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The History of Mass Movement Processes in the Redwood Creek Basin, Humboldt County, California

A Thesis in

Geology

by

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ABSTRACT

The widespread distribution of landforms and deposits indicative of mass movement in the Redwood Creek basin suggests that mass movement has been an important process for a considerable time. The presence of these features in many areas that are now apparently stable suggests that, on a long term basis, mass movement processes were formerly more extensive. However, comparison of sequential aerial photographs of the Redwood Creek basin indicates that there was an acceleration of mass movement activity in the basin over the past 25 years. The most important changes occurred adjacent to the channels of Redwood Creek and its major tributaries. Four major floods (in 1953, 1955, 1964, and 1972) and intensive timber harvest altered slope stability conditions in the basin. Evidence from photointerpretation and field observations indicates that both timber harvest and the severe floods played a major role in the increase in landslide activity, and that their effects are complexly interrelated. The most important effects of timber harvest on slope stability result from major slope disturbances associated with logging road systems, from the removal of root support, and from the action of fluvial processes on cutover land. Floods decrease slope stability mainly by eroding toe support from the lower slopes adjacent to stream channels, and by inducing high pore pressures and seepage

forces in these slopes. The concentration of landslides on the slopes adjacent to stream channels and the distribution of landslides in time suggest that floods have had the most direct effect on the increase in landslide activity.

INTRODUCTION

The North Coast Region of California is one of the most actively eroding areas in the world, and the sediment loads of the Eel River, Mad River, Redwood Creek, and other streams which drain this area are extremely high. Mass movement processes are actively shaping much of the landscape and appear to be responsible for much of the high stream sediment loads. The overall rapidity of erosion and the relative importance of mass movement in eroding the North Coast Region result from a distinctive combination of lithology, soils, tectonic history, climate, and land use.

This study examines the history of slope stability and mass movement in the drainage basin of Redwood Creek, a basin that is in many ways typical of larger portions of northwestern California. The history is documented primarily by sequential aerial photographs taken periodically since 1936. The principle objectives of the study are: 1) the identification of the nature and extent of mass movement in the Redwood Creek basin, 2) documentation of the changes in mass movement activity that have occurred in the last 37 years, and 3) an interpretation of the reasons for those changes. The study concentrates on mass movement processes rather than other erosional processes because various forms of mass movement appear to account for a large proportion of the total amount of erosion in this area, and because these processes can be easily observed on readily available aerial photography.

PREVIOUS WORK

Previous studies concerning mass movement processes in the North Coast region of California are scarce. Kojan (1968) has measured creep rates in various parts of the North Coast Ranges. Regional planning studies for the Eel and Mad River areas, including the basin of Redwood Creek, (U.S. Dept. of Agriculture, River Planning Staff and others, 1970), evaluated the role of landslides and other erosional mechanisms in stream sediment production by interpreting aerial photographs from a random grid and obtaining auxiliary field data. Landslide conditions in the Eel River basin were studied on a reconnaissance level by Lorens, Dwyer, and Scott (1971). Photointerpretation of landslide deposits and landslide susceptibility for land use planning is being done in parts of the San Francisco Bay area by the U.S. Geological Survey in conjunction with the U.S. Dept. Of Housing and Urban Development (See for example, Nilsen, 1972). The present study presents some o the most detailed maps of mass movement phenomena yet prepared for the North Coast region, and is the first attempt to summarize the recent history of these phenomena.

PHYSIOGRAPHIC SETTING

The regional location of the Redwood Creek basin is indicated in Figure 1. Plate 5 is a topographic map of the basin, and shows the location of the geographic names referred to in this study.

The basin is located in the North Coast Ranges of California, between the basins of the Mad and Klamath Rivers. Redwood Creek has its source near Board Camp Butte and flows in a north northwest direction, with a stream length of about 64 miles, entering the Pacific Ocean near Orick. In straight line distances, the basin is about 47 miles long and 4 to 7 miles wide. Thus, the basin is strongly elongated, with a circularity ratio[1] of 0.24. The basin (which in this study includes all of the drainage of Redwood Creek above the mouth of Prairie Creek,) has a drainage area of about 250 square miles, and lies wholly within Humboldt County.

In general, relief in the basin is high, with a total relief of about 5000 feet. Local relief for half mile distances ranges from about 400 feet to about 1300 feet. Slopes are moderately steep, generally ranging from 25 to

[1] Circularity ratio is defined as the area of the basin divided by the area of a circle having a perimeter equal to that of the basin (Fairbridge, 1968, p. 903).

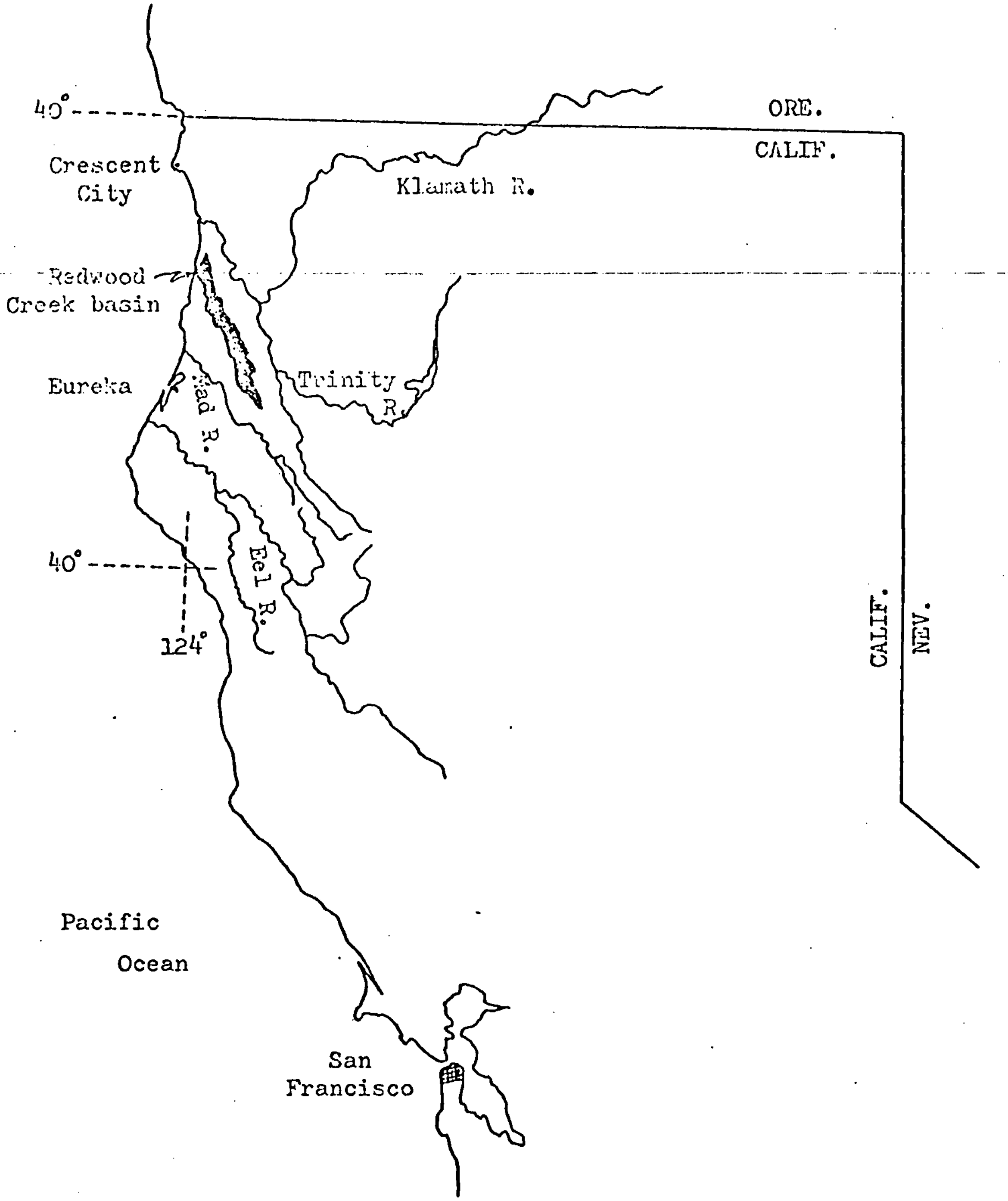


Figure 1. Location map.

40% for segments longer than a quarter of a mile, although shorter, steeper segments are common.

GEOLOGIC SETTING

The geology of the Redwood Creek basin has been studied only in reconnaissance fasion (Strand, 1963) because of a combination of sparce rock outcrop and poor accessibility. Nonetheless, it is apparent that many geologic conditions within the Redwood Creek basin adversely affect slope stability by causing low shear resistance or high shear stress; these conditions (from Sharpe, 1938) include the following:

1. Lithologic: inherently weak material such as leached, hydrated, decomposed, micaceous, or serpentinous rocks; shale, and argillaceous material.
2. Stratigraphic: massive beds overlying weaker beds; the presence of one or more permeable beds; alternation of competant (rigid) and incompetant beds, especially if some are argillaceous.
3. Structural: steep or moderate dips of bedding, foliation, cleavage, joint, or fault planes; rock badly fractured, jointed, or slickensided because of crushing, faulting, or folding; internal deforming stress still unrelieved near the surface because of orogenic activity or rapid erosion.

4. topographic: cliffs or steep slopes caused by erosion, faulting, folding, or previous landslides.

The bedrock of the Redwood Creek basin consists predominately of the Kerr Ranch Schist on the west side of the basin, and the Franciscan Formation on the east side (Manning and Ogle, 1950; Strand, 1963). These two units are serarated by the north northwest trending Grogan Fault which locally controls the course of Redwood Creek. Two other north northwest trending faults that also separate Franciscan rocks from Kerr Ranch Schist occur near the two subparallel drainage divides of the Redwood Creek basin. A number of smaller secondary cross faults displace these three major faults in the Blue Lake quadrangle (Manning and Ogle, 1950).

The Kerr Ranch Schist is comprised of highly contorted quartz - muscovite - albite schist (about 70%) with lesser amounts of "semi-schists[1]", slates (with bedding preserved), meta-conglomerate, meta-chert, green schists, and glaucophane schist (Manning and Ogle, 1950). The foliation of the quartz - mica - albit schist is contorted and highly variable. These rocks were regionally metamorphosed from sandstone, shale, conglomerate, chert,

[1] Manning and Ogle (1950) define this term as "sandstone with the first slight orientation of the intergranular micaceous material."

volcanics, and basic and ultrabasic intrusives; these same lithologies are found in the less metamorphosed Franciscan. Most of the Kerr Ranch Schist adjacent to Redwood Creek is slate and "semi-schist" of low metamorphic grade. The Kerr Ranch Schist is differentiated from the Franciscan primarily on the basis of the former being more metamorphosed. Field observations by the writer suggest that the slightly metamorphosed chert, slate, and "semi-schist" along Redwood Creek are geographically closer and lithologically more similar to the Franciscan rocks than to the quartz - mica - albite schist. Thus, in making the strip map (Appendix III), the cherts, slates, and "semi-schists" were included with the Franciscan, and the quartz - mica - albite schist with its metamorphosed intrusives was considered the Kerr Ranch Schist.

The Franciscan Formation is a complex of sedimentary, metamorphic, basic volcanic, and ultrabasic rocks. The term "formation" is used for lack of a better term since this characteristic assemblage of rocks has neither physical, spatial, or temporal coherence (Page, 1966). It is, however, a mappable rock stratigraphic unit. Fossils ranging from Late Jurassic to Late Cretaceous have been found widely scattered in the Franciscan. The Franciscan sediments are largely greywacke, with minor amounts of shale and conglomerate. Jumbled with the sediments are masses of an ophiolite suite of rocks, including chert, pillow lava and breccia, mafic rocks, and serpentized ultramafics. In the Redwood Creek basin glaucophane schist and other amphibolites are also found. The Franciscan is widely intruded by peridotite, dunite, and some gabbro. Usually there is an absence of contact effects around these intrusions, and the contacts may be readily interpreted as fault contacts (Barbat, 1971). In addition to a large amount of local low grade metamorphism, the Franciscan includes presumably high pressure, low temperature metamorphic rocks of the blueschist facies. The term "mélange" was suggested by Hsü (1966) to describe the largely incoherent jumble of blocks (from a few feet to a few miles in size) of a variety of rock types, sitting in a pervasively sheared matrix of fine grained material. In the Redwood Creek area the Franciscan generally crops out as discontinuous exposures of greywacke and bedded shale and siltstone, or as knobs of chert, greenstone (altered volcanics), and glaucophane schist in the mélange terrain. The thoroughly sheared, jointed, and fractured nature of the Franciscan promotes deep weathering, heavy soil cover, downhill soil creep, and landsliding (Barbat, 1971).

Considerable debate concerning the Mesozoic history of the Coast Ranges exists because of the complexity of the Franciscan, and because of the lack of detailed mapping. According to Crowell's (1968) interpretation, rapid eugeosynclinal sedimentation, vulcanism, downbuckling, and blueschist metamorphism was followed by rapid uplift, all in the Late Jurassic. Eugeosynclinal sedimentation continued to the end of Cretaceous, and was accompanied by major thrusting, very large scale gravity sliding, tectonic mixing, and intrusion of serpentine and ultramafic rocks in Middle Cretaceous. Tertiary deformation included near isoclinal folding, major thrusting, piercement structures, limited gravity sliding, and major strike-slip movement along high angle shear zones (Crowell, 1968).

A more recent interpretation of the origin of the Franciscan by Barbat (1971) involves the underthrusting of the oceanic block under the continental plate, cutting a prism of sediment, Late Jurassic to Late Cretaceous in age, that had been deposited across the oceanic - continental boundary. The footwall sedimentary block was greatly disturbed into a tectonic jumble of sedimentary and oceanic basement rocks. Peridotite from the oceanic crust or from the mantle was mobilized by serpentization, worked up the thrust plane, and was dispersed into the footwall melange. Tectonic overpressuring was responsible for some blueschist metamorphism. This tectonic event, called the Coast Range Orogeny, was ended in Eocene time, as strike-slip movement on the San Andreas Fault partially relieved the relative pressure of the oceanic crust towards the continent. The remaining strain has been responsible for compressional folding and faulting up to the present time (Barbat, 1971). It has also beem argued that there has been only tensional deformation and vertical movement since Eocene time (Wahrhaftig and Birman, 1965).

In addition to complex Cenozoic deformation, there were several marine transgressions during Neogene and Quaternary time. The resulting marine deposits have been affected by the continuing deformation (Barbat, 1971). Tectonically deformed Quaternary landforms and deposits (Wahrhaftig and Birman, 1965), as well as frequent earthquakes attest to continuing tectonism.

SURFICIAL DEPOSITS[1]

Soils developed from colluvium mantle most of the Redwood Creek basin. Residual soil is confined mostly to patches on gently sloping ridge crests. The soils are generally less than four feet deep, moderately to rapidly permeable, and highly susceptible to erosion by running water.

The soils on the schist terrain on the west side of Redwood Creek are generally more deeply oxidized and clayey than the soils on the sandstone and mélange terrain on the east side of Redwood Creek. These differences in type and degree of soil profile development probably reflect the more readily weathered, iron-rich soil parent material and the lower level of mass movement activity on the west side of the basin. The clay-imparted cohesion of the schist terrain soils tends to make them less susceptible to erosion by running water than the less cohesive soils on the sandstone and mélange terrain. Residual soils on the ridge

[1] Soil series descriptions and distributions are taken from a series of maps prepared by the Pacific Southwest Forest and Range Experiment Station, in cooperation with the University of California for the California Division of Forestry, at a scale of 1:31,250. For example, see quadrangle 26B-1 (NE 1/4 of USGS 15' Blue Lake quadrangle), edition of July 1960; classification and mapping by W. Colwell, J. DeLapp, and E. Gladish, 1957, 1958, and 1960; map compilation by T. Akawie, D. Johnson, and J. Klingensmith, 1960.

crests are quite variable in degree of development; some are quite deep and strongly weathered, but often these ridge crest soils are thinner and less intensely weathered than soils on the hillslopes.

The most common soil series are the Masterson, developed from colluvium derived from the Kerr Ranch Schist on the west side of Redwood Creek, and the Hugo, developed from colluvium derived from the Franciscan sedimentary rocks on the east side. There are also lesser amounts of Sites and Orick series soils associated with the Masterson series, and lesser amounts of Wilder, Tyson, Atwell, Kneeland, Kinman, and Yorkville series soils associated with the Hugo series. Table 1 summarizes some of the characteristics of these soils.

