Rate and Mechanics of Progressive Hillslope Failure in the Redwood Creek Basin, Northwestern California

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GEOMORPHIC PROCESSES AND AQUATIC HABITAT IN THE REDWOOD CREEK BASIN, NORTHWESTERN CALIFORNIA

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RATE AND MECHANICS OF PROGRESSIVE HILLSLOPE FAILURE IN THE REDWOOD CREEK BASIN, NORTHWESTERN CALIFORNIA

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ABSTRACT

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

Progressive creep having 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 earthfiows occur predominantly on slopes east of the Grogan fault underlain by sheared graywacke sandstone and mudstone. Movement rates range from 3.0 to 131.0 mm/a and characteristically display dominant rainy season movement.

INTRODUCTION

The Redwood Creek basin is approximately 60 km north of Eureka in the northern California Coast Ranges. Its 725-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 streambank cutting, are the result of a combination of rock types, geologic history, climate, and land use patterns that exist over large areas.

Recent major floods and attendant accelerated mass movement of mantle materials into channels have caused drastic changes in channel characteristics and sedimentation rates; these changes have resulted in part from timber harvest activities within this highly eroded drainage basin. 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; 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 U. S. Forest Service, in cooperation with the U. S. Geological Survey (USGS), began monitoring movement at eight sites on the east and west slopes of the basin. That 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 processes 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 6 years of data accumulated during the study. An assessment of the impacts of timber removal was not possible because the study sites designated for timber harvest were incorporated into an expansion of Redwood National Park and all logging plans were terminated.

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AREA DESCRIPTION

DRAINAGE CHARACTERISTICS

The drainage basin of Redwood Creek encompasses about 725 km^2 of rugged terrain within the Coast Ranges of northern California. The basin is strongly elongated north-northwestward 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; headwaters show slightly greater density than downstream areas (Iwatsubo and others, 1976). Total basin relief is about 1,615 m. Cross-sectional relief normal to the basin axis in the vicinity of this study is about 229 m. The average gradient in the basin is 14.4° (26 percent), but more than half of the individual hillslopes display average gradients in excess of 19° (35 percent).

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 having 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, 1976), 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 Prairie Creek Redwoods State Park. Prairie Creek data and the data obtained from the USGS 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. Seasonal variations in mean monthly precipitation, runoff, and temperatures for Redwood Creek at Prairie Creek Redwoods State Park for the water years 1954 to 1972 are shown in figure 2.

The estimated mean annual basinwide precipitation is 2,032 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 Prairie Creek Redwoods State Park from 1938 to 1980 is 1,748 mm (fig. 3). Annual precipitation at the Prairie Creek weather station during this study (1975-80) 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 42-year record occurred during the 1974 water year (the year immediately preceding this 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. 2). Snow is rare in this rain-dominated basin, but infrequent snowfall having 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 *(Sequoia sempervirens* [D. Don] Endl.) is the dominant tree on the relatively moist flood plains, 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 associated with western hemlock *(Tsuga heterophylla* [Raf.] Sarg.), tan oak *(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 Late Jurassic and Early Cretaceous in age.

Virtually unmetamorphosed sedimentary rocks underlie most of the eastern side of the basin. Graywacke

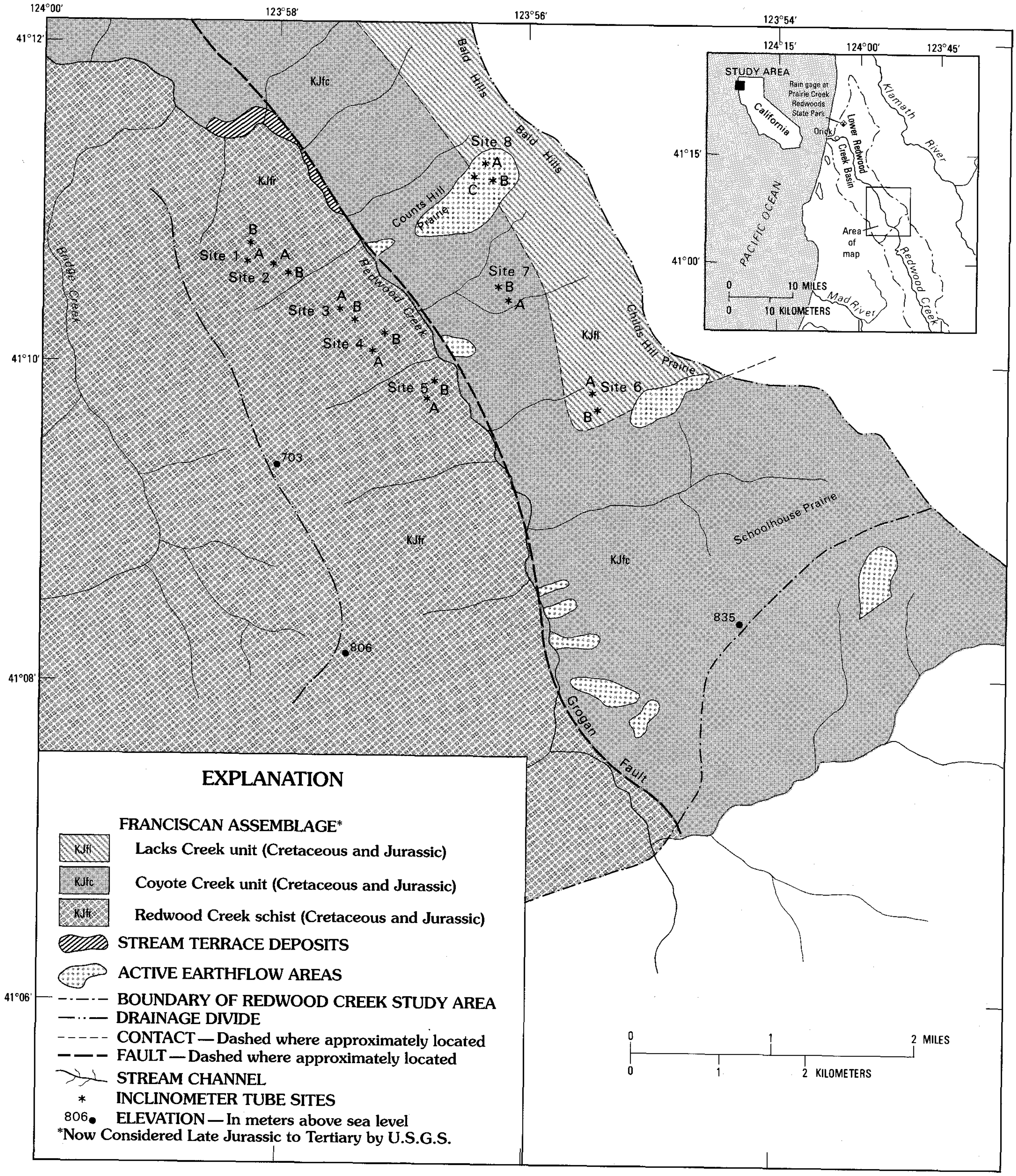

FIGURE 1.—Part of lower Redwood Creek basin showing important geologic units, structure, and monitoring locations (modified from Harden and others, 1981).

