FOREST SLOPE STABILITY PILOT PROJECT

UPPER DESCHUTES RIVER, WASHINGTON

for

Department of Ecology

by

Gerald W. Thorsen
Kurt L. Othberg

Open File Report 79-16

Department of Natural Resources
Division of Geology and Earth Resources
Olympia, WA 98504

1978

LIBRARY
DEPARTMENT OF NATURAL RESOURCES
GEOLOGY AND EARTH RESOURCES DIVISION
OLYMPIA, WASHINGTON 98504

SLOPE STABILITY PILOT PROJECT

for

Department of Ecology

by

Gerald W. Thorsen
Kurt L. Othberg

Department of Natural Resources
Division of Geology and Earth Resources
Olympia, WA 98504

1978

CONTENTS

	Page
Introduction	1
Upper Deschutes Basin Study	1
Physical setting	1
Geologic setting	2
Geomorphic terrains	4
Deschutes headwaters terrain	4
Weathered bedrock terrain	5
Glaciated terrain	7
Landforms	8
Moraines - Terraces	8
Landslides	9
Selected References	11-12
Proposed methodology for Forest Slope Stability Studies	12
Advisory group	12
Field teams	13
Representative basins	13
Background studies	13
Compilation	13
Reconnaissance	14
Field studies	14
Report - maps	14
Educational phase	14
Appendix	
Brief analyses of three other basins in Western Washington	
Sultan Basin, North Cascades	
Grays River Basin, Southwest Washington	
Upper Clearwater River Basin, Southwest Olympics	
Applicability of the DNR-SCS soil surveys to slope stability mapping, with specific reference to the upper Deschutes	
Introduction	
Background on DNR-SCS soils mapping	
Extractable data	
Summary and conclusions	
Annotated bibliography on forest slope stability	

ILLUSTRATIONS

Upper Deschutes River Basin maps	in pocket
Road system	in pocket
Bedrock outcrop	in pocket
Geomorphic terrain map	in pocket
Landform map	in pocket

Introduction

One of the areas of interest to the Washington State Department of Ecology in regard to its water quality responsibilities is "non-point pollution" in the form of stream turbidity. Some assumptions that have been made regarding sources of turbidity are that landslides may be important contributions and that logging and logging roads may influence such slides. Our role was as consultants to make a pilot study of slope stability factors in the upper Deschutes River basin and to develop a methodology for such studies in other basins of the state in which timber harvest was an important activity.

The contract period was from July 1, 1978 to September 30, 1978. The sum of $9,905.24 was made available from "Section 208 money" under a grant by the U.S. Environmental Protection Agency through the Department of Ecology. Jim Sachet was Project Coordinator under Rollie Geppert, both of the Department of Ecology. J. Eric Schuster administered the contract by the Department of Natural Resources' Division of Geology and Earth Resources. Carl McFarland and Ellis Vonheeder mapped the bedrock of the study area (see Appendix).

Upper Deschutes Basin Study

Physical Setting

The Deschutes Pilot Study consists of the upper portion of the Deschutes River Basin, upstream from Vail, Washington. The study area encompasses about 75 square miles of mountainous terrain which lies in southernmost Thurston County and northernmost Lewis County. The land is primarily managed for timber harvest. Elevations in the upper Deschutes River Basin range from about 500 feet at Vail to over 3,000 feet in the headwaters of the basin. The topography varies from relatively flat or gently rolling, to extremely steep valley sides and sharp-crested ridges.

Average annual precipitation in the study area may range from 50 to 90 inches. These numbers are extrapolations based on nearby rain gauges and the concept that precipitation increases with elevation, and therefore have a low level of confidence. The high, southern portion of the basin may receive 70 to 90 inches of precipitation annually, and probably includes a fair amount of snow. As the elevations drop off to the north, average rainfall decreases to about 50 inches near Lake Lawrence and Clear Lake.

Based on a National Weather Service atlas (Miller and others, 1973) storm intensity ranges from 2.5 to 6 inches per 24-hour period. The most probable storm rainfall, a 2-year event, is 2.5 to 3.5 inches per 24 hours. The least probable, a 100-year event, ranges from 5 to 6 inches per 24 hours*. These values are low compared with the Grays River and Clearwater River basins (see descriptions under "Three Representative Basins of Western Washington"). Calculations based on Miller and others (1973) indicate that the upper Deschutes Basin storm rainfall is only 51% of that in the Clearwater basin, and only 60% of that in the upper Grays River basin.

---

*These numbers are based on isopluvials from Miller and others (1973). The isopluvials were drawn using the following statistically-tested interstation interpolation factors: slope, normal annual precipitation, barrier to airflow, elevation, distance to moisture, location (latitude or longitude), and roughness. For western Washington, elevation alone was a poor interpolation factor. However, elevation combined with slope, height of intervening barriers, and distance to moisture source was significant.

Geologic Setting

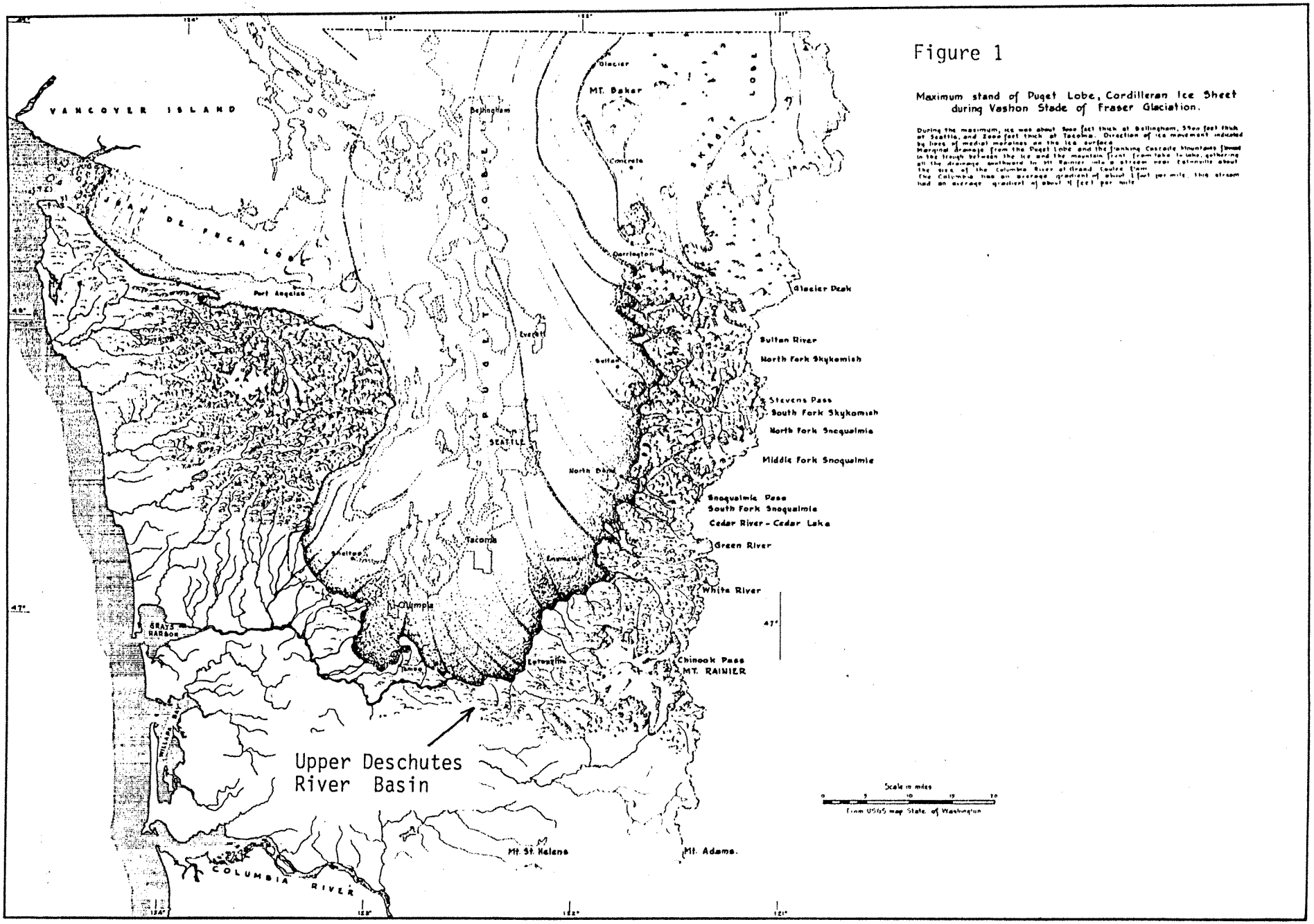
The upper Deschutes River Basin lies on the north flank of a northwest trending branch of the Cascade Mountains, which extends from the main crest of the Cascades northwest to Tenino. The rocks have been arched about a northwest-southeast axis, and erosion has exposed lower Tertiary volcanic rocks of the Northcraft Formation, and the overlying sedimentary rocks of the Skookumchuck Formation. The study area is underlain primarily by the volcanic rocks.

Relicts of ancient surfaces with deeply weathered bedrock and well developed soils can be found in several places in southwest Washington, including part of the study area. These surfaces may date from early Pleistocene to Pliocene (from one to several million years). The presence of the deep weathering suggests that pauses in uplift, and therefore pauses in erosion, occurred in the past and allowed deep in-place weathering and soil formation.

During the Pleistocene the northern and northeastern edges of the upper Deschutes River basin were glaciated. Also two small cirque glaciers occupied the very head of the Deschutes River valley. Glaciation had a two-fold character: (1) mountain valley glaciers, and (2) continental ice sheet. In addition to the minor effects of the small cirque glaciers, Mount Rainier valley glaciers and their associated meltwaters had a profound effect on the northeast portion of the basin, which is adjacent to the Nisqually River basin. Glacier ice spilling into the Deschutes basin from the Nisqually valley (site of Alder Lake) deposited till and meltwater sediments as well as rounding off ridges of bedrock.

The continental ice sheet, which postdated the mountain valley glaciers, filled the Puget Lowland as it pushed south from Canada (see Figure 1). At its maximum extent, it butted against the foothills along the northern edge of the basin. The effects of the continental ice sheet were: (1) the deposition of glacial sediments, resulting in the formation of moraines and terraces, and (2) the cutting of large channels when glacial meltwater was confined between an ice sheet on the north side, and the foothills on the south side (see Landform Map).

The Deschutes study area can be divided into three geomorphic areas, each with somewhat distinct geomorphic history, surficial processes, and topography (see Description of Geomorphic Terrain Units, below).



From: Allen S. Cary, 1968, AEG Guidebook to Field Trips, Seattle, Washington.

Geomorphic Terrains

The term slope stability is used herein as a measure of the level of activity of landsliding. In order to better understand the character and history of landsliding within the basin, we chose to broadly categorize the geomorphology of the area. This was not restricted to the study basin, but included reconnoitering adjoining areas, which allowed us to fit the study basin into a broader geomorphic picture.

