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Complex mass-movement terrains in the western Cascade Range, Oregon

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ABSTRACT

A variety of mass-movement processes interact to form complex mass-movement terrains in the western Cascade Range in Oregon. Slow, deep-seated (>5 m depth) processes of creep, slump, and earthflow operate simultaneously and sequentially, resulting in unstable conditions that may initiate rapid, shallow (<5 m) soil mass movements on hillslopes and debris torrents in stream channels. This combination of mass-movement processes supplies large volumes of sediment to streams and determines the geometry of the channel and valley floor.

Creep movement in western Oregon has been monitored at rates as high as 15 mm/yr. Relative movement between discrete blocks in the Lookout Creek earthflow ranges up to nearly 10 times as fast. Movement rate accelerates during periods of high moisture availability.

Geomorphic observations and tree-ring analysis indicate that mass-movement terrains may have histories spanning centuries and possibly millennia.

INTRODUCTION

Much of the literature on mass movement of soil and rock materials has focused on catastrophic landslide events. In many areas, the subtle, slow mass-movement processes of creep, slump, and earthflow may account for more erosion in the long term.

In the steep forest lands of the western Cascade Range in Oregon, areas of creep and earthflow activity form complex mass-movement terrains that pose important land-management problems. Road construction and timber harvest adversely influence slope stability and increase mass-movement activity, which in turn influence the stability of roads and the quality and quantity of timber produced from unstable lands. Impacts of creep and earthflow activity are most dramatic in the mountain-stream environment where earth movement shapes or displaces the stream channel and delivers large quantities of sediment and large organic debris.

These considerations have led to the examination of the processes, histories, movement patterns, and stream impacts of several complex mass-movement terrains in the Pacific Northwest.

Mass-movement terrains involve a great variety of processes that transport earth materials downslope by gravity. In the western Cascade Range, mass-movement phenomena need to be considered as an entire geomorphic continuum, as they act together in parallel and serial fashion. The mass-movement processes include a number of types of landslides, as well as related creep and certain stream-channel processes.

DEFINITION OF PROCESSES

Creep

Creep is the process of slow, downslope movement of mantle materials in response to gravitational stress. The mechanics of creep have been investigated experimentally and theoretically by a number of workers (Terzaghi, 1953; Goldstein and Ter-Stephanian, 1957; Saito and Uezawa, 1961; Culling, 1963; Haefeli, 1965, Bjerrum, 1967; Kojan, 1968; Carson and Kirby, 1972; and others). In a purely rheological sense, creep movement occurs as quasi-viscous flow under shear stresses sufficient to produce permanent deformation but too small to result in discrete failure. Mobilization of the soil mass is primarily by deformation at grain boundaries and within clay minerals. Both interstitial and absorbed water appear to contribute to creep movement by opening the structure within and between mineral grains, reducing friction within the soil mass. This permits a remolding of the clay fraction, transforming it into a slurry that lubricates the remaining soil mass.

Under field conditions, local variations in soil properties, degree of weathering, and clay and water content lead to variations in creep movement. Rapid creep may result in discrete failures and development of tension cracks, pressure ridges, radial crack patterns, and lobate features that grade into slumps, earthflows, and debris avalanches. Together, these processes and landforms produce the complex mass-movement terrain that characterizes much of the western Cascade Range.

Movement Rate and Occurrence. Movement rates monitored with borehole inclinometers at sites in complex mass-movement terrain in the western Cascades and Coast Ranges of Oregon and northern California range from 7.9 to 15.2 mm/yr at the base of the active creep zone (Swanston and Swanson, 1976). Movement is quite variable within this range, regardless of parent material or geographic setting.

The depth over which movement is active is also variable, depending largely on degree and depth of weathering, subsurface structure, and soil-water content. The depth of significant movement for all monitered sites ranges from 1 to 15 m and, on the basis of well-log data (D. N. Swanston, unpub. data), appears to be associated primarily with an abrupt increase in hardness and decrease in water content of the mantle materials. This well-defined, creep-zone boundary may correspond either to the lower limit of the saprolite zone or of the creep-prone bed-rock units.

Creep is generally the most widespread of all mass-erosion processes. It operates at varying rates in clayey soils at slope angles as low as two or three degrees. In small watersheds, developed in cohesive soils, creep may operate over more than 90% of the landscape. As a result of this activity, a continuing supply of soil material is dumped into the stream from encroaching banks and small-scale bank failures.

The quantity of soil delivered to a stream by creep-related processes may be quite large. For example, assuming that creep of soil material with a dry unit weight of 1,600 kg/m^3 advances a 2-m-high streambank at 10 mm/yr (conservative estimates for watersheds in volcaniclastic materials within the western Cascade Range in Oregon), approximately 64 t/km will be supplied to the channel annually. During high streamflow, this material is carried into the stream by direct water erosion of streambanks and local bank slumping. In areas characterized by low stream flow with only occasional storm flows, creep may fill the channel with soil and organic debris, and the stream water may move by subsurface flow and piping within the channel filling. Only during storm periods is flow great enough to open the channel and remove the stored debris, resulting in the periodic discharge of very high sediment loads and occasional debris torrents when debris dams fail. Such a mechanism is a dominant mode of sediment transfer into intermittent and first-order streams in the creep-dominated areas of the Pacific Northwest.

Earthflow

In local areas where creep-induced shear stress exceeds the strength of soil and rock material, failure occurs and slumps and earthflow landforms are developed (Varnes, 1958). Simple slumping takes place as rotational movement of a block of earth over a broadly concave slip surface, involving very little breakup of the moving material. Slow earthflow occurs where the moving material slips downslope and is broken up and transported either by a flowage mechanism or by a complex mixture of translational and rotational displacement of a series of blocks (Varnes, 1958).

Earthflows have been described by Varnes (1958), Schlicker and others (1961), Wilson (1970), Colman (1973), Swanson and James (1975), and others. In the western Cascades, these features may range in area from less than one hectare to more than several square kilometres. The zones of failure occurs at depths from a few metres to several tens of metres below the surface. Commonly, there is a slump basin with a headwall scarp at the top of the failure area. Lower ends of earthflows are typically incised by streams draining the movement terrain, and in some cases earthflows move directly into large streams. Transfer of earthflow debris to stream channels may take place by small-scale slumping, debris avalanching, gullying, and surface erosion. Therefore, the general instability set up by an active earthflow initiates erosion activity by a variety of other processes.

Movement Rate and Occurrence. Movement rates of earthflows vary from below detectable levels to metres per day. In parts of the Pacific Northwest, many earthflow areas appear to be presently inactive (Colman, 1973; Swanson and James, 1975). Areas of active movement may be recognized by fresh ground breaks at shear and tension cracks and by tipped, split, and bowed trees.

