UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY (U.S.)

INFLUENCE OF CLIMATE ON PROGRESSIVE HILLSLOPE FAILURE IN REDWOOD CREEK VALLEY, NORTWESTERN CALIFORNIA

By D. N. Swanston, R. R. Ziemer, and R. J. Janda

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INFLUENCE OF CLIMATE ON PROGRESSIVE HILLSLOPE FAILURE IN REDWOOD CREEK VALLEY, NORTHWEST CALIFORNIA

Open-File Report

UNITED STATES DEPARTMENT OF THE INTERIOR

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GEOLOGICAL SURVEY

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CONVERSION FACTORS

For use of readers who prefer to use inch-pound units, conversion factors for terms used in this report are listed below.

Multiply SI Units	By	To obtain inch-pound units
kilogram (kg)	2.205	pound, avoirdupois
kilometer (km)	6.22×10^{-1}	mile (mi.)
meter (m)	3.281	foot (ft.)
millimeter (mm)	3.937×10^{-2}	inch (in.)
square kilometer (km^2)	3.861×10^{-1}	square mile (mi^2)

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Abstract

Both creep and earthflow processes control hillslope erosion over large parts of the Redwood Creek basin. The type of process and displacement rates are largely dependent on underlying bedrock type and precipitation input.

Progressive creep with rates ranging from 1.0 to 2.5 mm/a dominates on slopes west of the Grogan fault underlain by sheared and foliated schists. Movement appears to respond primarily to annual increments of precipitation. Complex earthflows occur predominantly on slopes east of the Grogen fault underlain by sheared graywacke and mudstone. Movement rates range from 3.0 to 131.0 mm/a and characteristically display dominant rainy season movement.

Influence of Climate on Progressive Hillslope Failure in Redwood Creek Valley, Northwest California

by

D. N. Swanston[1], R. R. Ziemer[1], and R. J. Janda[2]

INTRODUCTION

Redwood Creek Valley is approximately 60 km north of Eureka in the northern California Coast Ranges. Its 730-km^2 drainage basin comprises some of the most rapidly eroding terrain in North America. High rates of erosion, produced by extensive soil mass movement and associated stream bank cutting, are the result of a combination of rock types, geologic history, climate, and land-use patterns that exist over large areas of northwestern California and southwestern Oregon.

Resulting in part from harvest activities within this highly erosive drainage basin, recent major floods and attendant accelerated mass movement of mantle materials into channels have caused drastic changes in channel characteristics and sedimentation rates. Both soil creep and earthflow processes appear to dominate hillslope erosion across large parts of the basin. The mechanics of these processes have been investigated experimentally and theoretically by a number of workers (Goldstein and Ter-Stepanian 1957;

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Saito and Uezawa 1961; Culling 1963; Bjerrum 1967) but field measurements are limited. Under field conditions, local variations in soil properties, degree and depth of parent material weathering, and clay and water content of mantle materials lead to substantial variations in movement processes and rates.

In 1974, in response to the needs of public and private land managers for quantitative information on the response of creep and earthflow processes to natural events and to harvest disturbances in the lower Redwood Creek basin, the USDA Forest Service, in cooperation with the U.S. Geological Survey, began monitoring movement at eight sites on the east and west slopes of the basin. This study is part of a broad study of creep and earthflow processes in the Coast Ranges and Cascades of Oregon, Washington, and northern California (Swanston, 1981). The study was designed to: (1) quantify natural rates of movement and define the mechanics of movement by process (creep or earthflow), (2) determine the influence of geologic materials on movement process and rates, (3) assess the impact of timber removal on movement, and (4) determine the effects of seasonal and annual rainfall on movement. This paper reports the results of six years of data accumulated during the study. That part of the study addressing the impacts of timber removal was eliminated when the study sites designated for harvest were included in the expanded Redwood National Park.

AREA DESCRIPTION

Drainage Characteristics

The drainage basin of Redwood Creek encompasses about 730 km^2 of rugged terrain within the Coast Ranges of northern California. The basin is strongly elongated north-northwesterly and is about 90 km long and 7.2 to 11.1 km wide through most of its length (fig. 1). Redwood Creek flows north-northwest along the axis of the basin and turns westward abruptly at the basin mouth to empty directly into the Pacific Ocean. Drainage density is about 4.8 km/km^2 for the basin as a whole, measured from standard 15-minute quadrangle maps, with the headwaters showing slightly greater density than downstream areas (Iwatsubo and others 1976). Total basin relief is about 1615 meters with the cross-sectional relief normal to the basin axis in the vicinity of this study is about 229 meters. The average gradient in the basin is 14.4 degrees (26%) but more than half of the individual hillslopes display average gradients in excess of 19 degrees (35%).

Climate

The climate of the northern part of the basin where this study was made is of the coastal Mediterranean type with mild, wet winters and short, warm, dry summers with frequent fog. The full spectrum of climatic variability within the basin is not well known because long-term climatological data have not been collected. Sixteen recording rain gages were installed by the U.S. Geological Survey in 1974 in various locations within Redwood National Park (Iwatsubo and others 1975), but the most usable body of climatological data is the daily recorded precipitation and temperature that have been collected continuously since 1937 near the mouth of the basin at Orick-Prairie Creek State Park. Prairie Creek data and the data obtained from the U.S.G.S. gage installed in the study area along the K and K Road show good correlation. Because of this and the 45-year record, it is the Prairie Creek data on which our subsequent analyses are based. The mean monthly precipitation, runoff, and temperatures for Orick-Prairie Creek State Park for the water years

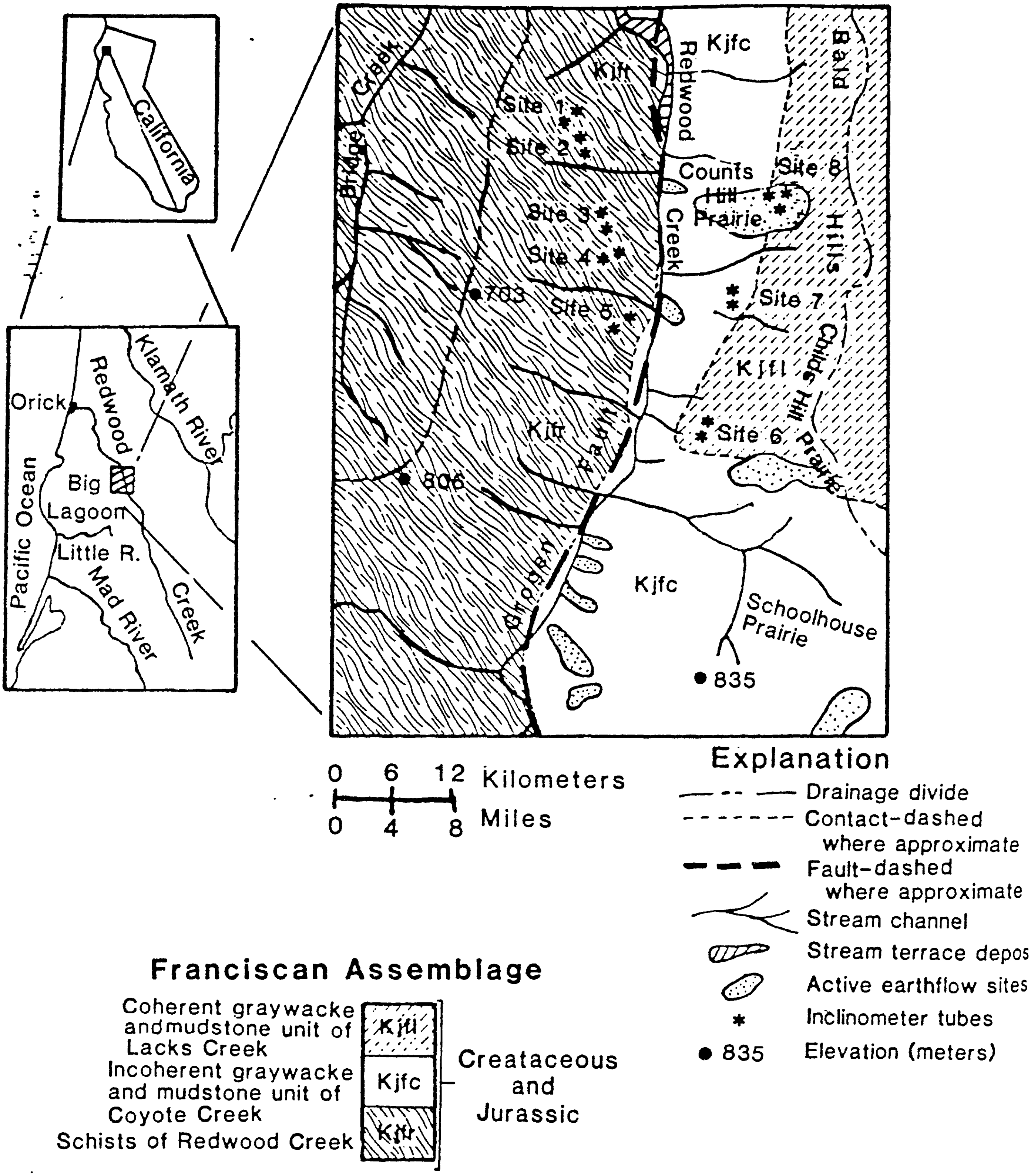

Figure 1. Map of part of lower Redwood Creek showing important geologic units, structure, and monitoring locations. Modified from Harden and others, 1981.

1954-1972 are shown in figure 2. The mean maximum temperatures in July range from about 20.5° to 34.6°C, and mean minimum temperatures in January range from about 0° to 2.7°C.

The estimated mean annual basin-wide precipitation is 2032 mm, but altitude, proximity to the ocean and slope aspect profoundly influence the amount of precipitation at any given location (Rantz 1964, 1969). It is common for the mean annual precipitation to vary by as much as 833 mm per thousand meters of altitude. The mean annual precipitation at Orick-Prairie Creek State Park from 1938-1980 is 1,748 mm (fig. 2). Annual precipitation at the Prairie Creek weather station during this study (1975-1980) was above the long-term average for two of the years and below average for four of the years. The greatest annual precipitation during the 45-year record occurred during the 1974 water year (the year immediately preceeding the study) when rainfall was 143 percent of the mean. The driest year of record was 1977, when annual rainfall was 46 percent of the mean. The seasonal distribution of precipitation is characterized by heavy winter rainfall and pronounced summer drought (fig. 3). Snow is rare in this rain-dominated basin, but infrequent snowfall with subsequent rapid melt contributes to the magnitude of some of the largest and most damaging floods.

Vegetation

Productive soils, moderate temperatures and seasonally abundant moisture support a mixed cover of dense forest and prairie vegetation. Mineral soil is exposed under natural conditions only where vegetal cover is disrupted by various forms of mass movement or lateral corrasion adjacent to the stream channel. In the area of study, redwood (<u>Sequoia sempervirens</u> [D. Don] Endl.)