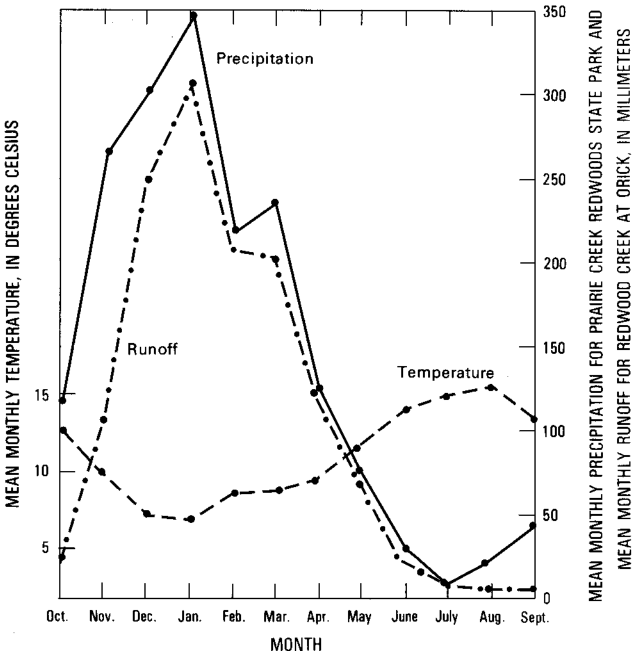

FIGURE 2. -Mean monthly temperature and precipitation for Prairie Creek Redwoods State Park and mean monthly runoff for Redwood Creek at Orick for water years 1954 to 1972 (from Janda and others, 1975).

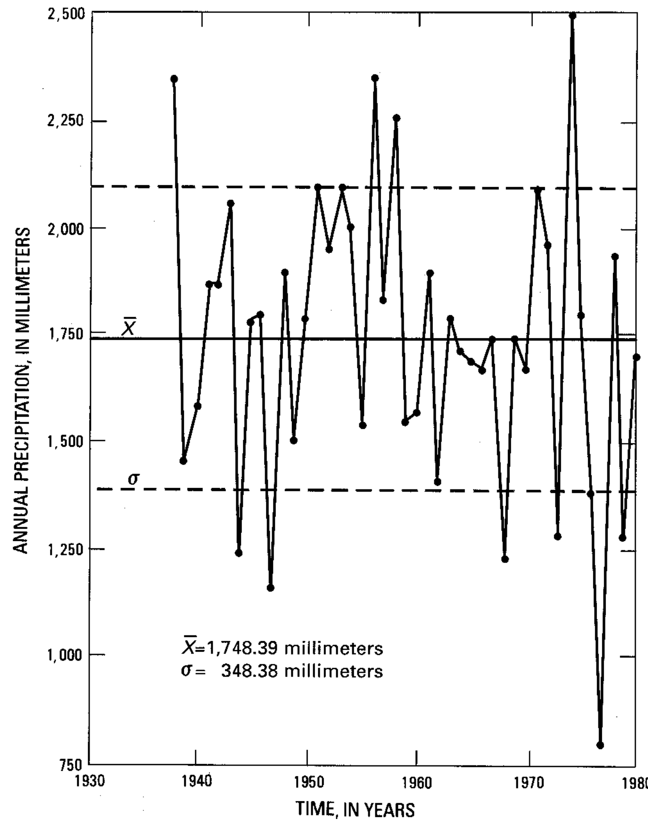

FIGURE 3. -Annual precipitation over the period 1938 to 1980 (42 years) recorded at Prairie Creek Redwoods State Park. Mean annual precipitation (x) is 1,748.39 mm; standard deviation (o) is 348.38 mm.

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 Redwood Creek schist 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 northnorthwest-trending Grogan 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 sandstone and mudstone underlying the east slope get finer grained and more intensively sheared toward the Grogan 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 graywacke sandstone and mudstone sequences of the Coherent unit of Lacks Creek (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 the Incoherent (graywacke sandstone and mudstone) unit of Coyote Creek, which consists of more highly sheared and fractured sequences having greater amounts of mudstone (fig. 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 nearly 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 and range from less than 0.6 m on hilltops and divides to more than 15 m beneath landslides and actively moving midslope 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 and 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.

LANDFORMS RELATED TO MASS MOVEMENT

Many hillslopes in the Redwood Creek basin are unstable and highly susceptible to mass-movement failure because of the steepness of the terrain and the low shear strength of much of the underlying saprolite and residual soil. According to Colman (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 earthflows, grass, grass-bracken-fern, and grassoak prairie vegetation dominate in marked contrast to the mature coniferous forest or cutover 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 that had been partly logged or that 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 earthflows. 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 1 through 4, located at midslope on the west side of the basin in saprolite overlying Redwood Creek schist, during fall 1974. Monitoring instruments were installed at sites 5 through 7 during fall 1975. Site 5 was located in saprolite overlying schist near the channel of Redwood Creek. Sites 6 and 7 were located at midslope on the east side of the basin; site 6 in saprolite overlying the Coherent (graywacke sandstone and mudstone) unit of Lacks Creek, and site 7 in saprolite overlying the Incoherent (graywacke sandstone 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 earthflow deposits of Counts Hill Prairie (site 8, fig. 1). The deposits are developed in deeply weathered graywacke sandstone and mudstone across the boundary of the Coherent and Incoherent units of Lacks Creek and Coyote Creek, respectively.

INSTALLATION OF BOREHOLE TUBES

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 (designated A and B) were installed at sites 1-7 approximately along the fall line of the slope to detect any similarities or differences in the rate and mechanics of movement with slope location. A third tube (designated C) was installed at site 8, the Counts Hill Prairie earthflow, to assess the complex nature of some the movement displayed at that site. The tubes were installed in 130-mm-diameter boreholes, drilled by a truck-mounted auger through active soil materials, and were anchored at the bottom in bedrock.

The anchoring 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-m 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-section 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. 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 m or until softer materials were encountered. Once bedrock was reached, the hole was drilled an additional 1 m, and the access tube was installed. Subsequent surveys indicated only small changes in inclination of the bottom 1 m 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 the one at hole 413 (site 4) were considered fixed for purposes of analysis. At hole 4B, the tube 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 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 irregularly shaped borehole. For maximum continuity, all these spaces had to be filled. In practice, the use of in-place materials proved impossible because of the loss of such materials through their compression into the sidewalk of the borehole as the drill bit was advanced and also because of the rather small volume of material that was 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 have, in theory, reached a maximum density and should have completely filled the annular space and any voids. Unfortunately, most of the holes intersected ground water 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 that this backfilling technique was successful in developing the required continuity at all but two holes (2A, 5B at sites 2 and 5, respectively). 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 PVC with a 76.2-mm inside diameter and were grooved longitudinally inside at 90°. A mechanical pendulum that had an 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 after installation.

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 this orientation. The azimuth of the plane defined by the north-south grooves was measured by using a Brunton compass to obtain true bearings. All subsequent data sets at each hole were oriented by using that azimuth.

The instrument has a sensitivity of 1 part in 1,000 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-m 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 that had to be contended with in obtaining data for this study. These were:

(1) opposite grooves 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 or 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 also were detectable by the above field check and, if not resolved by replacement and rereading of the inclinometer at a given depth, required withdrawal of the instrument from the hole and a complete resurvey. The fifth source of error generally required abandonment of the survey, repair or drying of the instrument, and resurvey 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.

