LANDSLIDING PROCESSES OCCURRING ON A McDONALD-DUNN FOREST HILLSLOPE

by

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ABSTRACT

Landslide processes occurring on a hillslope in McDonald-Dunn Forest on the eastern slope of the Oregon Coastal Range are described in terms of type, magnitude, minimum age and site characteristics. Debris flows and debris avalanches are the dominant types of slope movement occurring in the study area. Landslide events classified in the field were grouped according to process, and verification of field classifications were performed using morphometric indices and analysis of variance. The classification index (D/L) showed significant differences between landslides classified in the field and between process groups. Correlations between process, denoted by the classification index, and three morphometric indices were also significant. Landslide volumes are skewed towards smaller values, and have a mean of 1195 m^3. A general linear regression model was developed for the estimation of landslide volumes and was significant at the 0.00% level. Minimum ages of landslides are also skewed towards smaller values with the 1964 storm being well represented within the sample. Landslides were observed to have occurred on slopes ranging from 26-55%, and a majority occurred at or immediately below significant breaks in slope. Bedrock hollows occurring on the scarp slope element appear to

produce large debris flows. Changes in the landscape occurring since euro-american settlement preclude the use of the magnitude-frequency approach to investigate landsliding in the study area. Future research should concentrate on current rates of soil creep, hollow recharge and implications for sediment routing and landscape evolution.

INTRODUCTION

McDonald-Dunn State Forest in western Oregon is a research forest managed for multiple uses including research, timber production and recreation. It is situated on the eastern margin of the Oregon Coast Range amid steep and well dissected terrain. Like much mountainous terrain, the forest contains many sites that are prone to mass movements that often assume catastrophic proportions. This paper reports the results of a research project whose objective was to describe, in terms of their magnitude and frequency of occurrence and site conditions, the landslide processes operating on a hillslope on the western margin of the forest.

Geomorphologists concerned with mass wasting, slope instability, and sediment budget and routing studies have noted the need to gain insights into the controls of erosion processes (Dietrich et al. 1982; Swanson et al. 1982), and the need to follow rigid criteria in characterizing mass movement regimes in a given area or region (Swanson and Lienkaemper 1985). Criteria essential to "adequately analyze slope movement conditions" relevant to this study include quantification of the frequency of occurrence of rapid slope movements and the size distribution (volume and area) of each type of slope movement (Swanson and Lienkaemper 1985, 41).

Characterization of slope movement regimes should also seek to classify landslide phenomena in terms of both process and morphometry, thus providing information useful to researchers and land managers alike. Several landslide classification schemes are in usage today (Campbell 1951; Sharpe 1938; Varnes 1958), however, they are not always in agreement and are generally based on qualitative rather than quantitative criteria. Crozier (1973) has developed a system for the classification of landslides by process groups based on morphometric indices that is quantitative in approach and allows standardization in classification.

This study of landslide phenomena within McDonald-Dunn State Forest considered and incorporated into its design the recommendations offered by Swanson and Lienkaemper (1985), and utilized the morphometric indices of Crozier (1973) for the purposes of classification. The term landslide is utilized for the sake of brevity and simplicity as opposed to other analogous terms such as mass movement, slope movement and/or landslip.

STUDY AREA

The study area is located on the western margin of McDonald-Dunn State Forest in Sections 7 and 18, R. 5 W., T. 11 S., approximately 4.8 km northwest of Corvallis, Oregon (Figure 1). It occupies an east facing hillslope that ranges in elevation from 158-546 meters (500-1801 feet) above mean sea level (Figure 2).

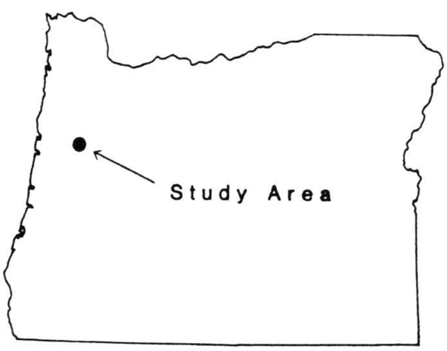

Figure 1. Study area location.

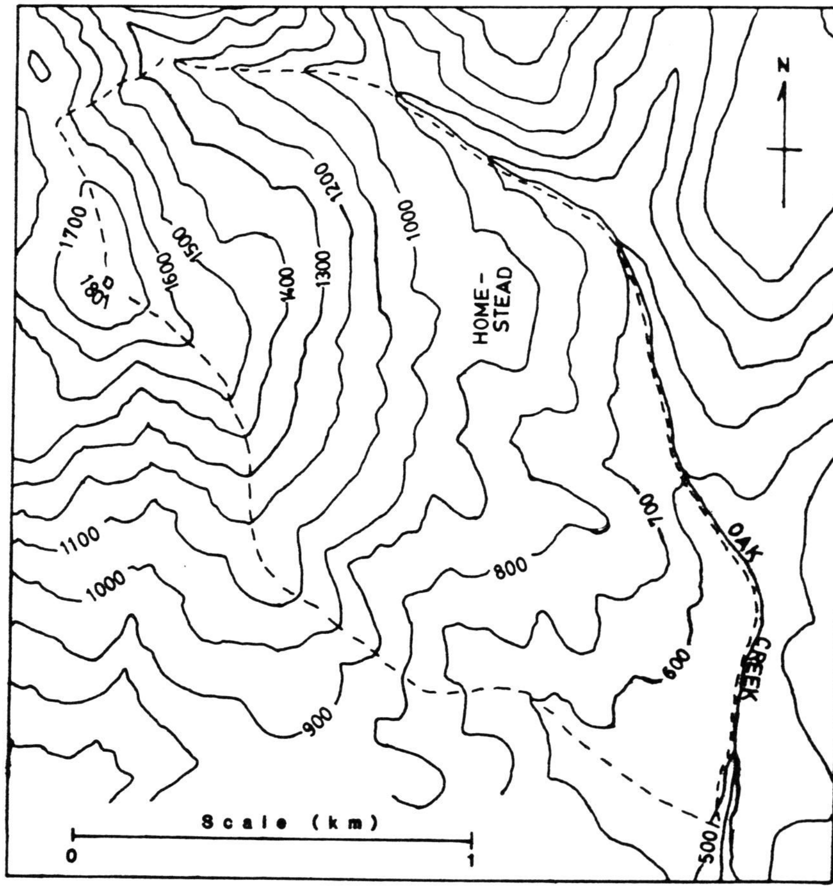

Figure 2. Study area topography (elevations in feet).

