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Landslide Inventory and Susceptibility Mapping of the Upper Canyon Creek Basin, Cascade Range, Skamania County, Washington

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THESIS APPROVAL

The abstract and thesis of Lawrence P. Growney for the Master of Science in Geology were presented October 17, 1994, and accepted by the thesis committee and department.

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ABSTRACT

An abstract of the thesis of Lawrence P. Growney for the Master of Science in Geology presented October 17, 1994.

Title: Landslide inventory and susceptibility mapping of the upper Canyon Creek Basin, Cascade Range, Skamania County, Washington

Contact relations, and bedrock and overburden characteristics for approximately 8100 ha of the upper Canyon Creek basin, Skamania County, Washington, have been assessed in order to determine the causes and extent of failures and to assign slope failure susceptibilities to the area. The study area is located in the western Cascade Range on land administered by the Gifford Pinchot National Forest. Clear-cutting over the past 30 years has impacted between 50% to 80% of the study area.

The total surface area occupied by failure deposits (198.6 ha) is less than 2.5% of the study area. Failures occur by one of seven processes, in decreasing order of abundance: rockfall (53.6%), rock avalanche (25.3%), slumps (15.6%), streambank failures (3.4%), soil and debris slips (1%), snow avalanches (debris falls) (1%), and translational slides (0.1%).

Integrity of the bedrock is primarily influenced by jointing characteristics, in particular: dilation, orientation and continuity. Groundwater is an important constituent in the failure of fragmental igneous bedrock, but has very little impact in inducing failure in compact igneous bedrock. Areas underlain by fragmental igneous bedrock have a proportionally greater number of translational and rotational failures. With increasing compact igneous bedrock content, small volume rockfall failures become more predominant.

Sixteen to twenty percent of the roadbed surfaces in the study area are experiencing some type of failure. Up to 99 percent of roadbed failures are confined to the roadfill prism. Failure due to degradation of the subgrade is rarely observed. Arcuate and sliver-like cracks, offsets, sinkholes, concentrations of potholes, broad slumps and chute formation in the roadfill are indicators of failure. Ditches without culverts, or with poorly placed, damaged or leaking culverts, result in oversaturation and piping within the fill which may lead to failure of the road.

The potential for slope failure is assigned a rating of low, moderate or high. These ratings are based on a qualitative assessment of the impact of various factors on the factor of safety, through their ability to reduce the cohesion and friction of affected rock and soil masses. Low susceptibility areas cover approximately 10 percent of the area (810 ha). Slopes are less than 3.5 degrees. Nearly 70 percent of the study area can be classified as moderately susceptable (5670 ha). Slopes in these areas range up to the natural angle of repose. The high susceptibility category covers areas with near vertical slopes, continuous rockfall, previous failures or strong indications of potential failure. These areas cover about 20 percent of the basin (1620 ha) and include areas of actual failure and adjacent areas which have not failed but possess similar bedrock, cultural and groundwater characteristics.

LANDSLIDE INVENTORY AND SUSCEPTIBILITY MAPPING OF THE UPPER CANYON CREEK BASIN, CASCADE RANGE, SKAMANIA COUNTY, WASHINGTON

by

LAWRENCE P. GROWNEY

A thesis submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE
in
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Acknowledgments

I wish to thank Stan Ross of the Washington Department of Natural Resources, Glenn Schneider, Steve Lowell and Lynn Moses of the Washington State Department of Transportation, Connie Manson and Tim Walsh of the Washington Division of Geology and Earth Resources and Helga Christensen and Robin DeJong of the Gifford Pinchot National Forest for their assistance in obtaining technical information, aerial photographs and geotechnical studies. I wish to acknowledge Dr. Scott Burns, Dr. Ken Cruikshank, and Dr. Paul Hammond of Portland State University, Dr. Terry West of Purdue University for enlightening discussions and advice. Special thanks to Dr. Abdul Shakoor of Kent State University for access to his personal research in the area of engineering geology and to Dallas Hughes and Jim Chamberlin of the Gifford Pinchot National Forest for their tremendous guidance, assistance and field support.

Chapter 1.
Introduction

Canyon Creek, a fourth order stream located in the northwest corner of Skamania County, Washington (45°55'N, 122°W), drains an area of approximately 17,415 ha (43,000 acres) (Fig. 1). The basin occurs in materials formed by Tertiary volcanism and sculpted by Quaternary glaciation, which, in turn, have been modified by post-glacial volcanism and stream incision. The study area (Fig. 2) covers approximately 8100 ha (20,000 acres), located in the upper Canyon Creek watershed, on lands administered by the Gifford Pinchot National Forest (GPNF) and is accessed from both the east and west by Forest Service Road 54. In addition to Canyon Creek, five major tributaries occur within the study area; these are, from west to east: Big Rock Creek, Sorehead Creek, Jake's Creek, Pelvy Creek and Puny Creek. Hackamore Creek is a major tributary of Puny Creek and also lies within the study area. These major tributaries drain areas ranging in size from 810 to 2430 ha (2000 to 6000 acres) and occupy individual glacial valleys.

As a result of extensive logging (>50% clearcut, basinwide) and associated road construction over the past 30 years, the GPNF has undertaken an integrated resource assessment (IRA) of the watershed to determine what impacts clear-cutting and road construction have had on the forest ecosystem. All aspects affecting the vitality of the forest are being considered including: stream quality, fisheries habitat, wildlife habitat, recreation, reforestation, and hillside and roadbed stability.

This study is designed to assess the geologic factor, specifically, to characterize the factors influencing the stability of the bedrock and overburden and the competence of roadfill materials. This study documents the extent of existing slope failures, assigns a

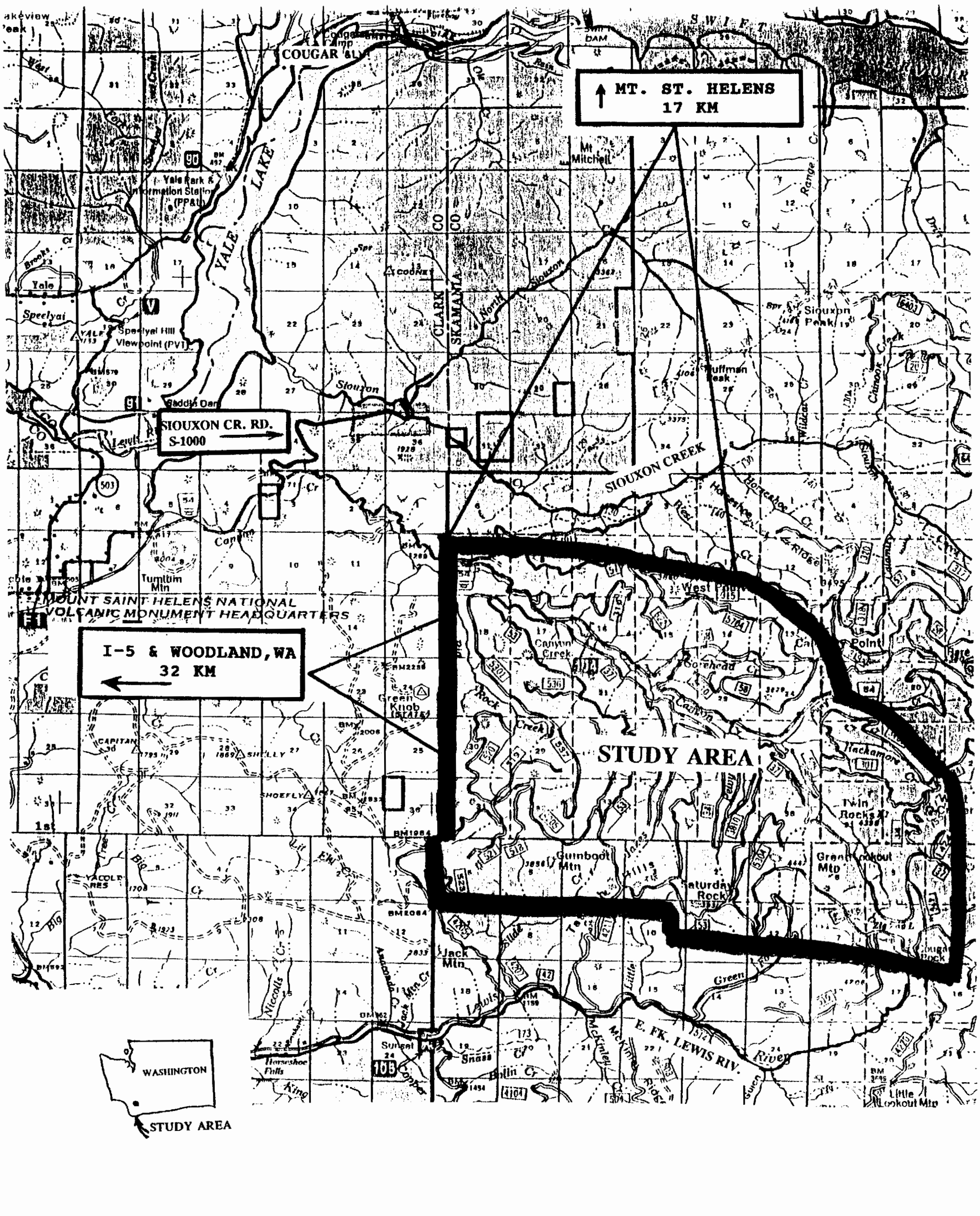

Figure 1. The Canyon Creek drainage basin and surrounding environs.

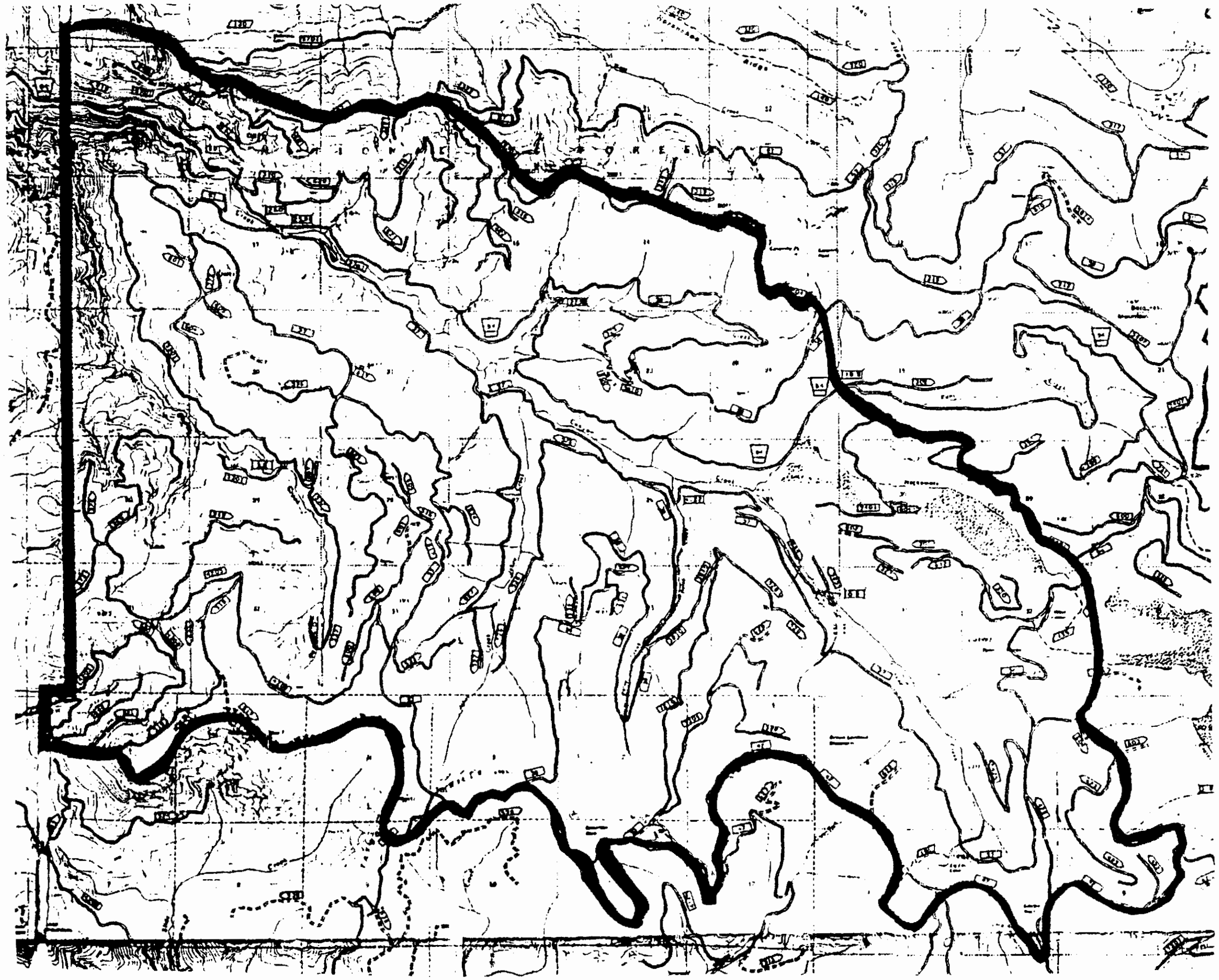

Figure 2. Outline of the Upper Canyon Creek study area. The Gifford Pinchot National Forest boundary forms the western edge of the study area.

slope susceptibility potential to the drainage basin, creates a generalized geologic map, and identifies the type and extent of Quaternary deposits.

Rainfall in the Canyon Creek drainage basin varies dramatically from 152 cm to 254 cm per year depending on location and elevation. During the winter months, precipitation generally falls as snow, with a maximum on-ground depth as great as 406 cm (WSDOT, 1992a). Elevations within the study area range from 308 m to 1366 m, with relief of up to 558 m/km. As a result of abundant snowfall and extreme relief, snow avalanches are a threat in localized areas during the winter months.

Mean average summer temperatures range from 14 to 17^{o}C and the mean winter temperatures range from -1^{o} to 3^{o}C. July, August and September are generally the driest months of the year (WSDOT, 1992a). The climatic conditions within the study area vary from montane to subalpine. Vegetation is dominantly coniferous forest (Douglas fir, hemlock, western red cedar, Pacific silver fir, noble fir, grand fir and true fir), with deciduous regrowth, primarily larch, associated with logged areas. Undergrowth plants include: vine maple, beargrass, ferns, huckleberry, wild blueberry and wildflowers (Wade and others, 1992).

Chapter 2.
Methodology

This slope susceptibility study is based upon the application and interpretation of data obtained from the Washington Department of Transportation, the Washington Department of Natural Resources, the Washington Division of Geology and Earth Resources and the Gifford Pinchot National Forest (GPNF). These data were verified and amended during the course of reconnaissance work conducted between the months of June and September, 1993. This investigation has consisted of: 1) use of aerial photography to identify possible fault trends and slope failures; 2) field mapping noting contact relations, failure locations, seeps and overburden deposits; and 3) field, laboratory and literature analysis of soil and rock properties.

This study examines a wide range of surficial factors such as bedrock characteristics, types of overburden, soil characteristics, glaciation, alteration, weathering, groundwater behavior, roadfill quality and deforestation, in order to characterize the impact of each on stability. The susceptibility of a hillside to fail has been subjectively based on identification and assessment of several factors found to influence the cohesion and friction of rock and soil masses. Observations made during the course of field work have been augmented, and in many cases confirmed, through an assessment of subsurface conditions as determined from GPNF and independent geotechnical studies.

The geologic map (Plate 1) outlines generalized areas based on contact relationships only. Rocks have been grouped into the following four broad age classifications, from youngest to oldest: Quaternary rocks, post-Silver Star Tertiary rocks, Silver Star equivalent diorites and pre-Silver Star Tertiary rocks. Areas identified as consisting of Quaternary rock have been taken from Polivka (1984) and occur in the Hackamore Creek tributary. Rocks identified as being pre-Silver Star Tertiary in age have been so designated based on their intrusion by dioritic rock presumed to be equivalent in age to the 19.6 ± .7 Ma (Felts, 1939) Silver Star pluton located to the southwest of the field area. Post-Silver Star Tertiary rocks lack this intrusive relationship with the diorite. Examination of bedrock has been conducted with a 20X hand lens. Throughout this thesis, the volcanic products will be referred to as either compact igneous (flows and intrusions) or fragmental igneous (pyroclastic and lahars). A definition of the rock types and classifications used in this study can be found in Table 1.

The units shown on the Quaternary deposits map (Plate 2) reflect the type of overburden deposit: colluvial, fluvial, glacial (undifferentiated), diamicton and residual. Bedrock and residual soil have been combined since they can be found in close association in the field. This map has been compiled on the basis of field observations.

The landslide inventory map (Plate 3) identifies areas of failure which have been located in the field or determined from aerial photographs and confirmed by ground truthing. To insure complete coverage, all roadbeds were traversed and examined over their entire length, the majority of hillsides were traversed and area-wide reconnaissance was frequently conducted from the highest points to insure that all areas of suspect terrain were identified. Areas of clearcutting were noted in the field and their areas calculated by approximation on the topographic map at a scale of 1:24,000. This study has used a modification of the mass movement features characterized by Varnes (1978) in the identification of failures. An illustration of the types of failures observed in the study area is given in Figure 3. All failure locations, whether active or inactive, were examined and mapped. These locations can be found on the landslide inventory map, Plate 3.

Table 1. Description and classification of rock types identified in the study area

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*Compact Igneous - Intrusive and flow rocks of any composition. These include:

basalt[1], basaltic andesite[3], andesite[1], dacite[1], rhyolite[1], gabbro[1], diorite[1], monzonite[1], and syenite[1]

*Fragmental igneous - Fragmental rock of pyroclastic origin. These include:

Tuff[2] = consolidated pyroclastic rock composed of fragments less than or equal to 4 mm in diameter.

Lapilli tuff[3] = a rock composed predominantly of pebble-sized fragments between 2 mm and 64 mm in diameter.

Tuff-breccia[3] = a rock composed of of angular to rounded chunks of rock greater than 64 mm in diameter in a matrix of fine-grained material less than 2 mm in diameter.

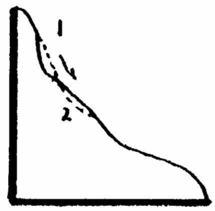
Lahars[2] = deposits consisting wholly or largely of pyroclastic fragments that have moved down the flanks of volcanoes in processes such as landslides or mudflows.

* P.E. Hammond, personal communication, 1994
(1) IUGS classification (Streckeisen, 1979)
(2) Thornton, 1982
(3) Williams and others, 1982

Three categories of failure susceptibility are used in this study: low, moderate and high and are identified on the failure susceptibility map (Plate 4). The extent and characterization of each category were accomplished during the course of field work through a qualitative assessment of ten factors found to reduce stability.

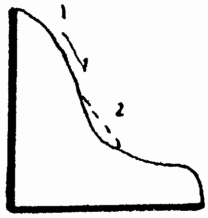
Slip Failure:

A very shallow slide parallel to the slope. The slip plane lies above the bedrock at some depth within the overburden.



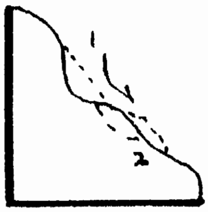
Translational Slide:

A failure along a plane of weakness within a slope such as a fracture, bedding plane or clay parting.



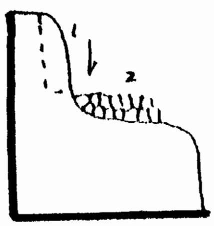
Slump/Flow:

In-place morphology similar in appearance to rotational failures. Occurs entirely within unconsolidated deposits. Lower portion of the displaced mass is characterized by flow morphology.



Rock Avalanche:

A failure in bedrock characterized by a joint network which is essentially continuous down to the potential failure surface resulting in failure of the entire mass above that point in one, or a very small number, of major events.



Rockfall:

Mechanical disaggregation from fractured or jointed bedrock and erosional disaggregation from unconsolidated deposits. Talus is created over a long period of time through continuous, small-volume events.

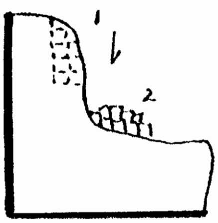


Figure 3. Illustration of the types of common failures observed in the Upper Canyon Creek study area (after Varnes, 1978).

The maps which identify seep locations (Plate 5) and roadfill failures (Plate 6) have been compiled on the basis of observations made during the course of field work. The roadfill failure and hazard locations map has been designed to identify: 1) failure locations, characterized by slumps, offset and cracks, 2) potential failure locations, based on pothole frequency, sinkholes, tilting or pistol-butt trees or persistent wetness and 3) areas with a high potential for road-blocking rockfall events.

Due to budgetary and technical constraints, this study has developed a failure susceptibility database (map), on a non-quantitative level, which should maintain its integrity when used in association with LISA-generated data. This has been done by qualitatively assessing the influence of factors observed in the field on the components of the LISA program. LISA is designed to model slopes in natural, clearcut and thinned situations (Wooten, 1988) through the calculation of the factor of safety (FS) using a modified form of the infinite slope equation taken from Prellwitz and others (1994):

$$FS = \frac{C_r + C_s + [q_0 + \gamma d + (\gamma_{sat} - \gamma_w - \gamma)d_w]\cos^2\alpha \tan\phi}{[q_0 + \gamma d + (\gamma_{sat} - \gamma)d_w]\sin\alpha \cos\alpha}$$

where:

C_r = tree root strength expressed as cohesion, psf
C_s = effective soil cohesion, psf
d = total soil depth to soil/rock contact, ft
d_w = height of phreatic surface above soil/rock contact, ft
q_0 = tree surcharge, psf
ϕ = effective soil angle of internal friction, degrees
γ = moist soil unit weight, pcf
γ_{sat} = saturated soil unit weight, pcf
γ_w = unit weight of water, pcf
α = slope of the ground surface, phreatic surface and failure surface (soil/rock contact), degrees

FS = factor of safety

Atterberg Limits have been calculated as per the procedure outlined in ASTM D423 and D424 (ASTM, 1983). These tests are performed on the cohesive portion of the soil. This includes all material which passes through a standard U.S. #40 sieve (<0.42 mm diameter particle size) and includes fine-grained sand, silt and clay.

Particle size analysis for grain-size distribution has been run in accordance with ASTM D422 (ASTM, 1983) and AASHTO T88 (AASTHO, 1990) procedures. Due to the extremely coarse-textured nature of the overburden deposits, only that portion of the deposit passing the #4 sieve (<4.75 mm) was analyzed. A visual approximation of this fraction versus the coarser fraction (>4.75mm) has been made in order to classify the material under the Unified Soil Classification system and assess soil mass properties.

Classification of bedrock characteristics in this thesis has been made using the Unified Rock Classification System (URCS) of Williamson (1978) (Fig. 4). The URCS provides a formalized, reproducible, reliable and rapid method of communicating detailed information about rock conditions that establish basic engineering properties of the rock and deals with four fundamental physical properties: 1) degree of weathering, 2) strength, 3) type of discontinuities and 4) density.

Field inspections and consultations with GPNF silviculturists were conducted in order to get an idea of tree age based on trunk girth. A period of 30 years was chosen as the cutoff in identifying the visual impact of logging on site stability. Areas of clearcutting were delineated on field maps during the course of field work. These areas were then planimetrically determined upon return from the field.

Degree of Weathering

Micro Fresh State (MFS) unaltered under 10X magnification A	Visually Fresh State (VFS) unaltered in hand sample B	Stained State (STS) C	Partly Decomposed State (PDS) > gravel size D	Completely Decomposed State (CDS) < sand size E

Estimated Strength

Elastic "rebound quality" (RQ) >103 MPa A	Tensional "pit quality" (PQ) 55-103 MPa B	Compression "dent quality" (DQ) 21-55 MPa C	Shears "crater quality" (CQ) 7-21 MPa D	Friable "moldable quality" (MQ) <7 MPa E

Discontinuities

Solid (random breakage) (SRB) A	Solid (preferred breakage) (SBP) B	Solid (latent planes of separation) (LPS) C	Nonintersecting open planes 2-D D	Intersecting open planes 3-D E

Unit Weight

>2.55 g/cc A	2.40-2.55 g/cc B	2.25-2.40 g/cc C	2.10-2.25 g/cc D	<2.10 g/cc E

Designation Notation

A-E weathering	A-E strength	A-E discontinuities	A-E weight

Example

A rock designated "BAEB" would have the following qualities:

- B - examined with the naked eye, the sample appears fresh
- A - when struck with a 1 lb. ballpeen hammer, no mark is made, approximate unconfined compressive strength >103 MPa
- E - the rockmass discontinuities intersect, forming blocks
- B - the rock has a density between 2.40 and 2.55 g/cc

Figure 4. Unified Rock Classification System (URCS) - Williamson, 1978

Chapter 3.
Geologic History

Previous work

Little direct work has been conducted in the upper basin. Phillips and others (1986) have provided an age date of 28.1± 2.7 Ma for a lava flow located at the National Forest boundary along Forest Service (FS) Road 54. On the south side of Gumboot Mountain in Sec. 31, T.5 N., R.5 E., also at the west end of the study area, fragmental igneous deposits are considered to be Oligocene in age on the basis of fossil flora (Phillips, 1987). Along the divide with the Wind River on the east, Polivka (1984) has documented Quaternary dates for numerous basalt and andesite flows and domes. Weaver and Smith (1981, 1983) have offered data suggesting that the active, right lateral strike-slip Mt. St. Helens Seismic Zone runs northwesterly through the central and eastern portions of the area. Mundorff (1964, 1984) and Mundorff and Eggers (1988) have provided compelling evidence for the presence of a northeasterly trending fault zone, as well as evidence for widespread glacial activity within the basin.

Volcanic Rocks

The upper Canyon Creek area is characterized by volcanic rocks dating from Oligocene to the Holocene. Formations identified by previous workers to occur in this area of the southwest Washington Cascades are, from youngest to oldest: Quaternary rocks of West Crater and Hackamore Creek (Polivka, 1984), upper Skamania andesite (Felts, 1939), Silver Star pluton equivalent dioritic intrusions (Felts, 1939), lower Skamania andesite (Felts, 1939) and the Ohanapecosh Formation (Wise, 1970). This succession is illustrated in Fig. 5.

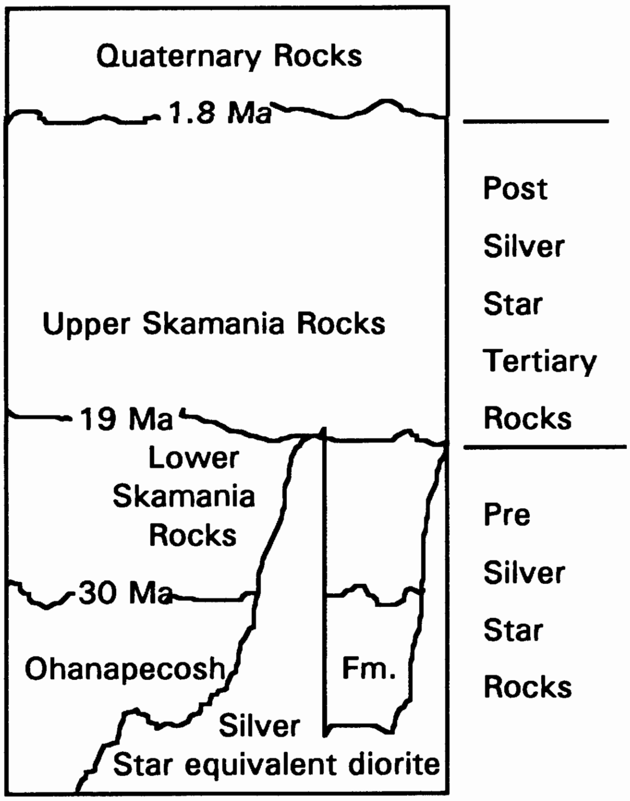


Figure 5. Stratigraphic relations found in the Canyon Creek field area.
Age date of 19 Ma taken from Felts (1939) as approximate age of Silver Star intrusion.

Lithologic relationships within the basin suggest a volcanic history characterized by initial basaltic/andesitic volcanism followed by intrusion of diorite and dacite, followed by predominantly andesitic eruptive activity as shown in Table 2. Undifferentiated Tertiary intrusive rocks include all post-Ohanapecosh age intrusive basaltic and andesitic rocks of Tertiary age. These rocks occur as plugs, sheeted dike complexes and individual dikes. The length of individual dikes ranges from outcrop exposure size to ridge-forming features up to 1.6 km in length. Textures are predominantly porphyritic and diabasic.

