Hillslope Evolution and the Genesis of Colluvium in Redwood National Park, Northwestern California: The Use of Soil Development in Their Analysis

By

Donna Carol Marron

B.S. (Tufts University) 1977
M.A. (University of California) 1979

DISSERTATION

Submitted in partial satisfaction of the requirements for the degree of

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Approved: Clyde Wahrhaftig 5/15/82
Chair Date
Luna B. Leopold 5/14/82
Paul L. Dreeper 5/13/82

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF PLATES

LIST OF TABLES

CHAPTER I - INTRODUCTION AND BACKGROUND

A. INTRODUCTION

1. Context

Models of landscape evolution proposed by Davis (1899) and Penck (1924) attributed differences in slope forms to different stages in a number of landscape evolution schemes. These models, which were widely accepted in the early and middle 1900's, interpreted landscapes in terms of their relative ages, or in terms of the lengths of time since those landscapes were dissected or rejuvenated in response to changes in climatic or tectonic conditions. Even before the publication of Davis' and Penck's ideas, Gilbert (1977) and Powell (1874) noted strong relationships between slope forms and the characteristics of underlying bedrock. These observations were later incorporated into Hack's (1960) suggestion that different erosional landforms are parts of larger erosional systems in states of dynamic equilibrium, adjusted to diverse lithologies, climatic and microclimatic conditions, and other environmental parameters.

In his paper on "The Interpretation of Erosional Topography in Humid Temperate Regions", Hack (1960) stated that in an "erosionally graded" topography, "the diversity of forms is largely the result of differential erosion of rocks which yield to weathering in different ways". This point of view, which rapidly gained acceptance, prompted researchers to focus on differences in processes and rates of erosion occurring on hillslopes of different forms. Many modern studies of

Figure 1 - Composite aerial photograph of the logging road network in Redwood National Park. One inch equals approximately two kilometers. Dashed lines are park boundaries.

slopes are empirical and specific, often concentrating on the description, measurement, and quantitative modeling of single slope forming processes. Resulting slope evolution schemes include Culling's (1963) and Kirkby's (1967) models of erosion by creep on soil-covered hillslopes; models presented by Carson and Kirkby (1972) of slope shaping by the removal of material in solution; and Carson's (1969) model of slope development by landsliding. While mathematically oriented studies such as these have provided new insights into the erosional development of slopes, they can lack the historical perspective which is important to an understanding of the evolution of different hillslope forms.

Widespread timber harvest activity in the Pacific Northwest has provided a good opportunity to combine historical and process oriented approaches to the study of weathering and erosion history, by creating continuous logging road networks such as the one seen in Figure 1. Roadcuts created expose the interface between tree roots and unweathered, in situ bedrock on a variety of rock types and in a variety of drainage basin positions. Information provided by roadcut exposures of residual soils and colluvium has been used in this study to generate models of slope evolution for hillslopes of different forms in Redwood National Park, which is underlain by two common rock types in the Franciscan Formation. Models developed in this study are process oriented because they link the characteristics of exposed surficial materials to the activity of specific weathering and erosion processes. This study also has a historical perspective because the surficial materials studied are a composite record of the activity of weathering and erosion processes which have been occurring on slopes of different forms over the past several million years.

Changes in climatic and tectonic regimes cause changes in rates and modes of weathering and erosion processes. In addition, the long recurrence intervals of many mass wasting processes make study by direct monitoring difficult. In view of these problems, the geologic approach of this investigation, which involves a search for evidence of the past and present activity of specific processes, in surficial materials which have been formed and altered by those processes, appears to be a promising one for the understanding and modeling of slope evolution.

2. Definitions

In this study, weathering profiles developed on bedrock showing eluvial/illuvial layers or horizons, which reflect the activity of such pedogenic processes as clay and iron oxide translocation, are called residual soils. Colors, textures, and soil structures of these horizons vary in a fairly predictable manner. As will be discussed in subsequent chapters, while *in situ* weathering has clearly occurred on most hillslope surfaces in the Redwood Creek drainage, it is important to recognize that the weathering profiles created are also influenced by slow random downslope movement. Despite the recognition that they may be partly colluvial, soil profiles which overlie bedrock and which show eluviation/illuviation horizons, are treated as residual soils in this study because their well defined pedogenic horizons suggest that if these materials are being continually moved downslope, the processes responsible are slow enough to be operating concurrently with pedogenesis. In contrast, surficial materials which have been moved by erosion processes acting fast enough to destroy, mask, or disrupt the

effects of pedogenesis, and which effectively create new parent material which is subsequently subjected to weathering and pedogenesis, is called colluvium. Colluvium which shows the effects of pedogenesis can be thought of as colluvial soil. Bedrock refers to material interpreted to be in place, showing at least some remnant of its initial structure, such as a continuous schistosity. Observed bedrock exposures are often highly weathered or mechanically broken, yet still appear to be in place. Bedrock which has been extensively chemically weathered, but still retains remnants of its initial structure is called saprolite.

Names for different mass wasting processes were taken from Varnes' (1978) classification scheme. Slumps are deep seated landslides which rotate failed material along failure surfaces which are roughly circular in cross section. Debris and block slides are deep seated failures which translate soil and rock materials downslope along approximately planar failure surfaces. Slumps, debris slides, and block slides can occur over time periods of minutes to hours, but may remain periodically active over time periods of years to centuries. Material above slide planes is transported but not necessarily disrupted by these deeply seated slides.

Debris avalanches are shallow failures of material characteristically containing over 50% gravel sized clasts, and occur over time scales of minutes to hours. Debris from these failures is commonly transported quickly to streams, which quickly remove or redistribute the failed material. Continuous detachment of rock fragments from debris avalanche scarps is called raveling. The transport of sediment by water flowing across debris avalanche scars is called sheet wash.

Earthflows are complex translational or rotational slides which move and mix mostly soil materials within well defined head and lateral slide boundaries. Earthflows in the Redwood Creek drainage cover areas as large as one half square km, and sporadically move materials downslope at rates which range from a few cm to more than 10 m per year (Harden et al., 1978). Creep refers to minute but continuous downslope translations of soil and rock material, caused by soil moisture and temperature variations, by activities of plants and animals, and by the steady application of a downhill shear stress. Creep activity grades into block and debris slides, as velocities increase, and as basal shear planes develop. Tree throw is treated separately from creep, and refers to downslope transport of soil and rock by the uprooting of trees which have fallen downhill.

3. Methodology of Research

Initial field and air photo examinations of logged areas in Redwood National Park were used to define three physiographic terrains in the park. Slopes in each of these terrains have distinctive forms, which reflect the activity of particular weathering and erosion processes. The types and rates of weathering and erosion processes on different slopes are in turn strongly influenced by bedrock characteristics.

Two small drainages with characteristic slope forms and particularly fresh and continuous roadcut exposures were located in two of the defined terrains. Observations of the residual soils and landslide-related deposits exposed in these roadcuts were used to characterize soil-colluvium associations on slopes in each of the two terrains.

Roadcut exposures showing evidence of particular erosion processes or sets of processes, such as deep seated slides or debris avalanches and related raveling and sheet wash, were photographed and described in detail. Color xeroxes of 35 mm slides of some exposures of colluvium deposits were annotated in the field. Drawings of these photographs emphasize noteworthy sedimentologic and weathering features of the deposits. Profile depths, clay films, pedogenic structures, and textures of residual soils were described by the methods of the U. S. Department of Agriculture and Soil Conservation Service (1974). Moist and dry soil colors were determined using a standard Munsell color chart. Selected soil profiles were sampled by horizon, and were analyzed for gravel and sand weight percents by wet sieving, and for silt and clay weight percents by the pipette methods described by Day (1965).

Reconnaissance descriptions of residual soils and colluvium were used to define units for detailed mapping of surficial materials on slopes in one small drainage in each terrain. Separate developmental sequences of residual soil profile development on schist and on relatively coherent graywacke and shale were established on the bases of variations in profile depth, color, abundance and thickness of clay films, pedogenic structure, and clay and gravel content. The use of the term developmental sequence implies that given analogous conditions of soil environment on any particular type of bedrock, all of the soils in the sequence will evolve through the more developed soils in the sequence to a final steady state product, if undisturbed for long enough periods of time.

On slopes where soil patterns could not be attributed to variations in topographic position, vegetation, climatic conditions, or bedrock characteristics, the degree of residual soil profile development was interpreted to reflect the soil age, which equals the length of time since weathered material was last stripped from the surface to expose unweathered parent material to the current cycle of weathering. Mapping of the distribution and character of colluvium on slopes was used to characterize types and intensities of different transport processes active in different parts of the Redwood Creek basin. Qualitative models of soil genesis and slope evolution were developed on the basis of this information on residual soils and colluvium.

4. Previous Work

The success of a lawsuit by the Sierra Club against the U.S. Department of the Interior regarding the protection of Redwood National Park, led the National Park Service to contract with the U.S. Geological Survey to gather and synthesize data on watershed conditions and modern erosion processes in the Redwood Creek drainage. The U.S. Geological Survey study, which was directed by Richard J. Janda, included the study by Harden et al. (1978) of the recent activity of specific mass wasting processes, particularly earthflows which are not considered in the present study; Coleman's (1973) study of slides directly feeding the main branch of Redwood Creek; and studies by Iwatsubo et al. (1975, 1976) and Bradford et al. (1978) of water chemistry in the basin.

Residual soils in the Redwood Creek drainage were mapped at a scale of 1 to 31,680 by Alexander et al. (1959-1962). The small scale of their maps and the fact that their survey was of the reconnaissance

type, which yields low accuracy under the dense forest cover which covered most of the area they mapped at time time of their study, make their work useful only as background information to more detailed studies. Bedrock in the area has been mapped and described by Manning and Ogle (1950), Strand (1962), Young, J. C. (1978), and Harden et al. (1981). Nolan et al. (1976) mapped erosional landforms in the Redwood Creek drainage.

The usefulness of the concept of developmental sequences of residual soils to the study of slope evolution was demonstrated by Zinke and Colwell (1965), who used information collected for California soil-vegetation surveys to define and interpret such sequences for forested mountainous regions underlain by sandstone, granite, schist, and volcanic rocks. More detailed studies of the nature and distribution of residual soils and of landslide-related deposits on forested slopes in the Redwood Creek and similar watersheds are rare, mostly due to the lack of adequate exposures. Previously proposed landscape evolution models by debris avalanching, and descriptions of colluvium observed on slopes in various places, provide useful data, and are reviewed in Chapter 2. Studies of soil-slope relations which include helpful information are reviewed in Chapter 3.

B. DESCRIPTION OF THE REDWOOD CREEK WATERSHED

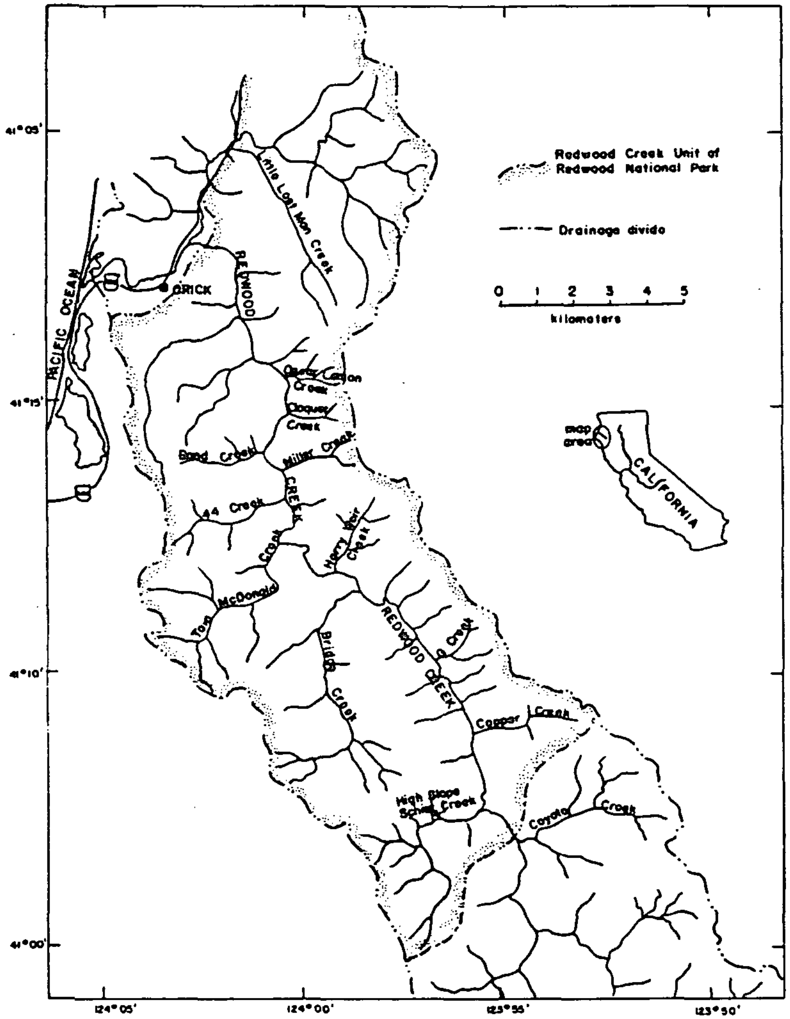
1. Location and General Basin Physiography

Redwood Creek drains a markedly elongate northwest trending 725-square-km drainage basin, the northern portion of which is shown in Figure 2. Some ridge tops and tributaries of different orders within the watershed are also aligned in a northwest-southeast direction, which is the orientation of most major structural features in the area. Redwood Creek enters the ocean just west of the town of Orick, California, which is located approximately 80 km south of the Oregon border on Interstate 101. Maximum relief within the watershed is approximately 1600 m.

According to Janda et al. (1975), the average hillslope gradient in the Redwood Creek drainage is approximately 26%. Over 50% of the hillslope segments measured for their study, however, had gradients of 35% or more. Slope segments directly adjacent to stream channels are often steeper than the side slopes and ridge tops above. Janda et al. (1975) referred to these steep-walled stream canyons as inner gorges.

According to Nolan et al. (1976), over 30% of the Redwood Creek drainage shows landforms which reflect former or current mass wasting activity. Large debris avalanche scars are present on footslopes along both sides of the Redwood Creek channel. Some slopes underlain by schist show back-rotated and irregular surfaces indicative of slumping or block sliding. Active earthflows occur on slopes underlain by sheared and broken graywacke and shale.

Figure 2 - Location map of Redwood National Park.



2. Bedrock and Associated Slope Characteristics

Most of the Redwood Creek drainage is underlain by rocks of the Franciscan Formation. According to Page (1981), and Blake and Jones (1981), Franciscan rocks are Jurassic to early Tertiary in age, and consist mostly of sediments and metasediments which were deposited in trench environments and were subsequently deformed, metamorphosed, and tectonically mixed with ophiolitic and other rock types in response to eastward subduction of oceanic crust under the western edge of the North American continent. Open ocean pillow basalts and radiolarian cherts are also common Franciscan rock types.

Sediments and metasediments of the Franciscan Formation have been subdivided by various researchers on the basis of a number of characteristics which are relevant to considerations of erosion and soil forming processes. Blake et al. (1967) defined three textural zones based primarily on metamorphic and cataclastic textures. Textural zone I rocks appear unmetamorphosed in hand specimen and only slightly metamorphosed in thin section. Textural zone II rocks have tectonically flattened or elongated clasts, and show some cleavage development. Textural zone III rocks display a well defined schistosity, which often completely obscures original sedimentary textures. This schistosity is a product of the growth of new mineral grains under temperatures and pressures greater than those of the environments in which the protolith sediments were deposited.

Superimposed on the textural zone classification proposed by Blake et al. (1967) are distinctions based on states of shearing of matrix materials, and on the lithologies of included blocks. Hsu (1968) defined coherent Franciscan graywacke as being structurally continuous; broken formation as consisting of tectonically sheared and broken matrix material surrounding blocks of material from the same lithostratigraphic unit; and melange as consisting of sheared and broken matrix material surrounding blocks which have been tectonically introduced from one or more different lithostratigraphic units. Melange is distinguished from broken formation by the presence of fossils and/or metamorphic minerals which imply deposition or metamorphism in a different geologic environment than that in which matrix materials were deposited and subsequently metamorphosed.

Geomorphic units within the Franciscan Formation differ only slightly from bedrock classification schemes proposed by Hsu (1968) and Blake et al. (1967). Slopes on textural zone III rocks tend to have convex profiles and gentle gradients. Slopes on coherent textural zone I rocks have straight to concave profiles and steeper gradients. Slope forms in areas underlain by melange and broken formation range from resembling steep slopes such as those underlain by coherent Franciscan, to showing what Maxwell (1974) referred to as "accidental topography", in which knobs upheld by erosionally resistant scattered blocks are surrounded by gentler slopes eroded in sheared and fine grained matrix materials. Savina et al. (1978) linked matrix lithologies (sheared graywacke vs. sheared shale) and ratios of block volumes to matrix volumes in areas underlain by the Franciscan Formation in northwestern California, to slope forms and susceptibility to rapid erosion by earthflow.

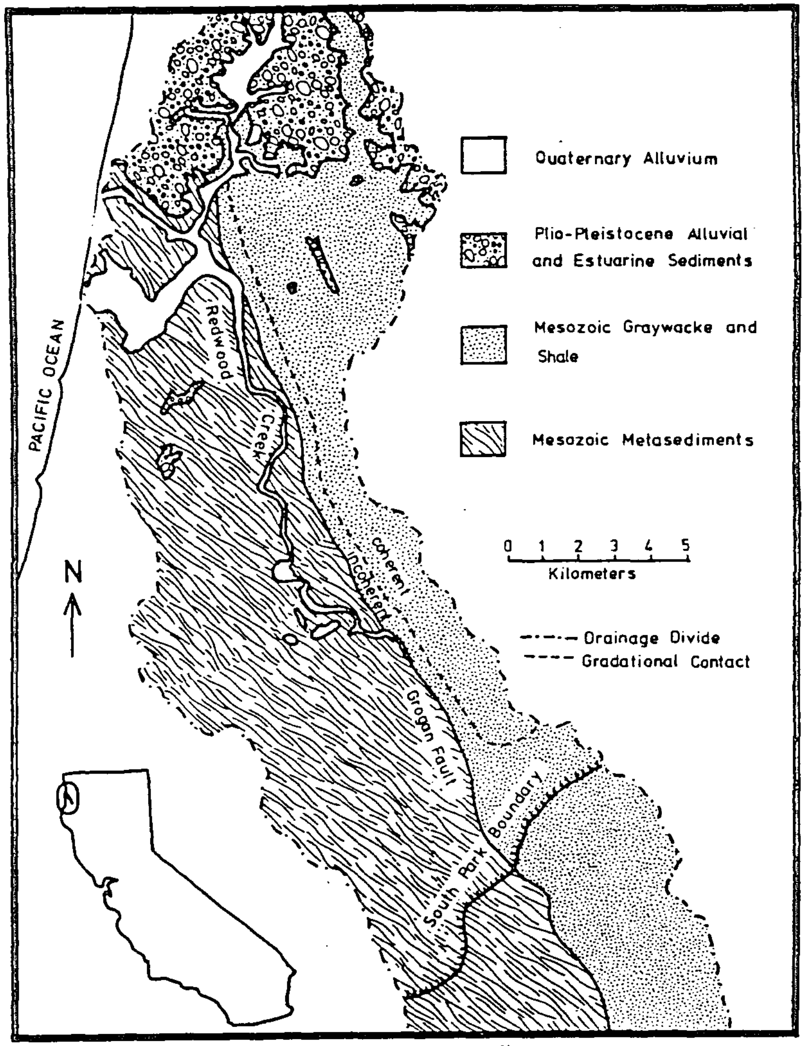
For the purposes of this study, Franciscan rocks in the Redwood

Creek drainage are divided into three units, whose distribution is shown in Figure 3. Southwest of the Grogan fault lie regionally metamorphosed and well foliated metasediments and metavolcanic rocks, which fit into the third textural zone defined by Blake et al. (1967). Rocks northeast of the Grogan Fault fit the description of textural zones I and II rocks, and are subdivided into relatively coherent and incoherent units. Both units fit Hsu's (1968) description of a broken formation, in that they include blocks which could be from the same lithostratigraphic unit, however they differ from each other in that the coherent unit has a relatively coarse and unsheared matrix, and appears to include exclusively graywacke blocks, while the incoherent unit is comprised of finer grained and more sheared matrix materials, and includes chert, greenstone, and graywacke blocks.

Processes of soil genesis and erosion in the Redwood Creek drainage were studied on slopes underlain by schist and on slopes underlain by relatively coherent graywacke and shale. In the following chapters, lithologic descriptions of the bedrock units precede descriptions of related pedogenic and erosion processes. Descriptions of rocks similar to the less coherent textural zone I and II rocks in the Redwood Creek drainage have been presented by Bailey et al. (1964) and Blake and Jones (1974).

Slope forms, drainage densities, and stream bifurcation ratios are closely related to bedrock characteristics in the areas studied. Areas underlain by relatively coherent graywacke and shale commonly have narrow rounded ridgetops and straight to slightly concave side slopes with gradients which mostly range from 30% to 50%. Some streams in these

Figure 3 - Geologic map of Redwood National Park.



Modified from Harden et al (1982)

areas have steep inner gorges. Areas underlain by schist commonly have broadly rounded ridgetops and side slopes with gradients between 20% and 40%. Inner gorges are more common and include more of the slope in areas underlain by schist than in areas underlain by relatively coherent graywacke and shale. As total relief is similar on east and west sides of the Redwood Creek drainage, drainage densities and stream bifurcation ratios are higher in steeper basins underlain by relatively coherent graywacke and shale, than in basins containing gentler slopes underlain by schist. Slopes developed on the incoherent graywacke and shale unit, which are not considered in this study, often show a hummocky microtopograpy that reflects the activity of slowly moving deep-seated translational and rotational landslides fitting Varnes' (1978) description of earthflows.

The essentially straight map pattern of the Grogan Fault, which is followed by much of the main channel of Redwood Creek, suggested to Harden et al. (1981) that the fault is vertical or near vertical. Kelsey and Hagans (1981) mapped the Grogan fault as a steeply dipping fault with roughly 80 km of right lateral displacement. Offsets in weakly lithified nonmarine Plio-Pleistocene sediments mapped by Young, J. C. (1978) in the very northern part of the Redwood Creek watershed, indicate that a strike slip fault just west of the Grogan fault was active in post-Pliocene times (Talley, 1976). Whether or not the Grogan fault is presently active is unclear. Earthquakes along active thrust faults near the shore and on land, however, periodically shake the Redwood Creek drainage, and have possibly adverse effects on slope stability.

3. Climate and Vegetation

Redwood Creek's climate is characterized by wet winters with mild temperatures, and dry summers. The northern part of the basin, which includes much of the area presently occupied by Redwood National Park, experiences frequent coastal fog during summer months. Yearly precipitation ranges from 180 to 230 cm, and occurs almost exclusively between October and June. According to Janda et al. (1975), orographic effects cause total amounts of rainfall in different parts of the basin to range substantially. Mean maximum temperatures in July range from about 21 to about 35 degrees C, while mean minimum temperatures in January range from about 0 to about 3 degrees C. (Janda et al., 1975).

Light to moderate intensity storms of long duration can drop 10 or more cm of rain on the basin in only a few days. Major storm events which caused substantial hillslope instability and aggradation in lower stream reaches have occurred several times in northern California during the past few hundred years, according to Helley and Lamarche (1973), who studied ages of trees growing on fill terraces in that area. Janda et al. (1975) indicated that while average winds are light in the area, strong winds are sometimes associated with severe storms. Occasionally, a light snow pack will accumulate on upper slopes and ridgetops in the basin.

Before logging, forests which were predominantly redwood (Sequoia sempervirens) and Douglas-fir (Pseudotsuga menziesii) covered most hillslopes in Redwood National Park, with Douglas-fir, tanoak (Lithocarpus densiflora), and madrone (Arbutus menziesii) trees becoming more abundant upslope and upstream, in response to drier soil conditions

(Janda et al., 1975). Other tree species which are found in remaining virgin forests include coast hemlock (Tsuga heterophylla), grand fir (Abies grandies), and Port Orford cedar (Chamaecyparis lawsonia). Red alder (Alnus rubra) and tanoak thrive in areas not vegetated by trees which provide a canopy and block sunlight. Such areas include landslide scars and gravel bars in streams, under natural conditions, and abandoned roads, roadcuts, and cutover lands following logging. According to Stone et al. (1969), timber stands on the southern side of the Redwood Creek basin are denser, contain older trees, and contain greater percentages of redwoods. Understory vegetation under natural conditions is typically dense and varied, and commonly contains sour-grass (Oxalis oregana), sword fern (Polystichum munitun), rhododendrum, black and red huckleberry (Vaccinium ovatum and parvifloium), salal (Gaultheria shallon), hazel (Corylus coruta var. californica), and other plants. Prairies covered by grasses and shrubby plants occur on some ridge tops and interfluves on the eastern side of the Redwood Creek drainage.

4. History of Base Level Changes

Miocene and Oligocene continental and marine deposits define a Miocene shoreline which lay east of the area presently drained by Redwood Creek (Wahrhaftig and Birman, 1965). Coastal terraces south of Orick at Agate Beach, in addition to streams deeply incised in Plio-Pleistocene gravels north of Orick in the Prairie Creek State Park reflect subsequent uplift. Strath terraces along Redwood Creek, stream gravels which lie approximately 250 m above the modern Redwood Creek channel on the north and south interfluves of Bond Creek, and the flat surface on the nortnern interfluve of Bond Creek, which is overlain by gravels which are possibly marine terrace deposits no older than four million years, (Harvey M. Kelsey, N.P.S., personal communication, 1981), also reflect uplift. Obvious northward downwarping of the coastal terraces at Agate Beach, however, and lagoons and drowned river mouths on some coastal sections indicate that some portions of the coast, including much of the area directly west of Redwood National Park, have experienced at least recent submergence. Strongly developed soils on seacliffs adjacent to lagoons attest to the submerged nature of these areas, as these soils would not have had time to develop on recently uplifted and exposed parent material. The residual soil on the schist bluff south of Freshwater Lagoon, which is located approximately 2 km south of the mouth of Redwood Creek, is more than 2 m thick, has horizons with 2.5YR colors, and contains abundant thick clay films.