Movement rates may be highly variable both in time and space, even within a single earthflow (Colman, 1973; Swanson and James, 1975). Presence and absence of open tension cracks and degree of disturbance of vegetation on earthflows indicate that some parts may move rather rapidly, whereas other areas appear to be temporarily stabilized. The history of individual earthflow landforms can span thousands of years. This is indicated by age estimates based on radiometric dating of included wood, comparison of modern mass-movement erosion rate with the total volume of material removed from an earthflow terrain, presence of 7,000-yr-old Mazama ash on pre-existing earthflow landforms and characteristics of drainage development over earthflow surfaces (Swanson and James, 1975; Swanson, unpub. data). Variations in earthflow activity may occur in response to changes in moisture availability on the scale of major climate change as well as shorter term seasonal and storm events. Progressive erosion by fluvial and mass-movement processes alter the configuration of landforms and the distribution of mass above the failure plan. These changes may effect the locations and rates of activity in a mass-movement terrain.

FACTORS INFLUENCING MASS-MOVEMENT PROCESSES AND LANDFORMS IN THE WESTERN CASCADES

Geologic, hydrologic, and vegetative factors control the spatial distribution and movement rates or frequency of occurrence of natural mass-erosion processes on forest lands in the western Cascade Range in Oregon.

Geology and Soils

The western Cascades are generally composed of Tertiary lava flows and volcaniclastic and intrusive rocks, which in many areas have undergone extensive alteration and weathering to form clay-rich soil and saprolite (Peck and others, 1964). Peck and others (1964) have mapped several major stratigraphic units including the Oligocene and lower Miocene Little Butte Volcanic Series and the upper Miocene Sardine Formation (Fig. 1). Little Butte volcanic rocks dominate the Western Cascades and consist of lava flows, variably altered ash flows, and laharic and epiclastic materials. In general, the overlying lava and ash flows of the Sardine formation are less altered. Pliocene to Holocene volcanic materials along the eastern margin of the range are composed predominantly of unaltered lava flows.

Bedrock materials, and the weathering products derived from them, influence both the distribution and morphology of terrains shaped by slow, deep-seated mass-movement processes. The most unstable landscapes in the western Cascades tend to be loacted in areas of altered volcaniclastic materials in the Little Butte Series and Sardine formation (Swanson and James, 1975). For example, in the H. J. Andrews Experimental Forest in the central western Cascades, more than 25% of the area underlain by volcaniclastic rock is mantled with recognized active or presently inactive earthflow landforms (Swanson and James, 1975). Less than 1% of the area of younger basalt and andesite flow rock exhibit earthflow landforms.

The soils developed on volcaniclastic materials tend to be deep, fine textured, and poorly drained on the gentler slopes. These conditions are particularly conducive to creep and earthflow activity. Where the volcaniclastic rocks have been extensively altered, Peath and others (1971) and Youngberg and others (1975) have identified highly unstable soils containing high concentrations of expandable clays. Soils derived from lava flows are generally stonier, coarser textured, better drained, and much more stable than soils derived from volcaniclastic bedrock.

Contrasting physical characteristics of bedrock units commonly play an important role in shaping complex mass-movement terrains. For example, in the Andrews Forest, Swanson and James (1975) noted that steep headwall scarps of slumps and earthflows occur at contacts where resistant flow rocks cap incompetent volcaniclastic rocks. In areas of earthflow activity where there is no capping resistant rock, headwall scarps are absent and earthflows form broad depressions of low relief (Colman, 1973). Creep and earthflow movement over irregular bedrock surfaces, commonly resulting from a mix of rock types of differing resistance, will result in an irregular landscape that is a subdued expression of the subsurface topography.

Climate

The western Cascades are characterized by a maritime climate consisting of wet, mild winters, and dry summers. Mean temperatures range from 6° to 10°C, and precipitation ranges from 100 to 200 cm/yr with 75% to 80% falling between October 1 and March 31 (Franklin and Dyrness, 1973). Precipitation and snowfall increase and mean temperature decreases with elevation. Middle elevation sites, which include large areas of potentially unstable terrain, are subjected to periods of high intensity precipitation and snowmelt during major storm events.

Rates and quantities of precipitation and snowmelt control the presence or absence of active piezometric levels in the subsurface. Moisture content and piezometric level affect the weight of the soil mass and control the development of positive pore pressures. Moisture content acts to reduce the resistance of the soil mass to sliding by mobilization of clay structures primarily through adsorption of water onto clay minerals. A rising piezometric level increases pore pressure, thereby reducing the frictional resistance of the soil mass along the failure surface. Such conditions are commonly believed to accelerate creep and earthflow movement (Swanston, 1969; Swanston and Swanson, 1976).