Table 2. Prevalent stratigraphic lithology by geologic association - Canyon Creek field area.

Quaternary rocks - andesite
Upper Skamania andesite - andesite
Silver Star Intrusives - diorite
Lower Skamania Rocks - andesite
Undifferentiated Tertiary Rocks - andesite and basalt
Ohanapecosh Fm. - basalt and andesite

Quaternary Rocks
[The information in this section has been condensed from Polivka (1984).]

Numerous monogenetic Quaternary volcanic centers, which range in age from about 360,000 to about 2000 years before present, occur in the headwater region of the Canyon Creek drainage. The rocks are primarily phyric olivine and olivine-pyroxene basalts and andesites, displaying blocky and /or platy jointing, with plagioclase phenocrysts to 3 mm and colors ranging from light gray to nearly black. The products produced by these Quaternary volcanoes are primarily lava flows, tephra and small scoria and andesite cones and domes. They display very minor, to no effects of regional propylitic alteration. The andesitic dome of West Crater is located at the head of Hackamore Creek. It is composed of pyroxene hornblende andesite. Andesite lava flows from West Crater moved both east and west from the base of the dome, partially filling glaciated valleys.

Silver Star Pluton

[The information in this section has been condensed from Howe (1938); Felts (1939); Heath (1966); Power and others (1981) and Evarts and others (1987).]

The Silver Star pluton is a north-northeast trending body approximately 16 km long and 3.2 to 4.8 km wide. It is the southernmost of a northeast-trending belt of large, generally intermediate composition intrusions stretching from near the Columbia River to north of Mount Rainier. These plutons share a dominantly early Miocene age and shallow emplacement depths.

Based on intrusive relations with the Skamania andesite and K-Ar age dates of 19.0 and 19.6 $\pm$ .7 Ma, the pluton is early Miocene. It is a medium- to fine-grained leucocratic granodiorite grading into subordinate amounts of augite diorite and quartz-diorite at and near its borders. Intermediate between the mafic and true granodiorite is a diorite more similar to the mafic diorite but containing five to twelve percent quartz and a little orthoclase.

Aplite dikes and hydrothermal replacement by quartz, tourmaline and sericite are locally developed within the intrusive body. The earlier-formed dikes contain silica, orthoclase, hornblende and biotite, while the later-formed dikes contain mainly silica and pyrite, with minor chalcopyrite. Xenoliths of intruded rock occur within the pluton up to more than 61 m from its contact with the country rock. Other hydrothermal effects, both within the intrusive and the wall rocks consist of epithermal quartz-sulfide veins; quartz-tourmaline-sericite replacement in shatter zones and as small veinlets; and post emplacement silicification and orthoclasization.

Skamania Rocks
[The information in this section has been condensed from Howe (1938); Felts (1939); Heath (1966) and Phillips (1987).]

Rocks of the Skamania andesite series range in age from late Oligocene to early Miocene. The lower two-thirds of this series has been identified as a gray to greenish-gray porphyritic andesite or andesite porphyry with interbedded flow breccia and tuff. Plagioclase phenocrysts range in size from 1 to 6 mm. They are blocky and tend to form glomerocrysts. The upper one-third of the series is believed to have accumulated after intrusion of the Silver Star pluton. It differs in dip and texture from rocks of the lower two-thirds and shows no effects of hydrothermal alteration. These rocks tend to be more vesicular and glassy and nearly fresh when contrasted with the propylitized lower rocks. They are characterized by rare quartz and carbonate veins and minor vesicle-filling chalcedony.

The Silver Star pluton intruded the lower two-thirds of this series producing contact metamorphic phases of varying extent within the host rock. Hornfelsed andesite consisting of sugary grained, recrystallized feldspar, augite, magnetite and quartz occurs at the contact with the pluton, with the intensity of alteration decreasing dramatically to a propylitization of the andesite anywhere from one meter to over 60 m from the contact. This propylitic alteration involves, chiefly, the development of epidote, chlorite, pyrite and quartz. Supergene alteration has altered the pyrite and chalcopyrite to carbonates and sulfate minerals, among them malachite and brochantite.

Undifferentiated Tertiary Intrusive Rocks
[The information in this section has been condensed from Polivka (1984).]

Fine-grained basaltic to andesitic dikes, plugs and sills of middle to late Tertiary age cut the Ohanapecosh Formation. Most of these intrusions are gray, grayish green or brown and contain anhedral to euhedral phenocrysts of plagioclase, augite or hypersthene in a fine-grained diabasic to felty groundmass. The dikes cannot be traced beyond their outcrop exposure due to forest cover and surficial deposits, and the plugs are small and difficult to distinguish from larger dikes.

Ohanapecosh Formation

[The information in this section has been condensed from Wise (1970); Frizzell and Vance (1983); Polivka (1984) and Phillips (1987).]

The Ohanapecosh Formation consists of basaltic and andesitic flows, dikes, sills, lahars and flow breccias. Flow breccias and fragmental igneous units contain 20 to 50 percent subangular to rounded clasts from several millimeters up to 25 cm in diameter. Outcrop colors vary from light blue green to light olive gray, while clast colors range from reddish brown to blue green to black. Lavas are medium to dark gray to olive black, phyric basalts to mafic andesites with 5 to 10 percent subhedral phenocrysts of plagioclase from 0.2 to 4 mm. All rocks exhibit effects of low-grade regional metamorphism, to zeolite and pumpellyite facies, and consist of an assemblage including one or more of the following: clay minerals, calcite, quartz, actinolite, epidote, chlorite, crystobalite and several zeolites.

Glacial History

Regional Glaciation

[The information in this section is condensed from Thayer (1939); Crandell (1965); Sharp (1972); Carver (1972); Scott (1977) and Williamson (1985).]

Glaciers in the Western Cascades consisted of two main types: tongues from the summit ice fields and local cirque and small valley glaciers on the higher ridges and peaks. At least three glacial episodes occurred in the late Pleistocene, the last during the Fraser glaciation between 25,000 and 10,000 years ago. During the earlier glaciations of the late Pleistocene, large valley glaciers and piedmont glaciers were fed by vast ice fields and ice caps in the Cascade Range of Oregon and Washington. Alpine glaciers were smaller during the Fraser glaciation, although ice fields still mantled much of the higher terrain.

In Washington, glaciation of the Cascade Range during Hayden Creek and Wingate Hill time (Table 3) is well-recorded in each of the valleys that head at Mount Rainier and includes two separate episodes. The tills deposited during these two successive episodes are progressively more deeply oxidized to depths of 2 m and 3-4 m, respectively. The altitude of the regional snowline in the Cascade Range northwest of Mount Rainier during the younger glacial episode was probably 900-1100 m.

During the Evans Creek Stade of the Fraser Glaciation, the Cascade Range south of the latitude of Seattle was occupied, principally, by cirque and valley glaciers, although ice fields existed along the crest of the range southeast of Mount Rainier. The regional snowline in the mountains around Mount Rainier was probably between 1300 and 1700 m. Till of Evans Creek age is generally oxidized to a depth of one meter, and stones in the profile are unweathered. During the Neoglaciation, cirques at altitudes of 2000 m and higher were reoccupied by glaciers, suggesting a regional snowline 300 to 700 meters higher than that of Evans Creek time.

Table 3. Quaternary glacial chronology.

Cascade Range		Cascade Range	
Washington Crandell and Miller (1974)	Northern OR. Scott (1977)	Southern OR Carver (1972)	Age (ybp)
Garda Drift	Jefferson Park	Neoglaciation II	
			2000
Burroughs Mt. Drift		Neoglaciation I	
			6700
			8000
McNeeley Drift	Canyon Creek	Zephyr Lake Drift	
			12500
Vashon Drift			
			13000
Evans Creek Drift	Suttle Lake	Waban Drift	{Fraser Glaciation}
			35000
Hayden Creek Drift (Amboy Drift)	Jack Creek	Varney Creek Drift	
			90000
			130000
Wingate Hill Drift	Abbott Butte	Moss Creek Till	

Local Glaciation

[The information in this section has been condensed from Mundorff (1964); Crandell and Miller (1974); Hammond (1980); Mundorff (1984) and Mundorff and Eggers (1988).]

The Canyon Creek basin contains glacial, glacio-fluvial and glacio-lacustrine deposits. During pre-Fraser time, in the early late Pleistocene, lobes of ice are believed to have extended down the Lewis River nearly to Woodland, Washington and spread south nearly to Battleground, Washington. The glacier would have been more than 24 km wide and nearly 400 meters thick where Canyon Creek flows into Chelatchie Prairie (Fig. 1).

North of the Canyon Creek basin, deposits associated with these pre-Fraser glaciers are referred to as Hayden Creek Drift. In the Canyon Creek basin, these deposits are referred to as Amboy Drift and appear to be restricted to elevations below about 600 meters. Younger, Fraser-age deposits occur above this level, having originated from cirques with an equilibrium line altitude ranging from 825 to 915 meters. Due to an almost complete lack of sorting, the till is dense and compact. The texture of the till varies, but is generally gravelly and bouldery, with boulders up to 2.5 m in diameter.

Structural and Tectonic Influences

[The information in this section has been condensed from Howe (1938); Felts (1939); Mundorff (1964, 1984); Heath (1966); Crandell and Miller (1974); Hammond (1980); Weaver and Smith (1981, 1983); Polivka (1984); Meyers et al (1985); Phillips (1987); Mundorff and Eggers (1988) and WSDOT (1992a, 1992b).]

The upper Canyon Creek basin may be part of a linear 80 km area of the southwest Washington Cascades transected by the north-northwest-Mt. St. Helens Seismic Zone. The seismic zone is interpreted to be an active, near vertical, right lateral strike slip fault zone characterized by the alignment of moderate magnitude (>2.5) earthquake locations (Fig. 6). The largest recorded earthquake had a Richter magnitude of 5.5 and was located 16.5 km northwest of Mt. St. Helens . The occurrence of crustal earthquakes (3.2 to 16 km deep) larger than 5.5 magnitude is credible within the seismic zone . Estimates of the maximum probable quake are in the range of 6.2 to 6.8.

While only one fault trend has been positively identified in the study area, many shear planes have been observed. These shear planes show little or no displacement and random orientations. They are characterized by either weathered gouge zones 15 to 30 cm wide or purple to green, very fine-grained angular fault breccia.

The area has been deformed into a series of broad northwest-striking folds which may have formed in a system exposed to northeast-southwest shortening and southeast-northwest extension. The age of folds and faults is difficult to determine but is believed to be Tertiary, as the Quaternary units are undeformed.

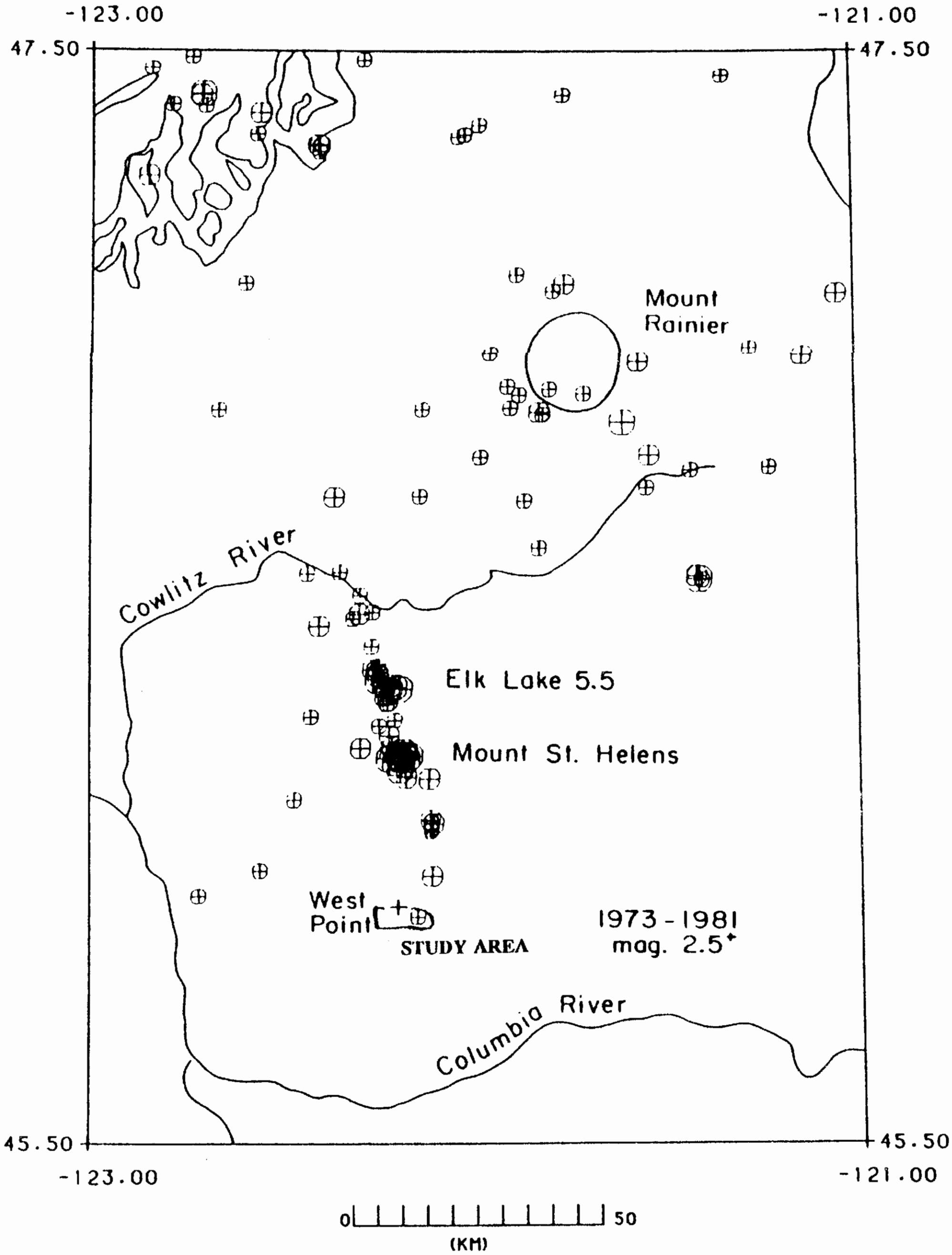


Figure 6. Map of interpreted epicenter locations suspected to lie within the Mount St. Helens Seismic Zone (Weaver and Smith, 1983). Note that the epicenter to the east of West Point corresponds to a strike-slip fault identified during this study and noted on the geologic map (Plate 1).

Chapter 4.
Previous geotechnical soil/rock analyses

Introduction

The following examples have been drawn from the geotechnical project files of the Washington Department of Natural Resources, Washington Department of Transportation and the Gifford Pinchot National Forest. These studies deal with analysis of actual or potential instability in settings and materials similar to those encountered in the Canyon Creek basin. As such, they have direct relevance to the problems faced during the course of field work for this study. Much of the Forest Service data has come from the study area and examines both the soil and the bedrock. These studies are of particular interest because they deal with subsurface exploration. Correlation of rock characteristics between the surface and the subsurface, on the basis of these core records, allows for an interpretation of rock mass stability to considerable depth, based solely upon the surficial characteristics documented during my field season.

Department of Natural Resources

[The information in this section has been condensed from Washington DNR Open-File Report (1991) and Growney (1993).]

S-1000 is a Washington State Department of Forestry logging access road which permits entry into the Siouxon Creek watershed which lies immediately to the north of the study area. A large slope failure 400 m long and 100 m wide resulted in 1.8 m of vertical offset in the roadbed at Milepost 3.2 along State Forest Road S-1000 in the NW NW 1/4 sec 35 T. 6 N. R. 4 E. (Fig. 1). Movement in 1980 is believed to have been the result of earthquake activity associated with the eruption of Mt. St. Helens. Aerial photographs suggest that sporadic movement has been occurring since the 1960's. The most recent incidence of movement, recorded in 1991, was associated with a heavy rainfall event.

In 1991, the Department of Natural Resources (DNR) requested the assistance of the GPNF geotechnical team to assess the subsurface characteristics of the failure. The resulting core logs located a potential failure surface at a depth of 4.5 to 5 m below the road surface, dipping out of the hillside. The critical groundwater level was found to be above this potential failure surface, resulting in an increase in the soil moisture content. The failure plane is associated with silty clay and clay derived from a weathered fragmental igneous unit which, in place, has a high moisture content and very low strength relative to adjacent units. Exposures in the cutslope reveal a soft, wet, fine-grained, completely decomposed layer that acts as a confining layer to groundwater flow. The unit exposed at the road (USCS: ML), consisted of 56% fines with a liquid limit of 45% and a plasticity index of 15%.

On the basis of visually observable parameters (slope, bedrock, weathering, seeps), the physical and hydrological conditions of this site are similar to those found at landslide locations identified in this study for the Canyon Creek basin. As expected, the consequence of these similarities on the stability of clearly disturbed areas within the study area has been equally destructive.

Washington Department of Transportation
Site Engineering Geology- State Route (SR) 504
[The information in this section has been condensed from WSDOT (1992a, 1992b).]

Geotechnical work conducted along the proposed route of the new Spirit Lake Highway (SR 504) has revealed many similarities with the Canyon Creek study area. The presence of intrusions, glacial deposits, mix of rock types and type and degree of alteration create hazardous and variable slope conditions in both instances. Failures are generally shallow slip features, although deeper failures do occur and evidence of past, large failures exist in both cases.

Bedrock geology consists of Oligocene and Miocene compact and fragmental igneous rocks including basalt, andesite, flow breccias, tuffs and agglomerates. These volcanic materials have been intruded by andesitic and basaltic dikes and sills. Much of the rock has undergone low grade metamorphism, and hydrothermal alteration occurs either within the groundmass or along discontinuities.

Overburden consists of tephra deposits, landslide deposits, colluvium and till. The observed thicknesses of colluvial deposits range from .67 m to 15.4 m, but most fall in the 1.6 to 3.2 m range. The colluvium generally consists of coarse gravel, cobbles and small boulders with a silty sand matrix. The larger clasts are commonly angular to subangular. Till deposits are composed of at least 50 percent subangular to subrounded cobbles and boulders and range in thickness from 0 to more than 12.3 m. Bedrock in much of the project area is overlain by less than 4.6 m of granular soil. Observations of groundwater suggest a very thin saturated zone at the overburden/bedrock contact, and another water level within the rockmass. Water within the rockmass is confined to discontinuities.

Gifford Pinchot National Forest Studies

A. Soil Characterization

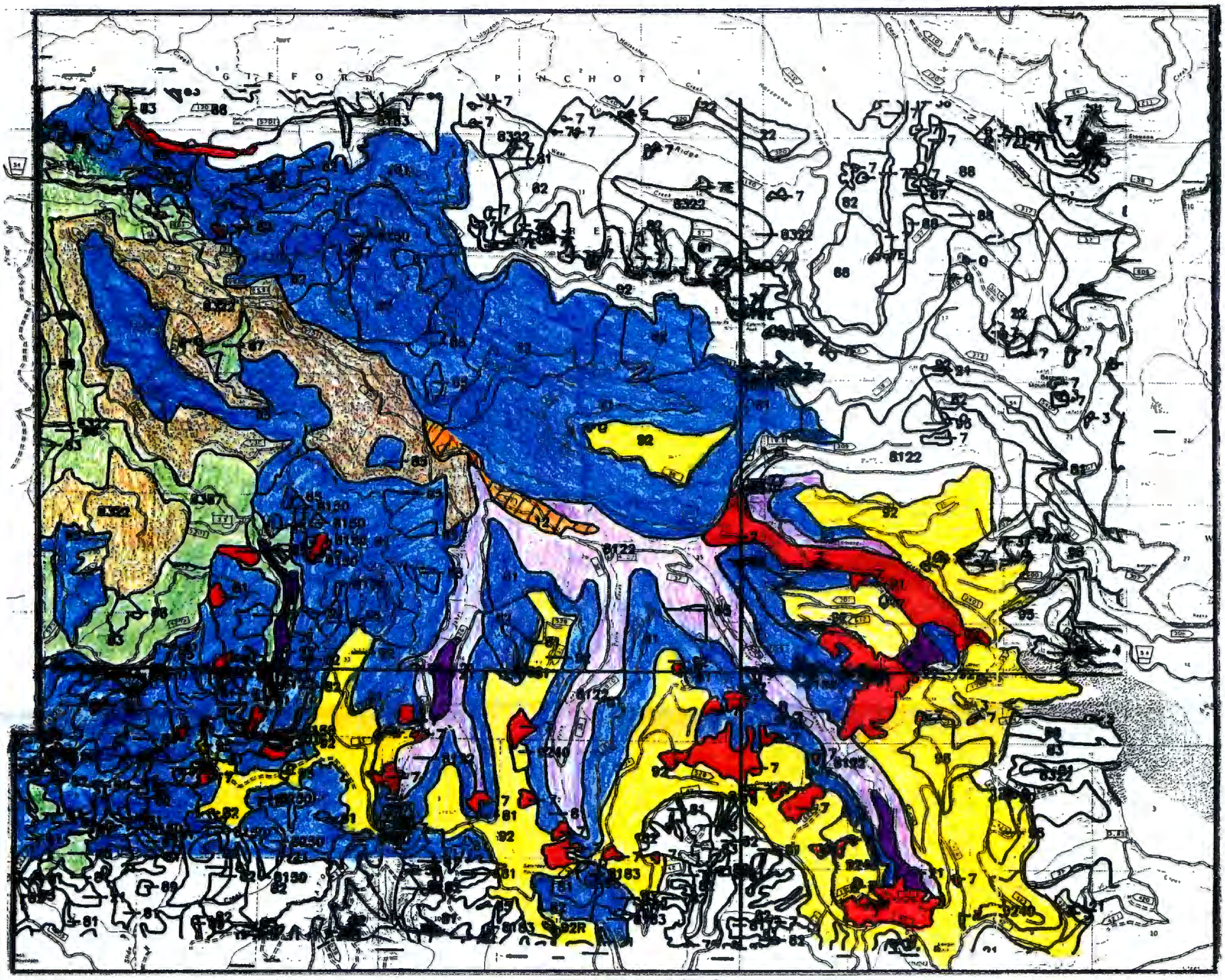
[The information in this section has been condensed from Carter (1981a,b); Polivka (1984); Phillips and others (1986); Phillips (1987) and Wade and others (1992).]

The Soil Resource Inventory (SRI) compiled by the Gifford Pinchot National Forest (GPNF) has identified seven primary soil types in the upper Canyon Creek area: 1) Andic Haplumbrepts, medial over clayey, mixed, frigid; 2) a combination of 60% (1) and 40% (5); 3) Typic Udivitrands, pumiceous over sandy skeletal; 4) a combination of 60% (6) and 40% (5); 5) Andic Haplumbrepts, medial over loamy, mixed, frigid; 6) Andic Haplumbrepts, medial over loamy skeletal, mixed, frigid and; 7) Andic Cryumbrepts, medial over loamy skeletal, mixed. These are generally, poorly developed, acidic and nutrient poor soils with a thick A horizon (> 15 cm) which still retain a predominant component of the original texture. The distribution of these soils is shown in Figure 7.

Soils listed under 1, 2, 3, 4 and 5 above are associated with stream bottoms and the lower valley slopes. The soil types listed under 1 and 2, are characterized by a higher clay content than the other soil types and bedrock composed of nearly 80% fragmental igneous rock. The soils listed under 1 and 5 occur as small, local, linear patches displaying an approximate 5:1 length to width ratio and are oriented along the stream bottom parallel to the axis of the glacial valley in which they occur.

The higher valley slopes, ridges and plateaus are characterized by a different association of soil types (6 and 7) characterized by a lesser amount of clay and a much higher percentage of exposed bedrock. The bedrock geology consists of aphanitic to porphyritic olivine and pyroxene basalt and andesite, diorite and fragmental igneous rock.

In two cases, the GPNF characterized the surface soil on the basis of data from cores recovered during quarry pit studies. The soil was found to be sandy (USCS: SM), or silty, sandy gravel (USCS: GM) with an estimated 20% fines, 30 to 40% sand and 40 to 50% gravel and larger. Depth to bedrock at the Sorehead Quarry Sec. 24 T. 5 N. R 5 E, was found to be 0.67 m and 2 m at the two sites drilled. Four holes were drilled at the Gumboot Quarry site, Sec 6 T. 4 N. R. 5 E., and encountered bedrock under 2, 2, 3 and 0.45 m of soil. No buried soil units were identified; however, flow breccia was encountered which would often grade from poor quality rock at the top of the unit to higher quality rock at the bottom, or vice versa. The zones of poorest quality material were classified as very poor quality rock and on the basis of core descriptions, have properties more similar to a Cr soil horizon.



1 Andic Haplumbrepts, medial over clayey, mixed, frigid

2 Andic Haplumbrepts, medial over loamy or clayey, mixed, frigid

3 Typic Udivitrands, pumiceous over sandy skeletal, frigid

4 Andic Haplumbrepts medial over loamy or loamy skeletal, mixed, frigid

5 Andic Haplumbrepts, medial over loamy, mixed, frigid

6 Andic Haplumbrepts, medial over loamy skeletal, mixed, frigid

7 Andic Cryumbrepts

Bedrock

Figure 7. Soil map for the upper Canyon Creek study area. Soil classifications taken from the GPNF Soil Resource Inventory (Wade and others, 1992).

B. Rock Quality/Characteristics

[The information in this section is condensed from Carter (1981a,b) and Shelmerdine (1984).]

The GPNF operates a number of rock quarry pits within or adjacent to the study area. Characterization of engineering properties of this rock is made using the Williamson (1978) classification system . These rocks (basalt, andesite and basaltic andesite) are almost always assigned a classification of BBEA for the fresh rock and CBEA for the stained rock (Table 4). BBEA means that the rock is visually fresh in appearance, will form tiny pits when struck with a ballpeen hammer, has an intersecting system of joints (3-D), and has a unit density greater than 2.55 g/cc (>160 pcf). The "C" designation (CBEA) is reserved for rock discolored due to some natural process, such as rusty discoloration due to the oxidation of the iron-bearing minerals. Distinguishing between stained and unstained rock is done so that greater care can be applied to stained material in order to assess the impact on rock strength of the weathering or alteration responsible for the discoloration.

Cores recovered from exploratory drilling in the Gumboot Quarry, Sec 6 T. 4 N. R. 5 E., on the southwest side of Gumboot Mountain, indicate that rock quality and characteristics to the bottom of the hole, 30.8 m below the surface, are similar to those observed at the surface for similar materials. These qualities include: 1) a very gradational contact between flow breccia and basalt, 2) most commonly a pattern of intersecting (3-D) joints, 3) unpredictable and variable water flow through fractures and joints and 4) high rock quality in the compact igneous units, but poor quality in fragmental igneous units.

Likewise, in all other rock quality studies performed by the GPNF which involved the drilling and examination of cores and construction of subsurface profiles, the character of the contacts, degrees of weathering and rock quality are similar to surface observations for similar rock types. Compact igneous rock quality is nearly always classified as BBEA, BBEB or CBEA, while rock quality classifications for fragmental igneous rocks range from CCCB to EEED.

Table 4. Rock quality test results for Forest Service pits located in the Canyon Creek drainage. (U.S. Forest Service, 1989a - 1989r)

Location	**Rock type**	**URCS**	**Fracture Pattern**
		- (Refer to Figure 4) -	
T5NR5E Sec 28	Basaltic andesite	*	3-D Fracture pattern
T5NR5E Sec 22	Basalt	BBEA	3-D Fracture pattern Highly fractured
T5NR5E Sec 17	Basalt	BBEA	3-D fracture pattern
T5NR5E Sec 7	Basalt	BBEA	*
T5NR5E Sec 12	Basalt	*	Massive
T5NR5E Sec 35	Basaltic andesite	*	Slightly fractured
T5NR5E Sec 32	Basaltic andesite	BBEA	3-D fracture pattern

* = no data given

Chapter 5.
Discussion of Field Work
Location and extent of failures

The following discussion divides the Canyon Creek basin into eight subdrainages: lower Canyon Creek, middle Canyon Creek, upper Canyon Creek, Big Rock Creek, Jake's Creek, Pelvy Creek, Sorehead Creek and Hackamore Creek (Fig. 8). The assessment has been conducted on a subdrainage basis to provide greater clarity in the description of location, identification and extent of failure features, influence of glaciation, and a synopsis of the local bedrock and cultural conditions. Each subdrainage discussion ends with a statement summarizing the percentage of roadbed failures occurring as a result of natural (subgrade) and induced (roadfill and cutface) degradation.