The upper Deschutes River basin was found to be divisible into three "terrains," each of which has more or less distinctive topography, soils, and geomorphic history. (See "Description of Geomorphic Terrain Units," below). We believe that these terrains originated through the interplay of the following geologic events:

- Crustal uplift of an old, deeply weathered land surface.
- Rejuvenation of the "mature" landscape resulting in a trend toward a "youthful" landscape through stream downcutting, erosion* of deep soils, and steepening of valley sides. Rejuvenation is not complete and may be partially dormant under the present climate and vegetation.
- A possible climatic change that may have altered hydrology and therefore landslide activity within the basin.
- Glaciation of the northern part of the basin, which affected topography, earth materials, hydrology, and rejuvenation.

Through the use of the terrain map and the landform map one can begin to predict where the major landslide elements (weak materials, slope, and water) may become critical on the landscape.

Deschutes Headwaters Terrain - dv "v"-shaped valleys and sharp-crested ridges - geomorphic characteristics - This unit consists of long, straight "v"-shaped valleys and sharp-crested ridges. Slopes are steep, commonly 70% (35°) and steeper. The southern end of the Deschutes Valley at one time supported two small cirque glaciers. Locally, the much oversteepened cirque walls are 100% (45°) to vertical. Fresh, generally fractured but competent andesite bedrock outcrops in places, and is generally very close to the surface. Most soils are thin (20" - 40" depth to bedrock) and contain fragments of andesite. Infiltration of water appears to be high; runoff is low.

Slope stability and erosion characteristics - The bedrock, although shattered in places, appears relatively stable even where it underlies precipitous slopes.

Evidence of deep-seated landslides was not observed, and because of the strength of the bedrock, deep-seated landslides will probably not occur in the future. Landsliding of soils does not appear to be occurring under

---

*"Erosion" is here used in the very broad sense in which it encompasses all processes that remove earth material from the landscape. Landsliding is therefore one facet of erosion.

stands of trees or in clear cuts. Relatively minor cut-slope failures may occur due to local steeply sloping smooth bedrock and/or shallow ground water concentrations.

Side casts and road fills, which are constructed largely of the gravelly soils and fractured bedrock, tend to form permeable but sediment-filtering masses. They characteristically are composed of fresh, large boulders at the toe of fill areas, with decreasing grain sizes toward the top.

Probably the only significant potential slope stability hazard might be side casting into stream channels. Here, periods of high runoff could result in debris flows (debris "torrents"). Such events, however, are not as serious with respect to turbidity as a similar failure in deeply weathered areas. This is because the coarser, relatively unweathered soils in this unit generally lack clay and do not remain in suspension.

Weathered Bedrock Terrain - This terrain occupies a belt of characteristic topography that extends roughly east-west across the Deschutes River basin. The higher elevations of this topography consist of relatively gentle, smoothly curving, convex slopes, and a few flat valley surfaces. Adjacent to these surfaces there often occurs an incised valley system.

Deep, fine-textured soils and deeply weathered bedrock typify much of this terrain. Our interpretation of the history of this terrain is that it consists of ancient landscape surfaces that have been partially eroded away. This erosion, which may still be active today, has resulted in the steep, incised valleys along the lower segments of some of the streams that head in the weathered terrain. In several instances nickpoints in the stream gradients mark the point of separation between the incised, "rejuvenated" valley segments, and the flatter, "mature" valley segments (see Landform map).

wg - gentle ridge tops and flat upland valleys - geomorphic characteristics - This unit consists of gentle slopes (usually less than 30%; or 17°) often occurring on ridges and flat upland valleys that are underlain by deep soils and deeply weathered bedrock. The soils contain a relatively high proportion of silt and clay. Infiltration of water is quite high regardless of the fine texture, because of well-developed soil structure.

Slope stability and erosion characteristics - Landsliding in this unit was not observed to be a problem, probably because of low slope angles. However, where road construction and tractor logging have bared the soil and caused rutting and compaction, soil erosion may be locally severe.

wn - steep, noncritical slopes - geomorphic characteristics - This unit consists of moderately steep convex slopes (often 20%-50%; or 11°-27°) that are underlain by deep soils and deeply weathered bedrock. The soils contain a relatively high proportion of silt and clay. Infiltration of water is high probably because of well-developed soil structure, the granular

nature of the weathered bedrock, and fractures in the underlying bedrock. The majority of the old slump-flows occur in this unit, and probably attest to a potential for landsliding, given sufficient changes in groundwater characteristics (see Landsliding section of text).

Slope stability and erosion characteristics - Although many old slump-flows are located within this unit, none appear to have been active during logging history. The landslide masses themselves appear to be as stable as adjacent, intact slopes. This may be due to the development of a vegetation-soil relationship that prevents a critical saturation of earth materials.

As in the previous, gentle unit, wg, the fine-textured soils are prone to soil erosion and liquefaction where road construction and tractor logging have removed the vegetative cover and disrupted the soils.

Where this unit borders the steep, critical unit (wc) and the steep, incised unit (wi), it may be prone to landsliding because of oversteepening downslope.

wc - steep, critical slopes - geomorphic characteristics - This unit borders the noncritical "mature" convex slopes of unit "wn". It is typified by the lower slopes of Lincoln and Lewis Creeks. Slopes may be steeper than in the noncritical unit, ranging up to 70% (35°). However, many slopes are no steeper than in the noncritical area. What is significant is their position at the base of a long slope, where ground water may be creating critical saturation conditions.

Soils tend to be deep in this unit, except where they have been removed by recent debris flows.

Slope stability and erosion characteristics - This unit is named "critical" because it has the highest number of observed recent landslides, and those landslides probably have occurred in response to road construction and logging. Typical features observed were: 1) road cut-bank slumping and flowage along roads, and 2) debris flows on steep, clear-cut slopes or road side-casting sites, some of which culminated into torrents of debris that reached a major tributary to the Deschutes River (Lincoln Creek and Lewis Creek). (See Landform map).

wi - steep incised valley systems - geomorphic characteristics - This unit is typified by the steep, incised segments of Fall Creek and Mitchell Creek (see, for example, section 14, T. 15 N., R. 2 E., and section 19, T. 15 N., R. 3 E.). Slopes average close to 60% (31°), are commonly up to 66% (34°), and in a few places are 100% (45°). In many ways this unit shares characteristics with the Deschutes Headwater Terrain "v"-shaped valleys and sharp-crested ridges (dv). That is, soils are shallow and gravelly, and slopes are steep to precipitous. However, this unit does not exhibit the long straight valleys and ridges found in the Deschutes Headwaters Terrain. The drainage pattern is dendritic, but more significantly, the main streams head in the gentle weathered terrain (wg) and pass over nickpoints as they enter the incised valley systems (see Landform map).

Slope stability and erosion characteristics - With the exception of two slump-flows in the upper reaches of Fall Creek drainage, where the incised and gentle-weathered units abut, landslides were not noted in the incised valley systems unit (wi). Because of the steepness of the slopes, road side casts may be potential sites of landsliding.

Glaciated Terrain - The Glaciated Terrain occupies the northern and northeastern edges of the Deschutes River Basin. From Green Hill (section 10, T. 15 N., R. 3 E.) westward, and below 1,000', the northern edge of the basin was affected by the most recent Puget lobe continental glaciation (Vashon). This resulted in the formation of moraines, terraces and meltwater channels (see Landform map). The large streams of meltwater that flowed westward carved and undercut the bedrock slopes as the water was confined by the foothills to the south.

East of Green Hill and including the Bald Hill uplands, an earlier glaciation had a modifying effect on the landscape. This earlier glaciation probably emanated from Mount Rainier, flowed down the Nisqually drainage and spread into a piedmont glacier that covered much of the area around the Little Deschutes River and the Bald Hill uplands.

gt - gentle terraces and till surfaces - geomorphic characteristics - This unit consists of flat terraces and gently rolling hills and valleys. Slopes probably average 8% (4.5^{o}) and range to a maximum of 20% (11°). West of Green Hill, Vashon Till and Vashon-age kame terraces probably underlie the surface of this unit. The permeability of these materials is relatively low. Therefore, infiltration is slow and wet ground is common. Since the last glaciation, streams tributary to the Deschutes River, downstream of Deschutes Falls (section 14, T. 15 N., R. 3 E.), have incised into portions of the glacial terrain (see unit gi). However, upstream, this downcutting is not as prominent.

Slope stability and erosion characteristics - Although the soils and glacial deposits are relatively weak and tend to be saturated, the low-slope angles reduce the probability of slope failures. Soil erosion potential is relatively high when soils and deposits are bared and disturbed, because of poor permeability and fine textures.

gb - glacially-smoothed bedrock - geomorphic characteristics - This unit consists of gentle to steep glacier and meltwater-scoured surfaces underlain by bedrock. Soils are shallow and contain both fractured bedrock and glacier-ice derived gravel. The bedrock is generally unweathered where exposed. Slope angles vary considerably, from flat ridges and saddles to greater than 100% (45°) ice-scoured rock slopes.

Slope stability and erosion characteristics - Two deep-seated landslides are located in this unit. However, they probably pre-date logging. Slope failures are not characteristic of this unit, but the occasional steep slopes can be treacherous for slope stability if soils are disturbed.

gi - steep incised valleys - geomorphic characteristics - This unit consists of steep-sided incised valleys cutting through glaciated terrain. They have some characteristics like "weathered terrain, steep, critical slopes unit" (wc), but landsliding occurs in glacial deposits as opposed to weathered bedrock. These incised valleys originated by: 1) channel-cutting of glacial meltwater streams, or 2) post-glacial rejuvenation (downcutting) of streams in response to new base levels.

Slope stability and erosion characteristics - Several large, deep-seated landslides are located within this unit (see Landform map). One of these (in sections 24 and 25, T. 15 N., R. 3 E.) is known to be more than 450 years old (see Landslide section of text). Most of the deep-seated landslides were probably activated when glacial meltwater streams critically steepened their channel sides.

The potential for erosion and landsliding is higher in this unit than in other glaciated terrain units, because: 1) slopes can be precipitous (up to 70% and 100%, or 35° and 45°), and 2) glacial deposits and soils are generally either fine textured with poor soil structure, or they are uncemented and easily eroded.

Landforms

A study of the landforms (or geomorphic features) of an area provides a variety of information, some of which may be relevant to slope stability. The landforms themselves are important clues to the kinds of geologic processes that have gone on (or are going on) in an area; and their distribution in space. The relative ages of the landforms can sometimes give useful information on the level of activity of these processes. Also, a knowledge of the processes necessary to produce a given landform can furnish insights regarding the geologic materials, their textures and their relationships that may not be visible in shallow surface exposures. The major landforms in the upper Deschutes River basin are moraines, terraces, and ancient landslides. The Landform Map (see appendix) show these as well as minor geomorphic features within the study area.

Moraines - Terraces - These features are largely of a constructional nature; being in almost every case the result of deposition along the border of the last continental ice sheet. They tend to be relatively low, rarely exceeding an elevation of 1,000 feet.