Vegetation

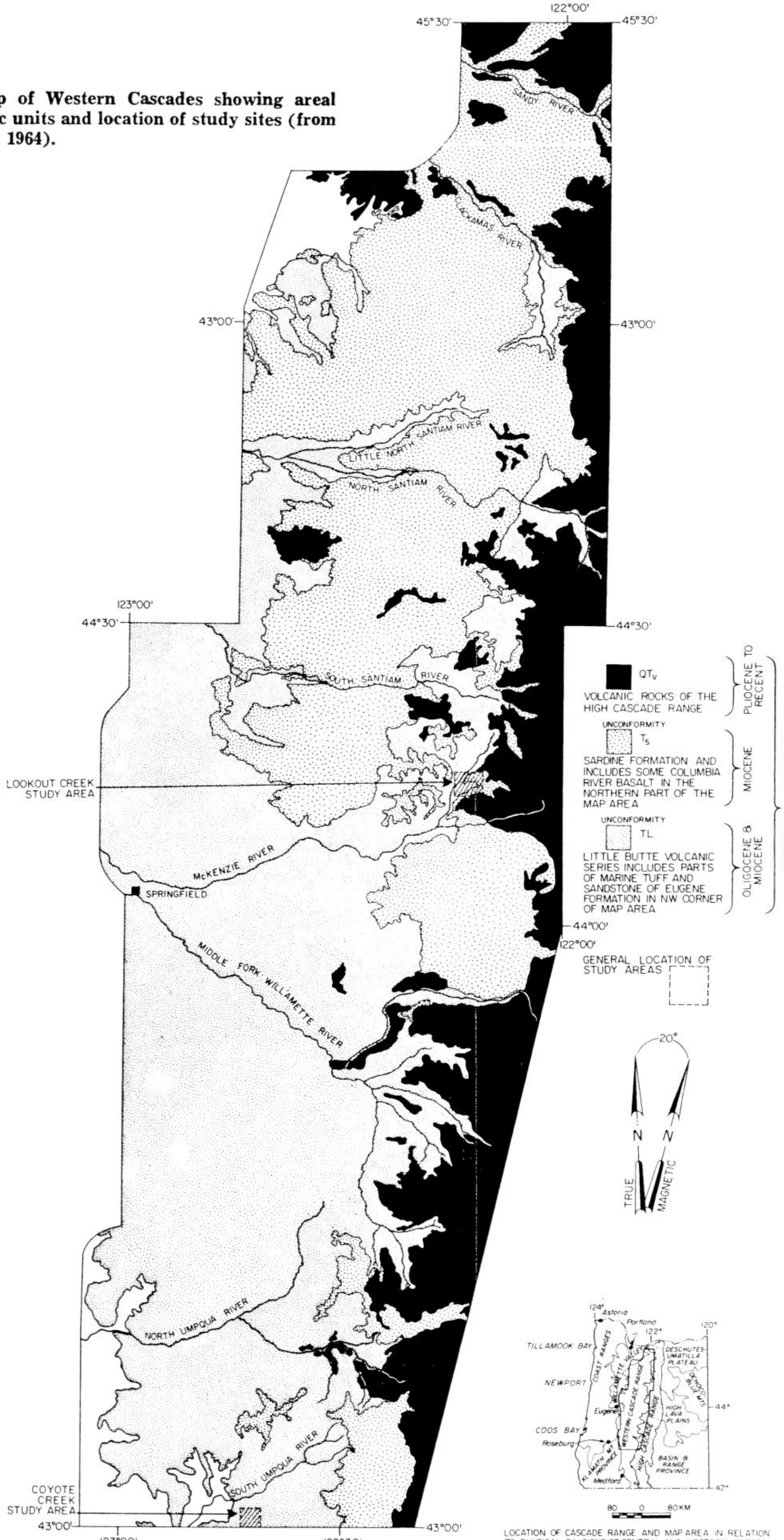
Slope stability in the western Cascades is controlled in part by the extensive cover of forests of Douglas fir, western hemlock, and other species. Forest vegetation exercises some control over the amount and timing of water reaching the soil and the amount held in storage as soil water and snow. Forests regulate hydrology through a combination of interception, evapotranspiration, and influence on snowmelt rate (Rothacher, 1963, 1971, 1973; Anderson, 1969; Harr, 1976, and others). In general these hydrologic influences of vegetation are thought to enhance slope stability (Gray, 1970; Swanston and Swanson, 1976).

Plant roots play a crucial role in the stability of slopes by contributing to the shear strength of soil. Roots add strength to the soil by vertical anchoring through the soil mass into fractures in the bedrock and by laterally binding the soil across potential zones of failure. In shallow soils both effects may be important. In deep soils the vertical rooting factor is negligible, but lateral anchoring and reinforcing may remain important.

Modification of Forest Cover

Removal of forest cover by fire or the activities of man will lead to decreased rooting strength and an altered hydro-

Figure 1. Map of Western Cascades showing areal extent of geologic units and location of study sites (from Peck and others, 1964).



logic regime at the site. Research in Japan (Kitamura and Namba, 1966, 1968), Alaska,[1] and British Columbia (O'Loughlin, 1974) has described a period of greatly reduced soil strength attributable to loss of rooting strength following timber cutting when there has been significant decay of root systems. Reduction in rooting strength may lead to increased creep and earthflow activity.

The hydrologic impacts of the loss of forest cover include modification of annual soil-water budget and changes in peaks of soil moisture and piezometric levels during periods of storm runoff. These modifications in the soil-water regime may result in prolonged periods of active creep and earthflow movement during a single season or reactivation of dormant terrain. Water-yield studies in experimental watersheds in Oregon (Rothacher, 1971; Harr, 1976) suggest that the hydrologic effects of deforestation may continue for more than a decade after cutting.

RELATIONSHIP AMONG PROCESSES: TWO CASE STUDIES

Creep and earthflow processes function as primary mechanisms of soil transport into streams in the western Cascades. The ultimate delivery of soil from slow, mass-movement forms of transport to the fluvial system commonly occurs as rapid, shallow-soil mass movements at stream banks. All of these mass-erosion processes interact with one another. Creep may be a precursor of earthflow activity, and the two processes may operate simultaneously on a column of soil. Both of these forms of deep-seated failure develop instabilities in the soil mantle that directly contribute to the initiation of rapid, shallow-soil failures by debris avalanches, slides, flows, and torrents (Varnes, 1958; Swanston and Swanson, 1976). Consequently, areas of active, deep-seated mass failure form complex mass-movement terrains, where a variety of erosion processes are interactive.

These relationships among processes, rates of movement, and histories of processes in complex mass-movement terrains are illustrated by analysis of two areas of ongoing research in the central and southern parts of the western Cascade Range.

Coyote Creek Mass-Movement Site

The Coyote Creek mass-movement site lies in the South Umpqua Experimental Forest, which is located in the South Umpqua Falls region, as defined by Kays (1970), about 64 km southeast of Roseburg, Oregon (Fig. 1). About a fourth of the region is underlain by deeply weathered, clay-rich rhyodacitic volcaniclastic rocks and subordinate lava flows of the Little Butte Volcanic Series (Kays, 1970). Relatively small parts of the region on the eastern and western edges are capped by andesitic flows of the overlying Sardine formation.

Creep and active and dormant earthflows are common throughout the region and constitute dominant erosion processes under natural conditions. Where present, the contact zone between Sardine flows and the underlying volcaniclastic rocks of the Little Butte Volcanic Series serves as a point of origin of extensive creep terrain and slump-earthflow features. Locally, however, creep and earthflow activity are controlled by interbedded rhyodacite flows and beds of massive welded tuff within the Little Butte Volcanic Series. Such is the case at the South Umpqua Experimental Forest.

The mass-movement study site is located on a 50-ha watershed (watershed 3) on the Coyote Creek drainage within the experimental forest. Active creep and minor earthflow activity are occurring throughout the watershed except for a prominent bluff of massive, welded-tuff breccia that bisects the drainage, separating the basin into two parts (Fig. 2). Above the bluff a history of slump-earthflow activity is indicated by sharply defined headwall scarps and associated earthflow landforms developed below a capping welded-tuff layer. These features encompass most of the upper part of the watershed. The earthflow areas are characterized by hummocky relief that terminates abruptly at the upper edge of the bluff. The earthflow zone on the west side of the upper watershed exhibits no observable evidence of active movement. The eastern earthflow zone exhibits numerous signs of active movement, including undrained sag ponds, tension cracks, and surface-water flow into pipes and underground channels resulting from inward-creeping channel banks. Soil and debris are spilling over the bluff into a perennial channel draining the eastern side of the lower basin. There are no perennial streams above the bluff. The bluff clearly serves as a lower boundary to creep and slump-earthflow activity in the upper part of the watershed and has a major impact on movement and distribution of ground water in the watershed. On the eastern side at least part of the ground-water flow into the watershed is trapped above this welded-tuff layer in the zone of active earthflow above the bluff. Above the bluff on the west, water is apparently able to pass through the tuff layer, and numerous springs at the base of the bluff feed water into deeply weathered clay-rich volcaniclastic bedrock into the lower basin.

