultant active pore-water pressures reduced the soil shear strength by as much as 60 percent.

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[8] Undisturbed pedestal samples tested by triaxial shear at the Civil Engineering Laboratory, Michigan State University, had an effective angle of internal friction ($\bar{\phi}$) of 37° and an effective cohesion (C) of 0.

[9] Unpublished field data from pumping tests at Hollis indicate a permeability range from 1.68 to 1.3 inches per hour.

These shallow till soils become saturated during storms with rainfall intensities in excess of 5 inches in 24 hours, an unusually high intensity with a 2- to 5-year-occurrence frequency in southeast Alaska (Swanston 1967b).

Although these till soils are physically cohesionless (see footnote 8), other factors combine to create a shear-resistant force--an "apparent cohesion"--that cannot be accounted for directly in soil physical properties. Part of this force may be a secondary cohesion produced by adhesion of organic colloids in the soil. Stephens (1967) has described an abnormally high organic colloid content for these till soils and attributes their surprisingly low bulk densities to its effect. Partial stabilization of the slide-prone soil masses is also produced by the anchoring of root masses through the soil and into the unweathered till (Patric and Swanston 1968; unpublished field data[10]). Stump excavations indicate that the tree root patterns on these oversteepened slopes consist of widely spread lateral roots lying along the unweathered till surface with sinkers penetrating into the upper 6-12 inches of partly weathered till at the B-C interface. Destruction of these root sinkers, by windthrow or decay following cutting, may substantially increase the susceptibility of these slopes to sliding.

Windthrow occurs frequently in southeast Alaska forests and has been correlated directly with debris avalanche and flow occurrence on soils derived from bedrock or colluvium (Swanston 1967a). Whether root decay following cutting causes increased susceptibility to landsliding is more difficult to determine. Bishop and Stevens (1964) observed a 4- to 5-year time lag in increased slide activity following logging on both types of soils which they related to a possible loss of root systems as "strength builders--retainers" in the soil mantle. Laboratory examination (see footnote 10) of stump laterals sampled from cuttings of different ages scattered throughout southeast Alaska support this observation. Tests of shear strength perpendicular to the grain on lateral roots greater than 1 inch in diameter reveal a very gradual decrease in shear strength with time since cutting. No signs of decay were observed on samples from cuttings less than 4 years old. Decay[11] was apparent almost universally on samples from stumps older than 4 years, frequently penetrating the root surface to a depth of one-half inch.

Evidence of soil creep in the form of catsteps, turfrolls, overturned soil profiles, and recurved tree trunks is abundant on oversteepened slopes. However, creep studies in the till soils have so far failed to show any direct relationship to occurrence of debris avalanches and flows. Quantitative creep measurements made in the Hollis area in 1966 and 1967, however, indicate that movement does occur, primarily in the first 6 to 12 inches of soil, and that the rate decreases rapidly toward the unweathered till surface. The soil appears to be moving as a flowing mass with no well-defined shearing planes. The maximum rate of movement is

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[10] Tree rooting and soil stability in coastal forests of southeastern Alaska, Study No. FS-NOR-1604:26; on file at the Pacific Northwest Forest and Range Experiment Station, Institute of Northern Forestry, Juneau.

[11] The fungi *Armillaria mellea* and *Fomes annosus*.

approximately one-fourth inch per year.[12] [13] Such movement undoubtedly produces a stress buildup in the soil over a period of time and may considerably increase slide susceptibility of the soil in critical areas.

Debris Torrents

Debris avalanches on extremely steep (40°-60°) sideslopes of deeply incised, steep-gradient stream channels or V-notch ravines are common to both soil series and occasionally produce massive debris flow and torrent flow deposits in the valley bottoms (Bishop and Stevens 1964).

