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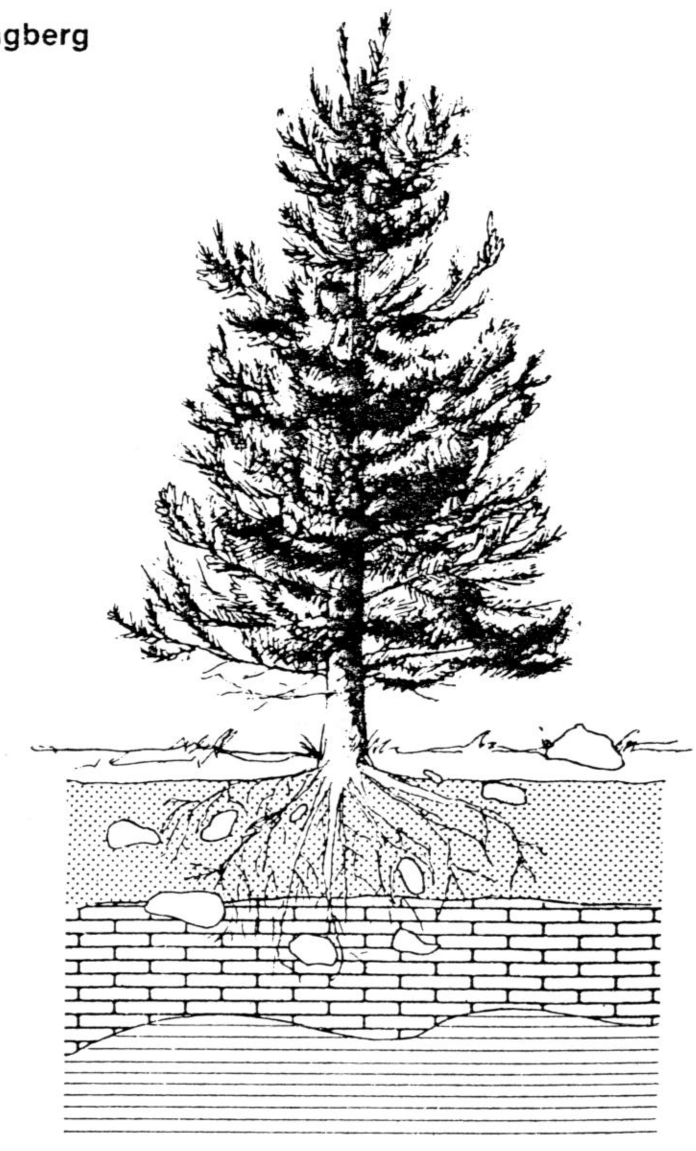

EFFECT OF GEOLOGY ON SOIL MASS MOVEMENT ACTIVITY IN THE PACIFIC NORTHWEST

Douglas N. Swanston[1/]

Soil mass movements, resulting in downslope transport of large volumes of soil, rock, and organic debris constitute a major natural process of erosion and a source of downstream sedimentation from sloping terrain in the Pacific Northwest. The activities of man in this mountainous region frequently initiate or accelerate the rate of occurrence of soil mass movement, resulting in reduced productivity of forest and agricultural lands, damage to roads, bridges, and other structures and substantial reductions in the quality of water and fisheries habitat. For effective and responsible land use planning in such terrain, the land manager must be able to recognize and understand the major factors influencing the occurrence of soil mass movement and be able to predict, at least on a qualitative level, potentially unstable sites.

Our present understanding of the controlling and contributing factors leading to soil mass movement activity is summarized on the following pages with particular reference to the basic influences of geology on movement mechanisms and occurrence. Both parent material and structural effects are discussed, with examples, in terms of the regional geology of the Pacific Northwest. The objective is to provide the land manager with a basic understanding of the strong control exerted by geologic factors on the character, distribution, and frequency of soil mass movement events.

SOIL MASS MOVEMENT TYPES

Soil mass movement can be grouped into four broad categories based on depth and rate of movement, mechanics, water content, and character of the mantle material. Each category has been well described in the literature and, as a group, the categories are used extensively in the Pacific Northwest to identify potential or existing landslide hazard (Varnes, 1958; Swanston, 1969, 1974b; Beaulieu, 1973, 1974, 1976, 1978; Beaulieu et al. 1974; Beaulieu and Hughes, 1975; Schlicker and others, 1972, 1973, 1974; Swanston and Swanson, 1976; Swanson and Swanston, 1977).