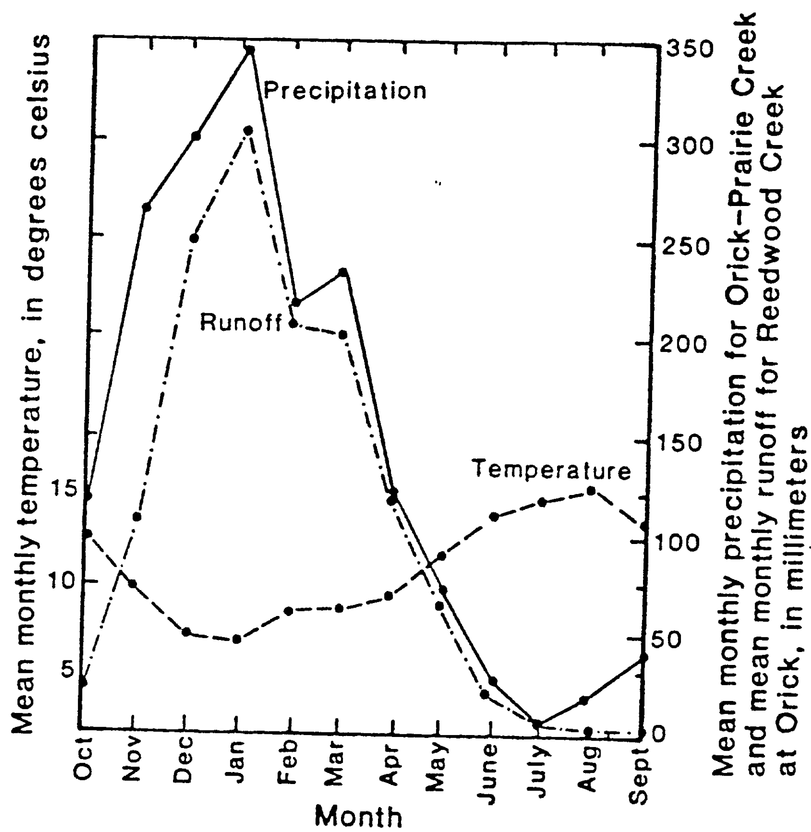

Figure 2. Mean monthly temperature amd precipitation for Orick-Prairie Creek State Park and mean monthly runoff for Redwood Creek at Orick for water years 1954-1972 (from Janda and others, 1973).

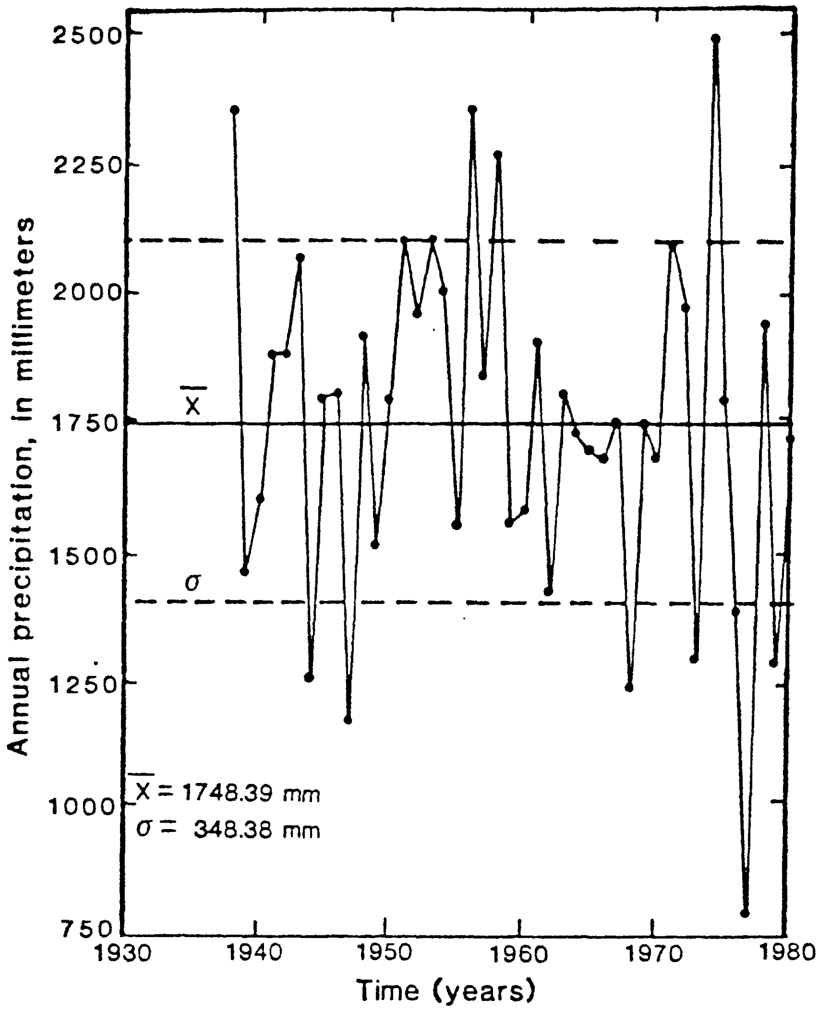

Figure 3. Annual precipitation over the period 1938-1980 (42 years) recorded at Orick-Prairie Creek State Park. Mean annual precipitation ($\bar{x}$) is 1748.39 mm - standard deviation (σ) is 348.38 mm.

is the dominant tree on the relatively moist floodplains, low stream terraces, and lower hillslopes adjacent to the main channel. On the upper slopes, Douglas-fir (Pseudotsuga menziesii [Mirb.] Franco) is the dominant conifer in association with western hemlock (Tsuga heterophylla [Raf.] Sarg.), tanoak (Lithocarpus densiflora [Hook. & Arn.] Rehd.), and Pacific madrone (Arbutus menziesii Pursh). Areas of natural prairie and woodland vegetation are intimately associated with forested areas throughout most of the basin. The most common communities of nonforest vegetation are grass prairies, grass-bracken-fern prairies, oak-grass woodlands, oak-poison oak-grass woodlands and oak-madrone-brush woodlands. The origin of the grass and grass-bracken-fern prairie is partly the result of mass movement (Coleman 1973), natural and Indian-set fires (Lewis 1973), and lateral variability in soil parent materials (Zinke 1966).

Geology

The lithologic and structural properties of the rocks of the Redwood Creek basin make them highly susceptible to chemical decomposition and erosion. The entire basin upstream from its mouth is underlain by the strongly indurated Franciscan assemblage of rocks, both Jurassic and Early Cretaceous in age.

Virtually unmetamorphosed sedimentary rocks underlie most of the eastern side of the basin. Graywacke sandstone (lithic and arkosic wacke) is the most abundant. Lesser amounts of mudstone and conglomerate are present.

Metamorphosed sedimentary rocks, mapped as the Kerr Ranch Schist by Manning and Ogle (1950) and the schist of Redwood Creek by Harden and others (1981) underlie most of the western half of Redwood Creek basin. These consist mostly of light-to-medium gray, well-foliated, quartz-mica-feldspar schists and mica schists. In most localities the rock is intensively sheared and foliation is well developed, steeply dipping and intricately deformed.

These main rock units are separated by the north-northwest trending Grogen fault, which is closely followed by the main channel of Redwood Creek in the northern part of the basin. Intensively sheared rocks, including serpentine, are associated locally with the fault, and mass movement failures or active creep movement commonly occur on either side of its trace. The interbedded graywacke and mudstone underlying the east slope gets finer grained and more intensively sheared toward the Grogen fault and southward of the mouth of the basin (Harden and others 1981). In the vicinity of the monitoring sites, the upper part of the slope is underlain by relatively coherent graywacke-mudstone sequences (fig. 1). High sandstone content, the presence of massive beds and less intense shearing and fracturing, result in steeper, straighter hillslopes. In contrast, the middle and lower slopes are underlain by incoherent, more highly sheared and fractured sequences with greater amounts of mudstone (Figure 1). The incoherent rocks underlie a subdued rolling landscape that has less deeply incised drainages than those developed on the coherent unit. Expanses of grass-oak woodland and grass-bracken fern prairies commonly develop on active mass movement terrain.

Naturally occurring bedrock outcrops are scarce in areas away from Redwood Creek because of a near-continuous mantle of colluvium, deep residual soil, and saprolite produced by hillslope erosion processes and mechanical and chemical weathering. Collectively, such surficial "regolith" thicknesses are highly variable, ranging from less than 0.6 meters on hilltops and divides to more than 15 meters beneath landslides and actively moving mid and lower slope sites.

The colluvium is mostly stony loam and stony-clay loam that appear to represent displaced saprolite and residual soil. The saprolites developed from both the schists and graywacke-mudstone units display alternating zones of fairly competent rock separated by sections extensively altered by chemical decomposition and leaching. Such altered zones are mostly associated with subsurface water movement.

Mass Movement Related Landforms

Many hillslopes in the Redwood Creek basin are unstable and highly susceptable to mass movement failure because of the steepness of the terrain and the low shear strength of much of the underlying saprolite and soil. According to Coleman (1973), at least 36 percent of the basin shows landforms that are the result of active mass movements or that are suggestive of former mass movement failures. Steep, straight colluvium veneered hillslopes underlain by coherent graywacke and mudstone are sculptured primarily by infrequent, shallow, debris avalanches and debris flows. Smooth convex-upward hillslopes typically developed on sheared schists, and incoherent graywacke and mudstones reflect erosion by creep and earthflow processes. The steep lower segments of these hillslopes, especially adjacent to the main channel of Redwood Creek, show numerous small-scale discrete failures involving both rotational and translational movement. Such discrete failures may be triggered by excessive strain in the creeping materials due to the loading of lower slopes with material from above or by removal of the slope toe by lateral erosion along Redwood Creek and its tributaries.

Complex associations of rotational slumping, translation, and flowing movement classified as earthflows are the most visually obvious forms of mass movement in the Redwood Creek basin. Such earthflows exhibit subdued scarps, flats, and hummocky and lobate microtopography. Some have clearly defined margins but many gradually merge with less active areas of soil creep. On many, grass, grass-bracken-fern and grass-oak prairie vegetation dominate in marked contrast to the mature coniferous forest or cut-over land on more stable slopes.

METHODS

Site Selection and Preparation

During summer, 1974, seven sites were selected with the cooperation of Simpson Timber Company and Louisiana-Pacific Corporation on private lands which had been partly logged or which were planned for logging within the following 5-year period (see fig. 1). Where possible, sites were paired to reflect any differences between logged and unlogged slopes. A concerted effort was made to avoid areas of current clearly definable active earthflow activity. The one exception to this was a recently logged dense conifer forest site (site 6) which exhibited surficial signs of active creep and earthflow. Monitoring instruments were installed at sites RC-1 through RC-4, located at midslope on the west side of the basin in saprolite overlying Schists of Redwood Creek, during fall 1974. Monitoring instruments were installed at sites RC-5 through RC-7 during fall 1975. Site RC-5 was located in saprolite overlying schist near the channel of Redwood Creek. Sites RC-6 and RC-7 were located at midslope on the east side of the basin; site 6 in saprolite overlying the coherent graywacke and mudstone unit of Lacks Creek, and site 7 in saprolite overlying the incoherent graywacke and mudstone unit of Coyote Creek (Harden and others, 1981) (fig. 1). In cooperation with the U.S. Geological Survey, one additional site was located and instruments installed in fall 1976 to investigate the subsurface movement occurring within the Counts Hill Prairie earthflow (fig. 1). The Counts Hill Prairie earthflow is developed in deeply weathered graywacke and mudstone across the boundary of the coherent and incoherent units.