The clayey Atwell and Yorkville soil series are especially closely associated with active landslides. The clayey texture of these soils leads to low permeability, high pore pressure, and low shear resistance. Additionally, the Atwell soils are usually developed from inherently unstable, pervasively sheared bedrock in shear zones, fault zones, or other areas of structural weakness. Serpentine is commonly found in these shear zones, and adds to their instability. Timber companies working in the area point to the instability of the Atwell soil as the cause of many landslides, but it is more likely that the inherently weak nature of the rocks in these areas is responsible for both the slope instability and the nature of the soils developed

TABLE 1

Soil Series Characteristics*

Series	Texture of Surface/Subsoil	Depth Range(in.)	Permeability	Erosion Hazard	Parent Material**
Masterson	loam/gravelly loam	30-60	moderate to rapid	moderate to very high	schist
Orick	loam/clay loam	40-70	moderate	moderate	schist
Sites	clay loam/clay	30-60	moderate	moderate	schist
Hugo	gravelly loam/ stoney clay loam	30-60	moderately rapid to rapid	moderate to very high	sandstone, shale, or schist
Wilder	sandy loam/gravelly sandy loam	25-50	rapid	high	sandstone or schist
Tyson	gravelly loam/very gravelly clay loam	18-48	moderately rapid to rapid	moderate to very high	sandstone or shale
Kneeland	clay loam/clay loam	18-40	moderate	moderate	sandstone or shale
Kinman	clay loam/clay	40-72	slow	slight to moderate	sandstone or shale
Yorkville	clay loam/clay	30-60	slow	slight to high	metamorphic rocks
Atwell	loam/gravelly clay loam	36-72	slow	moderate to high	sheared sandstone, shale, and schist

*From California Cooperative Soil-Vegetation Maps, legend, quadrangle 26B-1.

**The soils are actually developed from colluvium derived from these materials.

from them. In any case, the presence of Atwell soil is an excellent indicator of slope instability. Although the Atwell series is more common on the east side of Redwood Creek, it also occurs in shear zones on the west side.

Colluvium mantles most of the slopes in the Redwood Creek basin. In areas that have not experienced continual mass movement, the colluvium is typically 2 to 8 feet thick and is gradational with the bedrock. It is usually composed of a sandy, silty, or clay loam matrix, with angular to subangular cobbles of the underlying bedrock. In areas of continual mass movement, especially in shear zones or melange terrain, it is often extremely difficult to distinguish colluvium from bedrock. The bedrock in these areas has been disturbed by both tectonic and mass movement processes, and usually consists of blocks of various lithologies sitting in a highly sheared matrix. Where they can be separated, the colluvium usually exhibits fewer and smaller blocks of rock, a more irregular orientation of the blocks, and more shear surfaces than the underlying bedrock. Colluvium in areas of persistant and extensive mass movement is often more than 20 feet thick.

The colluvium, even in areas which appear to be presently stable, commonly exhibits shear planes dipping roughly parallel to the land surface, accumulated thicknesses in excess of 20 feet, and interfingering relations with alluvial deposits. These features all suggest past mass movement. Crude stratification dipping into the hillslope was observed in several places where it could not be explained by primary bedding, suggesting backward rotation by slumping.

ALLUVIAL DEPOSITS AND DRAINAGE PATTERNS

For much of its length, Redwood Creek has no banks, and the valley side slopes reach directly to the channel (Refer to Appendix III). In these areas the channel is usually about 75 to 300 feet wide. However, patches of floodplain are scattered along the length of the stream, especially near the mouth and between Lacks Creek and Minor Creek. In these areas the valley bottom may be up to 1500 feet wide. Discontinuous stream terraces, some up to 150 feet above the present level of the stream, are also present. The low water channel is generally sinuous between the confines of the valley side slopes, but braided reaches of significant length also exist, and at intermediate flows, braided reaches become more prevalent. Major meandering reaches occur only on Redwood Creek above the mouth of Lacks Creek. It is not known whether these meanders are structurally controlled or have been superposed. Alluvial deposits and channel characteristics of Redwood Creek were mapped as part of Appendix III.

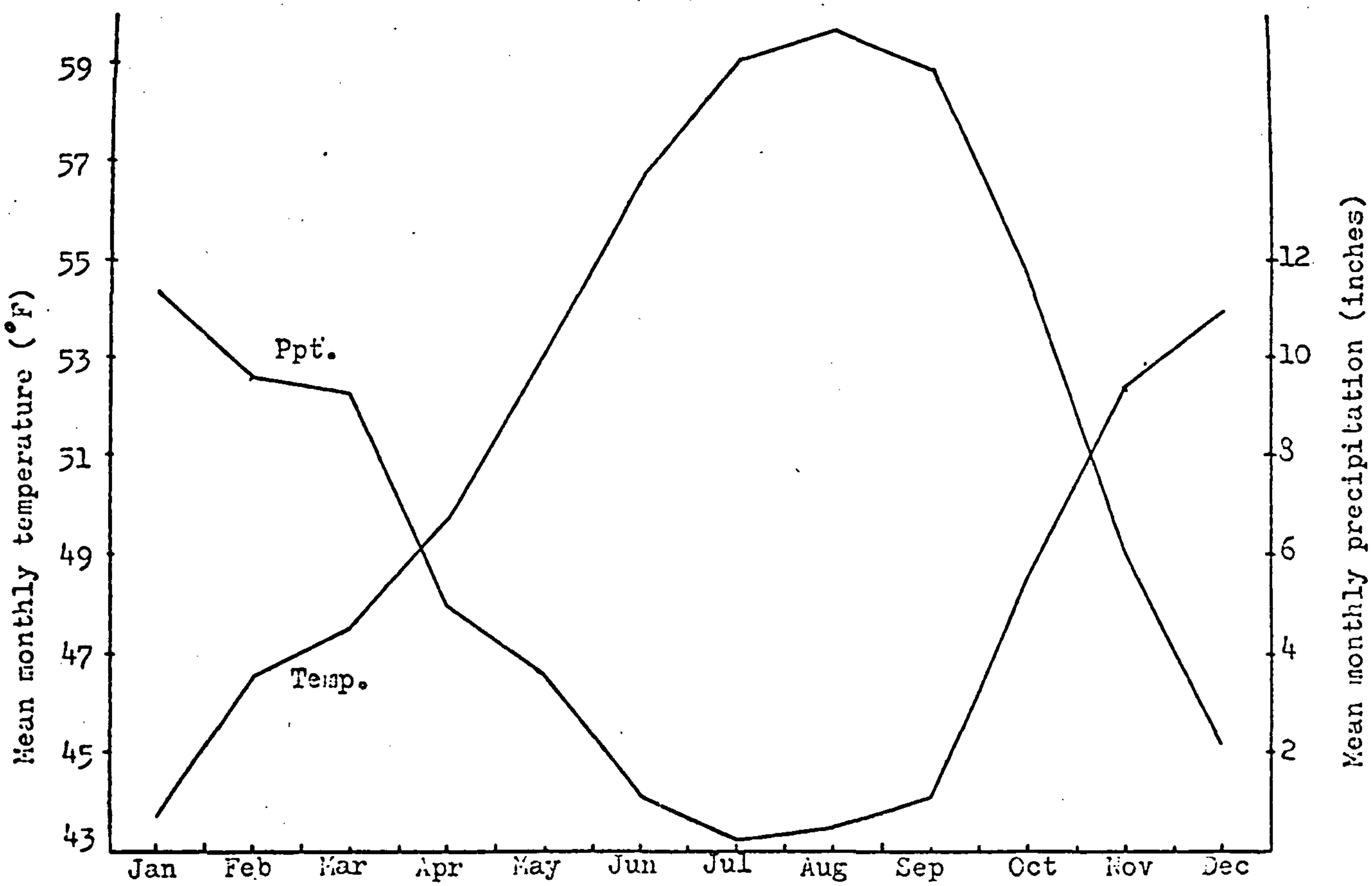
The floodplain and alluvial terrace deposits appear to be strath deposits less than 30 feet thick laid down on bedrock, rather than valley fill aggradation. As such, they are probably indicative of progressive downcutting rather than base level changes induced by sea level fluctuations or landslide dams (Fairbridge, 1968, p. 1117). Furthermore, some terraces are present at sufficiently high altitudes to be unaffected by Pleistocene sea level changes. The alluvial terrace deposits in the Redwood Creek basin are thus additional evidence for recent orogenic uplift. Near the mouth of Redwood Creek the alluvium is much greater than 3[illegible] feet thick and may reflect eustatically controlled incision and aggradation by the stream.

The evolution of drainage patterns in this region is complicated by a complex tectonic history. Diller (1902) proposed what now appears to be an oversimplified Davisian model of uplift and peneplanation for the development of the topography. According to a more recent model proposed by Wahrhaftig and Birman (1965), the oldest stream segments in the area are the segments near the drainage divides, and the mainstems of the larger streams; these segments are well adjusted to the structure. Some streams are consequent on formerly emergent coastal plains or on downwarped troughs. Many streams have managed to maintain antecedent courses and to avoid capture or defeat despite rising structure (Wahrhaftig and Birman, 1965). Streams emptying into the Pacific have had their mouths drowned by the Holocene rise in sea level.

The drainage patterns in the Redwood Creek basin are rectangular, and reasonably well adjusted to the bedrock structure. Redwood Creek and its drainage divides closely parallel the three north northwest trending faults, and its tributaries largely follow that direction or that of the perpendicular cross faults. A well defined but somewhat irregular slope break along the valley sides of Redwood Creek is possibly indicative of an older, less deeply incised, and more gentle outer valley, and a younger, steeper inner valler (Diller, 1902). Almost continuous tectonic uplift combined with drainage patterns adjusted to widespread zones of lithologic weakness has led to an area of high relief and rapid erosion rates.

CLIMATIC SETTING

The present climate of the Redwood Creek basin has highly seasonal precipitation and a limited temperature range. Monthly averages for 23 years of record of temperature and precipitation at Prairie Creek State Park (about 6 miles from Orick) are given in Figure 2. However, considerable variation in temperature and precipitation in the basin is brought about by differences in altitude and proximity to the ocean. The inland portions experience greater temperature and precipitation extremes. The lower portion of the basin receives only occasional snow and experiences few freeze-thaw cycles during the winter, while the upper basin experiences many freeze-thaw cycles and may be snow-covered for many weeks each year. In the lower portion of the basin, the frost-free period usually ranges from mid-April to mid-November and includes 200 to 250 days (R.J. Janda, U.S. Geol. Survey, oral communication, 1973). The higher slopes windward of the winter storm winds (generally from the southwest) receive the most precipitation, but there is a significant carry over of the orographic effects over the ridges, so that all of the



<u>Figure 2</u>. Monthly averages of temperature and precipitation at Prairie Creek State Park. Data compiled from U. S. Dept. of Commerce, Weather Bureau, Climatological Data, California Section, vol. 41-73.

higher slopes of the basin probably receive more than 100 inches of precipitation a year (R.J. Janda, U.S. Geol. Survey, oral communication, 1973). Much of the winter precipitation is concentrated in storms, which last approximately 24 to 72 hours. Rainfall intensities (R.J. Janda, U.S. Geol. Survey, oral communication, 1973) for two and ten year reccurrence intervals respectively, are: 6 hour: 2.0-2.6, 24 hour: 4.5-6.0; 6 hour: 2.8-3.4, 24 hour: 7.0-8.0. In the summer, thick fog caused by the upwelling of cold water offshore often blankets the coast and may extend 30 miles or more into the coastal valleys.

Data on Pleistocene climatic conditions in this region are scarce. In the nearby Trinity Alps of California, both the orographic and climatic Wisconsin snowlines were about 1000 feet lower than at present (Sharp, 1960). Although the Pacific Ocean probably had a moderating effect on the climate of Redwood Creek, it seems reasonable to assume that the climate of the study area was somewhat colder and wetter during parts of Pleistocene glacial episodes.

Climate and climatic change have an important influence on mass movement (Verhoogen and others, 1970, p. 331). Many mass movement processes are sensitive to both moisture conditions and temperature (particularly the number of freeze-thaw cycles). A frost climate is particularly conducive to creep and flow (solifluction) processes (Verhoogen and others, 1970, p. 331).

The concentration of precipitation in winter storms creates a large seasonal variation in the discharges of the streams in this area. The discharges of Redwood Creek during the period of record has varied from 10 CFS (cubic feet per second) at the end of a dry summer to 50,500 CFS during the 1964 flood (U.S. Geol. Survey, 1970). Winter storm precipitation has been responsible for a number of severe floods in this area. Major floods occurred in northern California in 1862, 1881, 1890, 1927, 1953, 1955, 1964, and 1972. Recurrence intervals for these floods are somewhat tenuous because of the lack of quantitative data for the earlier events and because of the concentration of floods since 1953. The 1964 flood was the largest one of historic record, and geologic investigation indicates that it may have a recurrence interval of as much as 400 years (Helley and LaMarche, 1968). The 1953 flood was initially estimated to have a recurrence interval of about 50 years in the Redwood Creek basin (Rantz, 1959), but since that estimate, three floods of about equal or greater magnitude have occurred. In fact, in the Redwood Creek basin, the peak flows of the 1953, 1955, and 1972 floods almost equalled that of the 1964 flood, although the volume of the 1964 flood was significantly greater than the others (Tables 2 and 3).

Despite the uncertainty about the recurrence intervals, it appears that there has been a major concentration of extreme floods in the past 20 years. Data

TABLE 2

FLOOD PEAK FLOWS

	MRA			RCBL			RCO		
Year	CFS	Stage	Date	CFS	Stage	Date	CFS	Stage	Date
'53	75,000	26.15	1/17	-	15.30	1/17	50,000	23.95	1/17
'55	77,800	27.30	12/22	12,100	13.68	12/21	50,000	23.95	12/22
'64	73,400*	23.40*	12/23*	16,400	16.05	12/22	50,500	24.00	12/22
'72	-	-	-	-	-	-	49,700	-	3/3
'72	-	-	-	-	-	-	45,300	-	1/22

(MRA=Mad River near Arcata, RCBL=Redwood Creek near Blue Lake (near Highway 299), RCO=Redwood Creek near Orick, *=flow regulated by Ruth Reservoir beginning in July 1961, -=data not available; data compiled from various U.S. Geological Survey Water Supply Papers).

TABLE 3

VOLUME OF FLOODS ABOVE FLOOD STAGE

Year	Basin	Total Mean CFS	CFS Days	Acre-ft.	Acre-ft./ sq.mi.
1953	MRA	169,610	1,526,490	3,022,450	6,231.6
1955	MRA	272,780	3,818,920	7,561,460	15,590.6
1964	MRA*	247,300	2,968,560	5,877,750	12,119.1
1972	MRA	-	-	-	-
1953	RCBL	-	-	-	-
1964	RCBL	-	-	-	-
1972	RCBL	-	-	-	-
1955	RCBL	37,640	526,960	1,043,420	15,458.1
1953	RCO	-	-	-	-
1955	RCO	134,150	1,878,100	3,718,638	13,376.4
1964	RCO	204,150	2,449,800	4,850,638	17,448.2
1972	RCO (Jan.)	108,170	973,530	1,927,589	6,933.8
1972	RCO (Mar.)	94,180	659,260	1,305,335	4,695.5
1972	RCO (Tot.)	202,350	1,632,790	3,232,924	11,629.3

Duration in days: 1953=9, 1955=12, 1964=12, 1972=6 each. (MRA=Mad River near Arcata, RCBL=Redwood Creek near Blue Lake (near Highway 299), RCO=Redwood Creek near Orick, *=flow regulated by Ruth Reservoir beginning in July 1961, -=data not available; data compiled from various U.S. Geological Survey Water Supply Papers).

for the peak flows and volumes of these floods are presented in Tables 2 and 3. Data for the Mad River at Arcata as well as data for Redwood Creek are included in these tables for the purposes of comparison; the Mad River is hydrolically similar, and in close proximity to Redwood Creek, but the Mad River has more complete hydrologic records. These floods have had a major impact on the geometry of the major stream channels and on the erosional processes operating on the adjacent slopes. The effect of floods on slope stability will be discussed at length in a later section.