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Swanston and Swanson, 1976; Swanson and Swanston, 1977). These hydrologic events control the short-term moisture content of the soil and determine the presence or absence of active piezometric levels in the soil mantle. Soil water content and rising piezometric levels influence the strength of the soil or its resistance to failure and control the development of positive pore-water pressures. In fine-grained materials, increasing soil water content reduces the resistance of the soil mass to downslope movement by mobilizing the clay fraction, primarily through adsorption of water into clay mineral structures. Pore-water pressures reduce the frictional resistance of the soil mass along potential failure surfaces by buoyancy effects.

Forest vegetation controls the amount and rate of water reaching the soil materials and the amount held as stored water. Vegetation also provides a substantial strengthening effect through the anchoring and binding of mantle materials by root systems. In high rainfall areas interception is negligable during the large storms that trigger most soil mass movements (Rothacher, 1963; Swanston and Swanson, 1976). Evapotranspiration reduces soil moisture during the dry months, reduces the degree of saturation that can result from the first storms of the fall recharge period, and accelerates the rate of soil water removal at the end of the wet season. Once the soil is recharged early in the wet season, however, the effect of evapotranspiration becomes negligible. In zones where substantial snow accumulates, forest vegetation cover also influences the amount and distribution of snow collected on the land surface and the rate of melting, where advection and condensation melting are important (Anderson, 1969). This is particularly important in warm rain-on-snow events that commonly occur several times each year at elevations between 305 and 1,219 meters in the Cascade Range. Such snowmelt events can add large quantities of water to the soil mantle over short periods.

The role of roots as an important factor in maintaining the strength of soil mantles has received increased recognition in recent years (Nakano, 1971; Zaruba and Mencl, 1969; O'Loughlin, 1972a; Swanston, 1974a, 1974b; Ziemer and Swanston, 1977; Burroughs and Thomas, 1977). Roots add strength to the soil mass by vertically anchoring through the soil into fractures and zones of weakness in the parent material and by laterally tying the slope together across zones of weakness or instability. In shallow soils, both effects are important. In deep soils, the vertical anchoring factor will become negligible, but lateral anchoring remains important (Swanston and Swanson, 1976).

Land management activities, including timber removal, road construction and excavation, and land leveling for construction of buildings modify existing mantle materials and slope conditions and may strongly influence the relative stability of a site. Some of the most important impacts of these activities are summarized in Table 1 (modified from Swanston and Swanson, 1976).

The hydrologic, vegetative, and land use factors discussed above alter the balance of forces existing in the soil mantle, the stability characteristics and physical properties of which have largely been determined by the character of the parent material (including bedrock type, mineral composition, and depth and degree of weathering), structural relationships, and dominant landforming processes. Knowledge of the regional and local geology thus provides a basic foundation for recognizing unstable terrain, identifying soil mass movement types and mechanisms, and estimating the relative impacts of the various factors contributing to slope failure.