Borehole Tube Installation

Movement within the soil mantle was determined by measuring the change in the shape of polyvinyl chloride (PVC) tubes at discrete time intervals after installation. Two access tubes were installed at each site approximately along the fall line of the slope to detect any similarities or differences in the rate and mechanics of movement with slope location. The tubes were installed in 130-mm diameter boreholes drilled by a truck-mounted auger through active soil materials and anchored at the bottom in bedrock.

The anchoring of the bottom of the access tubes was important for proper interpretation of the resulting data. If it could be reasonably assumed that the bottom of the tube was stable and did not move between surveys, a three dimensional coordinate system could be defined within which the deformation of the access tube could be calculated. The initial tube configuration and any changes between surveys were then reconstructed from the bottom upward. The depth to which access holes were drilled and the location of underlying stable material or "bedrock" were determined indirectly during the drilling operation by making penetration tests at 1.3-meter intervals until sufficient resistance to penetration was encountered. "Bedrock" was arbitrarily defined as material having a penetration resistance exceeding 60 blows per 30 cm penetration in a standard penetration test (each blow is a constant energy increment of 64 kg being dropped a distance of 76 cm, driving a standard cross-sectional bit). Great care was necessary in the interpretation of these penetration tests because solid blocks of bedrock are commonly incorporated into the moving materials. It was not uncommon to intersect such "floaters" during the drilling process with resulting high penetration resistance. As the approximate depth of weathering and alteration of these materials was known from local bedrock exposures and existing geologic reports, high penetration resistance at shallow depths was considered potentially anomalous and drilling was continued for an additional 3 meters or until softer materials were encountered. Once "bedrock" was reached, the hole was drilled an additional 1 meter and the access tube was installed. Subsequent surveys indicated only small changes in inclination of the bottom 1 meter of most of the access tubes throughout the study period. Instrument error accounts for a major part of these changes, although some minor deformation appears to be occurring in the more stable layers at sites 6 and 8. All tubes except RC-4B were considered fixed for purposes of analysis. Tube RC-4B clearly failed to penetrate the active movement zone and was excluded from further analysis.

After the tubes were installed, the annular space between each tube and the borehole wall around it was backfilled with sand and pea-gravel to provide maximum stable continuity between the tube and surrounding materials. Ziemer (1977) clearly demonstrated the need for such backfilling to obtain reliable quantitative data on movement rates and direction from borehole inclinometer installations. Based on a reanalysis of data obtained over an 8-year period from a network of inclinometer borehole tubes installed in 1964 without backfilling (Kojan 1967), Ziemer (1977) found that no consistent rate or direction of movement could be detected because of continuing differential settlement in the boreholes. Adequate backfilling was difficult at many of the Redwood Creek sites. During the drilling process, vibration and lateral migration of the drill bit caused by rocks or other resistance produced an irregular- shaped borehole. For maximum continuity, all these spaces had to be filled. In practice, the use of in-situ materials proved impossible because of the loss of such materials through their compression into the side-walls of the borehole as the drill bit was advanced and the rather small volume of material recovered from the drill cuttings. The common technique of grouting from the bottom up was considered but proved to be impractical because of the special pumping equipment required and the lack of an adequate water source at most sites. In the earliest installations, fine sand was used to backfill the holes. When air-dropped, fine sand should, in theory, each a maximum density and completely fill the annular space and any voids. Unfortunately, most of the holes intersected groundwater at shallow depths and tended to form a slurry with the churned cuttings. The air-dropped sand in these holes was generally supported on the slurry surface, bridged the hole, and made adequate backfilling below the upper level of the slurry impossible. As a compromise, pea-gravel was used; it generally sank into the slurry and filled the void spaces around the tubes. Subsequent analysis of survey results indicates this backfilling technique was successful in developing the required continuity at all but two tubes (RC-2A and RC-5B). Differential settlement is still occurring in these boreholes and they have been excluded from further analysis.

Instrumentation

The inclinometer access tubes placed in the boreholes were constructed of polyvinyl chloride (PVC) with a 76.2 mm inside diameter and were grooved longitudinally inside at 90 degrees. A mechanical pendulum with electronic readout, fixed in a rigid carriage riding in the grooves, was then passed down the tube to measure changes in inclination of the tube since installation.[3/]

The orientation of the readings, and thus of the relative movement taking place, is governed by the grooves inside the casing. It is, therefore, essential that the grooves be oriented in space as accurately as possible. The four grooves are conveniently referenced as cardinal compass points (north, east, south, and west) and, as far as practicable, tubes were installed with his orientation. The azimuth of the plane defined by the N-S grooves was measured using a Brunton compass to obtain true bearings. All subsequent data sets at each hole were oriented using that azimuth

The instrument has a sensitivity of 1 part in 1000 so that a tilt of as little as 3 minutes of arc can be detected. This means that a lateral displacement of less than 2 cm can be detected over a 30-meter depth. In practice, displacements of less than 2 mm over this depth were consistently identified in this study.

There were five sources of possible instrument error which had to be contended with in obtaining data for this study. These were:

[3/] Grooved tubing and inclinometer device used in this study were developed and are manufactured by Slope Indicator Company, Seattle, Washington. Mention of this product is for identification only and does not imply endorsement by the U.S. Geological Survey.

(1). opposite grooves were not parallel due to distortion of the casing, irregular groove depth, or dirt in the grooves;

(2). instrument not tracking in grooves because of misalignment of tube sections or distortion of casing shape;

(3). error in depth relocation during subsequent surveys;

(4). error in circuit balance or recording of readings and;

(5). instrument malfunction, either due to mechanical/electronic difficulties or to moisture entering the circuitry.

Errors (3) and (4) were primarily operator errors and were easily detected in the field by summing the corresponding pairs of readings at each depth for each cardinal plane. These sums should not vary more than three to five units from their mean for each depth in the vertical sequence. Errors (1) and (2) were also detectable by the above field check and, if not resolved by replacement and re-reading of the inclinometer at a given depth, required withdrawal of the instrument from the hole and a complete re-survey. The fifth source of error generally required abandonment of the survey, repair or drying of the instrument, and re-survey of the hole at a later date. Rainwater entering the instrument case at the surface was the most common cause of this error source. Any additional recording errors were detected by careful screening of data forms prior to computer analysis.

Monitoring Program

Because the Redwood Creek sites lie within a region characterized by high winter rainfall separated by pronounced summer droughts, each tube was surveyed semi-annually in late spring after fall and winter storms and in early fall after the summer dry period. The resulting data allowed the development of plots that relate variations in rate of horizontal movement at each site to depth, seasonal and annual rainfall, and any differences in parent material. The changes in water level in the tubes were also measured at each site in an attempt to relate seasonal water table fluctuations in the mantle to periods of maximum movement.

An earthquake registering 7.0 on the Richter scale occurred during the November 1980 survey with an epicenter at Big Lagoon, about 32 km southwest of the study area. Following this earthquake, sites RC-1 through RC-5 and site RC-8 were resurveyed to determine if any changes in movement rate or displacement had occurred as a result of the ground motion. No identifiable changes were found at the monitoring sites immediately following the event or in the following year of measurement.

Data Analysis

Changes in the inclination of borehole tubes were measured at 0.5-meter intervals from the bottom of the hole. The bottom of the hole was assumed to be fixed. This was based on the competence of the rock determined during drilling and the lack of change in inclination at the bottom of the tube during successive readings over the monitored period. Measurements at each interval were made in two planes (north and east) at 90°. To estimate the configuration of the tubes, the centerline of the casing was approximated by a series of "casing vectors" oriented point to tail from the bottom of the casing to the surface. The number of vectors corresponded to the number of measurement intervals, and their orientations were described by inclination (zenith angle), distance between intervals, and resulting coordinates in the north and east planes (azimuth). By adding the respective coordinates cumulatively up the hole, "position vectors" were defined. The coordinates for these determined the position of the measurement point in three-dimensional space. Subsequent surveys provided the necessary data for vertical profile plots showing distance and direction of movement between successive surveys thoughout the depth of the hole. The analytical methodology and computer programs used to display this data were developed by R. B. Thomas and R. R. Ziemer of the USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Arcata, California.

Variability in direction and distance of movement between successive surveys at each interval were occasionally large (fig. 4). This was due to several factors including, (1) changing movement characteristics of the soil in response to water content; (2) differential adjustment of individual blocks within the moving mantle; (3) settlement and differential movement of the

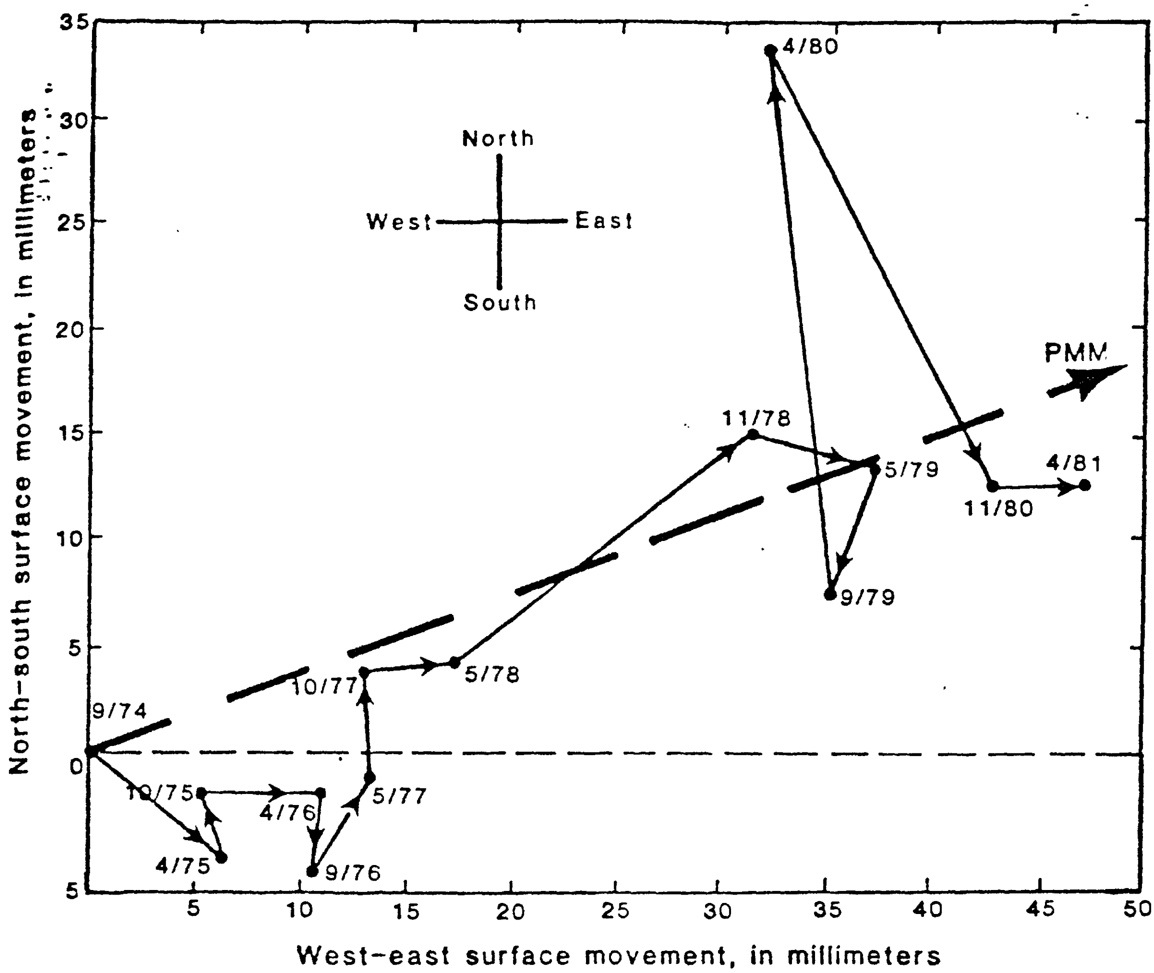

Figure 4. Plot of the surface movement at hole RC-4A on the west side of Redwood Creek showing the variability in distance and direction between successive seasonal readings. The plane of maximum movement (PMM) is determined by the direction of maximum extension of plotted points.

inclinometer tube within the drilled hole due to void spaces and inadequate backfilling, and 4) random instrument error.