Active creep and slumping in the lower part of the watershed is indicated by hummocky ground, tension cracks, and active slumping and debris avalanching along both sides of the stream channels. Locally, backward-tilted benches having long, linear depressions or trenches below headscarps mark the intersection of shear zones with the slope surface (Fig. 2). The area between the east and west perennial-stream branches exhibit some excellent examples of these backward-tilted benches. This area is composed of at least three massive slump blocks, beginning just below the central bluff and extending to the apex of the stream branching. These large-scale blocks are part of the complex mass-movement terrain moving downslope in a northerly direction above a welded-tuff layer that floors the watershed. Bank slumping as the result of mass-movement activity is pervasive along the channel from a point 20 m below the bluff to the confluence with the eastern branch. Throughout this section of stream, bank slumping supplies large volumes of sediment and organic debris to the

[1] D. N. Swanston and W. J. Walkotten, "Tree rooting and soil stability in coastal forests of southeastern Alaska" (Study No. FS-NOR-1604:26 on file at PNW Forestry Sciences Laboratory, Juneau, Alaska).

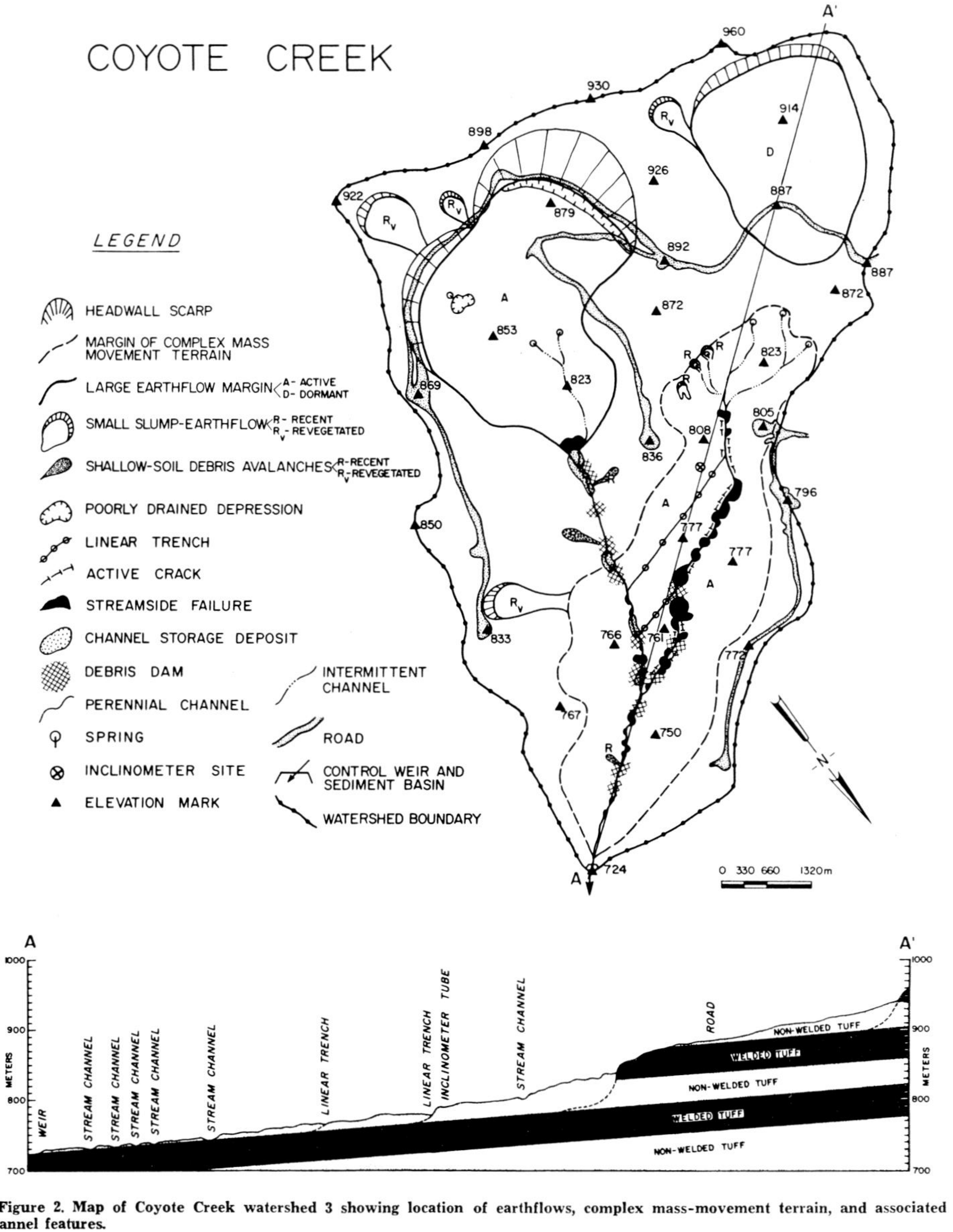


Figure 2. Map of Coyote Creek watershed 3 showing location of earthflows, complex mass-movement terrain, and associated channel features.

channel for later removal by streamflow.

Since 1966, both streamflow and sediment discharge have been monitored in the mass-movement study basin and three adjacent watersheds. The principal purpose is to determine water yield and nutrient outflow under forested conditions and following several types of management activities.[2] Two roads were constructed in watershed 3 in 1971, and the watershed was logged by clearcutting in 1972.

The annual bedload per metre of perennial stream channel was estimated from the volume of sediment removed from a weir at the mouth of the watershed. From 1966 to 1970 this was less than 0.01 $m^3/m{\cdot}yr$ (Table 1; R. L. Fredricksen, 1976, personal commun.). In 1971, sediment yield dramatically increased to approximately 0.05 $m^3/m{\cdot}yr$ as the result of unusually heavy winter precipitation and possibly increased runoff following construction of logging access roads. The bedload materials were derived primarily from debris avalanching and slumping along the banks of the stream draining the watershed. In 1972, the first year after the entire watershed was clearcut and also a year of exceptionally heavy rainfall, bedload movement tripled over prelogging and road-building levels to an estimated volume of 0.16 $m^3/m{\cdot}yr$. During this period, two new debris avalanches reached the channel from midslope, possibly resulting from reduction of rooting strength of vegetation following logging. Part of this overall bedload increase is due to surface erosion of severely scarified soil resulting from piling of slash after logging. However, the greater part can be directly linked to mass movements along the channel.