The terraces ("t") and modified moraines ("mm" on the landform map) tend to have little relief except along their largely angle-of-repose stream cut edges. Thus, exposures are few and almost non-existent on the upper surfaces. There probably is no sharp distinction between the materials of these two features. The poorly sorted and relatively unstratified morainal material may locally grade into or interfinger with the terrace deposits. The main large-scale distinction is the presence of meltwater channels across the upper surfaces of the modified moraines, while such features are lacking on the terraces.

The terraces upstream from the mouth of the Little Deschutes River are much older than the ones downstream from Deschutes Falls. These older terraces are apparently remnants of an early alpine and piedmont glaciation. Boulders within these deposits are in general deeply weathered. The deposits

themselves appear to be rather poorly drained, with abundant willow and even cattail in places.

The unmodified moraines (designated as "m" on the Landform Map) are characterized by extremely uneven terrain. Relief is low, however, so slope stability problems do not appear to be significant even where soils are wet. Ponds and boggy areas are common, suggesting poor drainage and/or high water tables.

Landslides - General - One of the main focal points of this study was to examine the role of landslides in sediment production from forest lands. All slide activity of mappable size that was observed, either on the ground or in aerial photographs, is shown on the Landform Map (Appendix). Obviously, failures of road cuts (surprisingly rare) were too small to show on a 1-inch per mile map. Debris flows, whether originating at roads or on undisturbed slopes, were mapped even though the map scale required considerable exaggeration of their widths.

Large deep-seated landslides, even after coming to rest, remain, in most parts of the world, as areas of instability. The slide mass itself is made up of broken and disrupted material inherently weaker than the in-place materials. The plane(s) of failure often remain as surfaces of weakness and disruptions of normal subsurface drainage. The scarp area is generally left oversteepened and subject to later, although generally smaller, slide activity.

Shallow slides, generally in the form of debris avalanches-debris flows (depending largely on their water content) are common symptoms of shallow ground water concentrations. They most commonly fail at the boundary between the "agricultural soil-vegetation mat" and the parent materials. Once failed, such slides usually become flows (at least in northwest coastal climates) and incorporate logging slash and whatever surface debris is at the site. Depending on water content, slope, and relationship with regard to streams, they may or may not continue downhill to year-round streams and be sluiced out.

Deep-seated landslides - These slides (designated "ls" on the Landform Map) have shear surfaces and/or zones of flowage significantly deeper than the limits of tree root penetration. In most cases this lower limit of disturbed material is tens or, in the larger slides, probably several hundred feet deep. Within the study area, as well as along the north flanks of the Skookumchuck drainage, these slide areas are common but, with one exception, inactive.

The age(s) of these deep-seated failures is difficult to determine. About all that can be said in this regard is that they are pre-old growth timber (on the order of 400 years in much of this area). The setting for some of these slides appears to have been prepared by the undercutting and steepening of slopes along meltwater channels of the last major glaciation (about 13,000-14,000 years ago). Some may have been actually triggered by

the undercutting but others show little modification of the slide mass by running water.

The fact that only one of these slides has shown even partial reactivation, (and this could have preceded logging), implies a certain margin of safety under present conditions. This suggests that they probably failed initially under quite different climatic and ground water conditions. In addition, it suggests that there has been time since their initial failure to reestablish some internal drainage and, at least partially, "heal" through weathering processes, some of the discontinuities that led up to and/or were developed by their initial failure. Thus, these ancient slide masses in general appear to be much more stable than similar masses in the Puget Lowland that reactivate periodically during unusually wet years.

In summary, these landforms, although making up a significant percentage of the lands' surface in the upper Deschutes, are apparently not contributing any more to the river sediment load than similar areas of undisturbed land.

Debris flow landslides - In contrast to the previously discussed slides, these are small, shallow, slides (shown as "dF" on the Landform Map) which respond to superficial factors, and have occurred recently (since road building and/or logging). They generally involve only the agricultural soil - root mat and whatever debris and/or sidecast material that may overly it. The fact that they tend to occur on the lower flanks of the ridges and that they move by flowage suggest that they are triggered by concentrations of shallow ground water at or near the base of the forest soil. In spite of the size and steepness of the study area there appear to be less than 20 of these small debris flows that were clearly not sidecast failures. Most of them occurred in a roughly two square mile area along lower Lincoln and Lewis Creeks and the nearby Deschutes River.

In view of the generally steep slopes and abundance of mechanically weak, deeply weathered rock, why are there not more active shallow landslides? The answer to this is not clear but it may relate in part to the relatively low rainfall in the area (see Physical Setting). Another, and possibly more important, factor might be a general lack of shallow water-perching surfaces in these areas of deep weathering. The age of the soils and depth of weathering appear to have produced a good soil structure that is relatively well drained in spite of the abundance of clay minerals.

The impact of these debris flow slides on surface water quality is complex. Because of the relatively small amount of material that has failed and the even smaller amount that reaches streams (probably less than from road runoff), the actual volume of sediment contributed is practically insignificant. Also, because of the fineness of material, most is probably flushed completely through the drainage system and dispersed in salt water. On the other hand, its fineness and vivid yellow-brown color probably do contribute a significant percentage of the pigmentation in Deschutes runoff.

Dry flow landslides - The collapse and/or dry flowage (ravelling) of relatively uncohesive glacial terrace materials is a phenomena different in many ways from the foregoing landslide forms. A thorough inventory of such sites was beyond the scope of this project. (Most would be unmappable at the scale used). The largest of these are, however, identified as "bc" on the Landform Map to designate areas of bank cutting in the thick terrace deposits. All are along the outside of tight curves along the main Deschutes River.

A spot check of the bank about half a mile downstream from the mouth of Mitchell Creek showed an actively eroding angle-of-repose 90-foot bank. It is composed of an estimated 10 percent gravel, cobbles, and boulders (almost entirely in the top 10-15 feet), 20 percent silt (dispersed within various sand/silt beds throughout the section), 30 percent coarse sand, and 40 percent fine sand; both as multiple beds throughout the section. The sands are largely made up of fine grained rock fragments, suggesting that the glacial meltwaters were reworking and redepositing much material derived from the central Cascades by the time they got this far south.

It is difficult to estimate the rate of activity of these slide areas as most of the undercutting no doubt takes place during periods of high water and the materials are immediately flushed downstream. The rate might be roughly estimated in an indirect manner by making the assumption that most of these slugs of fine sediment, introduced during periods of high flow, are flushed through the system. Sediment contributions from upstream appear to be minor (see "Debris Flows"). Thus, these high, actively eroding banks probably contribute the bulk of the 30,000 cubic yards (Nelson, 1974) of sediment deposited at the river mouth each year. The mineralogical characteristics of a sediment sample collected at Tumwater Falls tend to support this observation.

Selected References

Crandell, D. R., and Miller, R. D., 1974, Quaternary stratigraphy and extent of glaciation in the Mount Rainier region, Washington: U.S. Geological Survey Professional Paper 847, 59 p.

Miller, J. F., Frederick, R. H., and Tracey, R. J., 1973, Precipitation-Frequency atlas of the Western United States, Volume IX - Washington: U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration, National Weather Service, 43 p.

Nelson, L. M., 1974, Sediment transport by streams in the Deschutes and Nisqually River basins, Washington: U.S. Geological Survey Open-File Report, 33 p.

Noble, J. B., and Wallace, E. F., 1966, Geology and ground-water resources of Thurston County, Washington, Volume II: Dept. of Conservation, Div. of Water Resources, Water Supply Bulletin No. 10, 141 p., 5 plates.

Snavely, P. D., and others, 1958, Geology and coal resources of the Centralia - Chehalis District, Washington: U.S. Geological Survey Bulletin 1053, 159 p., 13 plates.

Steinbrenner, E. C., and Gehrke, F. E., 1964, Soil survey of the Vail Tree Farm: Weyerhaeuser Company, 1 volume.

Proposed Methodology for Forest Slope Stability Studies

The following proposed methodology should be a useful guide for the study of slope failure contributions to basin runoff turbidity and minimizing the number and severity of such events. Full use of this procedure was not made for the Deschutes study for various reasons including lack of time, money, and personnel. It should be emphasized that no procedure warrants rigid adherence to, as factors such as unique local conditions, lack of time, or focus on a certain aspect of the problem could make certain aspects of study pointless for a given project.

The suggestions are intended as much for the nonparticipants in such studies as it is for the specialists directly engaged in a particular forest slope stability research project. It is important that the whole spectrum of staff involved understand and agree on what is being attempted, as poor communication among the technical team or their advisors or lack of committment on the part of management can make even the best conceived research project a waste of effort.

For the purposes of discussion and to estalbish a logical sequence of action, this methodology is broken into the following phases:

1. Advisory Group
2. Field Teams
3. Representative Basins
4. Background Studies
5. Compilation
6. Reconnaissance
7. Field Studies
8. Report - Maps
9. Educational Phase

Some of these phases or steps should be conducted concurrently, while others will obviously need to remain in sequence.

Advisory Group - An interdisciplinary group of experienced professionals representing the following fields should be selected: forest soils, geology, hydrology, civil engineering, forestry and logging. This team should contain representatives of various state, federal, and private organizations. It is intended to serve as a guiding "board" and source of specialized experienced advice for the field teams. It should take an active part in phase 3 (Representative Basins) and meet periodically to hear progress reports and provide

constructive criticism to Field Teams. Members should be prepared to make occasional tours in the field either as a group or singly as needed by a particular field team.

Field Teams - These groups, generally composed of between two and four people, should be selected to ensure that each group has within it a good practical background in natural slope stability factors. Each should include someone with experience in geomorphology, slope analysis, and forest soils. Certain basins might require considerable hydrologic study and it is understood that forest hydrology advice will be available to all field teams.

Representative Basins - Important timber harvest areas of the state should be divided into broad groups with similar characteristics such as geology, geologic history, soils, climate, and topography. At least one representative basin should be selected from each of these groups. This grouping and selection process could be done by a task force composed of the Advisory Group, Field Teams, and other specialists selected for this task alone.

Background Studies - Assess availability of hydrologic and climatological data for the selected representative basins. Begin monitoring programs immeidately, to fill data gaps for these basins. Include some basins, if possible, that are in "park status" for use as long term reference stations. This phase will, of course, need experienced specialists with backgrounds in practical forest hydrology and climatological studies.

Compilation - All available data that could potentially relate to forest slope stability for the selected basin and adjacent areas should be gathered. This should include but not be limited to:

- climate and precipitation records; precipitation form and distribution
- topographic data (slope, aspect, base maps)
- bedrock geology
- surficial geology
- geomorphology and geologic history
- soils
- surface hydrology, including runoff distribution and water quality
- forest cutting and roading history (including history of early cuts)
- forest fire history of area
- vegetation

A careful review of the kinds of available information will help in planning and organizing the study. A choice of base maps and base map scales needs to be done early and should involve all participants in the particular study. Aerial photo coverage needs to be analyzed, selected and ordered. This must be done as soon as possible, especially for brief short-lead-time studies or where old or difficult to obtain materials are needed. For example, pre- and early-World War II aerial photograpy may, in some cases, be very helpful but can take months to obtain.