GEOLOGY, LANDFORMS AND SOILS

McDonald-Dunn Forest is underlain by the Siletz River Volcanic Series which consists of pillow basalts, basalt flows, flow breccia and coarse pyroclastics (Snavely and Baldwin 1948, 807; Peck 1961). Being of lower and middle Eocene age, this geologic unit is considered to be the oldest in the central Coast Range (Balster and Parsons 1966, 4). Its materials are highly resistant to erosion and produce landforms with steep slopes and high relief.

The study slope has a general convex-concave form, however, four distinct hillslope elements may be distinguished. These include: (1) the waxing slope or hill crest, (2) the free face or scarp slope, (3) the debris or talus slope, and (4) the pediment (King 1957; Wood 1942). The terms hill crest, scarp slope, debris slope and pediment will be utilized in this paper. The scarp slope element meets the debris slope element at an elevation of about 300 meters.

Soils formed from the volcanic parent materials are typically described as gravelly silty clay loams, silty clay loams and silt loams (Knezevich 1975; Rowley et al. 1983). In general, soils are better developed on the debris slope and pediment than on the scarp slope. Depth to bedrock ranges from 1-2 m from the hill crest to the pediment. Greater depths are often encountered in bedrock hollows on the scarp slope, and in debris fans and accumulations on the debris slope. Oak Creek at the foot of the study area has incised through its floodplain deposits some 2 meters to bedrock.

Mass movements of the creep, debris avalanche and debris flow type (Varnes 1958) are the dominant erosional processes that occur in the silt and clay rich soils of the study area. Bela (1979) and Rowley et al. (1983) have prepared maps showing the distribution of unstable slopes, areas prone to rapid mass movement and known landslide sites. These sources were utilized in the field investigation of landslide features in the study area.

Debris avalanches and flows in steep terrain often initiate in bedrock depressions or hollows which concentrate both sediment and water (Dietrich and Dunne 1978, 197-198; Pierson 1977). The concentration of subsurface flow into these depressions causes pore pressures within accumulated soils to be elevated to a point at which their shear strengths are reduced and failure may occur (Pierson 1977, 44).

Hollows are generally thought to originate from landslide events which extend into the regolith underlying shallow soils on steep slopes, and to develop further through successive slope failure at these sites following periods of infilling by processes collectively labeled creep (ravel, soil creep, biogenic transport) (Dietrich and Dunne 1978, 198; Dietrich et al. 1982).

CLIMATE, VEGETATION AND LAND USE

The climate of the Willamette Valley and adjacent slope of the Coast Range has been characterized as modified maritime with clear, dry summers and mild, moist winters (Jackson 1985, 50-51). Annual precipitation in the McDonald-Dunn State Forest ranges from 100-150 cm (Rowley et al. 1983, 3), and the study area with its eastern exposure receives annual amounts near the lower end of this range. The bulk of this precipitation is in the form of rain, however, snow falls infrequently at elevations above 450 m. Mean annual temperature is approximately 10° C.

The majority of the study area is heavily forested with Douglas Fir (*Pseudotsuga menziesii*, var. menziesii), Oregon white oak (*Quercus garryana*), and grand fir (*Abies grandis*) being the dominant overstory species, respectively. Bigleaf maple (Acer macrophyllum) and red alder (Alnus rubra) are important overstory species in moister sites. Important understory species include vine maple (Acer circinatum), snowberry (Symphoricarpos albus), tall Oregon grape (Berberis aquifolium), salal (Gualtheria shallon), poison oak (Rhus diversiloba), sword fern (Polystichum munitum) and various grasses. Grassland areas are also found throughout the study area, especially in sites with more southerly exposures.

The vegetation of the study area, due to its proximity to the Willamette Valley, has been subject to much manipulation throughout pre- and post-settlement history. Quite likely this has important implications for mass wasting and sediment routing in this area.

The pre-settlement vegetation of the Willamette Valley floor, as established from examinations of original land survey records from the 1850s, consisted primarily of grasslands or prairies with scattered oaks and was maintained by Native American burning (Habeck 1961, 76; Johannessen et al. 1971, 292; Towle 1974, 36). Surveyors distinguished between prairie occupied by grassland vegetation, oak openings in which individual trees being more than 50 feet apart, oak forests or timber in which individual trees were less than 50 feet apart, and fir timber dominated by Douglas fir (Habeck 1961, 69).

In documenting vegetation changes in the southern portion of the valley and surrounding hills, Johannessen et al. noted that "dense oak woodlands...extended nearly up to the crests of the surrounding hills" (1971, 301). An examination of original survey records from 1853, the findings of Sprague and Hansen (1946) and those of Towle (1974), indicates that this trend was apparent within the study area. The surveyors who conducted the original land survey in and around the study area noted that oak openings dominated the hillslopes whereas fir timber, alder, maple and brush were the dominant forms of vegetation within ravines and draws (Surveyor General's Office, 1853).