Reconnaissance of the area and dissection of the weir deposits immediately after a major storm during the winter of 1972 exposed layering of poorly sorted sedimentary materials separated by zones of organic matter defining short periods or pulses of heavy sediment deposition and channel flushing. Such pulses probably result from repeated episodes of slumping and debris avalanching into the channel above the weir. A survey of the channel above the weir showed that nine new bank slumps and debris avalanches had occurred as a result of the storm. Two of the slumps were each large enough to provide the volumes of material necessary to fill the weir basin (approximately 5.4 m^3). Since 1972, bedload yields have been much lower but still substantially greater than prelogging levels. This reflects accelerated bank erosion and removal of sediment stored in the channel owing to increased peak flows. A detailed survey of the watershed in 1974 revealed over 50 sites of active bank slumping and debris avalanching along the active stream channel with slump volumes ranging from 5.6 to 350 m^3. Much of this material moved into the channel, diverting it or causing water to flow beneath the surface. At least 12 debris dams have blocked the channel, leading to temporary storage of from 45 to 1,340 m^3 of alluvium, soil, and organic debris behind each dam. In 1974 the total volume of material available for stream transport was estimated to be 3,100 m^3. Of this, 1,090 m^3 was stored as slump blocks and 2,010 m^3 was stored behind debris dams.

[2]Study 1602-10, "A study of the effects of timber harvesting on small watersheds in the Sugar pine, Douglas fir area of southeastern Oregon" (USDA Forest Service, Forestry Sciences Laboratory, Corvallis, Oregon).

TABLE 1. ESTIMATED ANNUAL BEDLOAD EXPORT FROM COYOTE CREEK WATERSHED 3

Year	Precipitation (cm)	Total bedload volume (m^3)	Volume/unit stream length (m^3/m)	Basin condition
1966	120.5	3.9	0.0091	Forested
1967	118.5	0.5	0.0012	Do.
1968	87.6	0.6	0.0014	Do.
1969	110.9	0.2	0.0005	Do.
1970	116.3	1.3	0.0030	Do.
1971	155.7	21.9	0.051	Roads
1972	153.3	69.9*	0.163	Clearcut
1973	89.5	3.2	0.0074	Do.
1974	156.5	46.4	0.108	Do.
1975	122.6	7.7	0.018	Do.

*Minimum estimate: basin overflowed.

Inclinometer tube measurements in the soil and deeply weathered volcaniclastic rocks in the lower half of the watershed (Fig. 2) indicate movement along the plane of maximum deformation in a N50°E direction toward the mouth of the valley. Surface movement is approximately 10.5 mm/yr and movement at the base of the active movement zone at a depth of approximately 6.0 m is 9.1 mm/yr. This movement exhibits strong seasonal variation with most movement taking place during the fall and winter rainy period when maximum soil-water levels occur (Fig. 3). The similarity of the movement rates at the surface and the base of the movement zone suggests a fairly uniform rate of deformation of approximately 10 mm/yr above a lower boundary layer corresponding to the saprolite contact or the top of an intervening layer of relatively resistant welded tuff or flow rock.

The stream banks in the watershed average at least 1 m in height and show about the same magnitude of active creep and slumping into the stream on both sides of the channels. Thus, assuming an average mass-movement rate of 10 mm/yr, soil material is supplied to the stream channel in the lower part of the watershed at an annual rate of 0.02 m^3/m of channel. There are approximately 430 m of active perennial-stream channel in watershed 3. Therefore, approximately 8.6 m^3 of soil are made available annually for stream transport by creep-related processes. The average annual yield since 1972 has been 31.8 m^3/yr. This suggests that about 27% of the annual yield is being supplied by creep-related processes. The remainder is supplied from earthflow movement, surface erosion, debris avalanching, or reworking of channel deposits.

Lookout Creek Earthflow

The Lookout Creek earthflow site (sec. 30, T. 15 S., R. 6 E.) is a complex mass-movement terrain in the H. J. Andrews Experimental Forest approximately 90 km east of Eugene, Oregon (Fig. 1). Much of the earthflow has developed in a

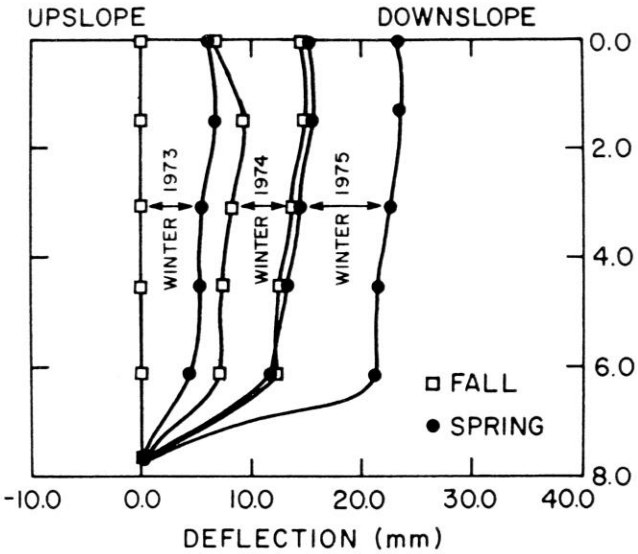


Figure 3. Apparent seasonal deformation along N70°E direction recorded in inclinometer tube installed in complex mass-movement terrain at Coyote Creek. Movement is directly plotted from field data and has not been projected into the plane of maximum deformation (N50°E). Note minor upslope movement of tube during summer of 1974 owing to settlement in hole.

variety of volcaniclastic rocks, but the headwall occurs in an area of capping basalt flows.

The area experiences average annual precipitation of more than 240 cm, falling mainly between October and May. A wet snowpack persists from December through April.

Most of the earthflow terrain is covered with a mixture of old-growth Douglas fir and western red cedar, 300 to 500 yr old, and a stand of the same species that developed following wildfire in the mid-1800s. About 1.5 ha of the forest at the earthflow was clearcut logged in 1968, and an equal area along the lower east side was clearcut in 1961.

The earthflow covers an area of approximately 20 ha on a south-facing valley wall. The flow extends from a rocky headwall at an elevation of 1,010 m downslope 900 m into Lookout Creek at a 790-m elevation (Fig. 4).