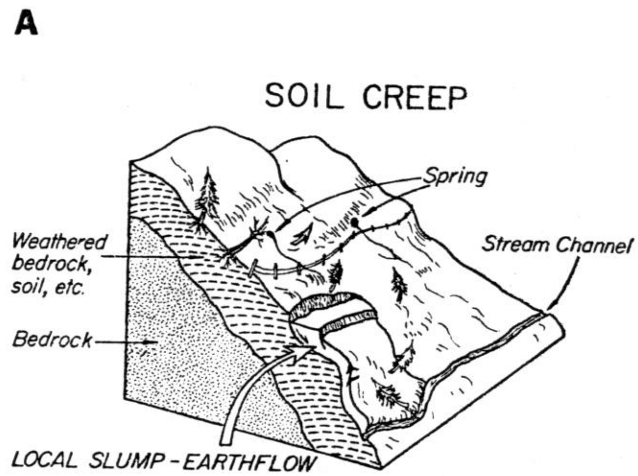
INFLUENCES OF PARENT MATERIAL PROPERTIES ON FAILURE TYPE AND DISTRIBUTION

Parent material characteristics have a major effect on the particle size distribution, depth and degree of weathering, and relative strength (resistance to failure) of steepland mantle materials in the Pacific Northwest. Thus, parent material can frequently be used as an indicator of relative soil stability. In the humid high rainfall areas west of the Cascade crest (Fig. 1), chemical weathering predominates and transformation of easily weathered primary and hydrothermally altered minerals to clays and clay-size particles is locally extensive. Fine-grained sedimentary rocks (siltstones, mudstones, claystones, shales, nonsiliceous sandstones), volcaniclastic rocks (welded ash, tuffs, agglomerates), serpentine-rich rocks, and glacio-lacustrine silts and clays are the most easily weathered and generally posses a high degree of cohesion. Sloping terrain underlain by such rocks are prone to soil mass movements of the creep and slump-earthflow types (Swanston and Swanson, 1976) (Fig. 2). Conversely, on the semi-arid east side of the Cascade crest, slopes underlain by these rocks may not experience soil mass movement processes of these types because of slow rates of chemical weathering and lack of enough soil moisture to mobilize existing clay minerals.

On slopes underlain by more resistant coarse-grained intrusives with quartz constituents, such as granites and diorites, and some glacial tills and recent pumice, shallow soils developed in residuum or colluvium are usually coarse textured and low in clay-sized particles. Such soils have low cohesion and are more likely to develop soil mass movements of the debris avalanche-debris flow or debris torrent types (Swanston and Swanson,1976) (Fig. 3).

Fine-grained andesite and basalt flow rock also tend to develop thin, coarse-textured soils on steep surfaces within which debris avalanche-debris flow soil mass movements occur. On flat-lying surfaces underlain by such rocks, deep weathering is common and slump-earthflows are the dominant type of soil mass movement. On near-vertical outcrops, rockfall and rockslides are most common.

Paricle size distribution or "texture" (which governs cohesion and angle of internal friction), soil moisture storage capacity, and gradient of the sliding surface control the relative stability of steepland mantle materials in this region. Shallow, coarse-grained soils low in clay-size particles have little or no cohesion. Frictional resistance



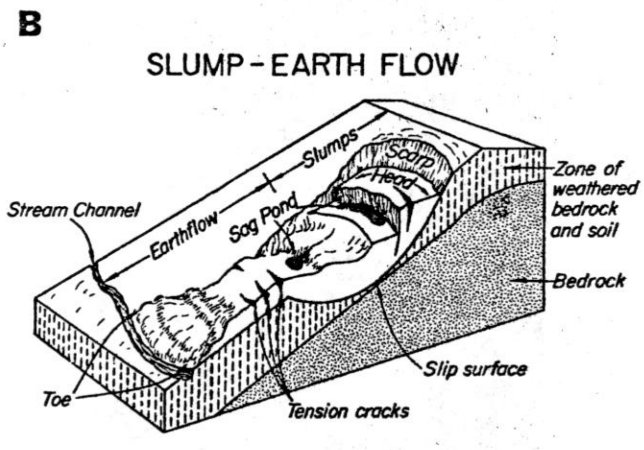


Figure 2. (A) Diagram of typical creeping terrain showing characteristic hummocky ground with local slump-earthflow failures; (B) diagram of slump-earthflow showing principal parts.

along the sliding surface, coupled with any resisting root strength, determines the strength of the soil mass. Frictional resistance in turn depends on slope gradient, angle of internal friction, and effective weight of the soil mass. The ratio indicator of the stability of low cohesion soils. Slopes at or above the angle of internall friction are in a highly unstable condition.

Soils and deeply weathered and altered bedrock with moderate to high clay content exhibit more complex behavior because resistance to failure is determined by both cohesion and frictional resistance. These factors are controlled to a large extent by clay mineralogy and soil moisture. In a dry state, clay-rich materials have a high shear strength with high internal angle of friction (30°). Increasing water content mobilizes the clay through absorption of water into the clay lattices (in effect reducing intragranular friction) and may approach zero under saturated conditions. In addition, interstitial water between grains may open the structure of the soil mass. This permits a "remolding" of the clay fraction, transforming it into a slurry, which lubricates the remaining soil mass. Some clays are more susceptible to deformation than others, making clay mineralogy an important consideration in areas characterized by quasiviscous flow deformation or creep. Swelling clays of the smectite group (montmorillonite) are particularly unstable because of their tendency to absorb large quantities of water and to experience alternate expansion and contraction during periods of wetting and drying which may result in progressive failure of a slope.