The debris avalanches begin in shallow soils developed in colluvium or glacial till. The slope gradients involved are far greater than the angle of internal friction of the particular soil, greatly intensifying any factors tending to reduce stability. The slopes are extremely unstable and on the verge of failure at all times. Downslope stress on the soil is increased due to the weight of added water during periods of high rainfall. Increased pore-water pressure or destruction of stabilizing root systems aggravates the condition and may initiate sliding, as may bank undercutting near a stream. Usually these slides have short runs, beginning at the tops of valley sideslopes and ending at the streams (figs. 7 and 8).

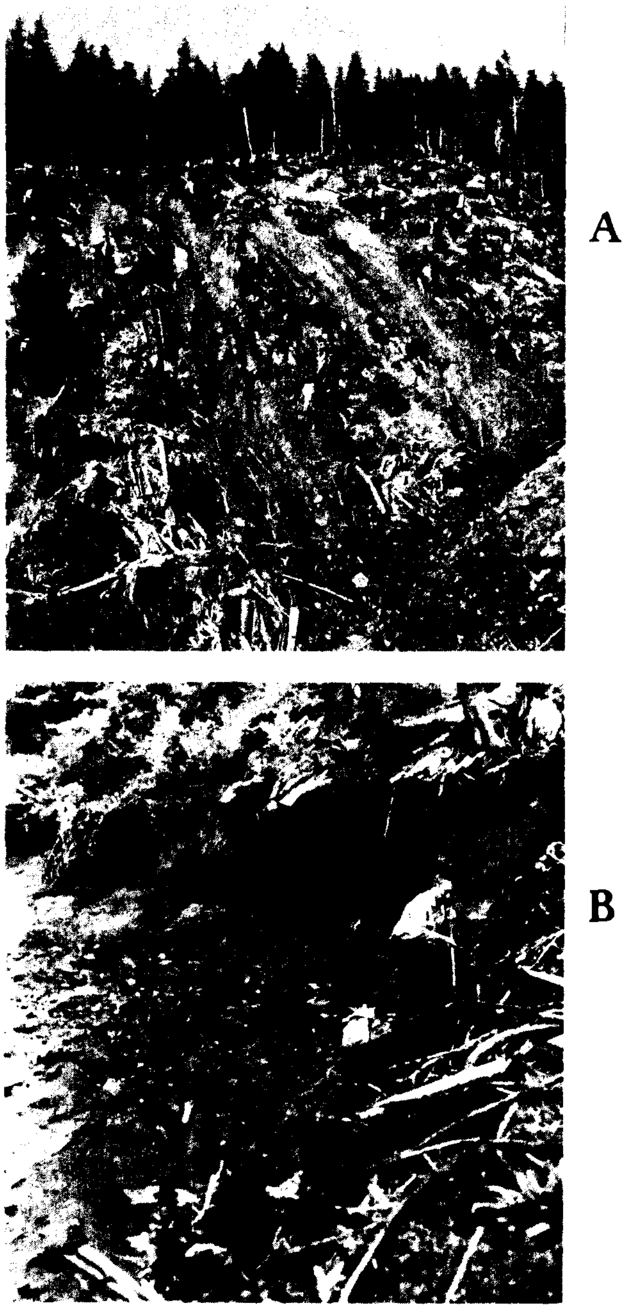

Figure 8.—Debris avalanches in steep-walled V-notch drainages. A, In till soil, Maybeso Creek valley. B, In bedrock-derived soil, Neets Bay. Note the masses of small roots overhanging the headwall of the slide. Many still remain firmly attached to the fractured and jointed bedrock substrata.

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[12] (a) Barr, D. J. Report of activities and results of the soil creep study (FS-NOR-1604:13), June-November 1965, Hollis, Alaska. (b) Barr, D. J. Report of the movement-measurement phase of of the Landslide Triggering Study (FS-NOR-1604:17). Both reports on file at the Pacific Northwest Forest and Range Experiment Station, Institute of Northern Forestry, Juneau.

[13] Barr, D. J., and Swanston, D. N. Measurements of creep in a shallow, slide-prone till soil. (In preparation for publication, Pacific Northwest Forest and Range Experiment Station, U.S.D.A. Forest Serv., Portland, Oregon.)