For purposes of constructing the vertical profile of movement and comparing profile changes over time, it was necessary to project cumulative "position vector" coordinates into a single plane with an azimuth approximating the dominant movement direction. This plane was designated the Plane of Maximum Movement (PMM). An approximate PMM for each hole was determined graphically from the general direction of a plot of surface movement points over the total period of monitoring (fig. 1).

Once the profiles had been plotted in the Plane of Maximum Movement, strain configuration with depth, displacement, and the location of zones of shear or accelerated deformation were ascertained. Both annual and seasonal rates of movement at the surface were also obtained by calculation and graphic scaling from the profiles. Displacement and rates were then regressed against both annual and seasonal precipitation to ascertain any relationships that might exist between movement and prevailing climatic conditions in the Redwood Creek basin.

RESULTS AND DISCUSSION

Seasonal and annual displacement at the surface for all sites are cataloged in tables 1 and 2 and figures 6, 8, and 10. Profiles constructed for each hole exhibit major types of strain configuration indicative of process mechanics dominating at a particular site (Figs. 5, 7, and 9).

							Survey Date (m-a): 4-75		10-75		4-76		9-76		5-77		10-77	
							Precipitation Between Surveys (mm): 1648		166		1323		123		693		291	
							Movement Between Surveys											
SITE	Disturbance	Parent Material	Movement Type	Hole/ Movement Depth (meters)	Slope Azimuth (degrees)	PMM Azimuth (degrees)	(mm) Total	(mm/d) Rate	(mm) Total	(mm/d) Rate	(mm) Total	(mm/d) Rate	(mm) Total	(mm/d) Rate	(mm) Total	(mm/d) Rate	(mm) Total	(mm/d) Rate
1A	Logged	Schist	Creep	10.5/ 9.6	45	55	-0.2	-0.001	-1.1	-0.007	+1.5	+0.012	-1.3	-0.010	+0.2	+0.002	-0.6	-0.006
1B	Logged	Schist	Creep	9.0/ 9.0	45	275	+2.0	+0.010	-0.5	-0.003	-1.0	-0.005	+1.0	+0.007	-0.5	-0.002	-0.8	-0.006
2B	None	Schist	Creep	4.3/ 4.3	45	45	+0.4	+0.002	+0.8	+0.001	0.0	0.000	+0.9	+0.010	-0.5	-0.002	+0.1	+0.001
3A	None	Schist	block glide	10.1/ 5.5	45	47	+8.9	+0.044	+5.4	+0.032	+12.8	+0.060	+4.0	+0.030	+5.0	+0.020	+3.8	+0.026
3B	None	Schist	block glide	8.1/ 6.4	45	50	+7.4	+0.040	+5.6	+0.030	+7.0	+0.030	+4.1	+0.030	+6.7	+0.030	+3.9	+0.030
4A	Logged	Schist	block glide	18.6/ 12.6	45	70	+4.4	+0.020	-0.8	-0.005	+5.9	+0.030	-1.5	-0.010	+4.0	+0.020	+1.4	+0.010
5A	None	Schist	creep	9.1/ 9.1	45	90	---	------	---	-----	+2.7	+0.010	-0.6	-0.005	+0.2	+0.001	+0.4	+0.003
6A	Logged	Igm*	creep & glide	11.0/ 6.5	225	215	---	------	---	-----	84.4	+0.440	-19.2	+0.130	+28.0	+0.120	+13.0	+0.090
6B	Logged	Igm*	creep & glide	7.6/ 6.1	225	230	---	------	---	-----	48.9	+0.250	+ 7.4	+0.051	+13.3	+0.057	+7.4	+0.054
7A	None	Cgm*	block glide	10.5/ 6.9	225	215	---	------	---	-----	+8.5	+0.040	+ 1.3	+0.010	+2.6	+0.010	-0.8	-0.010
7B	None	Cgm*	block glide	10.6/ 8.6	225	208	---	------	---	-----	+16.5	+0.080	- 4.6	-0.030	+8.4	+0.035	-2.0	-0.010
8A	None	Igm*	block glide	20.6/ 16.4	225	240	---	------	---	-----	-----	----	- 0.2	-0.001	+1.8	+0.008	-0.4	-0.003
8B	None	Igm*	creep & glide	10.2/ 6.6	225	240	---	------	---	-----	-----	----	----	-----	+4.8	+0.020	+0.8	+0.010
	"	"	creep	"	"	"	---	------	---	-----	-----	----	----	-----	+4.0	+0.018	+0.7	+0.006
	"	"	glide	"	"	"	---	------	---	-----	-----	----	----	-----	+0.8	+0.002	+0.1	+0.004
8C	None	Cgm*	creep & glide	12.1/ 8.0	225	220	---	------	---	-----	-----	----	----	-----	+17.0	+0.070	0.0	0.000
	"	"	Creep	"	"	"	---	------	---	-----	-----	----	----	-----	0.0	0.000	-2.0	-0.010
	"	"	glide	"	"	"	---	------	---	-----	-----	----	----	-----	+17.0	+0.070	+2.0	+0.010

TABLE 1a - BASIC SITE AND SURVEY DATA FROM APRIL 1975, TO OCTOBER 1977, MOVEMENT REPORTED IS SURFACE DISPLACEMENT ALONG THE PLANE OF MAXIMUM MOVEMENT.

* Incoherent greywacke and mudstone (Igm); Coherent greywacke and mudstone (Cgm).

SITE	Disturbance	Parent Material	Movement Type	Hole/ Movement Depth (meters)	Slope Azimuth (degrees)	PMM Azimuth (degrees)	SURVEY DATE (m-a) 5-78		11-78		5-79		9-79		4-80		11-80		4-81	
							PRECIPITATION BETWEEN SURVEYS (mm) 1608		251		966		188		1551		219		1076	
							MOVEMENT BETWEEN SURVEYS (mm) Total	(mm/d) Rate	(mm) Total	(mm/d) Rate	(mm) Total	(mm/d) Rate	(mm) Total	(mm/d) Rate	(mm) Total	(mm/d) Rate	(mm) Total	(mm/d) Rate	(mm) Total	(mm/d) Rate
1A	Logged	Schist	Creep	10.5/ 9.6	45	55	+0.8	+0.003	+11.0	+0.060	-2.1	-0.010	-1.2	-0.010	+1.2	+0.010	-1.4	-0.005	-3.2	-0.020
1B	Logged	Schist	Creep	9.0/ 9.0	45	275	+0.6	+0.003	+6.9	+0.040	-0.8	0.004	-1.0	-0.020	+1.9	+0.010	+0.9	+0.005	-6.0	-0.037
2B	None	Schist	Creep	4.3/ 4.3	45	45	+0.4	+0.002	+1.6	+0.010	+0.1	+0.001	+0.2	+0.020	-0.5	-0.002	+1.5	+0.010	-2.8	-0.017
3A	None	Schist	block glide	10.1/ 5.5	45	47	+14.6	+0.072	+5.1	+0.027	+8.2	+0.047	+5.4	+0.039	+12.7	+0.060	+9.5	+0.047	+3.1	+0.020
3B	None	Schist	block glide	8.1/ 6.4	45	50	+10.7	+0.050	+17.6	+0.090	+2.7	+0.020	+1.8	+0.010	+6.2	+0.030	+5.9	+0.030	+4.2	+0.026
4A	Logged	Schist	block glide	18.6/ 12.6	45	70	+4.4	+0.020	+16.5	+0.090	+5.2	+0.030	-4.0	-0.030	+6.0	+0.030	+4.3	+0.020	+2.4	+0.015
5A	None	Schist	creep	9.1/ 9.1	45	90	+1.0	+0.005	+12.5	+0.060	-1.2	-0.010	-3.1	-0.020	+1.8	+0.010	+1.1	+0.010	-2.2	-0.014
6A	Logged	Igw*	creep & glide	11.0/ 6.5	225	215	+253.6	+1.220	+58.0	+0.310	+56.0	+0.310	+25.0	+0.180	+77.0	+0.370	+29.0	+0.140	+10.4	+0.069
6B	Logged	Igw*	creep & glide	7.6/ 6.1	225	230	+189.4	+0.954	+49.0	+0.260	+42.0	+0.280	+17.0	+0.120	+109.0	+0.530	+42.0	+0.200	+37.0	+0.250
7A	None	Cgw*	block glide	10.5/ 6.9	225	215	+16.0	+0.080	-5.3	-0.030	+6.7	+0.040	+0.5	+0.004	+19.3	+0.090	-0.8	-0.004	+10.2	+0.069
7B	None	Cgw*	block glide	10.6/ 8.6	225	208	+20.3	+0.100	-13.6	0.070	+10.3	+0.060	-1.7	-0.010	Tube pinched below				0.6 m	
8A	None	Igw*	block glide	20.6/ 16.4	225	240	+4.2	+0.018	-0.4	-0.002	+3.6	+0.020	-1.1	-0.006	+3.6	+0.014	+0.7	+0.003	+2.6	+0.017
			creep & glide	10.2/ 6.6	225	240	+47.0	+0.230	-2.0	-0.010	+11.0	+0.060	-2.8	-0.021	+23.8	+0.120	-3.4	-0.012	+12.8	+0.079
8B	None	Igw*	creep	+	+	+	+25.0	+0.120	-4.4	-0.020	+5.8	+0.030	-3.6	-0.022	+11.0	+0.050	-3.5	-0.020	+6.7	+0.040
	"	"	glide	+	+	+	+22.0	+0.110	+2.4	+0.010	+5.2	+0.030	+0.8	+0.001	-13.6	+0.070	+0.1	+0.008	+6.1	+0.039
8C	None	Cgw*	creep & glide	12.1/ 8.0	225	220	+76.0	+0.370	+11.0	+0.060	+9.0	+0.050	+3.0	+0.020	+40.0	+0.190	+5.0	+0.020	+8.3	+0.050
	"	"	creep	+	+	+	+45.0	+0.220	+10.0	+0.050	+4.0	+0.020	+3.0	+0.020	+23.0	+0.110	+5.0	+0.020	+8.3	+0.050
	"	"	glide	+	+	+	+31.0	+0.150	+1.0	+0.010	+5.0	+0.030	0.0	0.000	+17.0	+0.080	0.0	0.000	0.0	0.000

TABLE 1b - BASIC SITE AND SURVEY DATA FROM MAY 1977, TO APRIL 1981, MOVEMENT REPORTED IS SURFACE DISPLACEMENT ALONG THE PLANE OF MAXIMUM MOVEMENT.