These soil mass movement-parent material relationships are clearly defined in many areas of the Pacific Northwest (Fig. 1).

The most unstable creep and slump-earthflow landscapes in the Cascade and Coast Ranges tend to be localized in areas of altered volcaniclastic materials or glacio-lacustrine and alluvial silts and clays. For example, in the western Cascades of Oregon, the Little Butte Series (predominantly volcaniclastics) and the overlying Sardine formation (interbedded volcaniclastic and flow rocks) commonly underlie unstable terrain (Peck et al. 1964; Beaulieu, 1971, 1974). A study of the relationship between bedrock type and soil mass movement on the H.J. Andrews Experimental Forest in the central western Cascades (Swanson and James, 1975) (Fig. 1, location A) revealed that more the 25% of the area underlain by volcaniclastic rock of the Little Butte Series is mantled with recognized active or presently inactive slump-earthflow landforms. Less than 1% of the areas of overlying younger basalt and andesite flow rock exhibits earthflow landforms (Fig. 4).

Slope stability investigations on the South Ump qua Experimental Forest (Swanston and Swanson, 1976; Swanson and Swanston, 1977) (Fig. 1, location B) have revealed similar massive slump-earthflow features developed in deeply weathered Little Butte volcaniclastics with overlying intercalated basalt flows and welded tuff (Fig. 5).

Spectacular creep and slump-earthflow features and deep bedrock failures occurring in the Columbia Gorge are predominantly the result of deformation and failure in older, altered, infompetent volcaniclastic rocks overlain by massive Columbia River basalt (Allen, 1958; Palmer,

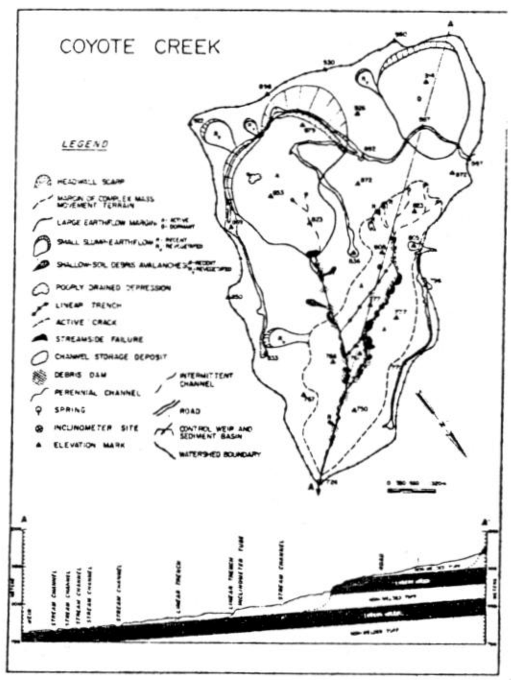


Figure 5. Map and geologic cross-profile of watershed 3, Coyote Creek, a tributary of the South Umpqua River, Oregon. Slump-earthflows developed in deeply weathered volcaniclastics (tuffs) of Little Butte Series. Headwalls of slumps lie just below welded tuff units (from Swanson and Swanston, 1977, used with permission).

In the Redwood Creek Basin of northern California, Colman (1973) (Fig. 1, location F) observed that a very high percentage of that part of the drainage occupied by slumps and earthflows is in clay-rich and pervasively sheared portions of Franciscan assemblage of rocks, whereas areas of the basin underlain by schists and other more highly metamorphosed rock are much less prone to slump-earthflow failures.

Hicks and Collins linked major slope stability problems in the Klamath Mountains of northern California and southwestern Oregon with three dominant bedrock terrains (Fig. 1, location G).[4/] The geology is complex but consists essentially of metamorphic rocks (schists, phyllites, slates, and altered volcaniclastics) intruded by granitic and ultramafic masses, mainly serpentine. Chemical weathering has decomposed and disintegrated the granitic rocks to a depth of several feet. The rock breaks down readily into sand and silt-size particles. Such granitic terrain is characterized by soil mass movements of the debris avalanche-debris flow and debris torrent types (Fig. 7). Among the metamorphic rocks, the Jurassic Galice Formation, composed principally of deeply weathered slate and phyllite with massive altered volcaniclastics and local graphite schist, contains numerous soil mass movements of the creep and slump-earthflow types. Gray reported that the weathered graphitic schist zones are particularly unstable in the presence of water.[5/] The highly fractured and sheared serpentinized ultrabasics occur scattered through the western Klamath Mountains and characteristically mark localized sites of creep and slump-earthflow activity.