Sprague and Hansen traced forest succession in and around the study area through extensive field surveys and dendrochronologic dating. They found that areas which were not originally forested were being invaded by Oregon white oak, and then by Douglas fir which became established under the shade cover of the oaks (1946, 97). They felt that in this area of western Oregon, in which western hemlock (Tsuga heterophylla) and western red cedar (Thuja plicata) are often considered to be climax dominants, Douglas fir and grand fir appear to be climax dominants due to the more mesic site conditions encountered on the east slope of the Coast Range (1946, 90).

The study area has been managed for timber production since the early 1900s (Jackson 1980, 238), and was first logged sometime during the period 1910-1930 (Jackson 1980, 399; Sprague and Hansen 1946, 92). Stand densities were probably quite low at that time and selective harvest practices appear to have been utilized. Logs were skidded to sawmills located along Oak Creek at the base of the study area. The site of one of these early sawmills was found just downslope of slide 24 at the confluence of the west fork of Oak Creek and a tributary which forms the northern boundary of the study area.

Evidence of a widespread understory burn has been found throughout the study area. It charred trees to a height of 1.0-1.5 m, and burned many of the stumps remaining from early logging activity. This burn occurred in October, 1949 (Marvin Rowley, pers. comm.).

Other human uses of the study area includes homesteading and associated grazing in the 1920s (Jackson 1980). A homestead site is located near the center of the study area on a large structural bench (Figure 2).

METHODOLOGY

Landslide sites within the study area were located primarily through intensive field reconnaissance. The maps prepared by Bela (1979) and Rowley et al. (1983) proved useful in identifying areas of slope instability and locating some of the larger sites. Site locations were approximated on the Corvallis, Oregon, 7 1/2 minute quad sheet, and elevations estimated for each.

CLASSIFICATION

Each landslide event was initially classified according to the classification scheme developed by Varnes (1958). Characteristics of the various types of landslides distinguished by Varnes that aid their recognition have been identified and described by Ritchie (1958, 50-51). Varnes' scheme, though it is qualitative in approach, is in common usage today and it was intended that adherence to it would provide for comparison of study results with other investigations of landslide phenomena within this and other regions.

Dimensions of each landslide were measured with either a 30 meter tape and stadia rod or basic surveying techniques. Crozier's system (1973) for the analysis and classification of landslides utilizes these measurements to develop morphometric indices which can be used to distinguish amongst different process groups which include different types of landslides (Table 1).

Process Group	Type of Movement (Varnes 1958)
Fluid-Flow	Mudflows, Debris Avalanches and Flows.
Viscous-Flow	Earthflows, Rock Fragment Flows.
Slide-Flow	Slump/Earthflow.
Planar Slide	Debris Slides, Rock Slides and Slumps, Block Glide.
Rotational Slide	Earth and Rock Slumps.

Table 1. Process groups and landslide types.

Dimensions measured include: (1) maximum depth (D or Dc) of the concave landslide scar, (2) total length of the event (L) including that of the concave scar (Lc) and that of the convex mass of displaced material lying outside of the scar (Lx), (3) length of the surface of rupture (Lr), and that of the displaced material (Lm) which when summed also equal the total length of the feature, (4) maximum width of the concave scar and convex mass of displaced material (Wc and Wx, respectively), and (5) slope of the plane intersecting the surface of each scar, which is hereafter referred to as the slope within (Figure 3).

Measurements of slopes above and below each event were also made, and scars occurring at substantial slope breaks (greater than 5%) were noted. All slope measurements were made with a clinometer and are expressed as percentages.

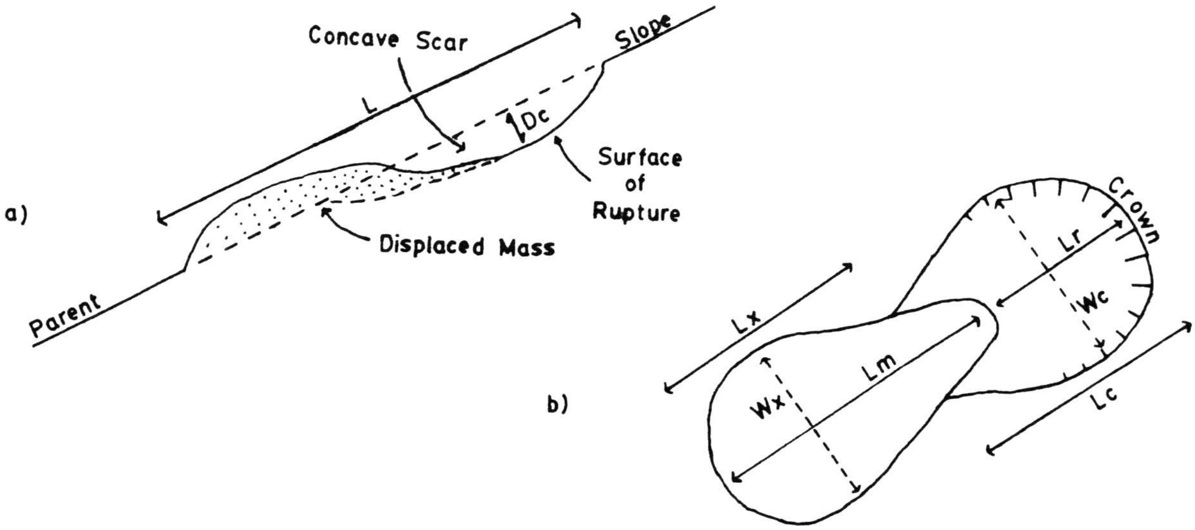

Figure 3. Landslide features and dimensions: a) vertical cross-section, b) planimetric view.

LANDSLIDE MAGNITUDES

Volumes of material transported from each landslide scar were estimated through the measurement of cross sections within concave scars. Transported material includes any soil and rock material that was removed from the concave scar whereas displaced material includes all material redistributed by each slope movement (Crozier 1973, 80). Because some infilling of scars through dry ravel and soil fall was observed. visual estimates were made of the amount of infilling thus allowing corrected volumes of transported material to be estimated.