Reconnaissance - An aerial photo scan, especially of "high altitude" (1 inch equals 1 mile) coverage, is very helpful at the beginning of this stage. Such an overview will put the selected basin in its regional perspective and serve as orientation. It also will rapidly acquaint the worker with major geomorphic subdivisions, drainage patterns, and other clues to an area's geology, geologic history, and soil parent materials. The following field recon should acquaint the Field Team with the kinds of materials present and the processes acting on these materials. A meticulous examination of available photography (and other remote sensing data, if available) is the next step in the recon phase of study. Actual examination of the basin from the air, along with taking oblique aerial photographs is often helpful at this stage. All landforms and slope stability/turbidity-producing features should be plotted on the base maps selected or base map overlays.

Field Studies - This phase is largely one of field checking observations and interpretations made in the aerial photo studies and the earlier field recon. Landforms will be mapped and landslides studied to determine when and why they failed. Working hypotheses regarding the origin of landforms can be refined or discarded. Detailed observations made on the ground can give a better understanding of the units chosen for the various maps as these units may vary from basin to basin. It is important that the Field Teams not get "bogged down" at this stage, with excessive numbers and details of map units (No amount of map detail will substitute for later site specific work such as road routing). Instead, they should be working towards providing the local land manager with a better understanding of his "territory", the processes at work, its diversity, and limitations. Some or all of the Advisory Group may be called upon for field consultations at this stage.

Reports - Maps - These end products should represent an attempt to provide the local forest land manager with the tools to make his work more efficient and interesting and thus encourage their use. Towards this end, an effort should be made to standardize mapping units from one study basin to another (basins will not, of course, all have the same units). A standard report format should be developed with the advice of the Advisory Group.

Educational Phase - Develop an educational system aimed at providing local managers and their assistants with a better understanding of the factors relating to slope stability and other erosional processes. Such a system should recognize personnel turnover and thus must operate on a continuing or at least periodic basis; either using experienced specialists within the respective areas or a "traveling" group drawn from the appropriate divisions in Olympia and/or consultants. The system should include some sort of practical manual that could be left with field personnel, as well as the usual slide presentations and lectures. Analyses of local problems could also be an effective teaching aid.

Appendix I

Brief Analysis of three other Basins in Western Washington

General

In this section we briefly summarize the physical factors of three basins in Western Washington. In each case we deal largely with the basin segment involved in timber production. Factors that relate to natural slope stability as well as the response of slopes to timber harvest operations are stressed. The purpose of this section is to put the upper Deschutes basin pilot study in perspective by pointing out the widely varying slope conditions in Western Washington. It is hoped that this will emphasize the problems inherent in attempting rigid or over-simplified solutions to forest slope stability problems.

Sultan Basin, North Cascades - Physical Setting - The segment of the Sultan River drainage considered here is from the west end of Blue Mountain to the headwaters. This basin is roughly 80 square miles in area, with elevations ranging from less than 1,000 feet in the Sultan River gorge to more than 6,550 feet on Del Campo Peak.

Average annual precipitation (1966-1975) at Olney Pass elevation (2,000 feet) varies from 121 inches to 174 inches but probably exceeds 200 inches in alpine parts of the basin. Snow accounts for 80 to 90 percent of the precipitation, largely falling between October 15 and May 15. "Precipitation events . . . are generally of low intensity and extended duration" (Dethier, 1977 U.W. Ph.D. thesis, p. 38); with the maximum 24-hour precipitation 6-5 inches.

Surface runoff ranges from small alpine streams flowing on bedrock, to large turbulent mountain streams, with a bed of large boulders and cobbles. Slopes in the timber producing areas of the basin range from a series of verticle rock walls interrupted by short angle-of-repose benches to the practically flat land of the glacial moraine, outwash, and lake deposits forming the northwest bank of Spada Lake.

Geologic Setting - History - As with most major drainages flowing west into the Puget Lowlands, the Sultan basin resulted from an interplay of alpine factors with continental glaciation. The Sultan drainage was already well developed when a tongue of the Puget Lobe continental ice sheet intruded up-valley, damming the Sultans' normal flow and temporarily deverting it through 2,000 feet-elevation Olney Pass. Later, the river formed a new channel along the north flank of Blue Mountain, eventually incising itself into what is now a rocky gorge. When the continental ice retreated it left a broad, gently sloping valley occupied by the newly-created Pilchuck River. The Sultan River stayed in its new channel, effectively dammed from its former channel by the thick wall of glacial materials left by continental ice tongue.

Geologic Materials - Materials making up the Sultan basin reflect the history outlined above. Glacial scour, fast mountain streams, and the brief time of exposure have resulted in bedrock that is strong, hard, and practically unweathered. Glacial materials range from a concrete-like till smeared on the north face of Blue Mountain to thick sections of silt deposited in the lake that was formed when continental ice dammed the valley. Overlapping and, in places, probably interfingering these glacial materials are deposits of talus, alluvial fans, and colluvial soils along the base of the steep mountain fronts. Forest soils are generally shallow or nonexistent on the relatively young glacial, post glacial, and bedrock surfaces.

Slope Stability - Slopes in the Sultan Basin are here grouped in three broad categories as follows: steep glaciated terrain, steep unglaciated terrain, and the "basin floor". Each of these appear to have significantly different slope stability characteristics.

The steep glaciated terrain is best characterized by the north face of Blue Mountain above about 1,600 feet elevation. Bedrock is steep (greater than 70%) glacially smoothed, and in places smeared with concrete-like till. The forest soils are generally very thin. Stability problems are largely limited to a narrow ribbon-like track of exposed bedrock extending from the point of origin to the valley floor.

The steep unglaciated terrain category makes up most of the rest of the upland timber producing portions of the basin. Slopes range from 70% to vertical. Forest soils are generally thin except on rocky benches or along the lower mountain flanks. Here, talus and colluvium may locally be tens of feet thick. Rock chutes, heading in the upper mountain flanks, are usually devoid of vegetation where active. Soils, where present are usually quite stable except in areas of ground water concentrations.

The basin's floor is defined as the areas of stream and glacial deposition that are generally less than 60% or so and predominantly below 1,600 feet in elevation. These areas are, in general, devoid of bedrock except in the gorge below Spada Lake. Glacial and alluvial soils are quite thick, probably exceeding 400 feet in the gently rolling terrain northwest of Spada Lake. The two large active and deep-seated landslides in the basin are apparently related to the glacial lake bed silts of this unit.

Grays River Basin, Southwest Washington - Physical Setting - The Grays River flows from headwaters in the core of the Willapa Hills to the Columbia River, a distance of approximately 20 miles. The area drained is approximately 127 square miles. All but about 10 square miles of the basin is managed for timber harvesting. The range in elevations is from sea level to nearly 2,800 feet msl. The topography varies from some low elevation terraces to highly dissected, steep mountainous slopes. The majority of the area can be categorized into three types of landscape: 1) convex and rolling with a maximum relief of 500 feet, 2) undulating gentle to moderately steep with ill-defined ridge tops and a 400' to 800' maximum relief, and 3) highly dissected with steep, straight slopes and a range of relief from 1,000 feet to 1,800 feet.

The climate is typical of coastal Washington: cool and moist with very wet winters. Data from this basin, nearby Naselle, and the west coast of the Olympic Peninsula provide some estimates for average and maximum precipitation levels. The majority of the Grays River basin area lies within the isoline for the 100-inch average annual precipitation. Average annual precipitation is 124 inches at about 1,000 feet elevation, and is probably higher in the nearly 2,800 feet elevation headwaters area.

Geologic Setting - History - The early to middle Tertiary rocks underlying the Grays River basin are exposed as a result of erosion accompanying the Willapa Hills uplift during the Pliocene and Pleistocene. Apparently, the only effect of the varying climatic and hydrologic conditions of the Pleistocene was the formation of low elevation terraces in the lower basin near the Columbia River. Erosion of an old landscape (evidence for which lies a few miles west of the Grays River Basin) has been progressing over several millions of years. Within this basin, no remnant of that landscape exists. The erosion has stripped away younger rocks, such that now a variety of ages and lithologies of rocks undergoing erosion provide a mosaic of terrains through which the Grays River and tributaries flow.

Geologic Materials - The types of rocks present in the basin are: 1) poorly indurated sandstone and siltstone, 2) indurated sandstone, 3) tuffaceous siltstone and sandstone, 4) interbedded basalt flows and volcano-sedimentary rocks, and 5) relatively massive basalt and gabbro. Each of these underlies a relatively distinct terrain that has characteristic mass-wasting characteristics, and therefore characteristic landforms.

Slope Stability - In general, the terrains with steeper slopes are underlain by rocks that are resistant to deep-seated landslides. Slopes, therefore, steepen to a point at which the stability of soils and weathered bedrock is critical. The natural variations in rainfall intensities and vegetative cover cause concomitant variations in the occurrence of debris flows, avalanches, and torrents that typify mass wasting on such terrain. At present, the relatively high intensity rainfall in the Grays River basin causes the steep terrains to be erosionally active in the geologic sense. It may not be an understatement to say that in the absence of vegetation to increase stability, most soils would be eroded off the slopes.

The less steep terrains are generally underlain by rocks that are subject to deep-seated landslides, primarily slump-flow phenomena. This process results in more gentle slopes upon which soils are disrupted, but are not catastrophically removed. The imprint of timber harvesting and road construction upon this natural system probably varies from insignificant to paramount. However, two primary conclusions may be that: (1) on gentle slopes where the fine-textured soils accumulates, the use of tractor logging probably increases the potential for sheet erosion, and (2) on steep slopes, where catastrophic mass wasting occurs under natural conditions, clear-cutting and midslope roads increase the potential for landsliding.

Upper Clearwater River Basin, Southwest Olympics by Allen Fiksdal - Physical Setting - The Clearwater River is a tributary of the Queets River on the western slopes of the Olympic Mountains. Stequaleho Creek, the Sollecks River, and the Clearwater River above the mouth of Stequaleho Creek (about 60 square miles) form the "Upper Clearwater drainage area. The minimum elevation is 400 feet and maximum elevation is 3,800 feet. Hill slopes range from 0 degrees to 50+ degrees with some rock cliffs of 90 degrees. The approximate average slope is between 20 and 30 degrees.

The Upper Clearwater drainage is subjected to high, and at times intense rainfall. The annual average is 130 to 200 inches per year, with a maximum of about 11 inches per 24-hour period and 45 inches in one month. Only 7% of the drainage area is above 3,000 feet elevation and winter temperatures are mild so a winter snow pack is probably not significant in precipitation or its retention. The Clearwater River area is underlain by siltstones and sandstones that are highly fractured in places, and have large fault zones and areas of mèlange (a chaotic mixture of clay and broken rock). The sandstones are quite erosion resistant, especially where thick and massive, and tend to form ridge tops, cliffs and rocky knobs. The siltstones underly flanks of ridges and are poorly exposed except in road cuts. These siltstones are generally thin bedded, and tend to slake into small chips when exposed in cuts.