* Incoherent greywacke and mudstone (Igw); Coherent greywacke and mudstone (Cgw).

Creep

Sites dominated by creep processes exhibit a progressive deformation profile with strain increasing toward the surface. Sites RC-1, RC-2, and RC-5, located on the west side of Redwood Creek in the schist of Redwood Creek, exhibit this type of strain configuration exclusively (fig. 5). Local zones within all the profiles show minor accelerated deformation or extension flow, but no clearly defined shear zones are present.

Total displacement at the surface is small for all the creep-dominated holes, ranging from a minimum of 0.7 mm for hole RC-1B to a maximum of 12.6 mm for hole RC-5A (table 2). The only significant movement measured at these creep-dominated sites occurred as the result of a single surge during summer 1978 (fig. 6). The reason for this surge is not clear. It occured during one of the wetter years of the study, but the precipitation was not unusual in an historical context (fig. 3).

Block Glide

Sites dominated by block glide type movement display a fairly uniform velocity profile with most of the displacement taking place along a well-defined shear zone (fig. 7). Creep deformation may be occurring within the moving block but generally accounts for only a small part of the total movement. Sites RC-3 and RC-4 (located in schist of Redwood Creek) site RC-7 (located in the incoherent graywacke and mudstone unit of Coyote Creek) and hole RC-8A, site 8 (located in the coherent graywacke and mudstone unit of Lacks Creek) exhibit predominantly block-glide-type movement. Total displacement at the surface of these sites is substantially greater than at creep dominated sites, ranging from a minimum of 2.9 mm/a at hole RC-8A in

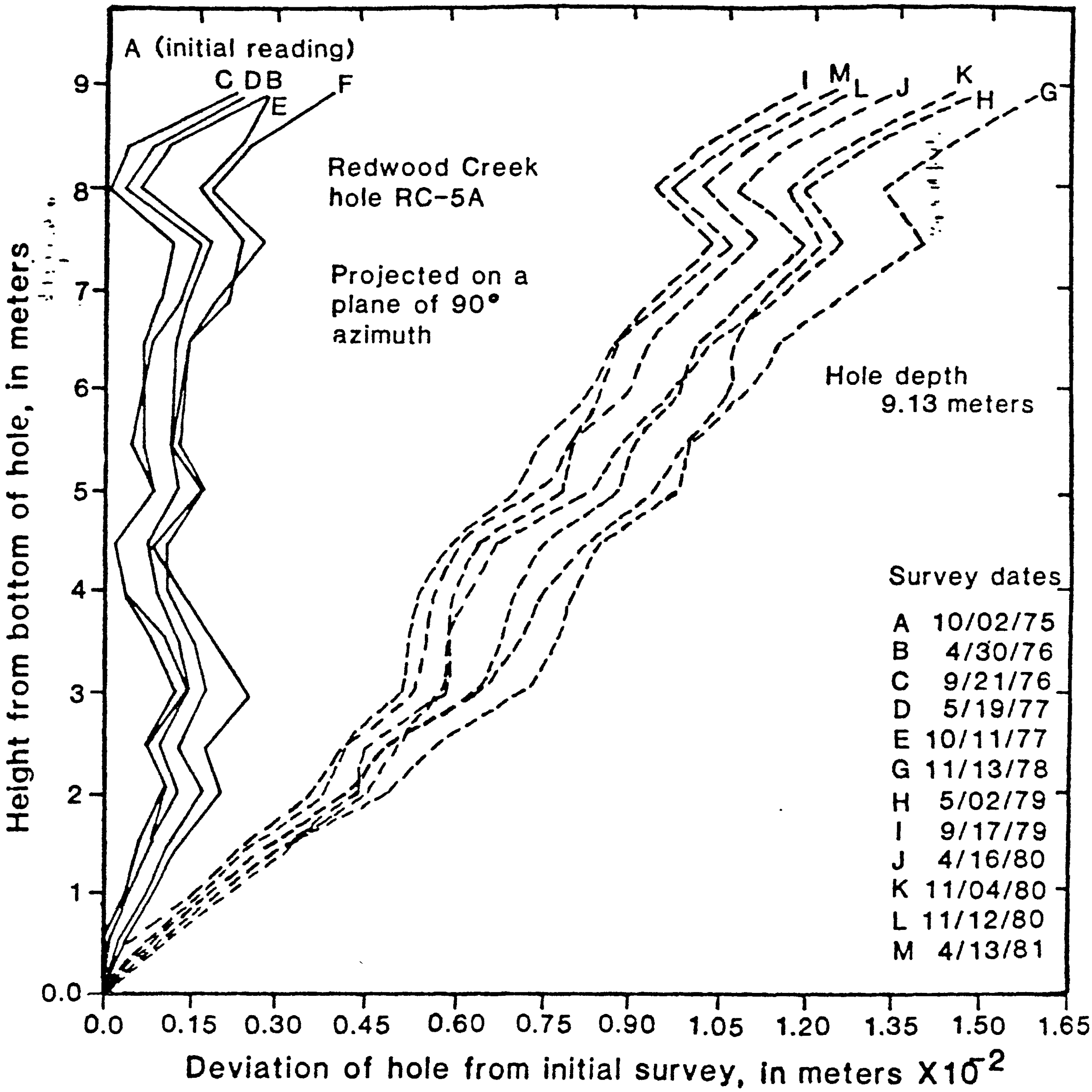

Figure 5. Profile of movement along PMM of hole RC-5A showing creep movement with negative upslope adjustments during winter periods. Note that most movement occurred in a surge during the summer of 1978 after a winter with highest precipitation during the survey period. (Movement after surge shown by dotted lines.)

TABLE 2.--DATA ANALYSIS SUMMARY - TOTAL, ANNUAL AND SEASONAL DISPLACEMENT AND MOVEMENT RATE FOR EACH HOLE

SITE	LOCATION	DEPTH (m) OF MOVEMENT	DEPTH (m) TO WATER TABLE	RECORD PERIOD DAYS	RECORD PERIOD YEARS	DISPLACEMENT TOTAL (mm)	DISPLACEMENT AVERAGE ANNUAL (mm/a.)	DISPLACEMENT AVERAGE SEASONAL (mm) SUMMER	DISPLACEMENT AVERAGE SEASONAL (mm) WINTER	RATE AVERAGE ANNUAL (mm/d)	RATE AVERAGE SEASONAL (mm/d) SUMMER	RATE AVERAGE SEASONAL (mm/d) WINTER	MOVEMENT CHARACTERISTICS
1A	Mid Slope-elev. 412 m	Above 9.63 (bottom)	DRY	2190	6.0	+ 3.5	+ 0.59	+ 0.90	- 0.26	+0.0015	+0.004	+0.001	Small summer increments-most movement occured in surge, summer 1978 - creep
1B	Mid Slope-elev. 381 m Below 1A	Above 8.95 (bottom)	7.0	2190	6.0	+ 0.7	+ 0.12	+ 0.75	- 0.56	+0.0003	+0.0038	-0.0036	Small summer increments-most movement occured in surge, summer 1978 - creep
2B	Mid Slope-elev. 366 m Below 2A	Above 4.31 (bottom)	DRY	2190	6.0	+ 2.2	+ 0.37	+ 0.85	- 0.41	+0.0010	+0.005	-0.002	Small summer increments - creep
3A	Mid Slope-elev. 305 m	Above Shear Zone 5.49 - 7.02	6.1	2190	6.0	+ 99.5	+ 16.62	+ 5.53	+ 9.33	+0.0450	+0.034	+0.046	Steady movement throughout year-small winter surges 1976, 1978, 1980' - blockglide
3B	Mid Slope-elev. 290 m* Below 3A	Above Shear Zone 6.35 - 7.49	6.1	2190	6.0	+ 83.8	+ 13.97	+ 6.48	+ 6.41	+0.0380	+0.037	+0.032	Steady movement throughout year-small surges beginning winter 1977 and continuing through summer 1978 - blockglide
4A	Mid Slope-elev. 305 m	Above Shear Zone @5.23	6.1	2190	6.0	+ 48.2	+ 8.03	+ 2.65	+ 4.61	+0.0200	+0.013	+0.024	Small incremental movement throughout year-winter dominant-surge summer 1978 - blockglide
5A	Lower Slope-elev. 198 m Above RW Creek	Above 9.13 (bottom)	DRY	2017	5.0	+ 12.6	+ 2.52	+ 2.06	+ 0.38	+0.0069	+0.010	+0.000	Small summer increments-most movement occurred in surge, summer 1978 - creep
6A	Upper Slope-elev. 625 m	Above Shear Zone @6.45	6.0	1824	5.0	+653.6	+130.72	+28.84	+84.90	+0.3581	+0.170	+0.422	Movement throughout year with dominant winter surges-large surges, winters 1977, 1979 - creep and glide
6B	Upper Slope-elev. 549 m Below 6A	Above Shear Zone 6.09-6.65	6.0	1831	5.0	+571.4	+114.28	+26.56	+76.77	+0.3131	+0.137	+0.387	Movement throughout year with dominant winter surges. Acceleration 1977, 1979, - creep and glide
7A	Mid Slope-elev. 305 m	Above Shear Zone 6.94 - 7.49	DRY	2004	5.0	+ 58.2	+ 11.64	- 1.02	+10.55	+0.0319	-0.006	+0.016	Dominant winter movement - blockglide
7B	Mid Slope-elev. 224 m Below 7A	Above Shear Zone 8.57 - 9.12	DRY	2004	3.0	+ 33.6	+ 11.20	- 5.48	+13.88	+0.0168	-0.030	+0.069	Dominant winter movement - blockglide
8A	Upper Slope-elev. 533 m Above active scarp	Above Shear Zone 16.37 - 16.95	4.5	1797	5.0	+ 14.4	+ 2.88	- 0.26	+ 3.16	+0.0080	-0.002	+0.015	Dominant winter movement in small increments - blockglide
9A	Upper Slope-elev. 518 m In Small Active Earthflow	Above Shear Zone 6.6 - 7.68	4.0	1650	4.0	+ 92.0	+ 23.00	- 1.85	+19.88	+0.0630	-0.008	+0.102	Dominant winter movement. Large surge 1977, 1979 - creep and glide
						+ 41.9	+ 10.48	- 2.65	+10.50	+0.0287	+0.014	+0.052	Creep
						+ 50.9	+ 12.73	+ 0.80	+ 9.54	+0.0349	-0.006	+0.050	Glide dominates
9C	Upper Slope-elev. 488 m In Small Active Earthflow	Above Shear Zone @8.04	2.4	1650	4.0	+162.3	+ 42.33	+ 4.25	+30.06	+0.1160	+0.025	+0.146	Dominant winter movement. Large surge 1977, 1979 - creep and glide
						+ 96.3	+ 24.08	+ 4.00	+16.06	+0.0660	+0.020	+0.080	Creep dominates
						+73.0	+ 18.25	+ 0.25	+14.00	+0.0500	+0.005	+0.066	Glide