Mass wasting processes in the drainage can be classified as one of the following: rockfalls, slumps, translational landslides, soil or debris slips and flows. Over 90% of streambank instability occurs as subtle slumping; however, due to the small areal extent of individual sites, these locations are not mappable at the scale of the landslide inventory map (Plate 3); however, an approximation of their total areal extent is presented in Chapter 6.

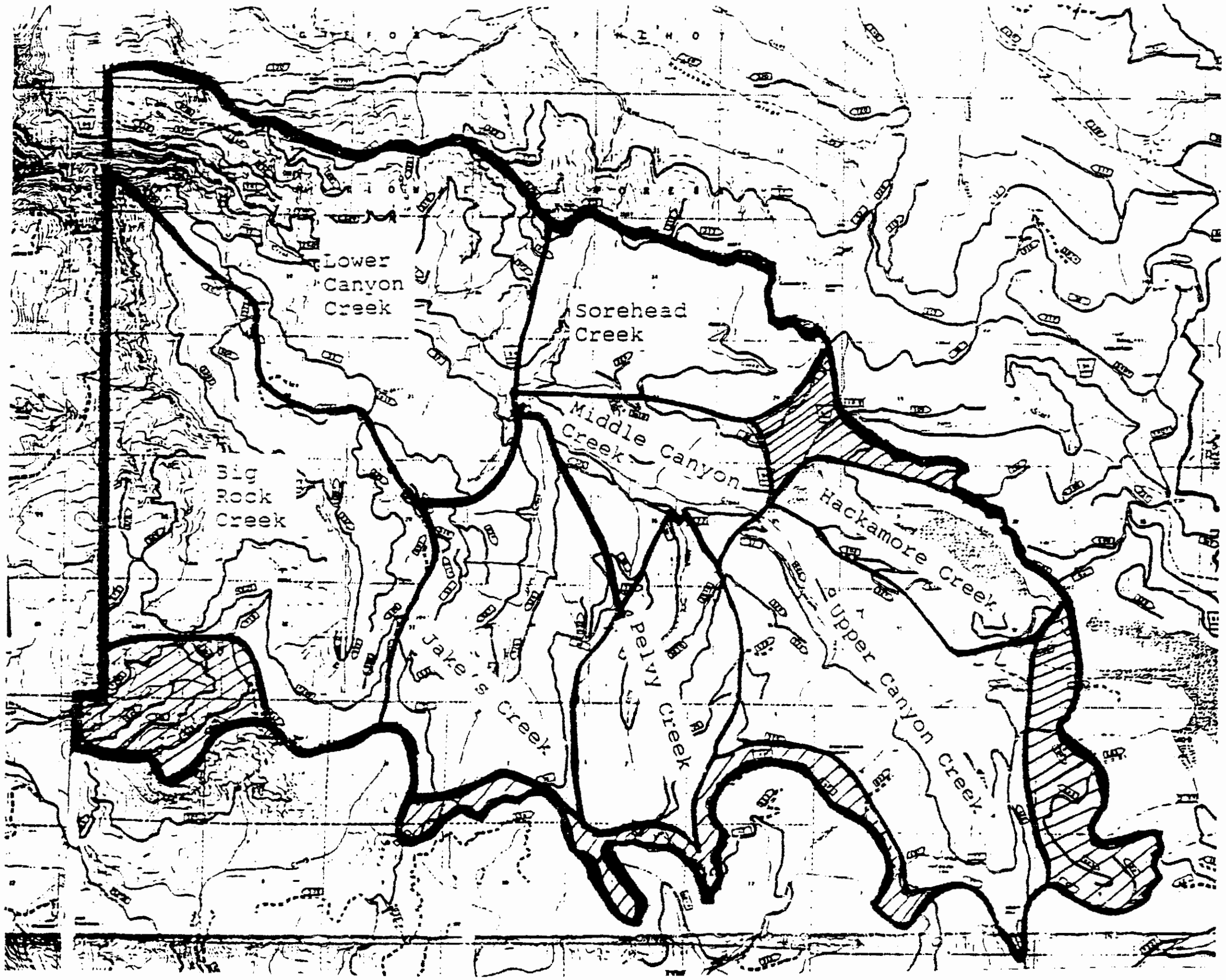


Figure 8. Upper Canyon Creek basin subdrainage location map. The hatchured areas fall outside the boundaries of the drainage basin, but within the study area.

Lower Canyon Creek

This portion of the field area covers 1822 ha (4500 acres) extending from the National Forest boundary to Sorehead Creek and Jake's Creek along the lowermost 2.4 km of Canyon Creek (Fig. 9). Bedrock units are composed of up to 80% fragmental igneous rock (lapilli tuff, tuff and tuff-breccia). Compact igneous bedrock occurs primarily as basaltic to andesitic dikes, plugs, and, possibly, sills. Glacial deposits are found from stream level (307 m) to high saddles between peaks (738 m). These deposits occur as varves and till and are often associated with diamicton on gradually sloping bench areas believed to represent the old scour surfaces. Over 80% of this area appears to have been clearcut within the past 30 years.

Rockfall, in terms of number of locations, is the most important type of mass wasting mechanism in this subdrainage; however, in terms of volume, rock avalanche deposits predominate. Seventeen locations of appreciable (> 0.1 hectare) rockfall occur over a minimum total of 4.8 ha. Of this number, all were a result of road building or quarrying operations; none were natural (Table 5). Three locations comprised of rock avalanche deposits occur covering a total of 10.6 ha (Table 6). Rock avalanche deposits are always the result of natural processes in this subdrainage. Failures due to other types of mass wasting mechanisms are volumetrically minor. Slumps occupy 2.4 ha of the subdrainage and debris slips 0.4 ha (Table 7).

A direct comparison between natural versus induced failures reveals that out of a minimum total mass wasting area of 18.2 ha in this subdrainage, 4.8 ha (26%) are the direct result of road building activity.

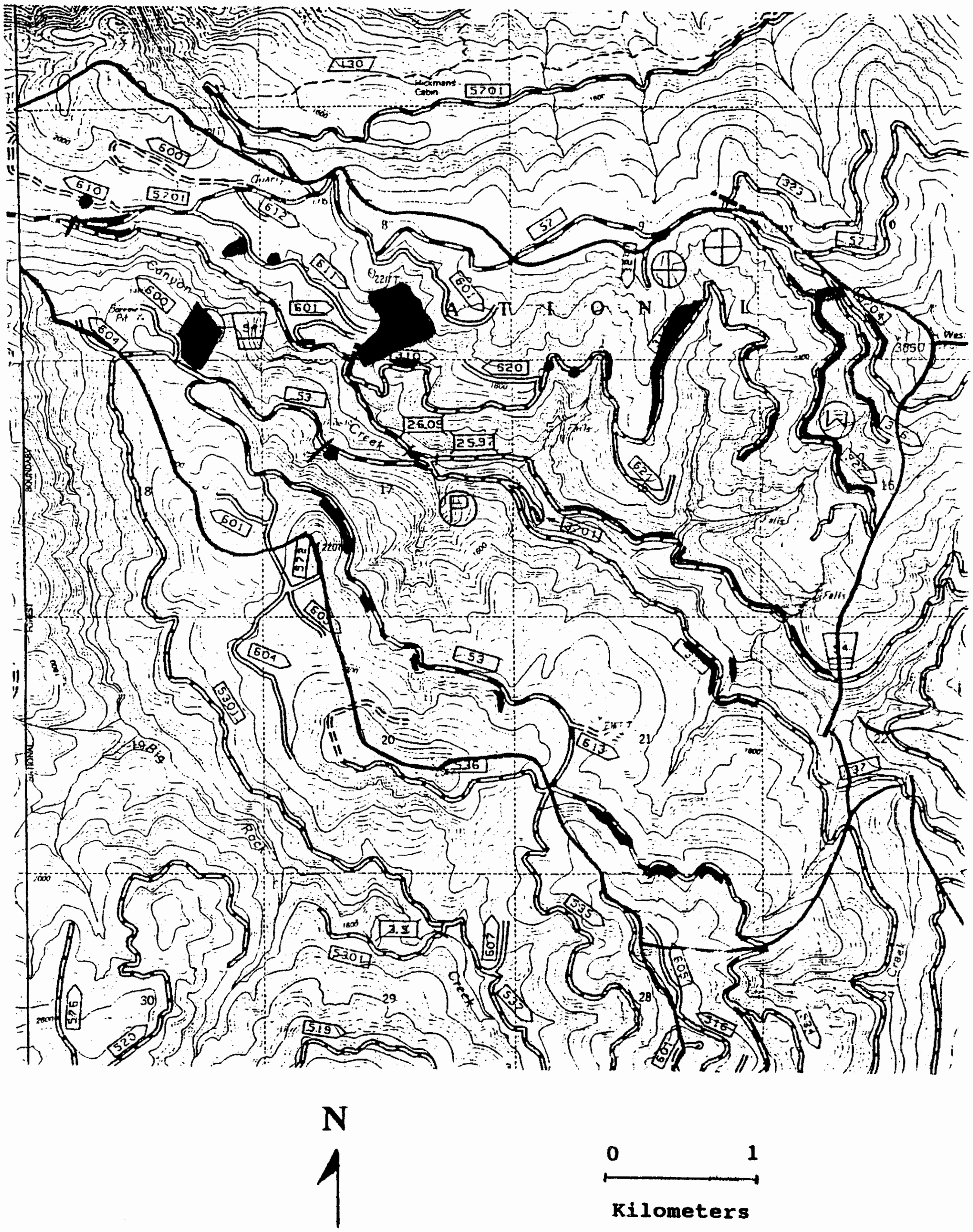


Figure 9. Lower Canyon Creek Subdrainage
Failure locations are shown in black and identified in Tables 5,6 and 7

Table 5. Rockfall locations, extent and cause

Location	Affected material	Slope degrees	Extent hectares	Cause of oversteepening
Section 7				
NE NE 1/4	Basaltic andesite	80+	0.5	roadcut
SW SE NW 1/4	Talus	35	0.1	roadcut
SW SE 1/4 Sec. 9	Lapilli tuff, lahars	35 - 40	2.1	roadcut
Section 10				
Ctr S 1/2 SW 1/4	Lapilli tuff, lahars	80+	0.1	roadcut
SE SW 1/4	Lapilli tuff, lahars	80+	0.1	roadcut
NW 1/4 Sec. 15	Tuffs, lahars basaltic andesite	60+	0.2	roadcuts
Section 16				
N 1/2	Tuffs, basaltic andesite	20 - 80	0.6	roadcuts/quarries
S 1/2 - FS Rd 54	Till, basaltic andesite	80+	0.2	roadcuts
Section 17				
SE NW 1/4	Basaltic andesite	80+	0.1	roadcut
NE SE NW 1/4	Basaltic andesite	80+	0.1	quarry
SW 1/4 - FS Rd 53	Basaltic andesite	80+	0.1	roadcuts
Section 20				
NE 1/4 - FS Rd 53	Till, basaltic andesite	50 - 80+	0.1	roadcuts
Ctr - FS Rd 536	Till, basaltic andesite	50 - 80+	0.1	roadcuts
Section 21				
S 1/2 - FS Rd 53	Basaltic andesite	70+	0.1	roadcuts
NE 1/4	Basaltic andesite	70+	0.1	roadcuts
NW 1/4 Sec. 22	Basaltic andesite	80+	0.1	roadcuts
NE 1/4 Sec. 28	Basaltic andesite	80+	0.1	roadcuts
			4.8	

These sites occupy approximately 0.06 % of the total study area.

Table 6. Rock Avalanches - locations and extent

Location	Bedrock	Extent hectares	Extent acres
SE SE SW1/4 Sec. 8	Basaltic Andesite	6.5	16.0
Ctr E1/2 Sec. 7/18 line	Basaltic Andesite	3.5	8.7
S1/2 NE NE1/4 Sec. 21	Basaltic Andesite	0.6	1.5
		10.6	**26.2**

These sites occupy approximately 0.13% of the total study area.

Table 7. Naturally occurring failures other than rockfall

Location	Affected material	Type of failure	Extent hectares	Extent acres
Section 7				
SE NW 1/4	Saprolitic lahar lapilli tuff	translational slide	0.1	0.2
NE SE 1/4	Diamicton	slump	1.8	4.3
NW SW 1/4 Sec. 8	Diamicton	slump	0.2	0.5
Section 9				
SE SW 1/4	Lapilli tuff	debris slips	0.4	1.0
SE SW 1/4 Sec. 10	Ashflow tuff lapilli tuff	translational slide	0.2	0.5
Section 17				
SE NW NW 1/4	Regolith	slump	0.1	0.2
			2.8	**6.7**

These sites occupy approximately 0.03% of the total study area.

Middle Canyon Creek

The middle section of Canyon Creek covers approximately 405 ha (1000 acres) from Jake's Creek on the west to Puny Creek on the east (Fig. 10). This area does not appear to have been more than 40% clearcut over the past 30 years. The bedrock along this stretch consists of fragmental igneous rocks on the south side and along the creek on the north side and primarily andesite and basaltic andesite above the creek on the north side. Below the confluence with Pelvy Creek, the intrusive rocks exposed in and along the stream are basaltic and andesitic. Above this confluence, rare dioritic dikes occur along with the andesite and basalt. Till and erratics can be found to an elevation of 740 m. Deposits interpreted to be till occur along the entire stretch at and just above creek level. Varve deposits are common on the south side of the stream from Jake's Creek to the intersection of FS Roads 37 and 526.

Rockfall appears to be the only type of mass wasting mechanism active in this subdrainage. All ten of the rockfall locations identified are the result of road building activity; however, three of the locations also have a component of natural degradation. The minimum total of 10.6 ha reflects both sources (Table 8). Rock avalanche deposits and failures due to other types of mass wasting mechanisms were not observed. Stream erosion of the till along Canyon Creek is occurring. A total streambank-area degradation value of seven hectares is based on qualitative factors such as bank height, type of material, stream energy, bank morphology and presence of groundwater.

A direct comparison between natural versus induced failures reveals that out of a minimum total mass wasting area of 10.6 ha in this subdrainage, 10.0 ha (94%) are the direct result of road building activity.

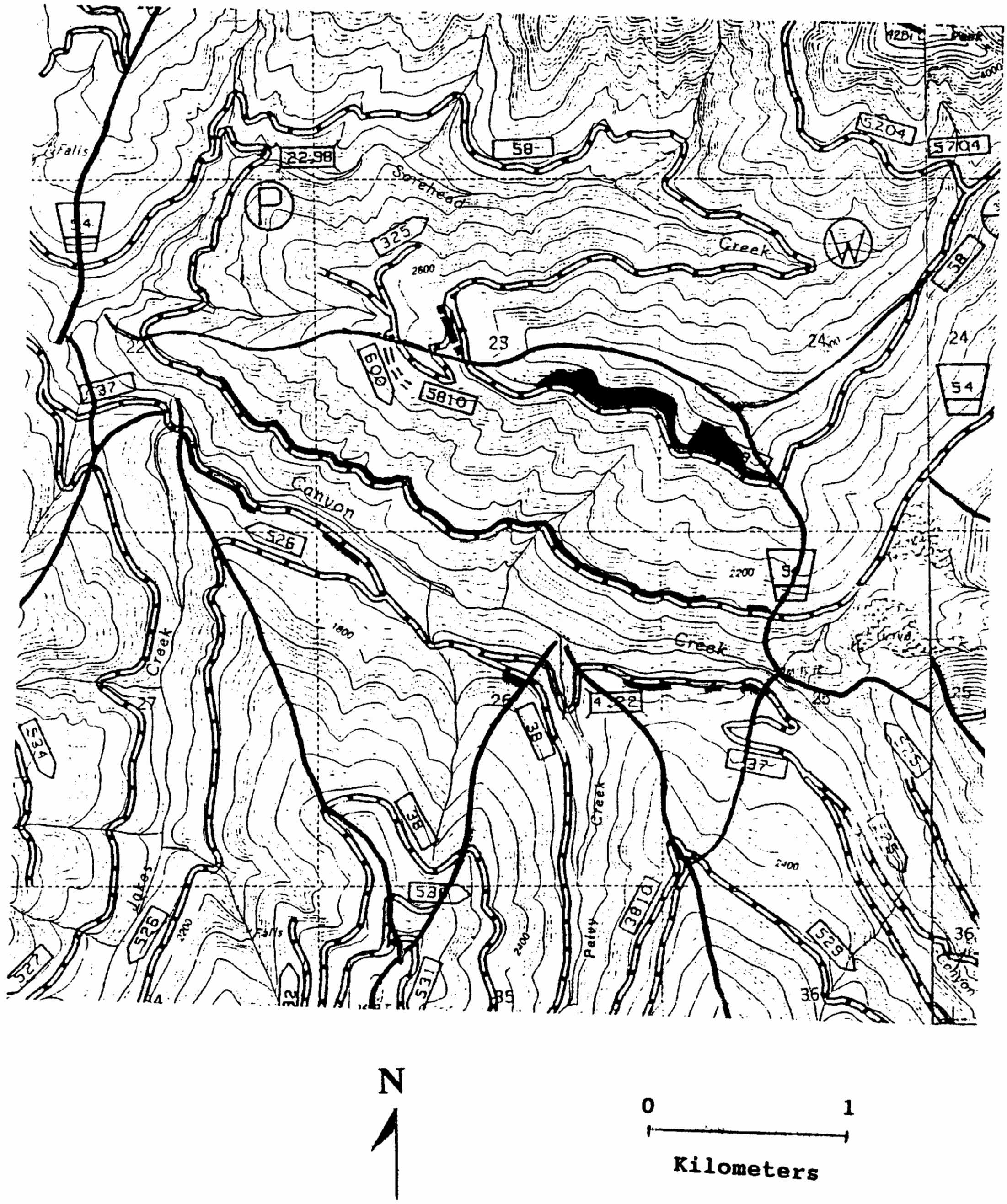


Figure 10. Middle Canyon Creek Subdrainage
Failure locations are shown in black and identified in Table 8

Table 8. Rockfall locations, extent and cause

Location	Affected material	Slope degrees	Extent hectares	Cause of oversteepening
Section 22				
SE 1/4 - FS Rd 54	Basaltic andesite lapilli tuff	60+	0.4	roadcuts
NW SE SW SE 1/4	Basaltic andesite	80+	0.1	roadcut/natural
SE 1/4 - FS Rd 37	Till	60+	0.3	roadcuts
Section 23				
S 1/2 NE SE 1/4	Basaltic andesite talus	45+	1.5	roadcuts/natural
SW 1/4	Lapilli tuff basaltic andesite	60+	0.1	roadcuts
Section 24				
SW 1/4	Basaltic andesite talus	45+	7.8	roadcuts/natural
Section 25				
N 1/2 NW 1/4	Basaltic andesite	70+	0.1	roadcuts
S 1/2 NW 1/4	Basaltic andesite till	60+	0.1	roadcuts
Section 26				
SE SW NE 1/4	Till, basaltic andesite, talus	60+	0.1	roadcuts
NW 1/4	Till	50+	0.1	roadcuts
			10.6	

These sites occupy approximately 0.13% of the total study area.

Upper Canyon Creek

Upper Canyon Creek is fed from numerous small tributaries headed in remnant cirque basins on the east side of the Green Lookout Mountain ridge, from springs on the north side of Cougar Rock and from springs on the west side of Twin Rocks and the ridge to its south. This upper section covers approximately 1100 ha (2700 acres; Fig. 11). At least 50% of this section has been clearcut within the past 30 years. Bedrock consists of andesite, basaltic andesite and possibly gabbro, dacite and monzonite. Widely scattered plugs and dike complexes can be found and are associated with block and ash flows and lapilli tuffs. Compact and fragmental igneous rocks appear to occur in fairly equal volumes. Till is common, but discontinuous, along the entire stretch of the upper stream and has been found from stream level (550 m) up to 950 m. Zag Zig Lake fills the center of a cirque basin and at least four other cirques occur along the ridge forming the west boundary of the upper drainage. Snow avalanche chutes are common on the north, southwest and southeast side of Cougar Rock.

Rockfall, in terms of number of locations and volume of material, clearly outdistances all other types of mass wasting mechanisms in this subdrainage. Eighteen locations of appreciable (> 0.1 hectare) rockfall occur for a minimum total of 24.3 ha. Of this number, twelve were a result of road building or quarrying operations, three were natural and three were a combination natural and anthropogenic (Table 9). One rock avalanche deposit was observed covering 5.3 ha (Table10). This rock avalanche deposit was a consequence of natural oversteepening. Failure of material above and along snow avalanche chutes is common on the north, east and south sides of Cougar Rock. While Table 11 shows that the amount of material associated with these features has a limited areal extent (2.5 ha) compared to the quantity of the other deposits in this subdrainage, their road-blocking potential is dramatic.

A direct comparison between natural versus induced failures reveals that out of a minimum total mass wasting area of 32.1 ha in this subdrainage, 3.8 ha (12%) are the direct result of road building activity.

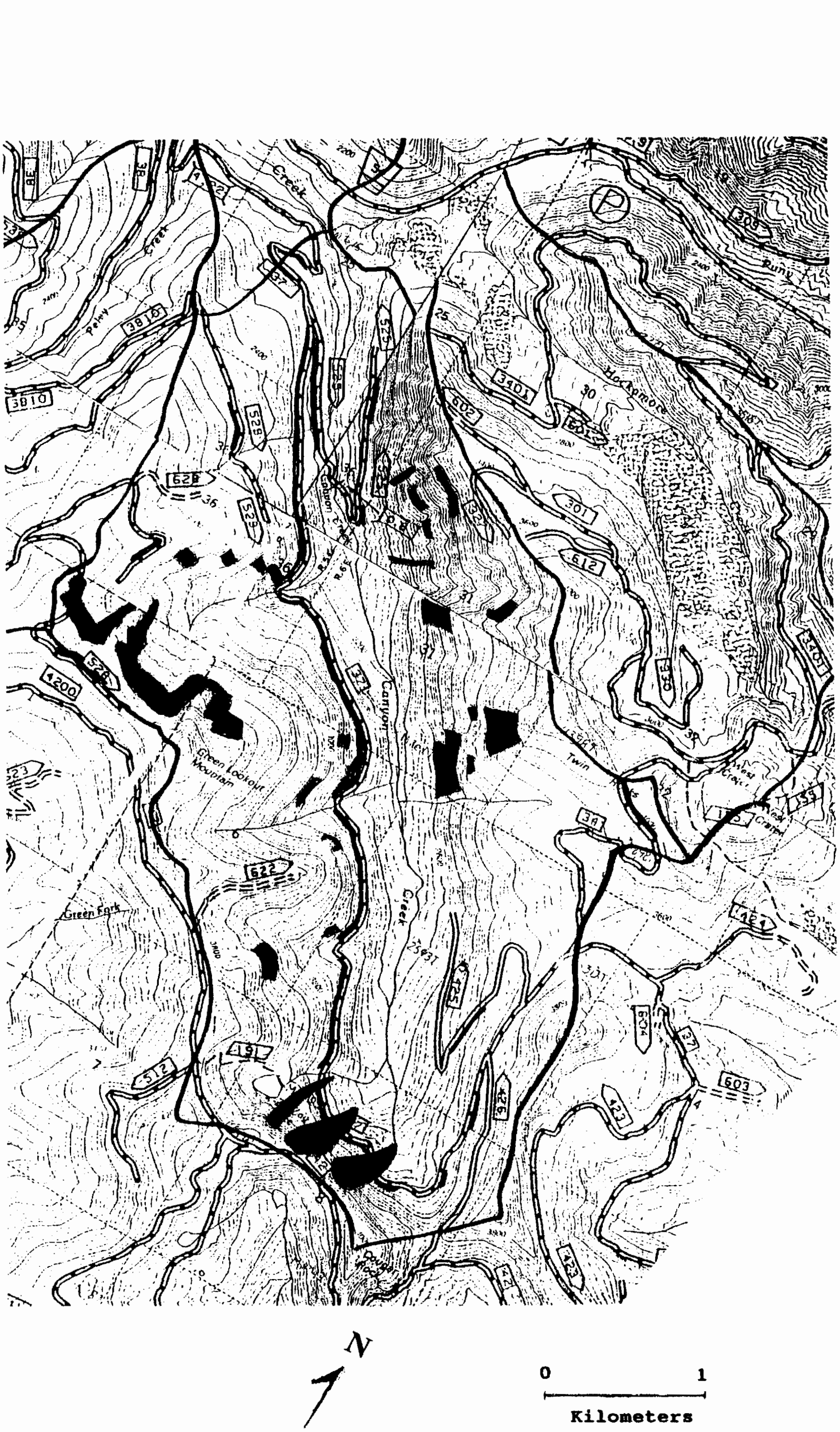


Figure 11. Upper Canyon Creek Subdrainage
Failure locations are shown in black and identified in Tables 9, 10 and 11.

Table 9. Rockfall locations, extent and cause

Location	Affected material	Slope degrees	Extent hectares	Cause of oversteepening
Section 25				
NE SW 1/4	Basaltic andesite till, talus	45+	0.2	roadcuts
SW SE 1/4	Talus, basaltic andesite	45+	0.4	roadcuts
Ctr SE 1/4	Andesite	70+	0.1	roadcuts
Section 36				
NE SE NW 1/4	Talus	45	0.1	roadcuts
SW 1/4	Andesite, dacite(?)	80+	0.1	roadcuts
S 1/2 N 1/2 NE 1/4	Basaltic andesite	60+	5.0	natural
NE SE 1/4	Basaltic andesite till, talus	40+	0.3	roadcuts **
Section 31				
SW 1/4	Basaltic andesite gabbro(?)	40+	0.9	roadcuts
Section 32				
E 1/2 SW 1/4	Basaltic andesite lapilli tuff	60+	0.1	roadcuts
Section 5				
SE SE 1/4	Andesite	80+	0.1	roadcuts
NW SE 1/4	Till, andesite	50+	0.1	roadcuts
NW SW 1/4	Basaltic andesite talus	45+	0.5	roadcuts/natural
SW SW 1/4	Lapilli tuff	40+	0.1	roadcuts

Table 9 (cont.). Rockfall locations, extent and cause

Location	Affected material	Slope degrees	Extent hectares	Cause of oversteepening
Section 6				
NE 1/4	Basaltic andesite lapilli tuff, talus	40+	0.7	roadcuts/natural
NW 1/4	Basaltic andesite	70+	5.0	natural
Section 1				
N 1/2 NE 1/4	Basaltic andesite	80+	9.8	natural
Section 8				
N 1/2 - FS Rd 37	Basaltic andesite talus, andesite till, monzonite(?)	50+	0.7	roadcuts/natural
NE SE NE 1/4	Basaltic andesite	80+	0.1	roadcut
			24.3	

These sites occupy approximately 0.3% of the total study area.

** Mainly as talus rock slides

Table 10. Rock Avalanches - locations and extent

Location	Bedrock	Extent hectares	Extent acres
SE SE SE1/4 Sec. 31	Andesite	5.3	13.0
		5.3	**13.0**

This site occupies approximately 0.07% of the total study area.

Table 11. Naturally occurring failures other than rockfall

Location	Affected material	Type of failure	Extent hectares	Extent acres
Section 8				
SW SW NE 1/4	Basaltic andesite lapilli tuff	snow avalanche chute	0.7	1.8
SE NW 1/4	Basaltic andesite lapilli tuff	snow avalanche chute	0.4	.9
SE SW NE 1/4	Basaltic andesite lapilli tuff	snow avalanche chute	1.4	3.5
			2.5	**6.2**

These sites occupy approximately 0.03% of the total study area.