In the Siskiyou Mountains of southwest Oregon, the Dothan Formation, believed to correlate with the Franciscan melange, consists of sheared and fractured greywacke with interbeds of mudstone and altered pillow lavas (Beaulieu, 1971; Dott, 1971) (Fig. 1, location H). Deeply weathered portions of the rock unit are particularly troublesome for engineering road construction because of continual active creep and slump-earthflow activity.

The Otter Point Formation--consisting of highly sheared and altered greywacke with subordinate argillite, mudstone, and volcaniclastics--correlates with the Franciscan assemblage in northern California (Lent, 1969) and is exposed in the northern and western Klamath Mountains near the southern Oregon coast (Fig. 1, location I). Much of this formation is highly altered to clay-rich material and is characterized by irregular, undulating slump-earthflow topography incorporating whole watersheds (Beaulieu, 1971; Swanson[6/]) (Fig. 8).

[4/] Hicks, W. G., and T. K. Collins. 1970. Use of engineering geology to reduce the impact of road construction and clearcut logging on the forest environment. Paper presented at the Annual Meet. Assoc. Eng. Geol., Washington, D.C. Oct. 1970.

[5/] Gray, D. H. 1977. Creep movement and soil moisture stress in forested vs. cutover slopes. Results of field studies. Final Rep. Coll., DRDA Proj. 012577, Natl. Sci. Found. Grant No. ENG74-02427, 144 p. Univ. Mich.

[6/] Frederick J. Swanson, unpublished data and maps, Forestry Sciences Laboratory, Corvallis, Oreg.

Creep and slump-earthflow processes also form extensive unstable terrain in the northern Oregon Coast Ranges. Most of the activity takes place in deeply weathered siltstones, sandstones, mudstones, and volcaniclastics of Tertiary age which cover most of the region (Schlicker et al. 1972) (Fig. 1, location J).

Along the coast, marine terraces composed of poorly bedded sand and silt occur in small narrow patches adjacent to beaches and bays. Most of these have been eroded by storm wave action and form bluffs up to 200 feet high. These are sites of continuing slump activity due both to undercutting by storm waves and weathering and seepage forces.

Shallow soil mass movements of the debris avalanche-debris flow and debris torrent types characterize major portions of the Oregon Coast Ranges, the steeper high elevation slopes of the southern and central Cascades, the recently deglaciated slopes of the Washington Coast Ranges, northern Cascades, Vancouver Island Mountains, and most of the Coast Mountains and Pacific Border ranges in British Columbia and southeast Alaska. Such failures are generally developed in shallow residual or colluvial soils overlying slightly altered bedrock or compact glacial till.

In the areas of the western Cascades where thick mantles of lapilli and ash have been deposited by late Pleistocene and Holocene volcanic activity, the terrain becomes particularly susceptible to debris avalanche-debris flows and debris torrents during major storm periods. Klock and Helvey (1976) reported massive increases (10 to 28 times) in debris flow and debris torrent frequency from such ash-mantled slopes on the Entiat Experimental Forest, west-central Washington (Fig. 1, location K), as the result of combined high intensity storms, rapid snowmelt, and destruction of vegetation by fire (Fig. 9). Major increases in occurrence of debris flows and debris torrents on ash-mantled slopes on the Umpqua National Forest, southern Oregon (Fig. 1, location L), also occurred after major storms in December 1964 and January 1965.[7/]

In the central Oregon Coast Ranges, soil mass movements of the debris avalanche-debris flow and debris torrent types dominate unstable landscapes developed in gently dipping sandstones and siltstones of the Tyee Formation (Fig. 1, location M; Fig. 10). The topography is characterized by structurally controlled east-west trending, narrow ridges, and deeply incised valleys with very steep hillslopes cutting across the gently dipping beds. On the steep, structurally controlled slopes, soils for the most part are thin, stony, relatively homogeneous colluvium, derived from the underlying sandstone and siltstone. The transition from soil to underlying bedrock is abrupt, and the bedrock is usually only slightly weathered. The bedrock surface usually functions as the failure plane for these shallow failures. In thicker siltstone units, particularly where extensive shearing has occurred, creep and slump-

[7/] A report of the Region 6 Storm Damage Evaluation Committee, USDA Forest Service, Pacific Northwest Region, December 1966; on file at Forestry Sciences Laboratory, Corvallis, Oreg.

earthflow features locally dominate unstable terrain as a result of widespread alteration of siltstone to smetite clay (Schlicker et al. 1974).