Asymmetry of valley or ridge slopes is a common phenomenon in virtually all climatic settings, and is often the result of different microclimates related to differences in slope aspect or exposure (Leopold, Wolman, and Miller, 1964, p. 367). Microclimates result from differences in precipitation (because of orographic effects), evapotranspiration, insolation, and exposure on slopes of differing aspect (facing direction) (Fairbridge, 1968, p. 30). Microclimatic variation can result in significant differences in soil moisture and runnoff, and temperature differences equivalent to several degrees of latitude (Leopold, Wolman, and Miller, 1964, p. 367). In the Shenandoah Valley of Virginia, Hack and Goodlett (1960) found that west-facing slopes were gentler and drier, and had higher drainage densities, better developed drainage networks, and different vegetation than east-facing slopes. Differences in rock type or attitude, differences in soils (which may in turn reflect differences in microclimate) and differences in the meander patterns of large streams can also produce slope asymmetry.

Evidence of significant microclimatic variation is abundant in the Redwood Creek basin, although topographic expression is often obscured by lithologic variation. Aerial photographs taken in the spring show distinctly more snow accumulation on north- and east-facing slopes in the upper basin. Road cuts throughout the basin show more moisture and seepage on north- and east-facing slopes than on south and west facing slopes. Prairie and grass-oak woodland vegetation is much more abundant on the drier south- and west-facing slopes, and coniferous forest is usually denser on north- and east-facing slopes. Large easthflows are more common on south- and west-facing slopes with the associated prairie type vegetation (See Plate 2).

The prevalence of earthflows and other forms of mass movement on the drier, less densely vegetated slopes seems to suggest that the roots of coniferous vegetation impart some strength to the surface soils. Conversely, the absence of coniferous vegetation on slopes dominated by mass movement may indicate that the trees are unable to withstand the movement. Because all slope are seasonally saturated, differences in soil moisture due to microclimatic difference may not have a direct impact on mass movement.

A good example of slope asymmetry due to microclimatic differences is developed on either side of the ridge separating Redwood Creek and Bridge Creek (See Figure 3). The two slopes are developed on the same lithology (Kerr Ranch Schist, with its highly contorted foliation), so that the slope asymmetry is probably due to microclimatic differences rather than differences in rock type or attitude. Because the number of freeze-thaw cycles is small on both slopes, the asymmetry is probably the result of microclimatic variation of soil moisture and runoff rather than temperature. Table 4 summarizes the attributes of each slope. The northeast facing slope will be discussed again in relation to creep and associated problems.

LAND USE

The Redwood Creek basin is sparsely populated, and has only a few ranches and recreational homes. The prairies in the basin have been used for grazing mules, horses, sheep, and cattle for well over 100 years. (Figure 6 presents a typical view of the prairies in this area). Most of the prairies are located in areas of active mass movement, so that overgrazing is potentially a factor influencing mass movement activity. However, overgrazing is presently a problem at only a few locations, and it does not appear to be an important factor affecting present mass movement activity.

Most of the Redwood Creek basin is heavily forested and owned by representatives of the forest products industry. The largest change in land use in the past 25 years has been an intensification of timber harvest. Only a small percentage of the original virgin timber is left outside of Redwood National Park and scattered in-holdings of Six Rivers National Forest. In 1947, less than 6% of the basin had been logged, mostly around the headwaters of Panther and Devil's Creeks; at present about 90% of the old growth of the watershed has been logged (Curry, 1973). The present status of the basin in terms of timber harvest is shown in Plate 4.

Both the method of harvest and the attendant road systems have an important impact on the subsequent erosional events on a logged slope. The effect of timber harvest on slope stability will be discussed in a later section; the section immediately below discusses the past and present harvesting proceedures.

Selective cutting was the dominant method of harvesting until about 1964, when even aged silvicultural management, or clearcutting, became the widespread practice (Curry, 1973). In terms of causing ground disturbance and impacting on slope proccesses, selective cutting has the disadvantage of neccessitating several repeated disturbances of a given area in order to remove the timber from that area. Clearcutting removes all the timber at once, but may involve intense surface disruption. Two common methods of yarding the timber harvested by clearcutting are high lead cable yarding, and tractor yarding. Tractor yarding is the most commonly used proceedure at the present time, and involves dragging the logs downslope to yarding areas with bulldozers. This usually results in a large number of deeply incised, downslope converging skid trails and a large amount of surface disturbance, and usually requires more midslope haul roads. Cable yarding involves dragging the logs upslope by cable, resulting in less ground disturbance, a downslope diverging pattern of shallow skid trails, and fewer midslope haul roads.

Timber harvest requires construction of a widespread road system for hauling the logs from the yarding areas to the mill. At the very least, these roads disturb the existing slope profile by cut and fill, and disrupt natural drainage patterns. At worst, roads may be responsible for massive slope failures, gullying, blocking of natural drainage ways by fill or side cast dirt, and excessive erosion below improperly placed culverts.

AVAILABLE DATA AND METHODS

The maps in this study were generated from a variety of photography. The 1936 photographs were flown by the U.S. Forest Service, the 1947 photographs were obtained from the Topographic Division of the U.S. Geological Survey, the 1958, 1966, 1970, and 1971 photographs are from the Humboldt County Tax Assessor, the 1972 photographs were taken for the National Park Service, and the 1973 photographs were taken for the U.S. Geological Survey. The photography and the maps that were generated from them are listed in Tables 5 and 6.

These photographs were examined with a three power magnification Abrahms stereoscope and with a three power magnification pocket stereoscope. Observations were transferred to U.S. Geological Survey topographic base maps by visual inspection. The map generated from the 1972 photographs was field spot checked, the map of the Minor Creek area was field checked in detail, and the strip map of Redwood Creek was field mapped using the 1973 photographs as a base.

Maps of different scales were generated from various scales of photography, depending on the size of the area and the size of the features to be portrayed. To portray the entire basin and the larger mass movement features on a reasonable size map, a map scale of 1:62,500

TABLE 5

PHOTOGRAPHY USED IN THIS STUDY

1.	1936-	1:30,000	northern 2/3 of the basin.
2.	1947-	1:45,000(?)	southern 3/4 of the basin.
3.	1958-	1:10,000	entire basin.
4.	1966-	1:10,000	entire basin.
5.	1970-71-	1:10,000	entire basin.
6.	1972-	1:36,000	entire basin.
7.	1973-	1:10,000	strip along Redwood Creek and entire basin above Lack's Cr.

TABLE 6

MAPS GENERATED

Photography	Original Scale	Methods and Features
1. 1936-47-	1:62,500	Photointerpretation of the mass movement features of the entire basin. (Plate 1).
2. 1970-71	1:31,250	Photointerpretation with detailed field check (1973) of mass movement features in the Minor Creek area. (Plate 3).
3. 1972	1:62,500	Photointerpretation with field spot check (1973) of mass movement features of the entire basin. (Plate 2).
4. 1973	1:10,000	Strip map of Redwood Creek, field mapped on aerial photograph base, 1973. (Appendix III).
5. 1972	1:62,500	Photointerpretation of the state of timber harvesting for the entire basin. (Plate 4).

MAPS GENERATED

Photography	Original Scale	Methods and Features
6. –	1:62,500	Topographic map of the entire basin, compiled from U.S.G.S. 15' quadrangle topographic maps. (Plate 5).
7. –	–	Location map. (Figure 1).

was chosen for the 1936-47 (Plate 1) and 1972 (Plate 2) maps, and photographs from 1:30,000 to 1:45,000 were used. These maps provide an adaquate representation of the large scale mass movement features of the entire basin. However, the lower size limit of individual features that could be seen and portrayed was about 20 feet wide for long narrow debris avalanches, and about 200 feet high for streamside slides and other slope failures.

The 1:31,250 map of the Minor Creek area (Plate 3) was generated from 1:10,000 photography to provide a more detailed view of a representative portion of the basin, and to provide a comparison of features with the 1972 map of the entire basin. Obviously, smaller features could be seen and depicted on the more detailed map; the lower size limit was about 100 feet in the longest dimension. In addition, more details of previously generalized large earthflows, such as individual scarps and slump bowls, were portrayed. However, mapping the entire basin at the detailed level was not possible because of time and fiscal restraints.

The strip map of Redwood Creek (Appendix III) was generated to study in detail an area that was critical to the history of mass movement processes in the basin. Because the mapping was done in the field on 1:10,000 scale photographs, features as small as 50 feet by 30 feet could be depicted. This map was used as a basis for the landslide data tables (Appendices I and II). Comparison of photography for other years for the landslides portrayed on the strip map was hindered in some cases because of differing scales and photographic quality of the various photography.

ADVANTAGES AND LIMITATIONS

The use of small scale, episodic (multi-year intervals), black and white aerial photography to interpret the history of mass movement processes in the Redwood Creek basin has several severe limitations. First, the episodic nature of the data collection automatically averages proccess rates over the time interval between photography. The more frequent photography of the Redwood Creek basin since 1970 has helped to alleviate this problem.

Second, mass movement processes are most active in the winter and spring, but during those seasons photography is hampered by cloud cover and storm conditions, and the high water levels in the stream channels obscure some features immediately adjacent to the streams. The 1972 photographs were taken immediately after a major storm in early March and were a useful comparison to the other photography, all taken in the dry season.

Third, the size of mass movement features varies by several orders of magnitude, so that different features are best observed on different scales of photography. For this reason, the study was limited to features that could be discerned on 1:10,000 or smaller scale photography. In addition, as discussed in the "Available Data and Methods" section, maps were generated at several levels of detail and scale from different scale photographs in order to define which features could best be observed on the different scales of photography.

The quality of the original photographs and their reproduction imposes a limitation on photointerpretation because of the effect of quality on resolution. With higher quality photographs, smaller features and more detail of larger features can be observed.

Another limitation is imposed by the vegetation of the area, particularly the dense stands of 150 to 300 foot tall conifers (principally Redwood and Douglas-fir), which obscure the detailed surface morphology beneath them. However, the presence of mature timber stands implies a degree of stability, so that the major difficulty was seeing relict landslide topography through the tree cover. Comparison of photography taken before and after timber harvesting in areas such as the upper part of the Bridge Creek basin indicates that in many cases, relict landslide topography simply cannot be seen through a dense tree cover, unless quite large scale features are involved. However, since much of the old growth timber of the basin has been harvested, this problem is important only in a small percentage of the basin. Field checks in old growth timber areas indicate two types of features that are difficult to see on aerial photographs: small scale relict landslide topography, and small landslides into deeply incised ravines and small tributaries. For the most part, slopes bearing mature stands of timber appeared to be quite stable. Areas that were field checked in this connection were: slopes on the east side of the basin upstream from Highway 299, the south and west facing slopes of the Minor Creek basin, and both the east and west facing slopes of Redwood Creek between Bridge Creek and Devil's Creek.

Finally, black and white aerial photography does not yield data concerning moisture conditions, detailed stress distribution, material strength properties, and other factors which may have important relationships with mass movement processes.

Some of these limitations could be resolved by the application of different techniques of study. Detailed field mapping of mass movement features, and in-situ measurements of stress-strain relations, detailed rates of movement, material strength properties, and moisture conditions would be useful. Detailed field work to delineate important fluvial processes and their interaction with slope processes would also yield valuable information. However, these techniques ordinarily involve large amounts or spans of time, and are usually of limited areal extent. More frequent photography and the use of several scales of photography would increase the available data. Different film-filter combinations would increase photograph quality, and the use of infrared photographs would give some indications of moisture conditions and stressed vegetation.

Aerial photograph interpretation offers a efficient means of studying a large area over a long time span, and yields a large amount of data in proportion to the time invested in the study. It provides and important regional view of landslide conditions and history, and enables limits to be put on rates of movement. It is also useful for regional planning and the design of future detailed studies.

MASS MOVEMENT PROCESSES AND ASSOCIATED LANDFORMS

The classification of mass movement processes used in this study is slightly modified from that developed by Sharpe (1938). The modifications involve the combination of debris slides and rock slides into simply slides, and the inclusion of only those processes which were observed in the Redwood Creek basin. The term "landslide" is used to designate slope failures in general. The areal extent of mass movement landforms is given in Table 7. These figures were obtained by sampling 100 grid intersections per square inch on the 1:62,500 1972 map (Plate 2).

SLUMPS: Slumps are intact blocks of soil and rock that have moved with a backward rotation, primarily along a concave-upward failure surface or zone. Pure slumps are relatively rare; complex associations of slumping and flowing are much more common. Minor flowage is almost invariable involved at the toe of slumps. This type of movement is identified by clearly defined crown scarps, surface disruption of the slump block, and bulbous toes. Slumps occur both on natural undisturbed slopes, and on slopes affected by man's activity, especially road construction. Failure of road fill is commonly (at least initially) by slumping. Also, the disturbance of an apparently stable slope by road

TABLE 7

AREAL EXTENT OF MASS MOVEMENT LANDFORMS

	Area, sq.mi.	% of total mass movement area	% of total area
Earthflows	33.09	36.4%	13.2%
Slumps	0.27	0.3	0.1
Slides	2.74	3.0	1.1
Debris avalanches	1.93	2.1	0.8
Older or questionable landslides	35.26	38.7	14.1
Unstable stream banks	8.76	9.6	3.5
Deeply incised amphitheaters	8.98	9.9	3.6
Total mass movement	91.03	100.0	36.4
Stable	159.08		63.6
Total	253.11		100.0

construction often leads to large scale, small displacement slumping, to achieve a more stable configuration. Rates of movement of active slumps is highly variable, ranging from less than one foot per year to several feet per hour. Slumps on slopes adjacent to stream channels usually move much more rapidly than those on the upper slopes. The streamside slumps contribute sediment directly to the streams, but slumps on the upper and middle slopes for the most part merely move sediment into temporary storage farther down the slope. Figure 4 contains an example of a slump.

EARTHFLOWS: Earthflows are complex associations of slumping and flowing movement. They are the most visually obvious and the most widespread form of mass movement in the Redwood Creek basin (Table 7). Individual slumps within earthflows are usually obscure, although backward rotation is often evident, and the dimensions of the scarp and flat associated with the rotation may be up to 100 feet. Earthflows display hummocky and lobate microtopography, scarps, flats, and clearly defined boundaries. Many earthflows in the Redwood Creek basin contain a clearly defined more active portion within a less active area. The more active areas exhibit prominant hummocky and lobate microtopography, unvegetated or partially vegetated scarps, open transverse tension cracks, ponded drainage or closed depressions, and disrupted surface vegetation. Earthflows grade into slumps, which

Figure 4. A slump adjacent to the channel of Redwood Creek. Note the clearly defined crown scarp, protruding toe, and upslope tilt of the trees. The scar is about 150 feet high. Landslide number 102.

usually involve a single slump block with a more or less clearly defined failure surface and minor flowage at the toe. Field examination of detailed morphology, comparison of sequential aerial photography, and observation of comparable features with known rates of movement in nearby areas suggest that surficial rates of movement are probably less than one foot per year in the less active portions of the earthflows, and between a few feet and several tens of feet per year in the more active portions. Depths of movement probably range from a few feet to several tens of feet.

While some earthflows merely move colluvium into temporary storage farther downslope, many other earthflows contribute large volumes of sediment directly into Redwood Creek and its major tributaries. Sediment delivery is effected by sloughing of the toes of these flows directly into major stream channels or into shallow, but well developed systems of gullies. Gully systems are particularly characteristic of large bowl shaped earthflows.

Earthflows often bear a different type of vegetation than adjoining stable areas. Vegetation on the large earthflows on the upper slopes is almost invariably grass or grass - bracken fern prairie, or grass-oak woodland. Dense thickets of young conifers (primarily Douglas-fir) and various hardwoods commonly separate these areas from more stable areas bearing mature coniferous forest. Some small earthflows that have recently become active on the lower slopes adjacent to stream channels have disturbed what once was mature coniferous forest. The prairies may exist because the trees cannot become established on the earthflows, or conversely, the earthflows may exist because of a lack of stabilizing aboreal vegetation. Implications of the observed vegetation patterns on the history of the earthflows will be discussed in the "Long Term History of Mass Movement" section.

Field examination indicates that earthflows are often associated with (but by no means confined to) shear zones, fault zones, or mélange terrain. This association with areas of lithologic weakness is superposed on a tendency for earthflows to be more prevalent on south- and west-facing slopes. As a result, south- and west-facing slopes underlain by shear zones or mélange are particularly susceptible to earthflows. Figures 5 to 7 contain examples of earthflows.