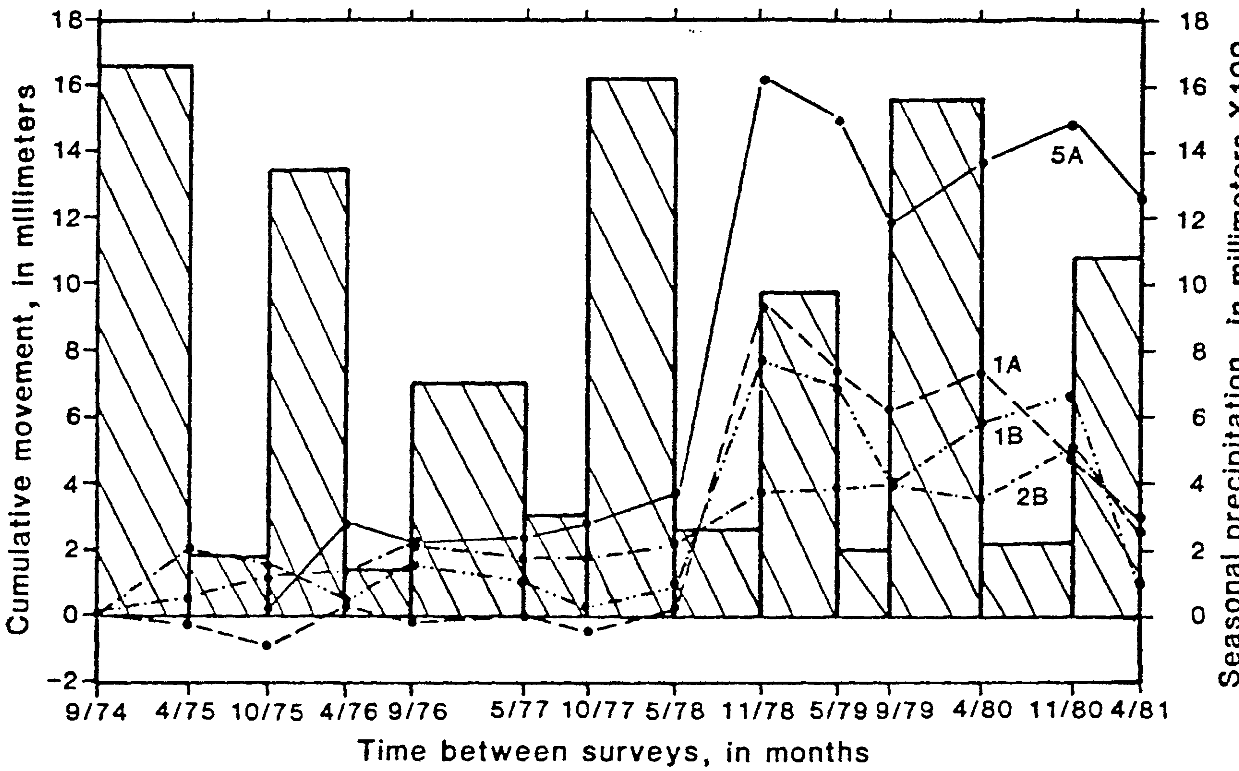

Figure 6. Plot of cumulative movement over monitoring period showing relationship to seasonal precipitation for actively creeping sites.

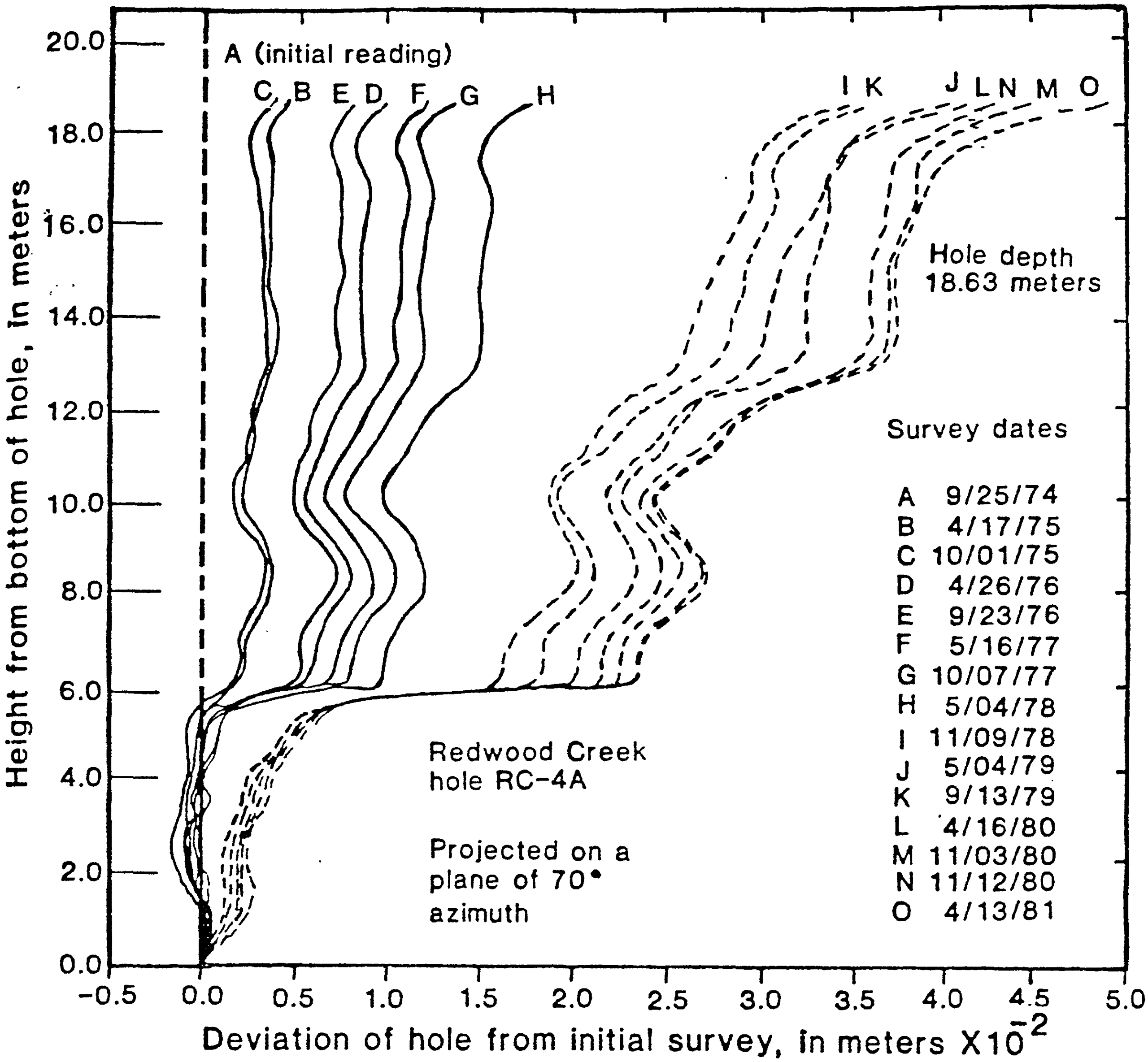

Figure 7. Profile of movement along PMM of hole RC-4A showing typical block-glide movement with summer negative (upslope) adjustments. Note that movement occurs predominantly during the winter except for a large surge during the summer of 1978 in response to the exceptionally high rainfall during the preceeding winter.

the coherent graywacke and mudstone to a maximum of 16.4 mm/a at hole RC-3A in the schist (table 2). Inspection of plots of cumulative movement over time for these holes (fig. 8) indicates that all holes experienced a nearly uniform annual displacement over the study period.

Holes RC-3A and RC-3B exhibit fairly constant displacement rates throughout the year with only small seasonal variation. Holes RC-4A, RC-7A, RC-7B, and RC-8A exhibit strong seasonal fluctuations with most of the displacement occurring during the winter rainy period (table 2). All the block glide dominated holes developed substantial increases in annual displacement rate in summer 1978: this followed the largest annual rainfall recorded during the study period. The rate of movement in holes RC-3B and RC-4A continued to accelerate over the following summer and winter but returned to pre-1977 levels by summer 1979. Shear at site 3 in the schists of Redwood Creek is occurring between 5 and 7 meters: at site 4 it is occurring at approximately 12 meters. Both these sites are at the same elevation and within 400 meters of each other which emphasizes the local control exerted by different zones of weakness in the parent material. Although both sites show substantial block-gliding within the profile, there is little surficial indication of this activity and both sites were or had been heavily forested.

Shear at site 7 in the incoherent graywacke and mudstone is occurring between 6 and 9 meters. This site is also heavily forested and exhibits little surficial indication of the active movement.

Hole 8-A, drilled near the upper edge of the Counts Hill Prairie earthflow, indicates shear at a depth between 16 and 17 meters. Total movement above this depth is small relative to that recorded in other holes drilled at the site, but has a good correlation with climatic events and probably defines the basal plane of failure of the earthflow.