Geologic Setting - History - During the Pleistocene large valley glaciers flowed down the Queets and Hoh Rivers, on either side of the Clearwater River, from a ice cap that covered the Olympic Mountain Core. Ice from this core covered only the very uppermost part of the Clearwater River and did not flow more than one or two miles down the Clearwater River Valley. Since the Pleistocene the Clearwater River has cut through the terraces formed from ice damming and is presently undergoing the natural processes of valley widening in the larger river valleys, and incising and headward erosion in the small tributaries.

Geologic Materials - The soils in the Upper Clearwater Drainage are unique in that they have not been removed by glacial scouring or are not deeply weathered residual soils similar to ones found in southwest Washington or other areas that have not been glaciated had millions(?) of years to develop. The soils mantling the Clearwater, Sollecks and Stequalcho drainages are predominately shallow to moderately deep colluvial soils. This would indicate substantial downslope movement of surface materials. This is not surprising considering the amount of rainfall and steepness of slopes throughout the drainages.

Slope Stability - In the Upper Clearwater drainage area the predominated mode of erosion is streambank and headward erosion. Numerous small landslides occur along streambanks and at the heads of drainages throughout the area. Undercutting of streambank by the normal process of valley widening is very apparent in the smaller tributaries. Progressive erosion of steep drainage heads sometimes cause dramatic debris flows that can scour stream channels to bedrock. Only a few large landslides have been mapped in this area and appear not to be as common as the smaller erosional landslides.

A failure of sidecast in the Stequaleho Creek drainage prompted a reconnaissance of natural and man caused mass wasting events in 1972. Road construction was found to cause numerous small landslides particularly where slopes were greater than 30 degrees (Fiksdal, unpublished report). No landslides were found relating to clearcutting alone but lack of time since logging may be an important factor. The recency of much of the logging may not have given time for stump root decay to have progressed to a critical level. In general, the report noted that road building disrupted the natural hillslope equilibrium by overloading, undercutting, or changing ground water conditions in a very dynamic area. The report did not relate instability with geology because of the lack of geologic mapping. It is apparent, however, that areas that have bedrock dipping down slope, or wide fault zones and mèlange areas are more apt to become unstable when effected by timber harvesting and road building activities.

Appendix II

Applicability of the DNR-SCS Soil Surveys to Slope Stability Mapping, with Specific Reference to the Upper Deschutes River Basin.

Introduction - Slope stability mapping may be accomplished in a variety of ways. The applicability of the maps to a particular need depends on their intended use and the methodology employed to make slope stability interpretations. It is our opinion that in order to develop concepts about slope stability that allow generalizations within a map unit, or extrapolation to areas with little on-site data, slope stability mapping should begin with a geomorphic study. By this we mean that one develops concepts about past and presently acting surficial processes. One important result of geomorphic study is a knowledge of the location, activity, and possible failure mechanisms of landslides.

The study of the geomorphology of any river basin requires gathering data and available information about many aspects of the basin, about characteristics of adjoining areas, and about distant but similar basins. For various reasons, soils are an important aspect of geomorphic study. Two important reasons are: 1) soils portray the effects of the interaction of environmental conditions with earth materials over time, and 2) soils are the major earth material that is lost through landsliding on unstable slopes.

It is the purpose of this appendix to analyze the applicability of available soil maps to the geomorphic study of the landscape and its processes, and therefore to slope stability mapping. This appendix is here written because of the slope stability mapping project in the Upper Deschutes River Basin, within which Department of Natural Resources and U.S. Soil Conservation Service (DNR-SCS) soil survey mapping is available. This analysis is brief and general because of difficulties in obtaining soil maps, and inadequate time for field checking to see how they relate to our observations. Nonetheless, it may provide a starting point from which others may further examine the application of DNR-SCS forest soils mapping to slope stability studies.

Background on the Department of Natural Resources - U.S. Soil Conservation Service (DNR-SCS) Soils Mapping - The DNR Private Forest Land Grading Program was developed to provide an equitable forest taxation base. A soil survey in cooperation with the SCS is the fundamental medium for delineating "land grades". The two land grading interpretations are: 1) potential productivity, and 2) operability.

Potential productivity is a measure of the potential volume of wood produced on specific mapping units. It is based on measurements of existing trees and to the properties of soil mapping units. Operability is an indirect measure of the ease or difficulty of forest land road construction and maintenance and the harvesting of trees. In a broad sense it is a measure of part of the relative costs of logging on specific mapping units. Operability is based on soil properties plus considerations of landform, geology, and other aspects of the landscape that affect road construction and timber harvest. Slope stability is one important part of operability class selection.

The DNR is mapping soils to National Cooperative Soil Survey standards. The work is being done in cooperation with the U.S. Soil Conservation Service. However, the state legislature did not provide that the DNR would publish soil survey maps. The final maps produced by the DNR show only potential productivity, operability and acreage for each map unit. Although the map unit boundaries are soil mapping unit boundaries, no soil designation is included. Orthophoto maps with soil designations will be unpublished but available through the DNR. Responsibility for publishing soil survey maps and reports based on this mapping effort lies with the SCS. Some county areas will have no updated soil survey report as a result of this program. However, all county private forest lands will have unpublished soil field descriptions kept on record at the DNR. For those counties which will have an updated soil survey published as a result of this program, the reports will be done according to SCS format. This has an important effect on extracting data that might be of use in broadly applying these maps to forest slope stability considerations (see below).

Extractable Data - Soil Maps and Slope Stability - Given that a soil survey report with accompanying map and legend will be published by SCS, the following information can be extracted to assist in making slope stability interpretations:

- Properties of soil series and phases (only relevant ones are listed here)
  - Texture
  - Depth
  - Wetness and permeability (soil "drainage")
  - Slope
  - Parent material
- Geographic setting
- Operability classes

For the soil series and phases the descriptions present specific properties of a type locality and the range of properties as mapped. However, the specific properties and variability of parent materials is lacking. Unfortunately, the published soil descriptions do not include details on landforms, and the occurrence of landslides, or observed slope stability characteristics even though such things may have been observed in the field by the soil scientist. A thorough discussion of the operability classes and the particular geomorphic features that were part of the basis for selecting those classes will not be available to users of the published maps. Unless the SCS makes a major change in the format and content of their soil surveys, or the DNR publishes specialized forest soil management interpretations as a result of the Private Forest Land Grading Program, published maps and reports from the DNR-SCS cooperative mapping will contain the operability interpretations, but not the background data.

What will be available are the unpublished records of the field mapping, primarily contained on mapping unit information sheets. These sheets are

a record of basic field data on soils and parent materials, landforms, drainage, climate, vegetation, and slope stability. The mapping unit information sheets are available for inspection through the DNR. For the Deschutes pilot study area the DNR-SCS soils mapping team for Lewis County was able to provide specific information about the soils of the Lewis County portion of the Deschutes River basin that would not generally be available. A brief observation of the soils mapping indicates that the properties of mapped soils and their delineations generally concur with those predicted by geomorphic study of the area. A specific correlation analysis of the two mapping projects was not attempted, nor should it be, because the geomorphic study did not map materials per se like the soils mapping did. Also, our map scale (1:62,500) was very small comapred to the soils mapping, and our field time was short. Because of their larger scale and more extensive field work, greater use of the Lewis County portion of the soils mapping would have helped to improve the accuracy and to refine the concepts of our geomorphic terrain map. Participation by a forest soils scientist, preferably one who had mapped soils in the Deschutes basin, would have speeded up and enhanced the accuracy of our geomorphology and slope stability study.

Operability and Slope Stability - The PFLG operability classes cannot be used to interpret slope stability. What one can ascertain from an operability class is that slope stability was one of several factors used to place that class on a soil mapping unit. Operability classes (1, 2, 3, 4) are not, nor were they intended to be a measure of relative slope stability. Because steeper slopes are more difficult to operate on, slope angle has a major influence on operability classes. However, not all steep slopes are more unstable than more gentle ones. For example, the Deschutes Basin Headwaters Terrain contains some of the steepest slopes in the entire basin. As a result, the operability classes are dominated by classes 3 (difficult) and 4 (extreme). This contrasts with our slope stability analysis that interprets the Headwaters terrain to have a low potential for landslides.

Summary and Conclusions -

1. The DNR-PFLG operability classes, by themselves, cannot be used to interpret slope stability.

2. The DNR-PFLG mapping program is for a specific purpose--taxation. One possible interpretative benefit of the mapping, slope stability, will not become available to map users given the present plans for publishing soil maps and reports.

3. The DNR-SCS soil survey publications are a valuable display of surficial earth materials on forested land. In that respect, they provide an important aspect of the data compilation necessary to make slope stability analyses.

4. The unpublished soil mapping unit information sheets kept on record by the DNR are a valuable source of data for slope stability studies on forested land.

5. Forest soil scientists, especially those with experience mapping in the DNR-SCS program, would be assets to slope stability studies.

Appendix III

Annotated Bibliography on Forest Slope Stability

by Debra Hanneman

Landslides - General

Anderson, H.W., 1971, Relative contributions of sediment from source areas and transport processes: In Proceedings of a Symposium on Forest Land Uses and Stream Environment, Oregon State Univ.,Corvallis, Continuing Education Publications, p. 55-63.
Past land use and projected land use in the Pacific Northwest is expected to greatly increase the sediment discharge.

Bell, J.M., 1969, Noncircular sliding surfaces: Journal of the Soil Mechanics and Foundations Division, Proceedings of the American Society of Civil Engineers, vol. ?, p. 829-844.
A mathematical treatment of slip surfaces.

Broscoe, A.J., and S. Thomson, 1972, Observations on an alpine mudflow, Steele Creek: Icefield Ranges Research Project, Sci. Results, vol. 3, p. 53-60.
The alpine mudflow observed was triggered by intense rainfall. The pulsating nature of the mudflow was attributed to a steep sided, high gradient notch, which in this case, was cut into a morainal terrace.

Brunsden, D., 1974, Landslides: In The Unquiet Landscape, D. Brunsden et. al., eds., Indiana University Press, Bloomington, Indiana, p. 41-46.
A short review of the factors involved in landslides.

Gray, D.H., 1970, Effects of forest clear-cutting on the stability of natural slopes: Bulletin of the Association of Engineering Geologists, vol. 7, p. 45-66.
Gray concludes that clear cutting can promote soil erosion and ultimately slope failure. A discussion is also included on variables affecting slope stability.

Gray, D.H., and R.P. Brenner, 1971, The hydrology and stability of cutover slopes: Journal of the Irrigation and Drainage Division, American Society of Civil Engineers.
The authors state that removal of large areas of slope vegetation can result in mass soil movement.

Henkel, D.J., 1967, Local geology and the stability of natural slopes: Journal of the Soil Mechanics and Foundations Division, Proceedings of the American Society of Civil Engineers, vol. 93, p. 437-446.
A study of landslide development in interbedded sand and clay strata.