The recent history of uplift and subsidence of parts of the Redwood Creek drainage is obscured by the complex climatic and tectonic history of that area. Southwest of the headwaters of the basin lies a triple junction between the Pacific, Gorda, and North American plates. According to Silver (1971), oblique, low angle subduction of the Gorda plate beneath the North American plate as the triple junction has migrated north along the San Andreas fault system has been responsible for late Tertiary and Quaternary uplift in many parts of the coastal regions of northern California and southern Oregon. Presently active northwest trending right lateral faults and associated folding, which Silver (1971) and Herd (1978) suggested result from the northward extension of the San Andreas fault system, are probably responsible for uplift and downwarping in some areas. Holocene rises in sea level, which began

around 15,000 years ago, have created lagoons and drowned river mouths in tectonically downwarped coastal segments such as the stretch of coast west of the lower third of the Redwood Creek drainage.

CHAPTER II - THE GENESIS OF RESIDUAL SOILS, COLLUVIUM, AND SLOPE FORMS ON COHERENT GRAYWACKE AND SHALE

A. INTRODUCTION

In this chapter, the history of soil genesis and slope evolution in areas underlain by relatively coherent graywacke and shale in the Redwood Creek drainage is discussed. Slope forms and soil-colluvium associations suggest that debris avalanching and associated raveling, tree throw, and sheet wash have been dominant erosion processes in these areas for at least the past few tens of thousands of years, and that surficial materials have recently been more frequently stripped on steep lower slopes than on some lower gradient ridge top and upper slope positions. The sections on residual soils and colluvium describe and discuss characteristics and map patterns of these surficial materials with regard to their genetic implications. In the final section in this chapter, information from the previous sections is incorporated into a model of landscape evolution for tributary drainages underlain by relatively coherent graywacke and shale in the Redwood Creek watershed.

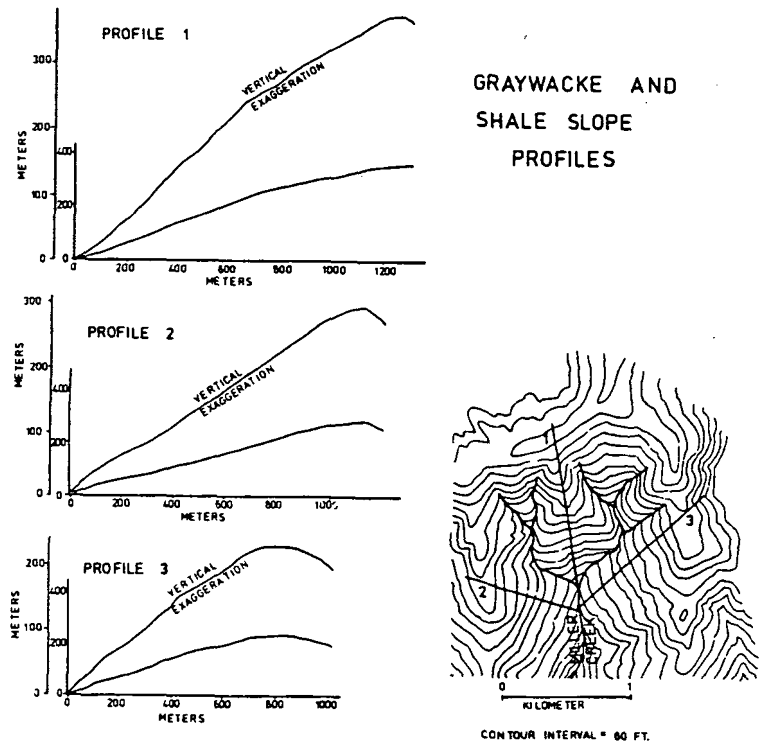
Areas discussed in this chapter include tributary drainages between Copper Creek and Lost Man Creek on the east side of the Redwood Creek watershed. The relatively coherent bedrock in the upper parts of these drainages grades into melange or incoherent graywacke and shale within approximately one half km of the Grogan Fault. Downstream portions of some of these drainages lie west of the Grogan fault, hence are underlain by schist. Residual soils on slopes cut in relatively coherent graywacke and shale tend to be shallow and poorly developed. They lack

cohesion, and have easily disrupted well-developed granular structures in their upper horizons. Consequently, roadcuts in these residual soils wear back rapidly following logging and road building. In contrast to residual soils, colluvium deposits on these slopes are deeper, rockier, and sometimes more densely packed, and are well exposed in roadcuts.

Selected profiles of slopes underlain by interbedded graywacke and shale are shown in Figure 4. Side slopes in these areas have gradients which range from 20% to over 50%, and have average gradients of approximately 35%. Iwatsubo _et al_. (1975) cited drainage densities ranging from 3.6 to 5.5 and averaging at 4.6 km of channel per square km for tributary drainages in these areas. Marked irregularities in interfluve, side slope, and stream channel profiles appear to reflect differences in the erosional resistances of large graywacke blocks which are in fault contact with the more sheared graywacke and shale around them, and of lithologic subunits which show different grain size distributions and degrees of shearing.

Relatively coherent graywacke and shale bedrock in the Redwood Creek drainage consists primarily of essentially unmetamorphosed bedded graywacke, which is interbedded with lesser amounts of mudstone, and still lesser amounts of conglomerate. The graywacke is medium grained, and contains angular to subrounded grains of quartz, feldspar, and lithic clasts. Matrix material commonly consists of clay and micaceous minerals. Beds are usually a few cm to a few m thick, but can be as thick as 10 m (Harden _et al_., 1981). Tectonically included blocks are surrounded by sheared and broken graywacke and shale, and appear to be exclusively graywacke in lithology.

Figure 4 - Profiles of slopes underlain by relatively coherent graywacke and shale in the Miller Creek drainage.



Exposures of relatively coherent graywacke and shale show breakage along joint cracks and fractures which creates angular fragments of pebble to cobble size. Edges of individual clasts in colluvium can sometimes be fitted together, as though breakage and separation had occurred in place. Most bedrock outcrops appear only slightly affected by chemical weathering, however rock colors redder than 10YR, and 1 to 2 mm thick weathering rinds on rock fragments, are occasionally observed.

Detailed study of residual soils and colluvium on slopes underlain by relatively coherent graywacke and shale was done mostly in the upper part of the Miller Creek drainage, which lies east of the Grogan fault. Reconnaissance work in the G Creek drainage, and in the upper parts of the Cloquet Creek and Harry Weir Creek drainages suggests that patterns of soil and colluvium observed in upper Miller Creek are characteristic of tributary drainages underlain by relatively coherent graywacke and shale.

B. RESIDUAL SOILS ON COHERENT GRAYWACKE AND SHALE SLOPES

1. Previous Work

Soil-vegetation maps done at a scale of 1:31,680 by Alexander *et al.* (1959-62) show residual soils of the Hugo series on most slopes underlain by relatively coherent graywacke and shale in the Redwood Creek drainage. Some ridge-top and north-facing slope positions are mapped as having residual soils in the Melbourne series. By definition, Hugo soils are 70 to 150 cm deep, and are grayish brown gravelly clay loams in surface horizons and pale brown stony clay loams in subsurface horizons. Melbourne soils are 75 to 150 cm deep, and are brown loams in surface horizons and strong brown clay loams in subsurface horizons. The parent material for both soils is Franciscan graywacke. Slightly redder colors and lower gravel contents of Melbourne as opposed to Hugo soils suggest that the Melbourne soils show a greater degree of soil profile development.

2. Definition of the Developmental Sequence

For the purposes of this study, weak and moderate degrees of residual soil profile development were defined by reconnaissance studies in the Cloquet Creek, Miller Creek, Harry Weir Creek, and G Creek drainages, and were mapped in the upper part of the Miller Creek drainage. Characteristics of the two soil units defined in this study are summarized in Table 1. While A horizons of the two units have similar depths and structures, and differ only slightly in colors and textures, B horizons of the 2 units are more distinct, and provide the

Table 1: Graywacke Residual Soil Characteristics

	Weakly Developed Soils	Moderately Developed Soils
A Horizons		
average lower boundary depth	0.30 m	0.30 m
maximum lower boundary depth	0.40 m	0.40 m
texture	gravelly sandy clay loam	gravelly clay loam
structure	moderate to strong granular	moderate to strong granular
color	10YR	10YR to 7.5YR
B Horizons		
average lower boundary depth	0.80 m	1.25 m
maximum lower boundary depth	0.95 m	1.55 m
texture	gravelly clay loam	clay loam
structure	weak subangular blocky	moderate subangular blocky
color	7.5YR	7.5YR to 5YR

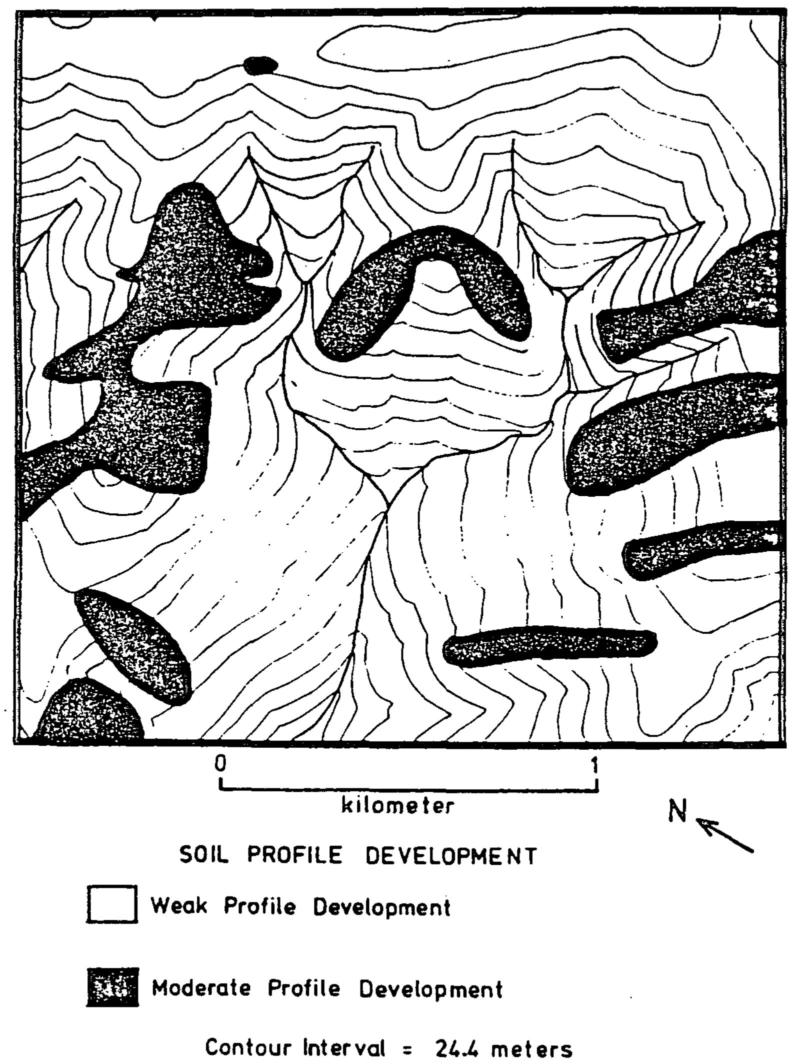
basis for separating the two units, and for characterizing their relative degrees of profile development. Moderately developed soils are considered more strongly developed than weakly developed soils because their B horizons are deeper, redder, more clay rich, and have more strongly developed pedogenic structures. The two soil units defined in this study are roughly analogous to the Hugo and Melbourne soil series, however map patterns in the upper part of the Miller Creek drainage, which are shown in Figure 5, do not resemble those on maps by Alexander et al. (1959-62).

3. Controls on Soil Profile Development

According to Jenny's (1941) state factor equation, residual soils are functions of the interacting influences of climate, organisms, parent material, topographic position, and time. In a general way, the first three of these conditions are constant in the upper part of the Miller Creek drainage, hence variations in degrees of residual soil profile development in that area can be attributed to variations in soil age, which equals the length of time since unweathered bedrock or soil parent material was exposed by erosion, and to variations in topographic position.

Decreases in soil profile development from some interfluves to stream channels in the Miller Creek drainage may be due to relatively more recent erosional activity in the downslope positions, or to lower pedogenic rates in lower slope positions due to drier soil conditions or downslope increases in solute concentrations of subsurface water. The explanations requiring lower pedogenic rates in downslope positions are

Figure 5 - Residual soil map of the portion of the Miller Creek drainage above the Grogan fault.

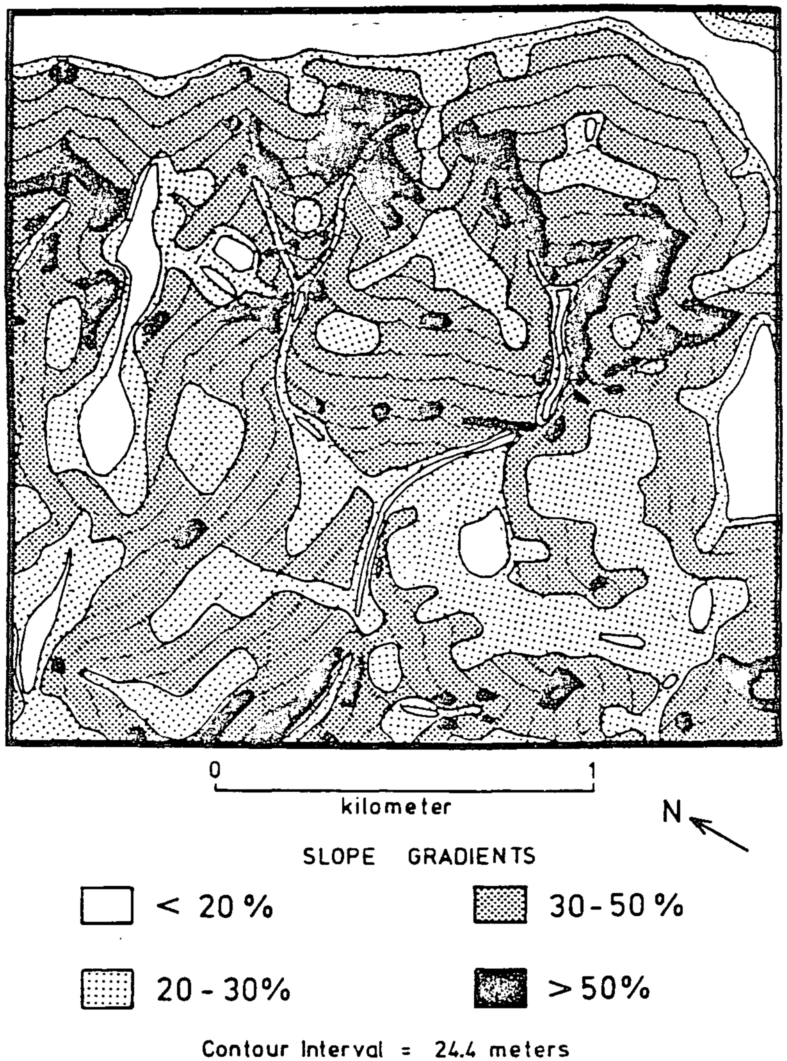


not favored in this study for the following reasons. Firstly, soils on lower slope segments are generally moister than upper slope soils due to the contribution of water from upslope by subsurface throughflow. Secondly, observations of downslope increases in degrees of soil profile development made by Nettleton et al. (1968) and Al Janabi and Drew (1967) on slopes elsewhere, suggest that accumulated water in downslope positions is sufficiently undersaturated to promote relatively rapid pedogenesis on lower slopes.

Observed downslope decreases in the degree of residual soil profile development in the upper part of the Miller Creek drainage are more likely a reflection of relatively more recent erosional activity in the downslope positions. Support for this premise can be obtained by comparing Figures 5 & 6. As can be seen, most moderately developed soils in the upper part of the Miller Creek drainage occur on slope surfaces with relatively gentle gradients, which do not reflect recent steepening by stream incision or debris avalanching. Possible causes of more recent erosional activity in downslope positions on relatively coherent graywacke and shale slopes are discussed in the final section of this chapter.

Residual soils on the eastern interfluve of the Miller Creek drainage may be more poorly developed than on midslopes below due to better drainage, drier soil conditions, and consequently lower pedogenic rates in the ridgetop and upper slope positions. Alternate explanations for these downslope increases in profile development stem from the fact that some soils currently under forest cover on the eastern interfluve of Miller Creek, have thick and organic-rich A horizons which may

Figure 6 - Isotangent or slope map of the portion of the Miller Creek drainage above the Grogan fault.



reflect genesis under prairie vegetation. Prairies which now exist on some graywacke and shale interfluves may have been more extensive in the past due to slightly drier climates. Support for this suggestion is provided by the observation made by Harden et al. (1978) of bands of young Douglas-fir around modern grasslands, which could reflect a recent encroachment of the forest on the prairies in parts of the Redwood Creek drainage.

Birkeland (1974) indicated that soils are commonly subjected to less intense leaching and clay and iron oxide translocation under prairie as opposed to forest cover. In addition, erosion processes differ under the two types of vegetation. It is possible that residual soils in some ridgetop and upper slope positions in Miller Creek appear less developed than soils topographically below them because their genesis proceeded more slowly under grassland vegetation, which may have once covered these presently forested sites. It is also possible that erosion processes, that may have been more active under prairie as opposed to forest cover, exposed fresh parent material more recently in the upslope positions. These possibilities illustrate that caution must be exercised in basing models of soil genesis and erosional history on modern vegetation and hydrologic conditions, which may be substantially different from those at the time of soil development and slope evolution.

C. COLLUVIUM ON COHERENT GRAYWACKE AND SHALE SLOPES

1. Introduction

Colluvium on slopes underlain by relatively coherent graywacke and shale in the Redwood Creek drainage most commonly occurs as small lenticular pockets of rocky, crudely bedded material. These deposits are referred to as colluvium pockets in this study, and are interpreted to be filled scars of small debris avalanches. The common occurrence of colluvium pockets suggests that if this interpretation is correct, debris avalanches have been important in the erosion of the slopes upon which the deposits are found. The colluvium pockets are discussed in detail in the following sections.

A less common type of colluvium found on coherent graywacke and shale slopes lacks bedding and contains angular to subangular, pebble to boulder size clasts of uniform lithology. Deposits of this type can be as much as 200 m in width along contour, are usually more than 5 or 6 m thick, and occupy subtle benches on slopes. Two of these deposits in the Redwood Creek watershed are located below prominent topographic knobs held up by knockers of relatively resistant graywacke lithologies, and are quite possibly related to intensive frost riving of those knockers during former cold periods. Related phenomena might be what Janda et al. (1975) interpreted to be products of frost riving in the southern part of the basin, which would also have been formed during colder periods in the past.

2. General Description of Colluvium Pockets

When observed in roadcuts which parallel slope contours, colluvium pockets are U- to V-shaped, and average 10 to 15 m in width and 3 to 4 m in thickness. They most commonly occur in subtle topographic hollows, though their locations range from the borders of channels of deeply incised streams to the sides of prominent secondary interfluves. Where exposed in three dimensions, they are seen to extend linearly downslope to streams or ravine bottoms. Some colluvium pockets thicken upslope, and have floors which are less steep than the modern pre-logging land surfaces above them. In the area east of the Grogan Fault within the Cloquet Creek, Miller Creek, Emerald Creek, and G Creek drainages, the colluvium pockets cover an estimated 20% of the landsurface, but do not occur within 300 m of the drainage divide between Redwood Creek and Tectah Creek to the northeast. When only partially exposed, they can be distinguished from the residual soils discussed in the previous chapter by their sharp contacts with bedrock which often dip steeply and truncate bedding and fracture patterns, and by their inclusions of clasts differing in lithology from the in situ bedrock below and to the sides. Included clasts are commonly in crude layers parallel to pocket boundaries, and show considerable variation in grain size distribution and angularity both within and between layers.

The next four sub-sections contain discussions of the nature and genetic implications of the sedimentology, weathering characteristics, map patterns, and relations to residual soils of colluvium pockets in the Redwood Creek drainage. The subsequent sub-section presents a summary of analogous or contrasting features noted by other researcher in similar deposits found elsewhere.

3. Sedimentology of Colluvium Pockets

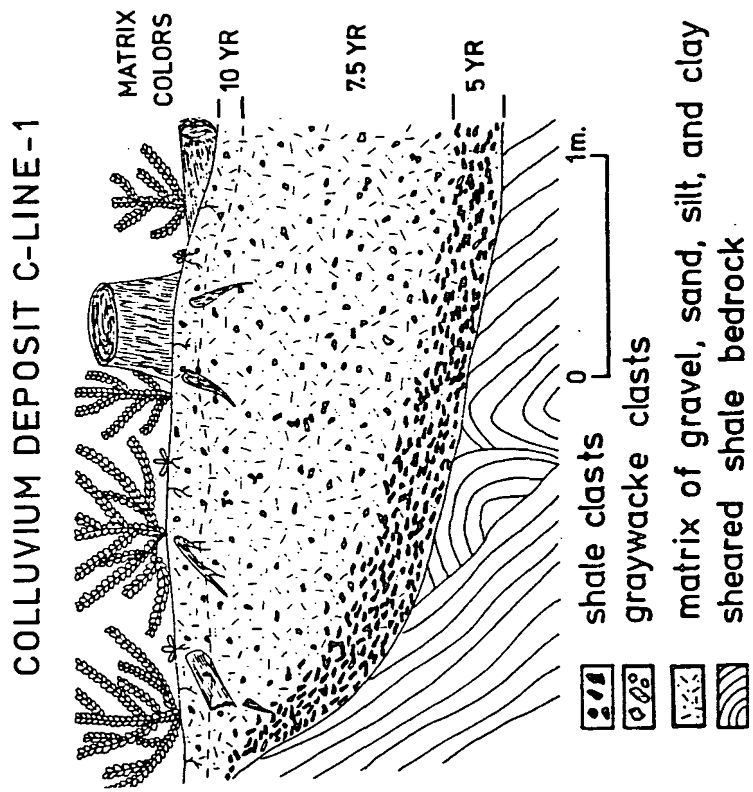
Descriptions of sedimentological features of colluvium pockets are presented with reference to detailed field descriptions of a number of well exposed and particularly instructive roadcut cross sections of colluvium pockets in the Redwood Creek drainage. Photographs and matching detailed drawings of these cross sections are presented in Figures 7 through 16. Locations are shown in Figure 17. The use of color xerox prints of color transparencies as guides for drawings was particularly helpful in documenting geometric, sedimentologic, and weathering patterns of colluvium.

Perhaps the most striking feature of the colluvium pockets in the Redwood Creek drainage, and the feature most frequently mentioned in descriptions of similar deposits elsewhere, is the concentration of coarse clasts in bands at or near the bases of most deposits and above the bases in a few deposits. Clasts smaller than 4 cm in diameter are included in matrix material in this discussion, hence the term clast concentration refers to the percentage of clasts larger than 4 cm, regardless of the nature of the finer material which includes them.

All observed deposits with exposed bases show layers of coarser and/or more concentrated clasts running along or subparallel to and slightly separated from lower contacts with bedrock. Examples include the C-Line-1 deposit (Figures 7 & 8) which exhibits a concentration of clasts directly along the base of the deposit, and deposits C-10-1 (Fig-

Figure 7 - Roadcut exposure of a cross section of the C-Line-1 colluvium deposit. The scale is a meter stick.

Figure 8 - Drawing based on a color xerox print of the C-Line-1 colluvium deposit. Tree stump which is visible in the photograph of this deposit marks the modern pre-logging ground surface.



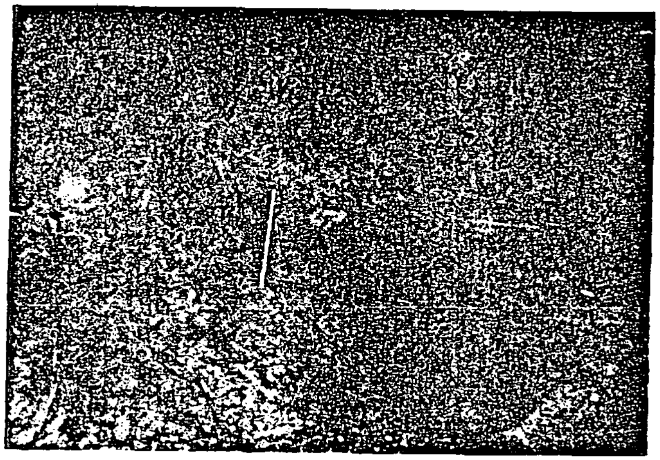
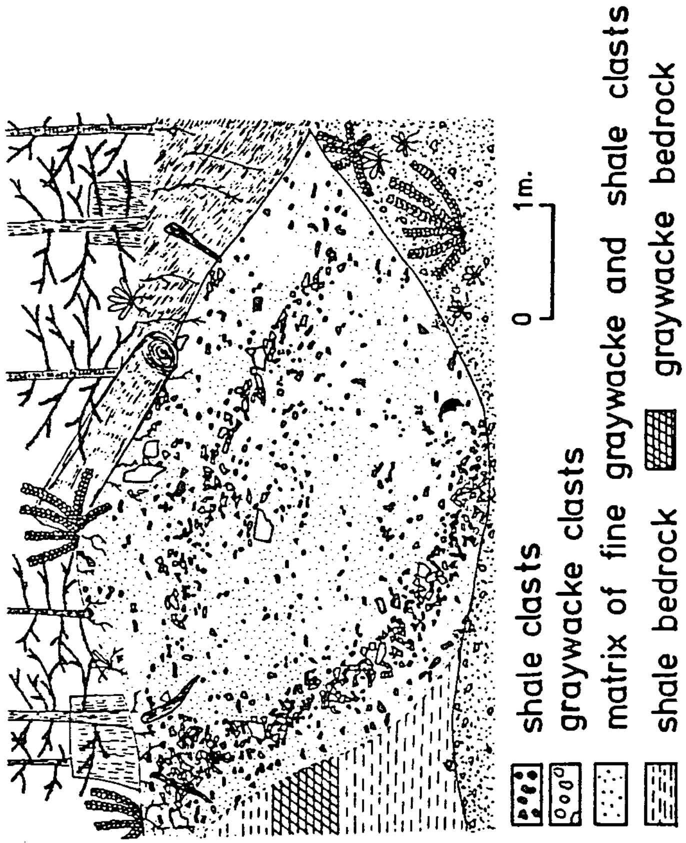


Figure 9 - Roadcut exposure of a cross section of the C-10-1 colluvium deposit. The scale is a meter stick.