Where older and less well defined landslide scars were encountered, only the following dimensions were measured: Lc, Lx, Lr, Wc, Wx, and Dc. Estimates of their original empty volumes (percent empty) were also obtained in hope that their actual volumes might be predicted using regression techniques.

Weights of sediment transported by landsliding events were estimated through the use of the volume estimates and bulk density values for the soils in the study area reported by Rowley et al. (1983). Bulk densities do not vary significantly from one soil type to the next, and a value of 1.32 g/cm^3 (1.32 metric $tons/m^3$) was derived through areal averaging for use in weight estimates.

DATING OF LANDSLIDES EVENTS

The age distribution of landslide events was determined through minimum-age dating of scars and deposits. Dendro-chronologic techniques have proven to be useful in dating geomorphic activity (Alestalo 1971; LaMarche 1968; Shroder 1978; Skempton 1953) and were utilized here. Red alder, vine maple and broadleaf maple are generally the first tree species to colonize mass movement sites in the study area, however, it was felt that cores would be difficult to take from these hardwood species (vine maple excluded) and that they would not be readable due to a lack of well defined seasonal growth rings. Boring was thus confined to coniferous species (Douglas fir and grand fir).

OTHER OBSERVATIONS

To identify the slip surfaces of each landslide event, dominant substrates of each scar were inspected. Substrate classes included soil/gravel, regolith/saprolite and intact bedrock. Those landslides that either occurred within or created bedrock hollows, distinguishable by topographic depressions, were noted as were the hillslope elements on which they were found.

Visual estimates of vegetative cover (percent cover) were made so that estimates of vegetation recovery times could be made. Scars and downslope areas channelized by the movement of debris were inspected for signs of overland flow, and seeps and springs were noted where they occurred. Flows were rated with respect to constancy (ephemeral, intermittent, perennial). Where landslide deposits reached downslope stream channels, notes were made of the length of channel affected and the types of impacts (degradation, aggradation, channel shifts) observed.

RESULTS

CLASSIFICATION

Twenty-five landslide sites were identified within the study area (Figure 4). Of these, 14 were initially classified as debris flows, nine as debris avalanches, and two as slump/flows (see Appendix A). Debris flows were distinguished primarily by the presence of levees extending downslope from the flanks of the concave scar and the highly deformed character of the displaced material. Debris avalanches showed less deformation of displaced material, levees were absent, and overall lengths were generally less than those of debris flows. The two slump/flow events were distinguished on the basis of their smaller size, lower relative amounts of transported material and lower degree of deformation of displaced materials.

Verification of field classifications of landslide events in terms of process was carried out utilizing several of Crozier's (1973) morphometric indices. These included: (1) the classification index (D/L), (2) the tenuity index (Lm/Lc), (3) the flowage index, and (4) the fluidity index.

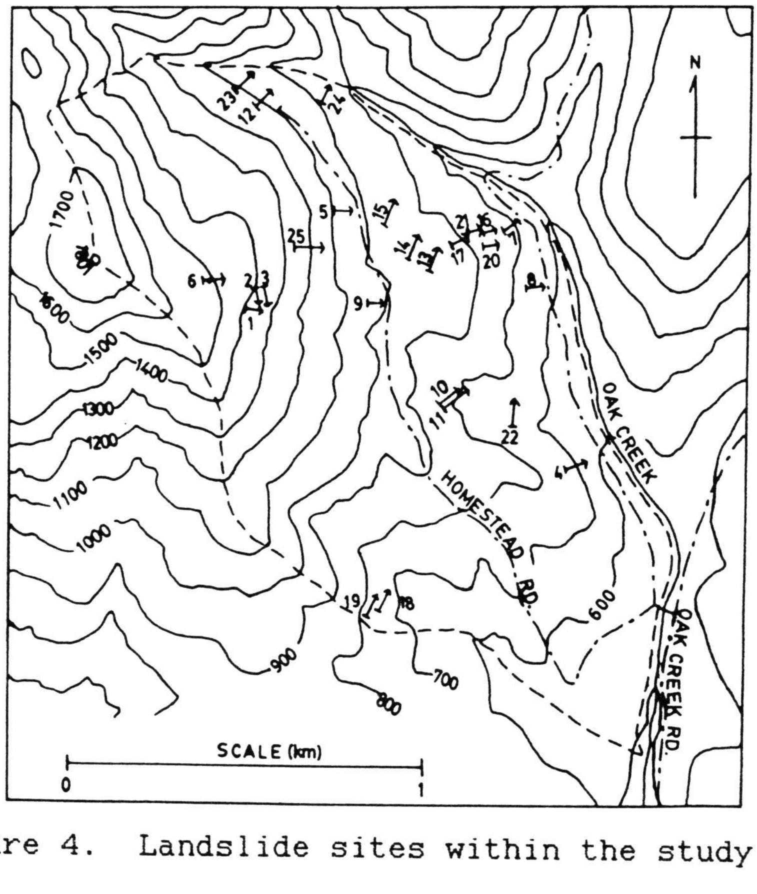

Figure 4. Landslide sites within the study area.

The derivations of the first three indices are described by equations 1a-3 in Appendix B. The fluidity index is derived by regressing tenuity (Lm/Lc) against the angle of the slope within and then calculating deviations in tenuity corresponding to each landslide. Deviations are then ranked on a percentage basis progressing from the largest negative deviation (B) to the largest positive deviation (A). Calculation of the fluidity numbers for positive and negative deviations are shown in equations 4 and 5 in Appendix B.