Topography on the earthflow surface is very irregular because of earthflow movement and stream erosion processes. Open cracks as much as 1.5 m wide have developed in areas of active tensional or shear deformation. Active crack systems bound major blocks or subunits of the earthflow that are presently undergoing differential movement (Fig. 4). There are also numerous inactive cracks defined by scarps or linear depressions. It appears that differential shear or tensional movement of less than about 1 cm/yr does not produce open, conspicuously active cracks, because litterfall, surface erosion, and growth of vegetation are effective in obscuring fine-scale features of ground breaks.

Drainage patterns on the earthflow are very irregular owing to frequent disruption by earth movement (Fig. 4). In several instances, streams have been channeled along tensional and shear cracks. Discontinued gullies, unusual features in the western Cascades, have developed along restricted stream reaches. Surface-water movement has been altered by the formation of poorly drained depressions on the uphill side of rotational slump blocks and where drainage has been obscured by fallen trees.

Movement History and Rates

A part of the history of earthflow movement may be learned from geomorphic and dendrochronologic observations, as well as by direct measurement. Various observation methods yield information on the age of the earthflow movement, rate of relative motion between discrete blocks within the earthflow, absolute movement of portions of the earthflow relative to stable reference points, and creep deformation within individual earthflow blocks.

Arrays of 4 to 9 stakes were established on several areas of the earthflow where shear and tensional movement appear to be very active (locations shown in Fig. 4). The stake arrays

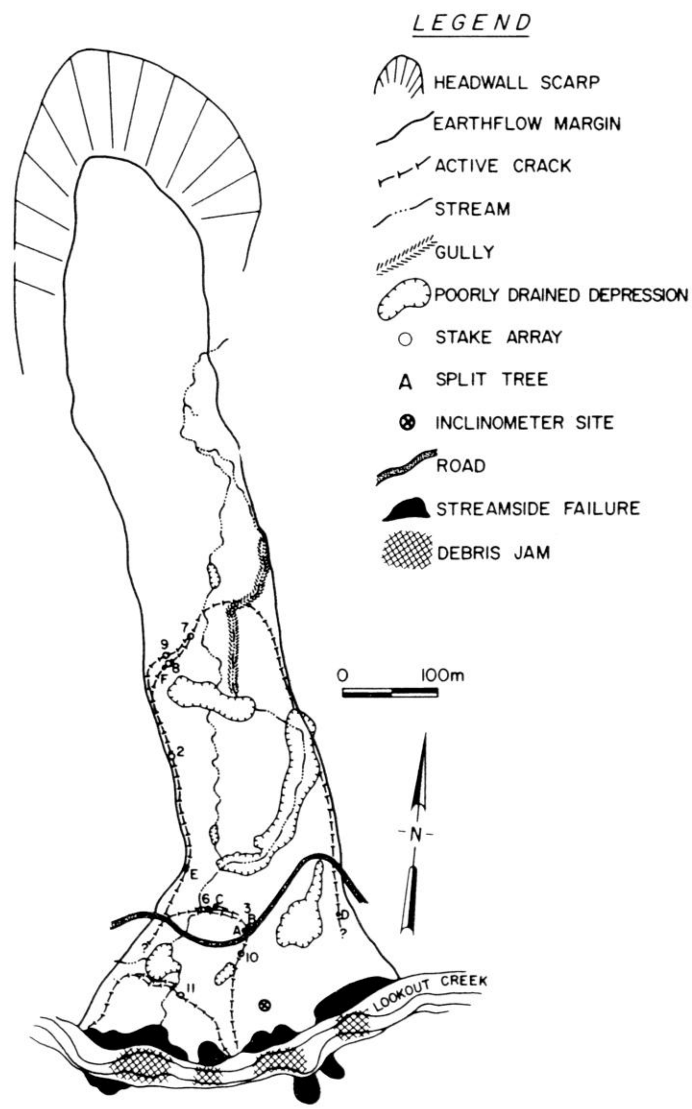


Figure 4. Map of Lookout Creek earthflow. Mapped by G. Lienkaemper using compass and range-finder. See also Tables 2 and 3.

recorded the relative motion between separate blocks within the earthflow and, in the case of set 2, between a block of earthflow and adjacent, relatively stable terrain.

Movement data for several stake arrays are shown in Table 2. Limited observations suggest that differential movement rates vary from 1.8 to 9.8 cm/yr. At arrays, which have been in for two years, movement for the 1974–1975 wet season (October through March) was only 50% to 70% of the 1975–1976 wet-season movement. Some of this difference may reflect the 8% lower precipitation of the 1974–1975 wet season and heavy precipitation early in the 1975–1976 wet season. (Cited precipitation data were collected at a meteorology station 8.5 km west of the earthflow.)

The influence of moisture on earthflow movement is seen more clearly in readings taken every 1 to 4 mo between August 1975 and June 1976. A plot of movement rate (centimetres per month) versus precipitation rate (centimetres per month) for the periods of observation clearly shows accelerated mass movement during periods of high-moisture availability (Fig. 5). Maximum rates of differential earthflow movement were recorded during the December 7, 1975, to February 9, 1976, period of highest precipitation. Early in the wet season, movement rates were low even for precipitation of 27 cm/mo because of very low antecedent moisture conditions. During spring snowmelt, late in the wet season, movement rate was high relative to precipitation because of the presence of residual water from earlier in the wet season, plus incoming water from snowmelt. In the month following May 18, differential movement at the three stake arrays was negligible.

An inclinometer tube installed near the toe of the earthflow has been used to record deformation within an individual block of the earthflow adjacent to Lookout Creek (Fig. 6). The tube (located in Fig. 4) reveals downslope movement of 8.25 mm/yr at the surface along a plane of maximum deformation oriented approximately S82°E. Near the base of the movement zone at a depth of 4.3 m, deformation is occurring at an average rate of 2.3 mm/yr to approximately S60°E. Creep deformation is occurring throughout the profile with

TABLE 2. MOVEMENT DATA FROM STAKE ARRAYS ON LOOKOUT CREEK EARTHFLOW

Stake array	Wet seasons 1974–1975 10/11/74–8/25/75	12/12/74–8/25/75	1975–1976 8/25/75–5/18/76	9/5/75–5/18/76
2	..	7.4	12.4	..
3	5.0	..	7.6	..
6	..	..	..	5.8
7	..	..	..	3.0
8	..	..	..	4.8
9	..	..	..	5.5
10	..	..	..	7.6
11	..	..	..	1.8

Note: Differential movement in centimetres. Precision of measurement is approximately ±2 mm. Locations of stake arrays shown in Figure 4.