Figure 10 - Drawing based on a color xerox print of the C-10-1 colluvium deposit. Tree stump which is not visible in the photograph of this deposit marks the modern pre-logging ground surface.

COLLUVIUM DEPOSIT C-10-1



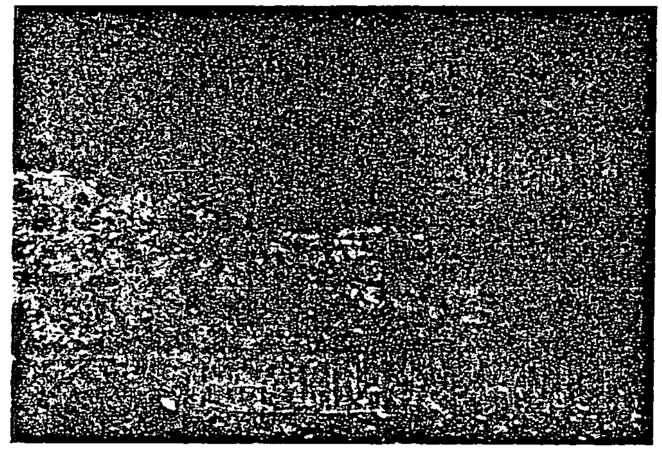
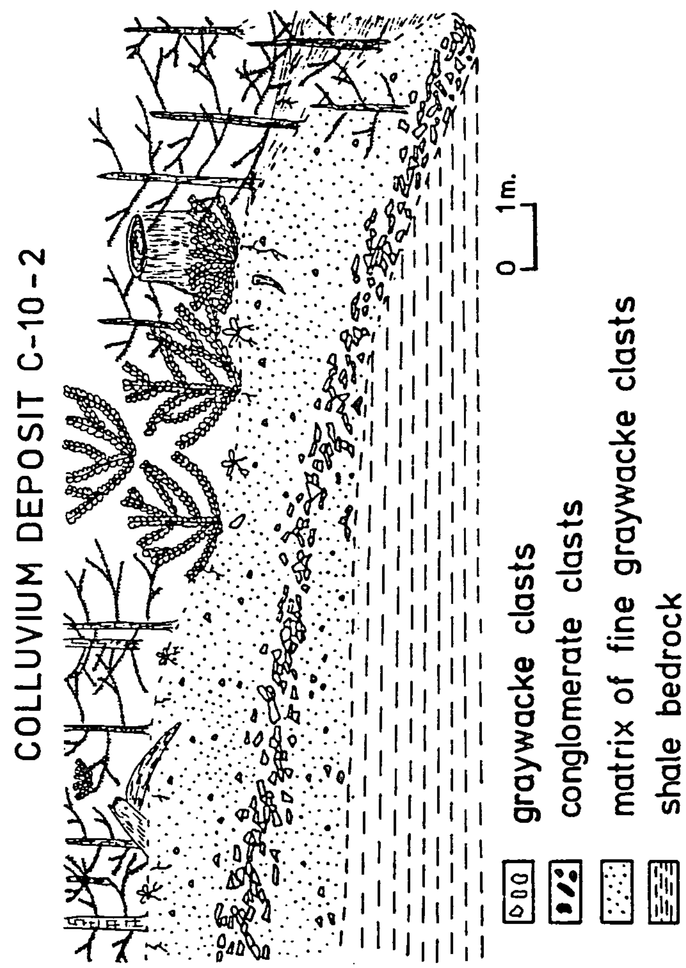


Figure 11 - Roadcut exposure of a cross section of the C-10-2 colluvium deposit. Yellow notebook case in the foreground is the scale.

Figure 12 - Drawing based on a color xerox print of the C-10-2 colluvium deposit. Tree stump which is hidden by foliage in the photograph of this deposit marks the modern pre-logging ground surface.



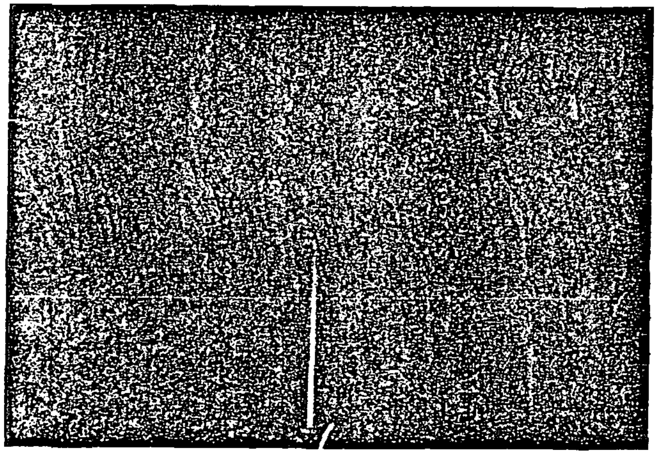
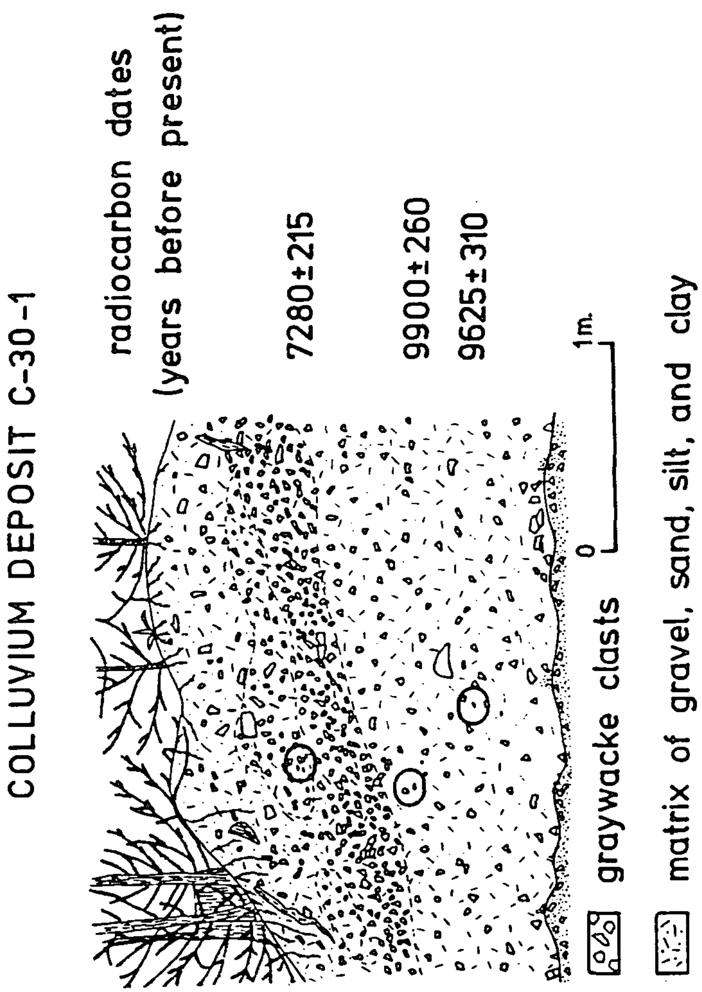


Figure 13 - Roadcut exposure of a cross section of the C-30-1 colluvium deposit. The scale is a meter stick.

Figure 14 - Drawing based on a color xerox print of the C-30-1 colluvium deposit. Tree stump which is not visible in the photograph of this deposit marks the modern pre-logging ground surface. Radocarbon dating was done on pieces of charcoal embedded in the colluvium.



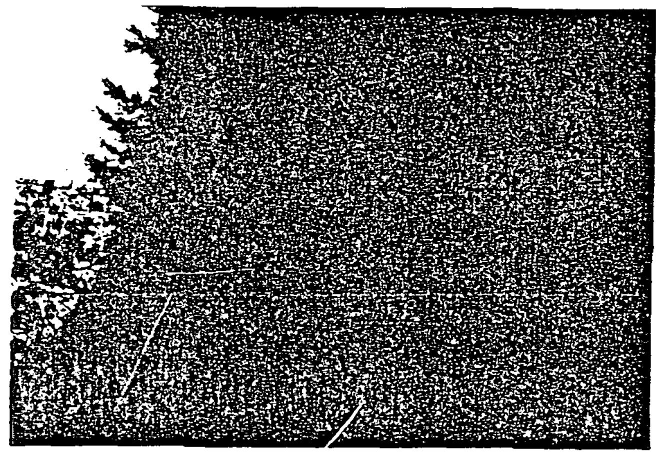


Figure 15 - Roadcut exposure of a cross section of the C-10-3 colluvium deposit. The scale is a meter stick.

Figure 16 - Drawing based on a color xerox print of the C-10-3 deposit. The tree stump above the tree roots which are visible in the photograph of this deposit marks the modern pre-logging ground surface.

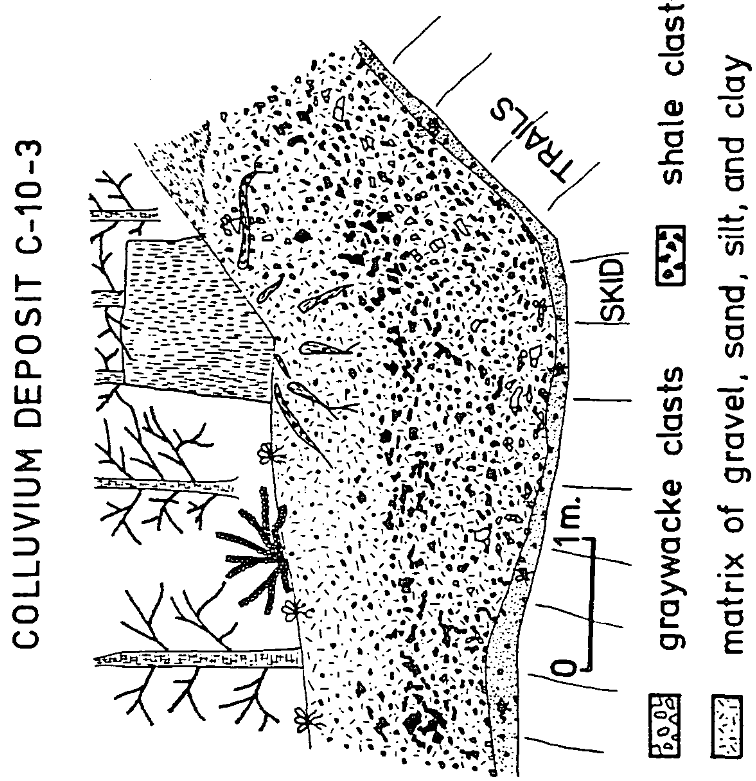
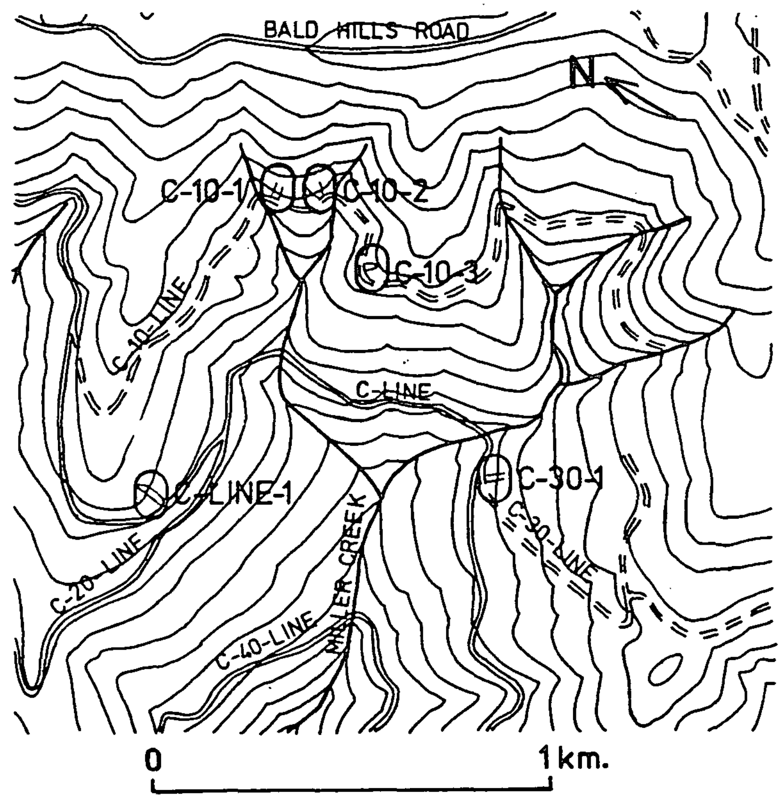


Figure 17 - Location map of colluvium deposits shown in figures 7 through 16.



ures 9 & 10) and C-10-2 (Figures 11 & 12), which show good examples of layers of coarser and more concentrated clasts running subparallel to and slightly above basal contacts with bedrock. As can be seen in deposits C-10-1 and C-30-1 (Figures 13 & 14), layers of coarser and/or more concentrated clasts also occur at higher levels in deposits. In cross section, upper layers appear more closely aligned with modern, pre-logging landsurfaces which are the upper surfaces of deposits, than with the basal surfaces of the deposits in which they occur. Many layers of coarse material near or along contacts with bedrock become thinner or pinch out as they approach the landsurface or top of the deposit, as is seen in deposit C-Line-1. Long dimensions of clasts in some coarse layers show a pronounced preferred orientation parallel to the layers in which they occur. Linear parallelism of clasts is not apparent in the predominantly two dimensional exposures studied. In some deposits, there is a hint of imbrication, with the long axes of some coarse particles plunging updip, or toward the closest lateral contact with bedrock. As a general rule, material in close proximity to the modern pre-logging landsurface is fine grained, and contains relatively low concentrations of larger clasts.

In places, clast lithologies clearly control clast sizes. This is markedly the case in deposit C-10-1, where graywacke clasts are larger than shale clasts, and is true to a lesser extent in deposit C-10-2, where conglomerate clasts at the base of the deposit are larger than graywacke clasts above them, and in deposit C-10-3, (Figures 15 & 16) where graywacke clasts are slightly larger than the shale clasts above them. The coarse band of graywacke clasts surrounded by finer graywacke clasts in deposit C-10-2 indicates that grain size patterns can also be

independent of lithology patterns. Grain size patterns are also independent of lithology patterns in deposit C-Line-1, where clast sizes of two different lithologies are approximately uniform in size throughout the deposit.

Deposits C-10-1, C-10-2, and C-10-3 show variations in clast concentrations, which clearly coincide with variations in clast sizes. In each of these deposits, larger clasts appear in layers showing relatively large clast concentrations. Contrasting patterns appear in deposits C-30-1 and C-Line-1. These deposits have layers with higher clast concentrations, surrounded by colluvium with similar sized clasts, but with higher ratios of matrix volumes to clast volumes.

Variations in clast concentrations which are not clearly related to variations in clast sizes are easily explainable as results of preferential removal of finer materials by sheet wash on raw unvegetated debris avalanche scar surfaces, as has been suggested by Lehre (1980) and Dietrich and Dunne (1978). Slope failures expose unvegetated surfaces with low infiltration capacities. In contrast to surrounding areas, these surfaces are subject to overland flow during storms. Shallow depths of water flowing in sheets prevents the buildup of velocities which are adequate to entrain gravel-sized particles. Coarse particles are concentrated, therefore, by the removal of fine materials around them. Increased degrees of preferred orientation of clasts in layers of concentrated clasts supports the idea that materials included have been reworked by overland flow. As vegetation becomes re-established, susceptibility to overland flow is reduced, and material of all grain sizes accumulates in scars.

Bands of concentrated coarse clasts are found at the bases of most or all colluvium pockets because these basal bedrock surfaces were exposed to sheetwash by the initial slope failures, which created the hollows into which fill material was eventually transported. Shallow slides emanating from partially or completely filled hollows expose unvegetated surfaces on colluvium which are also susceptible to the winnowing out of fine particles by sheet wash. Devegetation of surfaces due to these shallow secondary slides most likely causes the clast concentrations located well above deposit bases. Radiocarbon dates obtained as part of this study on charcoal above and below a band of concentrated coarse clasts in the C-30-1 deposit are shown in Figure 14. These dates document a 2,000 year time span between the initial filling of that debris avalanche scar and the filling of a shallower scar created by the partial removal of the initial fill material.

Layers of clasts which are coarser in addition to being more concentrated than the material around them are most easily explained by variations in transport mechanisms, as well as by variations in distances between clast sources and the debris avalanche scars into which materials are transported. Raveling of scar edges probably yields coarser particles than does the transport of material from greater distances by sheet wash before revegetation, and by creep after trees and shrubs have covered colluvium surfaces. Finer materials containing relatively low concentrations of coarser clasts appear below coarser layers in some deposits, suggesting that sheet wash can deliver materials into slide scars before coarser material is contributed by raveling.

Bands of coarse material in upper parts of deposits sometimes truncate finer layers below them, as seen in deposits C-10-1 and C-10-2. Some of these coarse bands, such as the upper one in the C-10-1 deposit truncate other coarse layers at lower levels in the same deposit. These truncations provide additional evidence that shallow slides occur after filling of initial slide scars has begun.

The most surprising sedimentologic feature observed in colluvium pockets in the Redwood Creek drainage is the segregation of clasts of different lithologies into distinct layers in a number of deposits. As was mentioned above, clast lithologies control clast sizes in some deposits, hence patterns of clast lithologies are often accentuated by their coincidence with patterns of clast size. Deposit C-10-1 shows the most striking lithologic banding. Boundaries between graywacke layers and shale layers are quite clear toward the base of the deposit, and become more diffuse toward the top. Layers in deposits C-Line-1 and C-10-3 are also sorted by lithology, though layer boundaries in these more weathered deposits are somewhat less well defined than those in fresher deposits, and may reflect some downslope transport of the colluvium by creep. Isolated conglomerate clasts along the base of the C-10-2 deposit constitute yet another example of the segregated occurrence clasts of a distinct lithology. As a general but not universal rule, clasts in layers directly in contact with deposit boundaries are the same lithology as the bedrock upon which the layers sit.

The fact that clasts of different lithologies occur in distinct layers in some colluvium pockets suggests that debris avalanche scars are filled episodically by processes which transport sediment from varying locations on slopes alongside and above the scars. Small slides in different positions upslope of unfilled scars are likely sources of lithologically segregated materials, because sediment contributed solely by the back wearing of scar edges or by creep would tend to have more homogeneous mixes of clast lithologies.

4. Weathering Characteristics of Colluvium Pockets

Four stages of weathering of the colluvium pockets were recognized and mapped in the upper part of the Miller Creek drainage. These stages are referred to as unweathered, slightly weathered, moderately weathered, and strongly weathered. The criteria for stage of weathering include color and grain size distribution of matrix materials, degree of angularity of clasts, and the thickness of weathering rinds on clasts. The lower layers in unweathered and slightly weathered deposits are no more weathered than surficial layers in these deposits, hence the time required to fill slide scars is probably short in comparison to that required to substantially weather the fills. Weathering states of deposits, therefore, are not only good indicators of the relative lengths of time over which the deposits have remained stable on hillslopes, but are also good indicators of the relative lengths of time which have passed since the debris avalanches which initially exposed different scars occurred.

Unweathered deposits contain angular clasts with no weathering rinds. Matrix material, when present, consists mostly of fine gravel and coarse sand, and shows no reddening or pedogenic structure. Slightly weathered colluvium pockets have subangular to angular clasts with occasional weathering rinds which are less than 1 mm thick. Matrix

material in these deposits is predominantly sandy, is rarely redder than 10YR, and has no pedogenic structure.

Moderately weathered deposits differ from unweathered and slightly weathered ones in that their matrices show substantial accumulations of clay particles and iron oxides. Material less than 2 mm in diameter in the moderately weathered scar fills is often 7.5YR and occasionally 5YR in color, and has a loam to light clay loam texture, (approximately 20-30% clay). Poorly to moderately developed subangular or angular blocky structure and thin to moderate clay films are commonly observed in these matrix materials. Clasts in the moderately weathered deposits are subangular to subround, and commonly show weathering rinds which are less than 2 mm in thickness.

Roadcut exposures of red clayey material thicker than 2 m on graywacke and shale slopes are interpreted in this study to be strongly weathered colluvium pockets rather than deeply weathered residual soils. Though intense weathering has obscured sedimentologic features which would confirm this interpretation, sharp contacts with in situ bedrock to the side, inclusions of clasts differing in lithology from the in situ bedrock below, and non-systematic variations in gravel contents from deposit tops to deposit bases support the conclusion that these materials are transported rather than residual. Fine fractions, which pass through a 2 mm sieve, have clay loam to silty clay loam textures (approximately 30-40% clay), show well developed subangular blocky and angular blocky pedogenic structures, and are commonly 5YR in color. Clasts are small, easily broken, and show thick weathering rinds.

Most weathering criteria of the C-30-1 deposit match those of the moderately weathered stage. Matrix materials throughout the deposit have occasional thin clay films, light clay loam textures, and poorly developed subangular blocky structures. Some included clasts show weathering rinds which are less than 1 mm thick. Matrix colors are mostly 10YR, however, suggesting that the C-30-1 deposit is less weathered than some others in the moderately weathered group. Radiocarbon ages of charcoal in this deposit are shown in Figure 14, and indicate that the entire deposit has been stable for approximately 7,000 years. Strongly weathered deposits are older than 7,000 years, therefore, while unweathered and slightly weathered deposits are younger. Similar weathering characteristics of colluvium in 9,000 year old and 7,000 year old layers in the C-30-1 deposit suggest either that essentially no weathering occurred in the lower materials during their first 2,000 years, or that weathering differences which existed at the time of deposition of the 7,000 year old material have been masked or obliterated during subsequent weathering of the entire deposit.

High initial permeabilities of deposits allow moisture to percolate quickly through unweathered colluvium pockets, promoting accumulation of moisture at colluvium-bedrock interfaces. It is not surprising therefore, that in slightly and moderately weathered deposits, clay contents are higher and colors are redder along basal contacts with bedrock. It is likely that clay minerals and iron oxides are produced by weathering at faster rates at the bases of deposits where soil conditions are moister, and are also translocated to those sites by downward rather than lateral movement of water through the initially permeable colluvial materials. Accumulations of organic matter at tops of deposits, forming pedogenic A horizons, appear in weakly, moderately, and strongly

weathered deposits.

Conditions that affect the rates at which colluvial deposits weather include topographic position, clast lithologies, and the initial grain size distribution of the matrix material. Most weathered deposits which contain layers of different clast size or lithology show clast angularity, clast weathering rinds, and matrix grain size distributions that are characteristic of only one of the four weathering states defined above, throughout the deposits. It is reasonable to assume, therefore, that for the most part, the effects of age and topographic position are more important than the effects of initial grain size and clast lithology in giving deposits their weathering characteristics. As will be discussed in the following section, deposits weather more quickly on north facing than on south facing slopes. The importance of age over topographic position in causing deposits to show particular weathering states is supported by a poor correspondence between wetter topographic positions, particularly ones close to stream channels, and the locations of relatively more weathered deposits.

Approximately half of the colluvium pockets observed in roadcuts across slopes underlain by relatively coherent graywacke and shale in Redwood Creek are moderately weathered. Another quarter of the observed deposits are slightly weathered. Unweathered and very weathered colluvium pockets are relatively rare, and make up the remaining quarter of colluvium pockets.

The numbers of colluvium pockets in each weathering stage can be accounted for in a number of ways. It is possible that the weathering states represent age groups which span equal lengths of time, and that debris avalanche frequencies have varied during the recent geologic past. In view of various weathering curves presented by Birkeland (1974), which show that rates of change of different weathering characteristics decrease over time, it is more likely that the different weathering states represent age groups which span different lengths of time. Using hypothetical numbers to illustrate this case, unweathered deposits may be less than 2,000 years old, slightly weathered deposits may be between 2,000 and 7,000 years old, moderately weathered deposits may be between 7,000 and 17,000 years old, and strongly weathered deposits may be older than 17,000 years. The relative scarcity of strongly weathered deposits and the relative abundance of moderately weathered deposits suggests that colluvium pockets become susceptible to removal by erosion, probably due to increased clay contents and consequently decreased angles of internal friction, over time periods which are less than those required to weather deposits to the strongly weathered state.