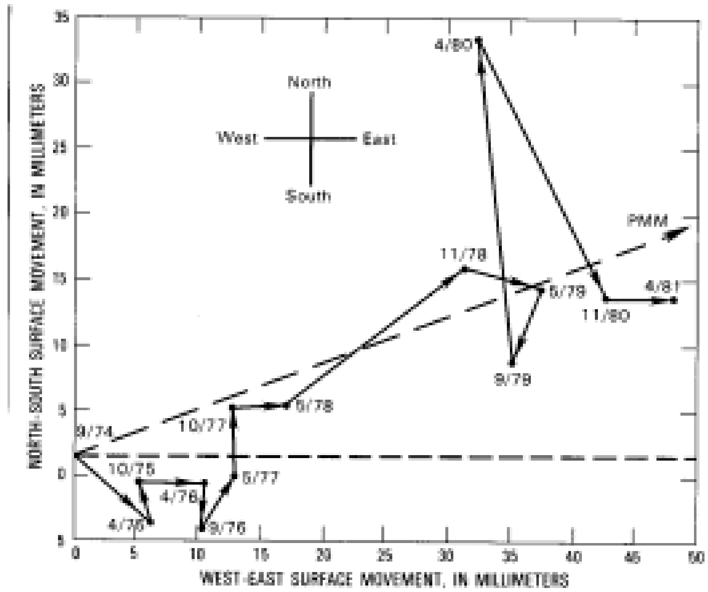

FIGURE 4.-Plot of the surface movement at hole 4A on the west side of Redwood Creek (site 4, fig. 1) showing the variability in distance and direction between successive seasonal readings. The plane of maximum movement (PMM) is determined by the direction of maximum extension of plotted points.

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 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 also were 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 and had an epicenter at Big Lagoon, about 32 km southwest of the study area. Following this earthquake, tubes at sites 1 through 5 and site 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-m intervals from the bottom of the hole. The bottom of the hole was assumed to be fixed. This assumption 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 vectors 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 throughout 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 U. S. Forest Service, Pacific Southwest Forest and Range Experiment Station, Arcata, Calif.

Variability in direction and distance of movement between successive surveys at each interval were occasionally large (fig. 4). Such disparities were due to several

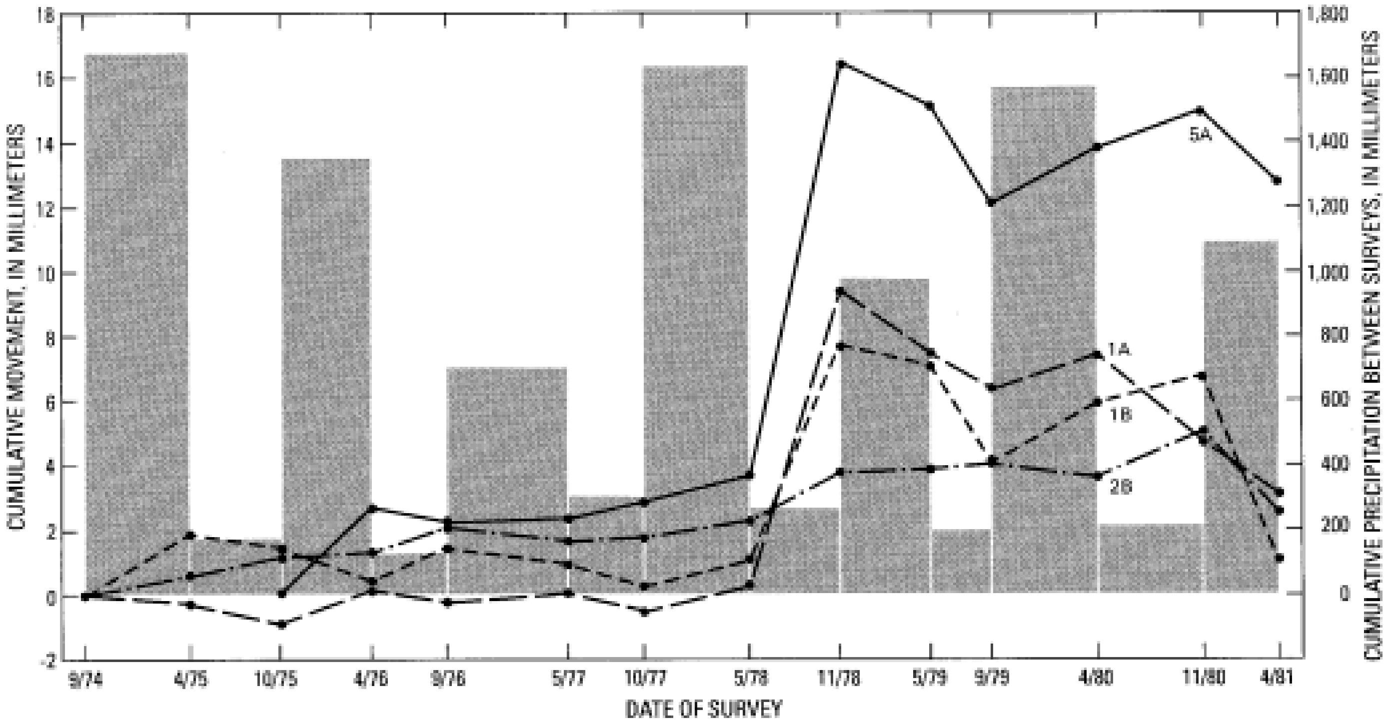

FIGURE 5.—Cumulative movement over the monitoring period showing relation of seasonal precipitation to sites of active creep.

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 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 having 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. 4).

Once the profiles had been plotted in the PMM, 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 also were obtained by calculation and graphic scaling from the profiles. Displacement and rates of movement were then regressed against both annual and seasonal precipitation to ascertain any relationships that may 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 is cataloged in tables 1 and 2 and figures 5-7. Profiles constructed for each hole exhibit major types of strain configuration indicative of process mechanics dominating at a particular site. Figures 8-10 show profiles for holes 5A, 4A, and 8B, respectively.

CREEP

Sites dominated by creep processes exhibit a progressive deformation profile with strain increasing toward the surface. Sites 1, 2, and 5, located on the west side of Redwood Creek in Redwood Creek schist, exhibit this type of strain configuration exclusively (see fig. 8, hole 5A). 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 1B to a maximum of 12.6 mm for hole 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. 5). The reason for this surge is not clear. It occurred during one of the wetter years of the study, but the precipitation was not unusual in an historical context (fig. 3).