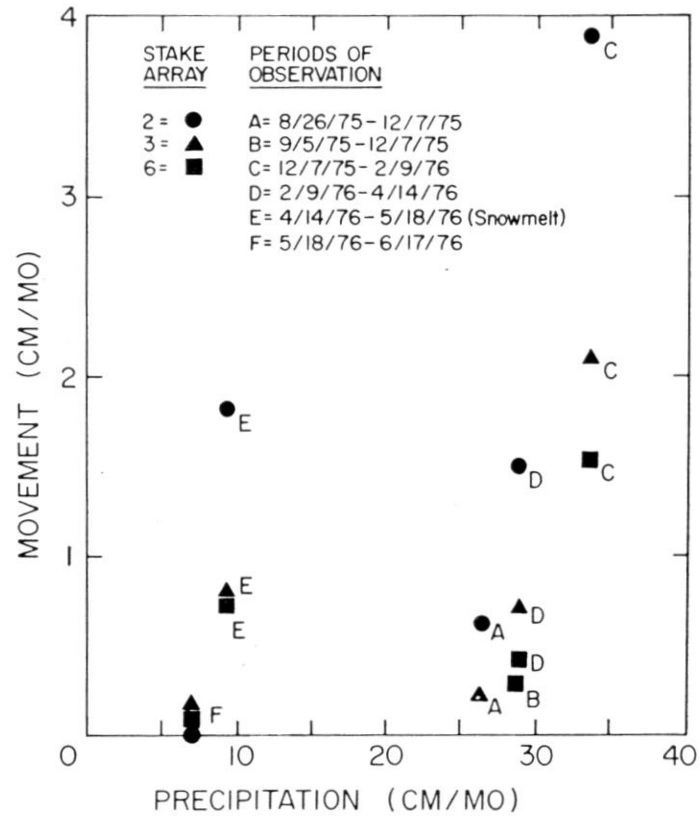


Figure 5. Rate of precipitation versus relative earthflow movement rate at several sites on the Lookout Creek earthflow for wet season of water year 1976.

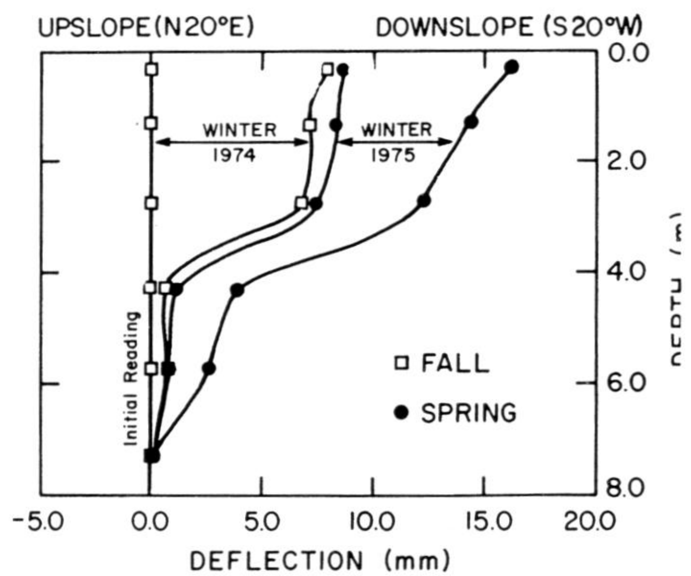


Figure 6. Apparent seasonal deformation along S20°W direction recorded in inclinometer tube installed in Lookout Creek earthflow. Movement is directly plotted from field data and has not been adjusted into the plane of maximum deformation. Note minor upslope movement of tube during summer of 1975 owing to settlement of tube.

probable discrete failure at about 4 m. This may be related to incipient streamside slumping and probably accounts for the difference in orientation of the plane of maximum movement activity, with the fastest movement occurring during the months of high precipitation.

Unlike the Coyote Creek site, which was logged before mass-movement studies began, the Lookout Creek earthflow still carries many trees and the historical record they embody. Numerous broadly curved old-growth Douglas fir trees on the earthflow indicate that the area has been active for at least the past several centuries.

Several of the active tension and shear cracks on the earthflow are straddled by trees split up the center to as much as 7 m above ground level. These trees have grown scar tissue onto the wound, and counts of the annual rings in the post-split wood yield estimates of the time since the split and differential earth movement began to develop. Measurement of the distance that fragments of a tree have been pulled apart at ground level may be used to make estimates of rates of differential movement between adjacent blocks (Table 3; Fig. 4). The splitting rates are generally only minimum estimates of differential earth-movement rates, because most of the trees are not tightly coupled to the blocks on opposite sides of the crack. Estimated rates of tree splitting, ranging from 0.3 to 9.3 cm/yr, are in general agreement with short-term rates of differential earth movement on the basis of direct measurements. Dated periods of tree splitting began as much as 74 years ago. Overall earthflow activity probably began well before that time.

Geomorphic considerations also suggest that earthflow movement was initiated at least several centuries ago. Cross profiles of the floor of Lookout Creek valley above, within, and below that earthflow area reveal a constriction of the valley bottom by about 30 m through the area of direct earthflow influence (Fig. 7). At a movement rate of 10 cm/yr, which is reasonable in light of dendrochronologic and direct measurements of movement, it would take about 300 yr to achieve the existing valley-floor geometry. Extensive bank cutting on the south side of Lookout Creek indicates the earthflow pushed Lookout Creek against the south valley wall at least several decades ago and probably much earlier.

TABLE 3. TREE SPLITTING ON LOOKOUT CREEK EARTHFLOW

Tree	Time since split initiation (yr)	Splitting rate (cm/yr)
A	⩾31*	⩽6.9*
B	37	1.3
C	74	0.3
D	51	1.3
E	23	9.3
F	43	2.7

Note: Location of trees noted in Figure 4.
*Minimum estimate of time since split initiation. Therefore, splitting rate is a maximum estimate.

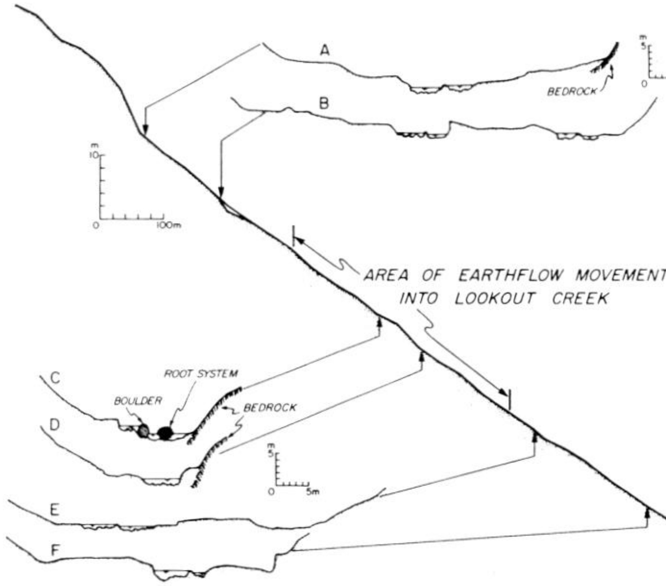


Figure 7. Long profile and cross profiles (A-F) Lookout Creek valley floor in the vicinity of the earthflow. Long profile based on field measurements of channel gradient over 30-m channel sections.