Big Rock Creek

Big Rock Creek is the westernmost and largest tributary of Canyon Creek and joins the main stem just outside the National Forest boundary. It drains an area covering 1823 ha (4500 acres) and emanates from springs to the north and northwest of Gumboot Mountain (Fig. 12). Bedrock in this drainage is composed of up to 80% fragmental igneous rock (lapilli tuff, and block and ashflow deposits). The majority of compact igneous bedrock crops out around the margins on the south and east sides. Elsewhere in the drainage, it occurs as small dikes and plugs. Glacial deposits are found from 492 m to 954 m and occur as till, moraines and kames. As much as 60% of this subdrainage has been logged over the past 30 years.

Rockfall, in terms of number of locations, clearly outdistances all other types of mass wasting mechanisms in this subdrainage; however, in terms of surface area, translational slide complexes located along lower Big Rock Creek predominate. Twenty-one locations of appreciable (> 0.1 hectare) rockfall occur for a minimum total of 17.9 ha. Of this number, four were natural covering 11 ha (Table 12). One rock avalanche location covers a total of 1.2 ha (Table 13). Failures due to other types of mass wasting mechanisms occupy the majority of failure deposits in this subdrainage. Slumps occupy at least 25.6 ha and debris flows 1.3 ha (Table 14).

A direct comparison between natural versus induced failures reveals that out of a minimum total mass wasting area of 46.0 ha in this subdrainage, 6.7 ha (14%) are the direct result of road building activity.

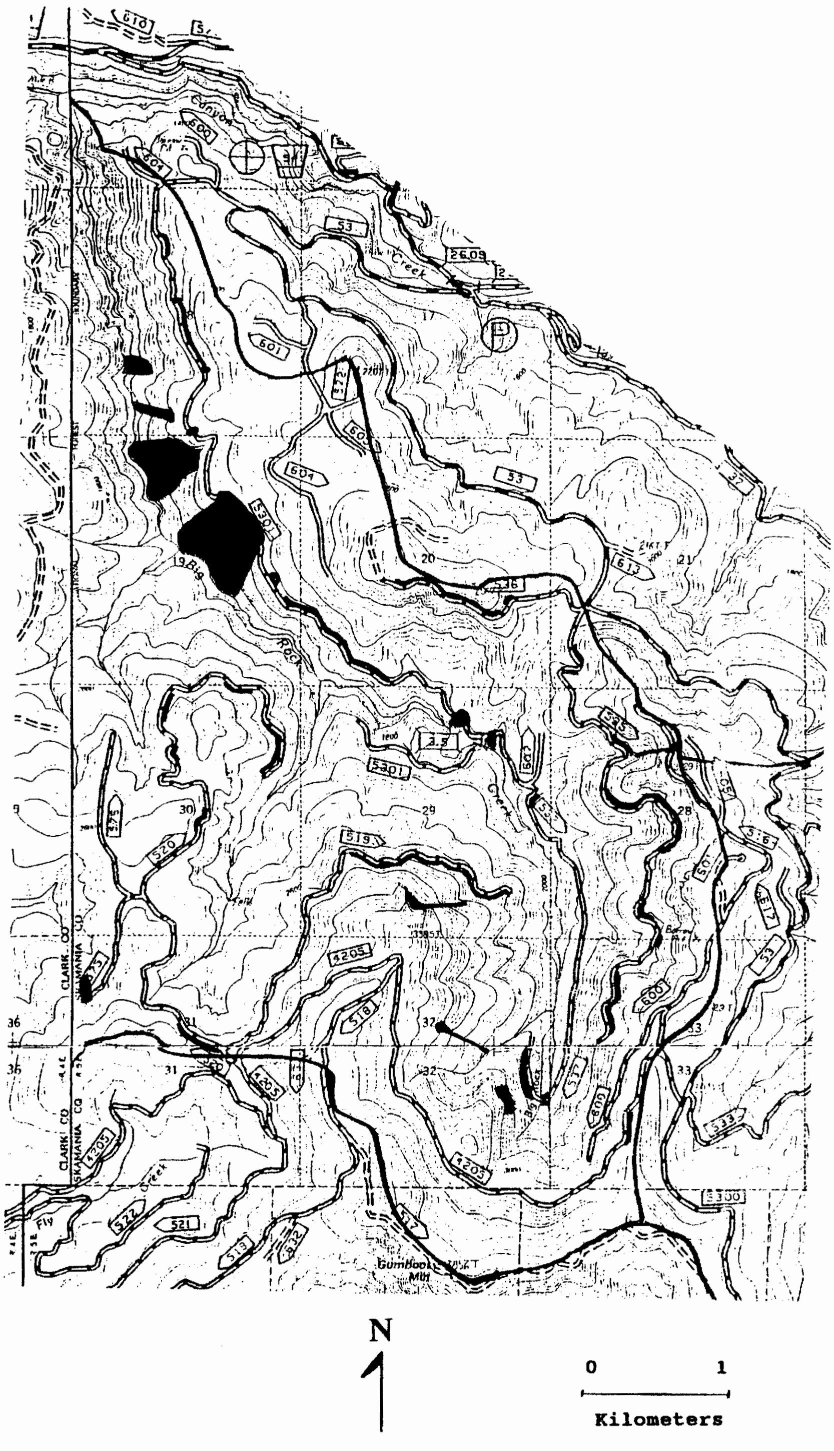


Figure 12. Big Rock Creek Subdrainage
Failure locations are shown in black and identified in Tables 12, 3 and 14.

Table 12. Rockfall locations, extent and cause

Location	Affected material	Slope degrees	Extent hectares	Cause of oversteepening
Sections 18, 19, 20				
FS Rd 5301	Basaltic andesite andesite	70+	2.9	roadcuts
Ctr Sec. 20	Basaltic andesite andesite, gabbro	40+	0.1	roadcuts
Section 28				
W 1/2 FS Rd 535	Lapilli tuff, basalt andesite, dacite(?)	60+	0.5	roadcuts
E 1/2 NW 1/4	Lapilli tuff, basalt andesite, gabbro	60+	0.1	roadcuts
Section 29				
NE SE NE 1/4	Basaltic andesite	80+	0.1	roadcut
N 1/2 FS Rd 5301	Andesite	70+	0.1	roadcuts
S 1/2 FS Rd 519	Basaltic andesite till, lapilli tuff	60+	0.6	roadcuts
SESW 1/4	Basaltic andesite	80+	2.3	natural
Section 30				
Ctr Sec. 30	Basaltic andesite	70+	0.1	roadcut
SE NW 1/4	Kames	80+	0.1	roadcut
NE1/4	Andesite basaltic andesite	60+	0.6	roadcuts
SE SW NE 1/4	Basaltic andesite	80+	4.7	natural

Table 12 (cont.). Rockfall locations, extent and cause

Location	Affected material	Slope degrees	Extent hectares	Cause of oversteepening
Section 31				
Ctr N 1/2	Lapilli tuff, basaltic andesite, till(?)	60+	0.2	roadcuts
NW NW 1/4 - FS Rd 575	Till, basaltic andesite	80+	0.2	roadcuts
SE1/4	Basaltic andesite	80+	0.1	roadcuts
Section 32				
NW 1/4	Basaltic andesite	70+	0.1	roadcuts
NE SE1/4	Moraine	70+	0.1	roadcut
W 1/2 NE 1/4	Basaltic andesite	70+	1.2	natural
Section 33				
Ctr NW 1/4	Lapilli tuff	70+	0.2	roadcuts
SE1/4	Basaltic andesite	80+	0.8	roadcuts
Ctr W 1/2	Basaltic andesite	80+	2.8	natural
			17.9	

These sites occupy approximately 0.22% of the total study area.

Table 13. Rock Avalanches - locations and extent

Location	Bedrock	Extent hectares	Extent acres
NW SE SE1/4 Sec.32	Andesite	1.2	2.9
		1.2	**2.9**

This site occupies approximately 0.01% of the total study area.

Table 14. Naturally occurring failures other than rockfall

Location	Affected material	Type of failure	Extent hectares	Extent acres
Section 18				
SW SW SE 1/4	Lapilli tuff	slump	0.1	0.2
Ctr Sec. 18	Basalt	slump	0.1	0.3
SW NW SE 1/4	Basalt	slump	0.1	0.3
Section 19				
SW NE 1/4	Flow breccia	slump complex	17.6	43.5
NW NE 1/4	Flow breccia	slump complex	7.0	17.4
Ctr N 1/2 NW NE 1/4 Sec. 29	Till	1) slump 2) debris flow	0.1	0.25
NW NW 1/4 Sec. 31	Till	developing slump	0.6	1.5
Section 32				
SE NW 1/4	Andesite	debris flow	0.1	0.25
NE SE NW 1/4	Lapilli tuff	debris flow	1.2	2.9
			26.9	**66.6**

These sites occupy approximately 0.33% of the total study area.

Jake's Creek

Jake's Creek lies just to the east of Big Rock Creek. It covers 900 ha (2200 acres). Its headwaters emanate from springs on the Tatoosh Hills and flow north to its confluence with Canyon Creek (Fig. 13). Approximately 60% of the area has been clearcut within the past 30 years. The lower portion of the stream, in Sections 22 and 27, is interpreted to flow along an alignment dictated by one of the north-northwest oriented, right-lateral strike-slip faults associated with the Mt. St. Helens Seismic Zone. Offset is found in two locations (along FS road 37 and SW1/4 SE 1/4 Sec. 27) along this stretch (Plate 1). Bedrock is predominantly fragmental igneous (lapilli tuff and flow breccia) from Canyon Creek through Section 27, becoming predominantly compact igneous to the south of this point. The incidence of intrusive units within the fragmental igneous section decreases markedly from the west side of the drainage (30%) to the east (5%). Remnants of moraines can be found almost continuously on the east side from the confluence with Canyon Creek up to the fork in the SW 1/4 of Section 34, and sporadically on the west side of the stream. Clear cirque locations occur in the SE 1/4 Section 33 and the NE 1/4 Section 34.

Rockfall, in terms of number of locations, clearly outdistances all other types of mass wasting mechanisms in this subdrainage; however, in terms of surface area, rock avalanche deposits predominate. Seventeen locations of appreciable (> 0.1 hectare) rockfall occur for a minimum total of 3.8 ha (Table 15). Of this number, only one is natural but accounts for nearly half the area covered by rockfall in the subdrainage (1.8 ha). Three locations comprised of rock avalanche deposits occur covering a total of 18.6 ha (Table 16). Failures due to other types of mass wasting mechanisms are volumetrically minor. Only one slump covering 0.7 ha was observed (Table 17).

A direct comparison between natural versus induced failures reveals that out of a minimum total mass wasting area of 23.1 ha in this subdrainage, 2.0 ha (9%) are the direct result of road building activity.

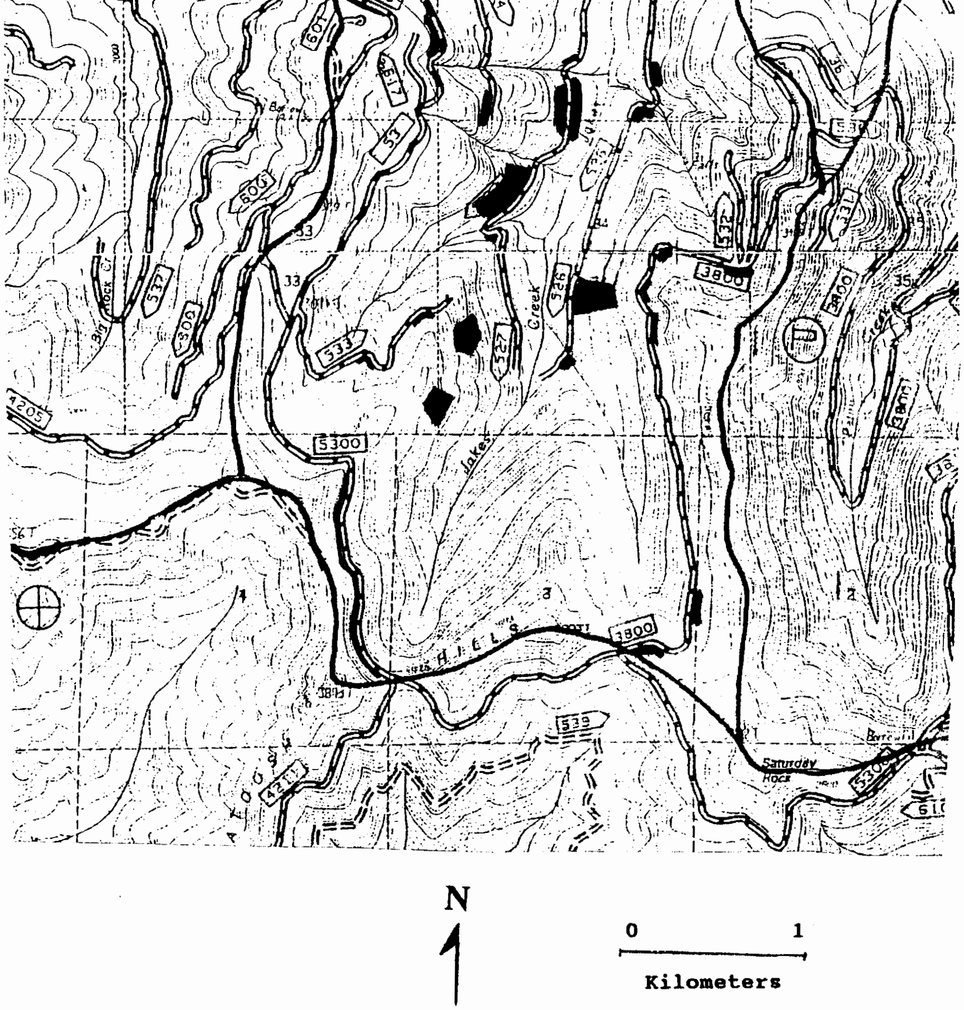


Figure 13. Jake's Creek Subdrainage
Failure locations are shown in black and identified in Tables 15, 16 and 17.

Table 15. Rockfall locations, extent and cause

Location	Affected material	Slope degrees	Extent hectares	Cause of oversteepening
Section 27				
SE NW 1/4	Lapilli tuff	70+	0.1	roadcut
SE SW1/4	Lapilli tuff	65+	0.1	roadcut
SE SW SE 1/4	Moraine	40+	0.1	roadcut
SW SW 1/4	Basaltic andesite	80+	0.1	roadcut
SE SW SE 1/4	Till, basaltic andesite	70+	0.1	roadcut
Section 28				
E 1/2 - FS Rd 53	Basaltic andesite	70+	0.2	roadcuts
N 1/2 SE 1/4	Lapilli tuff	70+	0.1	roadcut
Section 33				
NE SE 1/4	Diorite	80+	0.1	roadcut
Ctr SE 1/4	Moraine	40+	0.1	roadcut
Section 34				
NW NW 1/4	Basaltic andesite	80+	0.1	roadcut
W 1/2 - FS Rd 527	Talus, till	40+	0.1	roadcuts
NE SE SW 1/4	Moraine	40+	0.1	roadcut
Ctr Sec. 34	Andesite	45	1.8	natural
SE SE NE 1/4	Moraine	40+	0.1	roadcut
SE 1/4 - FS Rd 38	Andesite, dacite(?)	70+	0.1	roadcuts
Section 3				
E 1/2 - FS Rd 38	Andesite, diorite	70+	0.1	roadcuts
Section 4				
E 1/2 - FS Rd 53	Basaltic andesite	80+	0.4	roadcuts
			3.8	

These sites occupy approximately 0.05% of the total study area.

Table 16. Rock Avalanches - locations and extent

Location	Bedrock	Extent	
		hectares	acres
SE SE SW1/4 Sec. 22	Lapilli Tuff	14.0	34.8
SE SE SE1/4 Sec. 33	Diorite	2.3	5.8
NW SW SW1/4 Sec. 34	Diorite	2.3	5.8
		18.6	**46.4**

These sites occupy approximately 0.23% of the total study area.

Table 17. Naturally occurring failures other than rockfall

Location	Affected material	Type of failure	Extent	
			hectares	acres
SE SW 1/4 Sec. 27 and NE NW 1/4 Sec. 34 - FS Rd 527	Overburden	slump	0.7	1.8
			0.7	**1.8**

This site occupies approximately 0.01% of the total study area.

Pelvy Creek

Pelvy Creek, like Jake's Creek immediately to the west, is a north-south oriented drainage. It is fed by springs on the north flank of Saturday Rock and drains an area covering 650 ha (1600 acres; Fig. 14). Approximately 70% of the area has been clearcut over the past 30 years. This drainage forms one of the best preserved U-shaped valleys in the Canyon Creek basin. Densely vegetated moraines are common along FS Road 38 above its intersection with FS Road 3810. Bedrock is predominantly fragmental igneous (>90%) in the lower drainage in Section 26, but predominantly compact igneous (>70%) in the rest of the basin. Porphyritic green to blue-green andesite, dense, black basalt and fine-grained diorite represent the compact igneous rock on the west and south divides, with propylitic alteration very common in the andesite. Diorite, andesite and, possibly, dacite occur on the east divide, where silicification, tourmalinization and potassium enrichment are more common.

Rockfall, in terms of number of locations, is greater than all other types of mass wasting mechanisms in this subdrainage; however, in terms of surface area, rock avalanche deposits predominate. Thirteen locations of appreciable (> 0.1 hectare) rockfall occur for a minimum total of 2.6 ha (Table 18). Of this number, only one location is natural. Two locations comprised of rock avalanche deposits occur covering a total of 14.6 ha (Table 19). Failures due to other types of mass wasting mechanisms include only one slump covering 1.7 ha (Table 20).

A direct comparison between natural versus induced failures reveals that out of a minimum total mass wasting area of 18.9 ha in this subdrainage, 2.5 ha (13%) are the direct result of road building activity.

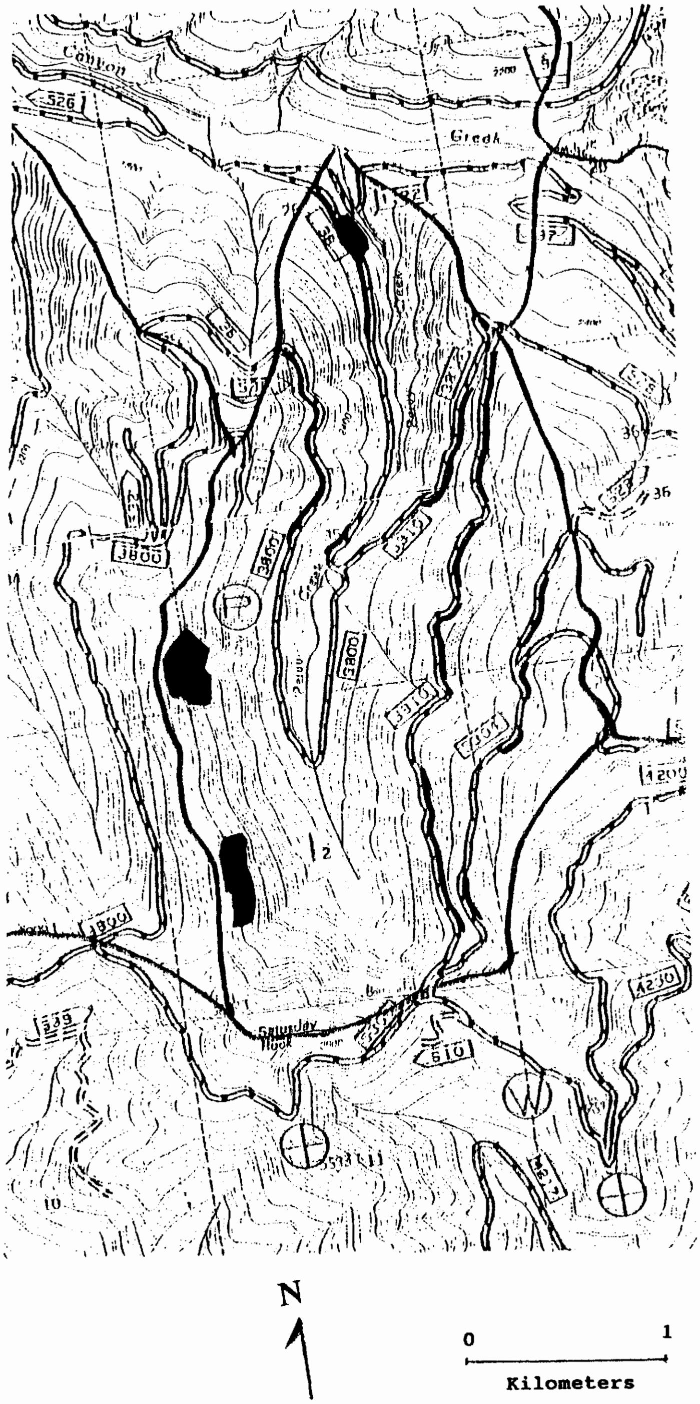


Figure 14. Pelvy Creek Subdrainage
Failure locations are shown in black and identified in Tables 18, 19 and 20.

Table 18. Rockfall locations, extent and cause

Location	Affected Material	Slope Degrees	Extent Hectares	Cause of Oversteepening
Section 26				
NW SE 1/4	Lapilli tuff	70+	0.1	roadcuts
SE SE SW 1/4	Lapilli tuff	70+	0.1	roadcuts
Section 35				
E 1/2 W 1/2	Lapilli tuff, andesite	40+	0.8	roadcuts
SW NW 1/4	Basalt	80+	0.1	natural
Ctr Sec. 35	Basaltic andesite	60+	0.1	roadcuts
NE 1/4 - FS Rd 3810	Basaltic andesite	60+	0.3	roadcuts
E 1/2 E 1/2	Andesite, basalt diorite, overburden	70+	0.5	roadcuts
Section 36				
NW NW 1/4	Andesite	70+	0.1	roadcuts
SW SW 1/4	Andesite	70+	0.1	roadcuts
Section 2				
NE NE 1/4	Basaltic andesite	80+	0.1	roadcut
SE SE 1/4	Basalt, diorite	80+	0.1	roadcuts
E 1/2 - FS Rd 5304	Diorite, andesite	80+	0.1	roadcuts
Section 1				
NW NW 1/4	Andesite, lapilli tuff, dacite(?)	70+	0.1	roadcuts
			2.6	

These sites occupy approximately 0.03% of the total study area.

Table 19. Rock Avalanches - locations and extent

Location	Bedrock	Extent hectares	Extent acres
CtrNW SW1/4 Sec. 2	Andesite/Diorite	7.3	18.0
SE SE SE1/4 Sec. 34	Diorite	7.3	18.0
		14.6	**36.0**

These sites occupy approximately 0.18% of the total study area.

Table 20. Naturally occurring failures other than rockfall

Location	Affected material	Type of failure	Extent hectares	Extent acres
E 1/2 W 1/2 SE 1/4 Sec 26	Lapilli tuff	slump	1.7	4.1
			1.7	**4.1**

This site occupies approximately 0.02% of the total study area.

Sorehead Creek

Sorehead Creek is the only major tributary to drain the north side of the Canyon Creek basin within the study area. This basin covers 780 ha (1920 acres) from West Point on the west end to Calamity Peak on the east and by an unnamed east-west oriented peak on the south (Fig. 15). Nearly 60% of this area has been clearcut over the past 30 years. This glaciated valley still retains a remnant U-shape, although the north side is fairly well dissected. Till can be found at the intersection of FS Roads 54 and 58 (elev. 575 m) and between 738 and 800 m on the west nose of the unnamed peak. Bedrock is predominantly lapilli tuff (90%) with widely scattered east-west and north-south oriented andesitic dikes in Sections 13, 14, 15 and 22. Basaltic andesite and andesite predominate in Sections 23 and 24 and occur almost exclusively as dikes. Complex intrusive relations exist on the peak forming the south divide. The abundance of dikes has resulted in widespread talus formation.. The lower reach of Sorehead Creek and its tributary in Sections 15 and 22 may be associated with the continuation of the right lateral strike-slip fault observed in Jake's Creek (Geologic Map - Plate 1). At least one east-west dike has been offset along this trend, and work by Weaver and Smith (1981, 1983) has suggested that the epicenter of a M 2.5+ earthquake associated with the Mt. St. Helens Fault Zone lies just east of West Point.

Rockfall, in terms of number of locations and volume, clearly outdistances all other types of mass wasting mechanisms in this subdrainage. Fifteen locations of appreciable (> 0.1 hectare) rockfall occur for a minimum total of 33.1 ha (Table 21). Of this number, two are natural locations covering a total of 13.5 ha, and two are a combination of natural and anthropogenic influences covering 15.0 ha. No rock avalanche deposits occur. Failures due to other types of mass wasting mechanisms are principally in the form of debris slips (0.7 ha) and debris flows (1 hectare; Table 22).

A direct comparison between natural versus induced failures reveals that out of a minimum total mass wasting area of 33.9 ha in this subdrainage, 19.0 ha (56%) are the direct result of road building activity.

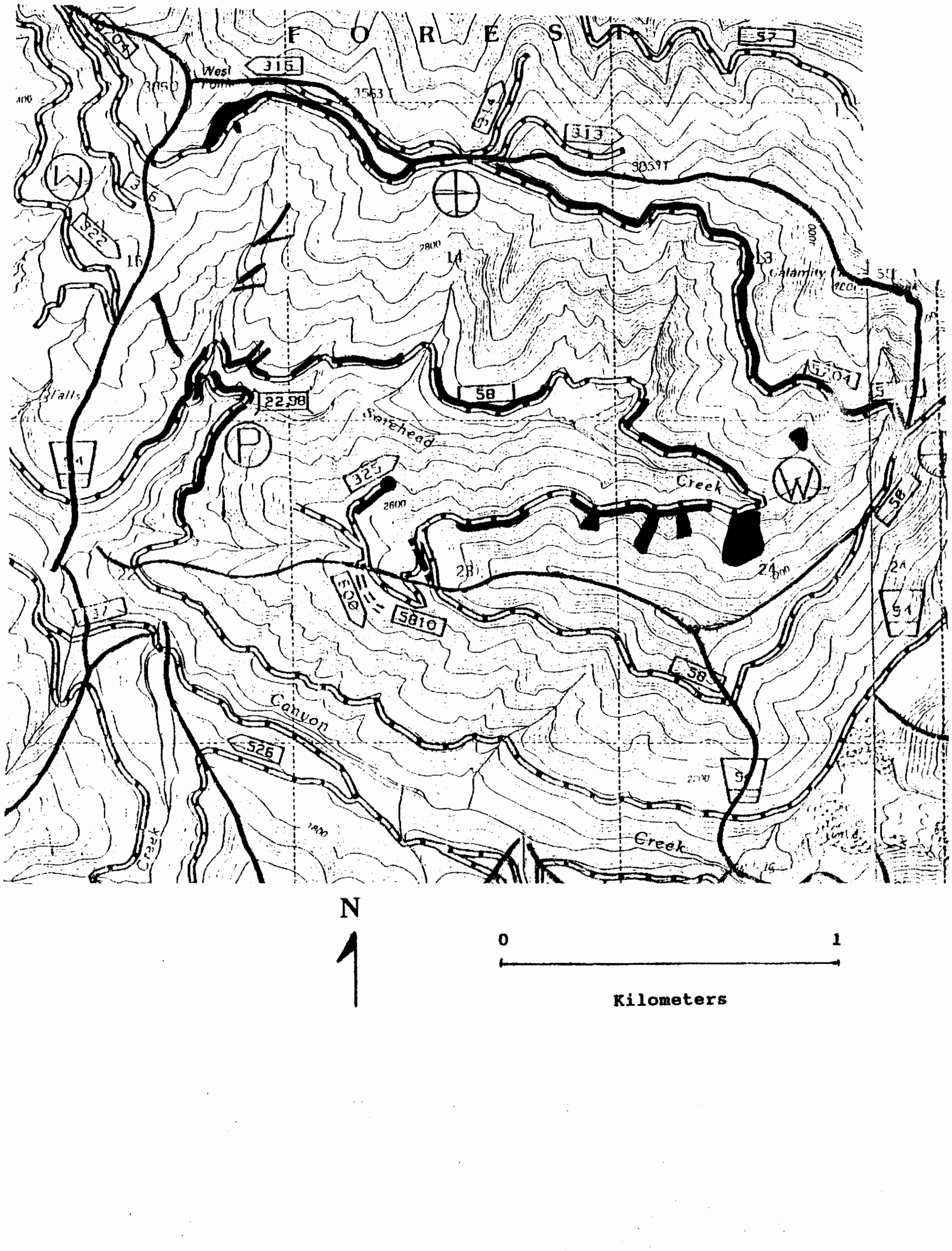


Figure 15. Sorehead Creek Subdrainage
Failure locations are shown in black and identified in Tables 21 and 22.