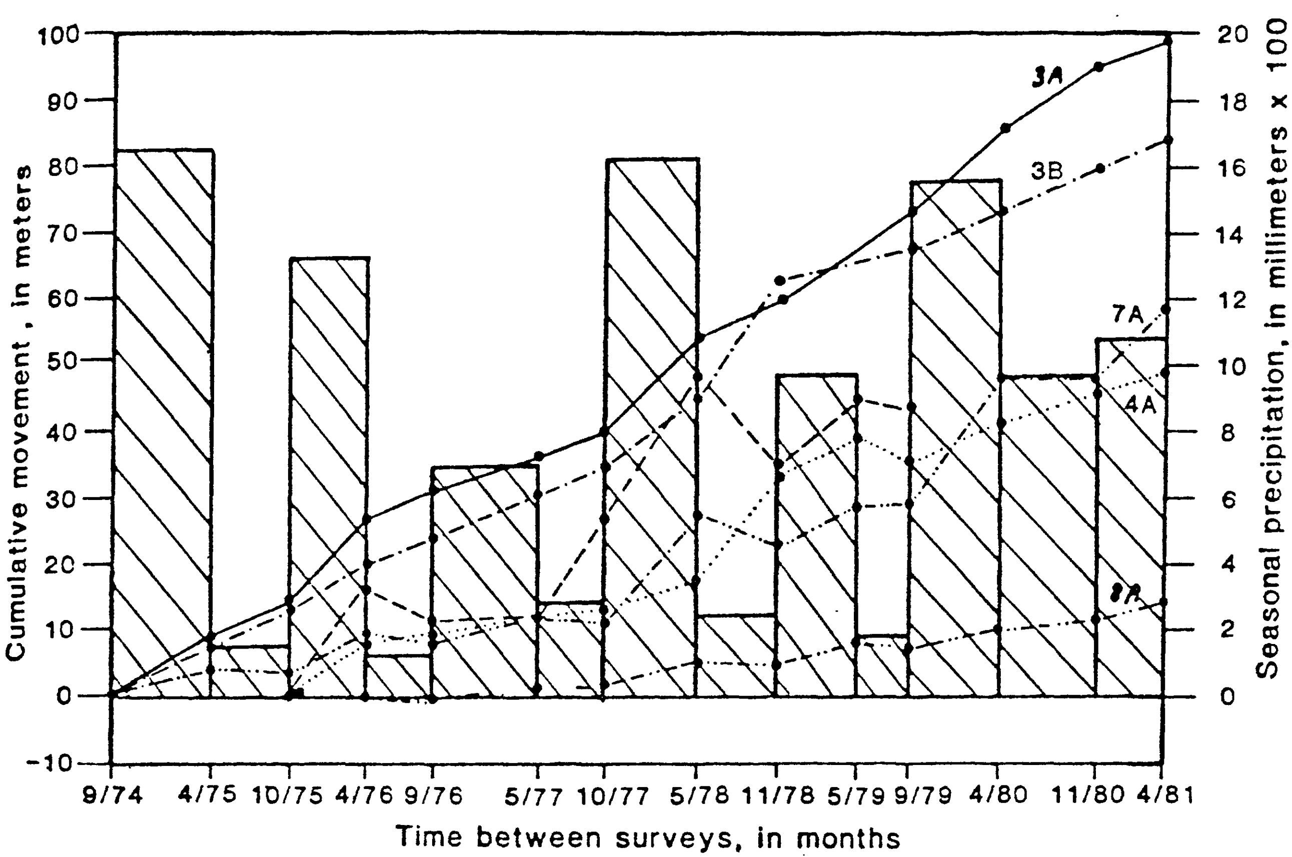

Figure 8. Plot of cumulative movement over monitoring period showing relationship to seasonal precipitation of block-glide dominated sites.

Combined Creep and Block Glide

Sites exhibiting a combined creep and block-glide type profile typically display a distinct zone of shear displacement with substantial progressive creep deformation occurring within the moving block (fig. 9). Holes RC-8B and RC-8C, within the Counts Hill Prairie earthflow, and site 6, in the coherent graywacke and mudstone of Lacks Creek, exhibit this combined movement. The surface at these holes exhibits evidence of active movement.

Total annual displacement at the surface for these holes ranges from a minimum of 23.0 mm/a for hole RC-8B to a maximum of 131.0 mm/a for hole RC-6A (table 2). Site 6 proved to be the most active site monitored during the survey, developing high displacement rates throughout the profile. This resulted in failure of the access tube in the zone of shear at a depth of about 6.5 meters early in the survey period. Although site 6 was originally located outside of what we felt to be a clearly defined zone of earthflow failure (fig. 1), the extreme rates of movement recorded and subsequent shearing of access tubes suggest that the entire slope below Childs Hill Prairie may be involved in active failure. Holes RC-8B and RC-8C, in the Counts Hill Prairie earthflow, reveal shear taking place at a depth between 6 and 8 meters, substantially above the basal failure plane of the earthflow defined in hole RC-8A. As holes RC-8B and 8C are below a distinct headwall scarp in an extremely active flow zone with the surface topographically much lower then the more stable surface at 8A, we believe that these holes also define the basal shear plane of the earthflow.

Plots of cumulative movement over time for holes RC-6A, 6B, 8B and 8C indicate that displacement is seasonal with a greater part of the movement taking place during the winter rainy season (fig. 10, table 2). Distinct surges in rates of movement occurred during the wetter winters of 1978 and 1980.

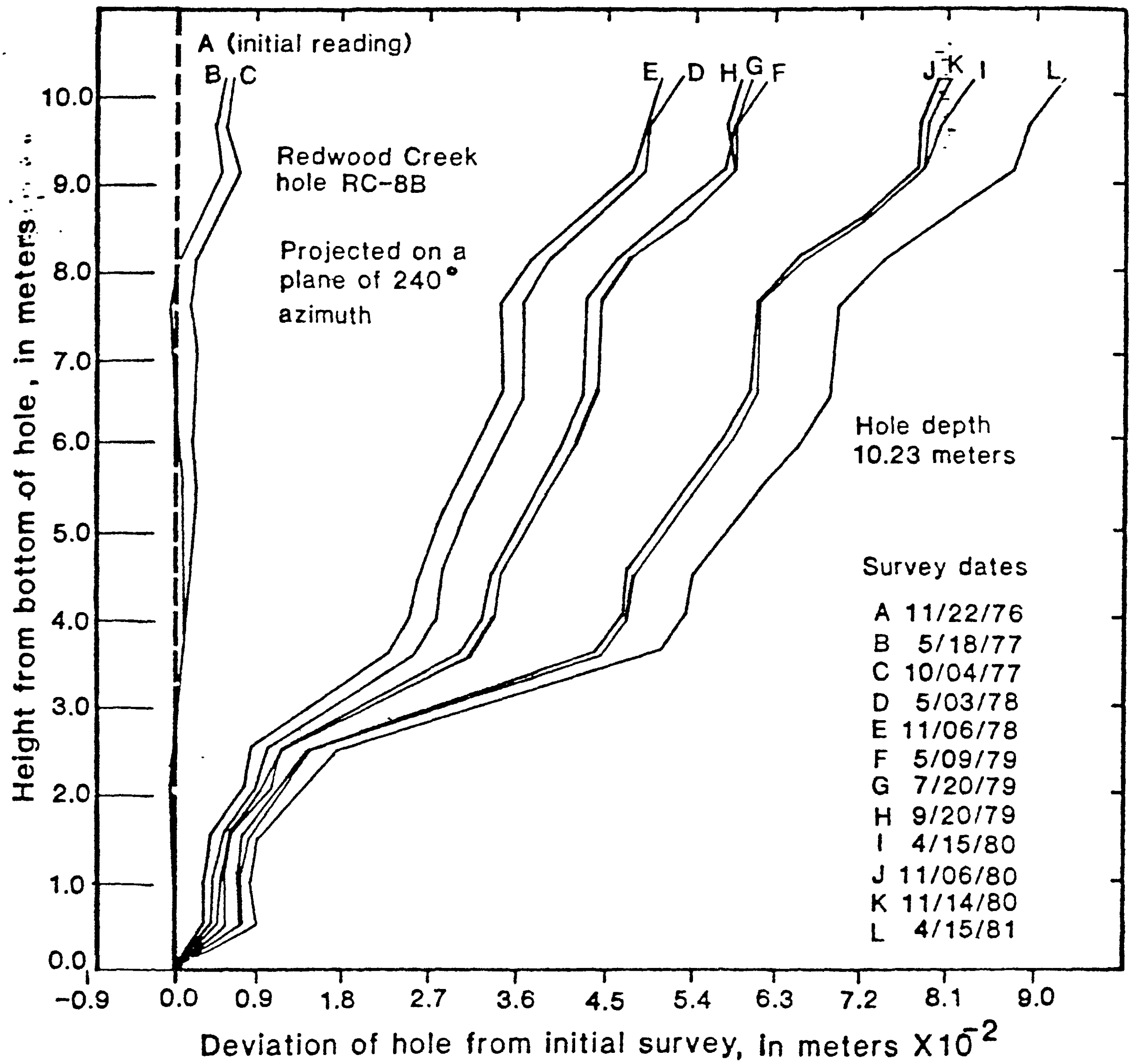

Figure 9. Profile of movement along PMM of hole RC-8B showing combined block-glide and creep occurring within the profile. Note that all movement occurs as winter surges.

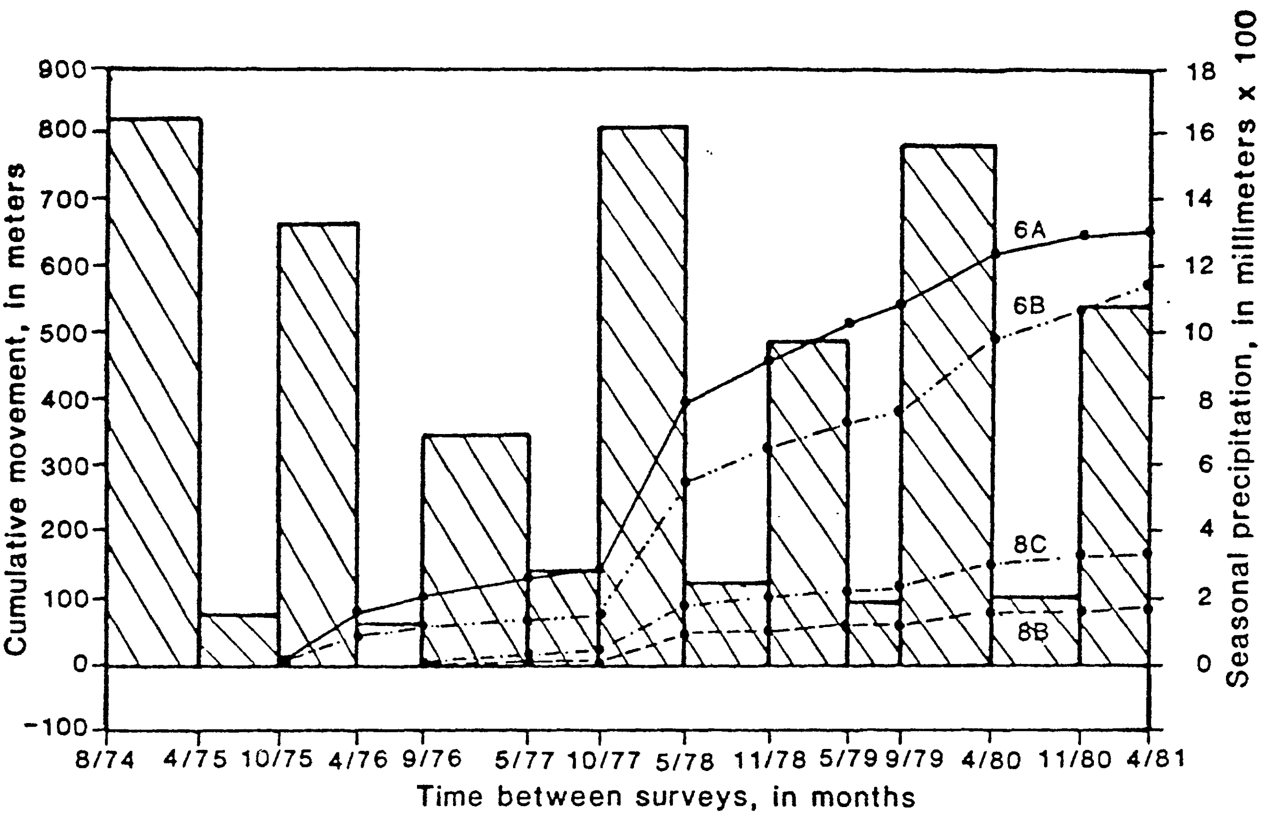

Figure 10. Plot of cumulative movement over monitoring period showing relationship to seasonal precipitation at sites exhibiting combined creep and block-glide.