The complete history of the earthflow most likely extends over a period much longer than three centuries.

Impacts on Lookout Creek

The Lookout Creek earthflow has a variety of impacts on Lookout Creek, both in the immediate area of the earthflow and for hundreds of metres downstream. The erosional history and landforms in the area of stream-earthflow interface are determined by the relative rates of earthflow processes that tend to close the channel and by fluvial processes that tend to erode and open the channel.

Movement of the earthflow has forced Lookout Creek against the south wall of the valley. Consequently, in plan view the channel has a broadly arcuate pattern shaped by the convex front of the earthflow (Fig. 4). Above and below the earthflow, the gross geometry of the channel pattern is the result of fluvial processes and changes in flow direction owing to accumulations of large organic debris. Outside the area of earthflow influence, the valley floor includes a low terrace and floodplain as much as 55 m wide and 1 to 4 above the active channel (Fig. 7). These broad, valley-floor cross profiles (Fig. 7) contrast markedly with the narrow, steep-walled channel and adjacent slopes characteristic of the stream reach through the active earthflow (Fig. 7).

The long profile of Lookout Creek is remarkably straight through the area of earthflow impact and for more than 200 m both upstream and downstream (Fig. 7). Impact of the earthflow on this long profile is not clear. If there were no earthflow impact, the channel might have a more typical concave long profile. Earthflow movement may have caused local increases in stream-bed elevation as a result of high levels of sediment and large organic debris inputs to the stream in the area of direct impact and immediately downstream. This effect could also lead to some increased deposition and decreased gradient just upstream from the earthflow.

Large quantities of mineral sediment and organic debris enter Lookout Creek by slumping, shallow debris avalanches, and root throw. Surface erosion and sloughing from undercut banks and debris-avalanche scars appear to be of significant but secondary importance because of rapid revegetation of bare soil areas. Most of the input comes from the earthflow side of the stream, but several small debris avalanches have occurred in response to stream undercutting of the opposite bank (Fig. 4).

Sediment input to the stream by bank failure appears to be an episodic process caused by a series of factors. The earthflow gradually constricts the channel, narrowing it at a rate measured in centimetres per year. The banks of the constricted channel become progressively more susceptible to undercutting and failures triggered by infrequent floods. Earth movement also tips the massive old-growth trees in the streamside area, making them more susceptible to windthrow, which may in turn trigger stream-bank failures. During extreme precipitation, high rates of subsurface water movement at the distal end of the earthflow also increase the potential for shallow failures where the front of the earthflow encroaches on the stream. The earthflow itself may experience a brief acceleration of movement as a result of prolonged periods of heavy precipitation. This combination of storm event and progressive long-term buildup of stress results in the occurrence of episodes of streamside failures.

Seven streamside debris avalanches and slides larger than 75 m^3 have occurred along Lookout Creek in the earthflow area since about 1950. The age of brushy and herbaceous vegetation, which covers much of the slide-scar surfaces, indicates that most of the erosion from these sites appears to have occurred in the severe storms of the winter of 1964–1965. Measurements of the geometry of slide scars show that approximately 5,000 m^3 of soil and rock debris has been supplied to Lookout Creek by the inventoried slides. Some of this material was probably moved into position for potential input to the stream by earthflow movement occurring more than 25 yr ago.

The annual rate of buildup of potential sediment supply to the stream may be estimated by assuming that the 300-m-long, 9- to 16-m-high front of the earthflow is encroaching on the stream at some assumed rate. A movement rate of 10 cm/yr would move 340 m^3/yr of earthflow debris to the stream. At this rate it would take about 15 yr to recharge the stream-bank areas with 5,000 m^3 of material available for input into the stream area. These calculations suggest that rather continuous earthflow may make material available for pulses of sediment input to the stream every few decades.

Downstream Impacts

During extreme floods large quantities of organic and inorganic debris may be flushed out of the section of earthflow-constricted channel and moved downstream for hundreds of metres as catastrophic torrents of debris. In the course of this movement the debris torrents damage or destroy vegetation on the floodplain and low terraces and expose mineral soil in the stream banks. Where a torrent stops, it sets up an area of sediment and large organic debris deposition that may cover several hectares. Such a chain of events was last triggered from the lower end of the Lookout Creek earthflow in the winter of 1964–1965.

Several characteristics of the area of interaction between earthflows and streams make them common sites for the triggering of debris torrents. The high sediment and organic matter inputs to the stream from the earthflow result in high concentrations of potentially mobile material temporarily stored behind loosely structured debris dams in the stream channel through the earthflow. Failure of debris dams during high flow may initiate debris torrents. Bank failures may lead to development of short-lived dams that are quickly overtopped and cut away, resulting in pulses of debris movement downstream. The narrowness of the valley bottom through the earthflow area restricts the lateral movement of the stream and reduces its ability to bypass obstructions in the channel. Stream energy during high flow is focused on obstructions until they are moved downstream. Where the valley floor is broader, the stream may spread out, flowing around and through debris deposits and slowly reworking the material over the course of decades and centuries.

SUMMARY

Areas of active creep and earthflow in the western Cascade Range form complex mass-movement terrains. Creep motion initiates discrete failure, locally resulting in slump and earthflow development. Thereafter, the processes operate together. Slow movement of large masses of earth develop unstable sites where smaller, rapid failure occurs.

A single mass-movement terrain may include a number of units moving at quite different rates. Recorded creep rates range from undetectable levels to 15 mm/yr. Observed differential movement between blocks within the Lookout Creek earthflow range to 10 cm/yr. Movement rate is regulated by moisture availability; periods of high precipitation and (or) snowmelt correspond with times of accelerated movement. Bedrock geology determines the characteristics of deep-seated mass-movement features. Extensively altered, deeply weathered volcaniclastic material is most prone to creep and earthflow activity. In areas of rock types with contrasting physical characteristics, bedrock configuration determines the distribution and morphology of mass-movement landforms.

Complex mass-movement terrains supply large quantities of sediment and organic debris to streams, thereby altering channel geometry. A comparison of sediment discharge to mass-movement activity and channel storage suggests that creep may account for as much as 27% of the annual sediment discharge from Coyote Creek. Although deep-seated processes may operate at slow rates, sediment input to streams may occur as infrequent pulses during major storms.

Geomorphic observations and tree-ring analysis indicate that the history of individual mass-movement terrains in the westen Cascades may have spanned centuries and possibly millennia.

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