Table 21. Rockfall locations, extent and cause

Location	Affected material	Slope degrees	Extent hectares	Cause of oversteepening
Section 13				
SW SW SW 1/4	Lahar	70+	0.1	roadcut
FS Rd 5704	Tuffs, andesite	60+	0.5	roadcuts
Section 14				
FS Rd 5704	Tuffs, andesite	60+	0.5	roadcuts
FS Rd 58	Tuffs, andesite	70+	0.4	roadcuts
Section 15				
NE 1/4	Lapilli tuff	40+	0.2	roadcuts
SE SE 1/4	Lapilli tuff, till	60+	0.9	roadcuts
Section 22				
Ctr N 1/2	Lapilli tuff basaltic andesite	60+	0.2	roadcuts
W 1/2 NE 1/4	Lapilli tuff basaltic andesite	45+	0.7	roadcuts
Section 23				
Ctr NE 1/4	Andesite, talus	45+	0.4	roadcuts **
Ctr NW 1/4	Till	45+	0.1	roadcut
N 1/2 SE 1/4	Talus	45+	5.0	roadcuts/natural
Section 24				
SE SW 1/4	Talus	45+	7.0	natural
SW NW 1/4	Talus	45+	6.5	natural
FS Rd. 58	Andesite dacite, diorite	70+	0.6	roadcuts
SW SW 1/4	Talus	45+	10.0	roadcuts/natural
			33.1	

These sites occupy approximately 0.41% of the total study area.

** Rockfall and very small earth flows

Table 22. Naturally occurring failures other than rockfall

Location	Affected material	Type of failure	Extent hectares	acres
Section 15				
SW NW NE 1/4	Lapilli tuff	debris flow	0.1	0.2
W 1/2 NE SE 1/4	Lapilli tuff	debris slips	0.1	0.2
N 1/2 SE SE 1/4	Lapilli tuff	debris slips	0.1	0.2
Section 22				
SE NW NE 1/4	Talus	debris slip	0.1	0.2
Section 2				
NW NE 1/4	Talus, lapilli tuff	debris slip	0.4	1.0
			0.8	**1.8**

These sites occupy approximately 0.01% of the total study area.

Hackamore Creek

Hackamore Creek drains an area of approximately 648 ha (1600 acres) at the east end of the Canyon Creek basin and is fed by springs flowing from the base of Twin Rocks and West Crater (Fig. 16). Over the past 30 years, over 90% of this drainage has been clearcut. The youngest volcanic features (Holocene) are found in this drainage (Hackamore Creek cinder cone and the andesitic dome of West Crater). The valley floor is filled by the young andesite flow from West Crater. The bedrock is over 90% andesite and basalt, with fragmental igneous rocks represented by widely scattered lapilli tuff units and the scoria/tuff association at West Crater. The resistant bedrock and valley floor lava flow have preserved the U-shape morphology of this glacial valley to the greatest degree seen in the study area. Very small, widely scattered deposits of till have been found in the elevation range from 800 m to 1100 m along the valley walls.

Rockfall is the predominant mass wasting mechanisms in this subdrainage. Ten locations of appreciable (> 0.1 hectare) rockfall occur for a minimum total of 8.8 ha (Table 23). Of this number, only one location is natural but accounts for 63% of the total volume (5.6 ha). Degradation of weathering tuff exposed in a roadcut along FS Road 301 is resulting in both rockfall and debris slips of sufficient quantity to block the road. No rock avalanche deposits occur. Failures due to other types of mass wasting mechanisms do not occur.

A direct comparison between natural versus induced failures reveals that out of a minimum total mass wasting area of 8.8 ha in this subdrainage, 3.2 ha (37%) are the direct result of road building activity.

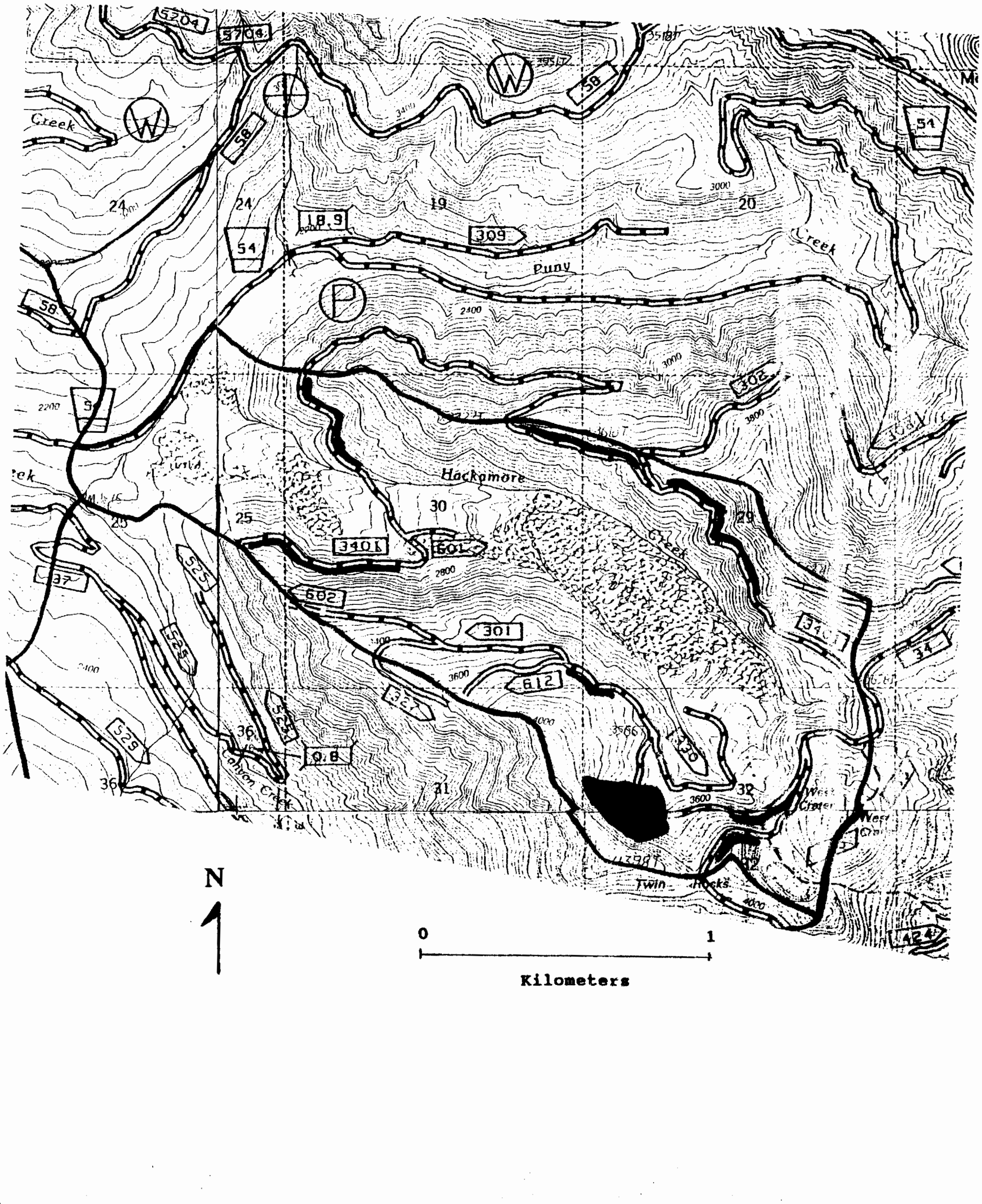


Figure 16. Hackamore Creek Subdrainage
Failure locations are shown in black and identified in Table 23.

Table 23. Rockfall locations, extent and cause

Location	Affected material	Slope degrees	Extent hectares	Cause of oversteepening
Section 25				
SE SE NE 1/4	Basaltic andesite	80+	0.1	roadcuts
Section 29				
FS Rd 3401	Basaltic andesite andesite	80+	0.8	roadcuts
Section 30				
NE 1/4	Basaltic andesite	80+	0.6	roadcuts
NW 1/4	Basaltic andesite	80+	0.6	roadcuts
N 1/2 SW 1/4	Basaltic andesite	80+	0.4	roadcuts
Section 32				
SW NW 1/4	Basalt, andesite	80+	5.6	natural
E 1/2 NW NW 1/4	Andesite	80+	0.1	roadcut
Ctr - FS Rd 301	Andesite, scoria	60+	0.3	roadcuts**
Ctr - FS Rd 34	Andesite, tuff	60+	0.3	roadcuts
			8.8	

These sites occupy approximately 0.11% of the total study area.

** Rockfall and debris slips

Summary of failures basinwide

A total of 155 failure locations were identified. The breakdown by category is given in Table 24. The total area occupied by failure deposits (198.6 ha) represents the minimum areal extent of mass wasting deposits and covers less than 2.5% of the entire upper Canyon Creek study area. This translates, on average, to one failure every 52 ha (128.4 acres). Of this 198.6 hectare area of failure material, 52.0 ha (26%) are directly attributable to road building activity either through oversteepening of the hillsides in roadcuts, destabilizing talus slopes by removing the toe, or increasing the efficiency of erosion through the incision of overburden.

Table 24. Total number and areal extent of failures by category

Slumps (12)	30.1 ha - 0.12% of total area
Rockfall (120)	105.9 ha - 1.31%
Streambank failures (unspecified)	7.0 ha - 0.09%
Rock Avalanches (10)	50.3 ha - 0.62%
Translational Landslides (2)	0.3 ha - 0.01%
Debris Slips and Debris Flows (7)	2.5 ha - 0.03%
Snow Avalanche Chutes (3)	2.5 ha - 0.03%
Total extent of failures:	**198.6 ha - 2.45% of total area**

Roadfill failures and hazards

Sixteen to twenty percent of the roadbed surfaces in the study area are experiencing some type of failure (Plate 6). Up to 99% of roadbed failures appear to be confined to the fill materials. Road failures due to subgrade degradation, i.e. overburden or bedrock decomposition, are associated with dip slope locations, and as such, occur primarily on south and southeast-facing slopes, in agreement with the regional dip orientation. In over 100 km of roadbed within the study area, only 0.13 km of roadbed failure could be attributed to subgrade instability (Table 25), while 16 to 20 km appears due to failure of the roadfill prism. Roadfill prism degradation was observed to occur as a result of one or a combination of the following influences: 1) a textural change between hillside and fill, 2) the use of poor quality fill material, i.e. non-durable or easily weathered, 3) incorporation of woody debris in the roadfill, 4) damaged culverts, 5) piping around culverts, 6) improper placement of culverts and 7) the lack of ditches.

In situations (Table 25) where failure has resulted from subgrade degradation, there may still be some element of anthropogenic influence contributing to the problem. At the site on FS Road 537 along Big Rock Creek, a 5 m length of the roadbed and the underlying glacial material has failed. A seep, presumed to be the source of the failure, occurs approximately 7 cm below the roadfill. In this case, the failure was driven by the oversaturation resulting from this seep and occurred entirely within the glacial subgrade below the roadfill. However, a clogged drainage ditch located along the road directly above this site may have had some influence on directing and concentrating surface water into this site, resulting in an accelerated rate of failure (Fig. 17).

Table 25. Locations and extent of roadbed failures associated with subgrade degradation

Drainage	Location T5NR5E	Forest Service Road No.	Subgrade Composition	Extent (Km)
Canyon Creek	W 1/2 Sec. 7	54 and 57	fragmental igneous	0.01
Canyon Creek	N 1/2 SE 1/4 Sec. 8	57 and 601	fragmental igneous	0.03
Canyon Creek	SW 1/4 Sec. 10	5704, 316, 322, 310	fragmental igneous	0.05
Canyon Creek	NWNENE 1/4 Sec. 15	5704	fragmental igneous	0.01
Canyon Creek	SENW 1/4 Sec. 17	53	weathering plug	0.01
Big Rock Creek	NE 1/4 Sec. 29	5301, 537	thick till	0.02
				0.13

This total is approximately 0.13% of the total road area.

Figure 17. Slump-flow failure in thick glacial deposit - Big Rock Creek, sec. 29, T.5 N. R.5 E. Road failure has occurred where thick till has become oversaturated due to the presence of a perched water table just below the roadbed at the top of the gravel in the left center. The fallen tree at the top of the failure lies in the position of the former roadbed. The stream is flowing from right to left across the bottom of the photo below the green ridge in the foreground, not through the cut below the log.

Chapter 6.
Discussion of Field Work
Factors influencing stability

Introduction

This chapter examines those factors found in the upper Canyon Creek basin to have the greatest influence in reducing the factor of safety (FS) and thereby, increasing the likelihood of failure. In the simplest terms, FS = resisting forces/driving forces. For situations where FS>1, the resisting force exceeds the driving force and the slope is stable. When FS<1, the slope is unstable and should fail.

The U.S. Forest Service Level I Stability Analysis (LISA) provides for a quantitative assessment of FS through the following equation (Prellwitz and others, 1994):

$$FS = \frac{C_r + C_s + [q_0 + \gamma d + (\gamma_{sat} - \gamma_w - \gamma)d_w]\cos^2\alpha \tan\phi}{[q_0 + \gamma d + (\gamma_{sat} - \gamma)d_w]\sin\alpha \cos\alpha}$$

where:

C_r = tree root strength expressed as cohesion, psf
C_s = effective soil cohesion, psf
d = total soil depth to soil/rock contact, ft
d_w = height of phreatic surface above soil/rock contact, ft
q_0 = tree surcharge, psf
ϕ = effective soil angle of internal friction, degrees
γ = moist soil unit weight, pcf
γ_{sat} = saturated soil unit weight, pcf
γ_w = unit weight of water, pcf
α = slope of the ground surface, phreatic surface and failure surface (soil/rock contact), degrees

FS = factor of safety

The susceptibility results of this study are expressed on the Failure Susceptibility Map (Plate 4). Unlike the quantitative assessment of the FS as would be calculated with LISA, the susceptibilities expressed on this map have been based on a non-quantitative assessment of factors found to be present at failure locations in the upper Canyon Creek drainage basin. These factors are:

alteration mineralogy	contact relations
faulting	groundwater
joint concentration	timber harvest
joint continuity	slope gradient: oversteepening
joint orientation	weathering: clay development

Four of the above factors (groundwater, contact relations, timber harvest and slope angle) occur as elements in the LISA slope stability program. However, the remaining six, dealing primarily with bedrock characteristics, are not found as specific elements in this program, suggesting that the use of a quantitative program for soil slopes, such as LISA, which omits rock slope factors, may not provide the best stability assessment for this basin.

Because of their ability to influence the degree of cohesion and friction in rock and soil masses, the ten factors listed above will be examined more closely in this chapter and will be associated with specific outcrop examples to illustrate their impact within the drainage. Table 26 provides a graphic representation of the impact of these factors on the degree of cohesion and friction noted in the failure locations previously identified in the subdrainage Tables in Chapter 5.

Table 26. Response of soil and rock mass cohesion and friction to factors most often associated with failure locations in the Canyon Creek drainage.

Factor	**Cohesion**			**Friction**		
	F	C	O	F	C	O
alteration mineralogy	-/*/+	-/*	*	-/*/+	-/*/+	*
contact relations	*	*	-/*	-/*	-/*	-/*
faulting	*	*	n/s	*	*	n/s
groundwater	-	*	-	-	*	-
joint concentration	-	-/*	n/s	-	-/*	n/s
joint continuity	-	-	n/s	-	-	n/s
joint orientation	-/*	-/*	n/s	-/*	-/*	n/s
slope gradient: oversteepening	*	*	-	-	-	-
timber harvest	-/*	*	-/*	-	*	-
weathering: clay development	-/*	-/*	*	-	-/*	-

+ = increases; - = decreases; * = no observable effect; n/s = the factor was not found to occur
F = Fragmental igneous bedrock; C = Compact igneous bedrock; O = Overburden

Alteration Mineralogy

Observations made during the course of field work suggest that, at many locations, the inclination of bedrock to fail is greatly influenced by the degree and type of alteration through the effect of this alteration on rock mass strength. The inception of failures in soil masses due to alteration was not noted within the study area. Alteration of the groundmass not affecting the texture (sodic or potassic enrichment of plagioclase, for example) does not appear to result in noticeable reduction in rock strength. However, replacement zones of alteration mineralogy often display noticeable differences in strength when compared to unaltered, or less altered, rock of the same lithology.

Observations in the field suggest three primary ways in which alteration reduces rock mass strength: 1) by replacement of the original texture with a more open texture, 2) through greater dilation of discontinuities and, 3) by degradation of the crystalline structure of the original rock due to acid attack or accelerated oxidation.

The types of alteration effects observed in the Upper Canyon Creek drainage are related to 1) low-grade regional metamorphism, 2) hydrothermal activity, and 3) post-magmatic (deuteric) cooling. These alteration mechanisms have resulted in one of the following rock-strength conditions:

1) Non-destructive "metasomatic" replacement which does not affect rock strength relative to the unaltered material, such as through sodic enrichment of plagioclase, as one example.

2) Destructive replacement or removal resulting in a rock of lower strength relative to the unaltered rock, such as through the alteration of mafic minerals to chlorite. The addition of iron sulfides would also be placed in this category where the weathering of the iron sulfide minerals accelerates decomposition (removal) along discontinuity surfaces, reducing the strength of the entire rock mass, but maintaining the strength of individual blocks.

The occurrence of intense iron-oxide staining on basalts and basaltic andesites is typical of the non-propylitized rock found adjacent to the intrusive bodies throughout the study area. Visual observations made during the course of field work have found that hydrothermally altered basalt and basaltic andesite rock masses contain a much greater amount of disseminated iron-sulfide (<5%) than less altered or unaltered rockmasses (<< 1%), and that the dioritic intrusions rarely contain visible amounts of iron-sulfide (<< 0.1%). Further, the altered rock masses often have a high degree of iron-oxide staining, are characterized by greater joint dilation (2 - 4 mm vs <2 mm) and have a larger number of easily dissociated blocks. Rockfall is common in these locations.

One very small area of orthoclasization appears to have developed in the SE NE SE 1/4 Sec 3, T.4 N. R.5 E., at the head of the East Fork of Jake's Creek along FS Road 38, where aphanitic basalt and porphyritic pyroxene andesite overlie a thin body of quartz diorite. The altered material has the appearance of coarse-grained, leucocratic, highly weathered diorite containing phenocrysts of light pink-brown orthoclase up to 1 cm. The rock is characterized by a coarse-grained alteration texture in places and a fine-grained to nearly aphanitic texture and darker color where less altered. Based on blow tests conducted in the field with a .45 kg hammer, disaggregation of the rock sample occurred more quickly in the coarser-grained rock than in the finer-grained, less altered rock. This outcrop is highly rust-stained on surfaces and along fractures due to the oxidation of iron-sulfides. There is no uniformity of alteration in this outcrop, suggesting that hydrothermal fluid migration may have been highly confined to the discontinuities.

Large rotational failures (slumps) occur in Sections 29 and 30 on the southwest side of Big Rock Creek. Bedrock materials have been affected by destructive alteration. Feldspar phenocrysts have been completely replaced by white, hydrous minerals and the mafic components have been altered to reddish iron hydroxides and green chloritic minerals. The rock found in the failure locations is composed entirely of fragmental igneous units which are highly weathered and easily crushed between the fingers. In contrast, adjacent outcrops of basalt exhibit very little, if any, groundmass alteration in hand sample and create a very minor amount of rockfall from roadcuts.

The rock capping the ridge between Jake's and Pelvy Creeks to the north of Saturday Rock in section 34, T.5 N. R.5 E. and section 2, T.4 N. R.5 E., shows very clearly the intense propylitic alteration of the Skamania andesites lying just above, or in contact with, the dioritic intrusion. The thermally metamorphosed andesites and basaltic andesites show great variability in the degree of alteration, from highly propylitized green and blue-green epidote-bearing rock, to light gray, fresh, porphyritic rock, to silica replacement bodies composed of quartz, plagioclase and, perhaps, minor orthoclase, and thick coatings of (oxidized) iron sulfide. In hand sample, protolith texture appears to be destroyed in the most highly propylitized rocks. Based on their response to repeated blows with a .45 kg hammer, rock samples containing secondary (alteration) minerals, such as chlorite or zeolites, visible with the naked eye, displayed more rapid disaggregation than both the fresh rock and propylitically altered rock composed of secondary minerals not visible to the naked eye.

Contact relations

In general, four types of contact relations are found to exist within the study area: 1) intrusive/extrusive, 2) compact igneous/fragmental igneous, 3) fresh/weathered and, 4) textural. Contacts, by themselves, do not cause failures; however, the presence of contacts magnify the effect of other factors at work along these surfaces. Failures occur along these contacts due to differences in the degree of weathering between units, jointing characteristcs, amount of dilation, permeability or degree of saturation, groundwater flow, root cohesion and so forth.

At the west end of the study area, contacts are almost always highly gradational between compact igneous bedrock and fragmental igneous material, and hackly and radial jointing occurs along the margin of some basaltic andesite dikes. There is, in almost every case, a very indistinct to nonexistent contact between the basaltic andesite dikes and the fragmental igneous rock. This very indistinct or extremely gradational contact between fragmental igneous and compact igneous rock has also been documented to depths of at least 30.8 m in cores recovered by the GPNF throughout the Canyon Creek basin (Carter, 1981a,b; Shelmerdine, 1984). In areas characterized by indistinct contact relations, root cohesion, soil cohesion, and depth to groundwater play important roles in stability.

Examination of other outcrop locations have shown that clasts in most fragmental igneous deposits are highly weathered; that small deposits highly suggestive of pillow/palagonite occur; and that numerous lapilli tuff deposits contain high concentrations of organic material, including tree trunks up to 3 m in length and 0.7 m in diameter. Thin hornblende andesite dikes cut these materials, particularly in the area around West Point, but possess a very distinct contact with the intruded deposits, often characterized by a baked or altered zone parallel to the contact. Because the outcrops are texturally heterogeneous, the strength characteristics exhibited by the rock mass, such as compressibility, permeability and durability, are not the same everywhere. This is manifest most clearly at the contacts where the dikes are solid and stable, but the intruded rock mass is disaggregating.

Volumetrically minor quantities of diorite and quartz diorite, presumed to correlate with the 19 to 19.6 $\pm$ .7 m.y. (Power and others, 1981) Silver Star pluton, crop out on or near the divide between the East Fork Lewis River valley and the Canyon Creek basin, as well as, in very small, scattered locations on many of the north/south-trending ridges south of Canyon Creek. The degree of rock mass strength exhibited at intrusive/intrusive and intrusive/extrusive compact igneous rock contacts was not found to differ from the rock mass as a whole. However, the rock mass strength of one outcrop was not necessarily the same as that of another, based on rebound testing with a .45 kg hammer. Rockfall is the only mass wasting process noted in these rock masses and occurs evenly across a rock mass.

North of Canyon Creek, contact relations seen in the unnamed peak which forms the south divide to the Sorehead Creek drainage, are more complex. Propylitically altered andesite has been variably silicified by fine-grained hornblende diorite and porphyritic dacite. Dacite tuff and pumice lapilli tuff units found at the top of the peak have been intruded by fresher-looking porphyritic andesite which forms the crest of the peak. Rockfall is common along FS Rd. 58 around this peak in response to one of three situations: 1) collapse due to undercutting, 2) oversteepened talus slopes and 3) disaggregation of blocky-jointed intrusive rock masses. In these cases, root cohesion is essentially non-existent and groundwater seems to have little effect, except as it contributes to freeze-thaw disaggregation. Components of shear strength, namely friction angle and normal stress, have the greatest role in creating the failures observed.

In summary, an extensive examination of contact relations throughout the study area has found that four types of contact relations exist: 1) intrusive/extrusive, 2) compact igneous/fragmental igneous, 3) fresh/weathered, and 4) textural. Field relations suggest that failures are more likely to occur along these contacts when the rock masses possess differing strength characteristics. These differences are manifest as a reduction in the degree of cohesion, friction or both, which are magnified at contacts due to the ease of accessibility of destabilizing processes along these surfaces.

Faulting

Seeping groundwater, gouge formation and offset characterize bedrock and soil areas interpreted to lie adjacent to fault trends in the study area. These influences on the factor of safety could not be adequately assessed due to the lack of suitable outcrop locations. In most cases where observed, these locations did not exhibit a greater tendency to fail; however, this may be due to the orientation of the outcrops, given that the presence of destabilizing elements was noted at all locations.

The Chelatchie Prairie fault zone (Mundorff, 1964, 1984) is the only mapped northeast-trending fault system in the Canyon Creek area. However, it lies to the west of the study area in the lower reaches of the basin and is documented no further east than the NE 1/4 sec 3, T.5 N. R.4.E. (Phillips, 1987). Interpretation of earthquake activity occurring since 1973 has suggested that the near vertical, right lateral, active Mt. St. Helens Seismic Zone (MSH) may pass through the study area (Weaver and Smith, 1981; 1983).

Identification of numerous near-vertical, gouge-filled fractures has been noted in the course of field work. These features are exposed in roadcuts and quarries but cannot be traced beyond these locations. Aerial photographs suggest that many of these locations may be associated with lineations. Often, gouge, lateral offset and/or seeping water is found somewhere along these trends. While these trends are coincident with the regional stream and ridge patterns, overwhelming physical evidence supporting the presence of the actual fault lines cannot be provided.

Interpreted near vertical, right lateral strike slip or oblique slip faults have been placed on both the east and west sides of West Point. These fault trends have been identified on the basis of offset along dikes and by the occurrence of vertical, gouge-filled fractures. The fault trend on the east side of West Point passes through an area

The evidence for the near vertical inclination of both northeast and northwest fault trends is further supported by the orientation of dikes of dioritic composition found along the ridges forming the southern divide of the basin. On Gumboot Mountain, cross-cutting, near vertical northwest- and northeast-oriented diorite dikes occur. In the southwest corner of the Tatoosh Hills 1.7 km to the southeast, diorite forms a prominent spire-like plug, which appears to be part of another northeast-trending dike system. However, between these two outcrop locations in the center of sec 4 T4NR5E along Slide Creek, hand sample analysis failed to identify the presence of diorite where expected if a feeder source had been continuous between the two centers. Therefore, it appears reasonable to suggest that the dioritic magma moved upward along essentially vertical fractures. In fact, all diorite dikes are found to occur along the axis of, or in line with, north/northeast-trending ridges.

In the NW SW 1/4 sec 7, T.5 N.R.5 E. just east of the National Forest boundary, a slow failure is resulting in the slumping of FS Roads 54 and 57 over an area of approximately 800 sq. meters. At this location, a NNW-oriented fault zone is characterized by both seeping and diamicton-filled fault traces. One diamicton-filled trace truncates a baked zone between a saprolite and an overlying flow unit. The second site is located on FS Road 37 in the SE NW SE 1/4 Sec. 22, T.5 N. R.5 E., 100 m above the Jake's Creek crossing. Here a 24.5 cm wide, vertical, gouge-filled crack splits the outcrop with no apparent vertical displacement; however, right-lateral displacement would account for the relative position of the outcrop around this fracture. The road passing over this spot is characterized by extreme roughness on the west side of the fault, due possibly to very minor offset which has exposed larger (cobble-sized) roadfill materials.

To summarize, northwest-oriented trends appear to be dominantly strike-slip and near-vertical in nature while the northeast-oriented trends appear to have a greater dipslip or oblique-slip component. Seeping groundwater, oversteepening, and gouge provide the potential for reducing the factor of safety around these locations. However, with the exception of the examples given above, neither trend, at present, appears to be having an adverse affect on the stability of the adjacent hillsides.

Groundwater

Many slides are driven by oversaturation of the subsurface where the failed material is found to overlie a coherent failure plane or textural change (Twelker & Assoc, 1972; Jones and Shakoor, 1989; Behringer and Shakoor, 1993). Studies conducted on failure locations associated with glacial deposits in northeastern Ohio found that the presence of an impermeable zone in the fill prevented free drainage and resulted in the build-up of pore pressure (Jones and Shakoor, 1989). This relationship between water and the potential for failure makes identification of seeps and areas prone to collect water a primary concern.