5. Map Positions of Colluvium Pockets

Relationships between drainage basin positions, and the abundance and weathering states of colluvium pockets, provide useful information on the role played by debris avalanching in the erosional history of drainage basins underlain by relatively coherent graywacke and shale in the Redwood Creek drainage. Important components of drainage basin position include hillslope aspect and proximity to interfluves and stream channels of different orders. Types and intensities of weathering and erosion processes appear to be related to variations in these

hillslope characteristics. Roadcuts on recently cut major haul roads, which contour slopes at two levels in the upper part of the Miller Creek drainage, have provided a good opportunity to document the locations of colluvium pockets, and to characterize their weathering states. Plate 1 shows map positions and weathering states of colluvium pockets in upper Miller Creek in relation to degrees of profile development of surrounding residual soils.

Because deep roadcuts adjacent to major haul roads provide most of the exposures in which colluvium pockets can be reliably recognized, the colluvium map of upper Miller Creek (Plate 1) characterizes colluvium pocket distributions most accurately along major haul roads. Though this is not an ideal situation, it is at least acceptable because of the symmetrical placement of major haul roads in the upper part of the Miller Creek drainage. Colluvium pockets cover approximately 20% of slope surfaces in well exposed areas adjacent to major haul roads. Numbers of colluvium deposits of different weathering states found in areas with different aspects, slope gradients, and degrees of residual soil profile development are tabulated in Tables 2 and 3. In columns headed by "Deposits per Km" in these tables, total numbers of deposits at each weathering stage on slopes in each gradient or soil category have been divided by the length of major haul road traversing slopes of that category, in order to compensate for the uneven distribution of mappable exposures in upper Miller Creek.

As a general rule, north facing slopes in upper Miller Creek contain greater concentrations of colluvium pockets than do south facing slopes. For the most part, this pattern continues to apply when collu-

Table 2: Weathering State of Colluvium vs. Profile Development of Surrounding Residual Soil

Colluvium Weathering State	Slope Aspect	Weak Soil Profile Development		Mod. Soil Profile Development		All Soil Types	
		deposits per km.	total deposits	deposits per km.	total deposits	deposits per km.	total deposits
Unweathered Deposits	North facing	0.3	1	0.0	0	0.3	1
	South facing	0.5	1	0.0	0	0.4	1
	West facing	1.4	2	0.0	0	1.3	2
	All aspects	0.6	4	0.0	0	0.5	4
Slightly Weathered Deposits	North facing	2.8	8	0.0	0	2.2	8
	South facing	2.6	5	0.0	0	2.0	5
	West facing	4.3	6	5.0	1	4.4	7
	All aspects	3.1	19	0.7	1	2.6	20
Moderately Weathered Deposits	North facing	6.9	19	5.7	4	6.4	23
	South facing	5.3	10	6.7	4	5.6	14
	West facing	6.4	9	15.0	3	6.9	12
	All aspects	6.1	38	7.3	11	6.4	49
Strongly Weathered Deposits	North facing	0.0	0.0	7.1	5	1.4	5
	South facing	0.0	0.0	1.7	1	0.4	1
	West facing	0.0	0.0	0.0	0	0.0	0
	All aspects	0.0	0.0	4.0	6	0.8	6
All Deposits	North facing	10.0	28	12.8	9	10.3	37
	South facing	8.4	16	8.4	5	8.4	21
	West facing	12.1	17	20.0	4	12.6	21
	All aspects	9.8	61	12.0	18	10.3	79

Table 3: Weathering State of Colluvium vs. Slope Gradient

Colluvium Weathering State	Slope aspect	Slope < 30%		Slope > 30%		All Gradients	
		deposits per km.	total deposits	deposits per km.	total deposits	deposits per km.	total deposits
Unweathered Deposits	North facing	0.6	1	0.0	0	0.3	1
	South facing	0.7	1	0.0	0	0.4	1
	West facing	1.4	2	0.0	0	1.3	2
	All aspects	0.9	4	0.0	0	0.5	4
Slightly Weathered Deposits	North facing	3.8	6	1.5	3	2.5	9
	South facing	3.6	5	0.0	0	2.0	5
	West facing	5.0	7	0.0	0	4.4	7
	All aspects	4.1	18	0.9	3	2.7	21
Moderately Weathered Deposits	North facing	5.6	9	6.5	13	6.1	22
	South facing	2.9	4	9.1	10	5.6	14
	West facing	7.1	10	10.0	2	7.5	12
	All aspects	5.2	23	7.6	25	6.2	48
Strongly Weathered Deposits	North facing	0.6	1	2.0	4	1.4	5
	South facing	0.0	0	0.9	1	0.4	1
	West facing	0.0	0	0	0	0.0	0
	All aspects	0.2	1	1.5	5	0.8	6
All Deposits	North facing	10.6	17	10.0	20	10.3	37
	South facing	11.5	10	10.0	11	8.4	21
	West facing	13.5	19	10.0	2	13.2	21
	All aspects	10.4	46	10.0	33	10.2	79

vium pockets are divided into weathering states. Very weathered, moderately weathered, and slightly weathered scar fills are more abundant on north facing than on south facing slopes, while unweathered colluvium pockets have slightly higher concentrations on south facing as compared to north facing slopes. The latter trend may simply be due to the limited sample of unweathered colluvium pockets mapped in upper Miller Creek. It may also reflect higher weathering rates on north facing slopes due to moister conditions. Unweathered deposits may be less commonly found on north facing slopes because colluvium in those positions might become slightly weathered during the same time interval in which a scar fill would remain unweathered on a south facing slope.

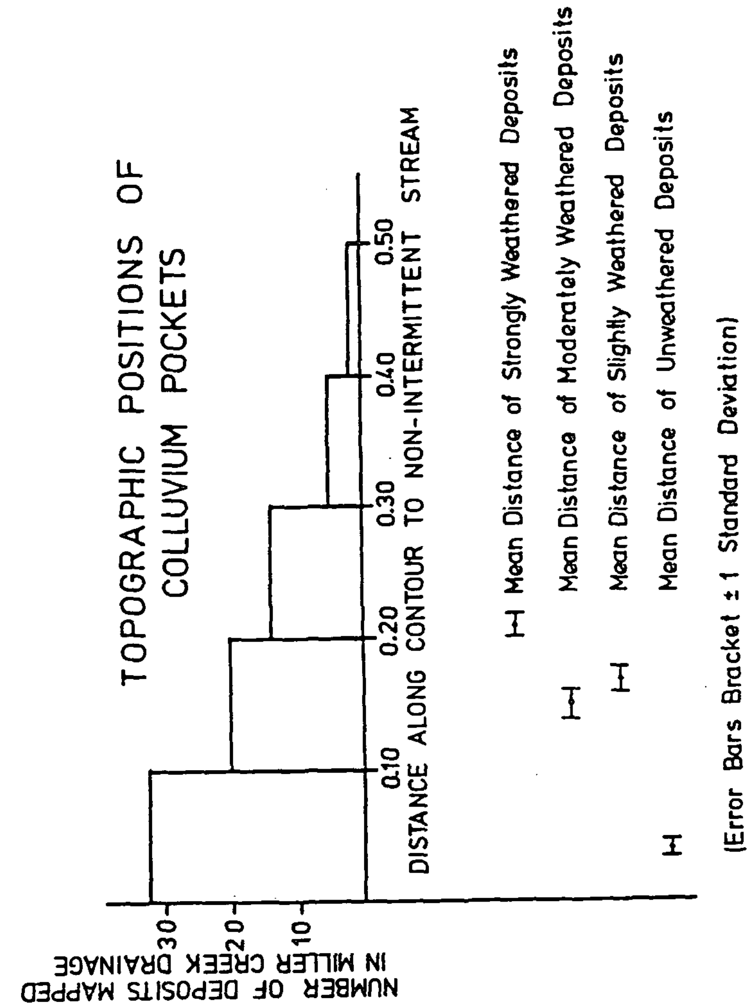
Other researchers, among them Pain (1969), and Savina (personal communication, 1981), have found debris avalanche frequencies to be higher on north facing as opposed to south facing slopes. This pattern is consistent with the fact that north facing slopes receive relatively less direct sunlight, particularly during the wet winter months, and retain greater amounts of moisture. In addition, north facing slopes accumulate thicker snow packs during the infrequent snowstorms which affect the study area. This is important in the Pacific Northwest because rain on snow events release this extra water, which saturates residual soils, broken bedrock and colluvium on slopes, and increases the susceptibility of those materials to failure by counteracting the component of their weight which holds them in place. The implication that debris avalanche activity is more abundant on north facing slopes is supported by the fact that in the upper part of the Miller Creek drainage, north facing slopes are steeper and shorter than south facing slopes in comparable drainage basin positions.

West facing slopes show densities of colluvium pockets which are consistently higher than those of north and south facing slopes. Once again, this pattern continues to apply when the colluvium pockets are divided into weathering states, with the exception of colluvium pockets in the very weathered category, which do not occur at all on west facing slopes. Rather than being due to aspect effects, relatively large number of unweathered, slightly weathered, and moderately weathered deposits on west facing slopes are more likely due to the proximity of west facing slopes to non-intermittent stream channels, as is discussed below.

The west facing slope segments in upper Miller Creek are steeper and closer to incised stream channels than most north and south facing slope segments in that drainage. Steeper slopes close to drainages have probably been more recently affected by debris avalanching, and can be considered to be relatively young erosion surfaces. The lack of very weathered colluvium pockets on these west facing slopes supports this interpretation, as soils and colluvial materials are stripped from erosionally active slopes before those surficial deposits weather to advanced stages.

Figure 18 shows decreasing numbers of colluvium pockets at greater distances along contour from non-intermittent stream channels. This pattern reflects more frequent debris avalanche activity on slopes which are adjacent to and probably undercut by streams. Figure 18 also shows similar mean distances along contour to non-intermittent stream channels, of slightly, moderately, and strongly weathered deposits. This pattern suggests that the distribution of debris avalanches on slopes has not varied substantially during the time period over which those

Figure 18 - Relationships between the abundance and weathering states of colluvium pockets, and their proximity to non-intermittent stream channels in the Miller Creek drainage.



colluvium pockets were created. Relatively small mean distances along contour from non-intermittent stream channels of unweathered deposits, however, suggest that during the more recent geologic past, a relatively large proportion of total debris avalanche activity has been somewhat more concentrated near streams.

As was discussed in the section concerning the weathering states of colluvium pockets, the relative lack of very weathered colluvium pockets suggests that over time, colluvium pockets must be removed from slopes by such erosion processes as debris avalanching, creep, and tree throw. Colluvium pockets may be less abundant closer to higher order interfluves because the continual removal of colluvium from slope surfaces has not been counteracted by the creation and filling of new scars by debris avalanching and associated raveling and sheetwash in those areas. The more weathered condition of colluvium pockets at greater distances from stream channels supports the premise that slopes near higher order interfluves have been subjected to less recent debris avalanching than slopes closer to stream channels.

6. Relations to Residual Soils and Slope Gradients.

As was discussed in the section on residual soils in the Miller Creek drainage, degrees of residual soil profile development show some correspondence to hillslope gradients in upper Miller Creek. Weathering states of colluvium pockets are themselves related to the gradients of, and the degrees of soil profile development on surrounding slope surfaces. Generally, degrees of weathering of colluvium pockets increase both as degrees of profile development of adjacent residual soils

increase, and as hillslope gradients decrease. The following discussion is based upon mapping of colluvium and residual soils in the upper part of the Miller Creek drainage, and refers to the superimposed residual soil and colluvium map in Plate 1, and to the isotangent map of upper Miller Creek in Figure 6. Relationships between colluvium weathering states, development of surrounding residual soils, and slope gradients are summarized in Tables 2 & 3.

For the purposes of this discussion, steep slopes are those with gradients greater than 30%, and gentle slopes are those with gradients less than 30%. Unweathered deposits in upper Miller Creek occur exclusively on steep slopes. Slightly weathered deposits also occur most commonly on steep slopes, though 17% of the slightly weathered deposits mapped occur on gentle slopes. Almost equal numbers of moderately weathered deposits were mapped on steep and gentle slopes, however dividing these numbers by the lengths of major haul roads in each slope division yields a substantially higher density of moderately weathered colluvium pockets on gentle than on steep slopes. Very weathered deposits occur almost exclusively on gentle slopes.

Models of slope evolution put forth by Wentworth (1943), and Carson and Petley (1970), suggest that the weathering of colluvium and the consequent reduction of its angle of repose are responsible for decreases in slope gradients over time. According to these models, gentle slopes with weathered surficial materials will not be steepened by stream undercutting because low friction angles of weathered regolith cause landslides to occur when gradients are increased. These models assume that landslides replace unstable slopes by slopes with similar or gentler gradients. This concept of slope gradient reduction due to landslide activity is sometimes appropriately applied to slump failures, which occur completely within weathered material, and which redistribute failed material in such a way as to achieve a gentler slope configuration, at which the failed material can be stable. Debris avalanches differ in that they tend to remove rather than redistribute material. An additional complicating factor is that at least in the Redwood Creek drainage, debris avalanches appear to extend into essentially unweathered bedrock, which has internal friction characteristics which differ from those of weathered regolith materials. While relatively lower angles of internal friction of weathered regolith may promote debris avalanching at relatively lower slope angles, it does not necessarily follow that the new slopes created have correspondingly lower gradients.

Lower slope gradients in selected drainage basin positions can also be attributed to the activity of such processes as creep and tree throw over the relatively longer periods of time since the slopes were affected by debris avalanching. If this is the case, greater degrees of weathering of colluvium, in addition to smaller numbers of colluvium pockets on flatter slopes also reflect their recent history of relative stability with respect to landsliding.

Unweathered colluvium pockets occur exclusively in areas showing weak residual soil profile development. Slightly weathered colluvium pockets are also mostly found in areas showing weak residual soil profile development. A larger number of moderately weathered deposits were mapped in areas showing weakly developed residual soils than in areas showing moderately to strongly developed residual soils. When the

numbers of colluvium pockets mapped in each soil unit are divided by the length of major haul road traversing that unit, however, the concentrations of moderately weathered colluvium deposits turns out to be greater in areas showing moderate to strong residual soil profile development than in areas showing weak residual soil profile development. Very weathered deposits occur exclusively in areas with moderately to well developed residual soils.

The section on the sedimentology of colluvium pockets suggest that raveling of scar edges, tree throw, shallow failures, and gullying of areas to the sides of and upslope of debris avalanche scars contribute the sediment which eventually fills slide scars during a time period which is small in relation to the time period over which the resulting colluvium pockets subsequently remain stable on hillslopes. If this is the case, initially unweathered material transported into colluvium pockets starts to weather at approximately the same time as freshly exposed bedrock adjacent to and upslope of the slide scars. Good correlations between degrees of weathering of colluvium pockets and degrees of residual soil profile development in areas around the colluvium pockets support the premise that erosion activities related to debris avalanching lower slope surfaces outside the confines of landslide scars only during a relatively short period of time after slope failure. The appearance of moderately weathered colluvium pockets in areas showing only weak degrees of residual soil development suggests either that contributed colluvial material was pre-weathered, or that colluvium pockets can weather more quickly than adjacent *in situ* weathering profiles. The higher permeability and greater degree of comminution of colluvium, and the tendency for water to accumulate and flow along interfaces between colluvium and bedrock, probably causes colluvium in bedrock depressions to weather more quickly than surrounding residal soils.

7. Previous Descriptions of Similar Deposits

The most detailed available description of deposits similar to ones described in this section was done more than 20 years ago by Parizek and Woodruff (1957), who coined the term "lenticular carpedolith" to describe composite stone lines at the bases of pockets of angular to subangular lithic clasts, which they observed on hillslopes in the Mid-Piedmont and foothills portion of the Blue Ridge Province of Georgia. Unfortunately, details on hillslope gradients, vegetation, and topographic positions of deposits are scant in their discussion, however drawings and photographs of the "lenticular carpedoliths" bear an impressive resemblance to material seen in roadcuts on graywacke and shale slopes in the Redwood Creek drainage.

Deposits described by Parizek and Woodruff are similar to ones in the Redwood Creek drainage in the following respects. They are U- to V-shaped in cross section, and have basal stone lines which are always more than one clast thick. Clast sizes are fairly uniform within layers, but vary considerably from layer to layer. The clasts are angular to subangular, and are commonly 7 to 15 cm in diameter. While Parizek and Woodruff indicated that there is a general lack of preferred orientation of clasts in the deposits that they described, photographs in their article show numerous clasts which are subparallel to the layers which include them. Layers commonly pinch out or become thinner

toward the land surface. Deposit boundaries truncate primary structures of surrounding bedrock. Toward the lower ends of deposits, basal contacts with bedrock extend downslope at gradients gentler than those of the modern topography. Finally, clast sizes and clast concentrations decrease toward the tops of deposits.

There are a number of features of the deposits described by Parizek and Woodruff which are characteristic only of the strongly and very strongly weathered deposits in the Redwood Creek drainage. The Georgian deposits contain basal stone lines which are overlain by essentially unbedded mixtures of clay, silt and sand. While more weathered deposits such as the C-Line-1 deposit in the Redwood Creek drainage also exhibit these features, less weathered scar fills, such as the C-10-1 and C-10-2 deposits commonly contain concentrated gravel clasts up to the ground surface, and show crude bedding in material well above their basal stony layers. Relatively loose packing of coarse fragments, which is characteristic of the stony layers of the Georgian deposits, is also observed in the more weathered Redwood Creek deposits, while the less weathered colluvium pockets differ once again by showing very close packing of coarse fragments in stony layers.

The deposits described by Parizek and Woodruff are most commonly underlain by unweathered bedrock. Colors of colluvium tend to be redder than those of surrounding bedrock. Slightly, moderately, and strongly weathered deposits in the Redwood Creek drainage also commonly occur on relatively unweathered bedrock, and show colors which are redder than the colors of surrounding bedrock. Unweathered deposits in the Redwood Creek drainage differ from the Georgian deposits by showing colors which are similar to the colors of surrounding bedrock. Strongly weathered deposits in the Redwood Creek drainage differ from the Georgian deposits in that they sometimes occur on substantially weathered bedrock.

A final point with regards to similarities and differences between deposits described by Parizek and Woodruff and ones found in the Redwood Creek drainage involves the distribution of clasts of different lithologies within deposits. Parizek and Woodruff noted that clasts lithologies are varied in the the deposits that they described, however they did not indicate whether clasts lithologies resemble those of surrounding bedrock, or whether clast lithologies vary from layer to layer in deposits. Some layers of Georgian deposits include combinations of angular clasts and fluvially rounded pebbles, which Parizek and Woodruff suggested are results of "mixed accumulations, in which transported materials of a former cycle of weathering are included".

Bryan (1940) described what may be similar surficial deposits which he observed on slopes in New Mexico, Texas, and the southern Appalachians. Schematic diagrams of these deposits show them either capping ridges, in which case they are characteristically weathered and impermeable, or occupying valley bottoms, where they are characteristically porous and permeable. Bryan attributed the formation of these deposits to the filling of gullies, which form on slopes when regolith becomes sufficiently weathered and clay-rich to prohibit infiltration and to promote runoff. Ridgetop colluvium deposits in the Redwood Creek drainage differ from ones described by Bryan in that they occupy small bedrock depressions cut in ridgetop surfaces, instead of capping entire ridgetops.

Lehre (1980) described U- to V-shaped hollows filled by colluvium on slopes in a small steep drainage, about 80% of which is vegetated by grass and brush, in the California Coast Range approximately 14 km northwest of San Francisco. These colluvial deposits occur exclusively in swales, and were interpreted to be the main loci of landsliding and gullying in the drainage basin in which they were observed. Local concentrations of coarse gravel were noted to be subparallel either to the underlying bedrock contact, or to the modern landsurface. Bedrock blocks in colluvium were observed as being oriented downslope. This arrangement might produce the horizontal and subhorizontal orientations of large clasts that is seen in roadcut cross sections of the Redwood Creek deposits.

The most important difference between deposits described by Lehre, and ones observed in the Redwood Creek drainage is the fact that Lehre's deposits are almost exclusively found in swales, whereas ones in Redwood Creek occupy more varied topographic positions. This contrast may be due to vegetation differences which control mass wasting activity, as will be discussed in the following section. Lehre also mentioned overthickened A horizons on soils in swale centers, which do not have analogs in the Redwood Creek deposits.

Dietrich and Dunne (1978) also reported the existence of small filled landslide scars, on slopes in a forested mountainous drainage in the Oregon Coast Range. They referred to these deposits as "wedges", and described them as filled U- to V-shaped depressions in bedrock, with relatively coarse clasts lying near and subparallel to their basal contacts with bedrock. Like deposits described by Parizek and Woodruff and

Lehre, as well as ones in the Redwood Creek drainages, material in wedges decreases upward in clast size and clast concentration. In a manner quite similar to that of many deposits in the Redwood Creek drainage, clast lithologies at the base of the deposits resemble those of underlying and surrounding bedrock, while proportions of clasts of contrasting lithologies increase substantially at short distances above deposit bases. Unlike deposits described by Parizek and Woodruff and deposits in the Redwood Creek drainage, deposits described by Dietrich and Dunne overlie bedrock which is more weathered than in surrounding areas. Stony layers and crude bedding well above deposit bases, as are seen in a number of relatively unweathered colluvium pockets in the Redwood Creek drainage, are not mentioned in Dietrich and Dunne's description. Like Lehre, Dietrich and Dunne regarded the colluvium-filled bedrock depressions that they described as loci of debris avalanche activity.

D. HILLSLOPE EVOLUTION ON COHERENT GRAYWACKE AND SHALE

1. Introduction

In this section, information obtained from observations and mapping of residual soils and colluvium on slopes underlain by relatively coherent graywacke and shale is incorporated into a model of drainage basin evolution in these areas. Preceding this synthesis is a review of pertinent soil mechanics concepts. After the model is described, it is compared with models of landscape evolution by debris avalanching developed by other researchers working in similar steep forested areas.

2. Review of Slope Stability Concepts

Debris avalanches occur on slopes when shear stresses applied to residual soils, colluvium, and underlying bedrock exceed the shear strengths of those materials. The ratio between slide resisting stresses, which are collectively called shear strength, and slide inducing stresses, which are collectively called downslope shear stress, is called the factor of safety. Slopes fail when their factors of safety are reduced to one or below.

Soil weight can be resolved into two components, one directed perpendicular to the slope surface and the other directed downslope. The downslope component, which equals the total soil weight times the sine of the slope angle, is the shear stress promoting slope failure. As the slope angle increases, its sine and hence the downslope shear stress also increases. The component of soil weight directed perpendicular to the slope is equal to the total soil weight times the cosine of the slope angle, and is directly related to the frictional component of soil shear strength. As the slope angle increases, its cosine decreases, reducing the effectiveness of the frictional component of soil strength in resisting slope failure. Another component of shear strength is called cohesion, and consists of attractions between clay particles, and of binding by roots. This component of shear strength is independent of slope gradient. Dietrich and Dunne (1978) suggested that binding by roots accounts for about 40% of the shear strengths of shallow soils on forested slopes on the west coast of the United States.

Under natural conditions, downslope shear stresses are increased and shear strengths are decreased by the steepening of slopes by undercutting. Soil shear strengths are also reduced by weathering, by wetting which reduces cohesion between clay particles, and by disrupting vegetation root mats. Even more importantly, saturating surficial materials with water decreases the component of their weight which holds them against slopes by making them buoyant, and adds the weight of interstitial water to the component of their weight that pulls them downslope. Forces within saturated soil pores which exert upward pressures on soil grains are referred to as positive pore pressures. Unsaturated but moist soils may have negative pore pressures due to surface tension, which adds to the strength of the slope. Debris avalanche activity is almost always associated with heavy rains, which saturate soils and generate positive pore pressures, according to Campbell (1975), Kelsey (1977), Pain (1969, 1971), Hack and Goodlett (1960), and numerous other authors.

3. Landscape Evolution Model

Common exposures of U- to V-shaped colluvium pockets interpreted to be filled scars of debris avalanches suggest that in forested areas underlain by relatively coherent graywacke and shale in the Redwood Creek drainage, debris avalanches occur in different parts of the landscape at different times in response to steepening of slope gradients by stream incision, to decreases of soil and rock shear strengths by weathering, and to the generation of positive pore pressures by intense rainfall. Stream bank undercutting and tree throw may also induce debris avalanche activity. Because unweathered and slightly weathered colluvium deposits observed in the Redwood Creek drainage occupy depressions cut in essentially unweathered rock, it is proposed that the slides which create those depressions extend below residual soils and transported colluvial material, and expose fresh surfaces on essentially unweathered bedrock.

After slope failure, scars are filled by raveling of scar edges, and by the contribution of sediment by sheet wash, upslope landsliding, and tree throw. Resulting deposits are referred to as colluvium pockets in this study. The segregation of clasts of different lithologies into distinct layers in some colluvium deposits observed suggests that material is contributed episodically from different positions on the hillslopes alongside of and above debris avalanche scars. In this way, the landsurface surrounding a debris avalanche is lowered by at least the volume of material initially removed by the landslide itself. Shallow failures periodically remove upper portions of the fill material. Sheet wash on unvegetated surfaces on colluvium removes fine particles, creating coarse lag gravels which appear at various levels in slide scar fill deposits.

Because unweathered and slightly weathered colluvium pockets observed in the Redwood Creek drainage do not show variations in weathering characteristics from their bases to their tops, it is proposed that the time period required to fill a debris avalanche scar is small in relation to the time period over which the resulting colluvium deposit sits stably on a hillslope and becomes weathered. Good correspondences between weathering states of colluvium and degrees of residual soil profile development on surrounding slopes support the premise that processes transporting colluvium to nearby debris avalanche scars expose fresh parent material around the scars to a new cycle of residual soil profile development, only during a relatively short period of time following slope failure.