SLIDES: Slides are characterized by dominantly translational movement of varying amounts of rock and regolith along a failure surface or zone that is essentially parallel to the hillslope. The material in the slide block is usually completely removed from its original location, leaving an unvegetated scar. Although the initial movement involves little internal disruption, most of these blocks have little cohesion and they commonly become intensely disrupted as the movement progresses. A single slide may involve one or

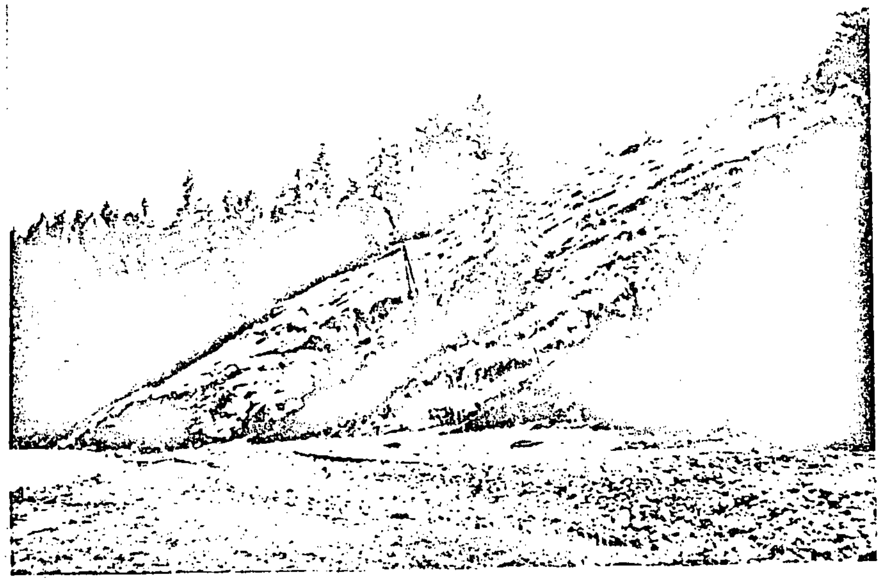


Figure 5. A very active earthflow adjacent to Redwood Creek. Note the straight to slightly convex upward slope profile with no prominant crown scarp or bulbous toe. Also note the hummocky, but largely unbroken surface, and the undercutting of the far side of the toe. This earthflow is just upstream from the mouth of Minor Creek and is about 550 feet wide at the toe. Landslide number 161.

Figure 6. An earthflow with large scale slumping in Count's Hill Prairie. Note the partially vegetated scarp on the right and the large scale stepped and hummocky topography. The trees in the middle ground are about 40 to 60 feet high.

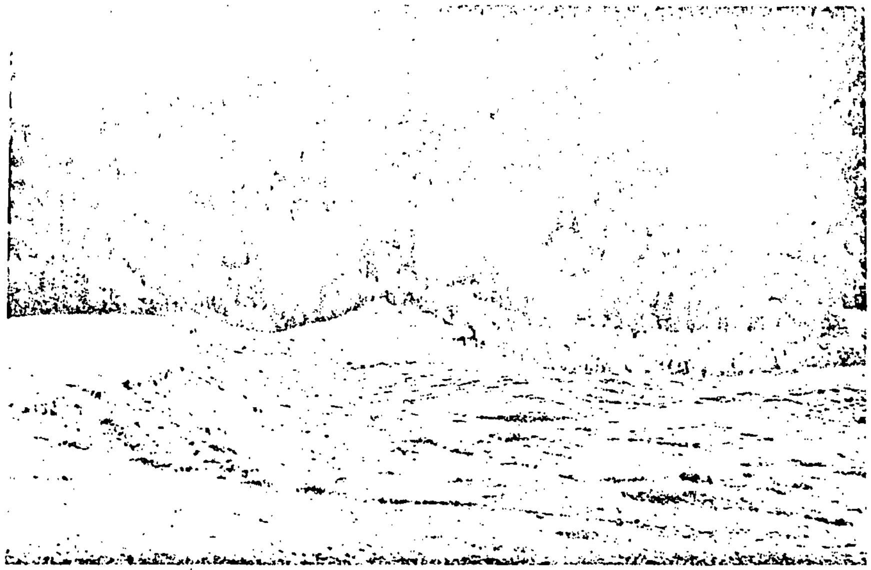


Figure 7. A very active earthflow within a more slowly moving earthflow, near the mouth of Minor Creek. Note the low but pronounced head scarp and the transverse ridges. The movement in this section was by many small slumps within a larger slump. Beyond the picture movement was mostly by flowage. The road in the middleground indicates the scale.

several individual slide blocks. Slides grade into avalanches, which involve the rapid movement of one or more intensely disrupted slide blocks. Slides are identified by unvegetated or partly vegetated scars, by failure surfaces or zones nearly parallel to the hillslope, and by less pronounced crown scarps or bulbous toes than those associated with slumps. Individual episodes of movement take place in a relatively short time (seconds to minutes). Some of the larger slides appear to have had multiple episodes of movement separated by hours or even years. Although slides have apparently occurred in this area for a long time, a large increase in the number of slides on the lower slopes adjacent to the stream channels has taken place in the last 25 years. Reasons for this large increase are discussed in the "Recent History of Mass Movement" section. Examples of slides are illustrated in Figures 8 and 9.

DEBRIS AVALANCHES AND DEBRIS FLOWS: Debris avalanches involve the rapid downslope movement of soil, colluvium, and associated organic debris along relatively narrow, well defined tracks. Unlike slumps or slides, the material in avalanche blocks becomes completely disrupted shortly after the inception of movement. The avalanche tracks often follow natural drainage ways or man-induced gullies. Debris flows and debris torrents involve successively greater water content and lower viscosity than debris avalanches. Debris torrents are indicated by scoured gully walls and floors,

Figure 8. A slide adjacent to the channel of Redwood Creek. Note the straight failure surface, absence of the slide block, and the lack of a pronounced head scarp or bulbous toe. The slide is about 260 feet high. Landslide number 228.

Figure 9. A slide adjacent to the channel of Redwood Creek. Note the position of the slide on the outside of a stream bend, undercutting of the toe, straight failure surface, and the beginning of revegetation. The slide is about 850 feet high. Landslide number 254.

and debris flows are indicated by levees, lobate forms, and other flow structures in debris deposited in the track. Debris avalanches, flows, and torrents are difficult to distinguish from one another on small scale aerial photographs, but avalanches appear to be the most common of these forms in the Redwood Creek basin. There often appears to be a gradation between these forms of mass movement. Debris avalanches, flows, and torrents are commonly caused by steeply deeply incised gullies or streams. Consequently, rapidly eroding cutover land, gullied skid trails, and road fill around culvert crossings are particularly vulnerable to debris avalanches. Illustrations of debris avalanches are contained in Figures 10 and 11.

ROCKFALLS: Rockfalls occur when blocks of rock break away from a steep rock outcrop and fall or tumble down a cliff or steep slope. A few small rockfalls have occurred in the Redwood Creek basin, but they could not be identified as such on small scale aerial photographs.

CREEP: parts of the Redwood Creek basin exhibit landforms, particularly long, smooth, convex-upward slope segments, suggestive of active creep (Verhoogen and others, 1970, p. 330), (See Figure 3). Where creep is the dominant erosion process on a slope, a convex-upward profile allows the velocity of creep to increase downslope, and thereby permit the continuous downslope transportation of an

Figure 10. A pile of debris deposited at the edge of the channel of Redwood Creek. Note the avalanche track behind the debris pile and the unsorted nature of the debris in the pile. The avalanche track is about 70 feet wide at its base. Landslide number 347.

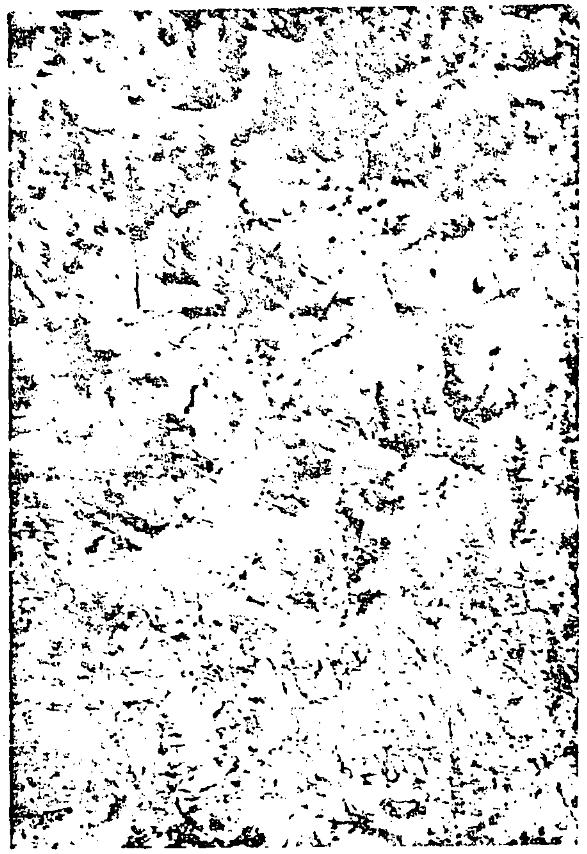


Figure 11. A gully that has become an avalanche track, in the upper Minor Creek basin. The debris avalanche was associated with failure of the walls of the deeply incised gully. Note the road in the middleground for scale.

increasing volume of material eroded from above (Gilbert, 1909; Schumm, 1956). The downslope increase in steepness on creep sculptured slopes in the Redwood Creek basin often is insufficient to transport all of the colluvium to the toe of the slope as a sheet of uniform thickness. Thus, some colluvium accumulates in downslope thickening wedges with straight or concave upwards surface profiles.

Creep in the Redwood Creek area occurs primarily in response to increased pore pressure and increased load, induced by high soil moisture content during the winter and spring. Freeze-thaw and wet-dry cycles are of minor importance in this area. Few creep rates have been measures in settings similar to the Redwood Creek region, and little agreement exists concerning creep rates or the relative importance of creep as an erosional process in these areas. Kojan (1968), using a strain gage inclinometer, measured rates of creep at various sites in the North Coast Range and presented 4 to 5 centimeters per year as a representative surficial rate of movement. R. Zeimer (U.S. Forest Service, oral communication, 1973) has re-examined Kojan's data and calibration proceedures and believes that the rates are much lower. Barr and Swanston (1970) measured creep in a similar setting in southeast Alaska and determined a rate of 0.64 centimeters per year.

Interpreting the long convex-upward slope segments as primarily the result of creep is somewhat problematical. Many of these slopes contain relatively stable road cuts and support stands of timber with straight trunks. The creep zone may be below the shallow depth of the tree roots and road cuts, or the soil may move around or through the tree roots. Differences of opinion exist as to how the depth profiles of creep movement can vary, and what the effect of tree roots is on soil creep movement (Leopold, Wolman, and Miller, 1964, p. 350). Another possibility is that the long convex-upward slope forms evolved during a time when creep rates were considerably more rapid than at present.

COMPOUND AND COMPLEX FORMS OF MASS MOVEMENT

Mass movement processes in the Redwood Creek basin usually occur in combination or in sequence in an individual slope failure. Landslides involving a single mechanism are relatively rare. The heterogeneity of the material strength properties and slope angles and the occurrence of progressive slope failures in this area are conducive to complex mechanisms of movement. In some cases the sequence of events can be deduced from the scar, but in other cases, such as in earthflows, this is not possible. Appendix I contains many examples of combined and sequential mechanisms involved in a single slope failure. Figures 12 to 14 illustrate landslides involving complex mechanisms.

Figure 12. A landslide in the Minor Creek basin involving the movement of colluvium and sheared bedrock by several mechanisms. The initial movement was by slumping or sliding, followed by rapid flowage through the narrow lower part of the landslide. Note the marginal levees along the constricted section where the flowing material overflowed into the trees. The lower portion of the landslide is about 250 feet wide.

Figure 13. A complex landslide on the hillslope adjacent to Redwood Creek. The landslide is teardrop shaped in plan view; in the wider portion movement was mostly by slumping, followed by flowage through the steeper narrow part. Note the lateral scarps and the tilted trees along the margins. The visible portion of the landslide is about 1500 feet long. Landslide number 54.

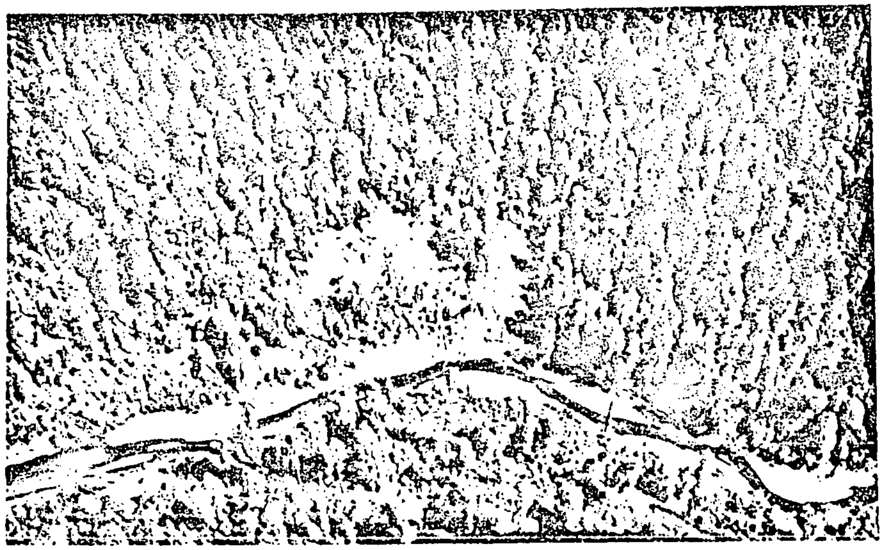


Figure 14. A compound landslide adjacent to the channel of Redwood Creek. The far right portion is an earthflow, while the left part is a slump. Note the rotated block and the difference in tone between the scar on the left and the surface of the earthflow, which is covered with grass. The landslide is about 450 feet wide at its base. Landslide number 102.

LONG TERM HISTORY OF MASS MOVEMENT

Features visible on aerial photographs and on the ground indicate that mass movement has been an important erosional process for a considerable time, and that, on a long term basis, mass movement processes were once more extensive than at present. Evidence supporting this conclusion involves large scale, persistently active features that leave a lasting mark on the landscape rather than small scale episodic features that are quickly modified and obscured.

Widespread landforms throughout the basin appear to have been formed by mass movement rather than fluvial processes. Long, smooth, convex-upward slope profiles of slopes receiving more than 100 inches of rain per year suggest that mass movement processes may be obliterating fluvial landforms in parts of the basin, since fluvial erosion tends to produce concave-upward or straight slope profiles (Gilbert, 1877). The abundant stepped, hummocky, lobate, and bowl-shaped topography that is found throughout the basin is indicative of mass movement rather than fluvial process, especially because such topography is seldom observed to be lithologically controlled.

The steeper lower slopes of the the valley of Redwood Creek are possibly an example of one of Diller's

(1902) "inner valleys", and they may have been caused by accelerated incision following a surge in tectonic uplift. Alternate explanations are possible however, because the elevation of the slope break above the channel is irregular. Among the alternatives is that active mass movement has led to an accumulation of material on the lower and middle slopes. The observed thickenning of colluvium downslope in many areas suggests such an accumulation.

Many areas in the basin exhibit subdued landslide topography that bears dense stands of mature coniferous forest. The mature forest implies present day stability and suggests that the subdued features may be relict landslide topography that has been modified by subsequent creep and slope wash. In some cases the subdued landslide topography cannot be seen on aerial photography until after the timber has been removed. Good examples are found below the Titlow Hill Road, along Nixon Ridge, in the upper Bridge Creek basin, and north of Count's Hill Prairie.

The large scale morphology of many tributary basins suggests that these basins may be stream-modified landslide areas. These areas are generally bowl shaped, with steep cirque-like rims, and are usually more deeply incised than other drainage areas on the same slope. This morphology suggests that these areas have been deeply eroded by one or more past episodes of complex mass movement. Only small portions of these areas appear to be presently unstable (Plate 2).

Surficial deposits indicative of mass movement processes are widespread throughout the basin, and in some areas suggest that mass movement activity was formerly more widespread than at present. Thin, immature soils developed on thick colluvium cover a large proportion of the basin, and little residual soil exists, even in areas that appear quite stable. Crudely stratified colluvium dipping into the hillslope, e.g. in the Miller Creek basin, suggests rotation by slumping. Shear planes oriented roughly parallel to the present land surface are found in areas that show no evidence of recent movement (e.g. in the lower Bridge Creek basin). In addition, landslide deposits are commonly found along the channel of Redwood Creek, and often interfinger with the alluvium.