Forty-seven ephemeral seep locations and 38 perennial seep locations were identified during the course of field work (Plate 5). Water is frequently seen issuing from talus, glacial deposits and jointed compact igneous bedrock. During wet times of the year, these seeps discharge at rates which can be measured in liters per minute, in many instances. During drier times, seeps associated with fragmental igneous outcrops will often display a highly variable discharge. In one instance, a seep was discharging two liters/minute at 8 AM, but was dry eight hours later. Compact igneous bedrock outcrops will be dry, except for widely scattered seeping joints. Talus and glacial deposits will be dry to slightly moist, but contain localized seeps discharging up to six liters/minute.

A major problem involves determining which rock unit is the aquifer when direct observation is obscured by loose surface deposits. This study, and geotechnical studies conducted by the GPNF (Carter, 1981a,b; Shelmerdine, 1984), suggest that the flowpaths are dictated by bedrock jointing characteristics and contact relations in the following manner: 1) through interconnected joints in coherent bedrock units, 2) along bedding contacts within fragmental igneous units, 3) along textural boundaries and 4) at the overburden/bedrock interface.

Given that the majority of non-rockfall-type failures occur as shallow soil and debris slips and flows, a flowpath at the overburden/ bedrock contact would appear to have a much greater short-term impact on the stability of slopes in the area (Fig. 18). Shallow soil and debris slips of small volume (<10 cubic meters) occur within the overburden and regolith. In all cases, these failures appear to have resulted from a combination of groundwater and steep slopes. Overburden, as used in this study, refers to all loose materials fitting the engineer's definition of soil (Bowles, 1984; Johnson and DeGraff, 1988) and includes the weathering surface areas of rock units which can be easily disaggregated from the rock mass by hand.

Seeps are frequently observed in roadcuts and quarry walls where the bedrock fracture pattern is exposed. Water migrating along interconnected fractures reinforces surface observations and scattered rock core interpretations suggesting that a pattern of 3-D jointing (Williamson, 1978) is common in the compact igneous bedrock of the area. During times of oversaturation, the water has been observed flowing out of jointed compact igneous rock with high velocity, presumably as a result of confined flow path width and large hydraulic head. Water has not been observed issuing from jointed or fractured bedrock which does not contain interconnected discontinuities.

While the steeper slopes of the study area (17 to 38 degrees) are generally covered with overburden less than one meter thick, the toe slopes at the base of these areas are characterized by talus deposits which can exceed five meters in thickness. These talus deposits generally occur adjacent to the streams and roadways and, therefore, produce a great deal of concern when found to be transmitting water. One or more of the following has been associated with seeping talus sites: 1) a reduction in roadbed integrity, 2) addition of silt to the stream, 3) road blockage, or 4) blocked culverts and ditches.

Figure 18. Debris slip at the bedrock/overburden contact - Sorehead Creek, sec. 15, T.5 N. R.5 E. Shallow debris slips are common throughout the area where thin overburden or residuum overlies bedrock. Steep, smooth slopes and oversaturation are the primary instigators of failure. Numerous, small debris slips are visible in the lower right of the photo.

Five kilometers northwest of the study area along lower Siouxon Creek, seeping, thick glacial deposits are failing in rotational slides due to saturation. These thick glacial deposits possess sufficient aerial extent and textural heterogeneity to create instability by concentrating water in perched aquifers (Growney, 1993). In the upper Canyon Creek drainage, failure morphology suggests that similar large accumulations of drift, located along Canyon Creek just above the confluence with Puny Creek, have responded in a similar fashion. Here numerous, large, concavities have formed around active seep locations.

The presence of hydrophytic plants such as horsetails and succulents, and the occurrence of green grass during the drier time of the year, provide good evidence for the occurrence of seeping water. Quite often roadfill failures are associated with these indicators, either as arcuate scarps or slivers, slumps, sinkholes or as steep chutes developed into the roadfill. The speed with which these features develop appears to be related to the nature of the seep. As such, seeps can be separated into two types: perennial and ephemeral (not necessarily seasonal).

Ephemeral seeps affect roadfill/roadbed stability in two general ways: 1) by making it extremely difficult, during road construction, to place culverts where they will have the maximum effectiveness in intercepting water before it soaks back into the ground, and 2) by making early detection of culvert-related problems more difficult. In every case, the problem develops in rapid, sporadic stages, and failure may occur without warning.

Perennial seeps affect roadbed stability in the following ways: 1) constant saturation of roadfill materials results in larger areas affected by slumping, 2) the probability of roadfill/roadbed washout at any given time is greater and 3) the probability of road-blocking failures is increased due to the constant saturation of the materials above the road.

In perennially wet areas, failures generally evolve with time and provide indicators of potential failure such as pistol-butt tree trunks, tilted trees, hummocky toeslopes, increased rockfall and broad slumps. FS Road 37, passing through the south and southwest portion of Sec.16, T.5 N. R.5 E. along Canyon Creek, is characterized by failures created by perennial seeps. This 1.6 km length of road traverses numerous seeps which are creating broad slumps, roadfill failures and differential settling of the roadbed.

Quite often a concentration of potholes (4+ per sq. m) can be found in sections of roadbed crossing problem areas associated with perennial seeps. Such a location occurs above the campground at the turnaround on FS Road 3701 along Canyon Creek where the potholes are located directly above a developing debris chute. Development of these "sinkholes" is attributed to localized settling or collapse of the roadbed due to removal of some portion of the roadfill material resulting from groundwater flow. Sinkhole-like features occur on FS Road 37 in the S 1/2 Sec. 16, T.5 N. R.5 E. - Canyon Creek, FS Road 5301 in the NW NE 1/4 Sec. 29, T.5 N.R.5 E. - Big Rock Creek, FS Road 526 in the SE.SW.SE 1/4 Sec. 27, T.5 N. R.5 E. - Jake's Creek and FS Road 301 in the SW NW 1/4 Sec. 32, T.5 N. R.6 E. - West Crater. A review of Plate 4 (Slope Failure Susceptibility Map) shows that, at all these locations, the road in question crosses an area characterized as possessing high failure susceptibility.

When occurring adjacent to roads, seeps are frequently responsible for the incision of deep road gullies and failure of the roadfill prism. Observations made in the course of field work suggest that ditches with poorly placed, damaged or leaking culverts, or containing no culverts at all, may create local areas of oversaturation by creating catchment basins when a textural barrier exists in the roadfill. Slumping is often present, particularly on roadbeds underlain by fragmental igneous bedrock. The impact of unconfined water on roadfill failure was clearly demonstrated in the case of the KM Mountain slide in southwestern Washington. The initial movement was noted as a slow creep below the road level and was expressed as pavement settlement on the roadbed (Lowell, 1990).

If seeping water is allowed to flow across the roadbed, roadfill erosion occurs, sometimes with devastating results as in the case of FS Road 527 along the west side of Jake's Creek. Here ponded and seeping water from numerous sources flowed onto and down the gravel roadbed for nearly 37 m. This surface water formed a series of gullies up to 0.3 m deep and washed out the roadfill to the degree that the road, in places, is 0.3 m to 1 m narrower than designed (Fig. 19). The bedrock on which this fill has been placed, dips steeply into the canyon (36 degrees). Hillside seeps, intercepted by the roadcut, continually channel water across this surface, jeopardizing the integrity of the still intact portion of the road by magnifying the destructive potential of the surface runoff through constant saturation of the fill.

Oversaturation of area soils has not resulted in recent failures covering more than 0.4 ha (1 acre). Slump and slip failures related to oversaturation of the overburden are common along most of the roads from the west boundary of the study area to the Pelvy Creek drainage and are particularly abundant in locations underlain by fragmental igneous bedrock. Lapilli tuffs often contain excess water which flows along one or a number of the exfoliation-like shells paralleling the surface of these rock masses, or along the contact with the overburden.

In the NWSESE 1/4 Sec.17 T5NR5E above Canyon Creek, a large patch of the overburden, 3.7 m wide by 18.7 m long, failed above a steeply sloping (77 degrees) tuff breccia unit. While the overburden was heavily vegetated, the roots did not pass into the massive tuff breccia below the overburden. The roots of the larger trees, where observable, were seen to be growing parallel to the overburden/bedrock contact for the most part. Water was observed running across this exposed surface the entire field season (June to September).

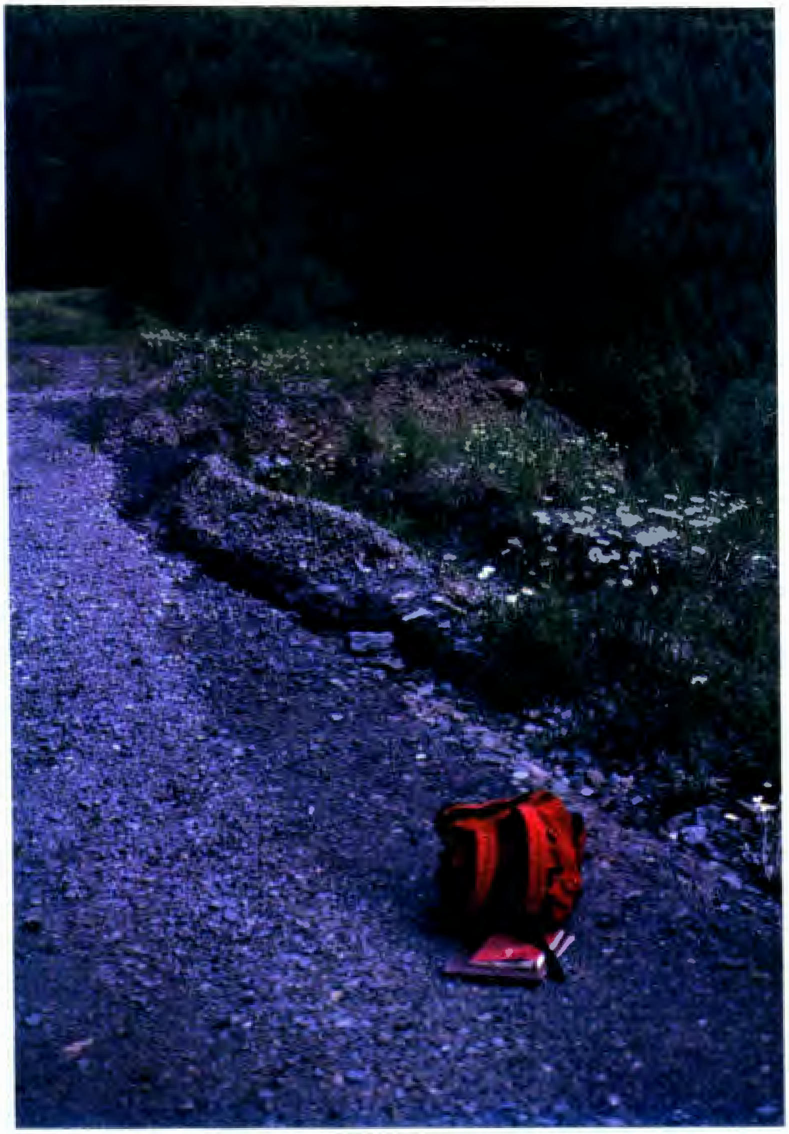


Figure 19. Roadbed destruction due to unconfined surface runoff - Jake's Creek, sec. 27, T.5 N. R.5 E. The two gullies in the photo are over .3 m deep. The boulder sticking out of the hillside in the background is part of the fill material and is exposed due to failure of the hillside resulting from surface runoff. This roadfill failure is occurring over strata dipping into the stream. The outermost gully is now a failure crack.

The development of a debris chute in the SW NE SW 1/4 Sec.10, T.5 N. R.5 E., on the southwest side of West Point, is occurring in tuff breccias, lapilli tuffs and lahars. To date, approximately 700 m^3 of material have failed. Numerous ephemeral seep locations occur vertically up this hillside for its entire length. In addition, the regional dip direction is out of the hillside. The presence of even larger fan-shaped, concave features along the ridge adjacent to the current debris chute (Fig. 20), suggests the possibility of continued failure at this site. Keough (1992) found that potentially large debris flows ($> 914\ m^3$) may have occurred just over the ridge on the northwest side of West Point, in the Siouxon Creek drainage, in the same lithologic and topographic setting.

In summary, groundwater plays a key role in the stability of hillsides and roadfills throughout the study area through the reduction of soil and rock cohesion and friction. Saturation of specific horizons within fragmental igneous rock, unconsolidated deposits, and roadfill, is common. The failures occur in the form of landslides, slumps, slips or flows. In the compact igneous rock, water is confined to a system of interconnected joints, and lacks the total rock mass saturation typical of the fragmental igneous rocks and overburden.

The erosive and destabilizing action of seeping groundwater is intensified by road construction through oversteepening, creation of impermeable roadfill barriers, and improperly located or functioning drainage networks. Slumps, cracks, concentrations of potholes and gullies on the roadbed delineate zones of potential roadfill stress.

Jointing Characteristics

Joint orientation, concentration, continuity, dilation, lubrication and roughness are major factors in the characterization of joint-related instability (Bieniawski, 1973). Over 150 bedrock outcrop exposures have been examined in the Canyon Creek study area. Of these, approximately 60% were fragmental igneous units (lahars, lapilli tuff, tuff breccia)

Figure 20. Active and ancient debris chute morphology - West Point, sec. 14, T. 5 N. R.5 E. A recent landslide has created a debris chute nearly 30 m across, visible in the upper right. Behind the tall, dead tree on the left is the scalloped-shaped scarp of an ancient slide which stabilized after encountering a dike on both sides. If dikes are the stabilizing factor, the younger feature may grow to nearly twice its present width, based on the location of the nearest dikes. The dip in this location is out of the hillside toward the viewer.

and 40% were compact igneous units (basalt, andesite, diorite). The primary jointing characteristics noted to be contributing to block disaggregation include: orientation, continuity and dilation.

One concern to slope stability in the basin, is the presence, in many rock masses, of a continuous, near vertical joint orientation which reduces the friction and cohesion of the whole rock mass without affecting the strength of the individual blocks. When viewed parallel to the strike of these joints, the rock mass is similar in appearance to a stack of cards viewed from the side (Fig. 21).

Figure 21. Vertically oriented jointing - FS Rd. 53, SE 1/4 sec. 28, T.5 N. R..5 E. Many bedrock units display a pronounced near vertical joint habit. Lack of a continuous, normal joint direction results in the unexpected degree of stability. Minor rockfall occurs but is very limited.

Because block strength is intact, all failures occur along joints and rockfall is the only mass wasting process present. In at least 90% of the exposures examined, rockfall consists of small to large (15 to 61 cm) blocks and slabs, reflecting the concentration (spacing) of discontinuities in the rock mass. The remaining 10% of rock masses observed fail along widely spaced joints and form angular blocks and slabs greater than 2 m in length.

Outcrops displaying platy jointing often have smaller accumulations of rockfall. This is most likely due to the near horizontal orientation of the continuous joint pattern. In the case of these outcrops, the dip angle is so low that the rock mass remains in place. Additionally, the interlocking, blocky habit of the rock mass provides a small amount of cohesion. While the degree of friction and cohesion currently allows the rock mass to exist as a coherent unit, an outside stimulus could easily alter this balance. As such, many areas of extensive compact igneous bedrock are considered to possess a high failure susceptibility, and in fact, all are associated with large underlying areas of talus.

In many cases where platy jointing occurs, the concentration and dilation of discontinuities decreases moving toward the center of the rock mass from the top surface. As a result, rockmass discontinuities grade from open planes of separation (dilated), with high block strength but lower rock mass strength, to latent planes of separation (visible but not dilated) to a massive-looking exposure characterized by preferred or random breakage with high rock mass strength (Fig. 22).

Figure 22. Variation in fracture dilation with depth - FS Rd. 310, NE 1/4 sec. 19, T.5 N. R..5 E. Typical compact igneous bedrock joint dilation habit. Rock mass joints are characteristically platy at the overburden contact (arrow), become more closed and latent with depth and nearly nonexistent furthest away from the contact.

Joint dilation is generally greater in fragmental igneous rock masses than in compact igneous rock masses; consequently, the degree of cohesion exhibited by fragmental igneous rock masses is less. The degree of joint dilation varies tremendously, from less than 1 mm to over 15 cm in all bedrock; however, over 95% of the compact igneous rock masses contain discontinuities less than 0.5 cm wide whereas, up to 95% of the discontinuities in fragmental igneous rock masses are greater than 0.5 cm.

Due to the translocation of weathered matrix or overburden material and accelerated weathering along the joints, a residue of fine-grained material has been found in essentially all joints examined regardless of rock type. In fragmental igneous bedrock, this fine-grained material reduces the friction of these outcrops along bedding planes as these rock units often display a jointing or parting along , or parallel to, the bedding. The result is a proportionally higher number of rotational and translational failures in the fragmental igneous bedrock as compared to the compact igneous bedrock.

Another factor responsible for the lesser degree of disaggregation of compact igneous bedrock is the increased roughness of the joint surfaces resulting from formation of iron-oxide. In the hydrothermally altered compact igneous rock, iron sulfides are common and the oxidization of these minerals on exposed surfaces has created an appreciable amount of roughness. Visual inspection has found that in many instances, this accumulation has created a weak iron-oxide cement bond which appears to counter the effect of increased clay by increasing the friction between blocks.

Along the main stem and tributaries between Sorehead Creek and Pelvy Creek, on the south side of Canyon Creek, rock avalanches contain blocks up to 4.6 m in diameter and cover areas ranging from 0.4 hectare to as much as 14 ha. The size of these blocks is a reflection of the spacing (concentration) of joints in the outcrop. Disaggregation from their respective bedrock outcrops is a result of a reduction in the degree of cohesion and friction due to joint orientation and continuity. Table 27 is a compendium of average block size documented for the rock avalanches identified in the drainage.

To summarize, the primary jointing characteristics contributing to bedrock disaggregation include: orientation, continuity and dilation. Dipping, connected and dilated joints reduce the cohesion and friction of a rock mass, while the accumulation of secondary cements within the joints may slightly increase the friction. Rock masses, with high block strength, containing joints characterized as being horizontal, discontinuous, non-dilated, or having rough surfaces, are less likely to fail due to the relatively higher degree of friction.

Table 27. Rock Avalanches - location, bedrock, block size

Drainage	Location	Bedrock	Block Size (in meters)
Big Rock Creek	NW SE SE1/4 Sec.32	Andesite	0.5 - 1.5
Jake's Creek	SE SE SW1/4 Sec. 22	Lapilli Tuff	1 - 4.6
	SE SE SE1/4 Sec. 33	Diorite	1 - 1.5
	NW SW SW1/4 Sec. 34	Diorite	1 - 1.5
Pelvy Creek	Ctr NW SW1/4 Sec. 2	Andesite/Diorite	1 - 1.5
	SE SE SE1/4 Sec. 34	Diorite	0.5 - 1
Canyon Creek	SE SE SW1/4 Sec. 8	Basaltic Andesite	0.5 - 1
	Ctr E1/2 Sec. 7/18 line	Basaltic Andesite	1 - 1.5
	S1/2 NE NE1/4 Sec. 21	Basaltic Andesite	1.5 - 1.7
	SE SE SE1/4 Sec. 31	Andesite	1 - 1.7

Slope Gradient: Oversteepening

Oversteepening in the drainage occurs in two ways: naturally and anthropogenically. The most direct impact of oversteepening to the stability of a slope is in the reduction of friction and normal stress at the cutface. A reduction in cohesion may also occur due to accelerated weathering of exposed bedrock surfaces.

In the study area, the most pronounced areas of failure related to oversteepening occur along the glacially scoured valley walls found in the five major tributaries and along upper Canyon Creek above the confluence with Puny Creek. All of these areas are characterized by rockfall. In some cases, this rockfall is extensive (>10 ha).

Large areas of rockfall (boulder fields) on oversteepened north and northeast-facing slopes appear to be remnants of rock avalanches. While moderately to highly jointed compact igneous bedrock is not experiencing more than minor rockfall at present, the effect of an earthquake on these oversteepened slopes could result in scattered areas of large volume rockfall.

Snow avalanche features are characterized by linear, clean chutes on steeper slopes and generally have snow accumulation zone inclinations between 30 and 45 degrees, with chute inclinations up to 70 degrees. Eighty percent of the chutes identified are located on east-facing slopes and 20 % occur on southwest-facing hillsides (Table 28).

Rockfall, debris fall and debris flow failures are associated with the snow avalanche chutes in the Canyon Creek area. These failures occur in response to a reduction in shear strength due to a decrease in friction and cohesion along the oversteepened chute walls. Increases in the unit weight of the soil and pore water pressure resulting from snow melt also reduce the factor of safety in these locations. While root cohesion aides in slope stabilization along the adjacent hillside, undermining eventually negates this effect.

Table 28. Location and aspect of snow avalanche chutes

Drainage/Landform	Location	Aspect
Upper Canyon Creek	SE NW NW 1/4 Sec. 8	east
Upper Canyon Creek	NE SE NW 1/4 Sec. 8	east
Upper Canyon Creek	SW NE 1/4 Sec. 8	east
Cougar Rock	NW SE SE 1/4 Sec. 8	east
Cougar Rock	Ctr S 1/2 NE SE 1/4 Sec. 8	east
Cougar Rock	NW SE SE 1/4 Sec. 8	east
Cougar Rock	SE SE SE 1/4 Sec. 8	east
Cougar Rock	SE SE SE 1/4 Sec. 8	east
Cougar Rock	Ctr N 1/2 NE 1/4 Sec. 17	southwest
Cougar Rock	NE SW SE 1/4 Sec. 8	southwest
Big Rock Creek	SW NE 1/4 Sec. 32	east

The second cause of oversteepening is due to the anthropogenic influence, namely the construction of logging roads. Failures have occurred as a result of one of the following construction-related conditions: 1) use of poor quality fill materials, 2) creation of roadfill permeability barriers, and 3) oversteepening. This is particularly evident along FS Road 37 at the tributary crossing in the NE SE 1/4 of sec 36, T.5 N. R.5 E. along upper Canyon Creek (Fig. 23). Here the road cuts through dipping basaltic andesite flows which are covered by a thin deposit of till, which in turn, is overlain by talus. As a result of the road cut, the talus is failing progressively upslope and road 37 is occasionally blocked by debris slips. Below the road at this location, a similar depositional relationship occurs but no instability was noted, even though the hillside had been

Figure 23. Effect of anthropogenic oversteepening. FS Road 37 in the NE SE 1/4 of sec 36, T.5 N. R.5 E. This roadcut has oversteepened the till and talus overlying basaltic andesite bedrock. Oversaturation has resulted in the progressive failure of the overburden which has blocked the road at times. The largest failure, on the left, is 30 m long. Note that the overburden is failing progressively uphill as highlighted by the overburden color changes.

clearcut. This suggests that oversteepening, rather than the loss of root cohesion, is driving the failure of the overburden on this hillside.

In the study area, the formation of rills and shallow concavities in till, and ravelling in varves, is an equilibrium response by these deposits to the oversteepening produced in roadcuts. Rills are no more than 0.7 m deep and form in till deposits as a result of erosion by surface runoff. Rockfall occurs as erosion dislodges cobbles and boulders onto the road.

In some glacial deposits shallow concavities occur rather than rills. These concavities are usually greater than 0.7 m in depth, suggesting that these deposits may be thicker than deposits characterized by rill formation only. Deposits exceeding some "critical" thickness may allow groundwater to perch along textural boundaries. During times of oversaturation, pore water pressure increases, decreasing the effective normal stress to the point that failure occurs along a critical circle, resulting in the concavity. Many concavities have developed rill overprints, presumably due to the thinning of the glacial deposit to below this critical thickness (Fig. 24). This relationship was observed for numerous failures in glacial materials in the Cincinnati, Ohio area (Behringer and Shakoor, 1993) and, most probably, for failures in thick glacial deposits in an area of lower Siouxon Creek located less than 5 km to the northwest of the study area (Growney, 1993).

Timber Harvest

A tremendous amount of logging has occurred within the basin. At present, no logging is occurring, but conservative estimates, based on field observations, would suggest at least 60 percent of the area has been clearcut over the past 30 years. All tracts have been replanted and are at least five years old.

The primary reasons that tree removal causes instability are the resulting increase in groundwater height and the reduction of root strength (Hammond and others, 1992).

Notations on the destabilizing effect of groundwater in the study area have been discussed previously. The influence of root strength is equally important, particularly the effect of the root mass as a stabilizing factor.

After timber harvest, root decay causes both the numbers of roots and the tensile strength of the remaining roots to decrease with time (Burroughs and Thomas, 1977). Studies by Ziemer (1981a,b) and O'Loughlin (1974) indicate that minimum root strength occurs within a period from about 3 years to 20 years after harvest. By 10 to 20 years after replanting, root reinforcement will increase to its uncut level if significant regrowth has occurred (Hammond and others, 1992).

Figure 24. Concavity and rill development in till - SE NE 1/4 sec. 34, T.5 N. R.5 E. The formation of rills and concavities in till deposits may be a reflection of the thickness of the deposits. Concavities (arrows) appear to form in thicker deposits as a result of failure along a critical circle, whereas, rills develop in response to surface wash. Note that the concavities have developed rill overprints due to the thinning of the deposits as a result of prior concave failure.

Failure morphology, noted during the course of field work, suggests that clearcutting had marginally reduced the stability of logged hillsides in locations where thicker overburden deposits are found to cover seeping dipslopes. Above FS Road 54 in Sections 7, 8, 16 and 17, to the intersection of FS Roads 310 and 621, in the lower Canyon Creek section, deposits of unconsolidated overburden occurring between 431 and 554 m in elevation appear hummocky in places. Sixteen ha (40 acres), or approximately 10%, of this zone have been mapped in failure. A soil pit dug in this zone failed to encounter bedrock within 1.6 m of the surface. However, based on the low number of pistol-butt trees, it appears that regrowth (root-related cohesion) has stopped, or nearly stopped, any movement which may have occurred immediately following logging. Without a quantitative assessment of the driving forces at work, and physical monitoring of these locations for continued movement, the true impact of reforestation can only be approximated based on the surficial field evidence collected.

All failure locations shown on the Failure Inventory Map (Plate 3) in the Big Rock Creek and lower Canyon Creek subdrainages are considered to have a high potential for future failure should logging occur on them. All of these locations are characterized by pistol-butt and tilting trees, hummocky terrain, thick overburden, seeping groundwater and low strength fragmental igneous bedrock. Further, many of these slope areas exceed the angle of repose and occur on dipslopes.

For most other locations throughout the study area, logging appears to have had a minimal impact due to the predominance of compact igneous bedrock units, with the exception of the thick talus accumulations associated with toe-slope locations. These locations are common in the upper Pelvy and Canyon Creek drainages. Removal of these toe areas or a decrease in root strength might result in reactivation of these deposits through a reduction in soil and root cohesion, friction and increased pore water pressure.

Within the study area, poorly constructed roadbeds, and hillsides oversteepened in roadcuts, are providing many more instances of failure (125) than areas which have been clearcut (14). This fact is corroborated by a related study by the Forest Service (Keough, 1992) conducted on the Siouxon Creek side of the divide forming the north boundary of the study area in the vicinity of West Point. In the Forest Service study, virtually no slope failures were observed outside the road prism in any of the clearcut areas inspected. Furthermore, the inspection was conducted on tracts with less than 10 to 15 years of regeneration and included steep headwall areas and locally steep slopes adjacent to streams. Keough (1992, page 3) concluded that "This appears to indicate that harvesting has minimal direct effect on mass soil movement in the area...".

Weathering: Clay Development

Observations in the field suggest that glacial scour has removed much of the weak, weathered surface material. Therefore, the speed with which present outcrops lose shear strength due to chemical and mechanical attack, appears to be highly dependent upon the groundmass texture, bedrock characteristics, and degree of alteration. Weathering in the compact igneous rocks is restricted to discontinuities and surfaces, unless the rock has been intensely altered. Fragmental igneous bedrock often displays more pervasive weathering due to its greater permeability.