After the initial period of infilling and susceptibility to shallow slides, which may last as long as a few thousand years, colluvium accumulated in debris avalanche scars achieves stability on slopes, and is capable of remaining stable for long periods of time. Because the radiocarbon data on the C-30-1 deposit indicates that it has been stable for roughly 7,000 years, and because the C-30-1 deposit is less weathered than a large proportion of the deposits observed, it is proposed in this study that colluvim pockets are commonly stable on slopes for time periods in excess of 7,000 years. This stability may be attributed to the spoon shaped geometry of the slide scar, as suggested by William E. Dietrich (personal communication, 1981). It is also possible that densely packed gravelly colluvial materials are denser and have higher

angles of internal friction than the broken sandstone and shale bedrock around them. Holtz (1960) cited smaller angles of repose for combinations of sand and gravel, which would be similar to residual soil materials, than for pure sand or pure gravel, which would be more analogous to material in the less weathered colluvium pockets. In addition, the rapid flow of water through gravelly materials may promote slope stability by preventing the build-up of positive pore water pressures which induce instability on slopes. Yee and Harr (1977) suggested that highly permeable strongly aggregated soils have an analogous effect on steep slopes in the Oregon Coast Range.

Some debris avalanche scars probably become part of the drainage network, and are kept clear and deepened by fluvial action. Debris avalanches, therefore, may cause drainage densities and bifurcation ratios to be higher in drainages underlain by relatively coherent graywacke and shale than in drainages underlain by schist. The stability of relatively steep slopes in terrains where erosion is dominated by debris avalanching necessitates these relatively high drainage densities and bifurcation ratios, since for a given overall relief, streams must be closer to drainage divides in areas with steeper slopes.

As they weather, stable colluvium pockets and surrounding slope surfaces become more susceptible to creep and tree throw, which gradually remove weathered colluvium pockets, and which decrease slope gradients in areas which are not kept steep by stream incision or active debris avalanching. On some gently sloping patches of land near ridgetops and on upper slopes, residual soils and some colluvium pockets remain stable enough to become substantially weathered. The lack of unweathered or slightly weathered colluvium pockets, and the fairly even distribution of moderately to well developed residual soils in such areas in the upper part of the Miller Creek drainage suggest that these areas have not been subjected to recent debris avalanching and related raveling, sheetwash, and tree throw.

Generally less weathered residual and colluvial materials on side and lower slope positions, where soil conditions are moister and slope gradients are steeper, suggest that colluvial and residual materials are removed more frequently from these areas by creep, tree throw, and debris avalanching. In these areas, new debris avalanche scars are periodically created, some of which are filled by fresh, unweathered colluvial material.

The lack of exposures showing colluvium pockets with weathered bedrock or weathered colluvium beneath or to the sides of unweathered colluvium, suggests that when weathered colluvium pockets are removed by debris avalanches, the slides remove the entire pocket in addition to weathered bedrock at colluvium-bedrock interfaces. Scars created by landslides removing weathered colluvium pockets, therefore, may differ in shape from the pre-existing scars into which colluvium was transported to form the colluvium pockets. It is possible that the geometry of slide scars resulting from the removal by debris avalanching of pre-existing colluvium pockets and associated weathered bedrock makes it unlikely that material contributed to the new scars by raveling, sheet wash, tree throw, and upslope sliding will remain stable. Large widths or small slope angles of lateral and upper slide boundaries might achieve this effect. Landslides which do not create narrow, spoon-

shaped scars which are apt to be filled by colluvium which will achieve at least a temporary stability, are proposed in this study to leave fresh slopes veneered by unweathered surficial materials, which are relatively resistant to slope failure by debris avalanching until undercutting increases shear stresses, or until weathering decreases shear strengths.

The apparently more frequent removal of colluvial and residual materials in steep lower slope positions may be explained in two ways. One possibility is that moister conditions on lower slopes cause regolith to become susceptible to slope failure when relatively less weathered than in upslope positions. Landslides in lower slope positions would then be shallow and more frequent, but would lower the landscape at the same rate as deeper, less frequent landslides in ridgetop and upper slope positions.

The relative convexity and lack of dissection shown by ridgetop and upper slopes underlain by relatively coherent graywacke and shale in the Redwood Creek drainage are unlikely consequences of the periodic removal of material by relatively deeper landslides in these areas. In addition, depths of colluvium pockets are similar in upper and lower slope positions in the Miller Creek drainage, suggesting that debris avalanches extend to similar depths in both areas. Consequently, an alternate explanation for the more recent erosional activity in downslope positions on relatively coherent graywacke and shale slopes is favored in this study. This interpretation regards gently sloping land surfaces with moderately rather than poorly developed residual soils as parts of an older, gentler landscape, which is presently being dissected in response to stream incision.

The sequence of erosion events and weathering stages described above can be considered a landsurface lowering cycle, which affects different slope positions over different lengths of time. During the course of the cycle, a landslide-prone slope surface with weathered residual materials is replaced by a relatively stable surface veneered with relatively unweathered surficial materials. Lower slope positions in upper Miller Creek may experience relatively short cycles, because streams undercut slope bases, and because water moves laterally through surficial materials into these positions, increasing weathering rates and promoting the generation of positive pore pressures.

An estimate of an average debris avalanche recurrence interval on slopes underlain by relatively coherent graywacke and shale in the Redwood Creek drainage can be made using a longterm regional landsurface lowering rate of 0.152 mm per year which Janda et al. (1975) calculated using measured volumes of dated offshore deposits near the mouths of several rivers in northwestern California. Assuming that debris avalanches have accomplished all of the landsurface lowering on the slopes under consideration, and that debris avalanche depths average at 3.5 meters, the length of time between successive debris avalanches that expose unweathered bedrock in a single spot equals the average slide depth divided by the longterm lowering rate. This quotient equals approximately 23,000 years. If shallow secondary slides remove on the order of half of the original slide volume from colluvium pockets and surrounding areas, the recurrence interval of debris avalanching in a single spot increases to approximately 34,500 years.

Similar debris avalanche recurrence intervals have been calculated by Kelsey (1977) for steep forested debris avalanche sculpted slopes underlain by coherent Franciscan graywacke in northwestern California. Kelsey measured percentages of drainage basins denuded by debris avalanches during a major storm in 1975, and estimated recurrence intervals of major hillslope erosion and associated stream channel aggradation events by radiocarbon dating suitable materials in preserved alluvial fills in north coast rivers. Kelsey reasoned that if 2 to 3 % of drainage basin surfaces are affected by debris avalanches once every 500 to 1,000 years, then recurrence intervals of debris avalanches in a given spot must range between 15,000 and 50,000 years.

The above debris avalanche recurrence interval estimates are compatible with suggestions made in earlier sections that several thousand years are required for debris avalanche scars to be filled and for the resulting deposits to become stable; that on the order of 10 to 15 thousand years are required for debris avalanche scar fills to weather to the point where they are susceptible to removal; and that another long period of time must pass before newly exposed bedrock weathers to the point where it is once again susceptible to debris avalanches which extend into unweathered bedrock.

A possible problem with extrapolating the effects of erosion activities with long recurrence intervals back in time, is that the effects of climatic change may not be recognized. Heusser (1981) suggested that during the last glacial maximum, which was between 15,000 and 18,000 years ago (Bloom, 1978), cool, temperate pine-conifer forests were extensive in central California, and were encroached upon by coastal redwood forest during warming trends in the Holocene. Disregarding the effects of changes in weathering rates and in the recurrence intervals of major storms, it appears quite possible that most presently forested slopes underlain by relatively coherent graywacke and shale in the Redwood Creek drainage have been vegetated by coniferous forests, and have been subjected to storms which saturate surficial materials, long enough for all slope positions to have undergone one or more debris avalanche cycles.

4. Comparison of Proposed Model With Other Models of Slope Erosion by Debris Avalanching

Dietrich and Dunne (1978) proposed a model of slope erosion for a small steep forested watershed underlain by basalt in northwestern Oregon, in which upslope positions are lowered primarily by shallow creep and tree throw. These processes were thought to gradually deliver sediments to swales, which are emptied continually by deep creep, and are periodically flushed by debris avalanching during major storms. According to this model, the initial depressions into which sediments are delivered are created by rare debris avalanches which remove bedrock and create U- to V-shaped depressions on slopes. More common debris avalanche activity was thought to mostly remove sediments which have been transported to pre-existing hollows or swales.

The primary difference between Dietrich and Dunne's model and the one proposed in this study is the quantity of landscape lowering attributed to debris avalanches which remove weathered and unweathered in situ bedrock. Dietrich and Dunne's model suggested that most material

removed by debris avalanching has been transported to swales by creep and tree throw. In contrast, the model proposed in this study suggests that while some debris avalanches remove material transported to colluvium-filled swales, a similarly important population of debris avalanches remove in situ weathered bedrock, and create new bedrock depressions. In order to explain the fact that less than a third of slopes surfaces underlain by relatively coherent graywacke and shale in the Redwood Creek drainage are occupied by colluvium filled bedrock depressions, yet that new scars are continually being created, the model proposed in this study suggests that debris avalanches which removed material from filled landslide scars may create new scars with geometries which preclude the stability of subsequently contributed fill material, leaving fresh bedrock surfaces on which residual soil profiles develop.

Colluvium filled swales which are wider and less sorted than colluvium pockets observed in upper Miller Creek are observed under prairie vegetation near the upper part of the G Creek drainage in the Redwood Creek watershed, and are possibly more logically generated by the processes outlined in Dietrich and Dunne's model, than by the ones proposed in this in this study. The contrast between these deposits and ones found in the upper part of the Miller Creek drainage affirms the importance of considering variations in vegetation, bedrock, and slope gradients when applying models developed in one area to slopes being studied in another.

Pierson (1977) studied a steep forested drainage underlain by basalt in the Oregon Coast Range, and developed a model of drainage basin evolution which does not differ substantially from that developed by Dietrich and Dunne (1978). Pore pressure measurements made as part of Pierson's study suggest that slope instability is unlikely within 40 meters of the heads of depressions. This suggestions is in conflict with the locations of some colluvium pockets on and close to interfluves in the Redwood Creek drainage.

While Hack and Goodlett (1960) observed that debris avalanches were generated out of colluvium filled hollows on slopes in the headwaters of the Shenandoah River in the Central Appalachians, they also noted that some debris avalanche scars occur adjacent to long grooves that appeared to have resulted from former debris avalanche activity. Kelsey (1980) made a similar observation with regards to the locations of modern debris avalanches on slopes underlain by Franciscan graywacke in the Van Duzen watershed in northwestern California. There, many slopes which showed obvious evidence of debris avalanches in the past did not fail during the large storm of December, 1964, while other slopes which appeared to have had more stable recent histories, did fail during that storm. These observations lend credence to the proposal put forth in this study that filled debris avalanche scars can be less susceptible to debris avalanche activity than the slope surfaces around them.

Wentworth (1943) proposed a model of slope evolution under forest cover on steep basalt slopes on Oahu in Hawaii, whereby shallow debris avalanches remove patches of residual weathering profiles from slope surfaces, in response to the reduction of shear strength of the residual materials by weathering. Areas stripped by debris avalanching, according to this model, do not slide again until sufficient time has passed to

allow renewed weathering and weakening of the newly exposed surface. Debris avalanche activity appears to extend up to and to undercut ridgetops in Oahu, making them sharp and serrated.

Wentworth's ideas are not wholly applicable to relatively coherent graywacke and shale slopes in the Redwood Creek drainage in that once created, the Hawaiian debris avalanche scars do not appear to be filled. This difference is probably due to the fact that the slopes Wentworth studied are steeper than the angle of repose of colluvium. In addition, ridgtops are rounded and convex in the Redwood Creek drainage, as opposed to being sharp and serrated in Oahu. This contrast may reflect faster downcutting rates in Hawaii, which cause debris avalanches to more actively undercut ridgetops. Wentworth's ideas do account for a patchy distribution of the degrees of weathering of residual and colluvial materials, which appears to resemble patterns observed within areas mapped as having weakly developed residual soils in the upper part of the Miller Creek drainage, in addition to ones noted by Kelsey (1980) in the Van Duzen watershed in northwestern California, and by Pain (1969) in the Hunua Ranges in New Zealand.

In summary, the models discussed above can be considered parts of a continuum of ideas regarding landscape evolution by debris avalanching. At one end of the continuum, Dietrich and Dunne's (1978) model suggests that once swales are formed by debris avalanche activity, they become likely sites for future debris avalanches, which mostly remove material transported into the swales. At the other end of the continuum, Wentworth's (1943) model suggests that a debris avalanche at a given site makes that site less susceptible to future sliding by removing weak weathered regolith and exposing fresher, stronger material. The model proposed in this study takes an intermediate position, by suggesting that the filling of debris avalanche scars, and the subsequent weathering and instability of the fill material, are only parts of a longer term cycle, during which the slopes originally subjected to debris avalanche activity become less susceptible to subsequent slope failure than surrounding slope surfaces.

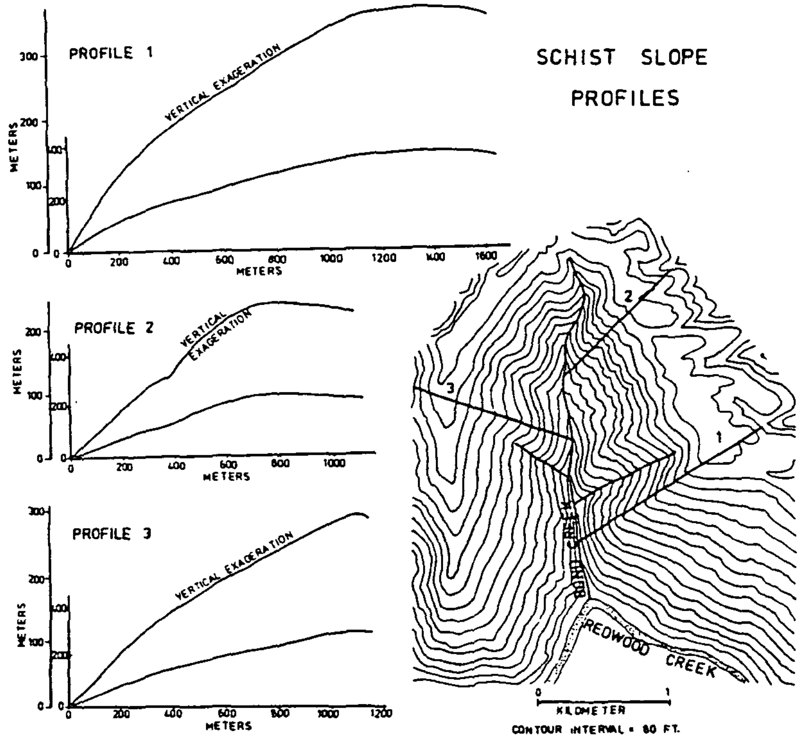
CHAPTER III - THE GENESIS OF RESIDUAL SOILS, COLLUVIUM, AND SLOPE FORMS ON SCHIST

A. INTRODUCTION

Residual soils and colluvium, and related weathering and erosion processes on slopes underlain by schist in the Redwood Creek drainage provide a good contrast with those characteristic of slopes underlain by relatively coherent graywacke and shale. Roadcuts across slopes underlain by schist expose surficial materials which are often deeply weathered, and are characteristically laterally discontinuous. Exposures of landslide deposits on these slopes suggest that dominant mass wasting activities have been deeply seated, and in many cases have transported material from point to point along slopes instead of delivering it immediately to stream channels. As in the preceding chapter, the sections on residual soils and colluvium describe the characteristics and map patterns of these surficial materials, and discuss their genetic implications. In the final section in this chapter, ideas regarding the evolution of different slope forms on schist bedrock are discussed.

Selected profiles of slopes underlain by schist are shown in Figure 19. Side slopes in these areas have gradients which commonly range from 20% to 40% and are an average of approximately 25%. Iwatsubo et al. (1975) cited drainage densities ranging from 3.0 to 4.9 and averaging at 3.9 km of channel per square km, for tributary drainages in schist areas. Variations in slope morphology reflect differences in aspect, and in bedrock structure and state of shearing. Slopes commonly steepen markedly adjacent to streams, creating what Janda et al. (1975) and

Figure 19 - Profiles of slopes underlain by schist in the Bond Creek drainage.



Kelsey (1977) have referred to as inner gorges.

Schistose rocks in the metamorphic unit which lies southwest of the Grogan Fault were mapped as the Kerr Ranch Schist by Manning and Ogle (1950). While rocks of the Kerr Ranch Schist resemble those mapped as South Fork Mountain Schist, which is a more extensive bedrock unit to the east of the Redwood Creek drainage, Monsen and Aalto (1980), and Talley (1976), have suggested that the presence of lawsonite and exotic tectonic blocks in the Kerr Ranch Schist prohibit direct lithologic and structural correlations with the South Fork Mountain Schist.

Rocks mapped as Kerr Ranch Schist are dull gray to pale green in color, are commonly fine grained in texture, and show pronounced metamorphic layering, which is often intensely folded and crumpled. According to Talley (1976), mineral assemblages usually include quartz, albite, chlorite, and phengitic muscovite, and sometimes include lawsonite, aragonite, and graphite. Elongate pods of quartz are abundant between micaceous layers in many outcrops. Minor amounts of relatively mica deficient and quartz rich rocks occur within the Kerr Ranch Schist in parts of the Bond Creek drainage. These rocks are more gently folded than the finer grained schists, and probably had a more sandy as opposed to shaly protolith.

The structural geology of the Kerr Ranch Schist is as yet poorly understood. Foliation is obscured by the weathered and broken nature of outcrops, and has been rotated in many areas by mass wasting processes. Intersecting schistosities formed during multiple stages of deformation are seen in many roadcut exposures. Offsets along faults are also frequently observed. Geologic maps by Harden et al. (1981) and Manning and

Ogle (1950) show a prevalence of NW-SE strikes and northeasterly dips of foliations in the Redwood Creek drainage.

The schist weathers readily into small platy fragments. Clay seams parallel metamorphic layering in many weathered outcrops, and cut across the metamorphic layering in some exposures. Weathered schist is notably red, probably as a consequence of the oxidation of iron in chlorite and other iron bearing minerals. Schist weathers more quickly than interbedded graywacke and shale in the Redwood Creek drainage, as a consequence of the higher mica content of schist and the higher quartz content of graywacke and shale. Mineralogic contrasts between schist and relatively coherent graywacke and shale in the Redwood Creek drainage suggest that the protolith for the schist was richer in clays than are the relatively coherent textural zones I and II rocks which presently lie northeast of the Grogan fault. The clay in the protolith sediments was recrystallized as mica in response to increases in temperature and pressure after deposition.

Residual soil map units were defined during reconnaissance work in the Bond Creek and Tom MacDonald Creek drainages, and on both sides of the long asymmetric ridge between Bridge Creek and Redwood Creek. Detailed descriptions and mapping of residual soils were mostly done in the Bond Creek drainage, where recent logging has left fresh exposures in a wide variety of drainage basin positions. The discussion of landslide deposits is based on observations of roadcuts in the Bond Creek watershed and on both sides of the divide between Redwood Creek and Bridge Creek.

B. RESIDUAL SOILS ON SCHIST SLOPES

1. Previous Work

Soil maps at a scale of 1:31,680 of the Redwood Creek watershed and surrounding areas were prepared by Alexander et al. (1959-62). These maps show most of the soils on schist slopes in the northern half of the basin as being in the Masterson, Orick, and Sites series, which are typically Inceptisols, Alfisols, and Ultisols respectively. Generalized profile descriptions of these series, presented by Lacke (1979), indicate that the three series increase in degree of soil profile development from Masterson to Orick to Sites. Map patterns and map unit descriptions presented by Alexander et al. (1959-62) agree only in a general way with the ones presented in this study, probably due to the relative lack of exposures available when the earlier work was in progress, and to the fact that the earlier work was a reconnaissance survey.

2. Definition of the Developmental Sequence

Five stages of soil development on schist bedrock were defined in the Redwood Creek drainage based on field criteria including horizon thicknesses, moist and dry color, gravel content, texture of the nongravel fraction, soil structure, and clay film abundance and thickness. Schist with no soil development shows 2.5Y to 5Y colors, traceable schistosity, and no pedogenic structure. Weakly developed soils differ in that their 7.5YR to 10YR B horizons extend to depths of less than one m, and show slight evidence of clay accumulation by their

weakly developed structure and gravelly to sandy clay loam texture. Moderately developed soils are distinguished from weakly developed ones by their 1 to 2 m profile depths, and by the 5YR to 7.5YR colors in their B horizons. Strongly developed soils differ in their greater than 2 m profile depths, and in the 2.5YR to 5YR colors in their lower B horizons. Very strongly developed soils are distinguished from strongly developed ones mostly on the basis of substantially decreased gravel content.

Parameters in the generalized stage descriptions included in Tables 4 through 7 are averages taken from at least three detailed field descriptions of profiles, which were determined by examination of continuous roadcut exposures to be representative of each stage. Profile descriptions are given in Appendix A. Locations of profiles are noted on Plate 2. Figures 20 through 24 are photographs of representative profiles in each of the stages. Weakly and moderately developed soils resemble those of the Masterson and Orick series, while soils in the strongly and very strongly developed stages resemble Sites series soils.

3. Solum and Horizon Thicknesses

While variations in solum and individual horizon thicknesses exist within units, average values of these parameters, which are shown in Figure 25, are helpful in characterizing the different stages of profile development. A1 horizons do not thicken substantially from unit to unit. A/B transition horizons thicken collectively from the weakly developed to the strongly developed unit, then remain approximately the same thickness from the strongly to the very strongly developed unit.

Table 4: Generalized Profile Description of Weakly Developed Residual Soil on Schist

Horizon	Depth (meters)	Color Moist	Color Dry	Texture	Structure	Clay Films	Boundary (Lower)
A_1	0.00-010	10YR 4/6	10YR 6/4	gravelly sandy clay loam	SMGR[a]	none[a]	clear to
A_3	0.10-0.21	7.5 - 10YR 4/7	7.5 - 10YR 5.5/6	gravelly clay loam	WMSBK to MMSBK	none	clear to abrupt
B_2	0.21-0.53	7.5 - 10YR 4/6	7.5 - 10YR 5/6	clay loam to gravelly clay	WMABK to MMABK	none	clear to abrupt
B_3	0.53-0.85	7.5 - 10YR 4/6	7.5 - 10YR 5/8	very gravelly clay loam to very gravelly clay	single grain WCSBK	none	clear to abrupt
C	Fresh to weathered 10YR to 7.5YR schist showing continuous schistosity, occasional 7.5YR clay seams						

[a]Explanations of structure symbols and clay film adjectives in U.S.D.A.-S.C.S. (1974).

104

Table 5: Generalized Profile Description of Moderately Developed Residual Soil on Schist

Horizon	Depth (meters)	Color Moist	Color Dry	Texture	Structure	Clay Films	Boundary (Lower)
A_1	0.00-0.22	7.5YR 4/6	7.5YR 5/6	loam to clay loam; rocks present	MMGR to SMGR	none	clear
A_3/B_1	0.22-0.45	7.5YR 4/7	7.5YR 5/7	clay loam; rocks present	MCG grades to WCSBK	none	clear
B_{21}	0.45-0.66	5 - 7.5YR 4/6	5 - 7.5YR 5/8	clay; rocks present	MCSBK	few thin	gradual to clear
B_{22}	0.66-0.98	5 - 7.5YR 4.5/8	7.5YR 4.5/8	clay; rocks present	MCABK	common thin to moderate	gradual to clear
B_3	0.98-1.75	5YR 4.5/8	5YR 4.5/7	gravelly clay	MCABK to WCCABK	common to many thin to moderate	clear to abrupt
C	Fresh to weathered 10YR to 5YR schist showing continuous schistosity, 5YR clay seams follow schistosity						

Table 6: Generalized Profile Description of Strongly Developed Residual Soil on Schist

Horizon	Depth (meters)	Color Moist	Color Dry	Texture	Structure	Clay Films	Boundary (Lower)
A_1	0.00-0.26	7.5YR 3/7	7.5YR 5/5	loam to clay loam; rocks present	SCGR to MMGR	none	clear
A_3	0.26-0.41	7.5YR 3.5/6	7.5YR 5.5/6	clay loam; rocks present	WCGR to MCGR	none	gradual to clear
B_{21}	0.41-.73	7.5YR 4/6	7.5YR 5/6	clay loam to silty clay	WCSBK	none	gradual to clear
B_{22}	0.73-1.17	5 - 7.5YR 4/8	5 - 7.5YR 5/6	clay; rocks present	WCSBK to MCSBK	common thin	gradual to clear
B_{23}	1.17-1.90	2.5 - 5YR 4/8	2.5 - 5YR 5/8	clay; rocks present	MCABK to MCABK	many thin to moderate	gradual
B_3	1.90-2.10+	2.5 - 5YR 4/8	2.5 - 5YR 4.5/8	gravelly clay	massive to WCSBK	common to many moderate	gradual to abrupt
C	Fresh to weathered 10YR to 5YR schist with 7.5YR to 5YR clay seams						

Table 7: Generalized Profile Description of Very Strongly Developed Residual Soil on Schist

Horizon	Depth (meters)	Color Moist	Color Dry	Texture	Structure	Clay Films	Boundary (Lower)
A_1	0.00-0.15	7.5YR 4/6	7.5YR 5/4	clay loam	SMGR	none	clear to abrupt
B_1	0.15-0.49	5 - 7.5YR 4/6	7.5YR 5/7	heavy clay loam	MCSBK to SCSBK	none	clear to abrupt
B_{21}	0.49-0.81	5 - 7.5YR 4/6	7.5YR 6/6	silty clay	MCSBK	common moderate	abrupt
B_{22}	0.81-1.34	5YR 4/8	5YR 4/7.5	clay	SMABK	many moderate	clear to abrupt
B_{23}	1.34-2.06	5YR 4/8	5YR 5/8	clay	WCABK	many moderate	clear
B_3	2.06-2.40+	2.5 - 5YR 4.5/7.5	2.5 - 5YR 5/8	gravelly clay	massive	many moderate	clear
C	Weathered 7.5YR to 2.5YR schist with traceable schistosity, 7.5YR to 2.5YR clay seams follow schistosity						

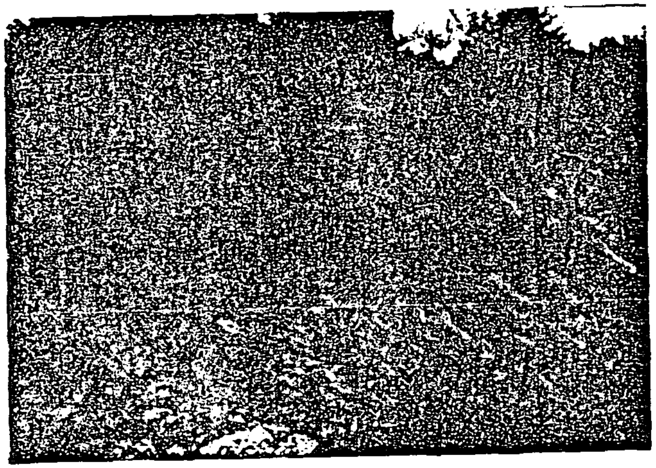


Figure 20 - Schist bedrock with no residual soil profile development. Photograph was taken near intersection of lower road and Bond Creek in the Bond Creek drainage (Plate 2).