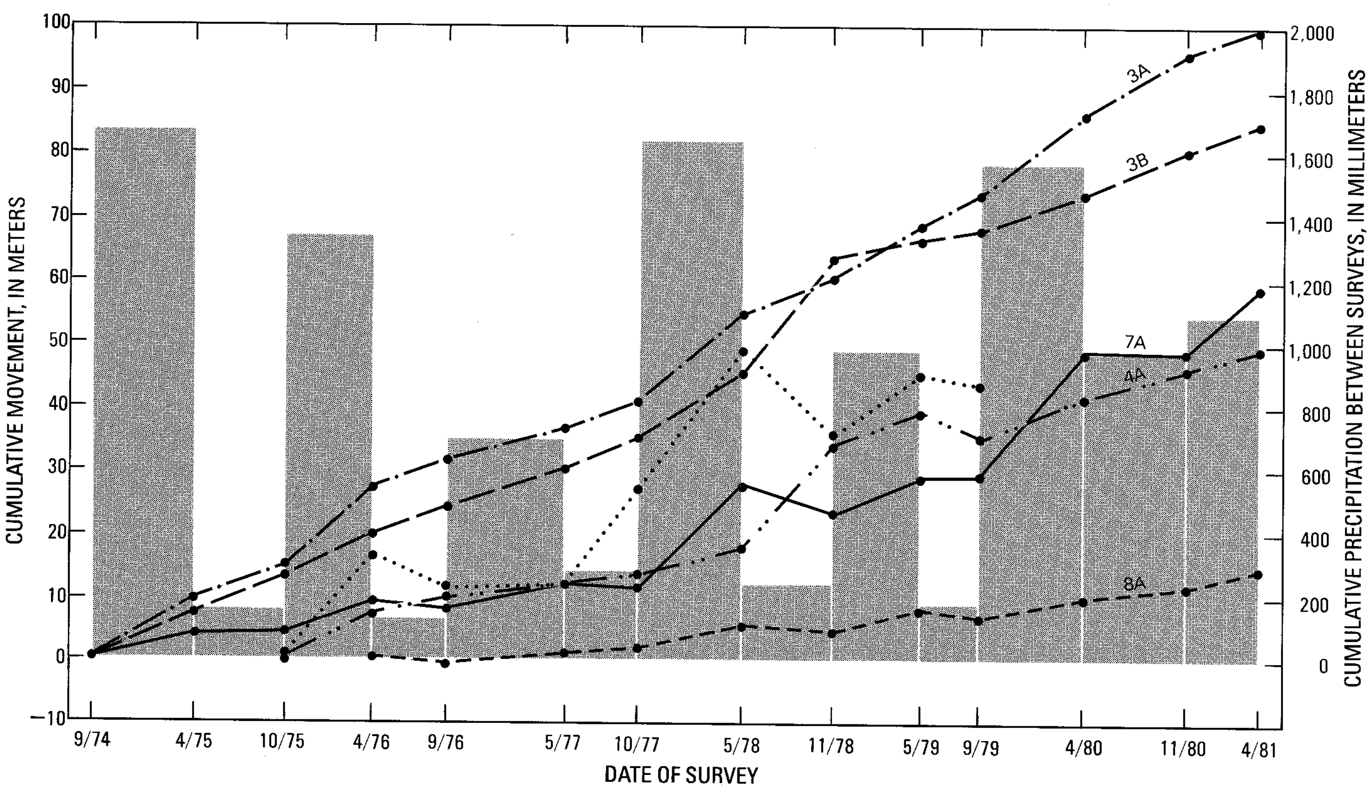

FIGURE 6.—Cumulative movement over the monitoring period showing relation of seasonal precipitation to block-glide-dominated sites.

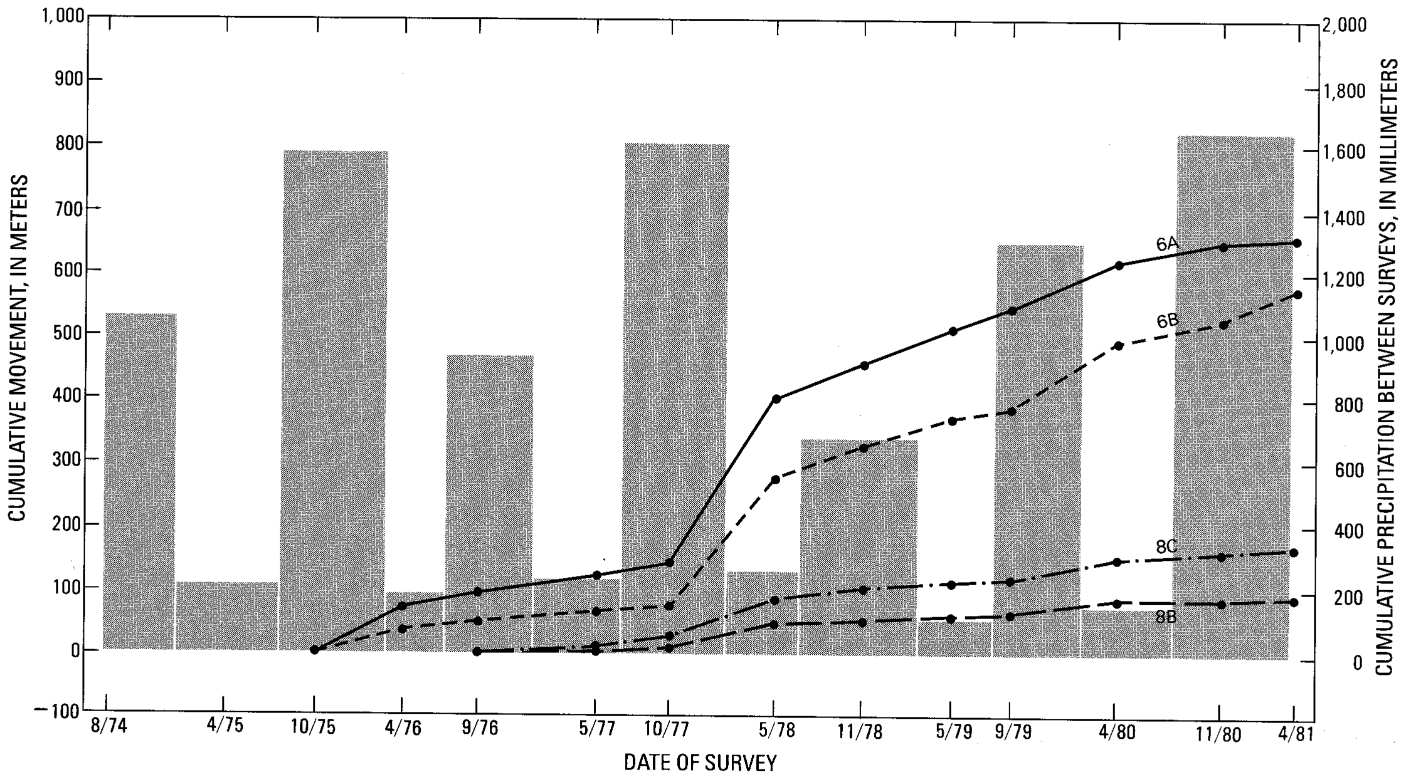

FIGURE 7.—Cumulative movement over the monitoring period showing relation of seasonal precipitation to sites exhibiting combined creep and block glide.

TABLE 1.—*Basic site and survey data from April 1975 to September 1976, May*

[Movement reported is surface displacement along the plane of maximum movement (PMM). Igm,

April 1975 to September 1976							SURVEY DATE							
							4-75		10-75		4-76		9-76	
							PRECIPITATION BETWEEN SURVEYS (mm)							
							1,648		166		1,323		123	
							MOVEMENT BETWEEN SURVEYS							
Hole[1]	Disturbance	Parent material	Movement type	Hole depth/ movement depth (m)	Slope azimuth (degrees)	PMM azimuth (degrees)	Total (mm)	Rate (mm/d)	Total (mm)	Rate (mm/d)	Total (mm)	Rate (mm/d)	Total (mm)	Rate (mm/d)
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
1B	Logged	Schist	Creep	9.0/9.0	45	275	+2.0	+.010	−.5	−.003	−1.0	−.005	+1.0	+.007
2B	None	Schist	Creep	4.3/4.3	45	45	+.4	+.002	+.8	+.001	.0	.000	+.9	+.010
3A	None	Schist	Block glide	10.1/5.5	45	47	+8.9	+.044	+5.4	+.032	+12.8	+.060	+4.0	+.030
3B	None	Schist	Block glide	8.1/6.4	45	50	+7.4	+.040	+5.6	+.030	+7.0	+.030	+4.1	+.030
4A	Logged	Schist	Block glide	18.6/12.6	45	70	+4.4	+.020	−.8	−.005	+5.9	+.030	−1.5	−.010
5A	None	Schist	Creep	9.1/9.1	45	90	—	—	—	—	+2.7	+.010	−.6	−.005
6A	Logged	Igm	Creep and glide	11.0/6.5	225	215	—	—	—	—	84.4	+.440	−19.2	+.130
6B	Logged	Igm	Creep and glide	7.6/6.1	225	230	—	—	—	—	48.9	+.250	+7.4	+.051
7A	None	Cgm	Block glide	10.5/6.9	225	215	—	—	—	—	+8.5	+.040	+1.3	+.010
7B	None	Cgm	Block glide	10.6/8.6	225	208	—	—	—	—	+16.5	+.080	−4.6	−.030
8A	None	Igm	Block glide	20.6/16.4	225	240	—	—	—	—	—	—	−.2	−.001
8B	None	Igm	Total creep and glide	10.2/6.6	225	240	—	—	—	—	—	—	—	—
8B	None	Igm	Creep only	10.2/6.6	225	240	—	—	—	—	—	—	—	—
8B	None	Igm	Glide only	10.2/6.6	225	240	—	—	—	—	—	—	—	—
8C	None	Cgm	Total creep and glide	12.1/8.0	225	220	—	—	—	—	—	—	—	—
8C	None	Cgm	Creep only	12.1/8.0	225	220	—	—	—	—	—	—	—	—
8C	None	Cgm	Glide only	12.1/8.0	225	220	—	—	—	—	—	—	—	—