In the NW SW NE 1/4 of Sec. 17, T.5 N. R.5 E. above Canyon Creek, FS Road 53 crosses over what is interpreted to be a highly jointed basaltic plug. The weathering margin around this feature is characterized by a blanket up to 20 cm thick, of small, medium brown, flat, rectangular chips generally less than 2.5 cm in length overlying bedrock with weathering rinds up to 5 cm thick. Where the road crosses the weathering margins of this feature, it is offset as a result of decomposition of the subgrade.

Likewise, hydrothermal alteration influences the degree and intensity of weathering. An intensely weathered porphyritic andesite outcrop occurs in the SE NE

SW 1/4 of Sec. 20, T. 5 N. R.5 E. on FS Road 5301 along Big Rock Creek. This rock mass is characterized by a leached groundmass, altered plagioclase phenocrysts, crumbly texture and forms grus-like talus. Chunks of this material can be easily crushed by hand; consequently, the cohesion of this rock mass is interpreted to be very close to zero. The cutface is essentially collapsing due to the apparent lack of shear strength.

Fragmental igneous deposits (lahars, flow breccias, lapilli tuffs and ashflow units) will often have weathering rinds up to 12 to 14 cm. and occasionally, be completely decomposed to a state identifiable as a Cr soil horizon. The most obvious effect of weathering on the stability of slopes underlain by these rock masses, appears to be a reduction in friction resulting from the development of exfoliation-like "shells" parallel to the surface, and the loss of cohesion due to pervasive weathering. Within the study area, rockfall, debris slips, and rotational and translational slides are common mass wasting processes in this type of bedrock.

Due to greater cohesion, dense, welded ashflow units do not display ravelling and exfoliation-like weathering habits to as great a degree as non-welded bedrock. They are characterized by less pervasive saturation and weathering. Their widely spaced, blocky jointing habit is more typical of compact igneous rocks. Rockfall is the most common mass wasting process in these rock masses. Slab blocks as large as four meters in length have been observed (Fig. 25).

An important residual weathering product found in many mountainous areas is saprolite. Saprolite is a condition brought about by chemical weathering such that the rock tends to crumble but still retains the original structure and texture. Geochemical weathering of a rock mass will disrupt the minerals orderly atomic arrangement and thereby, reduce the cohesion found within the rock mass (Carroll, 1970). The Gifford Pinchot National Forest has found saprolite to be pervasive in fragmental igneous deposits to at least 30.8 m below the surface (Carter, 1981a,b).

Figure 25. Slab block failure in a fragmental igneous unit - FS Rd. 310, ctr. sec. 16, T.5 N. R.5 E. Large failure blocks are common in the more welded ashflow units, which have jointing habits more similar to compact igneous bedrock. These slabs are as much as 4.7 m in length. Backpack (arrow) is .3 m for scale.

Interpretation of widely scattered surface outcrops and drill core samples has found that the greatest degree of saprolite development occurs at the west end of the study area from the National Forest boundary to a roughly northeast-trending line running between Gumboot Mountain and West Point on the east. The greatest incidence of translational and rotational failures is found within this area.

In summary, weathering contributes to slope instability by reducing the cohesion and friction of rock masses through accelerated chemical and mechanical attack of exposed joint and surface areas, and pervasive groundmass decomposition in fragmental and highly altered rocks. Approximations of rock strength, conducted in the field using a .45 kg hammer or crushing by hand, suggest that as the number of discontinuities, degree of permeability and extent of alteration increase, the relative shear strength of a rock mass is reduced as compared to less affected rock masses.

Summary

This chapter has identified and discussed factors associated with location failures in the upper Canyon Creek study area. The reducing of cohesion of soil and rock masses contributes to the creation of unstable slopes. The degree to which any factor has an influence on the factor of safety has been found to be very site specific.

Chapter 7.
Glacial Relations

General

The following discussion on glacial morphology and features is intended to show that the majority of overburden in the Canyon Creek basin has been derived through glacial scouring of high strength, competent rock masses, and not through the mass wasting of weak, low strength rock masses. This understanding will help to account for large areas of naturally oversteepened slope versus the apparent lack of instability observed in the drainage.

Diamicton refers to any non-sorted to poorly sorted terrigenous deposit which contains a wide range of particle sizes and appears somewhat similar to glacial till (Flint and others, 1960). While moraines and varves are clearly of glacial origin, deposits formed as a result of non-glacial processes are frequently difficult to distinguish from those of glacial origin, particularly when associated with glaciated areas (WSDOT, 1992a,b). Many mass wasting processes, which are now active or have been active in the basin, are recognized as capable of forming diamicton and include: landslides, earthflows, mudflows and possibly, snow avalanche activity.

Rock Avalanche Deposits

Highly jointed bedrock, once oversteepened by glaciation and left unsupported by glacier meltback, will collapse, thus obscuring the classic U-shaped valley morphology (Williamson, 1985). The resultant accumulation of blocks and boulders is interpreted to be rock avalanches initiated by the oversteepening of jointed, competent bedrock.

While individual talus accumulations and some rotational slide complexes cover more area within the drainage basin, rock avalanches represent the largest deposits of mass wasting origin to form in a singular event as glacially oversteepened valley walls were left unsupported after glaciation. Testing of rock strength in outcrop, both by the Forest Service (Carter, 1981a,b; Shelmerdine, 1984) and in the course of field work for this study, as described in the previous chapter, has found that compact igneous rock, which forms most of the near vertical valley walls, can be classified as high quality material (BBEA). Table 29 is a compilation of rock avalanche locations. Since many of these locations are associated with existing vertical outcrops, minor rockfalls continue to add material to the original rock avalanche deposit.

Glacial morphology and deposits

Plateaus located above cirque elevations, rockfalls, talus, broad U-shaped valleys, smooth, plucked bedrock surfaces and broad, bedrock-cored benches below scarp-like headwalls provide abundant evidence of the glacial impact on basin morphology. Broad, incised U-shaped valleys are associated with each major tributary (Fig. 26). Remnants of lateral moraines occur and occasionally intersect moraines from tributary valleys. Gently sloping, broad benches occur in the Jake's Creek and Big Rock Creek drainages along with rock avalanche deposits and very large deposits of talus. Smoothly sloping, scoured bench areas are very prominent along Canyon Creek from the Jake's Creek and Sorehead Creek area west to the National Forest boundary. In this area, the greatest accumulation of diamicton occurs and numerous quarry locations have exposed the bedrock/overburden contact to show that diamicton overlies the scoured bedrock surface and is often accompanied by till (Fig. 27). In the case of Hackamore Creek, located in the northeast corner of the study area, preservation of the U-shaped valley has been maintained due to resistant compact igneous bedrock in the valley walls, the lack of tributary streams, and filling of the valley floor by a young andesite flow.

Numerous locations consisting of either a chaotic jumble of very large blocks or extensive volumes of talus and rockfall are considered, at least in part, glacial in origin.

Table 29.   Rock Avalanches - location, bedrock, extent

Drainage	Location	Bedrock	Extent Ha	Extent Acres
Canyon Creek	SE SE SW1/4 Sec. 8	Basaltic Andesite	6.5	16.0
	Ctr E1/2 Sec. 7/18 line	Basaltic Andesite	3.5	8.7
	S1/2 NE NE1/4 Sec. 21	Basaltic Andesite	0.6	1.5
	SE SE SE1/4 Sec. 31	Andesite	5.3	13.0
Big Rock Creek	NW SE SE1/4 Sec.32	Andesite	1.2	2.9
Jake's Creek	SE SE SW1/4 Sec. 22	Lapilli Tuff	14.0	34.8
	SE SE SE1/4 Sec. 33	Diorite	2.3	5.8
	NW SW SW1/4 Sec. 34	Diorite	2.3	5.8
Pelvy Creek	Ctr NW SW1/4 Sec. 2	Andesite/Diorite	7.3	18.0
	SE SE SE1/4 Sec. 34	Diorite	7.3	8.0
			50.3	**20.5**

Rock avalanche deposits comprise 0.62% of the total study area

Large areas covered by accumulations of angular to subrounded boulders and blocks have been formed by either rock glaciers (lobate and hummocky) or rock avalanches (smooth, straight slope). Table 30 shows that the rock glacier-derived deposits, represented by large accumulations of blocks up to 4.7 m in length, cover sites ranging from 0.4 to 25 ha (1 to 61 acres) in size.

Figure 26. Remnant U-shaped tributary valley - Sec. 28/33 line, T.5 N. R.5 E. A short well-defined glacial tributary valley in the Big Rock Creek system. Till is common in many places along this small U-shaped valley.

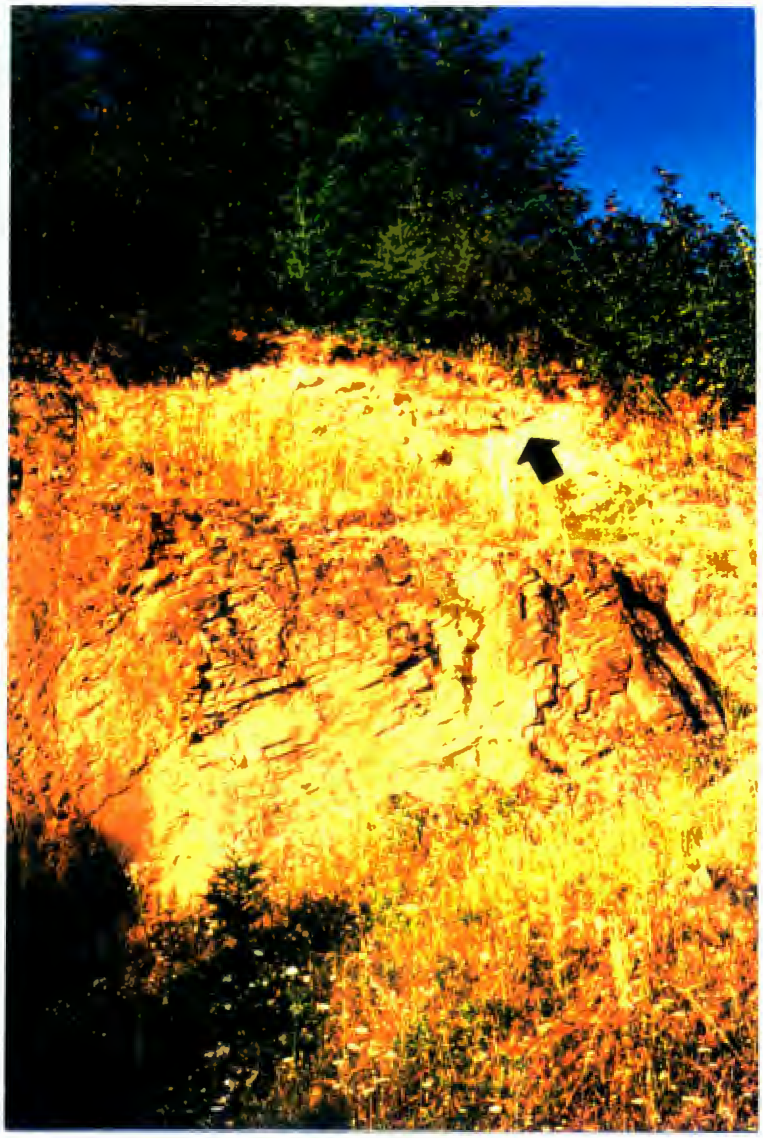


Figure 27. Scour surface contact with glacial overburden - FS Rd. 310, NE 1/4 sec. 19, T5 N. R.5 E. Scoured, dipping basaltic andesite bedrock overlain by cobbly fine-grained diamicton and also a small patch of cobble/boulder till (arrow). This clearly shows the impact of glaciation on the bedrock and suggests one reason for the dearth of weak or highly weathered surface material in the upper Canyon Creek basin.

Table 30. Rock Glaciers - location, bedrock, extent

Drainage	Location	Bedrock	Extent Ha	Extent Acres
Big Rock Creek	NE NE1/4 Sec. 5	Andesite/Basalt	14.0	34.8
Pelvy Creek	SE SE SE1/4 Sec. 2	Diorite	0.6	1.5
	SE SW SW1/4 Sec. 2	Diorite	7.3	18.0
Hackamore Creek	Btm Ctr S1/2 Sec. 32	Andesite/Basalt	7.0	17.4
Canyon Creek	T.4N., R.6E. -			
	Ctr E1/2 SE1/4 Sec. 6	Andesite	10.5	26.0
	NW NE1/4 Sec. 8	Andesite	18.8	46.4
	NE SW1/4 Sec. 6	Andesite/Basalt	11.7	29.0
	NW NW1/4 Sec. 6	Andesite/Basalt	5.3	13.0
	T.4N., R.5E. -			
	N1/2 NE1/4 Sec.1	Andesite/Basalt	24.7	61.0
SE corner of map	T.4N., R.6E. -			
	SW SW SW1/4 Sec. 4	Andesite	4.7	11.6
	SW NW SW1/4 Sec. 4	Andesite	3.5	8.7
	SW NW1/4 Sec. 9	Andesite	10.5	26.0
Fly Creek	SE SW NE1/4 Sec. 6	Andesite/Basalt	1.2	3.0
			119.8	**296.4**

Rock glacier deposits comprise ~ 1.45% of the total study area

On the basis of their association with glacial morphology and deposits, some very large talus deposits, in the Pelvy and Jake's Creek subdrainages, are interpreted to represent material plucked from resistant bedrock during the maximum valley ice, then dumped below the in situ location as the glacier melted away from the valley walls. These deposits have the appearance of being products of mass wasting. Arguably, they look similar to rock avalanches in many cases, and post-glacial rockfall has modified their appearance. However, unlike rock avalanches, the cobbles and boulders in these deposits are a mixture of rounded to subangular and angular clasts and generally rest on scoured bedrock. The source areas for these very large talus deposits are resistant cliffs which occur at the same elevation, or slightly above, adjacent scour surfaces.

Smooth, plucked bedrock surfaces and broad bedrock-cored benches are the result of glacier scour. In many cases, these features look like large landslide surfaces characterized by a steep headscarp and a broad, gently sloping bench. Upon closer examination, it becomes clear that their origin is directly attributable to glaciation. The benches are often covered with diamicton or till and resistant bedrock is occasionally exposed through the overburden. Quite often, exotic material is found in the overburden, and a bench often occurs across the valley at the same approximate elevation.

Many deposits have a dioritic influence. Soil pH testing, conducted as a part of this study, has shown that the dioritic source areas associated with Gumboot Mountain and Saturday Rock have pH values near 4.6. Andesitic and basaltic source areas appear to have values between 5.2 and 6.0. A soil profile of a cirque deposit from a site located on the west flank Gumboot Mountain is characterized by a pH value of 4.6 in the lower horizons and 5.2 in the upper horizons, reflecting the change in parent material. A highly leached and/or intensely altered rock occurs at the basalt/diorite contact on the southwest flank of Saturday Rock and has a pH value of 4.8. Likewise, the kame deposit referred to in the paragraph above, located 3.5 km northwest of Gumboot Mountain, has a pH value of 4.8. In both of these cases, the dioritic source is no longer exposed on the Canyon Creek side of the divide. As a result, post-glacial deposits of mass wasting origin contain very little, if any, dioritic material. As such, all deposits containing more than a rare component of dioritic material are interpreted to have formed through a glacial process.

In all bench locations where the overburden/compact igneous bedrock contact is exposed by roads or quarries, the bedrock has the appearance of being scoured. The contact is always a nearly flat, slightly rounded or gently sloped, plucked surface. Highly jointed bedrock appears to be more crushed or plucked than bedrock which is massive or has widely spaced joints, and the concentration of joints and the degree of dilation of these joints frequently increases as the overburden/bedrock contact is approached.

Along Canyon Creek above its confluence with Pelvy Creek, scour surfaces are frequently covered with a thin till which is covered by rockfall talus. Moraines are highly variable in length, generally about 3 to 4.6 m high and 2 to 3 meters in width. The numerous, small outcrops are interpreted to represent segments of a formerly large, continuous moraine preserved from erosion by virtue of their location.

Varve deposits are found along Canyon Creek above the confluence with both Big Rock Creek and Jake's Creek. These are interpreted to represent ponding of water above ice dams created when glaciers from these tributaries blocked the main channel (Fig. 28). The varves are composed of highly compacted silts and fine sands, which form deposits up to 7 m thick. In one outcrop, dropstones are found in horizontal varves overlying a contorted interval nearly one meter thick. Bedding sags can be found under the largest (> 1m) clasts. The degree of compaction and contortion of the strata is interpreted to have been the result of an overriding glacier.

Stability characteristics

In general, stability appears to be fair in the varve deposits and thin tills, but questionable in thick and extensive areas of drift. While varve deposits are slaking and raveling in the cutface along roads, no sign of larger-scale failure has been noted in these deposits within the study area. These deposits, in all cases, are compact, cohesive and non-dipping. All outcrops of varve deposits occur in roadcuts which expose the fact that root cohesion is essentially non-existent in these deposits, as no large, and very few small roots occur. Further, varve deposits will either be totally wet, or contain layers which are wet. This saturation appears to drive the raveling and slaking by contributing to the effects of wetting and drying, and freeze-thaw cycles, which reduce the degree of cohesion along the surface, and by increasing the unit weight of the surface soil mass.

The majority of glacial deposits are unconsolidated and non-cohesive as a result of the preponderance of gravel and larger-sized material which constitutes up to eighty percent (by volume) of these deposits. Consequently, thicker accumulations of these materials tend to exhibit slump-to-flow type failures due to their lack of cohesion, the presence of groundwater, and tremendous permeability. Thinner deposits appear to be affected more by surface runoff which forms deep rills and creates a small amount of rockfall due to the dissociation of clasts from the deposit.

Figure 28. Disrupted varves - FS Rd. 54, SE 1/4 sec. 8, T.5 N. R.5 E. The disruption in this varve sequence along lower Canyon Creek is interpreted to have occurred as a result of overriding by glacial ice. Cobble/boulder till (out of picture) forms the superjacent deposit. Dropstones up to 0.7 m can be found in this sequence above the level of the disruption.
Note bowing of varves over small dropstones (arrows).

Chapter 8.
Non-Cohesive Surficial Deposits

Overburden

In many locations, particularly where exposed during quarrying or road building, depth to bedrock can be seen to vary tremendously within 1.5 m to 3 m horizontally, from essentially a thin (<5 cm) humus cover to nearly 2 m of coarse-textured mineral soil. Core descriptions prepared by the GPNF (Carter, 1981a,b) show similar overburden depths (1.3 to 2.9 m). A number of the most prominent overburden/bedrock locations are shown in Table 31. Texturally, these deposits are characterized by one of the following: gravelly sandy loam, subangular to subrounded cobbles and boulders with a sandy to silty loam matrix, angular to subrounded cobbles and boulders, bedded silts and clays, and residual soils developing on bedrock.

In a volumetric evaluation of 41 deposits, 34 of these consisted of a 60% or greater volume of clasts larger than 4.75 mm. These volumetric approximations have been included in Table 32. The collection locations for these samples can be found on the Quaternary Deposits Map (Plate 2). When determining the grain size distribution for a coarse-grained deposit, larger test samples are required for the sieve analysis (Bowles, 1984). The largest standard U.S. sieve size is 101.6 mm (4"). The volumetric majority of material in the 34 deposits is greater than 101.6 mm. The grain size distribution values are based on the weight percent of that portion retained on the appropriate sieve. The volumetric values given in Table 32 are based on the apparent volume of the deposit occupied by material greater than 4.75 mm in diameter.

Table 31. Locations which allow clear observation of overburden/bedrock contact relations

Drainage	Location	FS Road No.	Outcrop Type
Canyon Creek	SE NW SW 1/4 Sec 21 T5NR5E	53	Quarry
Canyon Creek	SW NW NW 1/4 Sec 16 T5NR5E	310	Quarry
Canyon Creek	SW NW 1/4 Sec 8 T5NR5E	57	Quarry
Canyon Creek	SE NW SE 1/4 Sec 16 T5NR5E	54	Roadcut
Canyon Creek	SW SW NW 1/4 Sec 16 T5NR5E	54	Roadcut
Canyon Creek	SE NW SE 1/4 Sec 22 T5NR5E	37	Roadcut
Canyon Creek	NE SE 1/4 Sec 36 T5NR5E	37	Roadcut
Canyon Creek	NE SW SW Sec 17 T5NR5E	572	Quarry
Big Rock Creek	NE SE SE 1/4 Sec 29 and W 1/2 NE 1/4 Sec 32T5NR5E	519	Roadcuts
Big Rock Creek	W 1/2 NW SE 1/4 Sec 20 T5NR5E	536	Roadcut
Jake's Creek	SE SW SE 1/4 Sec 27 T5NR5E	526	Roadcut
Slide Creek	SW SE NE 1/4 Sec 5 T4NR5E	517	Roadcuts

Table 32. Volumetric estimation of deposit composition

Sample #	Deposit type	Percent greater than 4.75 mm	Percent less than or equal to 4.75 mm
1600	Drift	1	99
3167	Fragmental igneous	80	20
4200	Fragmental igneous	80	20
526/37	Varves	0	100
5301 -2	Drift	60	40
54	Saprolite	40	60
605	Fragmental igneous	70	30
B-1	Fragmental igneous	70	30
B-17	Fragmental igneous	60	40
B-21	Kame	30	70
B-28	Fragmental igneous	60	40
B-3	Drift	60	40
B-36	Fragmental igneous	60	40
B-4	Fragmental igneous	60	40
B-40+	Drift	70	30
B-6	Fragmental igneous	60	40
B-92+	Drift	60	40
B-94	Moraine	70	30
C-27	Drift	80	20
C-3	Fragmental igneous	60	40
C-30A	Fragmental igneous	90	10
C-30B	Drift	90	10
C-41	Fragmental igneous	60	40
C-47	Fragmental igneous	80	20
C-49+	Drift	70	30
C-54	Fragmental igneous	80	20
C-6	Fragmental igneous	60	40
CC-1	Varves	0	100

Table 32 (cont.). Volumetric estimation of deposit composition

Sample #	Deposit type	Percent greater than 4.75 mm	Percent less than or equal to 4.75 mm
CC-3	Drift	70	30
CC-4	Fragmental igneous	60	40
J-18	Fragmental igneous	1	99
J-24+	Moraine	70	30
J-32	Drift	60	40
J-43	Fragmental igneous	60	40
J-51	Fragmental igneous	70	30
J-53	Fragmental igneous	70	30
N-36	Fragmental igneous	60	40
N-41	Fragmental igneous	60	40
N-45	Drift	60	40
N-46	Varves	0	100
WC-1	Fragmental igneous	60	40

During construction of the Spirit Lake Highway (SR 504), zones of till were encountered in close association with colluvial deposits. The till was not easily discernible from the colluvium based on test hole data, as both types of material had similar clast roundness and matrix textures (WSDOT, 1992a, b). Similarly, in the study area, the ability to confidently identify the origin of an overburden deposit is difficult when the contact relationship can not be examined. Field relations and infrequent outcrop exposures would suggest that deposits of fine-textured, gravelly sandy silts and subangular to subrounded cobble/boulder deposits occurring on broad, gently-sloping (< 7 degrees) benches, are most likely of glacial rather than mass wasting or residual origin. These deposits are usually well-drained, allow excellent root penetration, and have low slope angles. Failures were noted only in areas where these conditions had been altered, such as along roads and in some logged areas.

Many areas of colluvium exist in association with oversteepened bedrock outcrops. The orientation and continuity of joints in the rock mass are the primary factors in generating this material through the reduction of friction along dilated joints, and cohesion for the rock mass on the whole. While the strength of the individual blocks accumulating below these outcrops remains high, these deposits often rest at or near the angle of repose and as such, are easily destabilized by oversteepening. Groundwater has been found to flow through these deposits with ease, but does not have much influence in causing stability problems due to the coarse, open and interlocking texture of these deposits.

Soil Development

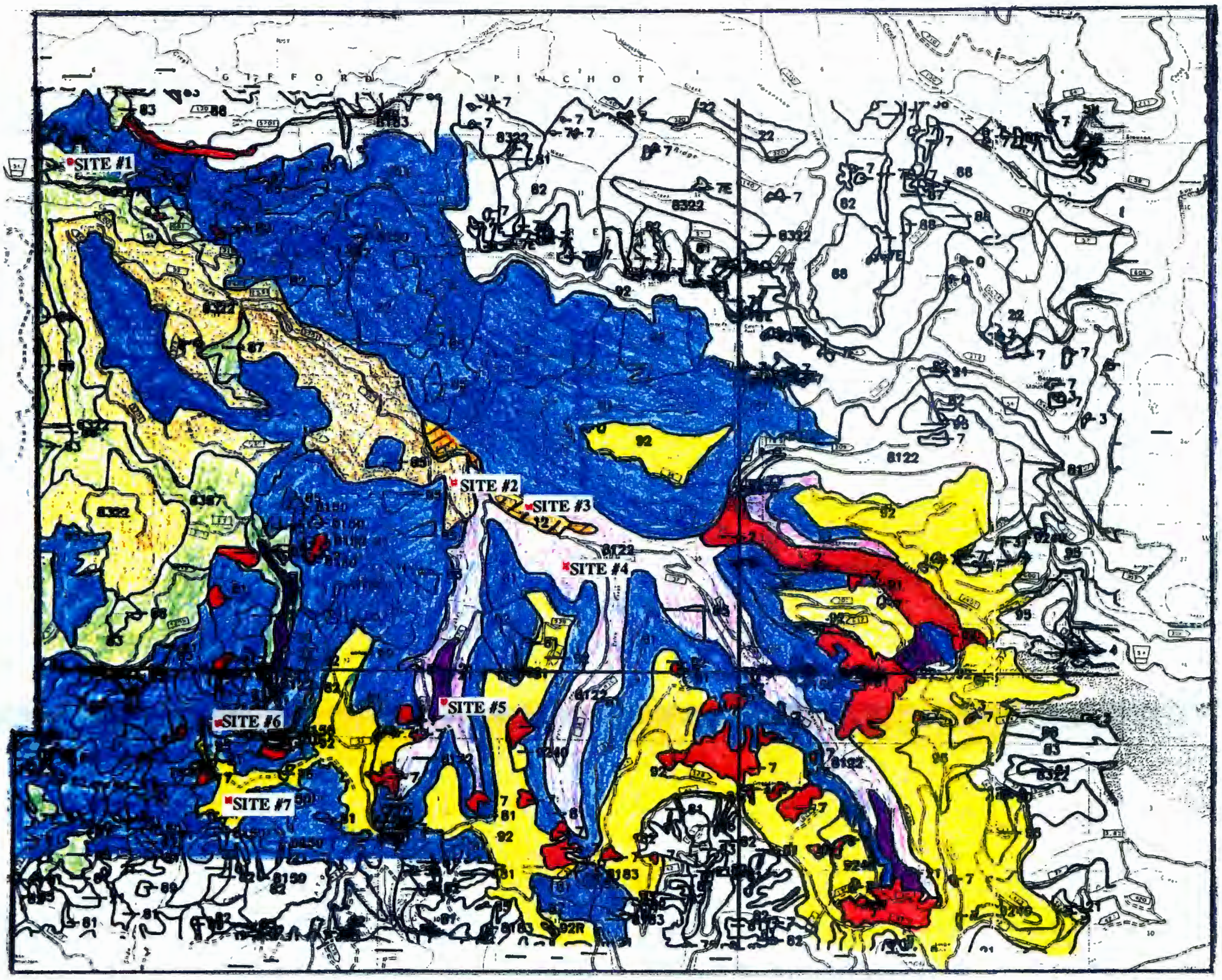
General

In assessing the factor of safety for slopes characterized by soil development, variables such as, but not limited to, soil cohesion, thickness of the soil, tree weight, root cohesion, degree of soil saturation, depth to groundwater, and textural and roughness conditions at the soil/bedrock contact must be considered. Quantification of these elements will provide a reasonable and reproducible estimate of hillslope soil behavior (Wooten, 1988). Due to budgetary constraints; however, quantification of these factors was not possible in this study, with the exception of soil consistency in the cohesive portion of the overburden.

The Forest Service has identified seven generalized soil types in the Canyon Creek basin. The geographic distribution of these is shown in Figure 29.

The soil types in areas 1 and 2 are identified in the Forest Service Soil Resource Inventory (SRI) (Wade, 1992) as being more clayey than the other soil types in the basin. These areas are underlain primarily by fragmental igneous bedrock (80%), whereas, the ratio associated with areas 3 - 6 is closer to 50/50. Soils associated with area 7 are underlain by >80% compact igneous bedrock.