Debris avalanche-debris flows and debris torrents dominate much of the unstable terrain in the Coast Ranges, Pacific Border Ranges, and Coast Mountains of northern Washington, British Columbia, and southeast Alaska (Fig. 1, location N). The terrain has been extensively glaciated. Slopes are steep; mechanical weathering dominates; and soils tend to be shallow and cohesionless, derived either from colluvium or glacial till (Swanston, 1967, 1969, 1974a; O'Loughlin, 1972a, 1972b; Fiksdal[8/] (Fig. 11). The direct influence of bedrock type on soil mass movement processes under these conditions is minimal, and the dominant geomorphic process operating here becomes the controlling factor. Soil mass movement processes and controlling and contributing slope and soil characteristics are largely determined by glacial activity and its modifications to pre-existing terrain.

STRUCTURAL INFLUENCES

Bedrock structure--including attitude of beds, jointing, fracturing and faulting--is a critical factor in the stability of most natural slopes, frequently controlling movement and distribution of seepage water and providing zones of weakness in parent materials along, or within which soil mass movements can develop.

Highly jointed or fractured bedrock slopes with principal joints and fracture planes parallel to or dipping with the slope provide little mechanical support to overlying soil materials and create avenues for concentrated subsurface water movement. Jointing also provides avenues for deep penetration of surface and ground water with subsequent development of springs at remote sites on the slope and excess hydrostatic pressures locally as a result of confining rock or soil layers. At near-surface locations, joint and fracture planes are ready-made zones of weakness that provide potential failure surfaces along which overlying materials can slide.

Bedding planes within sedimentary and volcanic units function in essentially the same way as joints and fractures. Downslope-dipping planes between units with differential composition, permeability or degree of alteration serve as boundaries to subsurface water movement, as layers restricting penetration and development of root systems, and as potential surfaces of failure. Conversely, horizontal bedding planes or those dipping into the soil frequently produce natural buttresses that may actually increase stability of slopes locally. Care must be taken in assessing the stabilizing influence of horizontal or in-slope dipping bedding planes, however, since jointing, which is always present to some degree, frequently cross-cuts the bedding planes. When this happens, it becomes the dominant factor in structural control of slope stability.

[8/] Fiksdal, A. J. 1974. A landslide survey of the Stequaleho Creek watershed. Suppl. to final report FRI-UW-7404, 8 p. Fish. Res. Inst., Univ. Wash., Seattle.

Shearing and faulting, where present, exert a controlling influence on location and distribution of subsurface water, depth and degree of weathering, and location of individual soil mass movement features. Valleys developed along high angle faults in mountainous terrain may have exceptionally steep slopes. Deep penetration of ground water into uneroded fault and shear zones can result in extensive weathering and alteration of zone materials into clay-rich soils causing generation of slump-earthflow type failures. Such zones can also form barriers to ground water movement causing concentration of water in potentially unstable sites.

Contrasting physical characteristics of bedrock units and bedding direction commonly play an important role in shaping complex mass movement terrains in the Cascade Range. In the west central Cascades of Oregon, Swanson and James (1975) observed that steep headwall scarps of slumps and earthflows occur at contacts where resistant, commonly flat lying, flow rocks cap clay-rich incompetent volcaniclastic rocks. Similar relationships have been noted for creep and slump-earthflow failures in the western Cascades of southern Oregon (Swanson and Swanston, 1977), the Columbia River Gorge (Palmer, 1977), and by numerous authors in the foothills of the western Cascade and Coast Ranges bordering the Willamette Valley (e.g., Beaulieu, 1974; Allison and Felts, 1956; Schroeder and Swanston[9/] (Figs. 4 and 5). In areas of creep and slump-earthflow activity where there is no resistant capping rock, headwall scarps are absent and earthflows form broad hummocky depressions of low relief. Such is the case for the majority of slump-earthflow features in the northern California Franciscan melange (Kelsey, 1978; Colman, 1973) and its southwest Oregon equivalents (Fig. 6). Creep and earthflow movement over irregular bedrock surfaces, commonly resulting from a mix of rock types of different resistance, will produce an irregular landscape that is a subdued expression of the subsurface topography or bedrock (Fig. 8).