May to October 1977							SURVEY DATE			
							5-77		10-77	
							PRECIPITATION BETWEEN SURVEYS (mm)			
							681		291	
							MOVEMENT BETWEEN SURVEYS			
Hole[1]	Disturbance	Parent material	Movement type	Hole depth/ movement depth (m)	Slope azimuth (degrees)	PMM azimuth (degrees)	Total (mm)	Rate (mm/d)	Total (mm)	Rate (mm/d)
1A	Logged	Schist	Creep	10.5/9.6	45	55	+0.2	+0.002	−0.6	−0.006
1B	Logged	Schist	Creep	9.0/9.0	45	275	−.5	−.002	−.8	−.006
2B	None	Schist	Creep	4.3/4.3	45	45	−.5	−.002	+.1	+.001
3A	None	Schist	Block glide	10.1/5.5	45	47	+5.0	+.020	+3.8	+.026
3B	None	Schist	Block glide	8.1/6.4	45	50	+6.7	+.030	+3.9	+.030
4A	Logged	Schist	Block glide	18.6/12.6	45	70	+4.0	+.020	+1.4	+.010
5A	None	Schist	Creep	9.1/9.1	45	90	+.2	+.001	+.4	+.003
6A	Logged	Igm	Creep and glide	11.0/6.5	225	215	+28.0	+.120	+13.0	+.090
6B	Logged	Igm	Creep and glide	7.6/6.1	225	230	+13.3	+.057	+7.4	+.054
7A	None	Cgm	Block glide	10.5/6.9	225	215	+2.6	+.010	−.8	−.010
7B	None	Cgm	Block glide	10.6/8.6	225	208	+8.4	+.035	−2.0	−.010
8A	None	Igm	Block glide	20.6/16.4	225	240	+1.8	+.008	−.4	−.003
8B	None	Igm	Total creep and glide	10.2/6.6	225	240	+4.8	+.020	+.8	+.010
8B	None	Igm	Creep only	10.2/6.6	225	240	+4.0	+.018	+.7	+.006
8B	None	Igm	Glide only	10.2/6.6	225	240	+.8	+.002	+.1	+.004
8C	None	Cgm	Total creep and glide	12.1/8.0	225	220	+17.0	+.070	.0	.000
8C	None	Cgm	Creep only	12.1/8.0	225	220	.0	.000	−2.0	−.010
8C	None	Cgm	Glide only	12.1/8.0	225	220	+17.0	+.070	+2.0	+.010

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. 9). Creep deformation may be occurring within the moving block but generally accounts for only a small part of the total movement. Sites 3 and 4 (located in Redwood Creek schist), site 7 (located in the graywacke sandstone and mudstone of the Incoherent unit of Coyote Creek), and hole 8A at site 8 (located in the Coherent graywacke sandstone 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 and ranges from a minimum of 2.9 mm/a at hole 8A in the coherent graywacke and mudstone to a maximum of 16.4 mm/a at hole 3A in the schist (table 2). Inspection of plots of cumulative movement over time for these holes (fig. 6) indicates that all holes experienced a nearly uniform annual displacement over the study period.

Holes 3A and 313 exhibit fairly constant displacement rates throughout the year with only small seasonal variation. Holes 4A, 7A, 7B, and 8A exhibit strong seasonal fluctuations with most of the displacement

to October 1977, May 1978 to September 1979, and April 1980 to April 1981

incoherent graywacke and sandstone; Cgm, coherent graywacke and mudstone; —, not measured]

May 1978 to September 1979

Hole[1]	Disturbance	Parent material	Movement type	Hole depth/ movement depth (m)	Slope azimuth (degrees)	PMM azimuth (degrees)	Survey date 5-78; precipitation between surveys 1,608 mm: Total (mm)	Rate (mm/d)	Survey date 11-78; precipitation 251 mm: Total (mm)	Rate (mm/d)	Survey date 5-79; precipitation 966 mm: Total (mm)	Rate (mm/d)	Survey date 9-79; precipitation 138 mm: Total (mm)	Rate (mm/d)
1A	Logged	Schist	Creep	10.5/9.6	45	55	+0.8	+0.008	+11.0	+0.060	−2.1	−0.010	−1.2	−0.010
1B	Logged	Schist	Creep	9.0/9.0	45	275	+.6	+.008	+6.9	+.040	−.8	−.004	−3.0	−.020
2B	None	Schist	Creep	4.3/4.3	45	45	+.4	+.002	+1.6	+.010	+.1	+.001	+.2	+.020
3A	None	Schist	Block glide	10.1/5.5	45	47	+14.6	+.072	+5.1	+.027	+8.2	+.047	+5.4	+.039
3B	None	Schist	Block glide	8.1/6.4	45	50	+10.7	+.050	+17.6	+.090	+2.7	+.020	+1.8	+.010
4A	Logged	Schist	Block glide	18.6/12.6	45	70	+4.4	+.020	+16.5	+.090	+5.2	+.030	−4.0	−.030
5A	None	Schist	Creep	9.1/9.1	45	90	+1.0	+.005	+12.5	+.060	−1.2	−.010	−3.1	−.020
6A	Logged	Igm	Creep and glide	11.0/6.5	225	215	+253.6	+1.220	+58.0	+.310	+56.0	+.310	+25.0	+.180
6B	Logged	Igm	Creep and glide	7.6/6.1	225	230	+189.4	+.964	+49.0	+.260	+42.0	+.280	+17.0	+.120
7A	None	Cgm	Block glide	10.5/6.9	225	215	+16.0	+.080	−5.3	−.030	+6.7	+.040	+.5	+.004
7B	None	Cgm	Block glide	10.6/8.6	225	208	+20.3	+.100	−13.6	−.070	+1.3	+.060	−1.7	−.010
8A	None	Igm	Block glide	20.6/16.4	225	240	+4.2	+.018	−.4	−.002	+3.6	+.020	−1.1	−.006
8B	None	Igm	Total creep and glide	10.2/6.6	225	240	+47.0	+.230	−2.0	−.010	+11.0	+.060	−2.8	−.021
8B	None	Igm	Creep only	10.2/6.6	225	240	+25.0	+.120	−4.4	−.020	+5.8	+.030	−3.6	−.022
8B	None	Igm	Glide only	10.2/6.6	225	240	+22.0	+.110	+2.4	+.010	+5.2	+.030	+.8	+.001
8C	None	Cgm	Total creep and glide	12.1/8.0	225	220	+76.0	+.370	+11.0	+.060	+9.0	+.050	+3.0	+.020
8C	None	Cgm	Creep only	12.1/8.0	225	220	+45.0	+.220	+1.0	+.050	+4.0	+.020	+3.0	+.020
8C	None	Cgm	Glide only	12.1/8.0	225	220	+31.0	+.150	+1.0	+.010	+5.0	+.030	.0	.000