As part of this study, one soil pit was dug in each of the soil types identified in the SRI with the location of each identified in Fig. 29. The amendments proposed in this study to the existing soil classifications reflect the degree of heterogeneity encountered. Table 33 compares the results of this study with that of the SRI. Textures are listed as they occur in the soil profile, for example, loam higher in the profile becoming more clayey with depth might be illustrated as L/SiCL, however, in most cases, the textures appear to occur as subtle variations within a single textural field. All soil nomenclature used in this study conforms to that developed by the Soil Survey Staff (1992).



1 Andic Haplumbrepts, medial over clayey, mixed, frigid

2 Andic Haplumbrepts, medial over loamy or clayey, mixed, frigid

3 Typic Udivitrands, pumiceous over sandy skeletal, frigid

4 Andic Haplumbrepts medial over loamy or loamy skeletal, mixed, frigid

5 Andic Haplumbrepts, medial over loamy, mixed, frigid

6 Andic Haplumbrepts, medial over loamy skeletal, mixed, frigid

7 Andic Cryumbrepts

Bedrock

Figure 29. Distribution of soil types found in the upper Canyon Creek study area. Areas 1 and 2 are identified in the Forest Service Soil Resource Inventory (Wade and others, 1992) as containing the most clay-rich material within the study area. This study has found that these areas are experiencing the greatest number of translational and rotational failures.

Table 33. Comparison of soil classification and texture for the soils found in the upper Canyon Creek basin.

Area Number	GPNF SRI	This Study
1	Andic Haplumbrepts medial over clayey, mixed, frigid	Typic Udipsamments
Texture:	L & SiL/SiL & CL	SL
2	Andic Haplumbrepts medial over loamy or clayey, mixed, frigid	Andic Hapludalfs
Texture:	SiL/SiL & CL	SiL
3	Typic Udivitrands pumiceous over sandy skeletal, frigid	Andic Udorthents
Texture:	SL/S & Gravel	SL
4	Andic Haplumbrepts medial over loamy or loamy skeletal, mixed, frigid	Andic Haplumbrepts
Texture:	SL/L	L/SiL
5	Andic Haplumbrepts medial over loamy, mixed, frigid	Andic Haplumbrepts
Texture:	L/SL & L	L/SiL
6	Andic Haplumbrepts medial over loamy skeletal, mixed, frigid	Andic Hapludalfs
Texture:	SL/L	SiL
7	Andic Cryumbrepts	Andic Cryumbrepts
Texture:	SL/L	L

Physical Characteristics

The distinction between a cohesive and a noncohesive soil is important in an assessment of the degree to which a soil may deform under stress. The soil responds to stress in a nonplastic, plastic or viscous manner and will change from one state to the next depending on the water content (Johnson and DeGraff, 1988). Terzaghi (1925) is credited with recognizing the usefulness of the liquid and plastic limits as consistency index values which could be useful in soil classification. Casagrande (1948) modified the procedure for determining the liquid limit to improve the reproducibility of the test.

Following are some of the general relationships between the Atterberg Limits and the physical properties for inorganic soils (Bowles, 1984).

1) The liquid limit (LL) is related to the compressibility - a high value indicates high compressibility.

2) The plasticity index (PI) is a measure of permeability - a high value indicates low permeability.

3) A high liquid limit and plasticity index is indicative of an active soil - one which will shrink or swell in response to changes in moisture content.

A total of forty-one soil samples were collected representing seventeen glacial and twenty-four fragmental igneous locations. The collection locations for these samples is shown on the Quaternary Deposits Map (Plate 2). The Atterberg limits presented in Table 34 show that 38 out of 41 samples (93%) have LL values less than 50%, and all samples have low to very low (0 to 12.5%) PI values. The values suggest that these materials are moderately compressible and have high permeability. Reexamination of sample locations confirmed this relationship. In general, the materials have very low plasticity index (PI) values and will behave in a non-plastic manner when subjected to stress. This may help to explain the frequent association of concavities and small debris flows with thicker glacial deposits. Only two lapilli tuffs and one till deposit, derived from a lapilli tuff source, are classified as high plasticity materials (LL > 50%). These three samples all came from sites within area 1, previously identified as containing the most clay-rich soils in the drainage, an area characterized by a much higher incidence of rotational failures.

The sieve analysis results shown in Table 35 represent the (-) No. 4 (<4.75 mm) portion of the deposits sampled. Applying the Unified Soil Classification (USC) System (Casagrande, 1948) to the grain-size results expressed in Tables 30 and 33, this study has found that overburden deposits in the study area can be categorized in the following manner:

1) varves - low plasticity silts (ML)

2) all other types of deposits - poorly graded gravels and silty gravels and poorly graded sands and silty sands (GP-GM and SP-SM)

Based solely on the fine-grained portion, varve deposits would make poor subgrade material, silty sands would make fair subgrade material (if not containing appreciable amounts of pebble and larger material) and silty gravels would make good subgrade material (if not containing a radical variation in clast size) (Johnson and DeGraff, 1988). However, given the amount of material larger than 4.75 mm found in over 90% of the deposits (Table 32), the ability to properly compact these materials during construction is severely restricted. Roadbeds constructed over these materials would be expected to suffer appreciable localized failure and, in fact, this is occurring.

Table 34. Study area soil samples - Atterberg Limits

Sample #	**Deposit type**	**Atterberg limits (in %):** Liquid limit	Plastic limit	Plasticity index
1600	Drift	41	35	6
3167	Fragmental igneous	48	43	5
4200	Fragmental igneous	34	32	2
526/37	Varves	33	30	3
5301 -2	Drift	43	36	7
54	Saprolite	46	40	6
605	Fragmental igneous	35	38	0
B-1	Fragmental igneous	52	46	6
B-17	Fragmental igneous	33	31	2
B-21	Kame	38	34	4
B-28	Fragmental igneous	44	43	1
B-3	Drift	59	54	5
B-36	Fragmental igneous	51	48	3
B-4	Fragmental igneous	45	40	5
B-40+	Drift	37	34	3
B-6	Fragmental igneous	33	31	2
B-92+	Drift	37	35	2
B-94	Moraine	23	21	2
C-27	Drift	46	42	4
C-3	Fragmental igneous	38	35	3
C-30A	Fragmental igneous	21	22	0
C-30B	Drift	27	28	0
C-41	Fragmental igneous	43	40	3
C-47	Fragmental igneous	41	37	4
C-49+	Drift	44	44	0
C-54	Fragmental igneous	34	36	0
C-6	Fragmental igneous	33	31	2
CC-1	Varves	31	30	1

Table 34 (cont.). Study area soil samples - Atterberg Limits

Sample #	Deposit type	Atterberg limits (in %): Liquid limit	Plastic limit	Plasticity index
CC-3	Drift	35	31	4
CC-4	Fragmental igneous	38	35	3
J-18	Fragmental igneous	43	37	6
J-24+	Moraine	34	32	2
J-32	Drift	40	37	3
J-43	Fragmental igneous	28	29	0
J-51	Fragmental igneous	39	37	2
J-53	Fragmental igneous	35	33	2
N-36	Fragmental igneous	40	42	0
N-41	Fragmental igneous	33	32	1
N-45	Drift	47	39	8
N-46	Varves	41	28	13
WC-1	Fragmental igneous	41	40	1

Table 35. Particle size analysis - area soil samples

Sample #	Deposit type	Percent retained on sieve: #4 - 4.75mm	#10 - 2mm	#40 - .475mm	#200 - .075mm	pan
1600	Drift	26.81	23.34	25.51	16.22	8.12
3167	Frag. igneous	28.14	11.22	42.46	14.08	4.1
4200	Frag. igneous	46.9	11.69	21.58	12.62	7.21
526/37	Varves	0	0	8	41	51
5301 -2	Drift	29.45	12.8	25.07	21.56	11.12
54	Saprolite	5.4	0.2	43.8	39.5	11.1
605	Frag. igneous	24.8	19.4	38.8	12.93	4.07
B-1	Frag. igneous	15.41	20.52	41.88	15.94	6.25
B-17	Frag. igneous	19.02	22.78	32.48	17.14	8.58
B-21	Kame	14.48	17.78	40.38	19.85	7.51
B-28	Frag. igneous	34.86	15.17	25.98	13.95	10.04
B-3	Drift	26.03	16.2	26.75	20.95	10.07
B-36	Frag. igneous	50.72	22.83	20.26	4.69	1.5
B-4	Frag. igneous	44.58	12.33	18.83	14.26	10
B-40+	Drift	12.93	16.06	47.01	17.48	6.52
B-6	Frag. igneous	34.71	14.3	24.63	18.26	8.1
B-92+	Drift	17.22	14.84	42.66	16.8	8.48
B-94	Moraine	6.34	16.57	41.74	20.98	14.37
C-27	Drift	20.56	19.87	32.99	17.07	9.51
C-3	Frag. igneous	30.35	17.6	32.92	15.21	3.92
C-30A	Frag. igneous	14.12	34.13	42.4	7.2	2.15
C-30B	Drift	8.06	10.92	45.73	20.2	15.09
C-41	Frag. igneous	6.59	4.62	54.31	25.17	9.31
C-47	Frag. igneous	10.89	20.01	44.95	16.34	7.8
C-49+	Drift	23.29	10.72	31.31	14.41	20.23
C-54	Frag. igneous	12.84	17.9	37.32	21.49	10.45
C-6	Frag. igneous	0	18.65	51.67	22.55	7.13
CC-1	Varves	0	1.3	2.9	45.84	49.96

Table 35 (cont.). Particle size analysis - area soil samples

Sample #	Deposit type	Percent retained on sieve: #4 - 4.75mm	#10 - 2mm	#40 - .475mm	#200 - .075mm	pan
CC-3	Drift	27.55	22.09	42.49	7	0.87
CC-4	Frag. igneous	29.86	14.42	39.57	14.21	1.94
J-18	Frag. igneous	0	2.32	62.09	30.31	5.28
J-24+	Moraine	18.35	14.35	32.89	19.75	14.66
J-32	Drift	31.9	17.64	20.73	17.24	12.49
J-43	Frag. igneous	14	26.15	47.61	9.87	2.37
J-51	Frag. igneous	14.29	8.98	38.72	25.79	12.22
J-53	Frag. igneous	12.95	9.88	37.18	27.64	12.35
N-36	Frag. igneous	9.95	22.05	54.75	11.85	1.4
N-41	Frag. igneous	32.41	22.6	29.89	10.48	4.62
N-45	Drift	8.74	7.28	21.46	34.1	28.42
N-46	Varves	0.06	0.38	19.6	29.77	50.19
WC-1	Frag. igneous	47.45	20.88	20.95	6.22	4.1

Maxwell (1971) determined the grain size distribution and Atterberg Limits on a fine-grained soil found at a site 80 m west of the persistent failure along FS Road 54 occurring just east of the FS Road 57/54 junction. To validate the Atterberg Limit results calculated in this study, tests were conducted on saprolitic material (sample # 54) presumably belonging to the same horizon. The results are presented in Table 36 and show good agreement.

Table 36. Comparison of Atterberg Limits calculated in an independent study (Maxwell, 1971) with those calculated in this study (sample #54)

	Maxwell	This study
(+)#200	81.5%	88.9%
(-)#200	18.5%	11.1%
Liquid Limit (%)	46	46
Plastic Limit (%)	39	40
Plasticity Index (%)	7	6

Glacial sample 5301-2 is associated with a failure location, and glacial samples N-45 and B-3 may be associated with very localized slump failures. Close agreement in the liquid limit and plasticity index values suggests that the soil mass properties of these locations may be similar to that of the previously described saprolitic failure location. The other samples have a significant departure in either the liquid limit or the plasticity index and are not associated with failure locations. Interpretation of stability based on Atterberg Limits is severely restricted in deposits with less than a 20% fine-grained fraction (Maxwell, 1971).

when considered on these bases alone. In the study area, a clayey silt varve deposit (sample N-46) in the SW 1/4 Sec. 8 along FS Road 54 above Canyon Creek, bears evidence of deformation in a 1 to 1.5 m wide zone within a horizontally-laminated 5 m thick deposit. Of three varve deposits examined, this is the only deposit to show any disruption in the horizontal varve pattern. The Plasticity Index value for this deposit is much larger than that for the other two varve deposits. However, the particle size distribution for all three samples is very close (Table 34), the degree of clay development and weathering is similar and the degree of cutface raveling is similar. These data suggest that the propensity for these cohesive deposits to fail is not dependent entirely upon PI and clay development. This supposition is supported by Mullineaux and others (1964) who found that, at least under some conditions, some weathered varve clays, produce higher swell pressures and may have lower shear strength than unweathered clays, yet the weathered clays do not show consistently higher Atterberg Limits.

Field relations suggest that the contribution of the fine-grained matrix in generating failures in essentially non-cohesive, coarse-grained deposits may be more related to the creation of textural barriers to groundwater flow than to the soil mass characteristics of the matrix. As such, an interpretation of stability through a comparison of PI values to clay content, while useful as a general guide, may grossly misrepresent the actual situation in the coarse-grained deposits and should not be made without additional, corroborative data such as the degree of saturation, textural relations, degree of weathering, and extent and thickness of the deposit.

Table 37. Atterberg comparisons for the glacial deposits

Sample #	Deposit type	Atterberg limits (in %):		
		Liquid limit	Plastic limit	Plasticity index
1600	Drift	41	35	6
526/37	Varves	33	30	3
5301-2	Drift	44	36	8
B-21	Kame	38	34	4
B-3	Drift	59	54	5
B-40+	Drift	37	34	3
B-92+	Drift	37	35	2
B-94	Moraine	23	21	2
C-27	Drift	46	42	4
C-30B	Drift	27	28	0
C-49+	Drift	44	44	0
CC-1	Varves	31	30	1
CC-3	Drift	35	31	4
J-24+	Moraine	34	32	2
J-32	Drift	40	37	3
N-45	Drift	47	39	8
N-46	Varves	41	28	13

Summary

Depth of surficial deposits within the study area varies tremendously from essentially a thin (<5 cm) humus cover to over 5 m of coarse-textured mineral soil. Overburden deposits are the result of both glacial and mass wasting processes and are predominantly coarse textured (gravelly sandy silt, cobbly or bouldery sands and silts, and gravel to boulder talus). Soil horizons have developed on these overburden materials. Seven generalized soil types can be identified. Soils identified as being more clayey are underlain primarily by fragmental igneous bedrock (80%) and contain a large number of translational and rotational failures. With increasing compact igneous bedrock content, soils become coarser-textured, better drained and less clayey. Areas underlain by compact igneous rock are characterized by continuous, but very small volume, rockfall, as opposed to the larger translational and rotational failures typical of the fragmental igneous bedrock.

A total of forty-one soil samples were collected representing a total of seventeen glacial and twenty-four fragmental igneous deposits. The Atterberg Limits calculated show that 38 out of 41 samples (93%) have LL values less than 50%, and that all samples have low to very low (0 to 13%) PI values. The values suggest that these materials are moderately compressible, have high permeability and in general, will behave in a non-plastic manner when subjected to stress. Only two lapilli tuffs and one till deposit, derived from a lapilli tuff source, are classified as high plasticity materials (LL > 50%). These three samples all came from sites previously identified as containing the most clay-rich soils in the drainage. However, observations in the field, coupled with laboratory results, have found that while there appears to be good correlation between the Plasticity Index and clay content, and the presence of failures, this relationship is not always clear, particularly in the coarser-grained deposits.

Chapter 9.
Assessing Susceptibility

General

For purposes of assessing slope susceptibility in the drainage basin, bedrock characteristics and slope angle provide the most appropriate indicators of potential failure due to their direct impact on the degree of cohesion of the affected rock masses. On a site specific basis, in areas with fairly uniform slope gradient, jointing characteristics such as: orientation, continuity and dilation can produce widely differing stability conditions. Likewise, physical changes to the rock mass such as the degree of alteration and extent of weathering, play important, but widely variable roles, in the stability of specific sites. Consequently, site specific assessments of bedrock characteristics and slope angles, as well as, the notation of seeping water, allow for a fairly reasonable qualitative assessment of bedrock competency and the associated likelihood of failure.

At present, the majority of natural slopes appear to be in a state of equilibrium, upset only by localized weathering- and mechanically-induced decomposition resulting from climatic conditions and the creation of a network of logging roads. The oversteepening created by road construction has resulted in widespread areas of minor rockfall due to accelerated weathering of bedrock cutfaces and disaggregation of overburden in response to climatic mechanisms or toeslope removal.

Basinwide, the disruptive effect of road-related permeability barriers on shallow perched aquifer systems has resulted in numerous failures and developing failures in roadfill prisms. The combination of cutface rockfall events and road prism failures account for over ninety percent of the most recent failures in the study area.

Based on an inspection of rock mass characteristics on over 150 locations, it is clear that fragmental igneous units possess a greater probability of failing in larger volume events than compact igneous rock. The fragmental igneous units, due to their clastic textures, are characterized by more pervasive alteration, weathering and saturation. These factors combine to reduce the cohesion of these rock masses, while slope gradients and joint patterns serve to reduce the stabilizing impact of frictional forces. In the compact igneous rocks, weathering and groundwater are primarily restricted to the joints so that, except in the uncommon cases of pervasive groundmass alteration, block strength is intact even though outcrop rock mass strength may be reduced. This results in very small volume rockfall involving discreet blocks, rather than failure of large portions of the rock mass in the form of landslides.

The areal extent of compact igneous failure material far exceeds the amount of material derived from the failure of fragmental igneous bedrock due to the preponderence of vertical compact igneous outcrops. Inspection of Table 38 reveals that failures in compact igneous bedrock (rockfalls and rock avalanches) account for 78.6 % of the total mass wasting debris (156.2 ha out of 198.6 ha total) leaving 21.4 % to be apportioned between failures in the fragmental igneous bedrock and the overburden.

Table 38. Failure types associated with source material as a percentage of total areal extent.

Process	Extent (ha)	Percent (total area)	Percent occurrence by parent material Overburden	Fragmental igneous	Compact igneous
Slumps -	30.1	.06	100	0	0
Rockfall -	105.9	1.31	5	10	85
Snow Chute related -	2.5	.03	75	25	0
Rock Avalanches -	50.3	.62	0	5	95
Translational Landslides -	0.3	.32	0	100	0
Debris Slips/ Flows -	2.5	.03	90	10	0
Streambanks	7.0	.08	100		
Totals	**198.6**	**2.45**			

Assigning slope susceptibility

This study classifies the susceptibility of the upper Canyon Creek basin into three categories: low, moderate and high (Plate 4). Areas identified as low susceptibility occur in the center of broad plateaus, benches and cirque basins with slopes less than 3.5 degrees, situated on compact igneous or highly competent bedrock. These areas lack the negative impacts of factors which serve to reduce cohesive and frictional forces in the bedrock and overburden. Areas characterized as possessing low susceptibility occupy ten percent (810 ha) of the study area.

Areas of moderate susceptibility are associated with slopes, composed of either overburden or bedrock, which do not, generally, exceed the natural angle of repose. Included in this category are fragmental igneous deposits not associated with perennial seeps, thin (<0.75 m) glacial deposits, bedrock of any type with a high concentration of connected joints, and unconsolidated overburden and residual soil. The level of cohesion in these materials is frequently less than that noted for materials in the low susceptibility category due to the presence of more water, greater dilation and continuity of joints, and steeper slopes. Slopes with moderate susceptibility cover seventy percent (5670 ha) of the study area.

Areas of high susceptibility display two or more of the following characteristics: topographic relief greatly exceeding the angle of repose, thick accumulations of overburden, zones of oversaturation, tremendous weathering or alteration, unfavorable dip, evidence of previous instability and distinct failure planes such as joints or bedding. Slopes classified as having high susceptibility include not only those mapped as failures (2.5% of the area), as shown on the Landslide Inventory Map (Plate 3), but include adjoining areas with similar bedrock/overburden, cultural and groundwater conditions (17.5% of the area). The high susceptibility category covers 20 percent (1620 ha) of the study area. Most of this is in the form of continuous, small volume rockfall resulting from oversteepening or removal of toeslope support.

Chapter 10.
Conclusions

Contact relations and bedrock and overburden characteristics for approximately 8100 ha (20,000 acres) of the upper Canyon Creek basin have been assessed to determine the causes and extent of existing failures and assign a preliminary slope failure susceptibility potential to the area. Ten factors found to exert tremendous influence in reducing the stability of slopes in the study area are: alteration mineralogy, contact relations, faulting, groundwater, joint concentration, joint continuity, joint orientation, oversteepening, timber harvest and weathering. Only four of these factors are considered in the LISA slope stability program (Prellwitz and others, 1994), suggesting that use of a quantitative soil slope program which omits rock slope factors may not provide the best stability assessment for this basin.

Deposits of mass wasting origin (198.6 ha) occupy less than 2.5% of the study area. Failures occur by one of seven processes, in decreasing order of abundance: rockfall (53.6%), rock avalanches (25.3%), slumps (15.6%), streambank failures (3.4%), soil and debris slips (1%), debris falls associated with snow avalanche chutes (1%), and translational landslides (0.1%). Of the 198.6 ha of failure material identified, 146.6 ha has resulted from natural processes and 52 ha in response to anthropogenic influences.

Rockfall is initiated in bedrock in response to a combination of outcrop oversteepening and alteration/weathering along joints or bedding planes. The erosion or destabilization of overburden deposits produces rockfall through a reduction in both friction and cohesion resulting from increased pore water pressure, oversteepening, or weathering. The most active areas of rockfall are presently located along logging roads and occur in response to removal of toeslopes, freeze-thaw cycles, joint orientation, and oversteepening.

Translational and rotational slides occur in fragmental igneous units and in thick glacial deposits. Unfavorable dip orientation, oversteepening, oversaturation and weathering are among the catalysts reducing the degree of cohesion at these sites. Very small debris falls are generated along the oversteepened walls of landslide and snow avalanche chutes as a result of oversaturation and undercutting.

In the Canyon Creek basin, slumps occur, exclusively, in thick overburden deposits associated with saturated conditions. Conversely, slip failures occur in thin deposits overlying coherent bedrock on steep slopes. The stabilizing influence of root growth appears to be directly related to depth of penetration in areas characterized by slumps and slips. Where the roots have penetrated through the overburden and into the bedrock, the slopes are held in place. Debris slips occur in cases where the roots are confined to saturated overburden lying on steeply dipping bedrock.

This study has examined the soil types found in the area. These are: Typic Udipsamments, Andic Hapludalfs, Andic Udorthents, Andic Haplumbrepts (some clayey) and Andic Cryumbrepts. The geographic distribution of these soil types, in general, mirrors the predominant type of bedrock. The soils identified as being more clayey are underlain primarily by fragmental igneous bedrock and have a proportionally greater number of landslides than areas underlain by compact igneous bedrock. With increasing compact igneous bedrock content, soils become coarser-textured, better drained and less clayey. Soils developing on drift occur throughout the study area and, in general, have textural properties more similar to soils developing on compact igneous bedrock. This study has found that, based on the Unified Soil Classification System, varves can be categorized as low plasticity silts (ML), and all other types of deposits, in general, as poorly graded gravels and silty gravels (GP-GM) and poorly graded sands and silty sands (SP-SM).

While the extent of clear-cutting varies tremendously from 50 to 80%, depending on the tributary drainage examined, the loss of root strength has not exhibited an appreciable influence on increasing the rate of failure. Surficial evidence of possible, localized slumping has been documented in this study, but without quantification of site specific impacts of tree root reinforcement, all that can be said is that the likelihood of future movement may exist in areas characterized by previous movement. The most obvious impact of logging, to date, has been the generation of rockfall due to oversteepening, and the removal of toeslope material in roadcuts. Up to 77% of current rockfall locations are associated with roadcuts. The combination of cutface rockfall events and road prism failures account for over ninety percent of the failures observed in the study area.

Up to 99% of the roadbed failures occur within the roadfill prism and are not the result of subgrade degradation. Failure of the road prism is the result of either poor quality fill material, or the disruption of shallow groundwater paths by impermeable or less permeable roadfill material. Arcuate and sliver-like cracks or offset, sinkholes, concentrations of potholes, broad slumps and chute formation in the roadfill are indicators of a developing failure. Ditches without culverts, or with poorly placed, damaged or leaking culverts, degrade roadfill intregrity through piping and oversaturation and may ultimately lead to failure.

While oversaturation is important in reducing cohesion in fragmental igneous bedrock and overburden due to their greater permeability, its impact in reducing the strength of compact igneous bedrock is minimal, as it is confined to discontinuities. Integrity of compact igneous bedrock is primarily influenced by jointing characteristics, in particular: dilation, orientation and continuity. In these cases, block strength is maintained but the strength of the rock mass on the whole, is reduced. Over 90 percent of bedrock exposures studied contain at least three intersecting joint sets oriented anywhere from 0 to 90 degrees, with most between 5 to 40 degrees off horizontal. However, the orientation of intersecting, continuous joint sets are most often nearly horizontal and nearly vertical. Consequently, large scale rockfall is not as common as the joint frequency would imply. Field relations suggest that the entire Canyon Creek basin has been glaciated. This analysis has interpreted that ancient mass wasting processes (rock avalanches) involved extensive areas of oversteepened valley walls in response to the disequilibrium produced when the glaciers melted away from these walls. Ongoing, minor rockfall continues in these locations in response to surficial degradation of the rock mass due to accelerated weathering along the joints and not as a result of decomposition of poor quality bedrock. Flat, smooth surfaces high on hillsides give the impression of being the tops of large landslide blocks with steep headwalls and broad underlying benches. Careful examination has found that these features are the result of glaciation, not mass wasting.

Non-cohesive glacial deposits such as moraines and kames, and cohesive varves, can be found throughout the upper Canyon Creek basin. Most deposits of drift do not display a propensity for large-scale failure, although slumps and rotational slides occur in thicker drift, and deep rill formation and erosion-related rockfall is common in all drift deposits. Oversteepening, weathering and oversaturation affect the degree of cohesion found in these deposits, and textural heterogeneities may locally reduce the internal friction of the larger deposits through localization of perched aquifers. The persistent saturation of varves drives raveling and slaking by contributing to the effects of wetting and drying and freeze-thaw cycles. These actions reduce the degree of cohesion along the surface, and increase the unit weight of the surface soil mass.

The susceptibility of a slope to fail has been assigned a rating of low, moderate or high. Areas with low susceptibility cover approximately 10 percent of the area (810 ha, 2000 acres) and are characterized by the absence of failures or indications of potential failure. Slopes are less than 3.5 degrees. Failures are not anticipated since these areas are not characterized by factors which serve to reduce cohesion or friction.

Nearly 70 percent of the area can be classified as having moderate susceptibility (5670 ha, 14000 acres). These are areas with slopes which do not, generally, exceed the angle of repose but may be associated with seeping groundwater, may exceed the angle of repose but are not associated with seeping groundwater, or are associated with thick overburden on shallow slopes.

Areas of high susceptibility cover about 20 percent of the area (1620 ha, 4000 acres) and are associated with vertical to near vertical outcrops, thicker glacial deposits, incised toeslopes, oversteepened streambanks and cutfaces, and areas characterized by previous failures or strong indication of potential failure. Slopes classified as having high susceptibility include not only areas of identified failure, but adjoining areas with similar bedrock/ overburden, cultural and groundwater conditions.

Future Work

Further study must be conducted in the areas of petrology, geochemistry and Quaternary geology in order to more carefully and accurately describe the geological evolution of this basin and create a decent structural interpretation. Seismic studies should be conducted in an attempt to determine the locations and orientations of faults. Detailed geotechnical testing should be performed to characterize the strength of bedrock, overburden and roadfill for use in quantitative, site-specific stability analyses; particularly following any clearcut. The U.S. Forest Service Level 1 Stability Analysis (LISA) should be run in this basin (characterized predominantly by rockfall), and the results compared with other basins characterized by a predominance of mass wasting events other than rockfall, to determine the applicability of this program to areas dominated by rockfall. An in-depth geological engineering analysis could be conducted on the roadcuts and roadfills with the purpose of establishing a monitoring protocol for the long-term maintenance of the roads for the expressed purpose of maintaining safe and open corridors through the area.

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