Structural control of subsurface water movement and distribution is almost universally associated with the location and initiation of soil mass movements of all types in the Pacific Northwest. Water is frequently trapped and transported laterally along bedding planes and joints or within more permeable rock units and fed directly into more incompetent materials, where failures occur. Such is the case for most of the creep and slump-earthflow features developed below capping rock in the western Cascades, where water is restricted above or within the rock units and fed into the underlying or overlying volcaniclastics where movement takes place. The pervasive shearing characteristic of much of the metamorphic terrain in northern California and southwest Oregon provides easy ingress of ground water into the formation and

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[9/] Schroeder, W. L., and D. N. Swanston. 1976. A landslide hazard study for Vineyard Mountain subdivision, Corvallis, Oreg. 36 p., illus., maps. Prepared for Vineyard Mountains, Inc.

form narrow east-west trending ridges with deep valleys. The steepest slopes and greatest debris avalanche-debris flow and debris torrent activity occur on the north aspect, and the gradient and straight slope configuration are apparently controlled by the joint system (Fig. 10). Slumping and block glide failures are more common on the gentler slopes facing south.

In southeast Alaska, Bishop and Stevens (1964) and Swanston (1967) identified jointing, fracturing, and bedding planes parallel to the slope as important factors in the occurrence of debris avalanche-debris flows in colluvium over bedrock. Stress release fracturing--closely spaced near-surface fractures caused by removal of the weight of ice from mountain slopes during the last major glacier retreat--has also been identified as a major contributor to unstable slope conditions in the Juneau area and several other locales in southeast Alaska (Swanston, 1972; Swanston, 1974a, 1974b; Miller[13/]) and is probably an important factor elsewhere in the Pacific Northwest where intense glaciation has occurred (Fig. 12).

Figure 12. Head scarp of debris avalanche near Petersburg, southeast Alaska, showing broken, platy nature of underlying diorite as the result of tension-release fracturing.

SUMMARY

The effects of geology on soil mass movement occurrence and distribution are major. Knowledge of these effects and their impact

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[13/] Miller, R. D. 1972. Surficial geology of the Juneau area and vicinity, Alaska. U.S. Geol. Surv. Open-File Rep., 108 p., illus. Anchorage, Alaska.

LITERATURE CITED

Allen, J. E. 1958. Columbia River Gorge, Portland to the Dalles. In Guidebook for field excursions, Cordilleran Section, Geol. Society of America, U. of Oregon, Eugene, March 27, 1958; p. 4-23.

Allison, I. S., and W. M. Felts. 1956. Reconnaissance geologic map of the Lebanon quadrangle. Oregon Dep. Geol. and Min. Ind. Map.

Anderson, H. W. 1969. Snowpack management. In Snow. Seminar of Oregon State University, p. 27-40. Oreg. Water Resour. Res. Inst., Corvallis, Oreg.

Beaulieu, J. D. 1971. Geologic formations of western Oregon. Oreg. Dep. Geol. and Min. Ind. Bull. 70, 70 p., illus.

Beaulieu, J. D. 1973. Environmental geology of inland Tillamook and Clatsop Counties, Oregon. Oreg. Dep. Geol. and Min. Ind. Bull. 79, 65 p.

Beaulieu, J. D. 1974. Geologic hazards of the Bull Run watershed, Multnomah and Clackamas Counties, Oregon. Oreg. Dep. Geol. and Min. Ind. Bull. 82, 77 p.

Beaulieu, J. D. 1976. Land use geology of western Curry County, Oregon. Oreg. Dep. Geol. and Min. Ind. Bull. 90, 148 p.

Beaulieu, J. D. 1978. Surficial geologic hazard concepts for Oregon: Ore Bin 40(3):41-56.

Beaulieu, J. D. and P. W. Hughes. 1975. Environmental geology of western Coos and Douglas Counties, Oregon. Oreg. Dep. Geol. and Min. Ind. Bull. 87, 148 p.

Beaulieu, J. D., P. W. Hughes, and K. Mathiot. 1974. Environmental geology of western Linn County, Oregon. Oreg. Dep. Geol. and Min. Ind. Bull. 84. 148 p.