April 1980 to April 1981

Hole[1]	Disturbance	Parent material	Movement type	Hole depth/ movement depth (m)	Slope azimuth (degrees)	PMM azimuth (degrees)	Survey date 4-80; precipitation between surveys 1,551 mm: Total (mm)	Rate (mm/d)	Survey date 11-80; precipitation 219 mm: Total (mm)	Rate (mm/d)	Survey date 4-81; precipitation 1,076 mm: Total (mm)	Rate (mm/d)
1A	Logged	Schist	Creep	10.5/9.6	45	55	+1.2	+0.010	−1.4	−0.005	−3.2	−0.020
1B	Logged	Schist	Creep	9.0/9.0	45	275	+1.9	+.010	+.9	−.005	−6.0	−.037
2B	None	Schist	Creep	4.3/4.3	45	45	−.5	−.002	+1.5	+.010	+2.8	+.017
3A	None	Schist	Block glide	10.1/5.5	45	47	+12.7	+.060	+9.5	+.047	+3.1	+.020
3B	None	Schist	Block glide	8.1/6.4	45	50	+6.2	+.030	+5.9	+.030	+4.2	+.026
4A	Logged	Schist	Block glide	18.6/12.6	45	70	+6.0	+.030	−4.3	+.020	+2.4	+.015
5A	None	Schist	Creep	9.1/9.1	45	90	+1.8	+.010	+1.1	+.010	−2.2	+.014
6A	Logged	Igm	Creep and glide	11.0/6.5	225	215	+77.0	+.370	+29.0	+.140	+10.4	+.069
6B	Logged	Igm	Creep and glide	7.6/6.1	225	230	+109.0	+.530	+42.0	+.200	+37.0	+.250
7A	None	Cgm	Block glide	10.5/6.9	225	215	+19.2	+.090	−.8	−.004	+10.2	+.069
7B	None	Cgm	Block glide	10.6/8.6	225	208	Tube pinched below 8.6 m					
8A	None	Igm	Block glide	20.6/16.4	225	240	+3.6	+.014	−.7	+.003	+2.6	+.017
8B	None	Igm	Total creep and glide	20.6/16.4	225	240	+23.8	+.120	−3.4	−.012	+12.8	+.079
8B	None	Igm	Creep only	10.2/6.6	225	240	+11.0	+.050	−3.5	−.020	+6.7	+.040
8B	None	Igm	Glide only	10.2/6.6	225	240	+13.6	+.070	+.1	+.008	+6.1	+.039
8C	None	Cgm	Total creep and glide	12.1/8.0	225	220	+40.0	+.190	+5.0	+.020	+8.3	+.050
8C	None	Cgm	Creep only	12.1/8.0	225	220	+23.0	+.110	+5.0	+.020	+8.3	+.050
8C	None	Cgm	Glide only	12.1/8.0	225	220	+17.0	+.080	.0	.000	.0	.000

[1] Numerals refer to sites (fig. 1).

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 increase followed the largest annual rainfall recorded during the study period. The rate of movement. in holes 3B and 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 Redwood Creek schist is occurring between 5 and 7 m; at site 4 it is occurring at approximately 12 m. Both these sites are at the same elevation and within 400 m of each other; these circumstances emphasize 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 sandstone and mudstone is occurring between 6 and 9 m. This site is also heavily forested and exhibits little surficial indication of the active movement.

Hole A, drilled near the upper edge of the earthflow deposits of Counts Hill Prairie (Counts Hill Prairie earthflow), indicates shear at a depth between 16 and 17 m. 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.

TABLE 2.—*Data analysis summary, including total, annual, and seasonal displacement rates and characteristics of movement for each hole*

Hole[1]	Location	Depth of movement (m)	Depth to water table (m)	Record period (days)	Record period (years)
1A	Midslope, elev. 412 m	Above 9.63 (bottom)	Dry	2,390	6.0
1B	Midslope, elev. 381 m; below 1A	Above 8.96 (bottom)	7.0	2,390	6.0
2B	Midslope, elev. 366 m; below 2A	Above 4.31 (bottom)	Dry	2,390	6.0
3A	Midslope, elev. 305 m	Above shear zone 5.49–7.02	6.1	2,390	6.0
3B	Midslope, elev. 290 m; below 3A	Above shear zone 6.35–7.49	6.1	2,390	6.0
4A	Midslope, elev. 305 m	Above shear zone at 5.93	6.1	2,390	6.0
5A	Lower slope, elev. 198 m; above Redwood Creek	Above 9.13 (bottom)	Dry	2,017	5.0
6A	Upper slope, elev. 625 m	Above shear zone at 6.45	6.0	1,894	5.0
6B	Upper slope, elev. 549 m; below 6A	Above shear zone 6.09–6.65	6.0	1,891	5.0
7A	Midslope, elev. 305 m	Above shear zone 6.94–7.49	Dry	2,004	5.0
7B	Midslope, elev. 224 m; below 7A	Above shear zone 8.57–9.12	Dry	2,004	3.0
8A	Upper slope, elev. 553 m; above active scarp	Above shear zone 16.37–16.95	4.5	1,797	5.0
8B	Upper slope, elev. 518 m; in small, active earthflow	Above shear zone 6.6–7.68	4.0	1,650	4.0
8C	Upper slope, elev. 488 m; in small, active earthflow	Above shear zone at 8.04	2.4	1,650	4.0

Hole[1]	DISPLACEMENT Total (mm)	DISPLACEMENT Average annual (mm/yr)	DISPLACEMENT Average seasonal (mm) Summer	DISPLACEMENT Average seasonal (mm) Winter	MOVEMENT RATE Average annual (mm/d)	MOVEMENT RATE Average seasonal Summer	MOVEMENT RATE Average seasonal Winter	Movement characteristics
1A	+3.5	+0.59	+0.90	−0.26	+0.0015	+0.004	+0.001	Small summer increments; most movement occurred in surge, summer 1978; creep.
1B	+.7	+.12	+.75	−.54	+.0003	+.0038	−.0036	Small summer increments; most movement occurred in surge, summer 1978; creep.
2B	+2.2	+.37	+.85	−.41	+.0010	+.005	−.002	Small summer increments; creep.
3A	+98.5	+16.42	+5.53	+9.33	+.0450	+.034	+.046	Steady movement throughout year; small winter surges 1976, 1978, 1980; block glide.
3B	+83.8	+13.97	+6.48	+6.41	+.0380	+.037	+.032	Steady movement throughout year; small surges beginning winter 1977 and continuing through summer 1978; block glide.
4A	+48.2	+8.03	+2.65	+4.61	+.0200	+.013	+.024	Small incremental movement throughout year; winter dominant; surge summer 1978; block glide.
5A	+12.6	+2.52	+2.06	+.38	+.0069	+.010	+.000	Small summer increment; most movement occurred in surge, summer 1978; creep.
6A	+653.6	+130.72	+28.84	+84.90	+.3581	+.170	+.422	Movement throughout year with dominant winter surges; large surges, winters 1977, 1979; creep and glide.
6B	+571.4	+114.28	+24.56	+74.77	+.3131	+.137	+.387	Movement throughout year with dominant winter surges. Acceleration 1977, 1979; creep and glide.
7A	+58.2	+11.64	−1.02	+10.55	+.0319	−.006	+.016	Dominant winter movement; block glide.
7B	+33.6	+11.20	−5.48	+13.88	+.0168	−.030	+.069	Dominant winter movement; block glide.
8A	+14.4	+2.88	−.36	+3.16	+.0080	−.002	+.015	Dominant winter movement in small increments; block glide.
8B	+92.0	+23.00	−1.85	+19.88	+.0630	−.008	+.102	Dominant winter movement. Large surge 1977, 1979; creep and glide.
	+41.9	+10.48	−2.65	+10.50	+.0287	+.014	+.052	Creep.
	+50.9	+12.73	+.80	+9.54	+.0349	−.006	+.050	Glide dominates.
8C	+169.3	+42.33	+4.75	+30.06	+.1160	+.025	+.146	Dominant winter movement. Large surge 1977, 1979; creep and glide.
	+96.3	+24.08	+4.00	+16.06	+.0660	+.020	+.080	Creep dominates.
	+73.0	+18.25	+.75	+14.00	+.0500	+.005	+.066	Glide.