The classification index was first utilized by Skempton (1953) to distinguish between surface slips, deep rotational slips and slumps in boulder clay soils of west Durham, England. All slope movements occurring in his study area were streamside slips whose deposits were truncated by downslope stream channels. Blong (1973) found this index useful in classifying slope failures whose deposits remained undisturbed by downslope streams in the Mangawhara catchment on the North Island of New Zealand, as did Crozier (1973) in the loess soils of eastern Otago, New Zealand.

Crozier (1973) developed the tenuity index primarily as a "quantitative, descriptive device" rather than a classificatory index (Crozier 1973, 87). It is an important term in the flowage index, which he expected to reflect fluidity and effects of slope angle on the velocity of flow of a rapid slope movement event. The fluidity index was intended as "a measure of the variation in the amount of flowage that occurs in a flow, over what would normally be expected with a particular material on a particular slope" (Crozier 1973, 88). He alternatively referred to this index as the "water content index."

One-way analysis of variance (ANOVA) was utilized to determine whether or not any significant differences exist between mean index values of landslides grouped by type and by process group. Results (summarized below in Tables 3 and 4) indicate that of the four morphometric indices, the classification index alone distinguishes between landslides classified in terms of process groups.

The F ratio for the classification index reported in Table 3 is of lower magnitude than that reported in Table 4 for the fact that debris flows and debris avalanches were grouped separately in the first analysis, whereas they were grouped together in the second. Further ANOVA indicated no significant differences between mean index values for debris flows and debris avalanches ($F = 1.205$).

Index:	Classn.	Tenuity	Flowage	Fluidity
F Ratio:	3.503*	1.796	1.709	1.895

Table 3. Significance of differences between mean index values of landslides grouped by type (*significant at the 5.0% level).

Index:	Classn.	Tenuity	Flowage	Fluidity
F Ratio:	5.7051*	0.642	0.755	1.043

Table 4. Significance of differences between mean index values of landslides grouped by process (*significant at 5.0% level).

Process can be represented by the classification index (D/L) (Crozier 1973, 95), and product moment correlation analysis performed with respect to the other three indices. Results are presented in Table 5, and all relationships are seen to be significant at the 5.0% level. Correlation coefficients calculated by Crozier (1973, 95) for 52 landslides of the flow process variety are presented for comparative purposes.

Index:	Tenuity	Flowage	Fluidity
r:	-0.5374*	-0.4942*	-0.5861**
Crozier's r:	-0.46**	-0.29*	-0.41**

Table 5. Product moment correlation coefficients for relationships between classification index and other morphometric indices (*significant at the 5.0% level, **significant at the 1.0% level).

All of the relationships can be seen to be negative or inverse. This is due to the fact that the overall lengths of landslides were observed to be controlled by the dimension Lx, which in turn is controlled by water content at the time of slippage. Hence, the highly significant relationship between D/L and the fluidity index.

The relationships are not linear, however, and all have the form of Figure 5. Their curvilinear character is due to the high D/L ratios corresponding to slides 2, 5 and 20 (shown in the lower right corner of Figure 5); otherwise they would take on a more linear character. The deposits of slide 2 were disturbed by those of slide 1, thus preventing accurate measurement of Lx.

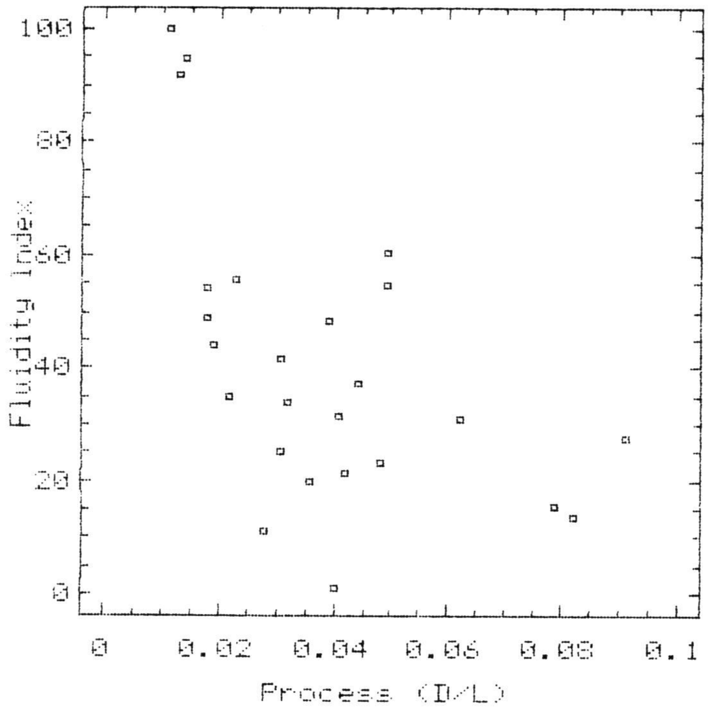

Figure 5. **Relationship between process (D/L) and fluidity.**

The measured value of Lx for slide 5 is shorter than would be expected for a debris flow as the deposits from this event terminate on a gentle slope immediately below the concave scar. Slide 20 is a slump/flow feature with a low value of Lx.

EVENT MAGNITUDE

Landslide magnitudes were estimated by the volume of material transported from the concave slide scar as previously mentioned. Twenty-one volume estimates were made out of the sample of 25 events, and the remaining four estimates were obtained using regression techniques as described below. These estimates are noted in Table 2 (Appendix B).

The landslide dimensions Lc, Dc, and Wc were evaluated with respect to their power in predicting landslide volume using multiple linear regression techniques. The use of untransformed independent and dependent variables yielded a general model that was non-linear in form and had unequal error variances across the range of observations. Transformation of the dependent variable (landslide volume) effectively rectified the response surface and remedied the problem of unequal error variances to yield the following general linear model:

$$Y^{1/2} = -10.453684 + 0.568262\ X_1 + 0.4666898\ X_2 + 0.772332\ X_3 \quad (6)$$

where: Y = Landslide Volume
X_1 = Lc
X_2 = Dc
X_3 = Wc

All model parameters are significant at the 0.00 % level with t values equal to -8.5650, 10.2897, 13.7964 and 8.3564 corresponding to parameters B_0, B_1, B_2, and B_3, respectively. An F test for a regression relation between the dependent variable and the set of independent variables was significant at the 0.00 % level with F equal to 588.883. The coefficient of multiple determination (R^2), adjusted for 20 d.f., is equal to 0.9888.