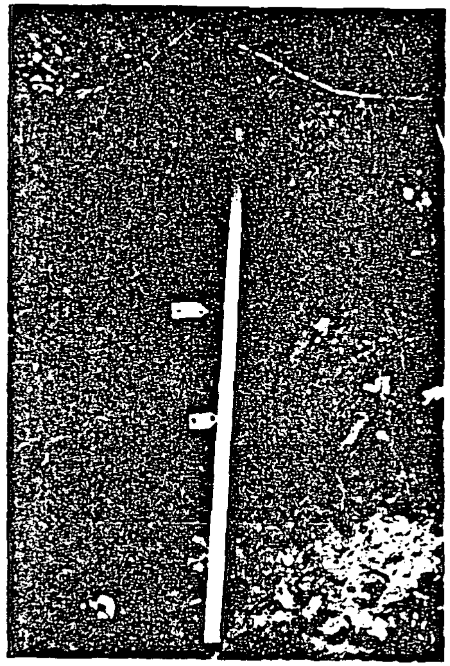


Figure 21 - Weakly developed residual soil on schist bedrock. Soil profile 2 in Appendix A. Location is on Plate 2.

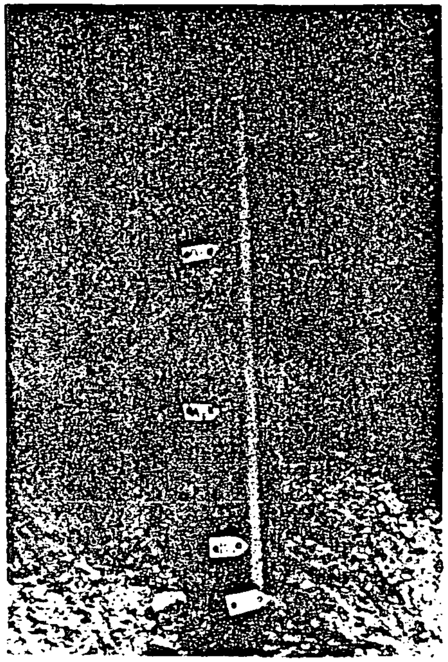


Figure 22 - Moderately developed residual soil on schist bedrock. Soil profile 5 in Appendix A. Location is on Plate 2. Meter stick extends above the top of the A horizon into material disturbed by logging activity on top of the pre-logging ground surface.

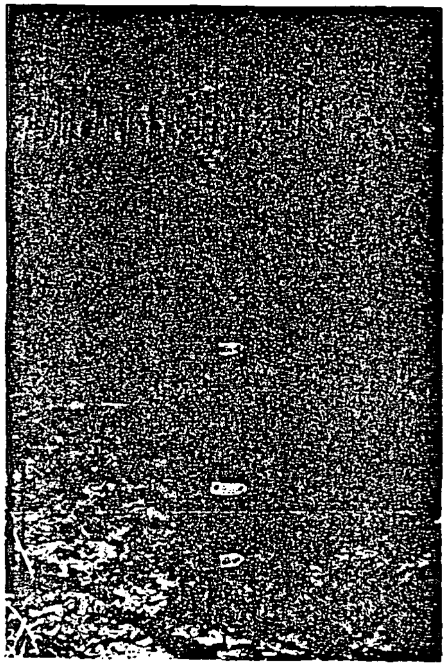


Figure 23 - Strongly developed residual soil on schist bedrock. Profile 7 in Appendix A. Location is on Plate 2.

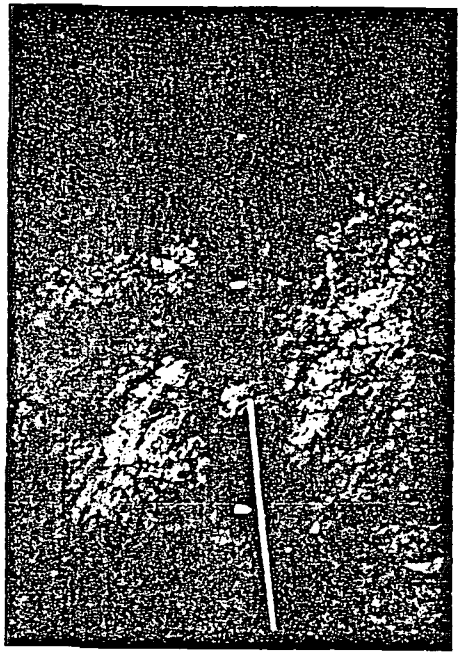
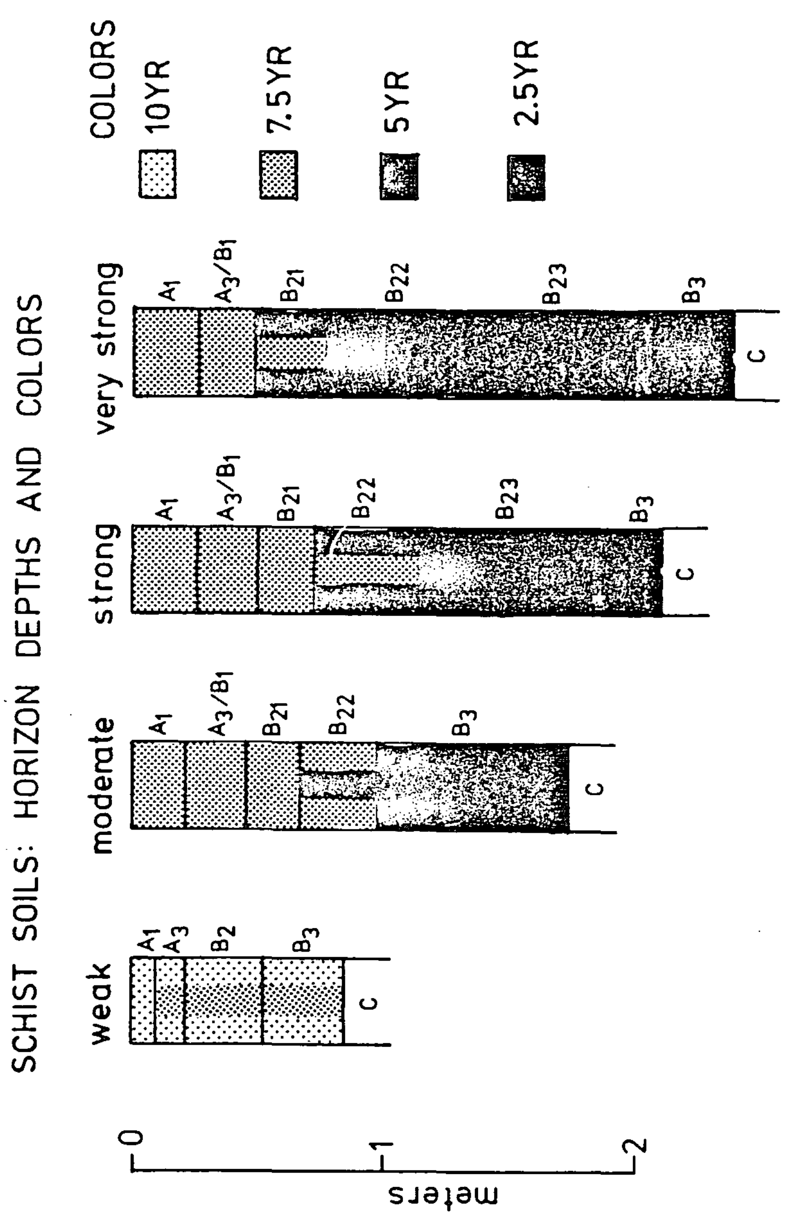


Figure 24 - Very strongly developed residual soil on schist bedrock. Soil profile 15 in Appendix A. Location is on Plate 2.

Figure 25 - Average horizon thicknesses and colors of different degrees of residual soil profile development on schist bedrock.



B2 horizons also thicken markedly from the weakly developed to the strongly developed unit, and then increase only slightly in thickness from the strongly to the the very strongly developed unit. B3 horizons increase in thickness from the weakly developed to the moderately developed unit. Trends in the thickness of this lowermost horizon for the more developed soils could not be determined accurately because of the difficulty of exposing the B/C horizon boundary.

Total solum depths clearly increase as the degree of soil profile development increases. The rate at which horizons thicken as soils become more developed is smallest in A1 horizons, increases slightly in combined A3 and B1 horizons, and increases more substantially in B2 horizons. The fact that A1 horizons thicken only slightly after soils reach the moderately developed stage, supports Birkeland's (1974) suggestion that A horizons probably attain steady state or dynamic equilibrium conditions more quickly than do B horizons.

4. Color

Moist and dry soil colors were determined using a standard Munsell color chart. Within single profiles, horizons increase in redness with increasing depth. In addition, entire profiles become redder with increased profile development. Figure 25 shows trends in moist hues for different horizons at each stage of development. As can be seen, 7.5YR to 10YR moist colors characterize the horizons of the weakly developed unit. The moderately developed unit differs in its exclusively 7.5YR A and A/B transition horizons, and in the appearance of 5YR colors in the B2 and B3 horizons. The strongly developed unit shows still redder hues, as 2.5YR colors appear in some B2 and B3 horizons.

In the three more strongly developed units, reddest colors commonly appear in B3 or C1 horizons, which lie below the B2 horizons, or zones of maximum clay accumulation. Very red colors are also found immediately surrounding fractured quartz pods in saprolite and in soil fillings of old root holes. Figures 26 and 27 show examples of these zones. Large pore spaces in the very red zones suggest that they are more permeable than horizons above and below, and may be zones where subsurface throughflow is concentrated during storms. Conacher and Dalyrymple (1977) found concentrations of iron oxides in the forms of discontinous grain and ped coatings in soils where they conjectured that lateral flow of subsurface water was of primary importance. Kojan (1968) noted similar iron stained zones below what he surmised was the base of the active creep zone in soils in the North Coast Range in California.

Hurst (1977) found good correlations between redness and iron oxide contents in subtropical and tropical saprolites. As iron bearing minerals weather, ferrous iron (Fe^{++}) is released, which is rapidly oxidized in the presence of oxygen to become ferric iron (Fe^{+++}). Iron oxides are commonly relatively insoluble under profile conditions resembling those in the Redwood Creek drainage, hence iron oxides accumulate in soils with increasing soil age and degree of weathering (Buol et al., 1973, and Birkeland, 1974).

If rocky red horizons at profile bases possess greater weight percents of iron oxides than the yellowish clay rich horizons above them, then iron oxide accumulation probably precedes clay accumulation during

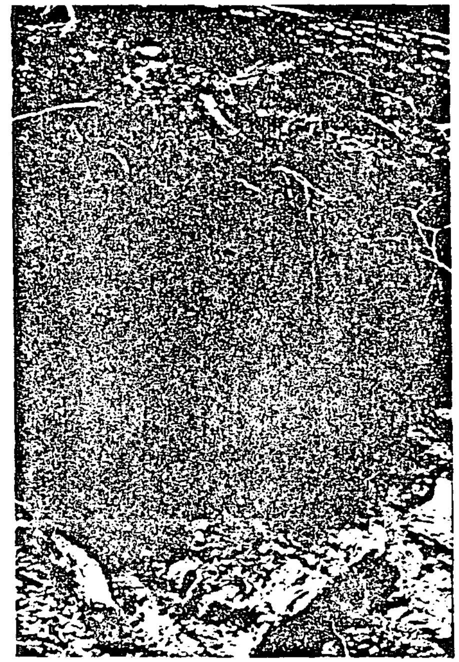


Figure 26 - Permeable red zone in old root hole. Photograph was taken on uppermost road on the northeast facing side of the interfluve between Bridge Creek and Redwood Creek (figure 33).

Figure 27 - Permeable red zone at the base of a residual soil profile. Photograph was taken on lowermost road on the northeast facing side of the interfluve between Bridge Creek and Redwood Creek (Figure 33).

profile development, during which B horizons encroach on the parent material below them. Birkeland (1974) pointed out, however, that iron oxides, as pigmenting agents, are diluted in finer grained soils, which possess greater surface areas. It is possible, therefore, that clay accumulation precedes iron oxide accumulation during soil profile development and deepening, and that while red stony horizons at the bases of soil profiles may possess similar total weight percents of iron oxides to the yellower clay rich horizons above them, they may appear redder because those iron oxides are distributed over a smaller surface area. The extremely clay-rich horizons may also accumulate water to the point where iron oxidation is inhibited, reducing the capacity of these horizons to accumulate iron oxides.

5. Structure and Clay Films

Variations in soil structure are more useful in recognizing horizons within profiles than in determining degrees of profile development of different soils. A1 horizons in soils at all four stages of soil profile development show moderate to strong medium granular structures. Transitions from A to B horizons universally involve changes from weak or moderate medium or coarse granular structure, to weak or moderate coarse subangular blocky structure. B22 horizons in soils at all four stages show mostly medium angular blocky structures, which are weak to moderate in the weakly and moderately developed stages, and moderate to strong in the strongly and very strongly developed stages. Most B3 horizons show massive, single grain, weak subangular blocky, or weak angular blocky structures.

According to Birkeland (1974), the binding action of mainly organic colloids causes granular structures to develop in A horizons. White (1966) suggested that shrinking and swelling activity, which is related to clay content, causes subangular blocky and angular blocky structures to develop in B horizons. The latter concept is consistent with the fact that soils with larger clay contents have stronger and more angular blocky structures in their B horizons.

The presence and thickness of clay films, in contrast to soil structures, are well correlated with degrees of soil profile development. Soils in the weakly developed stage contain no clay films. As can be seen in Tables 5, 6, and 7, B21, B22, and B3 horizons all show trends of increasing frequency and thickness of films with increasing degree of soil profile development. According to Birkeland (1974), clay films are generally thought to be produced by mechanical clay translocation. It is logical, therefore that films are thicker and more abundant in more developed soils, which are likely to have experienced more clay translocation.

6. Grain Size Distribution

Changes in grain size distribution in the developmental sequence of soils on schist in the Redwood Creek drainage yield useful information on processes of soil genesis. Grain size distributions were obtained using wet sieving for gravel and sand weight percents, and pipette methods described by Day (1965) for silt and clay weight percents. All horizons in each of two of the profiles chosen for detailed field description of each developmental stage were analyzed. Results are

included in Tables 8 through 11, and are presented graphically in Figure 28. While considerable variability exists within developmental stages, trends in the weight percent of each grain size fraction can still be defined. In the following discussion, fine fraction weight percents of sand, silt, and clay refer to the weight percents of these size fractions in the portion of the soil passing through a 2 mm sieve. Weight percents of different size fractions in complete soil samples are referred to as total sample weight percents.

For the most part, total sample gravel weight percents and fine fraction sand weight percents of soils in all four degrees of profile development decrease steadily from A1 to B2 horizons, and increase from B2 to B3 horizons. The decreases from A1 to B2 horizons probably reflect the downward translocation of fine particles, which concentrates coarse materials in upper horizons and dilutes them in lower layers. The increases in these sand and gravel contents from B2 to B3 horizons probably reflect closer proximities of the lower horizon to fresh, unweathered parent material, which makes up a greater percentage of the lower horizons. Binocular microscope inspection of gravel, sand and silt size classes indicate that while gravel and sand mostly consist of micaceous schist fragments, the silt size fraction consists mostly of monomineralic quartz grains. The fine fraction weight percent of silt remains relatively constant throughout each soil profile analyzed.

In general, fine fraction weight percents of clay increase downward from the A1 horizon to the B2 horizon. Though total sample weight percents of clay decrease from B2 to B3 horizons due to increases in gravel contents, the fine fraction weight percents of clay in B3 horizon tends

Table 8: Grain Size Distribution of Weakly Developed Residual Soils on Schist

		Total Sample Wt. %				Fine Fraction (<2 mm) Wt. %		
Depth (meters)	Horizon	% gravel	% sand	% silt	% clay	% sand	% silt	% clay
		Soil Profile 1						
0.00-0.08	A_1	27.7	27.1	27.9	17.3	37.5	38.6	23.9
0.08-0.32	A_3	20.6	20.1	35.3	24.1	25.3	44.4	30.4
0.32-0.59	B_2	21.3	17.1	35.3	26.3	21.7	44.9	33.4
0.59-0.74	B_3	44.3	15.4	21.8	18.5	27.7	39.1	33.2
		Soil Profile 3						
0.05-0.10	A_1	49.0	30.1	12.1	8.0	59.1	23.7	17.2
0.10-0.20	A_3	42.2	22.5	19.6	15.7	39.0	33.9	27.1
0.20-0.50	B_{21}	29.7	17.9	21.9	30.5	25.4	31.2	43.4
0.50-1.10	B_{22}	22.2	17.7	25.6	34.5	22.7	32.9	44.4

Table 9: Grain Size Distribution of Moderately Developed Residual Soils on Schist

		Total Sample Wt. %				Fine Fraction (<2 mm) Wt. %		
Depth (meters)	Horizon	% gravel	% sand	% silt	% clay	% sand	% silt	% clay
		Soil Profile 5						
0.00-0.17	A_1	20.3	32.0	17.5	30.3	40.1	21.9	38.0
0.17-0.35	B_1	11.5	21.2	33.9	33.5	23.9	38.3	37.8
0.35-0.66	B_2	8.8	14.4	34.9	41.9	15.8	38.3	45.9
0.66-0.84	B_3	9.1	14.4	28.3	48.3	15.8	31.1	53.1
		Soil Profile 4						
0.00-0.15	A_1	29.8	18.7	26.4	25.1	26.6	37.6	35.8
0.15-0.33	A_3	23.2	15.6	24.4	36.8	20.3	31.8	47.9
0.33-0.80	B_1	28.0	16.8	22.5	32.7	23.3	31.3	45.4
0.08-0.98	B_{21}	16.0	11.7	26.0	46.3	13.9	31.0	55.1
0.98-1.26	B_{22}	19.8	16.4	18.1	45.7	20.4	22.6	57.0
1.26-1.66	B_3	16.4	23.7	20.8	39.1	28.3	24.9	46.8

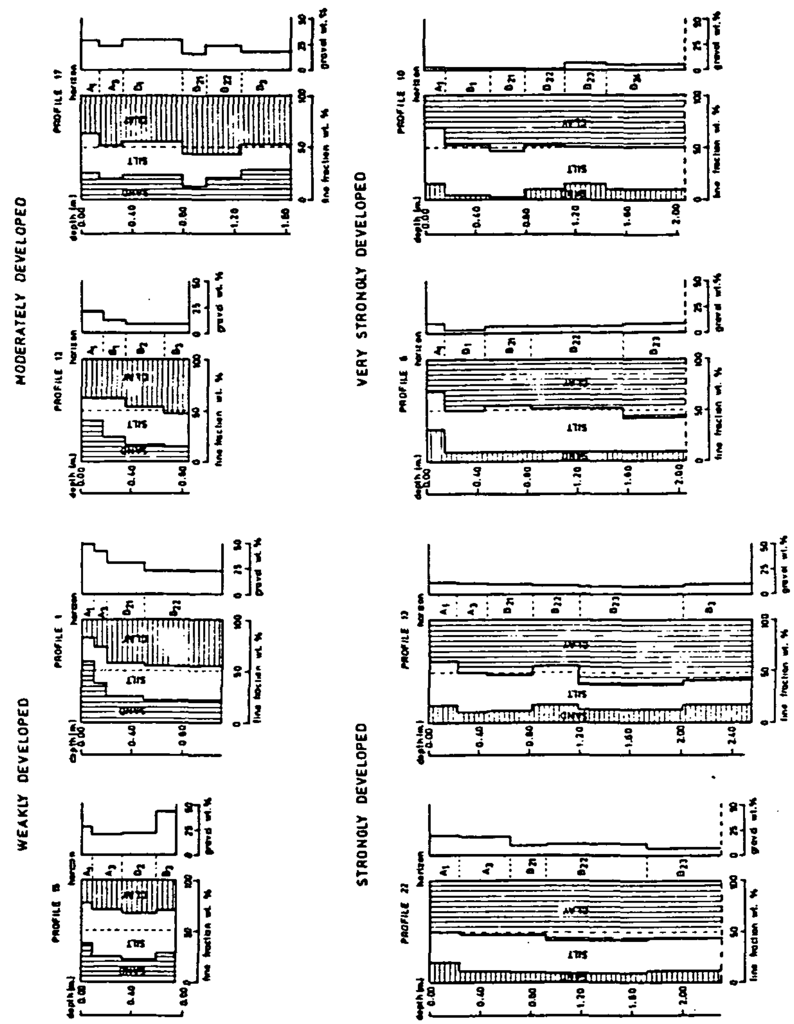
Table 10: Grain Size Distribution of Strongly Developed Residual Soils on Schist

		Total Sample Wt. %				Fine Fraction (<2 mm) Wt. %		
Depth (meters)	Horizon	% gravel	% sand	% silt	% clay	% sand	% silt	% clay
		Soil Profile 11						
0.00-0.23	A_1	19.1	16.3	23.1	41.4	20.2	28.6	51.2
0.23-0.63	A_3	17.8	9.0	31.0	42.3	10.9	37.7	51.4
0.63-0.92	B_{21}	9.8	9.2	32.4	48.6	10.2	35.9	53.9
0.92-1.72	B_{22}	10.5	8.4	27.9	53.2	9.4	31.2	59.4
1.72-2.30+	B_{23}	6.3	9.8	30.4	53.5	10.5	32.4	57.1
		Soil Profile 8						
0.00-0.22	A_1	11.1	14.7	38.0	36.2	16.5	42.8	40.7
0.22-0.47	A_3	10.2	9.8	33.9	46.2	10.9	37.7	51.4
0.47-0.82	B_{21}	9.3	11.2	31.7	48.0	12.3	34.9	52.9
0.82-1.19	B_{22}	8.1	16.2	34.9	40.9	17.6	38.0	44.5
1.19-2.02	B_{23}	7.3	12.7	21.4	58.6	13.7	23.1	63.2
2.02-2.54	B_3	10.1	15.7	21.5	52.7	17.5	23.9	58.6

Table 11: Grain Size Distribution of Very Strongly Developed Residual Soils on Schist

		Total Sample Wt.%				Fine Fraction (<2 mm) Wt. %		
Depth (meters)	Horizon	% gravel	% sand	% silt	% clay	% sand	% silt	% clay
		Soil Profile 15						
0.03-0.14	A_1	8.9	28.1	34.9	28.1	30.9	38.3	30.8
0.14-0.46	B_1	3.2	7.3	41.6	47.9	7.5	43.0	49.5
0.46-0.83	B_{21}	5.7	8.0	43.9	42.3	8.5	46.6	44.9
0.83-1.56	B_{22}	5.6	8.2	40.6	45.6	8.7	43.0	48.3
1.56-2.06	B_{23}	7.8	8.7	30.6	52.9	9.4	33.2	57.4
		Soil Profile 14						
0.00-0.16	A_1	1.9	15.1	53.2	29.9	15.4	54.2	30.5
0.16-0.51	B_1	1.3	4.5	48.3	45.9	4.6	48.9	46.5
0.51-0.79	B_{21}	1.0	3.6	42.6	52.8	3.6	43.0	53.3
0.79-1.11	B_{22}	0.9	10.2	42.1	46.9	10.3	42.5	47.3
1.11-1.44	B_{23}	6.2	15.3	32.8	45.6	16.3	35.0	48.6
1.44-2.06+	B_{24}	5.5	9.9	38.7	45.4	11.1	40.9	48.0

Figure 28 - Grain size distributions of residual soils developed on schist bedrock.



to be similar or slightly higher than those in B2 horizons. This trend suggests that clay is either transported to, or formed in place, at approximately the same rate in the B2 and B3 horizons.

Clay accumulations in soils can be due to mechanical translocation of clay particles, to the dissolution and reprecipitation of clay minerals, or to in situ creation of clay by weathering of silicate minerals. As was mentioned above, clay films, which are observed in moderately, strongly, and very strongly developed soils in Bond Creek, are generally interpreted to result from the downward transportation of clay particles, however the transportation can be from within the same horizon. Marked increases in fine fraction weight percents of clay in A1 horizons as profiles become more developed suggest that clay accumulations in soils developed on schist in the Redwood Creek drainage do not necessarily reflect translocation of clay from horizons above.