[1] Numerals refer to sites (fig. 1).

COMBINED CREEP AND BLOCK GUIDE

Sites exhibiting a combined creep and block-glide profile typically display a distinct zone of shear displacement that has substantial progressive creep deformation occurring within the moving block (fig. 10). Holes 8B and 8C, which are within the Counts Hill Prairie earthflow, and site 6, which is in the coherent graywacke sandstone 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 8B to a maximum of 131.0 mm/a for hole 6A (table 2). Site 6 proved to be the most active site monitored during the survey, and it developed high displacement rates throughout the profile. These high rates of movement resulted in failure of the access tube in the zone of shear

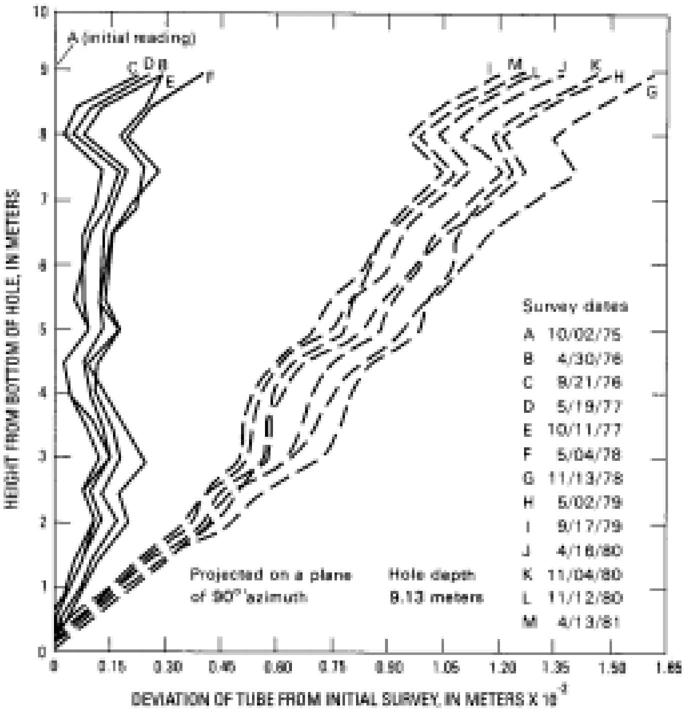

FIGURE 8.-Movement along PMM (plane of maximum movement) recorded at hole 5A (site 5, fig. 1) showing progressive deformation (creep) and strain increases toward the surface. Seasonal movement is very small. Negative or upslope adjustments represent periods of no real displacement and differential adjustment or wandering of the tube in the borehole. Note that most of the displacement recorded at this location occurred in a period of accelerated movement or surge during the summer of 1978 (surveys F-G), after a winter having the highest precipitation recorded during the survey period. (Movement after surge is shown by dotted lines.)

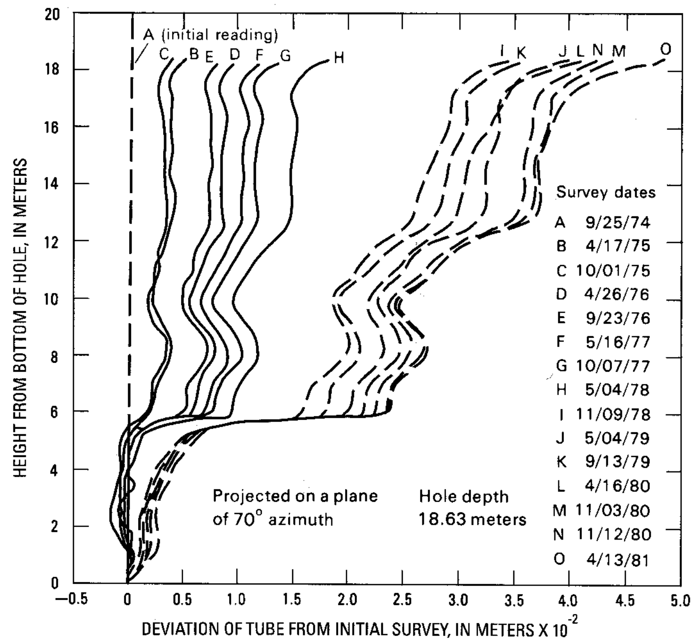

FIGURE 9.-Movement along PMM (plane of maximum movement) recorded at hole 4A (site 4, fig. 1) showing typical block-glide movement with accelerated displacement occurring above a well-defined plane of shear approximately 6 m above the bottom of the hole. Movement is predominantly seasonal. Occasional negative or upslope adjustments represent periods of no real displacement and differential adjustment or wandering of the tube in the borehole. Note that movement occurs predominantly during the winter (surveys C-D, E-F, G-H, h1, K-L) except for a large surge in movement during the summer of 1978 (survey H-I) in response to the exceptionally high rainfall during the preceding winter. (Movement after surge is shown by dotted lines.)

at a depth of about 6.5 m 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 8B and 8C, in the Counts Hill Prairie earthflow, reveal shear taking place at a depth of between 6 and 8 m, substantially above the basal failure plane of the earthflow defined in hole 8A. As holes 8B and 8C are below a distinct headwall scarp in an extremely active flow zone with the surface topographically much lower than 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 6A, 6B, 8B, and 8C indicate that displacement is seasonal and that a greater part of the movement takes place during the winter rainy season (fig. 7; table 2). Distinct surges in rates of movement occurred during the wetter winters of 1978 and 1980.

Creep 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 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 8B and 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 56 percent of total surface displacement at hole 8C and for about 45 percent of total displacement at hole 8B.