In general the lower third of the slope is the most active portion. However, at some localities the upper slope appears to be more active than the lower slope, and colluvium appears to be accumulating at mid-slope. In these instances the vegetation patterns often suggest progressive stabilization from the bottom of the slope upwards, although other explanations (such as a moisture gradient or weaker materials upslope) may also apply. Examples of slopes with mass movement activity concentrated on their upper portions are found on the south facing slopes of Lacks, Garrett, and Coyote Creeks, the west facing slopes of Minon and Bradford Creeks, and in the basin between Minor Creek and Highway 299.

The association between prairie vegetation and mass movement topography is important to the long term history of mass movement. Strong evidence indicates that mass movement in prairie areas is (or once was) too great to allow successful forest propagation.

Almost all of the prairies exhibit hummocky, stepped, lobate, or bowl-shaped topography, and are often associated with active or stabilized earthflows. Those prairies that lack these features are usually on ridge crests and continuous with prairies that do exhibit such features. These prairies may result from thin soil, which in turn may reflect removal of a former soil cover by mass movement. Examples are found along the Bald Hills, on the ridge south of Minor Creek, and near Titlow Hill. Soil and colluvium in prairies often thicken downslope, indicating downslope transport. Pig Pen Prairie, prairies in the Minor Creek and Minon - Bradford Creek areas provide good examples of downslope thickening of the regolith. Most of the prairies are on the east side of Redwood Creek (on south- and west-facing slopes) where mass movement processes, particularly earthflows, are more extensive than on the east side of Redwood Creek. Microclimatic and lithologic factors undoubtedtly are both important in this relationship.

Other explanations for the origin and persistence of prairies also exist. Thin soils, moisture stress due to aspect or wind dessication, and burning by Indians have been advanced as reasons for the prairies' existence. The soil pH is considerably higher in the prairies than in the surrounding forest (R.J. Janda, U.S. Geol. Survey, oral communication, 1973), and the high pH found in soils developed from sheared material may be responsible for the prairie type vegetation. However, mass movement may be at least partly responsible for the thin soils and the sheared material that are the basis for the other explanations. Once established, prairies tend to persist, because survival of tree seedlings is difficult because of competition from the dense grass cover, excessive temperature and soil moisture stress, dessication by the wind, and lack of the stabilizing influence of tree roots.

If mass movement is accepted as the controlling factor in the origin and persistence of prairies, then evidence that prairies were once more extensive also indicates that mass movement processes were once more extensive. Peripheral zones of hardwoods and young Douglas-fir around many of the prairies suggests radial encroachment by these species, and therefore, a progressive stabilization of movement inward from the edges of the prairies. It is not known whether the encroachment by the trees was responsible for the stabilization of the prairie margins, or whether the trees became established after the marginal areas had become stable. The peripheral areas of many of the prairies are now apparently stable and bear mature forest, but exhibit features suggesting that they may be stabilized mass movement areas. These features include stepped and hummocky topography, deeper incision by streams and more stream bank slides, and more stability problems than usual with road construction. All of the peripheral features that suggest both prairies and mass movement were once more extensive are especially well developed in the Count's Hill - Dolason Hill Prairie area.

Several reasons can plausibly explain why, on a long term basis, mass movement processes may have formerly been more extensive than at present. First, a cooler and (or) wetter climate during Pleistocene glacial episodes would favor many mass movement processes, by increasing the soil moisture and the number of freeze-thaw cycles. Pleistocene sea level changes caused stream incision and may therefore have been responsible for steeper slopes. However, sea level fluctuations probably only affected the lower most part of the basin. A major episode of tectonic uplift in the past could also have caused stream incision, steeper slopes, and greater mass movement activity. Finally, coincidence of major storm and seismic events is a theoretically possible combination that could have an impact on slope stability in this region.

RECENT HISTORY OF MASS MOVEMENT

Comparison of sequential aerial photographs offers a means of dating major movement during approximately the last 40 years, and forms the basis for this study. A variety of methods are available for dating older events, including soil development, stratigraphy, radiocarbon dating, and observations of features exhibited by the trees, which are up to 2000 years old. These features include growth rings of individual trees, age classes[1] of trees, and the curvature of the tree trunks.

The map of mass movement features interpreted from the 1936 and 1947 photographs (Plate 1) provides an indication of the mass movement conditions in the basin prior to intensive timber harvesting and the recent concentration of extreme floods (1953, 1955, 1964, 1972). The 1936 photos covered the northern 2/3 of the basin, and the 1947 photos covered the southern 3/4 of the basin. Comparison of the photographs from 1936 and 1947 in the area of overlap showed a negligible amount of change in mass movement activity in the intervening time period (See Appendix II). All of the mass movement processes previously

[1] An age class or species class of trees is a patch of trees of predominately one age or species, in contrast to the normal mix of ages and species in the forest.

Figure 15. The landslides in this picture are, from left to right, number 25, 26, 28, and 30. Number 30 is an earthflow at the lower end of the very large complex feature that makes up Count's Hill Prairie. The gully at the downstream side of number 30 may be a lateral tension crack of the larger feature. The other landslides are slides. Number 26 is about 200 feet wide at its base. Number 30 was about the same in 1947; the rest have appeared since then.

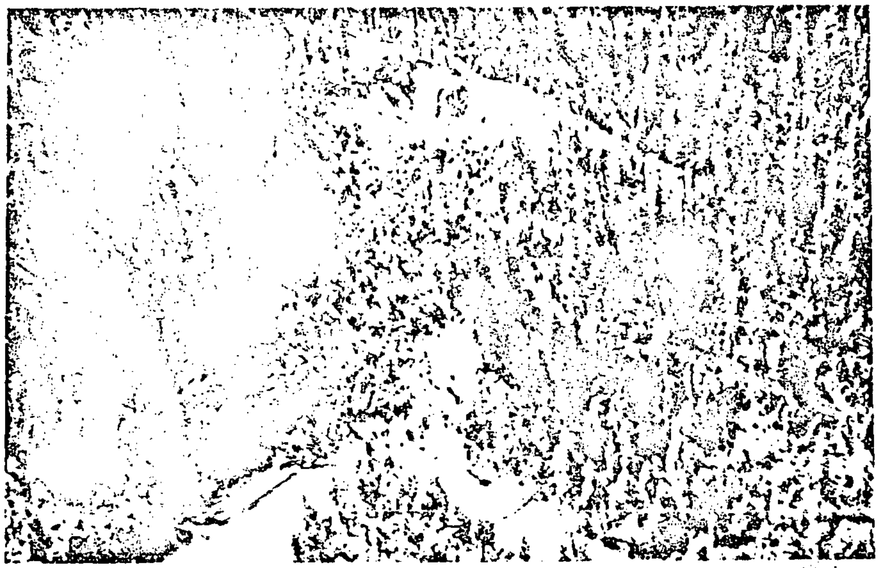


Figure 16. Some indications of this large area of slope instability were present in 1947, but it has greatly increased in activity since then. The movement has been mostly by sliding, with some flowage at the toe. Note that the slide is located on the ouside of a stream bend, that a group of younger trees remains in the center, and that the slide is closely associated with a road. The unstable area is about 400 feet wide at its base. Landslide number 205.

described were actively eroding the basin in 1936, and, in fact, appeared to account for a large proportion of the erosion occurring in the basin.

The map of mass movement features interpreted from the 1972 photographs (Plate 2), in turn, indicates the present status of mass movement processes in the basin. A comparison of the two maps indicates that important increases in mass movement occurred between 1947 and 1972. The observed changes occurred principally in the following three types of areas:

1. The lower slopes adjacent to Redwood Creek and its major tributaries.
2. Adjacent to new roads and skid trails.
3. The large prairie earthflows.

During this time the major changes in those basin conditions that control slope stability were an increase in the intensity of timber harvest and the occurrence of an unusual number of high reccurrence interval floods. These two factors were probably largely responsible for the observed increase in mass movement.

The most important and apparent change in mass movement activity between 1947 and 1972 was the great increase in number and area of landslides on hillslopes immediately adjacent to Redwood Creek. This change in activity has had an enormous impact upon stream channel geometry and erosion rates in the basin.

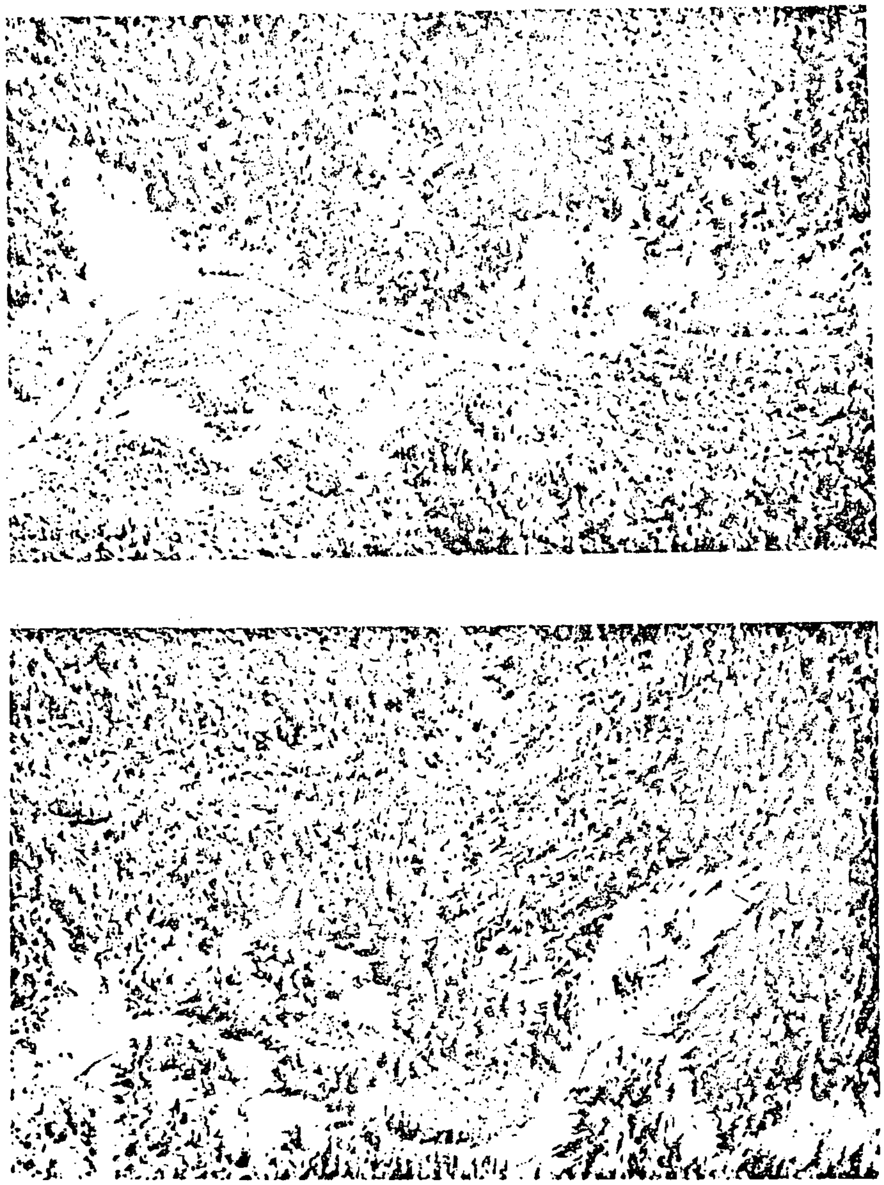


Figure 17. Present landslide conditions along the lower slopes adjacent to Redwood Creek. Landslide numbers 254 (upper left), 258 (upper right), (lower left), and 243 (lower right). 254 is about 450 feet wide at its base, and 243 is about 475 feet wide at its base.

The increased mass movement activity associated with roads and skid trails involves mostly relatively small slides, slumps, and debris avalanches, especially the latter. Although the individual road - related landslides are small, they are numerous and occur throughout the basin. Thus, these road - related landslides appear to have significantly increased rates of erosion. Moreover, some of these landslides were sufficiently large to modify the geometry of some tributary streams. The impact of timber access roads and skid trails on mass movement on the upper and middle slopes of the Redwood Creek basin is much greater than that associated with just the physical removal of the trees.

The increased activity of the large prairie earthflows is rather localized and probably has not had much effect on overall erosion rates.

Discussion of the effects of floods and timber harvest on slope stability will concentrate on slopes immediately adjacent to Redwood Creek because that is where the most obvious and important changes in mass movement occurred. These areas were studied by constructing a detailed strip map and by studying the history of individual landslides on aerial photographs. The strip map was prepared by field mapping on 1973 1:10,000 scale aerial photographs. Data on the volume, type of movement, materials, and present condition were tabulated for each slide during mapping. In addition, the geology along the channel and the state of erosion of the stream banks were mapped. (See Appendices I, II, and III).

In 1947 only a few large individual active landslides existed along the channel of Redwood Creek, but the streamside slopes showed abundant small scale instability and stabilized older landslides. Suggestions of a history of repetative slope failure, and a potential for large landslides includes:

1) Many landslide-shaped patches of age classes or species classes of trees.
2) Alder thickets and other types of vegetation indicative of excessive soil moisture.
3) Many gullies.
4) Disruption of surface vegetation and exposure of bare soil.
5) Stream bank erosion and small stream bank landslides.
6) A few large landslides.

The range in slope stability and activity that is evident along the stream side slopes in 1947 appears to reflect a natural cycle of instability, landsliding, and recovery. This cycle is enhanced by the inherent instability of the slopes and the rapid establishment of stabilizing vegetation. The fact that most of the landslides that occurred between 1947 and 1972 occurred in areas that were obviously unstable or were older slides in 1947 supports this interpretation. In such a cycle, the number of active and recently stabilized landslides should remain approximately constant over time spans long enough to include hydrologic extremes, assuming the conditions which affect slope stability remain constant. The large increase in the number and activity of discernable landslides between 1947 and 1972 in part represents a naturally occurring peak in mass movement activity following a sequence of major floods, but part of the increased activity may reflect changes in slope stability brought about by timber harvest and road construction.

THE EFFECT OF TIMBER HARVEST ON SLOPE STABILITY

The literature on the subject indicates that timber harvest (specifically clearcut logging) may lead to accelerated mass movement (Gray, 1970). Widespread surface disruption associated with timber harvest, including road construction and related activities, effects major changes in slope conditions. Surface disruption has a direct effect on soil moisture conditions, which influence slope stability in at least the following four ways (Varnes, 1958):

1) the weight of the pore water, which adds to the driving force for slope failure,
2) buoyancy in the saturated state which reduces intergranular pressure and thus internal friction,
3) intergranular pressure due to capillary tension, which is destroyed upon saturation, and
4) seepage pressure of percolating ground water resulting from viscous drag.

In other words, an increase in soil moisture, especially saturation, decreases slope stability. Changes in rates and loci of infiltration because of surface disruption, and a decrease in evapotranspiration and interception by trees are the main effects of timber harvest on soil moisture. However, direct observations and theoretical considerations suggest that the overall change in slope stability due to to increased soil moisture following timber harvest in the Redwood Creek basin is probably minor. First, the precipitation patterns in the Redwood Creek region are such that the soil is saturated for a time each winter, regardless of the vegetation conditions. Furthermore, the scant literature on the subject suggests that the infiltration rate is reduced rather than increased by clearcut logging (Bishop and Stevens, 1964). Thus, timber harvest probably only affects the duration of saturated conditions and infiltration - runoff conditions during frequent, low magnitude freshets.

Tractor yarded clearcut logging involves a tremendous amount of road construction, including main haul roads, secondary roads, and a particularly large number of skid trails. Sampling of aerial photographs of tractor yarded clearcuts in the Redwood Creek basin shows that 80 to 85% of the ground is disturbed and that 35 to 50% of the surface is covered with roads, skid trails, layouts, or landings (R.J. Janda, U.S. Geol. Survey, oral communication, 1973). Road construction stands out as the most damaging activity involved in timber harvest (Swanston, 1970). In the H.J. Andrews Experimental Forest during the winter of 1964-65, 72.4% of the observed mass movement events were road related, 17.0% were associated with logged areas, and 10.6% were in undisturbed areas (Dyrness, 1967).