Krohn, J.P. and J.E. Slosson, 1976, Landslide potential in the United States: California Geology, vol. 29, p. 224-231.
A review of landslide factors and landslide potential in the U.S.

Laury, R.L., 1971, Stream bank failure and rotational slumping: preservation and significance in the geologic record: Bulletin of the Geological Society of America, vol. 82, p. 1251-1266.
Preservation of stream bank slumps is scant in the geologic record. It is suggested that only certain gravitational failures are preserved, and that preservation of these failures also requires certain sedimentological conditions.

Peck, R.B., 1967, Stability of natural slopes: Journal of the Soil Mechanics and Foundations Division, Proceedings of the American Society of Civil Engineers, vol. 93, p. 403-417.
An overview of natural slope stability assessment and the nature of natural slope failures.

Pestrong, R., 1976, Landslides; the descent of man: California Geology, vol. 29, p. 147-151.
An overview of landslide causes, movement, and recognition.

Rahn, P.H., 1969, The relationship between natural forested slopes and angles of repose for sand and gravel: Bulletin of the Geological Society of America, vol. 80, p. 2123-2128. (see also vegetation section).
The results of the study indicated that vegetation does stabilize hillslope.

Swanston, D.N., 1973, Judging landslide potential in glaciated valleys of southeastern Alaska: Explorers Journal, vol. 51, p. 214-217.
A very general treatment of landslide potential.

Swanston, D.N., and C.T. Dyrness, 1973, Stability of steep land: Journal of Forestry, vol. 71, p. 264-269.
The erosional processes of steeply sloping terrain are broken down into two main areas - surface erosion, and mass soil movement. These two areas are then reviewed in greater detail.

Williams, G.P. and H.P. Guy, 1971, Debris avalanches: a geomorphic hazard: In Environmental Geomorphology, D.R. Coates, ed., State University of New York, Binghampton, New York, p. 25-46.
Debris - avalanche scars were analyzed in central West Virginia to determine possible causative factors. The primary factors found were intense rainfall, pre-existing hillside depressions, and hillside orientation.

Wright, H.E., Jr., 1974, Landscape development, forest fires, and wilderness management: Science, vol. 186, p. 487-495.
A discussion of the erosional and vegetation cycles, but the main emphasis of the article is placed on the management of wilderness areas.

Creep

Barr, D.J., and D.N. Swanston, 1970, Measurement of creep in a shallow, slide-prone till soil: American Journal of Science, vol. 269, p. 467-480.
A clear cut area near Hollis, Alaska was chosen for slope failure study. The results of the study indicated that surficial soil creep was the most significant short-term soil movement.

Kirby, M.J., 1974, Soil movement: In The Unquiet Landscape, D. Brunsden, et. al., eds., Indiana University Press, Bloomington, Indiana, p. 37-40.
A short review of the factors involved in soil creep.

Mitchell, J.K., H.B. Seed, and J. Paduana, 1965, The creep deformation and strength characteristics of soils under the action of sustained stress: Report to the U.S. Bureau of Reclamation, Dept. of the Interior, no. TE 65-8, 122 p.
The report includes a literature review of creep and creep strength characteristics, and analyses of creep strength characteristics for sand-bentonite mixtures and sand-clay mixtures.

Parizek, E.J., and J.F. Woodruff, 1957, Mass wasting and the deformation of trees: American Journal of Science, vol. 255, p. 63-70.
Similar content as Phipps (1974) paper, i.e., the curved tree is not an indicator of soil creep.

Phipps, R.L., 1974, The Soil Creep - Curved Tree Fallacy: Journal Research USGS vol. 2, p. 371-377.
The author maintains that curved tree trunks, upslope trailing of root systems, and downslope tilting of trees do not indicate soil creep.

Tabor, R.W., 1971, Origin of ridge-top depressions by large-scale creep in the Olympic Mountains, Washington: Bulletin of the Geological Society of America, vol. 82, p. 1811-1822.
In the alpine areas of the Olympics, trough shaped deposits on ridge tops are formed by large scale creep.

Ter-Stepanian, George, 1963, On the long-term stability of slopes: Norwegian Geotechnical Institute, Publication No. 52, p. 1-14.
A discussion of the factors involved in creep development in slopes of cohesive soils.

Ter-Stepanian, G., 1974, Depth creep of slopes: International Association of Engineering Geology Bulletin, vol. 9, p. 97-102.
The author suggests that most landslides are not sudden occurrences, but that they are preceded by creep.

Yen, B.C., 1969, Stability of slopes undergoing creep deformation: Journal of the Soil Mechanics and Foundations Division, Proceedings of the American Society of Civil Engineers, Proc. Pap. 6675, p. 1075-1096.

Vegetational influences on slope stability

Bethlahmy, N., 1962, First year effects of timber removal on soil moisture: Bulletin of the International Association of Scientific Hydrology, vol. 7, p. 34-38.
Clear cutting promotes accelerated recharge of soil moisture and reduces soil moisture depletion.

Black, P.E., 1971, Interrelationships of forest, soils, and terrain in watershed planning: In Environmental Geomorphology, D.R. Coates, ed., State University of New York, Binghampton, New York, p. 71-78.
A very basic theoretical treatment of watershed management.

Brown, C.B., and M.S. Sheu, 1975, Effects of deforestation on slopes: Journal of the Geotechnical Engineering Division, vol. , p. 147-165.
The authors maintain that clear cutting does not immediately cause slope instability. However, after the clear cutting is completed, some ground cover must be planted in order to preserve slope stability.

Cowan, I.R., 1965, Transport of water in the soil-plant-atmosphere system: Journal of Applied Ecology, vol. 2, p. 221-239.
The water potential of the soil is evaluated mathematically as a dynamic aspect with respect to the soil-plant-atmosphere system.

Federal Water Pollution Control Administration, 1970, Industrial Waste Guide, Logging Practices: U.S. Department of the Interior, Northwest Region, Portland, Oregon, 40 p.
The document contains suggestions for logging practices which would protect water quality.

Lutz, H.J., 1960, Movement of rocks by uprooting of forest trees: American Journal of Science, vol. 258, p. 752-756.
Uprooting of trees may contribute to downslope movement (creep) of the soil and rock mantle.

Gaiser, R.N., 1952, Root channels and roots in forest soils: Soil Science Society of America Proceedings, vol. 16, p. 62-65.
The network of decayed root channels may transport a large portion of the free water in a soil, and thus should be considered when determining the soil's physical and hydrologic characteristics.

Gardner, W.R., 1960, Dynamic aspects of water availability to plants: Soil Science Society of America Proceedings, vol. 89, p. 63-73.
A mathematical description of the movement of water to and within plants.

Gray, D.H., 1970, Effects of the forest clear-cutting on the stability of natural slopes: Bulletin of the Association of Engineering Geologists, vol. 7, p. 45-66. (see also landslide section).
The forest cover plays a soil protective role in two primary ways: 1) by root stabilization and 2) by modifying the hydrologic regime of the soil mantle.

McNutt, J.A., 1974, Effects of forest cover on slope stability: Unpublished paper, Dept. of Forest Engineering, Oregon State Univ., Corvallis, 23 p.
A thorough discussion of the effects of vegetative cover on slope stability.

Molchanov, A.A., 1963, The hydrological role of forests: Published for the U.S.D.A. and the National Science Foundation by the Israel Program for Scientific Translations, 407 p.
Emphasis is placed on the hydrological aspects of the forests, but there are also sections on soils and surface runoff on different soil types.

Patric, J.H., J.E. Douglas, and J.D. Hewlett, 1965, Soil water absorption by mountain and piedmont forests: Soil Science Society of America Proceedings, vol. 29, p. 303-308.
The study concentrates on the pattern of moisture extraction under the forest. The moisture extraction is explained in terms of the local root concentration, and the moisture, texture, and uniformity of the soil.

Rahn, P.H., 1969, The relationship between natural forested slopes and angles of repose for sand and gravel: Bulletin of the Geological Society of America, vol. 80, p. 2123-2128. (see also landslide section).
The results of the study indicated that vegetation does stabilize hillslope.

Steinbrenner, E.C., 1966, Logging on watersheds: what type, where, what disturbance?: Symposium on practical aspects of watershed management, March 29-30, 1966, Oregon State Univ., Corvallis, p. 109-115.
Steinbrenner discusses different logging methods and the environmental problems associated with them.

Swanston, D.N., 1971, Principal mass movement processes influenced by logging, road building, and fire: In Proceedings of a Symposium on Forest Land Uses and Stream Environment, Oregon State Univ., Corvallis, Continuing Education Publications, p. 29-39. (see also road placement).
The disrupting activity of man, with road building as the most influential, act as important initiating and accelerating factors of mass movements.

U.S. Environmental Protection Agency, 1973, Silviculture: In Methods for Identifying and Evaluating the Nature and Extent of Nonpoint Sources of Pollutants, EPA, Office of Air and Water Programs, Washington, D.C., p. 93-132.
This section of the document deals with silvicultural activities and their possible polluting effects.

Wright, H.E., Jr., 1974, Landscape development, forest fires, and wilderness management: Science, vol. 186, p. 487-495.
A discussion of the erosional and vegetation cycles, but the main emphasis of the article is placed on the management of wilderness areas.

Wyoming Forest Study Team, 1971, Forest management in Wyoming, timber harvest and the environment of the Teton, Bridger, Shoshone, and Bighorn National Forests: U.S. Forest Service, 81 p.
An overview of forest management policies in Wyoming. Possibly the most relevant section in the document is "Controlling Environmental Effects of Residue", which is more of an environmental quality treatment of erosion problems.

Road Placement

Burroughs, E.R., Jr., G.R. Chalfant, and M.A. Townsend, 1976, Slope stability in road construction, a guide to the construction of stable roads in western Oregon and northern California: U.S. Department of the Interior, Bureau of Land Management, Oregon State Office, Portland, Oregon, 102 p.
A study of the geologic features relevant to road building with minimized erosion effects.

Larse, R.W., 1971, Prevention and control of erosion and stream sedimentation from forest roads: In Proceedings of a Symposium on Forest Land Uses and Stream Environment, Oregon State Univ., Corvallis, Continuing Education Publications, p. 76-83.
A review of road construction and maintenance aspects in relation to minimized erosion.

Megahan, W.F., 1977, Reducing erosional impacts of roads: In Guidelines for Watershed Management, FAO Conservation Guide, Food and Agriculture Organization of the United Nations, Rome, p. 237-261.
Megahan discusses major guidelines for reducing the erosional impact of roads.

Swanston, D.N., 1971, Principal mass movement processes influenced by logging, road building, and fire: In Proceedings of a Symposium on Forest Land Uses and Stream Environment, Oregon State Univ., Corvallis, Continuing Education Publications, p. 29-39. (see also vegetation section)
The disrupting activity of man, with road building as the most influential, act as important initiating and accelerating factors of mass movements.