Bishop, D. M., and M. E. Stevens. 1964. Landslides on logged areas in southeast Alaska. USDA For. Serv. Res. Pap. NOR-1, 18 p., illus.

Brown, C. B. and M. S. Sheu. 1975. Effects of deforestation on slopes: J. Geotech. Eng. Div., Am. Soc. Civ. Eng. 101:147-165.

Brown, W. M., III. 1973. Streamflow, sediment and turbidity in the Mad River basin, Humboldt and Trinity Counties, California. U.S. Geol. Surv. Water Res. Invest. 36-73, 57 p.

Brown, W. M., III, and J. R. Ritter. 1971. Sediment transport and turbidity in the Eel River basin, California. U.S. Geol. Surv. Water Supply Pap. 1986, 70 p.

Lent, R. L. 1969. Geology of the southern part of the Langlois quadrangle, Oregon. Ph.D. thesis. 189 p., illus. Univ. Oreg., Eugene.

Megahan, W. F. 1972. Subsurface flow interception by a logging road in mountains of central Idaho. In National symposium on watersheds in transition, p. 350-356. Colo. State Univ., Fort Collins, Colo.

Nakano, H. 1971. Soil and water conservation functions of forest on mountainous land. Rep. For. Influences Dev. Gov. (Jap.) For. Exp. Stn., 66 p., illus.

O'Loughlin, C. L. 1972a. An investigation of the stability of the steepland forest soils in the Coast Mountains, southwest British Columbia. Ph.D. thesis. 147 p. Univ. B. C., Vancouver, B.C.

O'Loughlin, C. L. 1972b. A preliminary study of landslides in the Coast Mountains of southwestern British Columbia. In Mountain geomorphology: Geomorphological processes in the Canadian Cordillera, B. C. Geogr. Ser. 14, p. 101-113. Tantahes Res. Ltd., Vancouver, B.C.

Paeth, R. C., M. E. Harward, E. G. Knox, and C. T. Dyrness. 1971. Factors affecting mass movement of four soils in the western Cascades of Oregon. Soil Sci. Soc. Am. 1964 Proc. 35:943-947.

Palmer, L. 1977. Large landslides of the Columbia River Gorge, Oregon and Washington. In Landslides. Geol. Soc. Am. Rev. Eng. Geol. vol. III, p. 69-85, illus., Boulder, Colo.

Parizek, R. R. 1971. Impact of highways on the hydrogeologic environment. In Environmental geomorphology, p. 151-199. D. R. Coates, ed., State Univ. N. Y. Binghampton, N.Y.

Peck, D. L., A. A. Griggs, H. G. Schlicker, F. G. Wells, and H. M. Dole. 1964. Geology of the central and northern parts of the Western Cascade Range in Oregon. U.S. Geol. Surv. Prof. Pap. 449, 56 p.

Pierson, T. C. 1977. Factors controlling debris-flow initiation on forested hillslopes in the Oregon Coast Range. Ph.D. thesis, 166 p., illus. Univ. Wash., Seattle.

Rothacher, J. 1959. How much debris down the drainage. Timberman 60:75-76.

Rothacher, J. 1963. Net precipitation under a Douglas-fir forest. For. Sci. 9:423-429, illus.

Schlicker, H. G., R. J. Deacon, J. D. Beaulieu, and G. W. Olcott. 1972. Environmental geology of the coastal region of Tillamook and Clatsop Counties, Oregon. Oreg. Dep. Geol. and Min. Ind. Bull. 74, 164 p., illus.

Wahrhaftig, C., and R. R. Curry. 1967. Geologic implications of sediment discharge records from northern Coast Ranges, California. In Man's effect on California watersheds. Report of the California Assembly Committee of Natural Resources, Planning and Public Works, Sub-Committe on Forestry and Watershed., Management, Part III, p. 35-58.

Youngberg, C. T., M. E. Harward, G. H. Simonson, and D. Rai. 1975. Nature and causes of stream turbidity in a mountain watershed. In Forest soils and forest land management, Laval Univ., Quebec. p. 267-283. B. Bernier and C. H. Winget, eds.

Zaruba, Q., and V. Mencl. 1969. Landslides and their control. 205 p., illus. Elsevier, New York.

Ziemer, R. R., and D. N. Swanston. 1977. Root strength changes after logging in southeast Alaska. USDA For. Serv. Res. Note PNW-306, 10 p., illus.