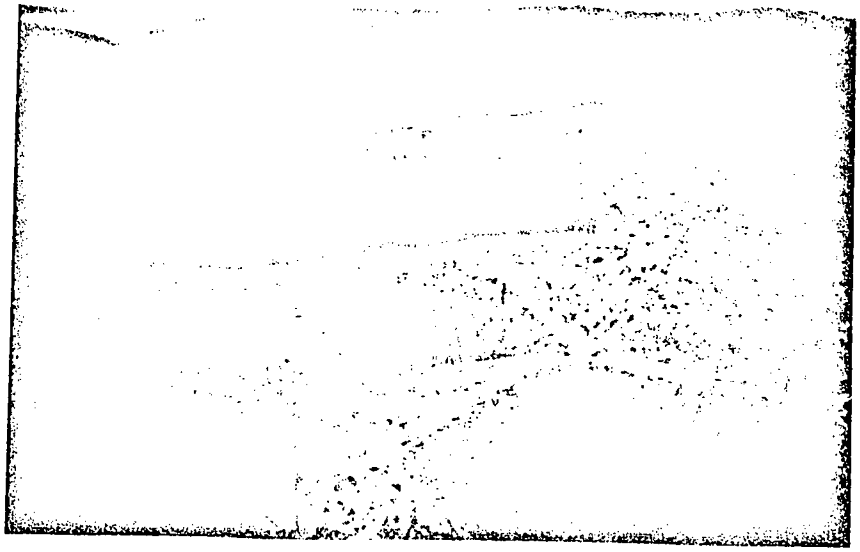


Figure 18. General and detailed views of timber harvest in the lower part of the Redwood Creek basin. In the upper view, note the scale and extent of the cut, and the pattern of roads and skid trails. The lower view is an extreme example of ground disturbance; note the debris in the drainage way and the road failure in the foreground.

In the Redwood Creek basin, three basic types of road related slope failures were observed. First, most mid-slope roads are constructed by the "cut and fill" method, and the greater the slope the more cut and fill is required. The fill piles are generally uncompacted, permeable, and less stable than the surrounding slope. They are susceptible to failure, often by slumping, particularly under saturated conditions. Roads in the upper Tom McDonald Creek and Minor Creek basins, and along the slopes adjacent to Redwood Creek provide many excellent examples of fill failures.

The second type of road related failure is the result of the disturbance of the stable or quasi-stable stress distribution of the slope by the cut and fill operation. These failures are deeper seated and more extensive than fill failures. Two types are common:

1) Slumps or earthflows which generally begin above the road and continue to the foot of the slope. Good examples are found along the main haul roads on the slopes adjacent to Redwood Creek, along Highway 299, and other areas which showed evidence of instability or older landslides prior to road construction.
2) Large scale, small displacement slumps covering an area both above and below the road, by which the stress distribution is slightly altered to a more stable configuration. Examples are found along

the roads on the south side of Coyote Creek, north of Count's Hill Prairie, and along Chezem road (old Highway 299, which is adjacent to the new highway). This type of failure generally occurs in areas which appear stable before road construction.

Perhaps the most important type of road - associated slope failure in terms of sediment production is the failures related to road drainage and stream crossings. Road construction disrupts natural drainage patterns and exposes significant amounts of unvegetated soil. Gullying (primarily of skid trails) in some tractor yarded areas in Humboldt County has eroded sediment equivalent to 6 to 7 inches per 100 years averaged over the whole area (Wahrhaftig and Cox, 1972). Even where roads are well drained, the runoff is frequently concentrated, causing severe gullying downslope. Rapid gully erosion is extremely conducive to landslide - gully feedback mechanisms. In addition, a large number of ravine and small tributary crossings are provided with inadaquate culverts. In many cases these culvert crossings amount to little more than a dam with a hole in it (Hicks and Collins, 1973). The culverts often become plugged, and the water backed up behind the "dam" can either overtop it and wash it away, or create seepage forces sufficient to cause the fill to fail by slumping (Hicks and Collins, 1970), or by piping. In

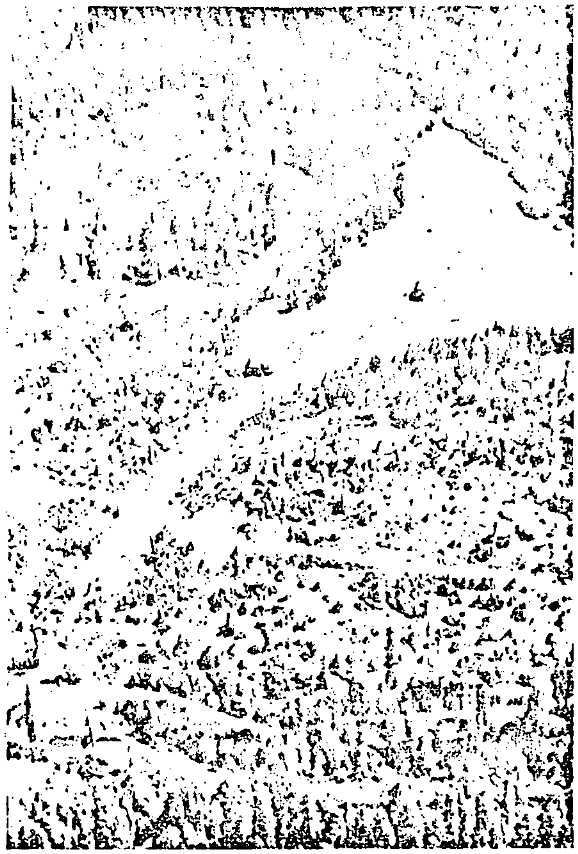


Figure 19. A large earthflow on the upper slope adjacent to Redwood Creek. The upper portion of the earthflow was clearly active on older photography, but the narrow lower part did not become active until the road was built. The narrow lower portion is landslide number 55.

Figure 20. Road drainage from Highway 299 has been concentrated at this point and has cut a deep gully.

either case the fill may fail rapidly and result in a highly erosive torrent of debris-laden water which can undercut the side slopes of the drainage way.

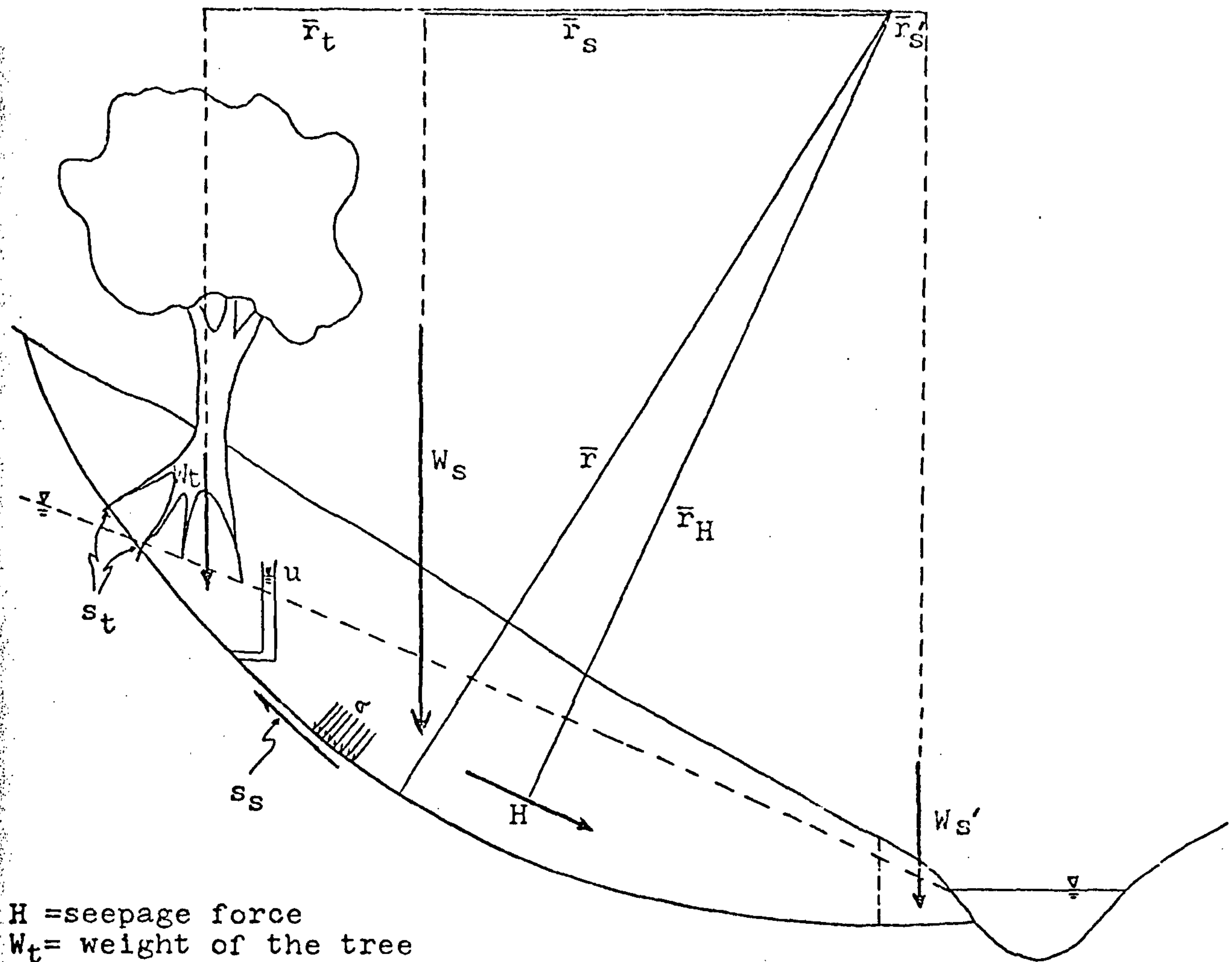
Large amounts of discarded timber, slash, and other organic debris are often by-products of logging. On steep slopes this debris can be relatively easily transported to the streams and accumulate in large log jams. Log jams are a naturally occurring phenomenon, but many log jams in the Redwood Creek basin are composed almost entirely of sawed logs, bridge supports, and other logging debris. Thus, timber harvest has apparently increased the frequency of occurrance of log jams. These log jams can contribute to slope failure in three ways. First, the log jam can deflect the stream current against the stream bank, resulting in the removal of toe support of the slope. The log jam at the south boundary of Redwood National Park, composed primarily of the wreckage of a log bridge, is a good example. Second, aggradation behind the jam, followed by collapse of the obstruction can create a highly erosive torrent that can undercut one or both of the streamside slopes downstream. Third, a raised water table behind the temporary dam can lead to high pore pressure in the adjacent banks, followed by rapid drawdown and high seepage forces after the collapse of the dam. The importance of rising water table conditions in slope stability has been documented by Lane (1967).

The weight of the trees and the strength imparted to the soil by the root network of trees are other factors controlling slope stability that are obviously affected by timber harvest (See Figure 21). The root network of trees creates a supporting and binding effect in the soil (Bishop and Stevens, 1964; Gray, 1970; Hicks and Collins, 1970). The gradual decay of tree root systems following logging may explain the time lag often observed between logging and new landslide activity, especially shallow slides and debris avalanches (Bishop and Stevens, 1964). The importance of root support in the Redwood Creek area is bolstered by several indirect observations. Many of the landslides on slopes adjacent to Redwood Creek involve the sliding of root-bound blocks and are quite shallow (approximately root depth). These landslides commonly have sharply defined, scalloped head scarps, suggesting small cohesive slide blocks. In addition, although other factors are also involved, this type of shallow landsliding is more prevalent in the Douglas-fir dominated forests in the upstream areas of the Redwood Creek basin. Redwood trees, whose root systems remain alive after cutting, progressively decrease upstream.

The weight of the trees can be divided into two force components: one normal and one parallel to the slope. The normal force is a compactive force and increases shear resistance, while the parallel force is a shear force and increases the driving force. Many of the slopes adjacent to the stream channels are about 45 degrees, and on such slopes the normal and parallel forces are about equal. However, the normal force does not have as great or as direct an effect on slope stability as the parallel force does. The normal force is most effective for shallow slides and avalanches, and least effective for deep-seated slumps. Thus, the removal of the trees decreases both the shear force and the shear resistance (Bishop and Stevens, 1964; Hicks and Collins, 1970), but the extent to which these decreases balance eachother is not known.

Finally, increased fluvial erosion, especially gullying, following surface disruption by timber harvest can lead to stream aggradation, diminished channel capacity, and undercutting of streamside slopes. The details of this process will be discussed with the effect of floods.

A summary of the factors influencing the stability of a potential landslide is presented schematically in Figure 21.



H =seepage force
W_t= weight of the tree
W_s=driving weight of the soil and pore water
W_s'=resisting weight of the soil and pore water
$\bar{r}$ =radius of curvature of the failure surface
$\bar{r}_H$=moment arm of H
$\bar{r}_t$=moment arm of W_t
$\bar{r}_s$=moment arm of W_s
$\bar{r}_s'$=moment arm of W_s
u =pore pressure
s_t=shear strength of the tree roots
s_s=shear strength of the soil $=c_s+(\sigma-u)\mu_s$

c_s=cohesion of the soil
σ =stress normal to the surface
μ_s=internal friction of soil
A_t=area of the tree roots
A_s=area of the potential failure surface

$$\text{Resistive force} = \int^A s_t \, dA_t + \int^A s_s \, dA_s$$
$$= \int^A s_t \, dA_t + \int^A c_s \, dA_s + \int^A (\sigma - u)\mu_s \, dA_s$$

$$\text{Driving force} = \frac{W_s\bar{r}_s + W_t\bar{r}_t + H\bar{r}_H - W_s'\bar{r}_s'}{r}$$

Figure 21. Schematic summary of slope stability factors.

THE EFFECTS OF FLOODS ON SLOPE STABILITY

The impact of large floods of high recurrence interval on slope stability results largely from the removal of lateral support from the lower slopes by large volumes of high velocity water. The large percentage of landslides along the lower slopes of the Redwood Creek basin that are on the outside of stream bends that were obviously undercut by the stream is evidence of the importance of flood erosion in triggering landslides (See Appendix I). A large proportion of the total sediment load of the rivers of northwestern California is transported by large infrequent floods. For instance, during 10 days of high flow during the 1964 flood, the Eel River carried about 1.5 times its sediment discharge for the entire previous 7 years (Brown and Ritter, 1971). Flood-triggered streamside landslides probably account for a large amount of of the stream sediment load during floods. Additionally, field observations of stream-eroded landslide debris resting on older flood gravels provide direct geomorphic evidence of the ability of flood waters to remove material from the toes of the lower slopes.

In many cases, the high sediment load carried by the streams during floods reinforces the tendency of the stream to erode their banks and lower slopes. Measurements of the low water channel elevations at gaging stations for North Coast streams show that most of the streams, including Redwood Creek, experienced net aggradation during the 1964 flood (Hickey, 1969). In addition, indications of large amounts of recent (less than 15 years old) aggradation were observed in many places along Redwood Creek, including:

1) 19 feet of gravel deposition behind the log jam at the south boundary of Redwood National Park (Gerald LaRue, U.S. Geol. Survey, oral communication, 1973), (See Figure 22),
2) high, coarse, unvegetated gravel bars on one or both sides of the stream, and
3) the entrance of gravel-choked tributary creeks higher than the present low water level of Redwood Creek.

Local residents report that Redwood Creek has raised and widened its bed over the last 25 years, and the stream bed appears wider on the 1972 photographs than on the 1947 photographs. Large amounts of aggradation diminish the channel capacity of a stream and raise its bed, strengthening the tendency for erosion of the lower stream side slopes. In some cases, rapid aggradation has caused a sudden shift of the channel, known as channel avulsion. In several locations along Redwood Creek, aggradation associated with major floods, followed by channel avulsion or a gradual displacement of the stream, has shifted the thalweg directly up against the valley side slopes. In the

Figure 22. The log jam at the south boundary of Redwood National Park. Aggradation behind the jam during the 1972 flood (off the picture on the left) shifted the thalweg up against the active earthflow at right. The jam itself has sharply deflected the stream against the left bank.

Bull Creek basin, a tributary of the South Fork of the Eel River, large amounts of aggradation following timber harvest and the 1964 flood have increased the tendency for stream bank erosion (Zinke, 1966).

Tributary streams also carry high sediment loads during major floods, and deposition tends to occur at the mouths of the tributaries. Side stream alluvial fans often deflect the current of the main stream against the opposite bank, increasing the tendency for bank erosion and removal of toe support of the lower streamside slopes. Large gravel fans were deposited at the mouths of Tom McDonald Creek, Bridge Creek, Snow Camp Creek, and several other creeks during the 1972 flood; it appears that these fans are slowly being removed by moderate flows following the flood event.