U.S. Environmental Protection Agency, 1975, Logging roads and protection of water quality: EPA Region X, Water Division, Seattle, Washington, 312 p.
A review of present management techniques for protecting water quality in respect to logging, road building, and maintenance.

Recognition, Interpretation and Classification of Landslides

Anonymous, 1972, Mudslide and landslide prediction: California geology, vol. 25, p. 136.
A review of the California Division of Mines and Geology (Open-File Report on the prediction of regional landslides.

Crozier, M. J., 1972, Some problems in the correlation of landslide movement and climate: International Geography, Congr., Pap. #22, vol. 1, p. 90-93.
The author suggests that the problems with landslide movement/climate correlation are twofold due to: 1) the multivariate nature of the landslide/climate relationship, and 2) the dynamic nature of the system in which the variables exist.

Denness, B., 1972, End of the landslide menace? New Scientist, vol. 53, p. 417-419.
The author suggests that instead of using the usual "ideal" test for slippage in homogenous materials, a post mortem analysis of real slippage areas should be analyzed for strength parameters. This data could then be applied to future slide areas.

Highway Research Board, 1958, Landslide and Engineering Practice: Special Report #29, Washington, D.C., 232 p.
Techniques are presented for use in the recognition, interpretation and correction of landslides.

Kojan, E., 1974, Regional evaluation of landslide hazard - a semi-quantitative method: Geological Society of America Annual Mtg. (abstr.), vol. 6, p. 829-830.
A mapping technique is suggested which is based on regional mapping/classification of landslide morphology and geometry, in association with slide incidence.

Ludowise, H., 1974, The recognition, investigation, interpretation and treatment of landslide in the Pacific Northwest, unpublished M.S. thesis, Portland State University, 61 p.
A review of methods for landslide recognition and interpretation. A case study of the Clackamas landslide, 30 miles east of Portland, Oregon, is also included.

Norman, J. W., 1970, The photogeological detection of unstable ground: Journal Inst. Highway Engineers, vol. 17, p. 19-22.
A brief summary of mass movement recognition with aerial photographs.

Norman, J. W., N. J. Price, and A. T. Moon, 1971, Orientation studies, a means of detecting old landslides: Geotechnique, vol. 21, p. 154-155.
Geologic structure which clearly contradicts the regional stress pattern could be used to detect old landslides.

Scheidegger, A. E., 1973, On the prediction of the reach and velocity of catastrophic landslides: Rock Mechanics, vol. 5, p. 231-236.
A mathematical treatment of the correlation between volume and the coefficient of friction of rapid landslides.

Simonett, D. S., R. L. Schuman, and D. L. Williams, 1970, The use of air photos in a study of landslides in New Guinea: Technical Report 5, Office of Naval Research, Geography Branch, Dept. of Geography, Univ. of Kansas, Lawrence, Kansas, 59 p.
Techniques are presented for determining relationships between air photo and field data on landslides.

Swanston, D. N., 1971, Judging impact and damage of timber harvesting to forest soils in mountainous regions of western North America: Western Reforestation Coordinating Committee, Western Forestry and Conservation Assoc., Portland, Oregon, 7 p. (see also landslide mechanism section).
Factors which influence slope stability and techniques for identification and control of unstable slopes are discussed in this article.

Swanston, D. N., ? , Landslide analysis and control, interpreting stability problems for the land manager: unpublished paper, 31 p.
Similar to Swanston 1974 article, but treats subject in more depth (see landslide mechanism section).

Zander, A. D., 1966, Typical landscape characteristics and associated soil and water management problems on the Mt. Baker National Forest: U.S. Forest Service, Pacific Northwest Region, Bellingham, Washington, 89 p.
The study deals with the recognition and evaluation of Mt. Baker landscape characteristics.

Zolotarev, G. S., 1961, Engineering-Geological study of shore slopes and the significance of the history of their development in evaluating stability: in The Stability of Slopes, I. V. Popov and F. V. Kotlov, eds., translated from transactions of the F. P. Savarenski Hydrogeology Laboratory, vol. 35, by Consultants Bureau, New York, 1963, p. 9-29.
Zolotarev outlines what information a slope classification should include. Much of the article consists of review of slope development in Crimea.

Landslide mechanisms as extracted from case studies

Adam, D.P., 1975, A late Holocene pollen record from Pearson's Pond, Weeks Creek landslide, San Francisco Peninsula, California: Journal of Research, U.S. Geological Survey, vol. 3, p. 721-731.
By using pollen samples for paleoclimatic information and by dating core samples, it may be possible to relate climatic conditions to landslide activity.

Artim, E.R., 1974, Genesis and stability of an ancient landslide province, Washington:. Cordilleran Section, 70th Annual Mtg., Geological Society of America, Abstracts, vol. 6, p. 140-141.
A series of multiple slides occurred in late Pleistocene adjacent to the Columbia River (Chelan and Douglas Co.). The major rock failure factor was the low strength of sand/silt interbeds and sandstone/siltstone strata.

Bailey, R. G., 1971, Landslide hazards related to land use planning in Teton National Forest, Northwest Wyoming: USDA Forest Service, Intermountain Region, Ogden, Utah. (Report), 131 p.
The study deals with the various types of landslides which occur in the Teton National Forest and with the effects that these landslides have on forest management practices.

Bishop, D.M. and M.W. Stevens, 1964, Landslides on logged areas in southeast Alaska: U.S. Forest Service, Res. Pap. NOR-1, Northern Forest Experimental Station, Juneau, Alaska, 18 p.
The article includes a literature review of landslides in timbered areas and a discussion on shear stress and shear strength of soils. These concepts are then used to understand landslide activity in southeast Alaska logging areas.

Campbell, R.H., 1975, Soil slips, debris flows, and rainstorms in the Santa Monica Mountains and vicinity, southern California, U.S. Geological Survey, Prof. Pap. 851, 51 p.
Debris flows generated by soil slips are prevalent in the Santa Monica area. The primary factors for the cause of soil slippage are: 1) a steep slope, 2) a mantle of colluvial soil, and 3) soil moisture which is equal to or greater than the liquid limit of the colluvial soil.

Cleveland, G.B., 1973, Fire & Rain - Mudflows, Big Sur, 1972: California Geology, vol. 26, p. 127-135. The major factors behind the Big Sur mudflows of 1972 were: 1) the physical characteristics of the rocks and soil, 2) the short and intense periods of rainfall, and 3) the loss of slope vegetation by fire.

Cleveland, G.B., 1977, Rapid erosion along the Eel River, California: California Geology, vol. 30, p. 204-211.
The erosion rate of the Eel River Basin is a primary management problem. Streambank erosion and landslides are the main erosive processes in the area, but the author concentrates on the analyses of the landslides (i.e. landslide age, pattern of landslide activity).

Dyrness, C.T., 1967, Mass soil movements in the H.J. Andrews Experimental Forest: U.S. Forest Service, Res. Pap. PNW-42, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon, 12 p.
The report analyses mass movements (most commonly earthflow and channel scouring) which resulted from severe winter storms. These movements are correlated with geologic and soil characteristics.

Eisbacher, G.H., 1971, Natural slope failure, northeastern Skeena Mountains: Canadian Geotechnical Journal, vol. 8, p. 384-390.
The factors which controlled the distribution and slip direction of the 25 rockslides studied were regional structural trend, deformation, and lithologic heterogeneity.

Fiksdal, A.J., 1974, A landslide survey of the Upper Clearwater and Solleks River areas, Jefferson County: Geology and Earth Resources Division, Department of Natural Resources, Olympia, Washington, 6 p. (unpublished report).
A comparison of the volume of man-related landslides with natural landslides.

Flaccus, E., 1958, White Mountain landslides: Appalachia, vol. 32, p. 175-191.
The article gives an historical account of White Mountain, Vermont landslides. These landslides were mostly debris avalanches with triggering factors cited as: 1) slope - the majority of landslides occurred on a 32° slope, 2) torrential rains, and 3) vegetation, which includes lumbering, fire and windthrow.

Fredriksen, R.L., 1970, Erosion and sedimentation following road construction and timber harvest on unstable soils in three small western Oregon watersheds: U.S. Forest Service, Res. Pap. PNW-104, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon. 15 p.
Within two of the watersheds, landslide activity provided the bulk of stream sediment. The landslide occurrence intensified following harvesting and where logging roads crossed stream channels.

Hicks, B.C. and T.K. Collins, 1970, Use of engineering geology to reduce the impact of road construction and clear-cut logging on the forest environment: Unpublished paper presented at 1970 Annual Mtg. of Association of Engineering Geologist, Washington, D.C., 26 p.
The paper deals with the placement of roads and logging areas in the Klamath Mountains and their associated problems of activating/reactivating landslides and debris flows. Some case studies are included, but these studies are only in the beginning stages.

Huffman, M.E., 1977, Geology for timber harvest planning, North coast California: California Geology, vol. 30, p. 195-201.
A review of logging techniques and the environmentally sensitive areas these techniques can potentially create.

O'Loughlin, C.L., 1972, A preliminary study of landslides in the coast Mountains of southwestern British Columbia: B.C. Geogr. Ser., no. 14, p. 101-111.
Slope failure in this area was attributed to three main factors: 1) slope steepness (most occurred on slopes between 31° - 39°), 2) presence of an impermeable till substratum, 3) heavy seasonal rainfall resulting in increased pore water pressure.

Paeth, R.C., M.E. Harward, E.G. Knox, and C.T. Dryness, 1971, Factors affecting mass movement of four soils in the western Cascades of Oregon: Soil Science Society of America Proceedings, vol. 35, p. 943-947.
The purpose of the study was to determine why soil movements were more apt to occur with soils formed on greenish tuff and breccia than with soils formed on reddish tuff and breccia. The results indicated that soils prone to slope failure included high amounts of smectite clay, moderate amounts of free iron oxide, with an absence of kaolin. The more stable soils were characterized by kaolin, more clorite, less smectite, and greater amounts of free iron oxide.

Patric, J.H. and D.N. Swanston, 1968, Hydrology of a slide-prone glacial till soil in southeast Alaska: Journal of Forestry, vol. 66, p. 62-66.
A soil which is included in the soil series that produces much of Alaska's timber was studied so as to obtain slide information. The results indicated that the Karta soil must be saturated to cause debris avalanches.

Swanson, F.J. and C.T. Dryness, 1975, Impact of clear-cutting and road construction on soil erosion by landslides in the western Cascade Range, Oregon: Geology, vol. 3, p. 393-396.
Results of a study conducted in the H.J. Experimental Forest indicate that landslide activity has increased due to logging and road construction.

Swanston, D.N., 1967, Debris avalanching in thin soils derived from bedrock: U.S. Forest Service, Res. Pap. PNW-64, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon, 7 p.
In southeast Alaska, many of the oversteepened slopes are not logged due to their poor timber quality. However, the author believes that in time these areas will be harvested and that the destruction of the rooting system will result in slides.