According to Mitchell (1976) and Birkeland (1974), clay dispersion is promoted by low electrolyte contents, and by low concentrations of positively charged colloids such as iron and aluminum hydroxides. These conditions generally prevail toward the tops of profiles, promoting clay mobility, while converse conditions, promoting clay flocculation and accumulation, are more likely to exist lower in the solum. Increased concentrations of iron oxides toward the bases of profiles may promote clay flocculation and accumulation in those lower levels. Deepening levels of iron oxide accumulation corresponding to increasing degrees of soil profile development may therefore cause the correspondingly deepening levels of clay accumulation. Mitchell (1976) suggested that low pH values also promote clay flocculation. Acidity measurements done on

Orick and Sites soils, (unpublished Soil Conservation Service data provided by Jim Poponoe, N.P.S), yielded pH values that decrease downward through soil profiles.

In the paragraphs that follow, a profile weight percent of a particular grain size fraction is defined as the average of the weight percents of that grain size fraction in each horizon in the profile. Profile weight percents of different grain size fractions for the different stages of profile development are summarized in Table 12. Profile weight percents of gravel decrease abruptly from the weakly developed unit to the moderately developed unit, and then decrease gradually from the moderately to the very strongly developed unit. Fine fraction profile weight percents of sand decrease at an abrupt but steady rate from the weakly developed to the strongly developed soils, and then decrease only slightly from the strongly to the very strongly developed unit. Clearly, changes in grain size distributions are more abrupt and marked in early stages of weathering, as has been noted by many researchers, among them Stevens and Walker (1970), and Birkeland (1974).

Pipette analyses of schist soils in the Redwood Creek drainage show that fine fraction profile weight percents of silt decrease rapidly from the weakly developed to the moderately developed unit, decrease more slowly from the moderately to the strongly developed unit, and then increase substantially from the strongly to the very strongly developed soils. In an appropriately opposite manner, fine fraction profile weight percents of clay increase quickly from the weakly to the moderately developed unit, increase more slowly from the moderately developed to the strongly developed unit, and then decrease notably from

Table 12: Total Profile Grain Size Distributions of Schist Soils

Weathering Stage	Total Sample Wt. %				Fine Fraction (<2 mm) Wt. %		
	% gravel	% sand	% silt	% clay	% sand	% silt	% clay
Weak Profile Development	28.5 - 35.8	19.9 - 22.1	19.8 - 30.1	21.6 - 22.2	28.1 - 36.6	30.4 - 41.8	30.2 - 33.0
Moderate Profile Development	12.4 - 22.2	17.2 - 33.8	23.0 - 28.7	37.6 - 38.5	22.1 - 23.9	29.9 - 32.4	43.7 - 48.0
Strong Profile Development	9.4 - 12.7	10.5 - 13.4	29.0 - 30.2	47.1 - 47.8	12.2 - 14.8	33.2 - 33.4	51.9 - 54.6
Very Strong Profile Development	2.8 - 6.2	9.8 - 12.1	38.3 - 43.0	43.4 - 44.4	10.2 - 13.0	40.8 - 44.1	45.7 - 46.2

the strongly to the very strongly developed unit. Though it is possible that these trends reflect the combination of decreasing contribution of clays to the very strongly developed soils due to the depletion of weatherable sand and gravel sized clasts, and the continued removal of clay particles from the soil solums by dissolution and clay translocation, it is more likely that problems with the dispersal of aggregates including silt and clay particles, which Birkeland (1974) and Barshad (1964) have indicated are strongly bonded in the presence of iron oxides, make the pipette analyses of clay and silt contents in the more strongly weathered soils unreliable.

7. Variability

A final point regarding the characterization of map units involves some consideration of the variability of soil features within each unit. Traditionally, soil variability on hillslopes has been a difficult subject to approach, as most studies have based their conclusions on small numbers of samples collected in auger holes or backhoe pits. Carson (1967) determined coefficients of variation of a number of soil and regolith characteristics which he measured in random samples taken at varying spacing along different length segments of straight midslope sections of slope profiles in the southern Pennines and on Exmoor. His data suggests that in the areas studied, depths of auger penetration, infiltration capacities, regolith stoniness, and soil resistance to penetration vary considerably more than do soil bulk densities, moisture contents, and proportions of material in the silt-clay range. Similarly, from profile to profile within the map units defined on schist bedrock in the Redwood Creek drainage, horizon depths and gravel contents vary considerably more than do soil colors, textures of the non-gravel fraction, and structures.

Roadcuts across areas mapped as having particular degrees of residual soil profile development typically expose soil profiles which fit the descriptions of more and less developed stages within the defined sequence. The scattered distribution and limited aerial extent of these variants makes it impractical to map them separately. For the most part, only soils in consecutive stages in the defined developmental sequence appear as variants within areas mapped as a single unit. Less than 10% of areas mapped as having no profile development show profiles that can be considered weakly developed. An estimated 15, 20, and 35 percents of areas mapped as having weakly developed, moderately developed, and strongly developed profiles respectively show degrees of soil profile development stronger or weaker than those of the mapped units. Variability decreases in areas mapped as having very strongly developed soils, which include on the order of 10 to 15 % of profiles with relatively weaker degrees of soil profile development. Areas showing extreme lateral variation in soil characteristics are mapped as a separate unit, and as will be discussed in a later section, are considered to be areas where soil profiles have been disrupted by the present or past activity of deeply seated, slowly moving mass wasting processes.

Most soil profiles which are more or less developed than the more characteristic soils around them occur in pockets of varying sizes. Small pockets, such as the one in Figure 29, could easily have resulted

Figure 29 - Small soil pocket in schist bedrock. Photograph was taken above lowermost road in the northwest quadrant of the Bond Creek drainage (Plate 2).

from tree throw, during which the roots of trees break and loosen rock material as the tree falls, leaving hollows into which material can be added from upslope. These local zones of broken and slightly transported bedrock are undoubtedly more susceptible to weathering than surrounding in situ bedrock. Soil descriptions done along roadcuts in areas showing abundant large soil pockets, such as the one pictured in Figure 30, show that A and B horizons commonly thicken and thin proportionately as total soil depths increase and decrease. These larger pockets are most easily attributed to variations in parent material and/or moisture conditions which have encouraged pedogenesis in some places and have impeded it in others. Variations in mica and quartz contents of schistose parent materials, drainage concentrations, and variations in degrees of shearing or comminution due to tectonic and/or mass wasting activity, are likely causes of these uneven rates of pedogenesis.

Another trend of variation within map units defined for this study involves the general tendency for profiles in the strongly and very strongly developed units to become redder and deeper downslope along the gently sloping interfluves north and south of Bond Creek. These trends probably result from increased moisture contents downslope, and may also reflect profile thickening by creep, and/or older ages of downslope soils which have been transported by creep for longer periods of time.

When observed in roadcuts, local zones showing anomalous degrees of soil profile development are fairly easily distinguished as aberrations from the norm. Auger hole and backhoe pit exposures, however, do not provide such continuous exposure, hence care must be taken in the use of data collected from these sources to characterize soils in similar steep

Figure 30 - Large soil pocket in schist bedrock. Photograph was taken above middle road on the northeast facing side of the interfluve between Bridge Creek and Redwood Creek (Figure 33).

forested areas. As was suggested by Steers and Hajek (1979), randomly selected line transects are more likely than randomly selected sample points to provide realistic data which can be used to characterize map units.

8. Soil-Topography Relations

Residual soils showing particular degrees of soil profile development occur in characteristic drainage basin positions in the Bond Creek watershed, as can be seen on Plate 2. The main stem of Bond Creek runs through areas showing no residual soil profile development. Major tributaries which feed Bond Creek from the south run mostly through areas showing soils with weak profile development. Noses separating these south flowing tributaries show soils which are moderately developed. Well developed soils are found on ridgetop positions on south facing and east facing interfluves of the Bond Creek drainage, while the very strongly developed soils are found on a range of slope positions on the north facing interfluve.

In evaluating the genetic implications of map positions of different soil units, it is valuable to call to mind Jenny's (1941) state factor equation for soils, which states that a given profile is a product of the interacting influences of climate, organisms, topography, parent material and time. In the Bond Creek drainage, all factors except topography and time can be considered constant in a general way, hence the use of Jenny's equation suggests that the distribution of different degrees of soil profile development in that area can be explained in terms of variations of topography or drainage basin position, and

soil age. Variations in soils on slopes can also be attributed to the impacts of different erosion and deposition processes which may be operating concurrently with pedogenesis.

The generally more strongly weathered nature of soils on north facing as opposed to south facing slopes in the Bond Creek drainage reflects the effects of aspect. North facing slopes receive less direct sunlight, hence are subjected to less evapotranspiration, and have moister soil conditions and consequently higher rates of pedogenesis. Studies by Finney *et al.* (1962) on the Allegheny Plateau, and Lotspeich and Smith (1953) in eastern Washington have also found that soils are more strongly developed on north facing as opposed to south facing slopes underlain by a common type of parent material.

The location of very strongly developed soils downslope of strongly developed soils on north facing slopes in the Bond Creek drainage, and the general tendency for profiles within the strongly and very strongly developed units to become redder and deeper downslope along the gently sloping interfluves north and south of Bond Creek, reflect the effects of slope position. Downslope positions receive more lateral subsurface water flow, and are consequently subject to faster rates of pedogenesis. Similar trends have been observed by Nettleton *et al.* (1968) in the Southern California Penninsular Range, and Al Janabi and Drew (1967) in southeastern Nebraska.

Increasing degrees of profile development in a downslope direction on gently convex slopes in the Bond Creek drainage may also reflect increasing ages of topographically lower soils, which have been transported downslope by creep for longer periods of time. Inclinometer tubes on schist slopes in the Redwood Creek drainage indicate that the top three meters of soil profiles move downslope at an average rate of approximately 1.5 m per 1,000 years (unpublished data provided by Richard J. Janda, U.S.G.S.). In their study of soil development in the Willamette Valley, which is slightly colder and wetter than the Redwood Creek basin, Parsons et al. (1970) found that soils there appear to take between 500 and 5,250 years to develop argillic B horizons. It is reasonable, therefore, to find soils with well developed argillic horizons near ridge tops on schist slopes subjected to soil creep in the Redwood Creek drainage. It is also possible that the increased degrees of profile development of the downslope soils are caused by creep activity, which may increase the mobility of clay particles, as suggested by Beinroth et al. (1974), or may thicken soil profiles by contributing more material from upslope than is removed in a downslope direction.

Downslope decreases in degrees of residual soil profile development in the south-facing half of the Bond Creek drainage can be attributed to downslope increases in the intensities of erosion processes which retard or reverse pedogenesis, or to variations in soil age in different drainage basin positions due to the exposure of fresh parent material at different times by erosion. According to the first interpretation, soils on slopes are in states of dynamic equilibrium and will not change over time unless the erosion processes responsible for the morphology of those soils change. In contrast, the second interpretation implies that the morphology of a soil profile in any hillslope position will evolve through a developmental sequence over time until fresh parent material is once again exposed in that site by erosion.

Dietrich and Dunne (1978) studied steep convex slopes in a small drainage underlain by basalt in western Oregon and found patterns of decreasing soil thickness and increasing gravel content, moving in a downslope direction on to surfaces of increasing gradient. They attributed these trends to increased downslope intensities of soil mixing by shear during creep and tree throw. Similarly, Furley (1968) found good correlations between soil properties and gradient in upper convex hillslope segments near Oxford England, where he felt that soil genesis is controlled by erosion.

A problem with attributing downslope decreases in soil profile development to downslope increases in the intensity of erosion processes in the south-facing half of the Bond Creek drainage is that steeper gradients, which probably cause more intense creep and tree throw, are not always associated with lesser degrees of soil profile development. This lack of correspondence can be seen on the slope segment between sample location 9 and Bond Creek on Plate 2. Even though the gradient of this slope segment is greater than the gradient of many slope surfaces showing weakly developed residual soils, its residual soil shows a moderate as opposed to a weak degree of residual soil profile development.

Another potential problem with attributing downslope decreases in residual profile development to downslope increases in erosional activity concerns the irreversibility of some pedogenetic processes. Mixing soil material with parent material by tree throw, and downslope transport by creep, may increase gravel content or decrease soil thickness, however the degree to which these erosion processes are capable of destroying clay films, and diluting iron oxide and fine fraction clay destroying clay films, and diluting iron oxide and fine fraction clay accumulations is unclear.

The problems with a dynamic equilibrium interpretation of the residual soils in the south-facing half of the Bond Creek drainage lend credence to the idea that these soil patterns reflect different ages of slope surfaces in different drainage basin positions. A similar interpretation in a different location was made by Adams et al. (1975), who attributed increasing degrees of soil profile development in an upslope direction to greater ages of slope surfaces toward hillslope summits in New Zealand. It may be that while such processes as tree throw and creep continually transport weathering profiles downslope, the effects of these processes on soil morphology are masked in some places by the more marked effects of variations in soil age caused by the stripping of residual weathering profiles from slope surfaces in different drainage basin positions at different times by erosion. Erosion processes responsible for the episodic exposure of fresh parent material are discussed in the final section in this chapter.

C. COLLUVIUM ON SCHIST SLOPES

Evidence of mass wasting activities in roadcut exposures across schist slopes in the Redwood Creek drainage is abundant and varied. Common exposures in which schistosities near the ground surface appear to have been rotated into parallelism with the slope surface probably reflect creep activity. Deep roadcut exposures sometimes show clay fillings of bedrock cracks which parallel slope surfaces. These clay filled cracks may be zones of weakness above which material is being transported downslope by slumping or block sliding. In places, soil profiles are laterally juxtaposed against different soils or bedrock, as can be seen in figure 31. In addition, exposures such as the one in Figure 32, showing large schist clasts embedded in inhomogeneous mixtures of soil and rock materials are common.

The fact that horizontal shear planes are only rarely exposed in roadcuts showing disrupted soil and rock materials, suggests that the mass wasting processes responsible for disruption are characteristically deeply seated, and extend below soil profiles into weathered bedrock. Because material transported by mass wasting on schist slopes is often exposed in roadcuts across those slopes, it appears that in contrast to debris avalanches which transport material immediately to stream channels in areas underlain by coherent graywacke and shale, block slides and slumps on schist slopes continuously or episodically move materials from position to position on slope surfaces before delivering them to stream channels.

The above mentioned signs of landslide activity are most abundant on gentle slopes with highly weathered surficial materials, hummocky

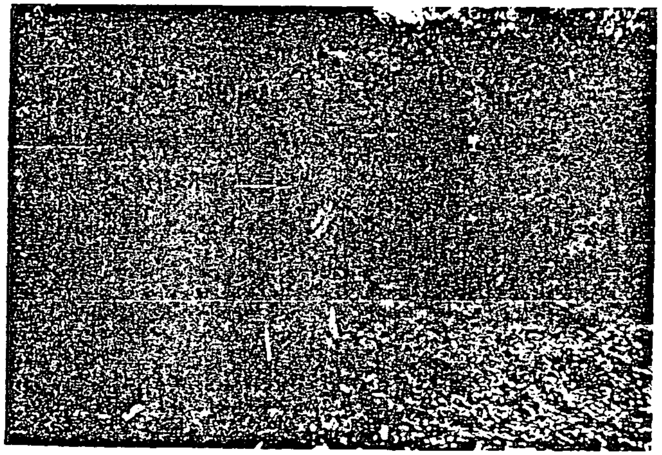


Figure 31 - Brown clay-rich soil in sharp lateral contact with red rocky soil. Photograph was taken in area mapped as having disrupted soils in the Bond Creek drainage (Plate 2).

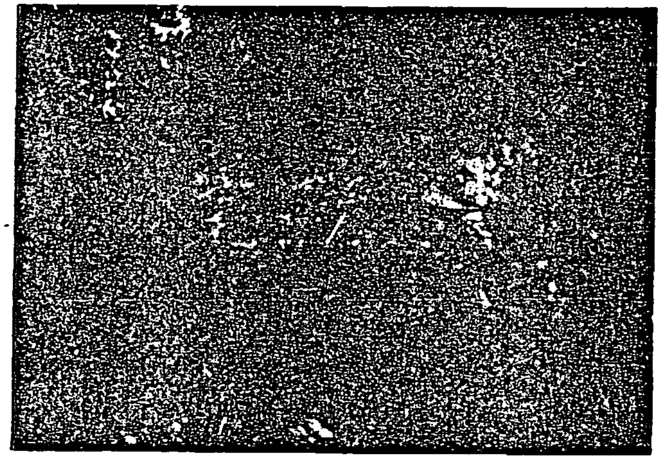


Figure 32 - Large schist clast embedded in soil-rock mixture. Photograph was taken near the intersection of the lower and upper roads in the southwest quadrant of Bond Creek (Plate 2).

pre-logging ground surfaces, and low drainage densities and bifurcation ratios. Examples of these areas include the zone of disrupted soils in the southwest quadrant of the Bond Creek drainage, and parts of the east facing side of the long divide between Bridge Creek and the main channel of Redwood Creek. Areas such as these do not necessarily show head scarps, side scarps, and other morphological indications of current landsliding, and may represent sites of ancient landslides, whose scarps and other morphological features have been subdued over time, but which broke up bedrock at some time in the past, creating colluvium that is currently being slowly translated downslope by creep and block sliding. These areas may also represent modern forested translational and/or rotational slides, which are transporting material that has been rendered particularly susceptible to downslope transport by past or present faulting and/or shearing.

D. HILLSLOPE EVOLUTION ON SCHIST

1. Introduction

Residual soils and colluvium exposed in roadcuts across schist slopes in the Redwood Creek drainage attest to the activity of a number of different erosion processes. Deeply weathered soils and saprolite suggest that rock material is chemically weathered and removed in solution. Roadcut exposures of shear planes, disrupted soils, and disoriented schist clasts embedded in a jumbled matrix attest to the activity of deeply seated block slides and slumps. Exposures in which schistosities near the ground surface appear to have been rotated into parallelism with the slope surface probably reflect creep activity. Pockets of jumbled regolith in shallow bedrock depressions suggest that tree roots break and transport soil and rock when trees fall.

Additional information on erosional processes active on schist slopes is provided by ground surface features in unharvested watersheds, and by flexible poly-vinyl chloride inclinometer tubes installed and monitored by the U.S. Forest Service and the U.S. Geological Survey (unpublished data provided by Richard J. Janda, U.S.G.S.). Landslide scars in inner gorge areas suggest that debris avalanching plays a role in sculpting steep slopes in those areas. Pit and mound topography on forest floors under natural conditions attests to the activity of tree throw. Inclinometer tubes on schist slopes in the Redwood Creek basin confirm the prevalence of continuous and slowly moving block sliding and creep on those slopes.

In the following section, the effects of different erosion processes on slopes forms are discussed. The final section in this chapter presents ideas regarding relationships between slope forms and different landsurface lowering processes active on schist slopes. Variations in slope forms are attributed to spatial and temporal variations in the activity of different processes.

2. Effects of Erosion Processes on Slope Forms

Carson and Kirkby (1972) have suggested that the removal of material in solution plays an important role in the lowering of the landscape in many watersheds in humid temperate climates. Landsurface lowering may be accomplished directly by solution, in which case weathered materials must collapse in response to the removal of some of their constituents in solution. Landsurface lowering by the removal of material in solution may also be accomplished indirectly, by lowering yield strengths of surficial materials, and increasing rates of creep and block sliding. Variations in chemical weathering along slope profiles affect the forms toward which the slopes evolve over time.

Day et al. (1980) buried rock disks in different positions on slopes in Wales, and found that weathering rates were highest on upper slopes, possibly due to the fact that water table levels fluctuate more frequently near ridge crests, subjecting rock particles in these positions to more wetting and drying cycles. Higher rates of removal of material in solution in upslope positions would decrease slope gradients over time. It is also possible that moister conditions in a downslope direction cause greater amounts of material to be removed on downslope as opposed to upslope surfaces. This would not be likely if rain water

becomes quickly saturated upon introduction to regolith materials. Both Day et al. (1980) and Young, A. (1978) found solution rates to be higher close to ground surfaces, possibly due to the fact that water becomes quickly saturated as it infiltrates soil solums. Higher rates of removal in solution in lower slope positions would increase slope gradients over time. More work is required to assess the role of the removal of material in solution in sculpting schist slopes in the Redwood Creek drainage.

In a classic paper, Gilbert (1909) attributed the convexity of hillslopes to the activity of processes which transport material from point to point along slope profiles at rates which are independent of distances to drainage divides or stream channels. Gilbert suggested that the velocities of downslope movement due to the point to point transfer processes which he included as components of creep, are dependent on slope gradients, which necessarily become steeper moving away from drainage divides, in order to move increasing amounts of material contributed from upslope without increasing regolith thickness, which Gilbert felt must remain constant in all places on slopes.

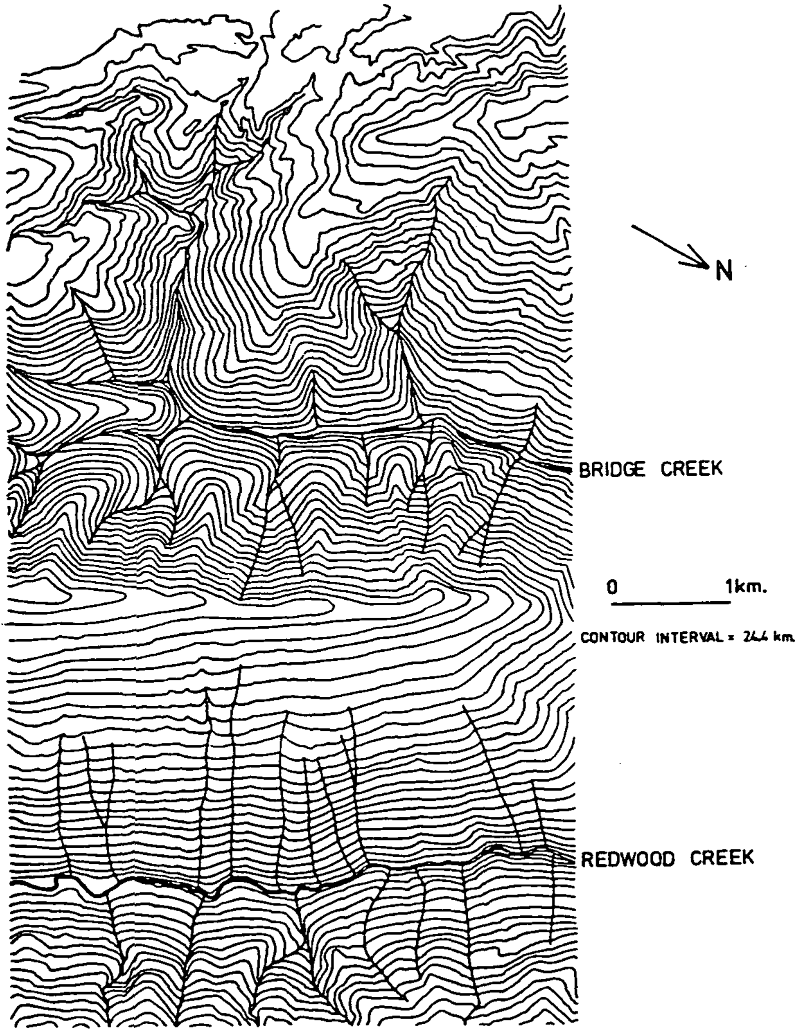
Carson (1976) questioned the validity of the assumption that the velocity of point to point transfer processes such as creep, tree throw, and block sliding are dependent solely on gradient, and not at all on distance to drainage divides or stream channels. Increasing soil moisture contents in downslope directions on schist slopes probably increase creep and block sliding rates in lower slope positions. Orographically controlled storm intensity patterns might also make rates of tree throw, creep and block sliding somewhat dependent on distance to drainage divides or stream channels.

Carson (1976) suggested that on straight slopes, the activity of distant independent processes requires constant combinations of process velocities and regolith thickness in order to satisfy the continuity equation, which insures that the volumes of material transported to a given slope area over a given time interval is equal to the volume of material removed from that area during the same time interval. In other words, Gilbert's (1909) requirement that gradients must increase moving away from drainage divides in order to accommodate greater and greater contributions of transported from upslope, can be satisfied by increasing soil thickness instead.

3. Controls on Slope Forms

The shapes of slopes underlain by schist in Redwood National Park are often related to aspect. Simplistically, two categories of slopes can be recognized. One is relatively undissected, has relatively convex slopes and gentle slope gradients, and shows well developed residual soils which are intensely laterally disrupted in places. Good examples of these slopes and their characteristic soil-colluvium associations are seen on the northeast facing side of the ridge between Bridge Creek and Redwood Creek (Figure 33), and in the north facing half of the Bond Creek drainage (Plate 2). Slopes in the second category are more dissected, slightly steeper, and have less developed residual soils. Examples of this second group of slopes are seen in the south facing halves of the Bond and Forty Four Creek drainages. Inner gorges exist at the bases of a majority of slopes in both categories.

Figure 33 - Topographic map of the drainage divide between Bridge Creek and Redwood Creek.



North facing slopes receive less direct sunlight, particularly during the wet winter months. Consequently decreased evapotranspiration rates on these slopes are responsible for generally moister soil conditions. Moister soil conditions spur chemical weathering and the removal of material in solution. Wetter regolith is also more susceptible to creep and block slide activity. The relatively gentle, convex, and undissected nature of many north facing schist slopes in the Redwood Creek drainage quite possibly reflects accelerated creep and block sliding rates. The general pattern of increasing soil thickness moving from upper slopes to mid-slopes, as is seen in the north facing half of the Bond Creek drainage may in part be caused by the contribution of transported materials from upper slopes. Drier, south facing slopes have less weathered regolith materials, which are less susceptible to creep and block sliding. On these slopes, the development of small order tributaries is not as inhibited, and slope gradients are not as readily decreased by these point to point transfer processes.