Creep activity is an important contributor to surface displacement in all these holes, although it cannot be separated from block glide in the total movement reported for site RC-6. This is because of the shearing of the tube above the established stable reference point at the bottom of the hole. All movement reported at this site after May 1977 is referenced to the configuration of the tube at the last survey prior to failure. All rates reported are thus conservative and absolute displacement rates cannot be determined.

Differentiation between creep and block glide movement at holes RC-8B and RC-8C was possible and reveals creep to be a major component of surface displacement within the main body of the Counts Hill Prairie earthflow (table 2). Creep accounts for approximately 57% of total surface displacement at hole RC-8C and is nearly equivalent (46%) to block glide at hole RC-8B.

Geologic Relationships

The most active terrain with the highest rates of movement encountered in this study occurs on the east side of Redwood Creek valley in the sheared, interbedded mudstone and graywacke. Highest rates of movement are associated with active earthflow terrain occurring at the defined contact zone between the coherent unit of Lacks Creek and the incoherent unit of Coyote Creek (fig. 1). Block glide type displacement was a major component of movement at all sites in this terrain with movement occurring above well-defined shear zones ranging in depth from 6 to 17 meters. A primary or secondary shear zone between 6 and 8 meters in depth was common to all monitored sites and probably represents the depth of surface weathering in these materials. Creep deformation constituted an important component in total surface displacement at active earthflow sites RC-6 and RC-8, but no purely progressive deformation profiles were encountered, perhaps because of the high rates of strain and subsequent shear failure which dominate this terrain. It would appear, based on these preliminary data, that mantle deformation by block gliding along well defined shear planes is the dominant soil mass movement process altering slopes underlain by the incoherent graywacke and mudstone along the east side of the creek. Where strains are great enough locally, individual earth flows develop, particularly at or near the contact with the coherent unit.

In contrast, the west side of the valley, underlain by well-foliated schist, displays much lower rates of movement with progressive creep dominating in three of the five monitored sites. Discrete failures of the block glide type occur locally, particularly on the mid to lower slopes as intensity and degree of shearing of bedrock increase toward the Grogen fault. Total displacement and annual rates, however, are small relative to the east side of the valley. Depth of the active profile at creep dominated sites ranges from 4 to 16 meters. At block-glide dominated sites, shear generally develops between 6 and 7 meters.

Precipitation Relationships

Two surveys a year were made of each access tube in order to assess the effects of winter rain and summer drought on movement. A curve of cumulative precipitation at Orick-Prairie Creek State Park during the study period with approximate survey dates is shown in figure 11. A study of the data presented in tables 1 and 2, coupled with an inspection of the velocity profiles and cumulative movement plots for each site (figs. 5-10) clearly reveal that both

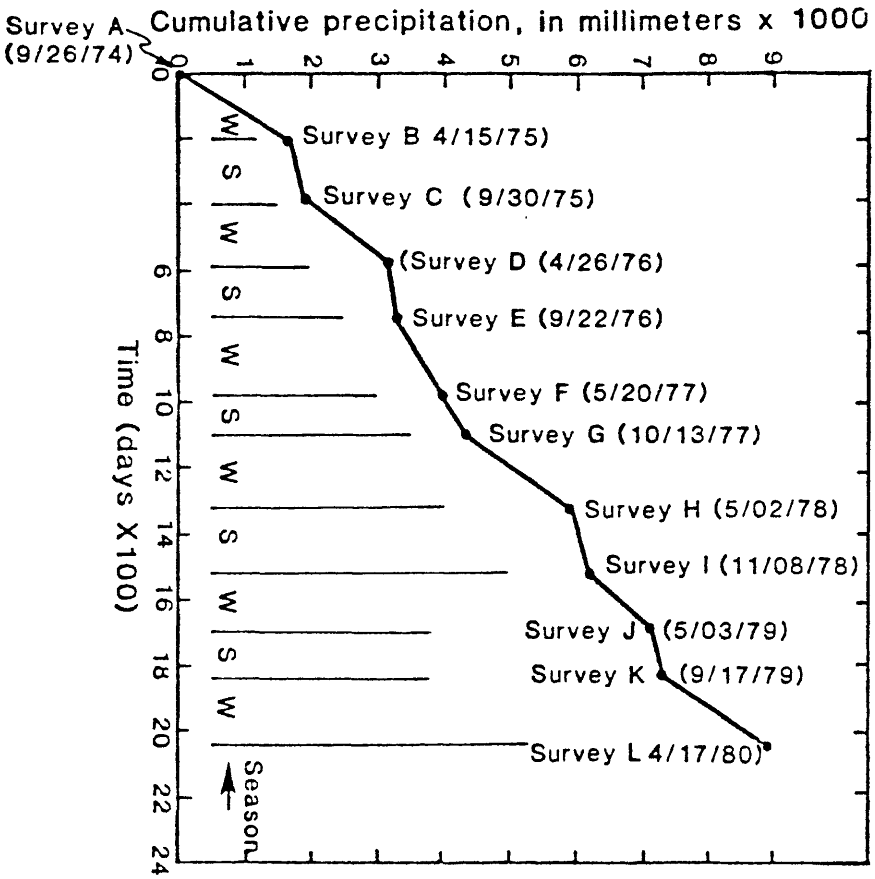

Figure 11. Plot of cumulative precipitation over survey period at Orick-Prairie Creek State Park showing survey dates.

displacement and movement rate are sensitive to seasonal and annual climatic events in the Redwood Creek basin.

At the sites dominated by creep (RC-1, RC-2, and RC-5), total displacement was small prior to a movement surge during summer 1978. A regression analysis of the relationship between seasonal movement and seasonal precipitation (current and preceeding season) reveal very low F-values suggesting that these variables have little predictive ability (table 3). This is due in part to most movement occurring during a single summer surge. In regression analysis, when an observation falls far from the fitted line, that observation, even though a probably legitimate one, is often removed and the analysis continued with the remaining data (Weisberg, 1980). In our case, however, nearly all the observed movement occurred during the surge, and a regression on the remaining observations would be of little value in predicting movements at the site based on precipitation. Regressions of annual movement against annual precipitation yielded significant relationships for two of the four access tubes (RC-1B, RC-2B) monitoring creep activity (table 3).

Sites dominated by block-glide type processes which are not within active earthflows typically display predominantly rainy season movement either as a steady movement throughout the year with small winter surges (holes RC-3A, B; RC-4A) or as winter movement only (holes RC-7A, B). Regression analyses of the relationship between annual movement and annual precipitation yield no significant correlation for these five holes. Three of the five holes have a highly significant relationship, however, between seasonal displacement and seasonal rainfall.

In the active earthflow sites, creep is mostly found above the block glide zone. These sites typically display movement throughout the year with rainy

BETA DISTRIBUTION (F) VALUES

SITE	NUMBER OF OBSERVATIONS		ANNUAL PRECIPITATION		SEASONAL PRECIPITATION		PRECIPITATION DURING PRECEEDING SEASON	
	ANNUAL	SEASONAL	DISPLACEMENT	RATE	DISPLACEMENT	RATE	DISPLACEMENT	RATE
1A	6	13	1.42	1.81	0.05	0.00	0.92	0.61
1B	6	13	8.04*	7.69	0.03	0.03	2.47	2.43
2B	6	13	22.44**	16.20*	2.49	2.43	10.45*	7.89*
3A	6	13	6.62	3.47	10.81**	7.01*		
3B	6	13	2.85	2.68	0.16	0.00		
4A	6	13	2.08	1.97	0.69	0.59		
5A	5	11	4.58	4.30	0.06	0.07	1.84	2.21
6A	5	11	4.71	3.76	7.21*	6.62*		
6B	5	11	17.01*	14.01*	11.42**	12.81**		
7A	5	11	6.47	5.25	48.05**	37.65**		
7B	3	7	0.01	0.01	37.73**	39.80**		
8A	5	11	20.25*	9.75*	59.48**	26.71**		
8B	4	9	5.85	4.59	32.58**	40.62**		
8C	4	9	5.93	4.34	10.74*	11.25*		

Table 3.--Listing of Beta Distribution (F) Values Obtained from Regression Analysis of Movement Against Seasonal and Annual Precipitation. [Regression is significant at 5 percent (*) or 1 percent (**) level].

season surges (holes RC-6A, B) or dominant rainy season movement (RC-8A, B, C). Regression analyses between annual movement and annual precipitation yield significant relationships for two of the five holes (RC-6B; RC-8A), however, all five holes have a significant correlation between seasonal displacement and seasonal precipitation (table 3).

Relationship to Level of Water in Tube

Water was intercepted in most of the access tubes as the result of penetration of one or more water bearing zones during the drilling process. The changes in water level in the tubes were measured from survey to survey to try to relate seasonal water table fluctuations to periods of maximum movement. No consistent changes in water level relative to measurement were detected during the monitoring period. This may be in part due to multiple sources of water fed into the holes by one or more confined water bearing horizons within the active mantle.

CONCLUSIONS

This survey clearly shows the sensitivity of some natural slopes to changes in slope stress produced by annual and seasonal rainfall.

Progressive creep with rates ranging from 1.0 to 2.5 mm/a dominates on slopes west of the Grogen fault underlain by sheared and foliated schists. Complex earthflows occur predominantly on slopes east of the Grogen fault underlain by sheared graywacke and mudstone. Movement rates in this terrain range from 3.0 to 131.0 mm/a.

Creep profiles are encountered only on the west side of the valley in the highly foliated, locally sheared schist and characteristically displayed predominantly summer movement. This movement was minor over most of the survey period except for a surge developed during summer 1978 following the largest annual rainfall recorded during the study. Two of the four tubes monitoring the creeping sites indicated that annual displacement was proportional to annual precipitation. No significant relationships were found between seasonal displacement and seasonal precipitation for any of the four tubes.

Sites exhibiting block glide or combined creep and block glide movement occur on both sides of the valley but are most active and display the greatest movement in the sheared graywacke and mudstone east of the Grogen fault. These sites characteristically display dominant movement during the rainy season. This may occur as constant downslope motion with winter surges or as winter movement only. On the schist, neither annual displacement nor movement rate were related to annual precipitation at any of the four tubes. Seasonal precipitation was related to seasonal movement at only one of the four tubes (RC-3A). On the graywacke and mudstone, annual displacement was related to annual precipitation at only two of the seven tubes. Seasonal precipitation was highly correlated, however, with seasonal displacement or seasonal rate at all seven of the tubes.

There is a direct relationship between seasonal precipitation and the corresponding amount of block-glide slope deformation in the Franciscan graywacke and mudstone on the east side of Redwood Creek Valley. There is a much less demonstrable relationship between precipitation and slope deformation on the schist on the west side of the Valley.

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