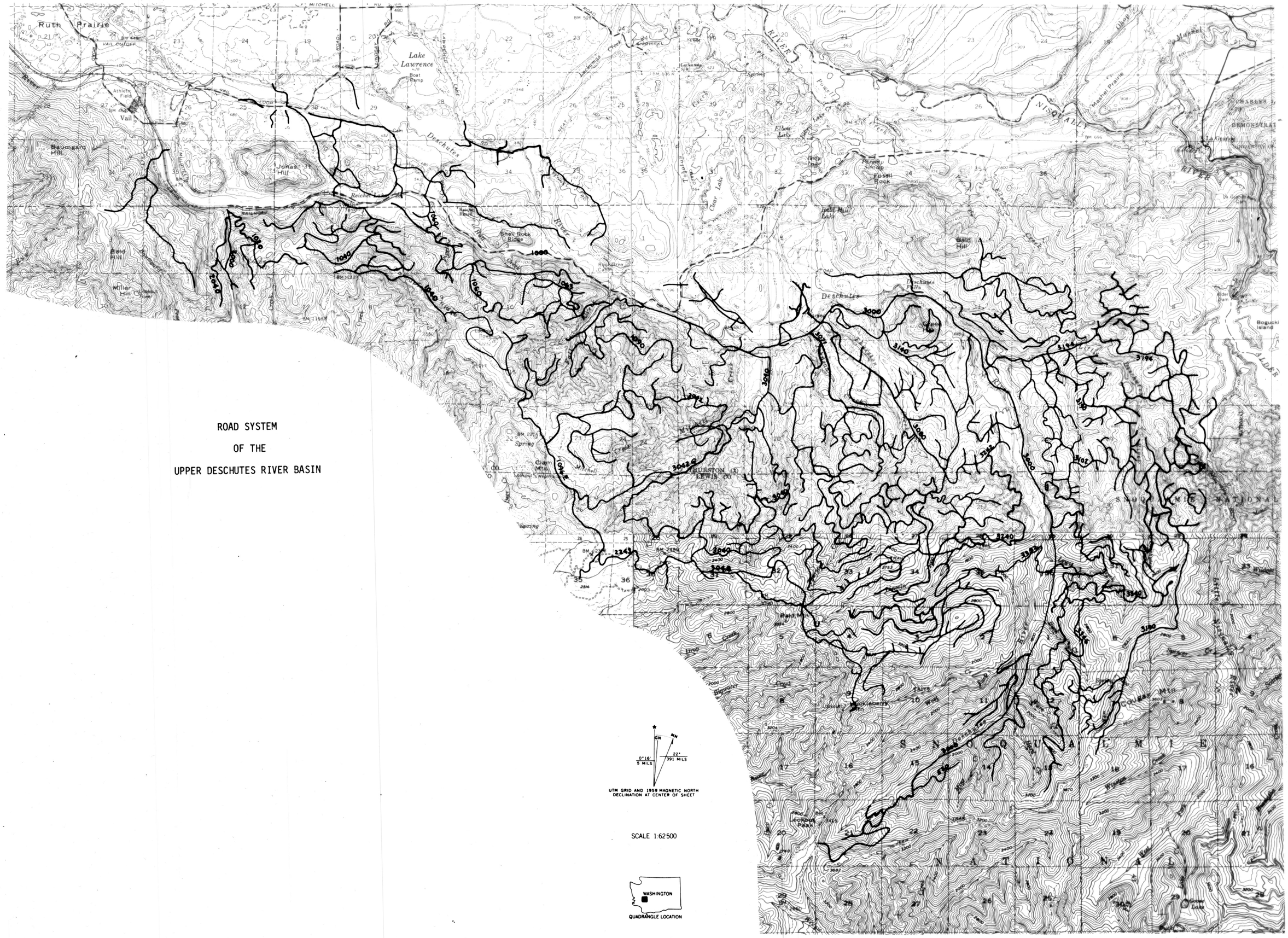
Swanston, D.N., 1967, Soil-water piezometry in a southeast Alaska landslide area: U.S. Forest Service, Res. Pap. PNW-68, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon, 17 p.
Increased porewater pressure increases downslope movement of glacial till soils.

Swanston, D.N., 1969, Mass wasting in coastal Alaska: U.S. Forest Service, Res. Pap. PNW-83, Pacific Northwest Forest and Range Experiment Station, Juneau, Alaska, 15 p.
Mass movements of all types are predominant in southeast Alaska. The main factors which promote these movements are steep slopes and excessive soil-water content. Destruction of both stabilizing root systems and the natural slope equilibrium are also important factors in the cause of mass movements.

Swanston, D.N., 1971, Judging impact and damage of timber harvesting to forest soils in mountainous regions of western North America: Western Reforestation Coordinating Committee, Western Forestry and Conservation Assoc., Portland, Oregon, 7 p. (see recognition, interpretation, and classification section).
Factors which influence slope stability and techniques for identification and control of unstable slopes are discussed in this article.

Swanston, D.N., 1974, Slope stability problems associated with timber harvesting in mountainous regions of the western United States: U.S. Forest Service, General Technical Report PNW-21, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon, 14 p.
The mass soil movements in this area can be divided into two groups: 1) debris slides, avalanches, flows, and torrents, and 2) slumps, creep, and earthflow. The main factors which promote these movements are: 1) steep slopes, 2) high soil moisture/heavy rainfall, and obliteration of natural mechanical support.

Thomson, S., 1971, Analysis of a failed slope: Canadian Geotechnical Journal, vol. 8, p. 596-599. A post-mortem analysis of a landslide which occurred in upper Cretaceous clay shale (in western Canada) is reported. The cohesion was initially lost along a lower part of the failure surface, and since the major slide movement, the cohesion has tended to zero over the entire slide surface.



ROAD SYSTEM

OF THE

UPPER DESCHUTES RIVER BASIN

UTM GRID AND 1959 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET

SCALE 1:62500

QUADRANGLE LOCATION

FOREST SLOPE STABILITY PILOT PROJECT,
UPPER DESCHUTES RIVER, WASHINGTON

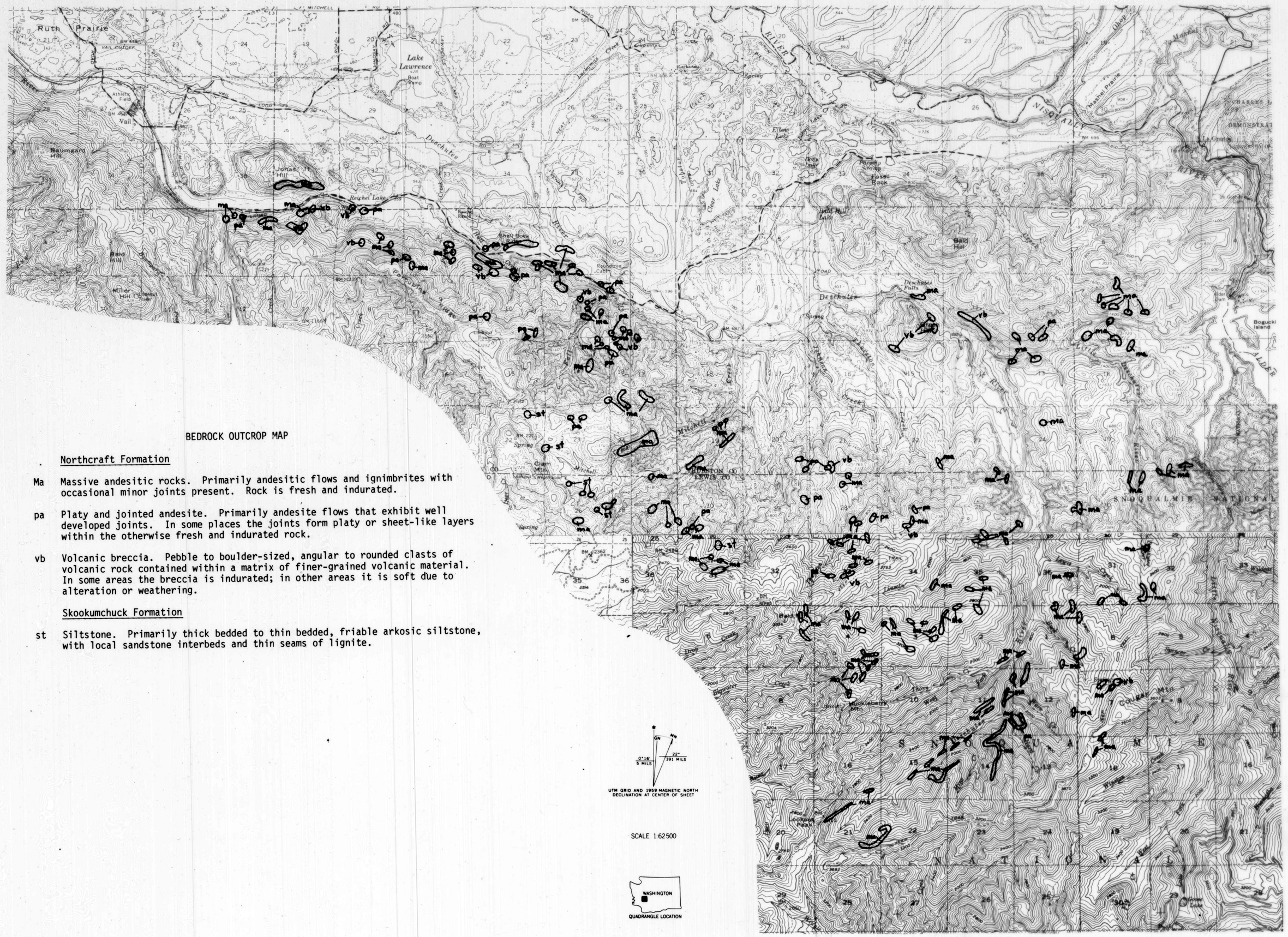
by

Gerald W. Thorsen and Kurt L. Othberg

Washington Department of Natural Resources
Division of Geology and Earth Resources

1978

Plate 1



BEDROCK OUTCROP MAP

Northcraft Formation

Ma Massive andesitic rocks. Primarily andesitic flows and ignimbrites with occasional minor joints present. Rock is fresh and indurated.

pa Platy and jointed andesite. Primarily andesite flows that exhibit well developed joints. In some places the joints form platy or sheet-like layers within the otherwise fresh and indurated rock.

vb Volcanic breccia. Pebble to boulder-sized, angular to rounded clasts of volcanic rock contained within a matrix of finer-grained volcanic material. In some areas the breccia is indurated; in other areas it is soft due to alteration or weathering.

Skookumchuck Formation

st Siltstone. Primarily thick bedded to thin bedded, friable arkosic siltstone, with local sandstone interbeds and thin seams of lignite.

FOREST SLOPE STABILITY PILOT PROJECT,
UPPER DESCHUTES RIVER, WASHINGTON

by

Gerald W. Thorsen and Kurt L. Othberg

Washington Department of Natural Resources
Division of Geology and Earth Resources

1978

Plate 2