Janda et al. (1975) suggested that instability resulting from the loading of lower slopes from above by point to point sediment transport processes may cause debris avalanches to strip surficial materials from slopes in the steep inner gorges which enclose many stream channels in schist tributary drainages in the Redwood Creek watershed. If the volume of material contributed to lower slope positions by creep, tree throw and block sliding equals the volume of material removed from lower slope positions by debris avalanching, the landscape is in a state of dynamic equilibrium, and is being lowered uniformly. An alternate explanation for inner gorges is that they reflect the relatively intense removal of material at slope bases due to stream incision. As was discussed in the preceding chapter, the pattern of decreasing degrees of soil profile development on slopes surrounding streams of increasing order in the south facing half of the Bond Creek drainage is interpreted to reflect varying ages of different slope surfaces on which fresh soil parent material was exposed at different times by erosion. It is possible that slopes with weak degrees of soil profile development adjacent to south-flowing tributaries to Bond Creek were more actively stripped of weathered surficial materials by debris avalanching at some time in the past, but have at present been stable long enough to permit residual soils to have become weakly developed.

A final comment on the controls of forms of slopes underlain by schist pertains to the long asymmetric divide which separates Bridge Creek from the main channel of Redwood Creek. Figure 33 is a topographic map of this divide. Coleman (1973) attributed the asymmetry of the divide between Redwood Creek and Bridge Creek to aspect effects, which have caused creep to dominate on the northeast facing side and other erosion processes to dominate on the southwest facing side. A problem with attributing this example of slope asymmetry solely to aspect effects is that the slope southwest of Bridge Creek is as similar to its counterpart northeast of Bridge Creek, as it is to the slope with the same aspect on the northwest side of the ridge between Bridge Creek and Redwood Creek.

Another explanation for the asymmetry of the divide between Bridge Creek and Redwood Creek was suggested by Harvey M. Kelsey (personal communication, 1979), and involves a subtle landsurface tilting, which has caused a drainage capture near the mouth of Bridge Creek, and has pushed

Bridge Creek against the slope to its northeast. According to this idea, slope undercutting caused by the lateral movement of Bridge Creek has caused the southwest facing side of the divide to be steeper than the northeast facing side. This hypothesis does not provide a satisfactory explanation of the fact that the slope southwest of Bridge Creek, which presumably is not being undercut, is similar in form to the slope northwest of Bridge Creek. Yet another explanation for the asymmetry of the divide between Redwood Creek and Bridge Creek involves a possible northwest striking and northeast dipping orientation of schist foliations between Bridge Creek and Redwood Creek, which would cause the dip slope on the northeast side of the divide to be gentler in gradient than the slope on the southwest side of the divide, which may cut across the upturned edges of foliation layers. Hack and Goodlett (1960) found the orientations of sedimentary beds to exert a similar influence on slope forms in the Central Appalachians.

In summary, erosion processes on slopes underlain by schist in the Redwood Creek drainage are strongly influenced by slope aspect, stream downcutting and possibly bedrock structure. Moister conditions on many north facing slopes promote faster weathering of regolith, and consequently greater rates of point to point transfer processes, which inhibit the development of small order stream systems. Resulting slopes have low bifurcation ratios and drainage densities. Drier conditions on many south facing slopes yield less weathered regolith, on slopes which can sustain steeper gradients, and are hence more susceptible to small order tributary development. Inner gorges are either caused by the loading of lower slopes by creep, block sliding, and tree throw, or by stream incision, and may have extended farther up small order tributaries at some time in the past than they do at the present time.

CHAPTER IV - SUMMARY AND SUGGESTIONS FOR FUTURE WORK

A. COMPARISON OF GRAYWACKE AND SCHIST SLOPES

The study of residual soils and colluvium on distinctive slope forms in Redwood National Park has yielded some insights into similarities and differences between the weathering and erosion processes which have been active on slopes underlain by schist as opposed to relatively coherent graywacke and shale. Major differences include weathering rates of regolith material, and the degree to which the activities of dominant mass wasting processes have removed surficial materials immediately from slopes, as opposed to having transferred them from point to point along slope profiles before delivering them to stream systems. The two terrain types are similar in that residual soil development is more advanced on low gradient ridgetop and upper slope positions than on steeper slopes closer to stream channels.

Slopes underlain by relatively coherent graywacke and shale have straight to gently concave profiles, and side slope gradients which usually range between 30% and 50%, and average at around 35%. Residual soils on these slopes are separated into two degrees of profile development in this study. Moderately developed soils are distinguished from weakly developed soils on the basis of greater thickness, larger clay content, smaller gravel content, and redder color. Soils in both units are rocky, less than 1.25 m thick, and typically 7.5YR or yellower. Most moderately developed soils are found on gently sloping ridgetop and upper slope positions.

Most colluvium on slopes underlain by relatively coherent graywacke and shale is found as fill material in small lenticular bedrock depressions, which are interpreted in this study to be debris avalanche scars. The colluvium pockets are found in a range of topographic positions, and cover an estimated 20% of slope surfaces. The common occurrence of these deposits is interpreted to reflect the importance of debris avalanching in the erosional development of graywacke and shale slopes. Sedimentological features of colluvium pockets suggest that landslide scars are filled episodically, by processes which transport material from varying locations on slope surfaces alongside and upslope of debris avalanche scars. Weathering characteristics of colluvium pockets, in conjunction with radiocarbon dates on charcoal in one deposit, suggest that after a relatively short period of accumulation and instability, colluvium in debris avalanche scars is commonly capable of remaining stable on slopes for periods of time in excess of 7,000 years.

On the basis of residual soil and colluvium information, a model of slope evolution by debris avalanching is proposed for slopes underlain by relatively coherent graywacke and shale. A landsurface lowering cycle, involving the removal of residual soils and bedrock by debris avalanching, filling of the slide scar, weathering and removal of the resulting colluvium pocket, and renewed susceptibility to the removal of residual soils and fresh bedrock by debris avalanching is proposed to affect all slope positions over time spans whose average is between 25,000 to 35,000 years. Because colluvium pockets are relatively more weathered and less abundant on gently sloping ridgetop and upper slope positions, and because there are moderately as opposed to weakly developed residual soils in these areas, it is proposed that gently

sloping ridgetop and upper slope positions have recently been subjected to less intense landsurface lowering by debris avalanching and related raveling and sheetwash, than steeper slopes closer to non-intermittent stream channels.

Slopes underlain by schist have gently convex profiles, and side slope gradients which usually range between 20% and 40% and average at approximately 25%. The high mica content and low quartz content of the schist make it more susceptible to chemical weathering than relatively coherent graywacke and shale. Five degrees of residual soil profile development on schist were defined in this study. The most developed of these soils are thicker than 2.5 m, have colors as red as 2.5YR, and have weight percents of clay in excess of 50% in some horizons. The distribution of degrees of soil profile development on schist slopes is attributed to variations in topographic position and soil age. Observed increases in degree of profile development in a downslope direction on some relatively undissected north facing slopes are interpreted to reflect moister soil conditions in downslope positions. Contrasting patterns of decreasing degree of profile development in a downslope direction observed on some steeper, more dissected south facing slopes are interpreted to reflect younger ages of soils on slope surfaces which have more recently been stripped of weathered regolith by erosion.

The distinction between colluvium and residual soil is less clear on slopes underlain by schist than on slopes underlain by relatively coherent graywacke and shale. Evidence of mass wasting on schist slopes consists mostly of exposures of large schist clasts floating in soil-rock mixtures, and of disrupted residual soil profiles. Deeply seated, slowly moving mass wasting processes such as slumping and block sliding appear to have been responsible for the formation of these colluvial materials.

High clay contents and low yield strengths of surficial materials upslope of inner gorges on schist slopes appear to have made these materials readily susceptible to downslope transport by continuous point to point transfer processes, which decrease slope gradients and inhibit tributary drainage development. Steep slopes adjacent to larger streams in areas underlain by schist are currently being stripped of weathered surficial materials by debris avalanches. These debris avalanches are probably caused by stream undercutting, and by loading by point to point transfer processes from hillslopes above. It is proposed on the basis of residual soil patterns that while lower slope segments adjacent to south-flowing tributaries of Bond Creek were stripped of weathered regolith by debris avalanching at some time in the past, these slope surfaces have recently been stable enough to permit a weak degree of residual soil profile development.

The stripping of weathered regolith appears to increase toward stream channels in both terrain types examined in this study. On graywacke and shale slopes, colluvium pockets are more abundant and residual soils are generally less weathered on steep lower slopes, than in more gently sloping ridgetop and upper slope positions. In drainage basins underlain by schist, weathered materials are stripped by debris avalanches in steep inner gorges adjacent to larger order stream channels. The degree to which more frequent stripping of surficial materials in lower slope positions reflects more active erosion in these

areas in response to stream incision, as opposed to differences in the types of erosional activity on different slope positions in a landscape that is being lowered at a fairly uniform rate, is unclear.

B. SUGGESTIONS FOR FUTURE WORK

Detailed studies of modern debris avalanches could be used to check and improve the proposed model of landscape lowering by debris avalanching on relatively coherent graywacke and shale slopes in the Redwood Creek drainage. Following a landslide inducing storm in areas not impacted by land use, careful mapping of the positions of slides, and observations of whether headscarps expose colluvium or in situ bedrock, will provide information on the degree to which debris avalanches evacuate colluvium transported to swales, or directly remove residual soils and bedrock. The stability of material contributed to debris avalanche scars whose ages can be determined from time sequential air photographs could be related to slope position and scar geometry. The effects of variations in bedrock type and vegetation on debris avalanche frequency, locations, and scar geometry and filling behavior should be noted.

Important questions regarding the interactions of pedogenesis and such slow continuous mass wasting processes as creep and tree throw remain unanswered. The degree to which these mass wasting processes control the composition of soils should be studied on slopes underlain by easily mapped and clearly contrasting rock types. In addition, studies of the genesis of and relationships between different soil characteristics used to define degrees of residual soil profile development, are needed both on large and small scales.

More generally, similar studies which characterize residual soils and colluvium patterns in other terrains in which timber harvest, strip mining, urbanization, and other land use activities have provided adequate exposures will provide interesting contrasts. The primary

objective of such studies should be to gain an understanding of of relationships between erosion processes and slope forms, and of spatial and temporal variations in the intensities of different erosion processes. In addition, detailed studies of rates and mechanics of currently active erosion processes will aid in the interpretation of surficial materials and slope forms which have been created created and/or altered by those processes.

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APPENDIX A - FIELD DESCRIPTIONS OF SOIL PROFILES ON SCHIST

Weak Profile Development:
- Soil Profile 1
- Soil Profile 2
- Soil Profile 3

Moderate Profile Development:
- Soil Profile 4
- Soil Profile 5
- Soil Profile 6

Strong Profile Development:
- Soil Profile 7
- Soil Profile 8
- Soil Profile 9
- Soil Profile 10
- Soil Profile 11
- Soil Profile 12

Very Strong Profile Development:
- Soil Profile 13
- Soil Profile 14
- Soil Profile 15

Disrupted Soils:
- Soil Profile 16
- Soil Profile 17

Locations of Soil Profiles are on Plate 2.

Explanation of structure abbreviations and clay film adjectives in U.S.D.A.-S.C.S. (1974).

Soil Profile 1: Field Description

Depth (meters)	Horizon	Color		Texture	Structure	Clay Films	Boundary (Lower)
		Moist	Dry				
0.00-0.08	A_1	7.5 YR 4/6	10 YR 6/4	gravelly clay loam	SMGR	none	abrupt
0.08-0.32	A_3	7.5 YR 4/6	7.5 YR 5/8	clay loam	WCG grades to WMSBK	none	clear
0.32-0.59	B_{2t}	7.5 YR 5/6	10 YR 6/6	gravelly clay? (some silt)	WMSBK	none	clear
0.59-0.74	B_3	7.5 YR 4/8	7.5 YR 5/8	very gravelly clay	MCSBK	none	abrupt
0.74+	C_R	fresh schist					

Soil Profile 2: Field Description

Depth (meters)	Horizon	Color		Texture	Structure	Clay Films	Boundary (Lower)
		Moist	Dry				
0.00-0.05	0						
0.05-0.11	A_1	10 YR 3/6	10 YR 6/6	gravelly sandy clay loam	SMGR	none	clear
0.11-0.50	B_2	10 YR 3/6	10 YR 4/6	(gravelly) sandy clay loam	MFABK grades to WMABK	none	abrupt
0.50-0.71	B_3	10 YR 4/4	10 YR 4/6	very gravelly sandy clay loam	single grain	none	abrupt
0.71+	C_R	gray weathered schist					

Soil Profile 3: Field Description

Depth (meters)	Horizon	Color		Texture	Structure	Clay Films	Boundary (Lower)
		Moist	Dry				
0.00-0.05	0	10YR 4/3	10YR 6.5				
0.05-0.10	A_1	10YR 4/3	10YR 6/4	gravelly heavy+ loam	SCGR	none	abrupt
0.10-0.20	A_3	7.5YR 4/8	10YR 6.5/4	gravelly clay loam	MMSABK	none	abrupt
0.20-0.50	B_{21}	7.5YR 4/6	7.5YR 5/6	(gravelly) light clay	SCSBK	none	diffuse
0.50-1.10	B_{22}	7.5YR 4/6	7.5YR 5/8	clay	WCSBK	none	clear
1.10+	C	broken weathered schist with seams of red clay					

Soil Profile 4: Field Description

Depth (meters)	Horizon	Color Moist	Color Dry	Texture	Structure	Clay Films	Boundary (Lower)
0.00-0.15	A_1	7.5YR 4/6	7.5YR 6/4	gravelly loam	MMGR	none	gradual
0.15-0.33	A_3	7.5YR 3/6	7.5YR 5/6	gravelly clay loam	MCGR	none	clear
0.33-0.80	B_1	7.5YR 4/8	7.5YR 6/6	gravelly clay+ loam	MCSBK	none	gradual
0.80-0.98	B_{21t}	5YR 4/8	5YR 5/8	clay	MCABK	many moderate on ped faces and in pores	gradual
0.98-1.26	B_{22t}	2.5 - 5YR 4/8	2.5 - 5YR 4/8	gravelly clay	MCABK	continuous moderate	clear
1.26-1.66	B_{3t}	5YR 5/8	5YR 5/8	very gravelly clay	massive	many to common moderate	abrupt
1.66+	C_R	fresh schist					

174

Soil Profile 5: Field Description

Depth (meters)	Horizon	Color Moist	Color Dry	Texture	Structure	Clay Films	Boundary (Lower)
0.00-0.17	A_1	7.5 - 10YR 4/6	7.5YR 5/6	heavy loam; rocks present	MMGR	none	clear
0.17-0.35	B_1	7.5YR 4/8	7.5YR 5/8	clay loam; rocks present	WCSBK	none	gradual
0.35-0.66	B_{2t}	7.5 - 5YR 5/8	7.5YR 5/8	(gravelly) clay	SCSBK	common thin	gradual
0.66-0.84	B_{3t}	5YR 4/8	5YR 5/8	gravelly silty clay	WCABK	few thin	clear
0.84+	C	weathered schist					

Soil Profile 6: Field Description

Depth (meters)	Horizon	Color Moist	Color Dry	Texture	Structure	Clay Films	Boundary (Lower)
0.00-0.22	A_1	7.5YR 3/4	7.5YR 5/6	clay loam	SMGR	none	mostly clear
0.22-0.39	A_3	7.5YR 4/6	7.5YR 5/6	heavier clay loam	MCGR	none	
0.39-0.74	B_{21}	5YR 4/6	7.5YR 5/6	light clay rocks present	WVCABK	none	
0.74-0.95	B_{22t}	7.5YR 4/8	7.5YR 5/8	clay rocks present	WMABK	common thin	
0.95-2.05	B_{23t}	5YR 5/8	5YR 5/6	clay rocks present	MVCABK	continuous weak	
2.05+	C_R	schist with 5YR to 2.5YR clay seams					

Soil Profile 7: Field Description

Depth (meters)	Horizon	Color Moist	Color Dry	Texture	Structure	Clay Films	Boundary (Lower)
0.00-0.22	A_1	7.5YR 3/4	7.5YR 5/6	(heavy) clay loam	SCGR	none	clear
0.22-0.47	A_3	7.5YR 4/8	7.5YR 5/8	gravelly clay loam	WCGR	none	gradual
0.47-0.64	B_1	7.5YR 4/6	7.5YR 5/6	silty clay	WMSBK	none	clear
0.64-0.76	B_{21t}	7.5YR 4/6	7.5YR 5/6	silty clay+	WMSBK	very few thin	abrupt
0.76-1.21	B_{22t}	5YR 5/8	5YR 5/6	clay	MCABK	continuous moderate	gradual
1.21-1.47	B_{3t}	2.5 - 5YR 4/8	5YR 4/8	gravelly clay	MCABK	many moderate	
1.62+	C	weathered schist					

Soil Profile 8: Field Description

Depth (meters)	Horizon	Color Moist	Color Dry	Texture	Structure	Clay Films	Boundary (Lower)
0.00-0.45	A_1	7.5YR 3/4	7.5YR 5/6	loam	SCGR	none	abrupt
0.45-0.78	B_1	7.5YR 4.5/6	7.5YR 6/6	silty clay loam	MCSBK	none	clear
0.78-1.13	B_{21t}	7.5YR 4/8	7.5YR 5/6	silty clay	MVCSBK	few thin	clear
1.13-1.49	B_{22t}	5YR 4/8	5YR 5/8	silty clay+	MCSBK	many moderate	clear
1.49-1.71	B_3	7.5YR 3/4	7.5YR 5/6	very gravelly silty clay	massive to WCSBK	common moderate	gradual
1.71+	C_R	weathered schist					

Soil Profile 9: Field Description

Depth (meters)	Horizon	Color Moist	Color Dry	Texture	Structure	Clay Films	Boundary (Lower)
0.00-0.24	A_1	10YR 3/6	10YR 6/4	gravelly loam	MMGR	none	clear
0.24-0.42	A_3	7.5YR 4/6	7.5YR 6/6	gravelly clay loam	MMGR grades to MCGR	none	clear
0.42-0.70	B_{11}	7.5YR 4.5/6	7.5YR 5/6	clay loam; some rocks	WMSABK	none	abrupt
0.70-1.18	B_{21}	7.5YR 5/8	10YR 6/6	clay loam; some silt some rock	MCABK to WCABK	none	gradual
1.18-2.34+	B_{2t}	5YR 5/8	7.5YR 5/8	gravelly clay	MCABK	common moderate	
	C	not exposed					

Soil Profile 10: Field Description

Depth (meters)	Horizon	Color Moist	Color Dry	Texture	Structure	Clay Films	Boundary (Lower)
0.00-0.23	A_1	7.5YR 3/4	7.5YR 4/4	loam	MMGR	none	clear
0.23-0.63	A_3	7.5YR 3/4	7.5YR 4.5/6	heavy loam	WCG grades to WMSBK	none	gradual
0.63-0.92	B_1	7.5YR 4/6	7.5YR 4.5/6	clay loam	WMSBK	none	gradual
0.92-1.72	B_{21t}	5 - 7.5YR 5/6	5 - 7.5YR 5/6	heavy clay loam	WCABK to massive	common thin	gradual
1.72-2.30+	B_{22t}	5YR 4/8	5YR 5/6	clay	WCABK	many thin to moderate	
	C	not exposed					

Soil Profile 11: Field Description

Depth (meters)	Horizon	Color Moist	Color Dry	Texture	Structure	Clay Films	Boundary (Lower)
0.00-0.18	A_1	7.5YR 3/4	7.5YR 5/4	gravelly loam	SCGR	none	clear
0.18-0.64	B_1	7.5YR 3/4	7.5YR 4/6	heavy loam	WCSBK	none	abrupt
0.64-1.06	B_{21}	2.5 - 5YR 4/8	2.5 - 5YR 4/8	heavy clay loam; rocks present	massive breaks to WCSBK	none	abrupt
1.06-1.43	B_{22t}	7.5YR 4/6	7.5YR 5/6	heavy clay loam; rocks present	massive breaks to WCSBK	few thin	gradual
1.43-2.09+	B_{3t}	2.5YR 4/8	2.5YR 5/8	gravelly clay	MCSBK	many thin	
	C	not exposed					

Soil Profile 12: Field Description

Depth (meters)	Horizon	Color Moist	Color Dry	Texture	Structure	Clay Films	Boundary (Lower)
0.00-0.38	A_1	7.5YR 4/6	7.5YR 5/6	clay loam; rocks present	MMGR	none	gradual
0.38-0.71	B_{21t}	5YR 4/8	5 - 7.5YR 5/6	clay (some silt); rocks present	MCSBK	none	abrupt
0.71-1.79	B_{22t}	2.5YR 4/8	5YR 4/8	gravelly clay; rocks present	SCABK	many moderate	gradual
1.79-2.03	B_{3t}	2.5YR 4/8	2.5 - 5YR 4/8	very gravelly clay; rocks present	massive to W[illegible]BK	many moderate	clear
2.03+	C_R	fresh schist					

Soil Profile 13: Field Description

Depth (meters)	Horizon	Color Moist	Color Dry	Texture	Structure	Clay Films	Boundary (Lower)
0.00-0.16	A_1	7.5YR 3/4	7.5YR 4/4	sandy loam	WMGR to MMGR	none	clear
0.16-0.51	B_1	7.5YR 4/8	7.5YR 4/6	clay loam	WCSBK	none	abrupt
0.51-0.79	B_{21}	5 - 7.5YR 4/6	7.5YR 5/7	silty clay	WCABK	none	clear
0.79-1.11	B_{22t}	5 - 7.5YR 4/8	7.5YR 5/8	clay	WCABK	common thin	gradual
1.11-1.44	B_{23t}	5YR 4/8	5YR 4/7	clay	WCABK	many moderate	gradual
1.44-2.06+	B_{24t}	2.5YR 4/7	5YR 4/8	clay	indeterminate	many moderate	
	C	not exposed					

Soil Profile 14: Field Description

Depth (meters)	Horizon	Color Moist	Color Dry	Texture	Structure	Clay Films	Boundary (Lower)
0.00-0.03	0						clear
0.03-0.14	A_1	7.5YR 4/6	7.5YR 6/4	heavy loam	SMGR	none	abrupt
0.14-0.46	$B_{1(t)?}$	5YR 4/6	7.5YR 5/7	clay loam	SCGR grades to SCSBK	none	clear
0.46-0.83	B_{21t}	5 - 7.5YR 4/6	7.5YR 5/7	silty clay loam	MCSBK	none	abrupt
0.83-1.56	B_{22t}	5YR 4/8	5YR 5/8	clay	MVCSBK	many moderate	gradual
1.56-2.06	B_{23t}	5YR 4/8	5YR 4/8	clay	WCSBK breaks to FABK	common moderate	clear
2.06-2.31	B_{3t}	2.5 - 5YR 5/8	2.5 - 5YR 5/8	gravelly clay	massive to WCSBK	common moderate	clear
2.31+	P.M.	weathered schist					

184

Soil Profile 15: Field Description

Depth (meters)	Horizon	Color Moist	Color Dry	Texture	Structure	Clay Films	Boundary (Lower)
0.00-0.22	A_1	7.5YR 4/6	10YR 6/6	clay loam	SMGR	none	clear
0.22-1.30	B_1	7.5YR 4/6	7.5YR 7/7	heavy clay loam	MCSBK grades to MVCSBK	none	abrupt
1.30-2.14	B_{2t}	2.5YR 4/6	5YR 4/6	heavy clay	WVCSBK breaks to SMABK	weak thin discontinuous on ped faces	abrupt
2.14-2.50+	B_{3t}	2.5YR 4/8	2.5YR 4/8	gravelly clay	massive	moderate films ped and rock faces	
	C	not exposed					

Soil Profile 16: Field Description

Depth (meters)	Horizon	Color Moist	Color Dry	Texture	Structure	Clay Films	Boundary (Lower)
0.00-0.05	O			organic matter			
0.05-0.19	A_1	7.5 - 10YR 4/6	10YR 6/6	clay loam	MCGR	none	clear
0.19-0.39	B_1	5YR 4/8	5YR 5/6	heavy clay loam	MMSBK	none	clear
0.39-0.60	B_2	5YR 4/6	5YR 4/6	clay	MCABK	few thin to moderate	gradual
0.60-0.88	II B_1	7.5YR 4/8	7.5YR 5/6	heavy clay loam	MCABK	few thin	gradual
0.88-1.46	II B_{21}	5YR 4/8	5YR 5/8	clay	massive	many moderate	gradual
1.46-1.76	II B_{22} ($B_{3?}$)	7.5YR 5/6	7.5YR 4/8	clay (less than above)	massive	many thin	abrupt
1.76+	C_R	schist					

Soil Profile 17: Field Description

Depth (meters)	Horizon	Color Moist	Color Dry	Texture	Structure	Clay Films	Boundary (Lower)
0.00-0.23	A_1	5YR 4/6	7.5YR 5/6	clay loam	MCGR grades to SCSBK	none	clear
0.23-0.73	$B_{21(t?)}$	5YR 4/6	5YR 4/6	heavy clay loam	SVCSBK grades to WCSBK	common thin	gradual
0.73-1.10	$B_{22(t?)}$	7.5YR 4/6	7.5YR 5/6	light clay loam	WCSBK	common thin	clear
1.10-2.20+	B_{3t}	7.5YR 4/8	7.5YR 4/8	light clay loam	massive	common thin	
	C	not exposed					