The distribution of landslide volumes (Figure 6) can be seen as being greatly skewed towards smaller event magnitudes reaching a minimum of 28.80 m^3, a maximum of 5425.99 m^3, and having a mean of 1195.80 m^3 and a median of 610.04 m^3. Slide 16, a slump/flow type event, was the smallest landslide event observed. The largest event observed was slide 12, a debris flow, which

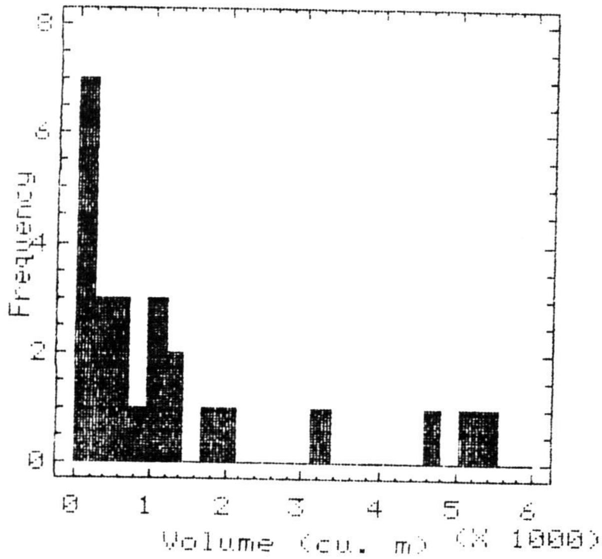

Figure 6. Distribution of volumes.

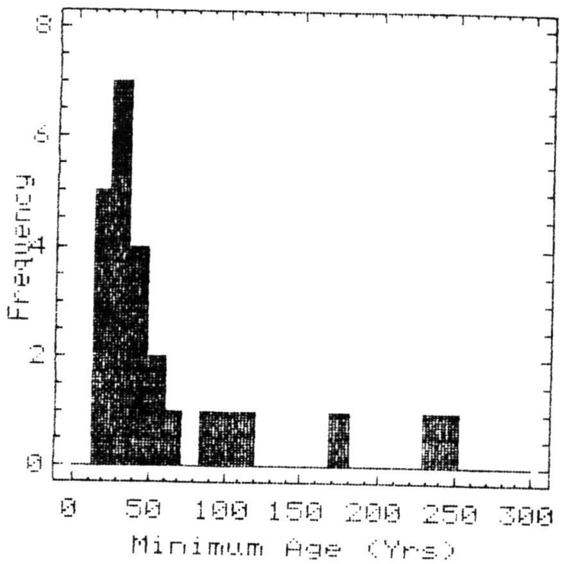

Figure 7. Distribution of minimum ages.

required the use of basic surveying techniques in order to obtain necessary measurements.

Correlation analysis and visual inspection of the data revealed no relationships existing between event magnitude and any other variable. Attempts to develop a regression model describing the magnitudes of landslides with regard to slope, elevation, slope element, occurrence in or creation of bedrock hollows proved unsuccessful.

MINIMUM AGES OF LANDSLIDE EVENTS

The distribution of estimated minimum ages of landslide events, like event magnitudes, is highly skewed toward younger or more recent events (Figure 7). Minimum ages of landslide events in the study area range from a minimum of approximately 20 years old (slide 16) to a maximum of approximately 245 years or more (slide 19). The mean is 65.04 years whereas the median is 40.0 years. A plot of estimated minimum ages versus event magnitudes (Figure 8) indicates no significant relationship between the two variables (r = -0.1197).

Minimum ages of the three oldest events were estimated from ring counts of large Douglas fir boles and/or stumps present within the area affected by the landslide. These boles and stumps are relics of logging activity which occurred throughout the study area around the year 1920 (Jackson 1980, 399).

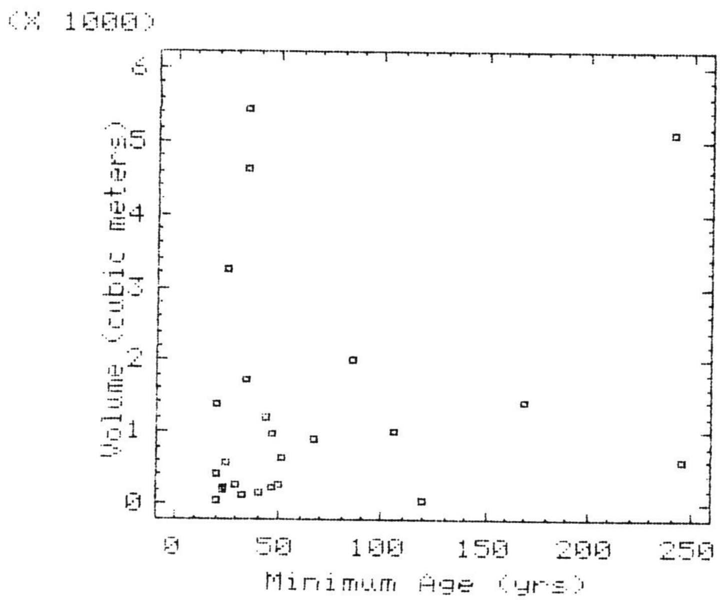

Figure 8. Plot of minimum age vs. event magnitude.