An additional effect of floods on slope stability is the high seepage forces in the lower stream side slopes resulting from rapid drawdown after the flood peak. Studies in the Eel River basin indicate that this mechanism was important during the 1964 flood (Lorens, Dwyer, and Scott, 1971). Comparison of aerial photographs taken in June and August, 1973 and in March, 1972 show that 26 new landslides adjacent to Redwood Creek either first appeared or increased in activity during the intervening time period. Because the 1972 photographs were taken after the 1972 flood peak but while the creek was still at flood stage, and because the winter of 1972-73 was extremely dry, these 26 landslides may have developed during the recession of the 1972 flood waters under the influence of high seepage forces. Floods can also decrease slope stability simply by raising the water table and increasing pore pressure, which usually decreases shear resistance (Lane, 1967). The stage of Redwood Creek, which directly affects the pore pressure and seepage forces in the adjacent slopes, varies by more than 20 feet.

COMBINED EFFECTS OF FLOODS AND TIMBER HARVEST

Timber harvest and major floods both have a negative effect on slope stability, and their combined effect is especially deleterious. Widespread ground disturbance resulting from timber harvest increases the impact of floods in a number of ways. First, large amounts of sediment eroded from the disturbed land increases the tendency for aggradation, channel avulsion, and deposition of side stream alluvial fans. Data compiled by Janda (1972) from several paired - basin studies in the Redwood - Douglas Fir region indicate that sediment yields from unroaded, clear-cut, cable yarded drainage basins was initially 3.3 to 8.2 times greater than from undisturbed control basins; and that road construction can initially increase sediment yield 2.5 to 109 times that of an unroaded control basin. Second, the decreased infiltration rate in cutover land (Bishop and Stevens, 1964) increases runoff rates and leads to a higher flood peak. Recent studies indicate that on permeable soils, such as are found in the Redwood Creek basin, most storm runoff results from precipitation falling directly onto water courses and onto small areas near the water courses where the water table intersects the land surface (Dunne and Black, 1970). This "partial area" contribution to runoff is enhanced in cutover areas where runoff rates are greater and where there is more gullying. The badly eroding cutover areas in many parts of the basin show abundant evidence of gully development and soil erosion.

Timber harvest effects runoff principally by increasing the annual runoff and the peak flows of low magnitude floods early in the rainy season (Rothacher, 1970). The reduction of evapotranspiration and interception by the trees following timber harvest increases the soil moisture in cutover areas. Thus, more precipitation is converted to runoff in the cutover areas than in forested areas where more soil moisture storage is available. The ground disturbance associated with timber harvest also creates many locations where the water flowing through the soil can return to the surface, creating saturated areas which increase the "partial area" contributions to runoff.

However, these effects occur only when the soil is not saturated. Most of the major floods in the North Coast area occur under saturated antecedent conditions, and all of the literature on floods agrees that the effect of timber harvest on these floods is minimal (Zinke, 1965; Rothacher, 1970).

Gully development on cutover land is obviously enhanced by the large amounts of runoff associated with major floods. Deep gullying disturbs the stress distribution of a slope and increases the chances of slope failure, especially debris avalanches or flows. Many examples of debris avalanches or flows initiated by failure of gully walls were observed, especially in the upper Minor Creek basin, on the east side of Rodger's Peak, along the Klamath - Korbell road in the Panther Creek area, and in many places in the upper basin (See Appendix I).

Flood runoff from land that has recently been subjected to timber harvest may transport large quantities os coaree organic debris (limbs, bark, broken tops, splintered logs, etc.). Often this organic debris accumulates in drainage ways and is subsequently flushed out by flood runoff, causing highly erosive debris torrents (Bishop and Stevens, 1964). Undercutting by these debris torrents often leads to failure of the side slopes of the drainage way. Failure of the side slopes may propagate upslope, leading to debris avalanches or debris flows. In addition, transportation of logging debris increases the chances of formation of log jams in the larger, lower gradient channels.

Even well designed road culverts often prove to be inadaquate to handle the large volumes of runoff during extreme floods, and culverts that are adaquate to handle the volume of water are often plugged by flood-transported debris. As discussed earlier, the resulting culvert failures can cause major slope and road failures.

The combined effects of floods and timber harvest involve a continuum of interrelated fluvial and slope processes. For example, indications of all gradations between gullies, debris torrents, debris flows, and debris avalanches were observed in the Redwood Creek basin. The effects discussed above usually occur in combination or in sequence, and often reinforce each other. Where reinforcement or positive feedback occurs, the effects become cumulative and particularly destructive. Figure 23 is a schematic representation of the possible feedback mechanisms that proliferate any individual slope or channel disturbance. For example, a landslide adjacent to the channel may contribute a large number of trees to the stream, which may subsequently form a log jam. The log jam, in turn, may deflect the stream against one bank, causing undercutting of the slope and a new landslide. The large number of feedback loops results in the propagation of any slope or channel disturbance through a complex of processes.

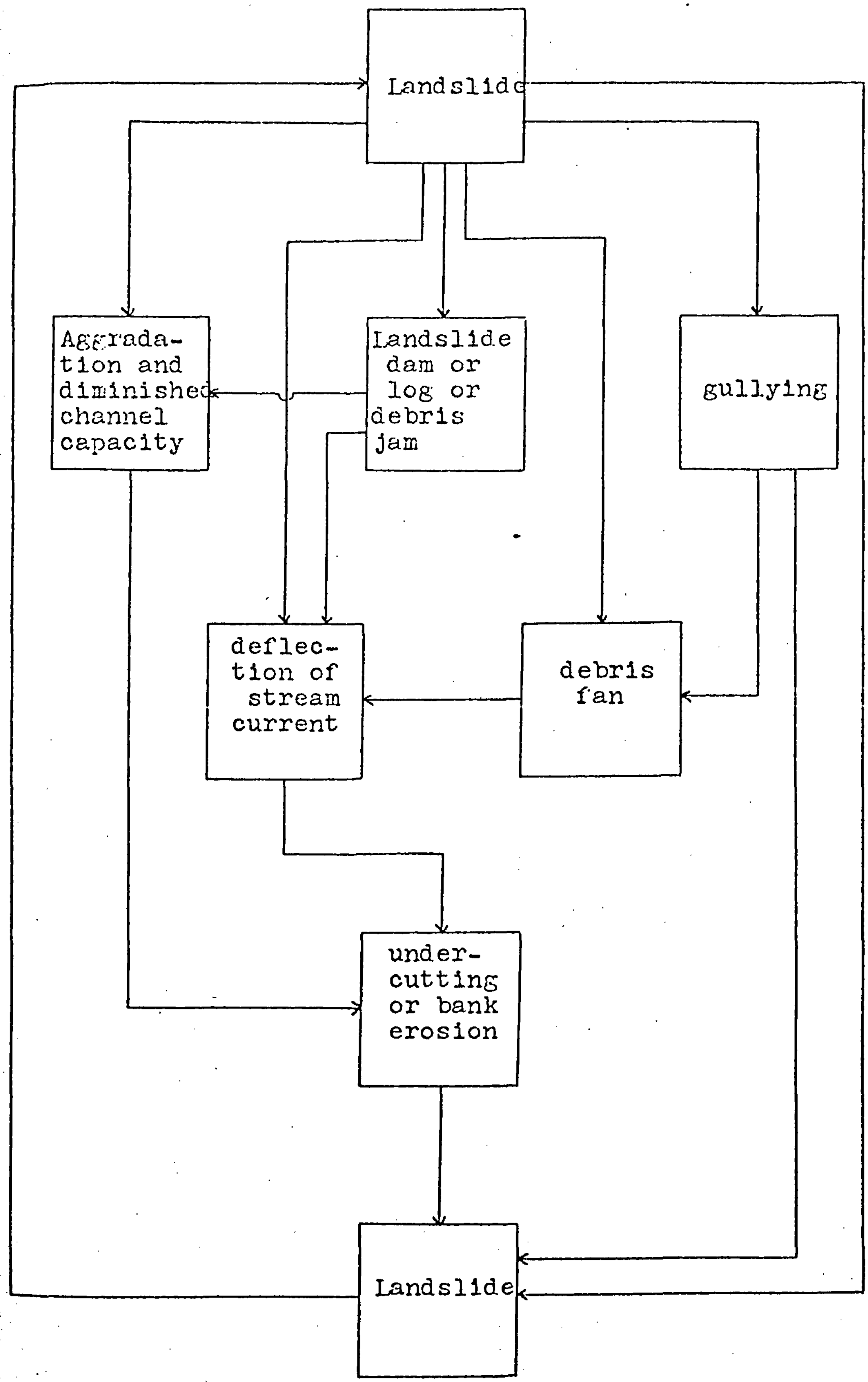


Figure 23. Schematic representation of interactions of processes.

RELATIVE EFFECTS OF TIMBER HARVEST AND FLOODS

Timber harvest and extreme floods have both played major roles in the recent large increase in landslide activity on the lower slopes adjacent to Redwood Creek. Major difficulties exist in attempting to assess the relative importance of these two factors. The fact that the effects often act in conjunction or in combination, and involve complexly interrelated processes is the major difficulty. Other problems result from the time lag associated with many processes, including the decay of root systems, transportation of sediment and debris, progressive slope failure, and gully development.

Evidence that suggests that timber harvest was the most important factor in the increase in landslide activity includes the following:

1) Some areas, particularly the area above Snow Camp Creek, did not experience major disruption until after they were logged, even though they had experienced major floods before they were harvested (See Appendices I and II).
2) Other areas (Redwood Creek in the Devil's Creek - Panther Creek area, Minor Creek, and several unnamed tributaries in the upper basin) experienced much more damage during floods

immediately after they were logged than during subsequent floods or during floods occurring before they were harvested.

3) Road related slope failures, possibly the major impact of timber harvest (Swanston, 1970), often require only saturated conditions and moderate runoff, which occur almost every winter.

4) Removal of root support following timber harvest is independant of floods and appears to be important, especially on slopes greater than about 30 degrees (58%) and in areas of non-Redwood vegetation.

5) Increased "partial area" contribution to runoff on logging disturbed lands increases the severity of frequently occurring moderate floods.

In contrast, evidence which suggests that extreme floods rather than timber harvest have been more directly responsible for the increase in landslide activity includes the following:

1) The major changes in slope activity in the basin occurred on the lower slopes adjacent to the stream channels.

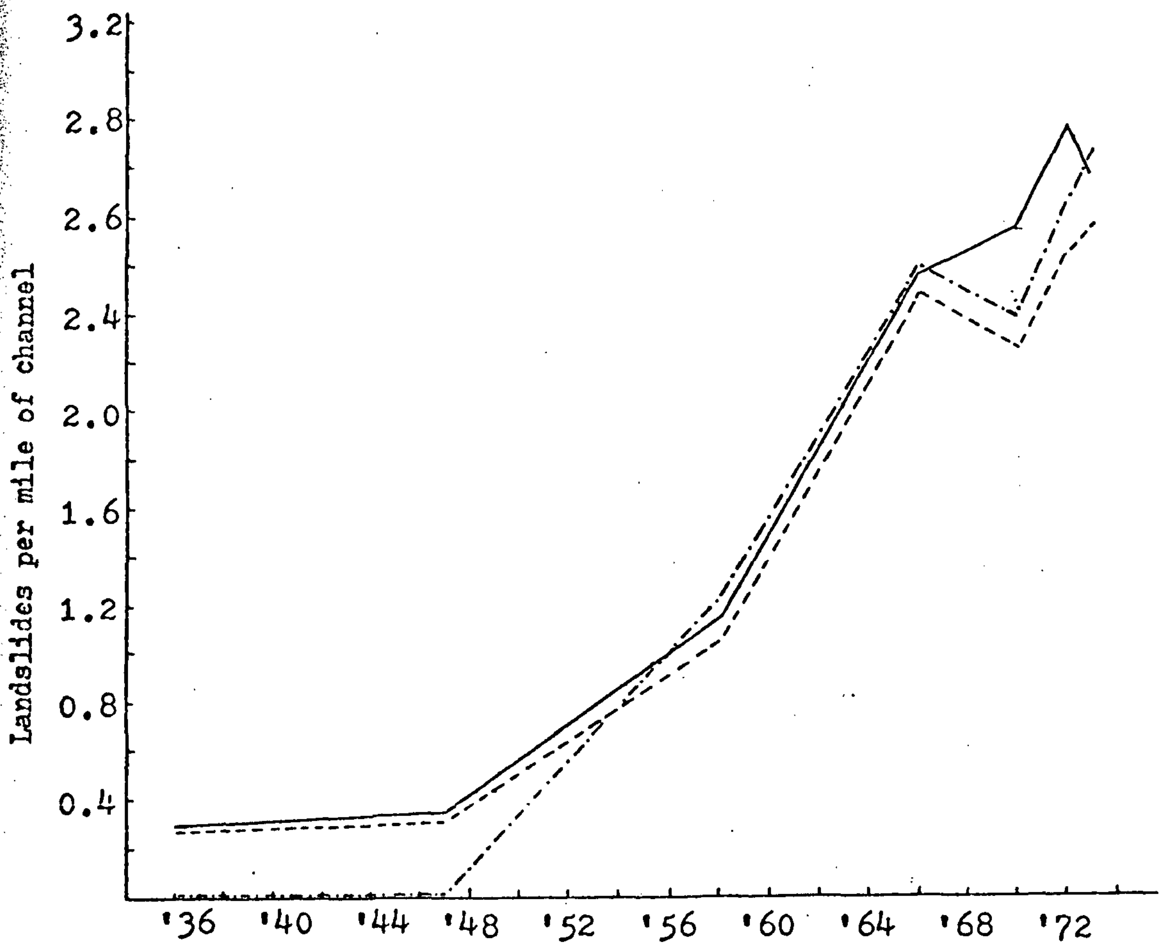
2) Figure 24 and Table 8 indicate that the number of landslides per mile of channel in logged areas has remained approximately equal to that in unlogged areas, and both have increased at about

TABLE 8

LANDSLIDES ADJACENT TO THE CHANNEL OF REDWOOD CREEK

	Number of slides				Miles of coverage				Slides/mile			
Year	1	2	3	4	1	2	3	4	1	2	3	4
1936	21	0	3	24	69.4	0.0	12.2	81.6	0.30	0.00	.24	0.29
1947	28	0	3	31	82.2	0.0	12.0	94.2	0.34	0.00	.25	0.32
1958	93	26	3	122	80.2	21.4	13.4	115.0	1.16	1.21	.22	1.06
1966	125	137	4	266	48.8	52.8	13.4	115.0	2.56	2.59	.30	2.31
1970	90	164	3	257	32.8	68.8	13.4	115.0	2.74	2.38	.22	2.23
1972	92	206	4	302	29.2	72.4	13.4	115.0	3.15	2.85	.30	2.63
1973	85	225	5	315	28.9	72.2	13.4	115.0	2.94	3.09	.37	2.74

(1=in timber, 2=in cutover land, 3=along the floodplain or low, untimbered terrace, 4=total.)



——in timber
–·–·–in cutover land
- - - -average, including flood plain and untimbered terrace

Figure 24. Landslides per mile of channel along Redwood Creek.

the same rate from 1947 to 1973. In addition, as of 1973, the volume of material contributed to Redwood Creek per mile of channel by these landslides was about the same in logged (13,900 cubic yards per mile) and unlogged (13,200 cubic yards per mile) areas.

3) The majority of the landslides on the slopes adjacent to the channel of Redwood Creek were triggered by removal of toe support by stream erosion (Appendix I).