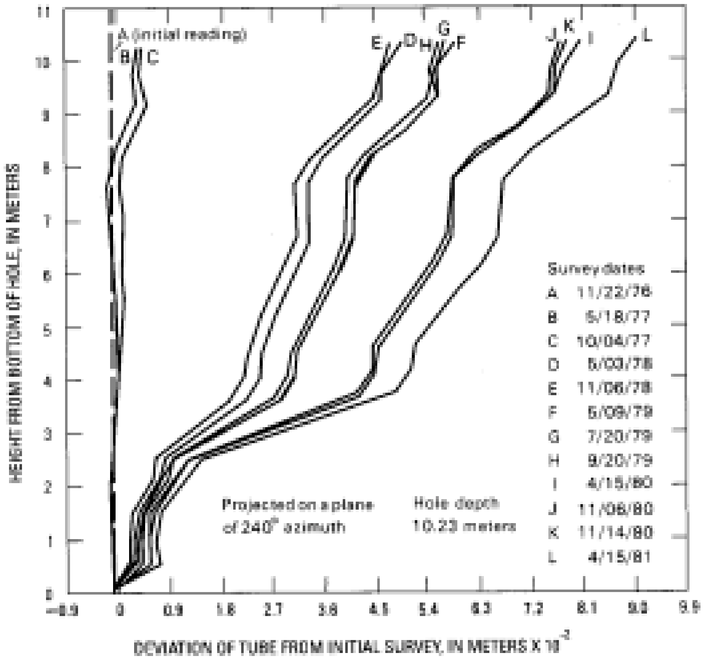

FIGURE 10.-Movement along PMM (plane of maximum movement) recorded at hole 8B (site 8, fig. 1) showing combined block glide and creep deformation occurring within the profile. Accelerated displacement is occurring within a zone between 2.5 and 4 m above the bottom of the hole. Above this zone, progressive displacement (creep) dominates, and strain increases toward the surface. Movement is predominantly seasonal. Occasional negative or upslope adjustments represent periods of no real displacement and differential adjustment or wandering of the tube in the borehole. Note that most movement occurred as winter displacement (surveys C-D, E-F, H-I, K-L).

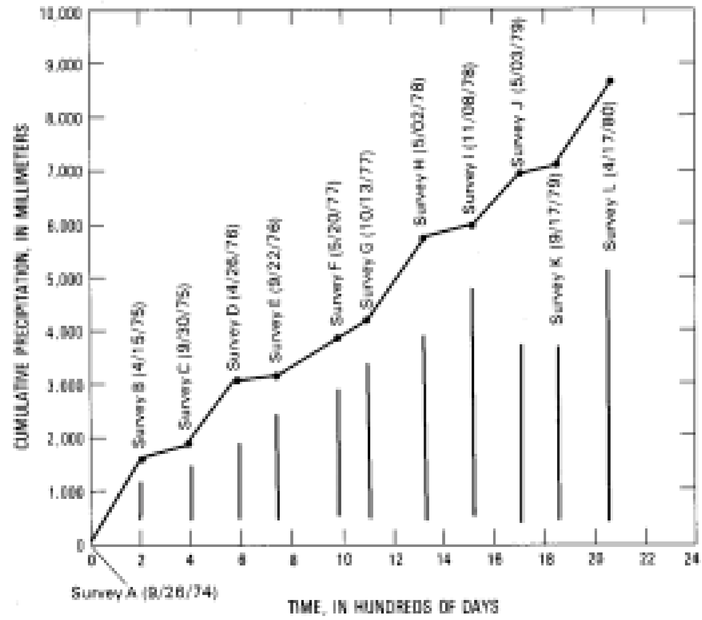

FIGURE 11.—Cumulative precipitation over survey period at Prairie Creek Redwoods State Park.

RELATIONS BETWEEN GEOLOGY AND MOVEMENT

The most active terrain having 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 sandstone units. 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; movement occurred above well-defined shear zones ranging in depth from 6 to 17 m. A primary or secondary shear zone between 6 and 8 m 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 6 and 8, but no purely progressive deformation profiles were encountered, perhaps because of the high rates of strain and subsequent shear failure that dominate this terrain. It would appear, on the basis of 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 sandstone and mudstone along the east side of the creek. Where strains are great enough locally, individual earthflows 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, and progressive creep dominates 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 Grogan fault. Total displacement and annual rates, however, are small relative to those of the east side of the valley. Depth of the active profile at creep-dominated sites ranges from 4 to 16 m. At blockglide-dominated sites, shear generally develops between 6 and 7 m.

RELATIONS BETWEEN PRECIPITATION AND MOVEMENT

Two surveys a year were made of each access tube to assess the effects of winter rain and summer drought on movement. A curve of cumulative precipitation at Prairie Creek Redwoods 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 profiles and cumulative movement plots for each site (figs. 5 - 10), clearly reveals that

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; n.d. = no data]

Hole[1]	Number of observations		Beta distribution (F) value					
			Annual precipitation vs.		Seasonal precipitation vs.		Precipitation during preceding season vs.	
	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	.03	.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*	n.d.	n.d.
3B	6	13	2.85	2.68	.16	.09	n.d.	n.d.
4A	6	13	2.08	1.97	.69	.59	n.d.	n.d.
5A	5	11	4.58	4.30	.06	.07	1.84	2.21
6A	5	11	4.71	3.76	7.21	6.62*	n.d.	n.d.
6B	5	11	17.01*	14.01*	11.42**	12.81**	n.d.	n.d.
7A	5	11	6.47	5.25	48.06**	37.65**	n.d.	n.d.
7B	3	7	.01	.01	37.73**	39.80**	n.d.	n.d.
8A	5	11	20.25*	9.75*	59.48**	26.71**	n.d.	n.d.
8B	4	9	5.85	4.59	32.58**	40.62**	n.d.	n.d.
8C	4	9	5.93	4.34	10.74*	11.25*	n.d.	n.d.

[1] Numerals refer to sites (fig. 1).

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

At the sites dominated by creep (1, 2, 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 preceding season) reveals very low *F* (beta distribution) values and suggests that these variables have little predictive ability (table 3). The low *F* values, however, are 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 if 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 plotted against annual precipitation yielded significant relationships for two of the four access tubes (at holes 1B, 2B) monitoring creep activity (table 3).

Sites that are dominated by block-glide-type processes and that are not within active earthflows (sites 3, 4, 7) typically display predominantly rainy season movement either as a steady movement throughout the year and small winter surges (holes 3A, 3B, 4A) or as winter movement only (holes 7A, 7B). 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 and rainy season surges (holes 6A, 6B) or dominant rainy season movement (8A, 813, 8C). Regression analyses between annual movement and annual precipitation yield significant relationships for two of the five holes (6B, 8A); however, all five holes have a significant correlation between seasonal displacement and seasonal precipitation (table 3).

RELATIONS OF MOVEMENT TO WATER LEVEL

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 lack of seasonal change in water level in the tubes may be in part due to the absence of a single, definable water table. The water in the access tubes was derived from multiple sources of water fed into the holes by several confined waterbearing 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 Grogan fault underlain by sheared and foliated schists. Complex earthflows occur predominantly on slopes east of the Grogan fault underlain by sheared graywacke sandstone and mudstone units. 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 (sites 1, 2, 5); movement in this part of the valley is predominantly in the summer. 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 at the creep-dominated sites (holes 1B, 5A) 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 (sites 3, 4, 6, 7, 8) but are most active and display the greatest movement in the sheared graywacke sandstone and mudstone units east of the Grogan fault. These sites characteristically display dominant movement during the rainy season. This movement may occur as constant downslope motion and winter surges or as winter movement only. On the schist, neither annual displacement nor movement rate was related to annual precipitation at any of the three holes (3A, 3B, 4A). Seasonal precipitation was related to seasonal movement at only one of the three holes (3A). On the graywacke sandstone and mudstone units (sites 6, 7, 8), annual displacement was related to annual precipitation at only two of the seven holes (6B, 8A). Seasonal precipitation was highly correlated, however, with seasonal displacement or seasonal rate at all seven of the holes.

There is a direct relationship between seasonal precipitation and the corresponding amount of block-glide slope deformation in the graywacke sandstone and mudstone units 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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