Slide 19 contained one Douglas fir bole with a diameter at breast height (dbh) of about 1.5 m (Figure 9). Its age at the time it was cut was estimated by a ring count to be about 175 years. Slide 22 also contained a large Douglas fir bole (dbh of about 1.5 meters) which was determined to have been 170 years old at the time it was cut. Slide 17 contained two rotten stumps with diameters of about 1.0 meters that were estimated to have been about 100 years old some 70 years ago. Slides 5 and 12 were dated using ring counts of cores backdated from sections of reaction wood (Shroder 1978, 171).

Slide 24 and its deposits are vegetated by red alder and sword fern, and contained no conifers which could be bored. It appeared to be a 1964 event due to the uniformly small size of the alders present, the "raw" appearance of the main scarp and edges and the fact that the stream below has not yet incised through the deposits which have elevated its channel. Marvin Rowley (ex-forest manager) had noted its presence in 1963 (pers. comm.), however, and its minimum age was placed at 35 years to correspond with those of slides 12 and 23 located in the same general area.

These estimates are rough due to the fact that the uncertainty regarding the period in which early logging activity occurred is great (about 20 years), however, they do allow approximate minimum age dating of these older landslide events. Original (1853) land survey records revealed no notes regarding landslide features observed in the study area at that time that would prove useful in the context of this study.

Figure 9. Slide 19 was estimated to be 245 years old by the large bole on which assistant is standing.

These estimates are rough due to the fact that the uncertainty regarding the period in which early logging activity occurred is great (about 20 years), however, they do allow approximate minimum age dating of these older landslide events. Original (1853) land survey records revealed no notes regarding landslide features observed in the study area at that time that would prove useful in the context of this study.

The high frequency of landslide events with minimum ages of 20-25 years (Figure 7) can be attributed to the December 1964 storm event. This storm was estimated to have a recurrence interval of between 6 and 86 years in the Oregon Coast Range depending on the catchment of interest (Dietrich and Dunne 1978, 197), and the recurrence interval for the Oak Creek basin in

Figure 10. Slide 18, with an estimated minimum age of 51 years, is located adjacent to slide 19.

which the study area is located probably approaches the high end of this range.

Several authors have reported on the impacts of the 1964 storm on hillslopes in the Pacific Northwest. Pierson (1977, 104) reported the occurrence of a large number of debris flows in the Mapleton Ranger District, Oregon, caused by this event. Balster and Parsons (1968, 65) noted an unusually large abundance of debris flows related to this event that had occurred in an area some 24 km northwest of the study area. This area is also underlain by rocks of the Siletz River Volcanic series and its vegetation and land uses are similar to that of the study area.

Dietrich and Dunne (1978, 197) documented nine 1964 debris flows contributing some 10,000 m^3 or 8,246 metric tons of sediment into stream channels in terrain with geologic substrates similar to those of the study area. These occurred in an undisturbed tract of old growth Douglas fir/western hemlock in the Rock Creek basin on the west slope of the central Oregon Coast Range.

The mean volume of 1964 debris flows reported in their study, 1,111 m^3 (916 metric tons) per landslide, is considerably greater than the mean 1964 slide volume for this study: 857.81 m^3. The mean weight of material transported from seven 1964 slide scars within the McDonald-Dunn study area is 1132.31 metric tons per slide, and this value is greater than that of Dietrich and Dunne because of the greater bulk density value utilized for the estimates (1.32 metric tons/m^3 in this study as opposed to their value of 1.0 metric tons/m^3).

The seven 1964 landslides that occurred within the study area include six debris flows and one slump/flow event, which has the lowest volume of transported material (28.80 m^3) of any observed landslide event. The mean volume of the six 1964 debris flows is 996.00 m^3 (mean weight of 1314.72 metric tons per slide), which is considerably closer to that reported by Dietrich and Dunne.

LANDSLIDE LOCATIONS AND SITE CONDITIONS

Landslide scars observed within the study area are more or less equally distributed between the scarp and debris slope elements. Of the 14 scars located on the scarp slope, 12 were observed to have occurred within or created bedrock hollows. Of the 11 scars located on the debris slope, none were observed to have occurred within such hollows. Slide 24 (a debris flow) has a concave scar that is quite deep (Dc = 2.93 m) and extends well into the regolith/saprolite layer, and it is likely that this event is responsible for the creation of a hollow. Perennial seeps were observed to emanate from slides 1, 11, 23 and 25, and no clear signs of intermittent or ephemeral flow were observed at any of the remaining sites. The occurrence of overland flow in slide scars appears to be related to scar depth and the exposure of regolith and or saprolite.

The mean value of slopes within scars is 39.32%, and slopes range from 26.0–55.0%. Nineteen of the 25 observed landslide scars are located at or immediately below significant breaks in slope, especially the larger events. All of the remaining scars, excepting those of slides 7 and 25, were of relatively low magnitude (less than 273 m^3) and were not observed to have occurred within hollows. Significant breaks in slope were observed within some 15–20 meters upslope of the crowns of slides 7 and 25.

A number of landslides were observed to have occurred immediately below the remnants of skid roads used in the period 1910–1930. These included slides 1, 2, 3, 5, 12, 23 and 25. Their occurrence at these sites is likely due to the effects of added weight, soil compaction and remolding (Crozier 1986, 46; Skempton 1953, 56; Varnes 1958, 43).

Recovery of observed slide scars may be defined in two different ways that are in many ways related: (1) recovery in terms of vegetation and soils (Wolman and Gerson 1978, 206), and (2) geomorphic recovery in terms of susceptibility to future landsliding events (Swanson et al. 1982, 161). With regard to vegetational recovery, no clear relationships between minimum ages of landslide events and vegetation cover were found to exist in the study area. This is likely due to varying site conditions (slope aspect, surrounding overstory vegetation, proximity to water courses) encountered.