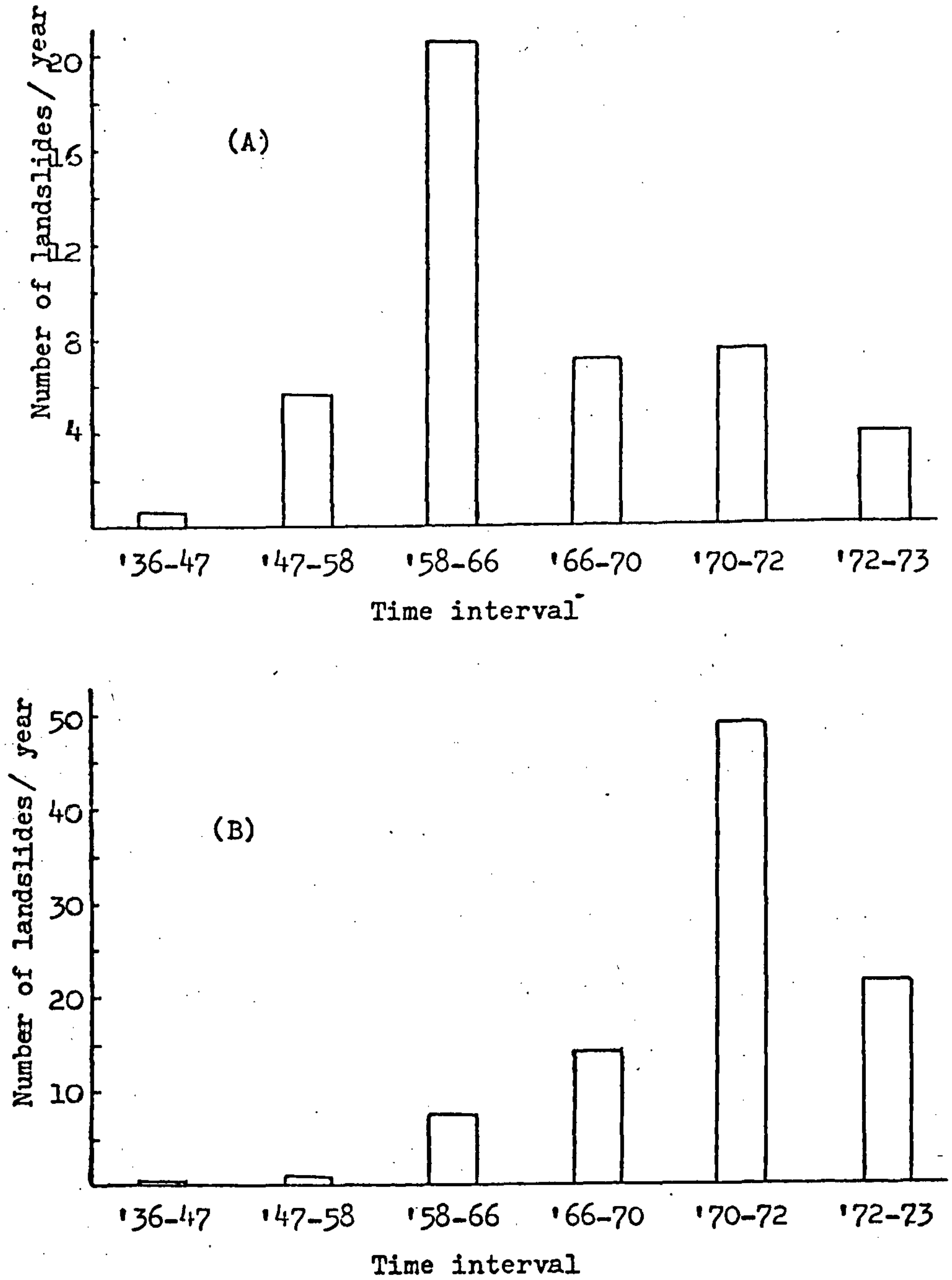
4) The severity of most of the effects of logging is directly related to the amount of water present, and thus is greatly aggravated by the occurrence of floods.

5) Although the distribution of landslides in time is limited to the intervals between photography, much more landslide activity occurred during intervals which included a major flood than during intervals which did not (Table 9 and Figure 25). The closer spaced photography between 1970 and 1973 indicates that most of the landslides occurred during or immediately after the flood event. Observations of landslide debris mixed with flood gravel is also indicative of a close association between flood and landslide events.

TABLE 9

COMPARATIVE LANDSLIDE ACTIVITY

	'36-47	'47-58	'58-66	'66-73	'70-72	'72-73
No. increased	2	15	60	57	98	22
No. same	62	91	94	167	143	248
No. decreased	9	7	28	57	16	14
No. total in both years	73	113	182	281	257	284
No. new	8	63	165	29	13	4
No. total	81	176	347	310	270	288
% increased	2.7%	13.3%	33.0%	20.3%	38.1%	7.8%
% same	85.0%	80.5%	51.6%	59.4%	55.7%	87.3%
% decreased	12.3%	6.2%	15.4%	20.3%	6.2%	4.9%
Number/year increased	0.18	1.36	7.50	14.25	49.00	22.00
No./year new	0.73	5.72	20.62	7.25	7.50	4.00
%/year increased	0.25%	1.21%	4.12%	5.75%	19.05%	7.80%



<u>Figure 25</u>. A: Number of new landslides per year along the channel of Redwood Creek.

B: Number of landslides which increased in size or activity along the channel of Redwood Creek, per year.

Table 9 and Figure 25 also give some indication of the effects of the individual floods. The number of new landslides per year rose sharply from 1947 to 1966 with a peak between 1958 and 1966. Thereafter it fell sharply from 1966 to 1970, rose slightly during 1970 to 1972, and fell again from 1972 to 1973. The number of existing landslides which increased in size or activity rose sharply to a peak in 1972, followed by a drop between 1972 and 1973.

These data are interpreted as follows; the 1953 and 1955 floods initiated the large increase in the number of landslides and partially contributed to the unstable conditions leading to the impact of the 1964 flood, which had the most deleterious effect on slope stability of any of the recent storms. By 1972, most of the areas prone to landsliding (old landslides, unstable areas, outsides of stream bends, etc.) had already experienced some slope failure, so that the major impact of the 1972 flood was the increase in size or activity of many of the pre-existing landslides. These data also indicate that the sequence and concentration of the floods added to their individual effects.

Tables 8 and 9 and Figures 24 and 25 contain important evidence that floods have had the most direct influence on the large increase in the number of landslides adjacent to Redwood Creek. However, these data are limited to some extent by the inequities in scale and coverage of the photography from various years, so that the areas compared are not exactly the same. The 1936 photographs, in particular, cover only the lower, less active portions of the basin. There are also minor gaps in the 1947, 1970, and 1973 photography. Comparison of the "floodless" time periods between 1936 and 1947, and between 1966 and 1970 for landslides that were covered in all four years demonstrates that, while there were many more landslides present in the latter period, the number that increased in size or activity was approximately equal to the number that decreased through both periods. Thus, the information obtained from the two periods is comparable; it appears that the gaps in the photocoverage do not seriously affect the conclusions reached from the data in Tables 8 and 9 and Figures 24 and 25.

CONCLUSIONS

A comparison of the maps depicting mass movement features made from 1936-47 and from 1972 aerial photographs indicates that the most important change in mass movement activity was the large increase in the number of landslides on the lower slopes adjacent to Redwood Creek and its major tributaries. Because the major changes between 1947 and 1972 in basin conditions which control slope stability were an unusual number of extreme floods and an increase in the intensity of timber harvest, these two factors are probably responsible for the observed change in mass movement.

Evidence presented in this study indicates that although both major floods and timber harvest have played a major role in the large increase in the number of landslides on streamside slopes, the floods were the most important factor. The fact that the number and volume of landslides per mile of channel in logged areas has remained approximately equal to that in unlogged areas, and that both have increased at about the same rate is a very strong argument for the major role of extreme floods. Although the number of landslides is not in itself convincing, the volumes of these landslides per mile of channel was also about the same for logged and unlogged areas (13,900 and 13,200 cubic yards per mile, respectively), as of 1973.

However, timber harvest has been an integral part of the conditions which led to the increase in landslide activity. Locally, timber harvest may be the determining factor in an increase in slope activity; the section of Redwood Creek above Snow Camp Creek is a particularly good example. The effects of timber harvest are more subtle and less direct in contributing to slope failure. Nonetheless, by acting through an interrelated complex of processes, the impact of timber harvest on slope stability is far reaching, particularly when combined with floods. The important point is not so much which factor has had the greater effect, but that the combination of extreme floods and timber harvest is particularly destructive to slope stability in this region. Many areas were observed in the Redwood Creek basin that "survived" either timber harvest or a major flood alone, but were devastated by the combination of the two. The effects of the combination of timber harvest and major floods probably are much greater than the sum of the individual effects of each one separately.

The importance of the combined effects results from the interrelationships, reinforcement, and positive feedback that exists among slope and fluvial processes. Any disturbance on the slope or along the channel is likely to propagate through a whole series of related events. A major flood not only produces both slope and channel disturbances, but creates settings in which those disturbances are propagated more rapidly and to a greater extent than usual.

similarly, timber harvest is often responsible for both slope and channel disturbances, and creates conditions which worsen the impact of floods.

REFERENCES CITED

Barbat, W.F., 1971, Megatectonics of the Coast Ranges, California: Geol. Soc. Am., Bull., vol. 82, no. 6, p. 1541-61.

Barr, D.J. and Swanston, D.N., 1970, Measurement of creep in shallow, slide-prone till soil: Am. Journ. Sci., vol. 269, p. 467-480.

Bishop, D.M. and Stevens, M.E., 1964, Landslides on logged areas in Southeast Alaska: U.S. Forest Service Research Paper NOR-1, 18 p.

Brown, W.M.III and Ritter, J.R., 1971, Sediment transport and turbidity in the Eel River Basin, California: U.S. Geol. Survey Water Supply Paper 1986, 70 p.

Crandell, D.R., 1965, The glacial history of Western Washington and Oregon: The Quaternary of the United States, Wright, H.E. Jr. and Frey, D.G. ed., Princeton University Press, p. 341-353.

Crowell, J.C., 1968, The California Coast Ranges: Univ. Missouri, Rolla, Journ. MO.1, p. 133-156.

Curry, R.C., 1973, Resource management actions affecting the Redwood Creek corridor - options paper: U.S. Dept. of the Interior, Office of the Assistant Secretary for Fish and Wildlife and Parks, 17 p.

Diller, J.S., 1902, Topographic development of the Klamath Mountains: U.S. Geol. Survey Bull. 196, 69p.

Dunne, T. and Black, R.D., 1970, Partial area contributions to storm runoff in a small New England watershed: Water Resources Research, vol. 6, no. 5, p. 1296-1311.

Dyrness, C.T., 1967, Mass soil movement in the H. J. Andrews Experimental Forest: U.S. Forest Service Research Paper PNW-42.

Fairbridge, R.W., ed., 1968, The Encyclopedia of Geomorphology, Reinhold Book Corp., New York, 1295p.

Gilbert, G.K., 1877, Report on the geology of the Henry Mountains, U.S. Geographical and Geological Survey of the Rocky Mountain Region, U.S. Government Printing Office, Washington, D.C., ch. 5, p.93-144.

Gilbert, G.K., 1909, Convexity of hilltops: Journ. Geol., vol. 17, p. 45-65.

GrAy, D.H., 1970, Effects of forest clearcutting on the stability of natural slopes: Bull. Assoc. of Engineering Geologists, vol. 7, no. 1, p. 45-65.

Hack, J.T. and Goodlett, J.C., 1960, Geomorphology and forest ecology of a mountain region in the Central Appalachians: U.S. Geol. Survey Prof. Paper 347, 66p.

Helley, E.J. and LaMarche, V.C., 1968, December 1964, a 400-year flood in Northern California: U.S. Geol. Survey Prof. Paper 600-D, p. D34-D37.

Hicks, B.G. and Collins, T.K., 1970, Use of engineering geology to reduce the impact of road construction and clearcut logging in the forest environment: Assoc. of

Engineering Geologists, Program, 13th National Meeting.

Hickey, J.J., 1969, Variations in low water streambed elevations at selected stream - gaging stations in Northwestern California: U.S. Geol. Survey Water Supply Paper 1879-E, 33p.

Hsü, K.J., 1968, Principles of mélanges and their bearing on the Franciscan - Knoxville paradox: Geol. Soc. Am., Bull., vol.79, no. 8, p. 1063-1074.

Janda, R.J., 1972, Testimony concerning stream sediment loads in Northern California and Southern Oregon presented in public hearings before the California Regional Quality Control Board, North Coast Region, in Eureka, California, July 19, 1972, 24p.

Kojan, E., 1968, Mechanics and rates of natural soil creep: Proceedings of the First Session of the International Assoc. of Engineering Geology, p. 122-154.

Lane, K.S., 1967, Stability of reservoir slopes: Failure and Breakage of Rocks, Proceedings of the Eight Symposium on Rock Mechanics, 1966, Fairhurst, C., ed., p. 321-336.

Leopold, L.B., Wolman, M.G., and Miller, J.P., 1964, <u>Fluvial Processes in Geomorphology</u>, W.H. Freeman and Co., San Francisco, 522p.

Lorens, P.J., Dwyer, M.J., and Scott, R.G., 1971, Reconnaissance study of landslide conditions and related sediment production on a portion of the Eel River and selected tributaries: Memorandum Report, September, 1971, State of California, The Resource Agency, Dept. of Water Resources, Northern District.

Manning, G.A. and Ogle, B.A., 1950, Geology of the Blue Lake Quadrangle, California: Calif. Div. Mines Geol., Bull. 148, 30 p.

Nilsen, T.H., 1972, Preliminary photointerpretation map of landslide and other surficial deposits of the Mount Hamilton Quadrangle and parts of the Mount Boardman and San Jose Quadrangles, Alemeda and Santa Clara Counties, California: U.S. Geol. Survey Miscellaneous Field Studies Map MF-33.

Rantz, S.E., 1959, Floods of January, 1953 in Western Oregon and Northwestern California: U.S. Geol. Survey Water Supply Paper 1320-D, p.321-339.

Rothacher, J., 1970, Regimines of stream flow and their modification by logging: Proceedings of a Symposium on Forest Land Uses and Stream Environment, Oct. 19-21, 1970, School of Forestry, and Dept. of Fisheries and Wildlife, Oregon State University, p.40-54.

Schumm, S.A., 1956, The role of creep and rainwash on the retreat of badland slopes: Am. Journ. Sci., vol. 254, p. 693-706.

Sharp, R.P., 1960, Pleistocene glaciation in the Trinity Alps of Northern California: Am. Journ. Sci., vol. 258, p. 305-340.

Sharpe, C.F.S., 1938, Landslides and Related Phenomena, Columbia University Press, New York, 137p.

Strand, R.G., 1963, Weed and Redding sheets, geologic map of California (1:250,000), Olaf P. Jenkins edition: Calif. Div. Mines Geol.

Swanston, D.N., 1970, Principal mass movement processes influenced by logging, road building, and fire: Proceedings of a Symposium on Forest Land Uses and Stream Environment, Oct. 19-21, 1970, School of Forestry and Dept. of Fisheries and Wildlife, Oregon State University, p.29-57.

U.S. Dept. of Agriculture River Planning Staff, Soil Conservation Service, and the Forest Service in cooperation with the California Dept. of Water Resources, 1970, Water, land and related resources, North Coastal area of California and portions of Southern Oregon; Appendix No. 1, Sediment yield and land use treatment, Eel and Mad River basins: Portland, Ore., June, 1970.

U.S. Geologial Survey, 1970, Surface water supply of the United States: U.S. Geol. Survey Water Supply Paper 1929, part II, vol. 2, 673p.

Verhoogen, J., Turner, F.J., Weiss, L.E., Wahrhaftig, C., and Fyfe, W.S., 1970, The Earth, Holt, Rinehart, and Winston, Inc., San Francisco, ch. 7, p.317-383.

Waananen, A.O., Harris, D.D., and Williams, R.C., 1971, Floods of December, 1964 and January, 1965 in the far western states: U.S. Geol. Survey Water Supply Paper 1866-A, p.A1-A265.

Wahrhaftig, C. and Birman, J.H., 1965, The Quaternary of the Pacific mountain system in California: The Quaternary of the United States, Wright, H.E. Jr. And Frey, D.G., ed., Princeton University Press, p.299-340.

Wahrhaftig, C. and Cox, A., 1972, Testimony presented to the (California) Assembly Committee on Natural Resources, concerning soil erosion in Redwood forests, and suggestions for legislation, Eureka, California, Jan. 14, 1972, 25p.

Zinke, P.J., 1965, Relationship of land use to 1964-1965 flood: Proceedings, State Board of Forestry Meeting, Feb. 26, 1965, State of California, The Resource Agency, Dept. of Conservation, Division of Forestry, p.47-52.

Zinke, P.J., 1966, The physiography of the watershed and relation to Redwood preservation: A Symposium on Management for Park Preservation -- A Case Study at Bull Creek, Humboldt Redwoods State Park, sponsored by the School of Forestry, University of California, Berkeley, 12p.