If the amounts of material are sufficient, they may become debris flows upon reaching the streams as a result of increased water content. More frequently, the debris is simply carried away as increased sediment load in the stream. Rapp (1961) in Scandinavia and Bishop and Stevens (1964) in southeast Alaska describe a phenomenon associated with this kind of flow resulting from debris avalanche accumulations in the bottoms of steep-sided channels. Debris forms a dam across a stream at the base of an avalanche. Subsequent material from upstream avalanches accumulates behind this barricade (fig. 9). When the dam gives way, a large volume debris flow or debris torrent occurs (fig. 10).

Figure 9.—Natural dam across V-notch drainage produced by accumulation of forest debris. Upstream debris-avalanching produces a buildup of soil and organic debris behind the dam which, when released, produces a large-scale debris torrent.

Figure 10.—Torrent flow deposit (center foreground) produced by failure of debris dam within the timber in center V-notch.

CONCLUSIONS AND RECOMMENDATIONS

Mass wastage is the dominant process of natural erosion and slope reduction in geologically youthful southeast Alaska. Steep slopes and excessive soil-water content are the principal causes of slide occurrence; destruction of natural slope equilibrium and stabilizing root systems are secondary factors.

Slope gradient alone characterizes the region as primed for mass movements of all types. Sections of almost every timbered slope exceed the natural angle of stability of the soil on them.

With the high rainfall of the region and resultant, almost continuous, saturation of the soils, these oversteepened slopes become particularly sensitive to events tending to disrupt their delicately balanced stability. Excess soil water, directly related to high intensity storms, is one such factor which causes instability in till soil areas, and it may be equally important in areas covered by colluvium or bedrock-derived soils. Natural catastrophic events such as rockfalls and tree blowdowns are also closely related to debris avalanche and flow occurrence in these oversteepened slopes, particularly in areas of colluvium or bedrock-derived soils.

Man's activities will aggravate such naturally unstable slope conditions. Therefore, the practical problem faced by land managers is the decision to accept the consequences of logging oversteepened slopes or to control the effects of these activities in order to minimize the occurrence of mass movements. Control may be done by application of direct methods of slope stabilization or avoidance of areas of known or expected instability.

At present, known slope stabilization techniques are not being applied extensively in southeast Alaska, but they may be in the near future as timber values increase. These techniques include (1) artificial drainage of the soil in slide-susceptible areas to reduce pore-water pressure, (2) removal of overburden to reduce shear stress in the soil, and (3) improvement of shear strength characteristics of the soil in hazard areas by the maintenance of living root systems which anchor through the soil and into the substratum. Soil drainage would involve placement of soil drain tile, construction of drainage ditches or, in some critical areas, artificial grouting of hazardous slopes to divert subsurface water concentrations. Overburden removal involves extensive heavy equipment operation. Root stabilization in areas of maximum instability would require maintenance of timber strips, parallel to and including the unstable areas, with a wide enough lateral spread to reduce windthrow hazard.

Probably the most practical and direct management policy at present is avoidance of areas of maximum slide susceptibility. The lower limit of internal friction angles for soils commonly found on these slopes is known ($\sim 34^{\circ}$). Slopes with gradients equal to or greater than this angle are highly susceptible to sliding, particularly if they are severely disturbed. With this information, general areas of maximum instability can then be identified. On aerial photos, these areas can be delineated by the occurrence and concentration of old debris avalanche and flow scars. A more accurate identification can be made from a slope-gradient map, which is constructed from scale measurements of slope angles on the aerial photographs and related topographic maps. A slope-gradient map can be used to (1) delineate potential slide areas, (2) determine percentage of slide-prone ground in the total area under consideration, and (3) establish cutting patterns which will best utilize these areas with minimum disturbance. Areas of imminent slide hazard, lying above a critical contour corresponding to the estimated angle of stability, should be given special management considerations.

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