Geomorphic recovery in the sense of refilling and recharge of landslide scars, especially those in hollows, has likely been affected in various indeterminable ways by the changes in vegetation and land use that have been described. It would be expected that rates of soil creep and hollow refilling would be lower under present forest conditions than they were previously. However, processes operating in the area today, such as timber harvest activities and infrequent wildfire, might trigger periods of accelerated refilling that might exceed pre-settlement rates (Swanson and Fredriksen 1982, 133).

The sequence of site colonization by overstory vegetation begins with red alder and vine maple/bigleaf maple in the moister and dryer sites, respectively. Fir species seem to establish themselves on displaced materials soon after slope failure, however, their growth appears to be slow judging by age/diameter relationships observed. Depending on scar depth (Dc) and dominant substrates at the surface of rupture, conifer establishment and growth may be delayed for several hundred years as is indicated by slides 19 and 22.

DISCUSSION AND CONCLUSION

Debris flows and avalanching in the study area are important in terms of sediment routing and landscape evolution. Their significance, however, has been made less clear due to widespread changes in vegetation and land use since euro-american settlement in the mid 19th century. The magnitude-frequency approach might be utilized in quantifying a sediment budget or routing scheme for the area in an attempt to gain insight into landscape evolution.

This approach has, however, at least two important limitations with regard to the analysis of processes occurring in steep and forested terrain. These limitations are: (1) the basic assumption of independence of successive events (Kelsey 1982, 152; Swanson et al. 1982, 161), which has both spatial and temporal implications; and (2) the steady-state assumption (Swanson and Fredriksen 1982, 130), which has been violated within the study area with fire suppression, vegetational change and land use activities.

The application of this approach to a study of landsliding in McDonald-Dunn Forest would require intensive study of only more recent events, stratification of events using a hollow/non-hollow criterion, and the investigation of soil creep rates in a variety of different site conditions. The latter requirement is limiting in that simple and accurate methods for measuring creep rates in the field are not available (Dietrich et al. 1982, 8), and such an investigation must necessarily be limited by time constraints.

Debris flow events, and the creation of bedrock hollows, appear to be an important mode of landscape evolution in the study area. The presence of perennial seeps, which likely develop into considerable flows during and following heavy winter storms, indicates that the drainage net is enlarged through debris flow activity (Dietrich and Dunne 1978, 200; Iida and Okunishi 1983). Debris flows which reach stream channels downslope build fans into which the streams incise new channels. These fans then remain as important elements of sediment storage. Such conditions were observed to have resulted from slides 11, 18, 19, 22, 23 and 24.

Though attempts at developing a model describing landslide magnitude in terms of site conditions proved fruitless, forest managers should note that all landslides were observed to have occurred on slopes greater than 26.0 % and less than 55.0 %, and that the majority occurred at or below significant breaks in slope. Otherwise, possible areas of slope instability are difficult to discern on the debris slope element (elevations less than about 300 meters or 1,000 ft.).

Topographic depressions on the scarp slope may represent bedrock hollows which are potential areas of slope instability. Hollows were observed to occur about every 50 meters on the lower portion of the scarp slope, and only four contained distinguishable landslide scars.

A sediment budget and/or routing study of the Oak Creek basin would require, among other things, information or data concerning soil creep rates under present conditions. As was mentioned before, such information is virtually impossible to obtain given temporal and technical constraints. The lack of complete streamgage records also poses some limitations, however, these might be circumvented through the analysis of clast characteristics at different sites within the drainage basin (Dietrich and Dunne 1978). Impacts of forest practices in McDonald-Dunn Forest on sedimentation could be elucidated through a sediment routing study that investigated mass wasting rates (soil creep, landsliding) before and after treatment.

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APPENDIX A

SLIDE	ELEV. (m)	FAILURE TYPE	SLOPE (%)	VOLUME (m^3)	WGHT. (m tons)	MIN AGE (yrs)
1	424	DF	43	390.48	515.43	21
2	424	DF	30	1360.31	1795.61	21
3	424	DF	35	193.62	255.58	24
4	212	DF	45	1194.19	1576.33	43
5	327	DF	52	552.88	729.80	25
6	455	DF	44	239.06	315.56	23
7	240	DF	40	1021.22	1348.01	105
8	235	DA	36	2024.93	2672.91	85
9	310	DA	34	206.65	278.78	46
10	260	DF	30	267.00	352.44	30
11	260	DF	27	117.50	155.10	33
12	340	DF	36	5425.99	7162.31	35
13	294	DA	35	252.30	333.04	50
14	294	DA	26	967.58	1277.21	47
15	297	DA	30	*155.55	205.33	40
16	275	SL	45	28.80	38.02	20
17	279	DA	55	*1409.59	1860.66	170
18	223	DF	43	646.51	853.39	51
19	220	DF	47	610.04	805.25	245
20	275	SL	35	49.38	65.18	120
21	277	DA	35	*909.80	1200.94	67
22	230	DA	53	*5120.21	6758.68	240
23	340	DF	30	4611.93	6087.75	35
24	303	DA	48	1711.98	2259.81	35
25	382	DF	49	3239.52	4276.17	25

Table 2. Landslides and their characteristics (DF = Debris Flow; DA = Debris Avalanche; SL = Slump/Flow; * = volume estimated utilizing equation 6, +/- 3.96 m^3).

APPENDIX B

Equations Utilized in Deriving Morphometric Indices (Crozier 1973)

Classification Index = Dc/Lc+Lx (1a)

= Dc/Lr+Lm (1b)

= D/L (1c)

Tenuity Index = Lm/Lc (2)

Flowage Index = (Wx/Wc-1) x Lm/Lc x 100 (3)

Fluidity number for pos. deviation (X) = 50(X/A) + 50 (4)

Fluidity number for neg. deviation (Y) = -[50(X/A) - 5] (5)